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PRELIMINARY

YUCCA MOUNTAIN PROJECT

A Summary of Technical Support Activities

January 1987 to June 1988

By:

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Submitted to:

State of Nevada
Agency for Nuclear Projects
Nuclear Waste Project Office
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Volume

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INTRODUCTION

The Nevada Nuclear Waste Project Office, State of Nevada, has developed a technical oversight program as provided for in the Nuclear Waste Policy Act of 1982 (NWPA). This Act and subsequent amendments has led to the selection of Yucca Mountain in Nevada for site characterization as a high-level nuclear waste repository. The intent and letter of the Nuclear Waste Policy Act is to establish a geologic repository for high-level nuclear waste that is predicated on long-term waste isolation soley supported by a combination of the geologic environment and engineered barriers. A 10,000 year time frame for waste isolation is required due to the long-lived nature of the radionuclides associated with high-level radioactive waste and the need to prevent these radionuclides from reaching the accessible environment in any significant concentrations. The technical and scientific challenge of establishing such a repository is unprecedented due to a combination of factors, including: the large volumes and heat-producing nature of the waste, the long period of time necessary for waste isolation from hydrologic or other natural systems, and the impossibility of using or relying upon engineered barriers for prolonged waste isolation.

The U. S. Department of Energy (DOE) has been charged with executing the selection, construction, and operation of the high-level nuclear waste repository program; and the U. S. Nuclear Regulatory Commission (NRC) has the regulatory responsibility of issuing the varying licenses for construction and operation of the repository. The State of Nevada, as an affected party under the NWPA, has an oversight role. The Nuclear Waste Project Office of the State of Nevada executes the technical oversight, and Mifflin & Associates, Inc. (MAI) is one of its technical support contractors in hydrogeology and closely-related technical areas.

This report is a summary of the technical support activities of Mifflin & Associates, Inc., during the 18-month period beginning 01 January 1987 and ending on 30 June 1988. It covers the following topics:

Vadose Zone Drilling Site Selection, Permits, and Quality Assurance (QA) Procedures
Climate Change
Geochemistry and Mineralogy
Disturbed Zone
Hydrogeology
Review of Technical Documents

The report is organized by generally discussing each topic from the following perspectives:

Issue(s)
Objective(s) of Activity
Finding(s)
Interpretation of Finding(s)
Additional Work Needed
Recommended Program
Existing Program

Each Topic/Section has its own Appendix and is preceded by a general introduction. In order to keep the size of the report reasonable, while at the same time, ensuring coverage of crucial points, only lists of technical procedures and research plans contained in the past monthly reports are provided as well as three samples of such technical documents: Technical Procedures for Documentation of Research Activities and Daily Drilling Activity Summary Form; Research Plan for Sampling at or near Yucca Mountain; Research Plan for Vadose Drilling and Cuttings Sampling at or near Yucca Mountain. However, all published works and important progress reports or findings emanating from our activities are included in the Appendices for each section.

Section A

Vadose-Zone Drilling Program

Vadose-Zone Drilling Program

Introduction

Review of the DOE vadose-zone drilling program and borehole history reports indicate that **water or water-based fluids have been injected into all drillholes which fully penetrated the vadose zone at Yucca Mountain.** In addition, UZ-1 borehole was drilled with a vacuum method at great expense but failed to fully penetrate a zone of (perched?) saturation. UZ-1 is so large in diameter that moisture conditions may not equilibrate to predrilling conditions before the useful lives of the emplaced monitoring instruments terminate. UZ-6 also did not fully penetrate the vadose zone using the same method and it also proved extremely costly. UZ-6 is also too large in diameter for useful monitoring of moisture with conventional instruments. Numerous shallow moisture-monitoring holes (N-series neutron logging) were drilled with the ODEX method using air as the circulation fluid, but the depths achieved (maximum is less than 400 ft.) are insufficient to study the full thickness of the vadose zone. The WT-series holes were drilled with air-foam, which requires addition of large amounts of water. The G and H series holes were drilled using conventional drilling fluids. **Therefore, not one borehole at Yucca Mountain project area exists for quality data development in the vadose zone below about 400 feet.** The ideal drilling method should be capable of air drilling to 2,000 feet for full penetration of the vadose zone in some areas.

The proposed State of Nevada vadose-zone drilling program sites are located to sample as many of the unsaturated tuff zones as possible without drilling on the repository block or in the DOE "core" area. The first round of drilling would establish the methodology in terms of drilling and sampling in the hydrogeologic environment of Yucca Mountain and allow analytical results on samples to be compared with DOE postulates. DOE samples of either water or rock from the repository block would not be comparable to sample obtained utilizing the proposed drilling methodology. Eventually, similar data must be developed from several boreholes on the repository block to confidently characterize the site.

The proposed State of Nevada sites are located to allow penetration in the vadose zone for suspected key hydrostratigraphic horizons at the repository block. The uppermost zone, which includes near-surface fractured rock, soils, and alluvial deposits, is hydrologically varied by surface topography and associated surface-water drainages. The uppermost zones are of interest because of the importance of determining the magnitude, timing, and distribution of recharge events that result from precipitation and surface-water runoff events. The second zone of special interest is the bedded and unwelded tuffs below the welded tuffs of the Tiva Canyon Member of the Paintbrush Tuff. This zone may act to perch and redistribute infiltration. Matrix as well as fracture flow may be important in this zone. The third zone of interest is the repository horizon and near-field environments in the welded tuff of the Topopah Spring Member of the Paintbrush Tuff. **Here both matrix moisture and fracture moisture are of great interest from the perspective of characterizing the ground-water travel time and the disturbed zone with respect to the regulatory criteria.** The fourth zone of interest consists of vitric and zeolitic tuffs of the Calico Hills which underlie the proposed repository horizon. This unit appears to be locally saturated near the repository block, and matrix flow may be important. **The geochemistry of water in this unit is critical to the resolution of ground-water travel times in the vadose zone.** The fifth and deepest zone targeted in the State of Nevada vadose-zone drilling program is "first fracture water" in the phreatic (saturated) zone. Some of the uppermost saturated fractures in the zone of regional saturation may contain relatively young water if active recharge is occurring. Boreholes finished in these fractures will provide uppermost water samples of the saturated zone. These waters may also yield definitive information on travel times.

The proposed drilling method, the dual-tube reverse circulation (DTRC) air-rotary method, is known to be capable of producing the desired rock and water samples as well as a useful borehole for monitoring; however, it has not been tested in the terrane of Yucca Mountain. Therefore, one objective of State of Nevada-sponsored vadose-zone drilling at Yucca Mountain is to demonstrate the utility of the dual-tube reverse circulation air-rotary method. This technique should permit hydrologically compatible exploration of the full vertical extent of the vadose zone at Yucca Mountain. It allows for the recovery of representative samples of rock and subsurface fluids that are unaffected by water-based drilling additives. The sampling of saturated regions (perched) in the vadose zone permits the execution of associated geochemical and isotopic studies of vadose-zone water samples. In addition, the resulting boreholes are of small diameter, rapidly constructed, and therefore have utility for temporal monitoring of relatively undisturbed soil gas and moisture conditions (using a variety of monitoring techniques, including: thermal couple psychrometers, lysimeters, tensiometers, heat-dissipation probes, and neutron logging).

The Nuclear Waste Project Office recognized the critical role air drilling should play in establishing useful information from the vadose zone at Yucca Mountain as early as 1984. Since that year, the State of Nevada has attempted to enter into a vadose-zone drilling program but has been blocked by a series of federal government actions. The nondrilling aspects of the State of Nevada's drilling effort have been pursued to date in order to maintain drilling preparedness should both funding and approval be established.

Vadose-Zone Drilling

ISSUES:

Vadose-zone drilling addresses the following issues:

Ground-Water travel time from the repository horizon to the regional water table under the prewaste emplacement condition of 10CFR60.113(2), and

Overall performance of the fractured-tuff vadose zone from the waste isolation perspective as related to 10CFR60.112 and 40CFR191.13.

OBJECTIVES:

The fundamental objective of State of Nevada sponsored vadose-zone drilling at Yucca Mountain is to establish a useful drilling technique, specifically, the dual-tube reverse circulation air-rotary method, for the exploration of the full vertical extent of the vadose zone without the use of water near the Yucca Mountain Site.

This drilling technique should permit the recovery of representative rock samples and water held within the rocks with very little disturbance to the ambient conditions found in the field.

The following site characteristics of Yucca Mountain are addressed by the vadose-zone drilling program:

The distribution of perched water (i.e. localized saturated zones) within the vadose zone in time and space;

The distribution of fracture flow in the vadose zone and its importance to water movement through tuff formations; and

The natural recharge water flux to the repository horizon and its distribution in time and space below the repository horizon.

ACTIVITIES:

A review of potential drilling sites was completed, taking into consideration geology, hydrogeology, political boundaries, and drilling-rig access. Field reconnaissance of road conditions was carried out on the western and eastern sides of Yucca Mountain.

Potential drilling sites located west and east of Yucca Mountain have been selected based on hydrogeology, geology, and access for drilling equipment.

In anticipation of the commencement of the vadose-zone drilling program (tentatively scheduled for November 1987), sample containers and storage facilities were obtained and equipment for water sampling was ordered for the drilling operations. The storage facility, which was leased in August of 1987, is used for equipment and sample container storage and archiving preparation prior to the actual drilling.

Two polycarbonate air-exclusion flow cells were built. During water-sampling operations, these will allow simultaneous measurement of pH, electrical conductivity, temperature, redox potential, and dissolved oxygen, while leaving four ports free for buffers and/or standard solutions.

QA procedures were finalized and forwarded to the State of Nevada QA Manager. Furthermore, the staff at MAI developed draft technical procedures for the drilling program (for a complete list see Appendix A-II).

After MAI staff reviewed the geology and hydrogeology of the proposed drilling sites, the sites were archaeologically surveyed by Dr. R. K. Rafferty (Environmental Research Center, University of Nevada, Las Vegas) and application has been made to the U. S. Bureau of Land Management (BLM) for drilling permits, Appendix A-II).

The vadose-zone drilling program start-up (Phase I) was delayed due to the lack of a timely response by the BLM to MAI's right-of-way drilling application (submitted on September 30, 1987). The delay in granting approval to the MAI drilling permit, as explained by M. Moran (BLM, Las Vegas) was due to the fact that BLM felt that DOE's application takes precedence over MAI's application and because the drilling sites proposed by MAI application dated September 30, 1987 are located within the DOE right-of-way area as presented to BLM in their application. Additional drilling-site applications outside of the DOE requested right-of-way area but in the Yucca Mountain tuff sequence were then developed by MAI.

On April 26, 1988, Drs. M. D. Mifflin and Atef Elzeftawy met M. Moran (BLM, Las Vegas) and staff and a BLM adjudicator (Denver office) at Moran's request, to discuss the second group of MAI drilling permit applications for vadose-zone drilling sites AZ-9 and AZ-10, located beyond the DOE right-of-way. Mifflin explained the technical objectives and goals of the vadose-zone drilling project. Moran stated that his staff have been uncertain as to how to proceed with MAI's first group of applications, presently under litigation with the State of Nevada. Moran asked whether MAI wants his office to process the two applications together or separately (the first group was submitted October 1, 1987; the second group was submitted on April 4, 1988). Mifflin's response was that MAI needs the drilling permits for all drilling areas submitted (Areas AZ-1 through AZ-10 as soon as possible. Moran stated that his office could proceed only with the second applications for areas AZ-9, and AZ-10, submitted on April 4, 1988, because of litigation involving the first permit applications.

The U. S. BLM office in Las Vegas was in contact with Dr. A. Elzeftawy (MAI) concerning the second MAI drilling permit applications for areas AZ-9 and AZ-10. We were informed that a drilling permit for area AZ-9 (Site on the Nellis Air Force Bombing Range) may not be granted by BLM due to disagreement between BLM and the Air Force on air space restrictions. However, the BLM office in Las Vegas sought additional advice from their Washington, D. C. Headquarter office and their opinion was to be transmitted in writing to MAI. In addition, we were informed by E. Arellano (BLM) that the permit for area AZ-10 would be issued within the month of July 1988.

As promised by E. Arellano of the U.S. BLM, we received two drilling permits Nos. N-48327 and 48282 on 30 June 1988 (see attached letters and permits from BLM in Appendix A-V).

ADDITIONAL WORK NEEDED:

It is necessary to maintain the warehouse, sample containers, etc. as well as test the equipment to be used for sampling.

RECOMMENDED PROGRAM:

We judge that the same issues and associated objectives remain to be resolved and accomplished. The DTRC drilling is a key element in the State of Nevada oversight program that allows for independent sample collection and associated verification vadose-zone hydrology. Neither useful site-specific data nor plausible or conservative conceptual models of the vadose-zone hydrology have been put forth by the DOE program to date.

The drilling capability is being maintained by continued operation of the warehousing of necessary sample containers and the refinement and testing of sampling equipment.

Appendix A

Vadose-Zone Drilling Program

List of Appendices

Appendix A-1

List of MAI Research Plans and Technical Procedures

LIST OF MAI RESEARCH PLANS AND TECHNICAL PROCEDURES

MRP-1.0	Research Plan for Drilling at or near Yucca Mountain.
MRP-2.0	Research Plan for Water Sampling at or near Yucca Mountain.
MTP-3.01	Position Titles, Descriptions, and Minimum Qualifications.
MTP-3.02	Technical Procedure for Documentation of Research Activities.
MTP-3.12	Technical Procedure for Installation of Surface Casing in Yucca Mountain Exploratory Boreholes.
MTP-3.13	Technical Procedure for Daily Drilling Activity Summary Form.
MTP-3.14	Technical Procedure for Drilling Time Form.
MTP-3.15	Technical Procedure for Neutron Probe Moisture Data Form.
MTP-3.16	Technical Procedure for Photographic Log Form.
MTP-3.17	Technical Procedure for Sample Identification (ID) Form.
MTP-3.18	Technical Procedure for Record of Sample Custody Form.
MTP-3.19	Technical Procedure for Dual-Tube Drilling Flow Test and Field Chemistry Form.
MTP-3.21	Technical Procedure for Collection and Sampling of Yucca Mountain Drill Cuttings.
MTP-3.22	Technical Procedure for Collection and Preservation of Colloid Samples for Laboratory Analysis.
MTP-3.23	Technical Procedure for Thief-Type Sampling of Natural Waters in the Field.
MTP-3.24	Technical Procedure for Water Sampling with a Double-Valve Purge Pump System.
MTP-3.31	Technical Procedure for Field Filtration of Natural Water Samples.
MTP-3.41	Technical Procedure for Relative Field Measurement of Water Level in a Borehole with an Electrical Tape.
MTP-3.51	Technical Procedure for Preparation of Water Samples for Carbon-14 Analysis by Accelerator Mass Spectrometry.
MTP-3.71	Technical Procedure for Field Measurement of pH.
MTP-3.711	Technical Procedure for Determination of Aluminum in Samples of Natural Water.
MTP-3.72	Technical Procedure for Measurement of Electrical Conductivity of Water Samples in the Field.
MTP-3.73	Technical Procedure for Field Measurement of Reduction-Oxidation Potential: including

Preparation and Storage of Reduction-Oxidation Solutions of Standard Potential, and Calibration of REDOX Electrodes.

MTP-3.74 Technical Procedure for Field Measurement of Dissolved Oxygen in Water Samples by Membrane Electrode Probe.

MTP-3.75 Technical Procedure for Field Measurement of the Total Alkalinity of Water Samples.

MTP-3.76 Technical Procedure for Field Measurement of Dissolved Sulfate in Natural Water Samples by Portable Spectrophotometer.

MTP-3.77 Technical Procedure for Determination of Ferrous Iron in Natural Waters.

MTP-3.78 Technical Procedure for Field Measurement of Dissolved Oxygen in Water Samples by Titration.

MTP-3.79 Technical Procedure for Field Measurement of Aqueous Sulfide in Water Samples by Portable Spectrophotometer.

MTP-3.80 Technical Procedure for Field Measurement of Total Dissolved Iron in Water Samples by Portable Spectrophotometer.

MTP-3.81 Technical Procedure for Measuring Air Temperature Statically and with a Wet-Bulb Thermometer near a Borehole Drilling Site.

MTP-3.9 Technical Procedure for Operating a Downhole Video Camera System with Gyro.

MTP-12.1 Technical Procedure for Calibration of pH Meter.

MTP-12.2 Technical Procedure for Calibration of Electrical Conductivity Meter.

MTP-12.3 Technical Procedure for Air Calibration of Dissolved Oxygen Meter and Membrane Electrode Probe.

MTP-13.1 Technical Procedure for Preparation of Water Sample Containers.

Appendix A-II

Research Plan for Vadose Zone Drilling and Cuttings Sampling at or near Yucca Mountain, MRP-1.0.

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MRP-1.0 RESEARCH PLAN FOR VADOSE ZONE DRILLING AND CUTTINGS SAMPLING AT OR NEAR YUCCA MOUNTAIN.

BACKGROUND

Review of DOE hole history reports indicates that water has been injected into most drillholes which fully penetrated the vadose zone at Yucca Mountain; an exception is UZ-1, which was drilled with a vacuum method at great expense and failed to fully penetrate a zone of perched saturation. Numerous shallow moisture-monitoring holes (the N-series) were drilled with the ODEX method using air as the circulation fluid, but the depths achieved are insufficient to consider these holes representative of the full thickness of the vadose zone. The WT-series holes were drilled with air-foam, which requires addition of large amounts of water. The fundamental objective of State-sponsored vadose-zone drilling at Yucca Mountain is to develop and demonstrate a drilling technique, specifically the dual-tube reverse circulation (DTRC) air rotary method, that permits exploration of the full vertical extent of the vadose zone at Yucca Mountain without addition of water. This drilling technique should permit recovery of representative samples of rock and subsurface fluids that are unaffected by water based drilling additives, and may allow geochemical studies of saturated regions in the vadose zone.

A significant component of this plan is methodology assessment with respect to DTRC air-rotary drilling. Monitoring system design has been specifically excluded from the drilling plan. The Plan mandates collection of all drill cuttings and associated fluid, with specific criteria for initiating and terminating activities that support the (separate) water sampling research plan, MRP-2.0.

Site characteristics of Yucca Mountain addressed by vadose zone drilling, sampling, and hydrogeologic testing are:

1. The three-dimensional distribution of perched water in the vadose zone;

2. The three-dimensional distribution and importance of fracture flow in the vadose zone;

3. The natural flux of recharge waters to the repository horizon, and the distribution, in both time and space, of that flux from the repository horizon to the saturated zone;

4. The paleohydrologic conditions of saturation and flux in the vadose zone during a pluvial climate (a wetter/colder climate of the Pleistocene); and

5. The three-dimensional pattern of gas circulation within the vadose zone (air and water vapor).

Issues that may be addressed include:

1. Travel time of water from the repository horizon to the water table under pre-waste-emplacement conditions;

2. The sorption that might be expected and the geochemical and mineralogical reactions (including water release) under the thermal load of the repository;

3. Climate change hydrology;

4. Disturbed zone extent, as viewed from the hydrogeological perspective; and

5. Overall performance of the fractured-fuff, vadose-zone environment from a waste-isolation perspective.

The vadose-zone drilling is designed to systematically obtain the samples of rock, water, and gas for analytical work while constructing boreholes for in-situ hydrologic monitoring. Drilling will be distributed over three years.

Rationale for Borehole Locations

Ten proposed borehole locations (Figure MRP-1.0-1. and Table MRP-1.0-1.) were based on the following criteria:

- Proximity to the repository block;
- Hydrogeologic setting;
- Surface hydrologic environment;
- Estimated depth to regional saturation; and
- Access.

Five zones will be investigated by vadose-zone drilling. The uppermost zone, which includes near-surface fractured rock, soils, and alluvial deposits, is hydrologically varied by surface topography and associated surface-water drainages. The uppermost zones are of interest because of the importance of determining the magnitude, timing, and distribution of recharge pulses that result from precipitation events.

The second zone of interest is the bedded and unwelded tuffs below the welded tuffs of the Tiva Canyon Member of the Paintbrush Tuff. This zone may act to perch and redistribute infiltration. Matrix as well as fracture flow may be important in this zone.

The third zone of interest is the repository horizon and near-field environments in the welded tuff of the Topopah Spring Member of the Paintbrush Tuff. Here both matrix moisture and fracture moisture are of great interest from the perspective of characterizing the disturbed zone.

The fourth zone targeted for investigation consists of vitric and zeolitic tuffs of the Calico Hills which underlie the proposed repository horizon. This unit is locally saturated, and matrix flow may be important. The geochemistry of water in this unit is critical to the resolution of ground-water travel times in the vadose zone.

The fifth and deepest zone targeted in the vadose-zone drilling is "first water" in the phreatic zone. Some of the uppermost saturated fractures in the zone of regional saturation may contain relatively young water if active recharge is occurring. Boreholes finished in these fractures will provide uppermost water samples of the saturated zone.

Drilling Activity Decision Criteria

Figure MRP-1.0-2. is a logic flow chart that illustrates criteria that shall be used to initiate and terminate the various field activities associated with drilling and sampling. A Staff Geoscientist (minimum position required, see MTP-3.01) designated by the Principal Investigator as Drilling Supervisor, will make the field decisions required in the Figure MRP-1.0-2 Logic Chart. These decisions are in response to variable field conditions.[1]

1. Drilling Supervisor is an informal title applied to the designated person responsible for all activities at the drilling site. The person designated as Drilling Supervisor may change from morning to afternoon, day to day, week to week, etc., and when this person leaves the drill site, he/she is no longer Drilling Supervisor.

This plan calls for selection of a drill pad area to accommodate research objectives, followed by acquisition of drilling and right-of-way permits. If drilling pad preparation is required, it is without water (normally used to assist compaction and dust suppression), followed by setup of the rig and support equipment and calibration of moisture analyzers and any other instruments used to monitor the drilling process. The Staff Geoscientist shall determine whether it is feasible to proceed with drilling or repeat the setup process. Once drilling has begun, the drilling and cuttings sampling activity (governed by MTP-3.21) apply until the alluvium is penetrated or free water is encountered.

When the drill cuttings indicate that alluvium has been fully penetrated, a steel surface casing will be set approximately one meter into the underlying rock to prevent caving of alluvial materials, and will extend a convenient distance above ground level. Drilling and cuttings sampling will resume until free water is evident in the drill cuttings returns, at which time drilling will pause. The drill pipe string will be broken at the first drill pipe joint above ground level, and static water level will be measured.

If standing water can be detected in the drill pipe, a thief-type water sample (BAT hypoprobe sampling system)will be attempted immediately; if no standing water is detected in the drill pipe, the drill pipe will be pulled and an insert bit will be installed and run downhole prior to attempting the thief-type water sampling. Thief-type sampling will continue until the hole goes dry or the Drilling Supervisor determines that sample quantity and quality is sufficient. The water sample research plan (MRP-2.0) will take effect upon completion of thief-type sampling if sufficient standing water is available for production using the Solinst pump. Drilling may or may not be continued below the sampling zone, depending upon the information established in the drilling area. If a flow test is conducted, water will be collected in a water truck(s) or tank to prevent perturbation of the surface moisture regime by air-lifted ground water.

Minimum Equipment:

1. Drill rig: The drill rig utilized for vadose zone drilling at Yucca Mountain shall consist of an Ingersoll-Rand TH100A Angle Drill or equivalent.

    a. Torque: The rig shall be fully hydraulic and equipped with a tophead drive capable of delivering 1,233 kg-m (107,000 inch-lb) of torque at zero to 130 revolutions per minute (rpm).

    b. Mast capacity: Mast capacity shall be at least 29,500 kg (65,000 lb).

    c. Pullback (hoist capacity): Pullback shall be at least 26,760 kg (59,000 lb).

    d. Air compressor: The air compressor shall deliver at least 750 cubic feet per minute (cfm) at 250 pounds per square inch (psi).

    e. Drill pipe: The drill rig shall be supported with sufficient 114 mm (4-1/2 inch) dual-tube drill pipe for the specific depth objective.

    f. Recorder: The drill rig shall be configured to allow continuous recording of clock time, compressor output (pressure, temperature, and flow rate), and mast load.

    g. Wireline and deviation tool: The drill rig shall be equipped with at least 2,000 feet of logging cable for conducting deviation surveys, and a deviation tool shall be provided.

2. Heavy-duty truck with enclosed bed and lift gate for hauling cuttings from drill site to warehouse and returning with supplies.

3. Water truck or tank configured to receive any excess water airlifted during flow tests.

Documentation of Drilling Activities:

Documentation of Vadose-Zone Drilling and cuttings sampling shall be governed by the following Research Plan and technical procedures:

1. MRP-2.0, Research Plan for Water Sampling at or near Yucca Mountain.
2. MTP-3.01, Position Titles, Descriptions, and Minimum Qualifications.
3. MTP-3.02, Technical Procedure for Documentation of Research Activities.
4. MTP-3.13, Technical Procedure for Daily Drilling Activity Summary Form.
5. MTP-3.14, Technical Procedure for Drilling Time Form.
6. MTP-3.16, Technical Procedure for Photographic/Video Log Form.
7. MTP-3.17, Technical Procedure for Sample Identification (ID) Form.
8. MTP-3.18, Technical Procedure for Record of Sample Custody Form.
9. MTP-3.19, Technical Procedure for Dual-Tube Drilling Flow Test and Field Chemistry Form.
10. MTP-3.21, Technical Procedure for Collection and Sampling of Drill Cuttings.
11. MTP-3.23, Technical Procedure for Thief-Type Sampling of Natural Waters in the Field.
12. MTP-3.41, Technical Procedure for Relative Field Measurement of Water Level in a Borehole with an Electrical Tape.

In addition, a bound Drilling Summary Notebook (log of drill-site activities) shall be established. Drilling Supervisor shall summarize the day's activities at the drill site, including but not limited to the following:

1. Drilling progress, and associated problems;
2. Samples collected;
3. Samples shipped (picked up for transport to storage); and
4. Personnel, weather, and any unusual conditions.

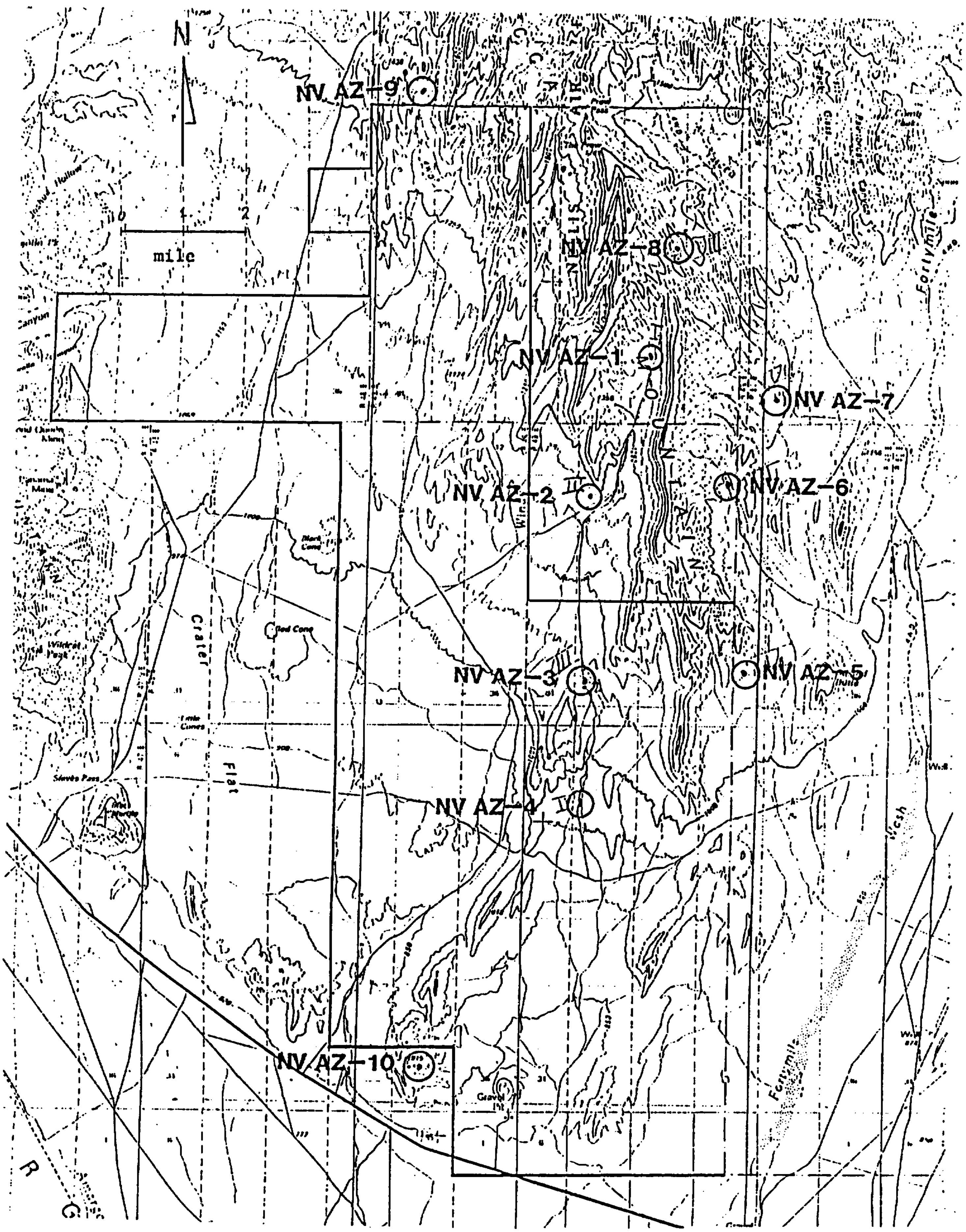

Figure MRP-1.0-1.

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STATE OF NEVADA
AGENCY FOR NUCLEAR PROJECTS
NUCLEAR WASTE PROJECT OFFICE

STATE OF NEVADA
PROPOSED DRILLING SITES AREAS*

Mifflin & Associates, Inc.
Las Vegas, Nevada

AREA	NV AZ-1	NV AZ-2	NV AZ-3	NV AZ-4	NV AZ-5	NV AZ-6	NV AZ-7	NV AZ-8	NV AZ-9	NV AZ-10
Approximate Location	N 767, 200 E 557, 100 SE1/4, SE1/4, SW1/4. Sec. 26, T12S, R49E (about 0.4 mi west of USW H-5 well)	N 754, 000 E 552, 400 SE1/4, SW1/4, NW1/4. Sec. 9, T12S, R49E (about 1/2 mi southwest of USW WT-7 well)	N 741, 000 E 552, 150 NE1/4, NW1/4, NW1/4, Sec. 32 T13S, R 49E (about 1.5 mi south USW WT-10 well)	N 728, 650 E 551, 800 NW1/4, SW 1/4 NW1/4, Sec. 8, T14S, R49E (about 1.5 mi southwest of USW WT-11 well)	N 740, 200 E 565, 300 (about 0.4 mi northwest of UE25 WT-12 well at N 739, 725 E 567, 011)	N 755, 300 E 564, 000 (about 0.4 mi north of USW WT-1 well at N 753,651 E 563, 739)	N 762, 400 E 565, 550 (about 1.4 mi north-west of UE25 WT-14 well at N 761,650 E 575, 210)	N 771, 000 E 560, 000 (about 300 ft north-west of USW UZ-1 well at N 771, 275 E 560, 220)	N 789, 000 E 538, 000 SE1/4, SE1/4, Sec. 6, T12S, R49E (about 5.5 mi north-west of USW UZ-1 well at N 771, 275 E 560, 220)	from N 707, 500 to 708, 000 from E 538, 000 to 541, 000 SE 1/4, NE 1/4 and SE 1/4, NW 1/4, Sec. 35, T14S, R48E (about 6.5 mi southwest of USW WT-11 well)
Approximate Site Elevation AMSL	1323 m 4340 ft	1162 m 3810 ft	1055 m 3460 ft	960 m 3150 ft	1098 m 3600 ft	1213 m 3980 ft	1195 m 3920 ft	1349 m 4425 ft	1450 m• 4350 ft	966-1050 m 2900-3150 ft
Approximate Water Table Elevation AMSL	775 m 2543 ft	775 m 2543 ft	775 m 2543 ft	774 m 2539 ft	730 m 2395 ft	731 m 2398 ft	732 m 2402 ft	800 m 2642 ft	1150 m• 3450 ft	700 m• 2100 ft
Approximate Lithology thickness in feet	15-30 QTac 220 cu 1100 tu 110 Tht >200 Tcpp-Tcb	10-30 QTac 400 cu 1100 tu 130 Tht >100 Tcpp	10-50 QTac 310 cu 950 tu >150 Tht	0-80 QTac 300 cu 1000 tu >130 Tht	20-50 QTac 180 cu 900 tu >30 Tht/ Tcpp-Tcb	20-50 QTac 480 cu 900 tu 180 Tht >100 Tht	20-40 QTac 450 cu 1100 tu 504 Tht/ Tcpp-Tcb	15-40 QTac 50 cu 150 pc 50 bt >1200 tu	10-100 QTac 30-300 Tht 30-600 Tcpp 0-50 bt 50-500 Tcb	0-20 QTac 0-350 cu 0-650 tu 0-60 Tw• 150-600 Tcpp 300-600 Tcb 0-120 Tbx• 0-600 Tbt•

LEGEND**

QTac	Alluvium	pc	Pah Canyon Member	Tht	Tuffs of Calico Hills	Tw•	Bedded Tuff (Miocene)	mi	miles
cu	Tiva Canyon Member	bt	Bedded Tuff	Tcpp	Prow Pass Member	Tbx•	Depositional breccia from Bullfrog member	m	meters
bt	Bedded Tuff	tu	Topopah Spring Member	Tcb	Bullfrog Member	Tbt•	Bedded Tuff (Miocene)	ft	feet

* Data compiled based on DOE published reports.
** Geologic legend from USGS-OFR-84-494 by Scott and Bonk, 1984.
• Swadley and Carr-Geology, Big Dune Quad., Nevada-California (MAP 1-1767).

Table MRP-1.01-1.

MY880527a

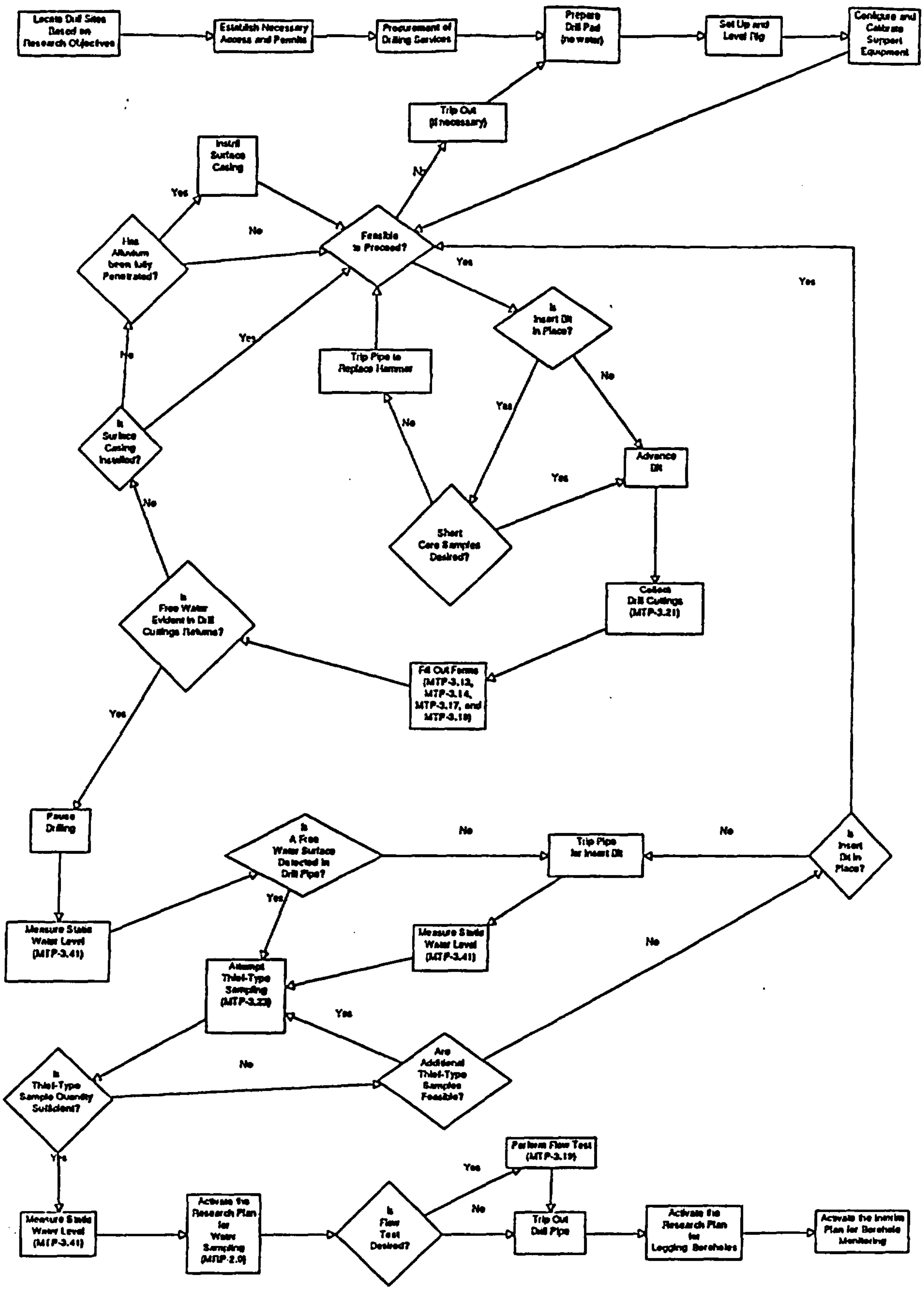

Figure MRP-1.0-2.

Appendix A-III

Research Plan for Water Sampling at or near Yucca Mountain, MRP 2.0.

Mifflin & Associates, Inc.
2700 East Sunset Road, Suite C25
Las Vegas, Nevada 89120
(702)798-0402 & 3026

MRP-2.0 RESEARCH PLAN FOR WATER SAMPLING AT OR NEAR YUCCA MOUNTAIN.

Objective

As stated in the Research Plan for Vadose Zone Drilling (MRP-1.0), when free water is encountered in a borehole, as indicated by a fine mist emerging from the cyclone or as wet or dripping cuttings, drilling ceases, the static water level is measured, and a thief-type water sampling method is attempted. If sufficient thief-type samples are collected and if sufficient free water remains in the borehole (as determined by another static water level measurement), then the following research plan is activated.

The objective of this research plan is to obtain water samples and associated chemical, isotopic, and colloidal analyses of any free water encountered in the vadose zone(may include uppermost part of saturated zone) during drilling research activities. This will be accomplished by pumping water encountered during drilling to the surface to: (1) fill appropriate sample containers for laboratory analysis of various chemical and isotopic constituents; (2) establish field analyses of certain unstable constituents; and (3) obtain samples for colloid analyses. Appropriate preservative treatments and environmental control of samples will ensure that the water samples brought to the surface and shipped to various laboratories are representative of the subsurface geochemical environment. Appropriate sample containers and container preparation techniques will minimize contamination of the water samples by leaching of the container or loss of constituents to the container's walls by sorption.

The period of performance of this research plan is at the minimum three years, the duration of planned research drilling activities.

Field Activities

The field activities at the drilling site are: (1) collection of water samples for various laboratory analyses, (2) measurement of certain unstable constituents of the water as it emerges at the surface, and (3) collection of representative colloid samples.

The logic flow diagram (Figure MRP-2.0-1.) outlines the various procedures that will take place in the field after free water is encountered, all thief-type water samples have been obtained, and sufficient water remains in borehole to justify pumping. These conditions are part of the research plan for vadose zone drilling and cuttings sampling (MRP-1.0) and the water sampling research plan is activated only if all these conditions are met.

After free water is encountered, in a borehole, a designated Field Technician or Designee (see MTP-3.01) shall calibrate the instruments for field measurements (pH meter and electrode, electrical conductivity meter and cell, dissolved oxygen meter and membrane probe, the redox electrode, and the portable spectrophotometer). Calibration may begin during the thief-type sampling, but shall be completed before any water from the pump reaches the land surface.

When pumping of water from the borehole begins, simultaneous activities occur that require several people. A trained person (minimum position required: Field Assistant) is required to operate and constantly monitor the Solinst pump during its operation (for example: if the borehole is pumped dry, gas pressure must be shut off immediately). The second activity involves operation of the flow cell: obtaining all the operation of the flow cell constitutes another activity requiring measurements from the probes penetrating into the flow stream (temperature, pH, electrical conductivity, and dissolved oxygen content). If dissolved oxygen is below detection limit, then a redox (Eh) measurement is performed, followed by determination of sulfide content. Total alkalinity is determined, followed by spectrophotometric , total iron content, and sulfate content. One person may be sufficient to perform all of these measurements, as well as the aluminum extraction.

Filling water sample containers with filtered and unfiltered water samples is the third and last major activity. A minimum of two trained Field Assistants or Designee (MTP-3.01) are required for filling water sample containers: one to fill and operate the pressure vessel for filtered samples and the other to collect the unfiltered samples. Upon arrival of water at land surface from the Solinst pump, the first 11 liters of output (capacity of water line from pump) should be used to rinse sample containers (for unfiltered samples only) and the pressure vessel. Thereafter, the pressure vessel shall be filled first until all filtered samples are obtained; however while the pressure vessel is in operation, personnel shall also be collecting the unfiltered samples. Thus, in practice, the two subtasks of collecting filtered and unfiltered water samples may be more integrated than is apparent from the flow chart. Table MRP-2.0-1. is a summary of all water samples collected according to this plan and interfacing Technical Procedures.

In summary, a minimum of four persons are needed are required to carry out the water sampling research plan.

Equipment Required

In addition to equipment specified in the Technical Procedures listed in this research plan, the following are necessary:

1. Solinst pump system - double valve purge pump capable of pumping lifts to 2,000 feet and with appropriate support equipment (nitrogen gas cylinders, generator, and tubing, fittings, and valves for controlling sample stream at the surface).

2. Laboratory facility - a small 12 to 15 foot air-conditioned trailer outfitted for performing all required field measurements related to the flow cell, aluminum extractions, and sample preparations.

3. Polycarbonate flow cells (minimum of two, one for backup) - with ports for electrodes, cells, and temperature sensors.

Documentation

The following Technical Procedures provide for all appropriate documentation related to personnel, samples, custody, field measurements, calibrations, extractions, and preparations.

MTP-3.01, Position Titles, Descriptions, and Minimum Qualifications.

MTP-3.02, Technical Procedure for Documentation of Research Activities.

MTP-3.17, Technical Procedure for Sample Identification (ID) Form.

MTP-3.18, Technical Procedure for Record of Sample Custody Form.

MTP-3.22, Technical Procedure for Field Collection and Preservation of Colloid Samples for Laboratory Analysis.

MTP-3.23, Technical Procedure for Thief-Type Sampling of Natural Waters in the Field.

MTP-3.24, Technical Procedure for Water Sampling with a Double-Valve Purge Pump System.

MTP-3.31, Technical Procedure for Field Filtration of Natural Water Samples.

MTP-3.51, Technical Procedure for Precipitation and Extraction of Dissolved Inorganic Carbon from Natural Water Samples for Carbon-14 Analysis.

MTP-3.71, Technical Procedure for Field Measurement of pH.

MTP-3.711, Technical Procedure for Determination of Aluminum in Samples of Natural Water.

MTP-3.72, Technical Procedure for Measurement of Electrical Conductivity of Water Samples in the Field.

MTP-3.73, Technical Procedure for Field Measurement of Reduction-Oxidation Potential: including Preparation and Storage of Reduction-Oxidation Solutions of Standard Potential, and Calibration of REDOX Electrodes.

MTP-3.74, Technical Procedure for Field Measurement of Dissolved Oxygen in Water Samples by Membrane Electrode Probe.

MTP-3.75, Technical Procedure for Field Measurement of Total Alkalinity of Water Samples.

MTP-3.76, Technical Procedure for Field Measurement of Dissolved Sulfate in Natural Water Samples by Portable Spectrophotometer.

MTP-3.78, Technical Procedure for Field Measurement of Dissolved Oxygen in Water Samples by Titration.

MTP-3.79, Technical Procedure for Field Measurement of Aqueous Sulfide in Water Samples by Portable Spectrophotometer.

MTP-3.80, Technical Procedure for Field Measurement of Total Dissolved Iron in Water Samples by Portable Spectrophotometer.

MTP-12.1, Technical Procedure for Calibration of pH meter.

MTP-12.2, Technical Procedure for Calibration of Electrical Conductivity Meter.

MTP-12.3, Technical Procedure for Air Calibration of Dissolved Oxygen Meter and Membrane Electrode Probe.

MTP-13.1, Technical Procedure for Preparation of Water Sample Containers.

Mifflin & Associates, Inc.
2700 East Sunset Road, Suite C25
Las Vegas, Nevada 89120
(702)798-0402 & 3026

Summary of Water Samples

	Sample	Container[2]	Filter[3]	Preservation
1.	Major Cations	1 L cubitainer	0.45 µm	1 mL Ultrex HNO_3, chill
2.	Major anions	"	0.45 µm	chill
3.	Deuterium	12 mL scintillation vials	no	"
4.	Oxygen Isotopes	"	no	"
5.	Carbon-13	1 L glass bottle	0.45 µm	"
6.	Tritium	1 L glass	no	"
7.	Uranium-series	20 L cubitainer	no	
8.	Sulfur Isotopes	1 L cubitainer	no	"
9.	Carbon-14 by A.M.S.[1]	1 L glass	0.45µm	"
10.	Carbon-14 by Liq. Scint.	50 L carboy with spigot	no	"
11.	Aluminum	12 mL scint. vials for extract		"
		0.5 mL glass for total Al	0.1 & 0.45 µm	
12.	Thief samples by BAT hypoprobe	500 mL special glass bottles	0.45µm	"
		2 x 150 mL special glass bottles	0.45µm	
13.	Chlorine-36	4 L cubitainer	no	"
14.	Colloids	2 x 60 mL B.O.D. bottles	no	"
		2 x 300 mL B.O.D. bottles	no	
15.	Trace Metals	125 mL HDPE bottle	no	1 mL Ultrex HNO_3, chill
16.	Colloid Identification	0.5 mL thru 5 mL thru	30 nm filters in culture dishes	N/A

1 A.M.S. = accelerator mass spectrometry.

2 L = liter, mL = milliliter, B.O.D. - biological oxygen demand, HDPE = high-density polyethylene.

3 µm = micron or micrometer, nm = nannometer.

Table MRP-2.3-1.

Research Plan for Water Sampling

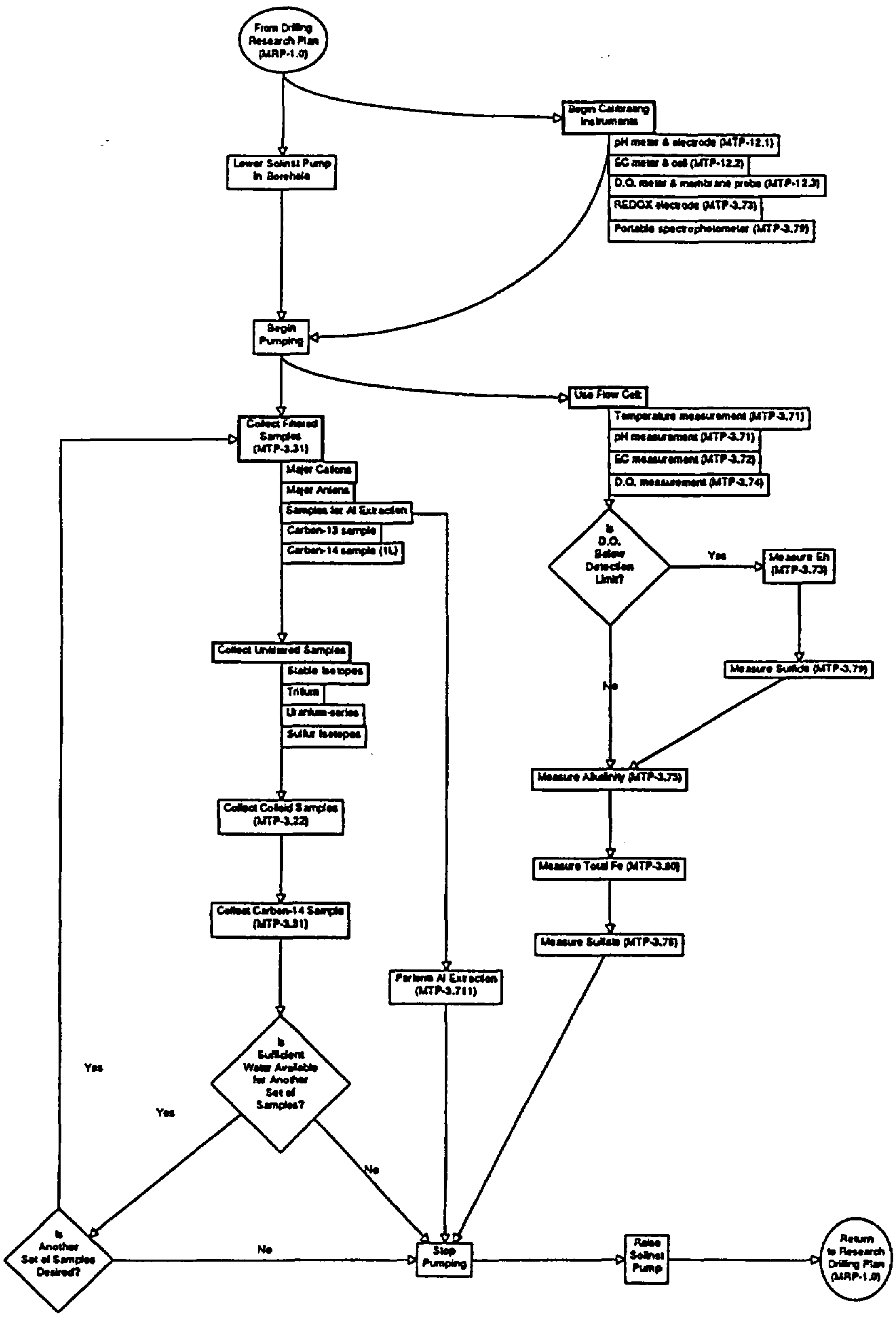

Figure MRP-2.0-1.

Appendix A-IV

Technical Procedures MTP-3.02 AND MTP-3.13

STATE OF NEVADA
AGENCY FOR NUCLEAR PROJECT
NUCLEAR WASTE PROJECT OFFICE
TECHNICAL PROCEDURE

MTP-3.02
REVISION 1 (DRAFT 1)
MAY 20, 1988

TITLE: Technical Procedure for Documentation of Research Activities

APPROVED:

______________________ Project Manager

______________________ Quality Assurance Manager

______________________ Administrator of Technical Programs

1.0 PURPOSE

1.1 This procedure describes the requirements for documentation of research activities that are not covered by technical procedures.

1.2 This procedure governs the activities of Mifflin & Associates, Inc. (MAI) personnel and their subcontractors under contract to the State of Nevada, Nuclear Waste Project Office (NWPO).

2.0 DEFINITIONS

2.1 Research Activity - work of an experimental nature that is to be accomplished before or as part of the preparation of approved detailed technical procedures. A recognized part of these efforts involve the change of concepts and subsequent experimental methods. The discovery and interpretation of the results of the activity will be performed under controlled conditions by procedures that may or may not be established or qualified. The activities that are designated as research activities must be documented according to an approved procedure that will ensure that all aspects of the activity area adequately documented and tracked to allow the preparation of a governing technical procedure, if appropriate, in a timely manner.

3.0 INTERFACING PROCEDURES

3.1 QAP-2.2, Preparation and Control of Technical Procedures.

3.2 QAP-6.1, Document Distribution List and File Index.

3.3 QAP-17.1, Quality Assurance Records.

4.0 REQUIREMENTS AND ACTIVITIES

4.1 The Principal Investigator (P.I.) or Designee shall indicate in writing to the Project Manager which activities performed by the P.I. and/or MAI personnel or subcontractors should be classified as research activities based on the above definition and one or more of the following:

1) Degree of operator skill required to perform activity

2) Complexity and sensitivity of equipment required for the task

3) Degree of professional judgment required to organize the activity and interpret the results

4) The likelihood of inspection yielding meaningful results

4.2 The Project Manager shall recommend in writing the to NWPO Administrator of Technical Programs the activity/activities to be classified as a research activities.

4.3 Upon the classification of an activity as a research activity, the Principal Investigator shall prepare a Research Plan for submittal to the Project Manager. If Project Manager finds the Research Plan satisfactory he/she shall submit the plan to the Administrator of Technical Programs for review and approval.

4.3.1 If the Research Plan is not approved, the Principal Investigator shall revise the plan and resubmit the plan to the Project Manager, per Section 4.3 above.

4.4 The Research Plan shall consist of, but not be limited to, the following items, as appropriate:

1) Activity Title

2) Name of the Principal Investigator responsible for the research activity

3) Objectives.

4) Period of Performance.

5) Description of Field Work: purpose; duration; frequency; type of samples to be taken; equipment to be used and calibration requirements; methods to be attempted or utilized.

6) Description of Laboratory Work: purpose; duration; type and number of samples to be analyzed; preparation and analytical methods to be attempted or utilized; equipment calibration/standardization requirements.

4.5 Complete and thorough documentation of the actual process of the activity shall be performed during the activity and shall be submitted by the Principal Investigator to the Project Manager. The Project Manager shall submit the activity documentation to the QA Manager and Administrator of Technical Programs per Subsection 4.6.1.3 and Section 5.0 of this procedure.

4.6 Documentation or research activities shall include, but not be limited to, the following:

1) Fieldbooks, logbooks, and laboratory notebooks

2) Hardcopy output from equipment or instrumentation

3) Drawings, figures, and maps

4) Calculations

5) Photographs (micro- and/or macro-) and/or video tape recordings

6) Paper tapes or magnetic media containing data output by equipment or instruments

7) Copies of computer codes/software utilized in data reduction or in performing calculations for interpretation of results.

8) Records of custody of samples and sample transmittal forms.

4.7 Fieldbooks, logbooks, and laboratory notebooks shall contain the following daily entries, as applicable, in a clear and legible manner.

1) Date of entry and Preparer's name

2) Name of the Principal Investigator in charge of the research activity

3) Description of work in progress

4) Equipment used and calibration performed

5) Sample (core specimen, section, thin section, etc.) identification history while in preparer's possession

6) Data entries; data sheets

7) Comments relative to work in progress, such as expected or unexpected results, limiting factors known or possible, immediate goal or objective

8) Any changes in the basic approach

9) Interim conclusions, if appropriate

10) Summary describing any results

4.7.1 All entries to fieldbooks, logbooks, and/or laboratory notebooks shall be made in ink. Successive entries shall be made on consecutively numbered pages, leaving no open spaces for additional entries on partially filled pages. Entries shall be signed and dated by the Preparer on the date the entry is made. If revisions to the entries are necessary, the original entry shall be lined out, initialed and dated by the Preparer making the revision. The initial entry shall remain legible. White-out or erasures are not acceptable.

4.7.2 All fieldbooks, logbooks, and laboratory notebooks shall be reviewed and verified by the Principal Investigator, or, if the Principal Investigator is the Preparer, the Project Manager, at regular intervals but no less than monthly. The Principal Investigator or Project Manager shall sign and date the section of the books reviewed and shall also indicate the dates of the entries reviewed. Copies shall be made of the reviewed and verified entries and these copies shall be submitted to the QA Manager.

4.7.3 Completed fieldbooks, logbooks, and laboratory notebooks are considered Quality Assurance Records and these books shall be submitted to the Qa Manager as required in Section 5.0 of this procedure.

4.8 Each piece of output from an instrument, each drawing, figure, map, photograph, tape, floppy diskette, or calculation, etc., shall be signed and dated by the Preparer or Instrument Operator, and verified, signed, and dated by the Principal Investigator or Designee. The Designee shall have the necessary expertise and experience to be able to understand and verify the documentation.

4.9 Calculations developed during the research activity shall be prepared, documented, reviewed, and approved according to QAP-3.1, Calculations.

4.10 Documentation of computer software utilized in the research activity shall conform to the content of NUREG-0856, as applicable.

4.11 The adequacy of the research activity documentation shall be determined by the Project Manager, Administrator of Technical Programs, and the QA Manager.

4.12 After the research activity is completed, the Principal Investigator shall prepare a report, summarizing the results of the activity, the methods used, and the determination of whether the activity has led to the development of a governing technical procedure.

4.12.1 The Principal Investigator shall submit the summary report to the Project Manager for review. The Project Manager shall review the report and, if the report is satisfactory, shall indicate approval by signing and dating the report.

4.12.2 If the report is not satisfactory, the Project Manager shall return the report to the Principal Investigator for revision, as necessary. The Principal Investigator shall resubmit the report after making any revisions, according to Subsection 4.12.1.

4.13 The Project Manager shall submit the approved summary report to the Administrator of Technical Programs for review.

5.0 OUTPUT DOCUMENTS

5.1 The Principal Investigator or Designee shall ensure marking of the category file index designation on the records listed below, per QAP-6.1, and the transmittal of these records to the QA Manager for processing and filing in the NWPO Records Center, per QAP-17.1.

Written recommendations for activities to be classified as research activities

Research Plans

Fieldbooks, logbooks, and laboratory notebooks.

Hardcopy output for equipment/instrumentation

Drawings, maps, figures

Calculations

Photographs, videotapes

Paper tapes, magnetic media (floppy diskettes, magnetic tapes)

Optical storage media (compact discs - read-only memory)

Computer software listings and documentation

Copies of Custody of Samples and Transmittal Forms

5.2 The Principal Investigator or Designee shall ensure distribution of the above documents to the Project Manager, Administrator of Technical Programs, and others, as necessary, per the Document Distribution List of QAP-6.1.

5.4 The Principal Investigator or Designee shall maintain copies of documents on file.

6.0 REVISIONS

6.1 Revisions to the documents resulting from this procedure shall be prepared, reviewed, verified, approved, and distributed in the same manner as the original issue and in accordance with QAP-2.1 and QAP-2.2 as applicable.

6.2 Revisions may be made to a single page, several pages, or the entire document.

6.2.1 If single page revisions are made, only the revised page(s) need be issued as replacement pages.

6.2.2 Revised portions of documents shall be identified by bold-face type, except as noted in Subsection 6.2.3 of this procedure. When later revisions are made, the earlier revision indicators shall be deleted.

6.2.3 Technical documents from this procedure marked "Preliminary" or "DRAFT" may be revised without adherence to Subsections 6.1 and 6.2.2 above. Preliminary documents shall be controlled by the Preparer to prevent distribution and use before review, verification, and approval. The "Preliminary" or "DRAFT" markings shall be removed before submission for approval.

6.3 A revision summary shall be included as a part of all revised technical documents. The dated signatures of the revision Preparer, Reviewer, Verifier, and Approver shall be included as a part of the revision summary. The revision summary shall indicate the pages revised.

6.4 The Recipients of technical documents shall destroy superseded pages or mark them "VOID" or "SUPERCEDED."

7.0 REFERENCES

7.1 NWPO, 1988, Quality Assurance Manual, Sections 3.0.

7.2 NUREG-0856, Final Technical Position on the Documentation of Computer Codes for High-Level Waste Management

8.0 FLOW CHART

8.1 None

STATE OF NEVADA
AGENCY FOR NUCLEAR PROJECTS
NUCLEAR WASTE PROJECT OFFICE
TECHNICAL PROCEDURE

MTP-3.13
REVISION 1 (DRAFT 1)
June 3, 1988

TITLE: Technical Procedure for Daily Drilling Activity Summary.

APPROVED:

Project Manager

Quality Assurance Manager

Administrator of Technical Programs

1.0 PURPOSE

1.1 A record of daily drilling activity is based on individual activities, recorded by date and clock time. The NWPO/MAI Daily Drilling Activity Summary form is intended to portray the full scope of each day's activities in chronologic fashion, overlapping the time intervals as necessary. Categories of activities should be general and provide an overview of each work day.

1.2 This procedure governs the activities of Mifflin & Associates, Inc. (MAI) personnel and their subcontractors under contract to the State of Nevada, Nuclear Waste Project Office (NWPO).

2.0 DEFINITIONS

2.1 Refer to the NWPO Quality Assurance Manual Glossary for any other terms.

3.0 INTERFACING PROCEDURES

3.1 QAP-2.2, Preparation and Control of Technical Procedures.

3.2 QAP-6.1, Document Distribution List and File Index.

3.3 QAP-17.1, Quality Assurance Records.

3.4 MTP-3.01, Position Titles, Descriptions, and Minimum Qualifications.

3.5 MTP-3.12, Technical Procedure for Installation of Surface Casing in Exploratory Boreholes.

4.0 REQUIREMENTS AND ACTIVITIES

4.1 Requirements:

4.1.1 NWPO/MAI Daily Drilling Activity Summary form (MTP-3.13-1.).

4.1.2 Ink pens.

4.2 Activities:

4.2.1 The Principal Investigator or Designee shall designate and train Field Technician (minimum position requirement, see MTP-3.01) to perform activity specified in this procedure.

4.2.2 The Field Technician shall ensure that all requirements are on hand before departing for the field, drill site, or sampling site.

4.2.3 The Field Technician shall record the following information on the NWPO/MAI Daily Drilling Activity Summary form using an ink pen:

4.2.4 Beginning and ending times of each activity, and a description of each activity, shall be entered on the Daily Drilling Activity Summary form. Examples of activities include: drilling, welding casing, rig maintenance, etc. Each NWPO/MAI Daily Drilling Activity Summary form shall be signed and dated by the preparer.

4.2.5 The Field Technician shall sign and date as preparer each page of the NWPO/MAI Daily Drilling Activity Summary form as completed or at end of the day.

4.2.6 Each person authorized to make entries into a notebook or onto a form shall use a separate page each day. Only one authorized person as preparer shall use any single page of a notebook or any single form.

4.2.7 Upon review and approval, the Principal Investigator or Designee shall sign and date the NWPO/MAI Daily Drilling Activity Summary form as verifier.

5.0 OUTPUT DOCUMENTS

5.1 The Principal Investigator or Designee shall ensure marking of the category file index designation on the following documents per QAP-6.1, and transmittal of same to the QA Manager for processing and filing in the NWPO Records Center per QAP-17.1.

5.1.1 NWPO/MAI Daily Drilling Activity Summary form (Figure MTP-3.13-1.).

5.2 The Principal Investigator or Designee shall ensure distribution of copies of the above documents to the Project Manager, Administrator of Technical Programs, and to others on the Document Distribution List per QAP-6.1.

5.3 The Principal Investigator or Designee shall maintain copies of documents on file.

6.0 REVISIONS

6.1 Revisions to output documents shall be prepared, reviewed, verified, approved, and distributed in the same manner as the original issue and in accordance with QAP-6.1 and QAP-2.2 as applicable, and requirements stated in these procedures for the original documents.

6.2 Revisions may be made to a single page, several pages, or the entire document.

6.2.1 If single page revisions are made, only the revised page(s) need be issued as replacement pages.

6.2.2 Revised portions of documents shall be identified by boldface type, except as noted in Subsection 6.2.3 of this procedure. When later revisions are made, the earlier revision indicators shall be deleted.

6.2.3 Technical documents marked "Preliminary" or "**DRAFT**" may be revised without adherence to Subsections 6.1 and 6.2.2. above. Preliminary documents shall be controlled by the preparer to prevent distribution and use before review and approval. The "Preliminary" or "**DRAFT**" markings shall be removed before submission for approval.

6.3 A revision summary shall be included as part of all revised technical documents. The dated signatures of the revision preparer, reviewer, and approver shall be included as a part of the revision summary. The revision summary shall indicate the pages revised.

6.4 Recipients of revised technical documents shall destroy superseded pages or mark them "**VOID**" or "**SUPERSEDED**".

7.0 REFERENCES

7.1 NWPO, 1988, Quality Assurance Manual, Section 3.0.

7.2 MRP-1.0, Research Plan for Vadose Zone Drilling at or near Yucca Mountain.

8.0 FLOW CHART

8.1 None.

STATE OF NEVADA
AGENCY FOR NUCLEAR PROJECTS
NUCLEAR WASTE PROJECT OFFICE

Mifflin and Associates, Inc.
Las Vegas, Nevada

MTP-3.13-1

Borehole ID ______
sheet ____ of ____

MAI job no. ______

DAILY DRILLING ACTIVITY SUMMARY

Project Name:
Location:
Client:
Date:

Contractor:
Equipment type:
Driller and crew:
MAI crew:

Item	Description	Time From	Time To	See Note	Unit	Quantity	Rate	Amount

notes: weather; description of site:

signed Preparer: Date:
Verifier: for Mifflin and Associates, Inc. Date: for Contractor Date:

distribution: original to office, copy 1 to contractor, copy 2 remains in the field book.

Figure MTP-3.13-1.

Appendix A-V

Drilling Permits from BLM

United States Department of the Interior

BUREAU OF LAND MANAGEMENT
LAS VEGAS DISTRICT OFFICE
4765 Vegas Drive
P.O. Box 26569
Las Vegas, Nevada 89126

TAKE PRIDE IN AMERICA

IN REPLY REFER TO:

N-48327
2800
(NV-050.1)

JUL 28 1988

CERTIFIED MAIL NO. 13969
RETURN RECEIPT REQUESTED

Mifflin & Associations
2700 E. Sunset Rd C-25
Las Vegas, NV 89120

Gentlemen:

Enclosed is a copy of Mifflin & Associates R/W grant (serial number N-48327) which has been approved by the Bureau of Land Management along with a receipt for the rental and monitoring payments thereto.

Sincerely,

Charles Frost

for Ben F. Collins
District Manager

2 Enclosures
1. Right-of-Way Grant
2. Receipt

Form 2800-14
(August 1985)

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF LAND MANAGEMENT
RIGHT-OF-WAY GRANT/TEMPORARY USE PERMIT

| Issuing Office
| Las Vegas District
| Serial Number
| N-48327

1. A (right-of-way) (permit) is hereby granted pursuant to:

   a. /X/ Title V of the Federal Land Policy and Management Act of October 21, 1976 (90 Stat. 2776; 43 U.S.C. 1761);

   b. /_/ Section 28 of the Mineral Leasing Act of 1920, as amended (30 U.S.C. 185);

   c. /_/ Other (describe)____________________.

2. Nature of Interest:

   a. By this instrument, the holder Mifflin & Associates receives a right to construct, operate, maintain, and terminate a Right-of-Way for site characterization studies on public lands (or Federal land for MLA Rights-of-Way) described as follows:

      T. 13S., R. 49E., section 32, SE¼NW¼NW¼. (Site III)
      T. 14S., R. 49E., section 8, SE¼NW¼NW¼. (Site IV)

      A map showing the location of the right-of-way is on file with the Bureau of Land Management, Las Vegas District (N-48327).

   b. The right-of-way or permit area granted herein is 150 feet wide, 10 feet long and contains 0.03 acres, more or less. If a site type facility, the facility contains 4.0 acres.

   c. This instrument shall terminate on July 27, 1998, 10 years from its effective date unless, prior thereto, it is relinquished, abandoned, terminated, or modified pursuant to the terms and conditions of this instrument or of any applicable Federal law or regulation.

   d. This instrument /X/ may /_/ may not be renewed. If renewed, the right-of-way or permit shall be subject to the regulations existing at the time of renewal and any other terms and conditions that the authorized officer deems necessary to protect the public interest.

   e. Notwithstanding the expiration of this instrument or any renewal thereof, early relinquishment, abandonment, or termination, the provisions of this instrument, to the extent applicable, shall continue in effect and shall be binding on the holder, its successors, or assigns, until they have fully satisfied the obligations and/or liabilites accruing herein before or on account of the expiration, or prior termination, of the grant.

3. Rental:

For and in consideration of the rights granted, the holder agrees to pay the Bureau of Land Management fair market value rental as determined by the authorized officer unless specifically exempted from such payment by regulation. Provided, however, that the rental may be adjusted by the authorized officer, whenever necessary, to reflect changes in the fair market rental value as determined by the application of sound business management principles, and so far as practicable and feasible, in accordance with comparable commercial practices.

4. Terms and Conditions:

a. This grant or permit is issued subject to the holder's compliance with all applicable regulations contained in Title 43 Code of Federal Regulations parts 2800 and 2880.

b. Upon grant termination by the authorized officer, all improvements shall be removed from the public lands within 120 days, or otherwise disposed of as provided in paragraph (4)(d) or as directed by the authorized officer.

c. Each grant issued pursuant to the authority of paragraph (1)(a) for a term of 20 years or more shall, at a minimum, be reviewed by the authorized officer at the end of the 20th year and at regular intervals thereafter not to exceed 10 years. Provided, however, that a right-of-way or permit granted herein may be reviewed at any time deemed necessary by the authorized officer.

d. The stipulations, plans, maps, or designs set forth in Exhibit(s) A, dated July 28, 1988, attached hereto, are incorporated into and made a part of this grant instrument as fully and effectively as if they were set forth herein in their entirety.

e. Failure of the holder to comply with applicable law or any provision of this right-of-way grant or permit shall constitute grounds for suspension or termination thereof.

f. The holder shall perform all operations in a good and workmanlike manner so as to ensure protection of the environment and the health and safety of the public.

IN WITNESS WHEREOF, The undersigned agrees to the terms and conditions of this right-of-way grant or permit.

(Signature of Holder)	(Signature of Authorized Officer)
President, Mifflin + Assoc Inc (Title)	District Manager (Title)
July 21, 1988 (Date)	July 28, 1988 (Date)

EXHIBIT A

SPECIAL STIPULATIONS

N-418327

1. Holder shall clearly mark the exterior boundaries of the right-of-way. All activities directly or indirectly associated with construction or maintenance on this right-of-way must be conducted within the boundaries thereof.

2. If cultural resources are discovered during operations under this grant, the Holder shall immediately bring them to the attention of the Authorized Officer. The Holder shall not disturb such resources except as may be subsequently authorized. Within two working days of notification, the Authorized Officer will evaluate or have evaluated any cultural resources discovered and will determine if any action may be required to protect cultural resources discovered. The cost of data recovery for cultural resources discovered during operations shall be borne by the BLM unless otherwise specified by the Authorized Officer of the BLM. All cultural resources shall remain under the jurisdiction of the United States until ownership is determined under applicable law.

3. Holder shall comply with the applicable Federal and State laws and regulations concerning the use of pesticides (i.e., insecticides, herbicides, fungicides, rodenticides, and other similar substances) in all activities/operations authorized under this grant. The Authorized Officer shall approve a written plan prior to the use of such substances. The plan must provide the type and quantity of material to be used; the pest, insect and fungus to be controlled; the method of application; the location of or storage and disposal of containers; and other information that the Authorized Officer may require. The plan should be submitted no later than December 1 of any calendar year that covers the proposed activities for the next fiscal year (i.e., December 1, 1988, deadline for a fiscal year 1990 action). Emergency use of pesticides may occur. The use of substances on or near the right-of-way shall be in accordance with the approved plan. A pesticide shall not be used if the Secretary of the Interior has prohibited its use. A pesticide shall be used only in accordance with its registered uses and within other limitations if the Secretary has imposed limitations. Pesticides shall not be permanently stored on public lands authorized for use under this grant.

4. The BLM retains the right ot occupy and use the right-of-way, and to issue or grant rights-of-way or other land uses for other purposes, upon, over, under, and through the lands, provided that the occupancy and use will not unreasonably interfere with the rights granted herein.

5. No hazardous materials will be disposed of on public lands.

6. All desert tortoise found in area where their continued presence constitutes a hazard to themselves, will be removed to a safe shady area (at least 150 yards from surface disturbance). Construction personnel will be informed that collection of tortoises is prohibited and punishable by a minimum $100,000 fine.

United States Department of the Interior

BUREAU OF LAND MANAGEMENT
LAS VEGAS DISTRICT OFFICE
4765 Vegas Drive
P.O. Box 26569
Las Vegas, Nevada 89126

TAKE PRIDE IN AMERICA

IN REPLY REFER TO:
N-48282
2800
(NV-050.1)

CERTIFIED MAIL NO. 13968
RETURN RECEIPT REQUESTED

JUL 28 1988

Mifflin & Associates
2700 E. Sunset Rd. C-25
Las Vegas NV 89120

Gentlemen:

Enclosed is a copy of Mifflin & Associates R/W grant (serial number 48282) which has been approved by the Bureau of Land Management along with a receipt for the rental and monitoring payments thereto.

Sincerely,

for Ben F. Collins
District Manager

2 Enclosures
1. Right-of-Way Grant
2. Receipt

Form 2800-14
(August 1985)

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF LAND MANAGEMENT
RIGHT-OF-WAY GRANT/TEMPORARY USE PERMIT

| Issuing Office
| Las Vegas District
| Serial Number
| N-48282

1. A (right-of-way) (permit) is hereby granted pursuant to:

   a. /X/ Title V of the Federal Land Policy and Management Act of October 21, 1976 (90 Stat. 2776; 43 U.S.C. 1761);

   b. /_/ Section 28 of the Mineral Leasing Act of 1920, as amended (30 U.S.C. 185);

   c. /_/ Other (describe) ________________________.

2. Nature of Interest:

   a. By this instrument, the holder Mifflin & Associates receives a right to construct, operate, maintain, and terminate a right of way for site characterization studies on public lands (or Federal land for MLA Rights-of-Way) described as follows:

      Mount Diablo Meridan
      T14S., R.48E., Section 35, SE¼NE¼,
      SE¼NW¼.

      A map showing the location of the right-of-way is on file with the Bureau of Land Management, Las Vegas District (N-48282).

   b. The right-of-way or permit area granted herein is 10' feet wide, 7,920 feet long and contains 1.82 acres, more or less. If a site type facility, the facility contains 3.0 acres.

   c. This instrument shall terminate on July 27, 1998, 10 years from its effective date unless, prior thereto, it is relinquished, abandoned, terminated, or modified pursuant to the terms and conditions of this instrument or of any applicable Federal law or regulation.

   d. This instrument /X/ may /_/ may not be renewed. If renewed, the right-of-way or permit shall be subject to the regulations existing at the time of renewal and any other terms and conditions that the authorized officer deems necessary to protect the public interest.

   e. Notwithstanding the expiration of this instrument or any renewal thereof, early relinquishment, abandonment, or termination, the provisions of this instrument, to the extent applicable, shall continue in effect and shall be binding on the holder, its successors, or assigns, until they have fully satisfied the obligations and/or liabilites accruing herein before or on account of the expiration, or prior termination, of the grant.

3. Rental:

For and in consideration of the rights granted, the holder agrees to pay the Bureau of Land Management fair market value rental as determined by the authorized officer unless specifically exempted from such payment by regulation. Provided, however, that the rental may be adjusted by the authorized officer, whenever necessary, to reflect changes in the fair market rental value as determined by the application of sound business management principles, and so far as practicable and feasible, in accordance with comparable commercial practices.

4. Terms and Conditions:

a. This grant or permit is issued subject to the holder's compliance with all applicable regulations contained in Title 43 Code of Federal Regulations parts 2800 and 2880.

b. Upon grant termination by the authorized officer, all improvements shall be removed from the public lands within 120 days, or otherwise disposed of as provided in paragraph (4)(d) or as directed by the authorized officer.

c. Each grant issued pursuant to the authority of paragraph (1)(a) for a term of 20 years or more shall, at a minimum, be reviewed by the authorized officer at the end of the 20th year and at regular intervals thereafter not to exceed 10 years. Provided, however, that a right-of-way or permit granted herein may be reviewed at any time deemed necessary by the authorized officer.

d. The stipulations, plans, maps, or designs set forth in Exhibit(s) A, dated July 28, 1988, attached hereto, are incorporated into and made a part of this grant instrument as fully and effectively as if they were set forth herein in their entirety.

e. Failure of the holder to comply with applicable law or any provision of this right-of-way grant or permit shall constitute grounds for suspension or termination thereof.

f. The holder shall perform all operations in a good and workmanlike manner so as to ensure protection of the environment and the health and safety of the public.

IN WITNESS WHEREOF, The undersigned agrees to the terms and conditions of this right-of-way grant or permit.

(Signature of Holder)	(Signature of Authorized Officer)
President M. H. Lin & Assoc Inc (Title)	Acting District Manager (Title)
July 21, 1988 (Date)	July 28, 1988 (Date)

EXHIBIT A
Special Stipulations
N-48282

1. Holder shall clearly mark the exterior boundaries of the right-of-way. All activities directly or indirectly associated with construction or maintenance on this right-of-way must be conducted within the boundaries thereof.

2. If cultural resources are discovered during operations under this grant, the Holder shall immediately bring them to the attention of the Authorized Officer. The Holder shall not disturb such resources except as may be subsequently authorized. Within two working days of notification, the Authorized Officer will evaluate or have evaluated any cultural resources discovered and will determine if any action may be required to protect cultural resources discovered. The cost of data recovery for cultural resources discovered during operations shall be borne by the BLM unless otherwise specified by the Authorized Officer of the BLM. All cultural resources shall remain under the jurisdiction of the United States until ownership is determined under applicable law.

3. Holder shall comply with the applicable Federal and State laws and regulations concerning the use of pesticides (i.e., insecticides, herbicides, fungicides, rodenticides, and other similar substances) in all activities/operations authorized under this grant. The Authorized Officer shall approve a written plan prior to the use of such substances. The plan must provide the type and quantity of material to be used; the pest, insect and fungus to be controlled; the method of application; the location of or storage and disposal of containers; and other information that the Authorized Officer may require. The plan should be submitted no later than December 1 of any calendar year that covers the proposed activities for the next fiscal year (i.e., December 1, 1988, deadline for a fiscal year 1990 action). Emergency use of pesticides may occur. The use of substances on or near the right-of-way shall be in accordance with the approved plan. A pesticide shall not be used if the Secretary of the Interior has prohibited its use. A pesticide shall be used only in accordance with its registered uses and within other limitations if the Secretary has imposed limitations. Pesticides shall not be permanently stored on public lands authorized for use under this grant.

4. The BLM retains the right to occupy and use the right-of-way, and to issue or grant rights-of-way or other land used for other purposes, upon, over, under, and through the lands, provided that the occupancy and use will not unreasonably interfere with the rights granted herein.

5. No hazardous materials will be disposed of on public lands.

6. All desert tortoise found in areas where their continued presence constitutes a hazard to themselves, will be removed to a safe shady area (at least 150 yards form surface disturbance). Construction personnel will be informed that collection of tortoises is prohibited and punishable by a minimum $ 100.00 fine.

7. Trenches, shafts, and bores shall be marked, fences, or otherwise protected so as not to constitute a hazard to the public or to wildlife.

8. Core holes or wells containing potentially usable water should be left in a manner which facilitates their development as water sources and prior to termination of the agreement or abandonment of the holes/wells, MAI will consult with BLM to determine if they will be sealed and capped, plugged back, or turned over to the BLM as is.

9. The District Manager, Las Vegas District Office, Las Vegas, Nevada, shall act as a BLM's authorized officer for implementation of this right-of-way reservation.

Section B

Climate Change Program

Climate Change Program

Introduction

The State of Nevada recognizes that the climate-change issue for Yucca Mountain is complex and critical to repository performance under the regulatory requirements (see: 10CFR60.112, .113, .122(c)(23)). A conservative analysis of the existing database indicates that several of the Potentially Adverse Conditions (10CFR 960.4-2-4(c) (2)) exist:

> "Evidence that the climatic changes over the next 10,000 years could cause perturbations in the hydraulic gradient, the hydraulic conductivity, the effective porosity, or the ground-water flux through the host rock and the surrounding geohydrologic units, sufficient to significantly increase the transport of radionuclides to the accessible environment."

Vadose-zone changes in response to climates with increased effective moisture would conservatively include increases in the hydraulic conductivity (due primarily to greater degrees of fracture flow) and ground-water flux (due to marked increases of infiltration). The database suggests increased local saturation (perched water) and a rise in the position of the water table. The Qualifying Condition (10CFR960.4-2-4(a)) states:

> "The site shall be located where future climatic conditions will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in 960.4-1. In predicting the likely future climatic conditions at a site, the DOE will consider the global, regional and site climatic patterns during the Quaternary Period, considering the geomorphic evidence of the climatic conditions in the geologic setting."

Licensing criteria therefore recognize the potential adverse impacts that a climate change may have on site hydrology. The vadose-zone repository, by its very position in the hydrologic system, is an environment that is potentially subject to significant hydrologic change if the climate changes. An increase in effective moisture (moisture from precipitation which escapes evapotranspiration and is either rejected as surface-water runoff or infiltrates as ground-water recharge) is caused by a climate change to either greater precipitation or lower temperature, or a combination of both. The present Great Basin arid and semiarid climates are such that most precipitation is lost to evapotranspiration in many environments. However, on both a short-term and long-term basis, relatively small deviations from the normal climatic conditions can markedly impact the hydrology by producing more or less effective moisture. There is abundant paleohydrologic evidence in the Great Basin of past climates which produced significant increases in effective moisture during the Quaternary.

The vadose-zone position of the repository over a 10,000 year period of performance with potentially differing moisture conditions is a key issue. The best available evidence indicates that a climate change to a pluvial climate (more effective moisture for runoff and infiltration) is likely to occur within the next 10,000 years. The climate of the last pluvial period in the Great Basin, and its associated hydrologic impact, is the most reasonable pluvial climate and hydrology likely to occur in the next 10,000 years. The increased availability of effective moisture for infiltration due to a pluvial climate may markedly increase the vadose-zone flux, increase the extent of local perched saturation, establish a shallower position of the regional water table, and cause new patterns of ground-water flow and ground-water discharge. As these factors directly affect waste isolation, the fundamentally important climate-change issue must be fully explored in establishing the performance of the proposed repository at Yucca Mountain. Appendix B-I established a Nevada draft technical position on the climate-change issue.

The DOE, in dealing with climate-change issue in their Environmental Assessment of the Yucca Mountain site, interpreted that the available data indicated that there would be no significant impact on the repository performance. Our response to this theme is found in Appendix B-II.

Both site-specific and regional analyses are necessary to confidently characterize the pluvial hydrology of Yucca Mountain. Ideally, hydrologic evidence demonstrating the conditions of saturation and flux in the vadose zone of Yucca Mountain during the past pluvial climate should be based on site-specific data. These data should be distributed to confidently assess the heterogeneity of both the subsurface and the surficial or near-surface hydrogeologic environments that give rise to varied infiltration rates and percolation paths. Unfortunately, only a few techniques are recognized that may establish site-specific information on the paleohydrologic conditions, and these are unproven at this time. Therefore, regional analyses, using proven methodologies, must refine and constrain anticipated uncertainties represented by the site-specific evidence.

Confident assessment of the site-specific pluvial hydrologic conditions in the vadose zone at Yucca Mountain constitutes a research challenge. Even confidently characterizing the existing hydrology of the vadose zone at the site is yet to be achieved after years of characterization activities. The climate-change issue is recognized as one of the most fundamental questions for waste isolation over protracted time, and the State of Nevada oversight effort has incorporated several activities designed to further explore this issue:

I. Investigate the site-specific authigenic mineral assemblages in the vadose zone, particularly those associated with fractures, in an attempt to determine the history and perhaps (technique development necessary) timing of fracture flow. Also, on the basis of plant macrofossils from packrat middens, determine the available record of the last 50,000 years of vegetative cover in the general area of Yucca Mountain.

II. Investigate the regional paleohydrologic evidence within the surrounding basins (such as the extent of late Pleistocene pluvial lakes as indicated by the associated lacustrine deposits) and basin deposits related to former areas of ground-water discharge.

III. Investigate the long-term paleohydrologic record within the Yucca Mountain drainage basin (Amargosa River) as recorded by the Tecopa "Lake Beds".

IV. On the basis of the above investigations, establish the order of magnitude of the increase in pluvial climate vadose-zone flux, the distribution of ground-water discharge, the position and extent of perched water, the former position of the water table (paleowater table), and the increase in fracture flow within the vadose zone that would attend a shift in climate to a full pluvial climate.

Climate Change

ISSUE:

Key Issue:

Will the proposed repository in the vadose zone at Yucca Mountain provide the required waste isolation for the 10,000 year period after emplacement if the climate changes to a full pluvial climate of the Quaternary?

OBJECTIVE OF ACTIVITY:

Establish the paleohydrologic history of the Quaternary in the Amargosa River drainage basin (which includes Yucca Mountain) through the study of the "Lake Tecopa" deposits.

ACTIVITY SUMMARY:

A field study of the Tecopa "Lakes beds" is being made in an attempt to establish the history of lake cycles and their associated extents in the Tecopa basin during the Quaternary. The study includes basinwide stratigraphic studies of the exposed basin deposits, using volcanic ashes (and remnant magnetism) for marker horizons and dating.

FINDINGS:

The exposures indicate several high standing lakes occupied the Tecopa basin during the Quaternary. The well-exposed stratigraphic record is estimated to include most of the Quaternary, extending from greater than 2 millions years B.P. to perhaps about 250,000 years B.P. The maximum extents of the larger lakes suggest former basin closure significantly higher than the apparent closure offered by the terrane at the south end of the basin, and there are tufa deposits indicating zones of former spring discharge on both sides of the basin. Those on the east side occur high on the basin flank.

INTERPRETATION OF FINDINGS:

In general, the maximum (highest recognized) lake extent seems too large for the Amargosa River catchment basin and associated effective moisture (hydrologic index, Mifflin and Wheat, 1979) when compared to the late Pleistocene pluvial-lake hydrologic indices of the adjacent Great Basin region. Preliminary regional correlation with other long climatic records do not seem particularly close (see Appendices B-III and B-IV).

ADDITIONAL WORK REQUIRED:

Refinement of the stratigraphic positions of previously determined magnetic reversals and identified ash beds as well as more detailed analyses of the origin of carbonate units will increase the confidence level in the pluvial-lake cycle history. In addition, more work on the tectonic history of the basin and surrounding region may establish the reason for the anomalous size of the ancient lakes and the poor correlations with other long records of the region.

RECOMMENDED PROGRAM:

The dating control on the exposed sequences needs to be refined. Morrison's careful stratigraphic work, including marker units, needs to be firmly tied to previously establish magnetic profiles and ash identifications. Areas that may have been formerly integrated with the Amargosa River basin should be examined for evidence of connection, such as Pahrump Valley. Careful comparative regional correlations of the pluvial cycles, including careful reviews of previous work in the Searles Lake basin and the Great Basin, are warranted.

EXISTING PROGRAM:

A modest level of field-data reduction and analysis, and an effort to confidently tie the established magnetic-reversal sections and dated ashes into the stratigraphic sequences established by R. B. Morrison is underway for the 1989 effort.

Principal Investigator

Dr. R. B. Morrison (MAI consultant) .

Climate Change

ISSUE:

Key Issue:

Will the proposed repository in the vadose zone at Yucca Mountain provide the required waste isolation for the 10,000 year period after emplacement if the climate changes to a full pluvial climate of the Quaternary?

OBJECTIVE OF ACTIVITY:

Determine the approximate magnitude of the increase in ground-water recharge/discharge in the region surrounding Yucca Mountain that corresponds to full pluvial climates such as those experienced between 20,000 yrs. B.P. and 11,000 yrs. B.P. Also, establish the associated changes in pattern of ground-water discharge and water-table position in the areas of former ground-water discharge.

ACTIVITY SUMMARY:

The basin deposits that relate to the former extents of ground-water discharge are being studied and mapped on either a reconnaissance basis or a detailed basis in terms of distribution, age, and details of depositional environments and associated ecology. In addition, modern-analog environments of ground-water discharge have been studied to verify interpretations of former depositional environments based on the sedimentological and faunal records. On the basis of these data of extent and type of discharge, quantitative comparisons will be made with respect to the associated ground-water discharge, water levels, and flow patterns now present.

FINDINGS:

A number of areas of former ground-water discharge have been recognized and studied in southern Nevada and adjacent areas of California. All of these areas extend well beyond areas of current ground-water discharge. Some have no current discharge, whereas other areas have residual, but much diminished, discharge still occurring. In general, there has been established clear evidence of important changes in the distribution and amount of ground-water discharge, and major changes in the position of saturation. Some deposits have been confidently radiocarbon dated back to approximately 15,000 years, and the general patterns of discharge are understood for the areas mapped in detail. Ground-water levels have declined in some areas by over 100 m. Appendices B-V and B-VI are reports that summarize some of the results from these efforts.

INTERPRETATION OF FINDINGS:

The extents and character of the ground-water discharge areas indicate that effective moisture, in a regional sense, was significantly greater during the last major pluvial climate as well as earlier pluvial climates. A preliminary evaluation suggests that the magnitude of increase in ground-water discharge over modern discharge is similar to the regional increase of effective moisture indicated by Great Basin pluvial-lake hydrologic indices. Mifflin and Wheat (1979) found effective moisture to be about one order of magnitude greater than that indicated by modern lake indices in the Great Basin region. Should this quantitative relationship be affirmed by additional studies of the paleoground-water discharge areas, it suggests that a full pluvial climate would, in a regional sense, increase the ground-water recharge and discharge rates over modern rates by about 10 times. This increase in recharge rate would tend to greatly decrease travel times in the vadose zone by forcing fracture flow to increase proportionally. The release rates of radionuclides from the repository would also proportionally increase due to the rapidity of travel time within the vadose zone, the only possible geologic barrier offering the possibility of long travel times (matrix flow only).

ADDITIONAL WORK REQUIRED:

Several areas warrant additional field studies, either detailed mapping and sampling or reconnaissance mapping and sampling. These include Coyote Springs Valley and possibly Garden Valley and Hot Creek Valley. The latter two basins occur in the region of the Great Basin normally characterized by pluvial lake deposits rather than ground-water discharge deposits. These areas may give an opportunity to compare ground-water discharge rates of pluvial climate in the higher basin of central Nevada. In addition, careful analyses of the modern ground-water conditions in terms of water-table position and flow are needed for each studied area of former ground-water discharge.

A third area of study is directed towards establishing reliable temperature indicators for the full pluvial climate. One method to establish estimates of former ground-water discharge rates requires annual temperature estimates for evapotranspiration rates. Several approaches using stable isotopes are under investigation, and considerable progress is being made in the use of soil carbonates (see Appendix B-VII).

RECOMMENDED PROGRAM:

The climate-change analyses planned in the DOE characterization studies do not approach the pluvial climate ground-water recharge rate change issue from the above perspective. Therefore, the Nevada program should include:

Reconnaissance mapping of all areas of ground-water discharge deposits in the regions surrounding Yucca Mountain, including enough detailed studies and sampling to establish age relationships,

Detailed mapping and sampling studies in the areas with favorable exposures to allow for ground-water discharge estimates,

Stable isotope studies designed to increase the confidence of establishing paleoclimate temperatures, and

Ground-water analyses of water-table position changes, and estimated total flux changes based on flow net analyses in the areas of ground-water discharge deposits.

EXISTING PROGRAM:

Field work and analytical efforts have been reduced due to budget constraints. The present program is analytical work on areas already studied and limited field work at Coyote Springs Valley (see Appendix B-VI). In addition, ground-water data that are available in each area are being assembled. Sampling of buried paleosoil carbonates is planned.

Principal Investigators:

Mr. J. Quade (MAI and University of Utah); Dr. T. E. Cerling (University of Utah); Dr. J. D. Bowman (University of Utah); and Dr. M. D. Mifflin. (MAI).

Reference:

Mifflin, M. D. and M. Wheat, 1979, Pluvial lakes and estimated pluvial climates of Nevada: Nevada Bureau of Mines and Geology, Bull. 94, 57 p.

Climate Change

ISSUE:

Key Issue:

Will the proposed repository in the vadose zone of Yucca Mountain provide the waste isolation required for the 10,000 year period after emplacement if the climate changes to the pluvial climates of Quaternary.

OBJECTIVE OF ACTIVITY:

Establish the site specific evidence, if present, for shallow saturation in the vicinity of Yucca Mountain that may be preserved as macrofossils and pollen from past communities of phreatophytic plants.

ACTIVITY SUMMARY:

Reconnaissance search, sampling, and analyses of packrat middens were made in a scoping effort to establish the feasibility of locating, collecting, and analyzing packrat middens to determine the existence and timing of former areas of phreatophytic vegetation. Phreatophytes are plants with deep root systems that tap near-surface saturation in arid and semiarid climates.

FINDINGS:

The study indicates that macrofossils of phreatophytic vegetation occur in at least one midden collected near Fortymile Canyon. Packrat midden sampling near areas of former ground-water discharge in basin lowlands may not be feasible due to the absence of favorable terrane for midden preservation in the low relief areas. Analytical results to date demonstrate plant macrofossils indicative of former moist subsurface conditions in a section of Fortymile Canyon.

INTERPRETATION OF FINDINGS:

The method has the potential to demonstrate the presence and timing (within the last 50,000 years) of areas of shallow saturation on a site specific basis at and around Yucca Mountain. Because of the requirement for rugged terrane that provides stable rock overhangs and fissures for the preservation of ancient middens, it is not as useful in many bolson areas where the former extent and timing of ground-water discharge has been documented and dated by other criteria.

ADDITIONAL WORK REQUIRED:

A careful sampling and associated analysis of packrat middens needs to be made along and around all terrane features which are plausible sites of former seeps, springs, or streams in and around Yucca Mountain. In addition, all bedrock terrane closely adjacent to known or suspected areas of paleoground-water discharge areas in the region should also be sampled. Stable isotope studies of plant macrofossils may prove useful in characterizing soil moisture/ground-water isotopic signatures. More scoping work is required to test this approach. Appendices B-VIII and B-IX are reports that discuss and interpret the findings within the context of previous work and regional relationships.

RECOMMENDED PROGRAM:

The magnitude of the needed program is such that staged studies are most appropriate, concentrating sequentially on either areas or terrane features, and refining the field collection focus on the basis of analytical results.

EXISTING PROGRAM:

Analytical work on the scoping-study middens (determination of macrofossils of plants and animals and pollen) and development of quality-assurance procedures constitutes the existing program. Budgeting constraints have prevented the expanded sampling and analytical studies since the feasibility of the approach has been established.

Principal Investigator:

Dr. W. G. Spaulding (University of Washington).

Appendix B

Climate Change Program

List of Appendices

Appendix B-I

Draft Technical Position on Climate Change by Mifflin & Associates, Inc.

Draft Technical Position on Determination of the Plenipluvial Climatic Conditions to Evaluate Adverse Climate Change Impacts for the Proposed Yucca Mountain High-Level Nuclear Waste Repository.

1.0 Purpose.

This document presents site-specific objectives and approaches for determining the plenipluvial hydrologic changes in the hydrogeology at Yucca Mountain so the impacts on repository performance can be judged for licensing purposes.

2.0 Regulatory Framework.

The State of Nevada recognizes that the climate change issue for Yucca Mountain is complex and key with respect to repository performance under the regulatory requirements (see: 10CFR60.112, .113, .122(c)(23)). A conservative analysis of the existing data base indicates that several of the Potentially Adverse Conditions (10CFR 960.4-2-4(c)(2)) exist:

> "Evidence that the climatic changes over the next 10,000 years could cause perturbations in the hydraulic gradient, the hydraulic conductivity, the effective porosity, or the ground-water flux through the host rock and the surrounding geohydrologic units, sufficient to significantly increase the transport of radionuclides to the accessible environment."

Vadose zone changes in response to the plenipluvial climate would conservatively include important perturbations in the hydraulic conductivity (due to a greater degree of fracture flow) and ground-water flux (due to markedly increased effective moisture). The data base is less clear with respect to increased local saturation (perched water) and the change in the position of the water table. The Qualifying Condition (10CFR960.4-2-4(a)) states:

> "The site shall be located where future climatic conditions will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in 960.4-1. In predicting the likely future climatic conditions at a site, the DOE will consider the global, regional and site climatic patterns during the Quaternary Period, considering the geomorphic evidence of the climatic conditions in the geologic setting."

The proposed vadose-zone repository in fractured volcanic tuff would occupy an environment that is sensitive to changes in climate and the associated changes in effective moisture (changes in the amount of precipitation that is either rejected as runoff or accepted as infiltration). In the fractured rock terrane of Yucca Mountain, increased infiltration of effective moisture would result in potential increases in ground-water flux through the repository horizon and increasingly significant fracture flow, which is believed to be several orders of magnitude more rapid than matrix flow. The aridity of the current climate creates the potential for a small flux of infiltrated effective moisture (but as yet it has not been site-specifically demonstrated as to how small the flux is, and what proportions of the flux percolate as matrix flow and as fracture flow).

3.0 Issue.

The Yucca Mountain repository performance in terms of waste isolation is highly dependent upon the flux rate and distribution of moisture in the vadose zone (that zone which is commonly called the unsaturated zone, where hydraulic continuity over broad areas does not exist because of discontinuous saturation). The waste-containment concept of the Yucca Mountain repository is that of little or no flux of moisture through the vadose zone due to the aridity of the climate, and that flux which does occur is primarily in the very low-permeability rock matrix. The repository is positioned above the regional zone of saturation.

Licensing criteria (section 2.0, above) recognize the potential impacts that a climate change may have on site hydrology. The vadose-zone repository, by its very position in the hydrologic system, is an environment that is potentially subject to significant hydrologic changes if the climate changes. An increase in effective moisture (moisture from precipitation which escapes evapotranspiration and is either rejected as surface-water runoff or infiltrates as ground-water recharge) caused by a climate change to greater precipitation, lower temperature, or a combination of both, will produce greater effective moisture. The Great Basin arid and semi-arid climates are such that most precipitation is lost to evapotranspiration in many environments. However, on both a short-term and long-term basis, relatively small deviations from the normal climatic conditions can markedly impact the hydrology by producing more or less effective moisture. There is abundant paleohydrologic evidence in the Great Basin of past climates which produced significant increases in effective mositure during the Quaternary.

The vadose zone of Yucca Mountain is likely to be immediately impacted by any short or long-term climatic changes which produce a change in the rate of infiltration, as rate of travel of infiltrated moisture via fracture networks is measured in months or years. The vadose-zone position of the repository creates a key issue with respect to climate change in the forthcoming 10,000 years, the required period of assured waste containment. The best evidence available indicates that a climate change toward a pluvial climate (more effective moisture for runoff and infiltration) is likely to occur in the future. The State of Nevada currently accepts that the last major pluvial climate to occur in the Great Basin is a reasonable measure of the degree of future climate change to anticipate for future pluvial climates of the Great Basin during the forthcoming 10,000 years. Therefore, the paleoclimate and associated paleohydrology of the last pluvial climate, indicative of the magnitude of increase in effective moisture over that which occurs in the modern climate, is a currently accepted measure of climatic and hydrologic conditions under which the site should successfully isolate the repository waste with respect to standards of radionuclide releases and other performance criteria.

The State of Nevada recognizes that the increased availability of effective moisture for infiltration due to the plenipluvial climate may markedly increase the vadose zone flux, the extent of local perched saturation, and establish a shallower position of the regional water table. As these factors directly affect waste isolation, the fundamentally important climate change issue must be fully explored in establishing the performance of the proposed repository at Yucca Mountain. Also associated are the potentials for local areas of ground-water discharge and changes in paths of flow to the accessible environment.

4.0 <u>Technical Position</u>:

The vadose zone at Yucca Mountain may be subjected to major changes in moisture regimes induced by climates producing more effective moisture. Such climates producing more effective moisture are anticipated in the future based on the past record of climatic change and associated paleohydrologic evidence on a regional scale in the Great Basin. Support for a vadose-zone repository in highly fractured rock is predicated upon very small moisture flux conditions and the general absence of fracture flow to ensure acceptable performance in waste isolation. Therefore, the proposed repository site must be confidently demonstrated in site characterization studies to not have been subjected to the following conditions during the plenipluvial climates:

I. Extensive or dominance of fracture flow;

II. Extensive zones of perched water;

III. Water-table rise sufficient to flood the repository zone; and

IV. Markedly shortened flow paths from the repository horizon to the accessible environment.

Both site-specific and regional analyses are necessary to confidently characterize the plenipluvial hydrology of Yucca Mountain. Part of the evidence to demonstrate the absence of the above conditions during the past plenipluvial climate must be based on site-specific data and be distributed to confidently assess the heterogeneity of both the subsurface and the surficial or near-surface hydrogeologic environments that could give rise to varied infiltration rates and percolation paths. At least two investigative objectives are appropriate for site-specific evaluations at Yucca Mountain:

I. Establish the site-specific distributions, concentrations, conditions of genesis, and age relationships of secondary minerals in the fractures and rock matrix to characterize the past hydrologic regimens operating in the vadose zone.

II. Establish the climatic conditions of the plenipluvial climate at Yucca Mountain and immediately surrounding terrane through comprehensive sampling and analysis of the site-specific evidence (fossil plant remains, paleosol, surficial deposits, and landform evidence).

In order to confidently evaluate the available site-specific data, regional analyses also must be established to refine and constrain anticipated uncertainties represented by the site-specific evidence. The following regional analyses currently are recognized as necessary to establish:

I. Regionalized characterization of ground-water flux during the plenipluvial climate. Regional scope should include ground-water flow systems within and proximal to the NTS region.

II. Distribution of plenipluvial ground-water discharge and associated positions of shallow saturation. Regional scope should include ground-water flow systems within and proximal to the NTS region.

III. Regionalized characterization of plenipluvial plant communities. Regional scope should include both basin and mountain range environments of south central Nevada, southern Nevada, and closely adjacent areas of California.

IV. Long-term climatic variations as recorded by the paleohydrologic evidence in hydrographically closed basins in the Great Basin.

V. Direct <u>in situ</u> analysis of vadose zone hydrology in appropriate analog environments (welded tuff terranes in plenipluvial climate settings). Position of saturation, occurrences of perched water, relative importance of fracture and matrix flow, and ground-water recharge and discharge relationships are of basic interest in the plenipluvial climate and terrane analog environments.

Appendix B-II

Response to the DOE-EA on Climate Change by Mifflin & Associates, Inc.

B. Climate Change:

Climate Change Guideline, Section 6.3.1.4 (10 CFR 960.4-2-4).

> "The site shall be located where future climatic conditions will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in Section 960.4-1." (DOE, 1986, vol. II, page 6-227).

Several repository-performance issues are directly related to climatic change in the southern Nevada region, since waste isolation is predicated on the aridity of the site. Evidence for paleoclimates creating significantly greater effective moisture and dramatic differences in hydrology has been recognized since the earliest 19th-century geological surveys in the Great Basin. In many currently arid basins pluvial lakes were present as recently as 10,000 years BP and ancient shoreline deposits are often easily recognized. Therefore, a vadose-zone repository in the region raises the question: Will future climatic shifts to climates similar to paleoclimates adversely affect the performance of the repository? The EA theme is that great uncertainty exists in analyses but the available data indicate no significant impact on repository performance. We believe climate change to a plenipluvial climate (significantly more effective moisture for runoff and recharge) creates repository performance issues of: 1) water-table position; 2) extent of perched water; 3) ground-water travel time in the vadose zone; 4) recharge rates; and 5) in general, the ability of the proposed repository to isolate the waste. In-depth treatments of these issues <u>within the context of existing data</u> have been avoided in the EA. We therefore focus our review on the EA postulate that has been used to avoid dealing with available quantitative estimates.

The EA (pages 6-238 and 6-239) discounts the results of preliminary modeling by Czarnecki (1985) of the potential hydrologic impacts of a pluvial climate as based on the estimate by Spaulding, _et_ _al_. (1984) of 100% precipitation increase above modern values. We think the Czarnecki (1985) model is a reasonable and conservative scoping analysis. By adopting the 100% greater-than-modern precipitation and then establishing recharge by considering the Maxey-Eakin estimates for such precipitation, his model recharge rate became 15 times the modern recharge rate. Mifflin and Wheat (1979, page 46) also demonstrate at least _one order of magnitude greater total effective moisture_ between modern climates and pluvial climates in Nevada. The 100% greater-than-modern precipitation increase in the Czarnecki (1985) model also compares reasonably well with the Mifflin and Wheat (1979) estimates (from 52% to 80% greater-than-modern).

The EA adopts the possibility mentioned in Czarnecki (1985, page 20) that two-thirds of the markedly increased moisture available for recharge in a pluvial climate (15 times modern) may constitute surface runoff. This idea was apparently developed by Rush in 1984 from comparing a newly developed Maxey-Eakin recharge estimate of 86,000 acre-ft/yr for Huntington Valley in northeast Nevada with a 30,000 acre-ft/yr discharge estimate (Rush and Everett, 1966, Table 8). However, we find little evidence to demonstrate the accuracy of the 30,000 acre-ft/yr discharge estimate or evidence for less recharge/ more runoff in that portion of the basin analogous to the Yucca Mountain terrane. The following discussion summarizes our findings.

In arid and semi-arid terrane, there are numerous factors which may influence runoff, infiltration, and net ground-water recharge. Among the most important are: 1) how the precipitation occurs in time and space; 2) the temperature regimen of the climate; 3) the hydrogeologic characteristics of the terrane, including regional transmissivity; and 4) the position of saturation with respect to closely related surface-water drainages. Mifflin (1968) discusses some of these relationships observed in Nevada, including the regional transmissivity or flow capacity of terrane and its effect on the position of saturation, recharge, discharge, and response of ground-water flow systems to climate changes. Mifflin and Wheat (1979) review factors such as the relative importance of temperature and precipitation on runoff rates and evapotranspiration, and the associated effects on hydrologic budgets for both the modern and plenipluvial climates of the Great Basin. A good understanding of these above principles and observations helps establish if the Yucca Mountain/Huntington Valley hydrologic analog is reasonable.

Huntington Valley, cited as providing suggestive evidence that two-thirds of the increased effective moisture for recharge would become surface-water runoff, is a reasonable choice in terms of a homoclimate for the plenipluvial climate of Yucca Mountain. Mifflin and Wheat (1979, pages 45 to 46), independently reached a similar conclusion based on the distribution and size of plenipluvial lakes in Nevada. However, we believe that it is not an accurate analogy in terms of basinwide hydrogeologic characteristics. The fractured volcanic tuffs of Yucca Mountain are markedly more transmissive than extensive crystalline-rocked areas of the Huntington Valley hydrographic basin. In addition, the range of terrane altitude within Huntington Valley is greater than that of the Yucca Mountain area. If both the hydrogeologic and the climatic analogies were to be accepted, the Huntington Valley analog would demonstrate that: 1) Fortymile Wash and its major tributaries experienced perennial stream flow during the plenipluvial climates; 2) regional saturation was at or near the principal drainage channel levels; and therefore 3) an important part of the repository horizon may have been in the regionally saturated zone.

To explore in more detail the EA postulate of surface-water runoff limiting recharge, Tables 1 and 2 have been included to demonstrate the importance of the hydrogeologic characteristics of terrane in the Huntington Valley hydrographic basin. Table 1 tabulates estimated ground-water recharge based on the Maxey-Eakin method, with the recharge estimates grouped based on two broad hydrogeologic terrane categories: 1) volcanic and carbonate rocks of significantly greater transmissivity than 2) low-permeability igneous and metamorphic crystalline rock terrane of the northern Ruby Mountains. The volcanic and carbonate rock types establish a closer terrane analog to the fractured tuff terrane of Yucca Mountain in terms of regional transmissivities. It should be noted that the Maxey-Eakin recharge estimate method, as applied in Table 1 to large areas (534,600 and 284,000 acre subbasins), probably results in reasonably good approximations of recharge. This may not be the case for small areas.

Table 1 demonstrates that, even though the crystalline rock terrane represents only one-third of the total basin area, it should receive a little less than one-half of the recharge according to Maxey-Eakin recharge estimates. However, Table 2 compiled by Moore, in Rush and Everett (1966), illustrates that almost 75% of the runoff from the entire basin is derived from the crystalline terrane. The more transmissive terrane, representing two-thirds of the basin and receiving nearly two-thirds of the precipitation, produces only 25% of the runoff. There are several causative

Table 1. Estimated Recharge to Huntington Valley Using the Eakin, et al., (1951) Method.

(1) Ruby Mountains south of Harrison Pass, ranges on west side of Huntington Valley (volcanic and limestone bedrock).

Elevation	Acres	Average Annual Precip. (feet)	Average Annual Precip. (acre-feet)	Estimated Recharge % precip.	Estimated Recharge Acre-feet/yr.
above 8000	24,300	2.0	43,600	25	12,150
7000-8000	43,700	1.46	63,800	15	9,570
6000-7000	207,600	1.12	232,500	7	16,275
below 6000	259,000	.83	215,000	3	6,450
Totals for Area 1	534,600		554,900		44,445

(2) Ruby Mountains north of Harrison Pass (igneous and metamorphic crystalline bedrock).

Elevation	Acres	Average Annual Precip. (feet)	Average Annual Precip. (acre-feet)	Estimated Recharge % precip.	Estimated Recharge acre-feet/yr.
above 8000	47,600	2.0	95,200	25	23,800
7000-8000	34,300	1.46	50,100	15	7,515
6000-7000	50,000	1.12	56,000	7	3,920
below 6000	152,300	.83	126,400	3	3,792
Totals for Area 2	284,200		327,700		39,027
Basin Total	818,800		882,600		83,472

Table 2: Table 4 from Rush and Everett, 1966; prepared by D. E. Moore.

-- Estimated average annual runoff

(Based on the years of record at South Fork Humboldt River near Elko: 1869-1909, 1910-18, 1920-22, 1923-32, 1936-63)

Mountain segment	Location	Area: Acres	Area: (percent of runoff area)	Estimated runoff: (Acre-feet per year)	Estimated runoff: (percent of total runoff)
Ruby Mountains	West flank of mountains north of Harrison Pass above 6,000 feet	120,000	16	124,000	73
Ruby Mountains	West flank of mountains south of Harrison Pass above 6,000 feet	69,000	9	13,000	8
Sulphur Spring Range & Diamond Mountains	East flank of mountains on west side of valley above 6,000 feet	144,000	20	17,000	10
Valley uplands	Valley uplands below 6,000 feet, which contributes to runoff only in northern two-thirds of valley	398,000	55	16,000	9
Total (based on years of record)		731,000	100	170,000	100
(Adjusted to long-term average period 1912-63)		731,000	100	a 148,000	—

a. Of this total, 134,000 acre-feet is the runoff at the mountain front and 14,000 acre-feet is generated on the valley uplands.

factors recognized. The crystalline rock terrane has over twice as much area above 8000 feet MSL and thus receives about twice as much high-country precipitation, and much of this precipitation eventually becomes snowmelt runoff. However, the crystalline terrane also has a very limited capacity to accept and transmit this abundance of moisture available for recharge. The terrane saturates to near land surface, and rejects most of the moisture.

Farvolden (1963) was the first to demonstrate varying hydrogeologic behavior of mountainous terrane in Nevada. Dudley (1967) studied differences in runoff behavior and hydrogeology of the crystalline and carbonate rock terranes in the central Ruby Mountains, including portions of Huntington Valley. Mifflin (1968, pages 17 to 19) used the contrasting hydrogeology of carbonate and crystalline rock terrane of these same Ruby Mountains to illustrate the concept of ground-water flow capacity of terrane. Depending upon the availability of moisture for recharge and the transmissive capacity of the terrane, a saturated condition may be reached where no additional <u>net</u> ground-water recharge can occur, and the local discharge to the incised drainages and topographic depressions constitutes the excess infiltration which maintains perennial streams, as well as seeps, and springs. In the Huntington Valley drainage basin, this phenomenon is widespread in the northern Ruby Mountains crystalline-rock terrane, whereas, in the southern mountainous part underlain by carbonate rocks, there are few perennial streams, seeps or springs. Here, similar mean annual precipitation and availability of moisture for recharge does not exceed the ground-water flow capacity of the terrane, and therefore there is little local rejection of the infiltrated moisture.

Assuming that the present Huntington Valley climate represents an accurate homoclimate of plenipluvial climatic conditions for Yucca Mountain, Tables 1 and 2 provide considerable insight into the Yucca Mountain plenipluvial hydrologic conditions. First, it should be noted that the Maxey and Eakin recharge estimates of Table 1 suggest that, overall, about 10% of the estimated basin precipitation becomes recharge, or about 1.2 in/yr (30.48 mm/yr). Czarnecki (1985, page 20) presents similar conclusions for both Huntington Valley and his Yucca Mountain model. Following the Maxey-Eakin estimation method, the recharge rates within the basin vary from 0.3 in/yr (7.6 mm/yr) below 6,000 feet MSL to 6.0 in/yr (154.4 mm/yr) above 8,000 feet MSL. Thus, even the <u>lowest</u> estimated rate of recharge in the plenipluvial climate analog area markedly exceeds (by one order of magnitude) the small modern values estimated in the EA (0.5 mm). <u>It should be carefully noted that 15 x 0.5 mm/yr is equal to 7.5 mm/yr</u>. This is the source of the recharge estimate in the Czarnecki (1985) model.

Table 2 illustrates that the orders of magnitude of these recharge estimates are reasonable, if not of detailed accuracy. Note that based on streamflow measurements, 170,000 acre-feet/yr was estimated to have runoff from the basin (Table 2) from a total of 882,600 acre-feet/yr of estimated precipitation (Table 1). In summary, about 19% of the estimated precipitation becomes surface-water runoff, whereas Table 1 estimates that about 9.5% of estimated precipitation become ground-water recharge. <u>However, only about 5% of the estimated precipitation appears to become surface-water runoff in that part of the basin underlain by the carbonate and volcanic rocks</u>. We conclude that, as a very conservative minimum estimate, 5% of total estimated precipitation becomes recharge in this part of the basin;

and based on the runoff data of the crystalline terrane, up to a maximum of around 20% of total estimated precipitation may become recharge in that part underlain by carbonate and volcanic rocks. In summary, the hydrologic relationships in the Huntington Valley basin support recharge rates comparable to or greater than those estimated in Czarnecki's plenipluvial model.

We believe repository performance issues during a plenipluvial climate have not been appropriately addressed in the EA nor resolved with respect to the existing paleohydrologic evidence in the region. Available evidence indicates that recharge rates during a plenipluvial climate may greatly exceed the transmissive capacity of the rock matrix, and hence fracture flow may constitute the majority of the recharge flux in the vadose zone and zones of perched water could become extensive. If fracture flow dominates, the ground-water travel time for majority of flux through the vadose zone would be very rapid. In addition, perched zones of saturation, the site-specific position of regional saturation, and the total flux rate of recharge to the thermal envelope all become serious and unresolved repository performance issues.

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Appendix B-III

Quaternary NonGlacial Geology: Conterminous U. S., DNAG, vol. K-2,
16 March 1989 by R. B. Morrison.

K2intro 8-15-86; 12-18-88; 2-20-89; 3-16-89

DNAG VOL. K-2 "QUATERNARY NONGLACIAL GEOLOGY: CONTERMINOUS U.S."

(PREFACE)

"When the work of the geologist is finished and his final comprehensive report is written, the longest and most important chapter will be on the latest and shortest of the geological periods."

Grove Karl Gilbert, 1890, p. 1

INTRODUCTION

Roger B. Morrison

This volume attempts to provide an up-to-date overview of the Quaternary geology of the conterminous United States beyond the glacial limits. Knowledge of this "young geology" has become increasingly important because of its application to engineering geology, hydrogeology, neotectonics, environmental geology, and even to exploration for mineral and hydrocarbon deposits.

If the Tertiary-Quaternary boundary is placed at the Gauss-Matuyama geomagnetic Chron boundary, 2.48 Ma (which seems preferable to the currently widely accepted boundary at 1.65 Ma, see footnote 5 to Table 1), the Pleistocene Epoch began approximately when glaciers started in the Northern Hemisphere (after >50 m.y. without significant glaciation), and also about when modern Man's ancestors originated. *Homo sapiens* evolved in the late Pleistocene, and began to change from a hunter-gatherer to an agrarian society (the start of "civilized" man) 10-9 k.y. ago, soon after the start of the present interglacial, the Holocene. From this perspective it is easy to understand why knowledge of the climatic, tectonic, erosional, and depositional history of the Quaternary Period is important in attempts to comprehend our status in a changing environment and to try to predict our future.

Flint (1957, chapter 1; 1971, chapter 2) gives in-depth summaries of the development of concepts about the Quaternary and Pleistocene. The Pleistocene was first defined (Lyell, 1839) on the basis of fossil mollusks; later it became equated to widespread glaciation (the Great Ice Age), and to the appearance of humanoids (the Age of Man) and other vertebrates. Modern research proves that all these criteria are fuzzy and contadictory as to the chronologic and stratigraphic conditions that are necessary for precise chronostratigraphic definition of an internationally acceptable boundary between the Pliocene and Pleistocene Epochs (Tertiary and Quaternary Periods). Formal decision about this period boundary and selection of an internationally acceptable boundary stratotype has not yet been achieved either by INQUA (International Association for Quaternary Research) or by the International Geological Congress (See footnote 5 to Table 1, this chapter). Therefore, the time range of the regional chapters in this volume extends back at least to 2.5 Ma.

This volume begins with reviews of topics of general interest to students of the Quaternary: paleoclimatology, applicable dating methods, volcanism, and tephrochronology. A proposed chapter on Quaternary tectonism was eliminated because this subject is treated comprehensively in the volume accompanying the Neotectonic Map of North America (Schwartz, 1989), in GSA's Decade of North American Geology (DNAG) series. Therefore, the authors of the regional chapters have been encouraged to provide data on Quaternary tectonism within their regions, and many have done so.

Most of this book is given to regional syntheses that summarize the Quaternary non-glacial geology of various physiographic provinces of the conterminous U.S., mostly as delineated by Fenniman (1933) but in places with minor boundary adjustments in order to accomodate new information, and also a few extensions into adjoining provinces in order to accomodate the wishes and expertise of various authors.

Despite the primary focus on Quaternary geology, all the regional chapters summarize the pertinent features of the pre-Quaternary substrate (bedrock units and late Tertiary tectonic, erosion-deposition, and geomorphic history). A few chapters give correlations with local glacial stratigraphy, but discussion of glacial geology usually is avoided because this topic is covered in a recent comprehensive synthesis of the glacial geology of the entire U.S. (Richmond and Fullerton, 1986).

The regional chapters in this volume emphasize stratigraphy rather than geomorphology and geomorphic processes because the regional geomorphic aspects for North America are given in another DNAG volume (Graf, 1987). Most space is given to regions west of the Mississippi River because of the considerably better degree of accumulation and preservation of Quaternary sediments west of the Mississippi, and because few people have done definitive studies of Quaternary stratigraphy in the eastern U. S.

This volume also tends to subordinate the Holocene and late Wisconsin records, because "Late Quaternary Environments" (Wright and Porter, 1984) focuses on these records; also, another DNAG volume (Ruddiman and Wright, 1987) covers part of this time span.

<u>The Quaternary Period is different</u>

Climatic change is the outstanding characteristic of Quaternary time, compared to most of the Phanerozoic. Starting about 2.4 Ma, the amplitude of climatic cycles increased greatly (Fig. 1), causing frequent large changes in rate and type of deposition in both marine and terrestrial environments, to a degree that makes the better Quaternary stratigraphic records exceptional in geologic time.

Fairbridge (1962) commented:

> "Seen from the vantage point of the whole geologic time scale,...we must say: the present climatic, oceanographic, structural, and sedimentological picture of the Earth is abnormal. If we use the Lyellian philosophy of assuming the present is the key to the past we run a grave danger of being wrong. There is nothing wrong with that basic logic, but processes and relative factors are liable to great changes in velocity, scope, volume, etc."

Butzer (1961, p.35) stated the contrast of Quaternary climates with those usual for the Phanerozoic as follows:

> "During the greater part of geologic time...world temperatures were higher and, above all, more uniform. There were no polar ice caps and the temperature gradient between the Equator and poles was very considerably less than today, subtropical fauna and flora being able to survive at the Arctic Circle during a number of stages of earth history. As can be expected with such temperature distributions the general circulation of the atmosphere was slack, with widespread aridity even in higher latitudes during several geological epochs. This then is the 'normal climate of geologial time.' Those few Ice Ages which have occurred--periods in which polar and continental ice sheets drastically changed the climatological picture- were of comparatively brief duration."

The most comprehensive record of late Cenozoic climatic change on a global scale is the oxygen-isotope (delta ^{18}O- ^{16}O) record from deep-sea cores (Emiliani, 1955, 1967, 1970, 1972; Shackleton, 1969; Hays and others, 1969; Shackleton and Opdyke, 1973; Shackleton and others, 1984; Johnson, 1982; Imbrie and others, 1984; Ruddiman and Kidd, 1985; Ruddiman and Wright, 1987). This record shows chiefly changes in the volume of ice stored on the continents during glaciations, and subordinately, temperature changes in the ocean-surface layer (Mix, 1987). According to this record, major cooling began about 2.4 Ma, shown by an abrupt decrease in calcium carbonate in cores from the North Atlantic, marking the onset of ice rafting into the North Atlantic and appearance of moderate-sized ice sheets in the

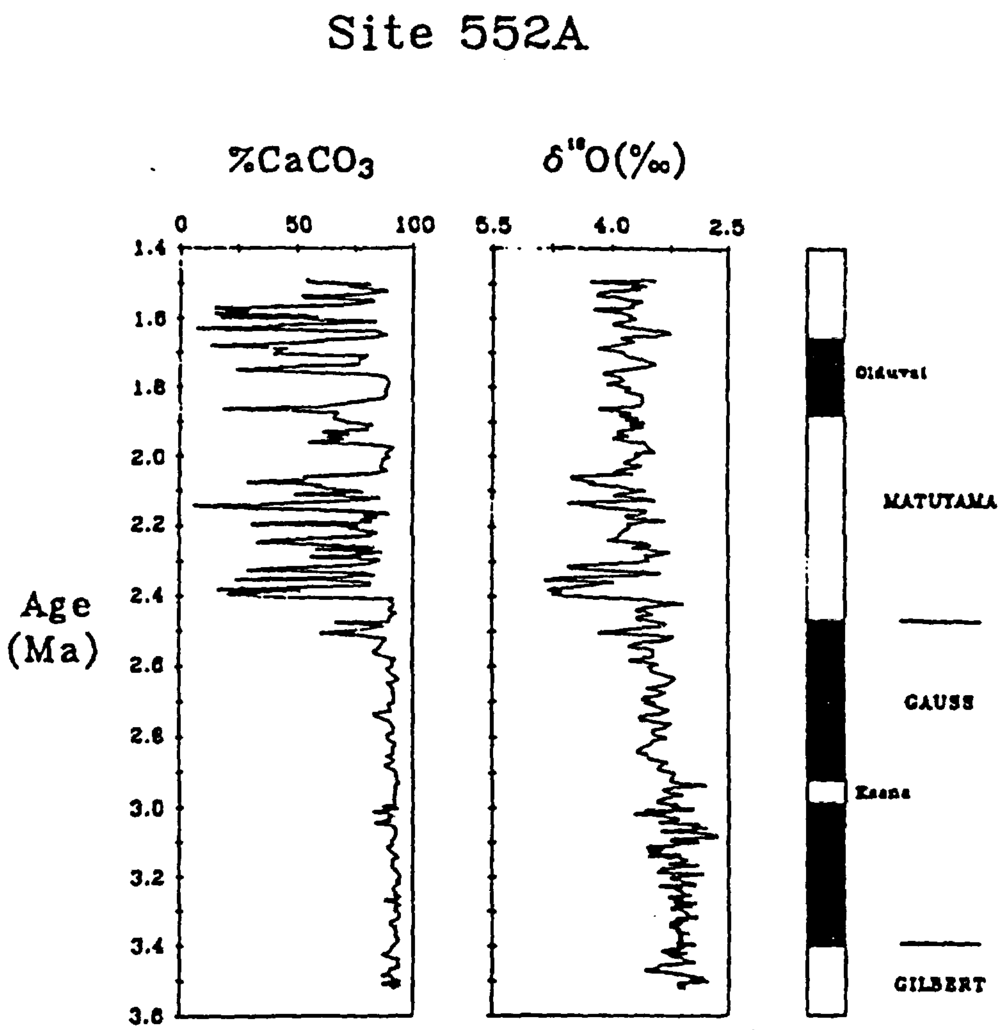

Figure 1. Late-Pliocene and early-Pleistocene records of percent $CaCO_3$ and benthic foraminiferal $\delta^{18}O$ from Site 552 in the North Atlantic at 56°03'N, 23°14'W (after Shackleton and others, 1984; Zimmerman and others, 1985). Abrupt decrease in $CaCO_3$ near 2.55 to 2.4 Ma marks the onset of ice rafting into the North Atlantic brought about by appearance of Northern Hemisphere ice sheets of moderate size. (From Ruddiman and Wright, 1987). Note the lack of distinctive features in these parameters associated with the Olduvai Subchron.

Northern Hemisphere (Blackmon, 1979; Shackleton and others, 1984; Zimmerman and others, 1985; Ruddiman and Kidd, 1986; Ruddiman and Wright, 1987). This cooling ended a Pliocene warm period characterized by small-scale climatic changes and initiated the larger-amplitude climatic cycles that characterize the Quaternary (Fig. 1).

Quaternary deep-sea oxygen-isotope cycles correlate strongly with 'Milankovich'-type earth-orbital cycles, suggesting that various earth-orbital mechanisms were 'pacemakers' for Quaternary climatic cycles (Hays and others, 1976; Johnson, 1982; Imbrie and others, 1984; Ruddiman and Wright, 1987). These correlations indicate:

(1) From about 2.4 to 0.9 Ma the early ice-accumulation cycles oscillated chiefly in a 41 k.y. rhythm, corresponding to that of orbital tilt (changes in obliquity, from perpendicular, of the earth's axis to its orbital plane) (Fig. 1).

(2) After 0.9 Ma (end of the Jaramillo normal polarity Subchron), the amplitudes of changes in delta ^{18}O and CaCO3 concentrations increased about two times, suggesting that in the Northern Hemisphere ice-volume maxima became twice as big as they were before the Jaramillo Subchron. The first really large delta ^{18}O maximum (indicating a huge buildup of ice on continents) occurred during O-isotope stage 22, about 0.89 to 0.79 Ma.

(3) Between 0.9 and 0.65 Ma the precession (of equinoxes) orbital mechanism (cycles lasting 19-23 k.y.) tended to modify the effect of the tilt cycles, albeit with a lag of several thousand years.

(4) After 0.65 Ma, a ~100 k.y. cycle dominated, corresponding

to the Earth's eccentricity cycle. This poses an enigma: The eccentricity cycle produces almost negligible changes in insolation. Various hypotheses are proposed to explain this serious nonlinearity vs known inputs from the earth-orbital mechanisms (Kukla, this volume; Ruddiman and Wright, 1987).

<u>Significant conclusions from the marine oxygen-isotope record and correlative loess records in central Europe and China</u>

The deep-sea oxygen-isotope record has become a standard for Quaternary chronology, even among geologists studying terrestrial deposits, because the better deep-sea-core records are far more complete, with fewer time-gaps than any terrestrial records. Also, the deep-sea record has been dramatically reinforced by correlation with long loessial records from central Europe (Kukla, 1975, 1977; Fink and Kukla, 1977) and China (Liu Tung-sheng and others, 1985; Kukla, 1987; Kukla and others, 1988; Kukla and An, 1989).

These data lead to the following conclusions:

(1) At least seventeen complete interglacial-glacial cycles (IG-G cycles) occurred since the end of the Olduvai normal-polarity Subchron (about 1.65 Ma) and perhaps as many as 44 such cycles since the Gauss-Matuyama Chron boundary (about 2.48 Ma) in the loess record in China (Kukla and An, 1989). [Both paleomagnetic boundaries currently are candidates for selection of the international Tertiary-Quaternary (Pliocene-Pleistocene) boundary; see note 5 in Table 1.] Individual IG-G cycles were mostly within the range of 70 to 120 k.y.; thus they were similar but not identical in duration. Also, they commonly differ in their

amplitude of climatic change. Some cycles were cooler than normal during their glacial or interglacial phases and others were warmer than normal during either or both phases. Therefore, early investigators of terrestrial sequences tended to recognize only the more pronounced, larger-amplitude manifestations, essentially megacycle sets of more than one IG-G cycle.

(2) Between 12 and 15 percent of the last 500 k.y. was as warm or warmer than now. About the same percentage of the youngest complete IG-G cycle (Sangamon through Wisconsin) also was as warm or warmer than today (Emiliani, 1967, 1970, 1972; Johnson, 1982; Imbrie and others, 1984).

(3) The last (Wisconsin) glacial (oxygen-isotope stages 5d-2) began about 115 ka, and markedly increased about 70 ka (O-stage 4/5 boundary); its deglaciation began about 14 ka, and the current interglacial (O-isotope stage 1) began 12-10 ka (footnote 1, Table 1). The previous interglacial (Sangamon in the strict sense, O-isotope stage 5e) lasted about 13,000 years (Table 1).

(4) From this record and earth-orbital insolation data projected into the future, it is likely that within several thousand years the Earth will commence upon another glacial phase lasting at least several tens of millenia--an environment that civilized man has never experienced. It portends crises in energy and food supplies far more severe than any that "Civilized Man" has previously experienced. We are privilged to live in an exceptional time by paleoclimatic standards.

Chronostratigraphic division of the Quaternary

In the past, glaciations, the most striking manifestations of climatic change in the terrestrial stratigraphic record, have been the basis of division of the Pleistocene. The "classic" divisions in North America and Europe were based on the few then-recognized glaciations and interglaciations, and these divisions commonly were used akin to chronostratigraphic units. Now, as a result of more advanced stratigraphic and chronometric research, many more glaciations (and interglaciations, stadials, and interstadials) are recognized throughout the Northern Hemisphere (Sibrava and others, 1986). Also understood is the fact that the boundaries of the physical units in glaciated areas (tills, outwash deposits, paleosols, etc.) in all the stratigraphic sequences are strongly time-transgressive ("diachronous") (Richmond and Fullerton, 1986, p. 6, 8, 183-184, Chart 1).

Consequently, Quaternary workers are moving toward defining chronostratigraphic boundaries on the basis of geologically isochronous units, such as tephra layers and geomagnetic reversals. Geomagnetic Chron and Subchron boundaries have global extent and are deemed the most suitable for international boundaries. This is illustrated by the recommendation of the INQUA 1987 Congress that the Matuyama-Brunhes Chron boundary be adopted internationally as the boundary between the Lower and Middle Pleistocene. Also, both the upper boundary of the Olduvai Subchron and (preferably) the Gauss-Matuyama Chron boundary currently are candidates for marking the Pliocene-Pleistocene [Tertiary (Neogene)-Quaternary] boundary internationally (see footnote 5, Table 1).

<u>Additional significant revisions</u>- Much of the "classical" chronostratigraphic/morphostratigraphic structure of classifying Quaternary deposits is now revised on a global basis (Sibrava and others, 1986). Quaternary geologists in the U.S. should note

that terms such as Yarmouth(ian), Kansan, Afton(ian), and Nebraskan are recommended to be abandoned (Richmond and Fullerton, 1986, p. 6-7, 183-184), because they have been widely misused as chronostratigraphic names; although originally based on litho- and pedostratigraphic units, they oversimplify a complex stratigraphic record, and have led to much miscorrelation of units. Other classical terms, including Sangamon, Illinoian, and parts of the Wisconsin are more narrowly redefined (Richmond and Fullerton, 1986, p. 6-7, 189-194, Chart 1).

Quaternary boundary dates used in this volume

Table 1 gives the boundary dates of key chronostratigraphic divisions of the Quaternary according to usage in this volume. The boundary dates are based chiefly on correlations between astronomical data on variations in Earth's orbit (eccentricity, axial tilt, and precession of equinoxes) and oxygen-isotope data from deep-sea cores (these chiefly record the amount of ice build-up on land). These correlations provide the best currently available chronometry for the entire Quaternary, although they remain somewhat controversial (see footnotes 2 and 4 to Table 1).

TABLE 1

QUATERNARY BOUNDARY DATES USED IN THIS VOLUME

	HOLOCENE (Oxygen-isotope stage 1)	
		10-12 ka [1]
LATE PLEISTOCENE	LATE WISCONSIN (Oxygen-isotope stage 2)	
		~28 ka [2]
	MIDDLE WISCONSIN (O-isotope stages 3 & 4)	
		~70 ka [2]
	EARLY WISCONSIN (O-isotope stage 5a - 5d)	
		~115 ka [2]
	SANGAMON (<u>sensu</u> <u>strictu</u>; O-isotope stage 5e)	
		~128 ka [2]
MIDDLE PLEISTOCENE	LATE-MIDDLE PLEISTOCENE ("Illinoian" of Richmond and Fullerton, 1986; O-isotope stages 6-8)	
		~300 ka [2]
	MIDDLE-MIDDLE PLEISTOCENE (O-isotope stages 9-15)	
		~620 ka [3]
	EARLY-MIDDLE PLEISTOCENE (O-isotope stages 16-19)	
	(Matuyama-Brunhes Chron boundary)	750-770+ ka [2,4]
	EARLY PLEISTOCENE	
	Upper boundary of Olduvai Subcron	1.65 Ma [5]
OR	Gauss-Matuyama Chron boundary	2.48 Ma
	PLIOCENE	
		5.0-5.5 Ma [6]
	MIOCENE	

FOOTNOTES FOR TABLE 1, QUATERNARY BOUNDARY DATES

1. Based on the deep-sea record, the Pleistocene-Holocene boundary should be placed at the boundary between O-isotope stages 2 and 1 (Termination I), commonly given as 11-12 ka (e.g., Rudiman and Wright, 1987a; Imbrie and others, 1984, Tables 6 and 7). However, in deep-sea-cores throughout the world this boundary is time-trangressive between about 9 and 13 ka. Its best terrestrial litho/biostratigraphic representations in North America and western Europe appear to be at about 10 ka. Hopkins (1975) proposed an abritary date of 10,000 yrs as a compromise for divergent opinions based on land data. However, this proposal does not meet the requirement of an internationally acceptable stratotype for this important chronostratigraphic boundary. Richmond and Fullerton (1986) accept 10 ka as a provisional date for the Pleistocene-Holocene boundary; however, they note (p.186) that it is a geochronometric boundary without stratigraphic basis; it does not date the termination of continental glacial activity in the U.S. and it has no significance in the overall record of glaciation in the United States. Neither INQUA nor the International Geological Congress have decided upon a suitable stratotype and date for this boundary.

2. Astronomical age of marine O-isotope stage boundary based on Tables 6 and 7 _in_ Imbrie and others (1984) and, older than 620 ka, corrected as described below.

Many deep-sea core-record chronologies were presented before Johnson (1982) published the first attempt to link the deep-sea oxygen-isotope and earth-orbital records by statistical analysis, using O-isotope data from one core from the central-western

Pacific Ocean. Imbrie and others (1984) used data from this and four other deep-sea cores (from the Southern Atlantic, Indian, and Southern Oceans, and the Caribbean Sea; three of these cores penetrated the M/B boundary) and more sophisticated statistical techniques to correlate these deep-sea records with earth-orbital parameters. They initially used two calibration points: 127 ka for the O-stage 5/6 boundary, and 730 ka (from Mankinen and Dalrymple, 1979) for the M/B Chron boundary. After the oxygen-isotope curves were "tuned" to the precessional parameters and averaged, the final ages of these calibration points were 128 and 734 ka, respectively. Most knowledgeable workers in Quaternary science believe that Imbrie and others (1984) product is the most accurate available chronology for the deep-sea oxygen-isotope record; most of its data are used as a standard in this volume, in Table 1, Figure 2 and elsewhere.

However, minor correction seems to be indicated because Imbrie and others (1984) used too young a date (734 ka) for the Matuyama-Brunhes Chron boundary, one of their calibration points. (Likely, the correct date is somewhere between 750 and 770 ka; see footnote 4.) Nevertheless, their deep-sea O-isotope data are fine-tuned to close agreement with astronomical data back to about 620 ka, before which they are discordant, particularly with terrestrial data (G.J. Kukla, written and oral commun., 1989). Fig. 2 graphs their data on O-isotope variation with time, showing both their original time scale and a modified time scale (beginning at 620 ka in order to adjust the Matuyama-Brunhes Chron boundary to 760 ka instead of 734 ka; Table 2).

13a

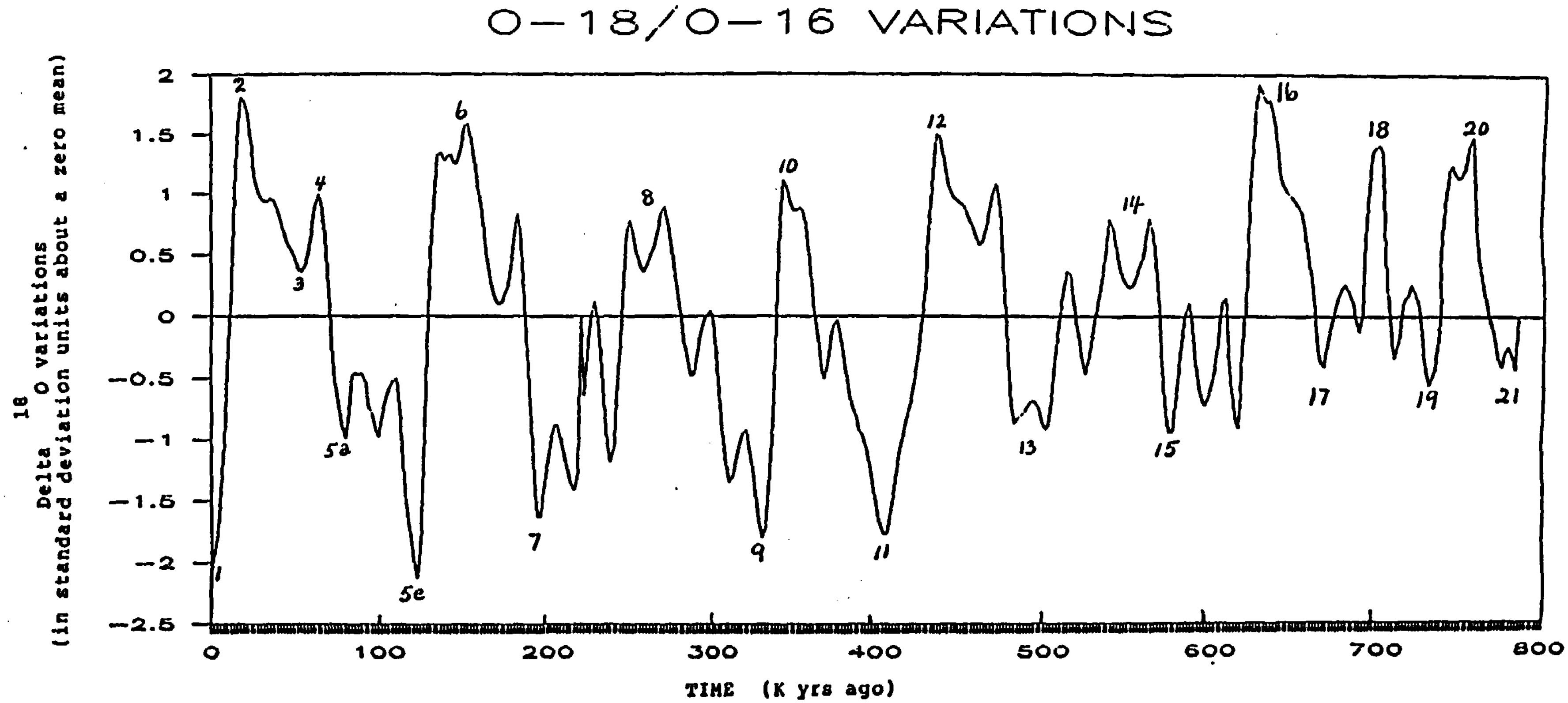

Fig. 2. Record of 18O/16O variations in five deep-sea cores, tuned to each other and to earth-orbital parameters, as a function of time, from Imbrie and others, 1984, Table 7. The graph in color shows an incremental adjustment of the data for the period before 620 ka, based on better data for the M/B Chron boundary (see Table 1, footnote 4, for explanation). The numbers along the graph refer to oxygen-isotope stages; the even-numbered peaks are glacial maxima, and odd-numbered troughs are interglacial minima.

Note to reviewers: The "graph in color" is in preparation

Table 2. Proposed time-interval changes from those given in Imbrie and others (1984, Table 7), between 620 and 800 ka (see Table 1, footnote 4, for explanation).

Original time scale (k.y.)	Original data	Modified time scale (k.y.)	Original time scale (k.y.)	Original data	Modified time scale (k.y.)
620	0.09	620	700	1.42	718
622	0.86	622	702	1.36	721
624	1.42	625	704	0.76	723
626	1.77	627	706	0.08	726
628	1.92	630	708	-0.21	728
630	1.84	632	710	-0.32	731
632	1.77	635	712	0.16	733
634	1.79	637	714	0.10	736
636	1.69	640	716	0.15	738
638	1.49	642	718	0.18	740
640	1.25	645	720	0.26	743
642	1.10	647	722	0.21	745
644	1.05	649	724	0.08	748
646	1.01	652	726	-0.14	750
648	0.98	654	728	-0.43	753
650	0.94	657	730	-0.55	755
652	0.90	659	732	-0.49	758
654	0.86	662	734	-0.42	760
656	0.74	665	736	-0.18	762
658	0.51	667	738	0.39	764
660	0.23	669	740	0.91	767
662	-0.05	672	742	1.19	770
664	-0.25	674	744	1.25	772
666	-0.38	676	746	1.18	775
668	-0.40	679	748	1.14	777
670	-0.23	681	750	1.15	780
672	-0.02	684	752	1.22	782
674	0.11	686	754	1.40	784
676	0.18	689	756	1.48	787
678	0.24	691	758	1.18	789
680	0.26	694	760	0.75	792
682	0.21	696	762	0.40	794
684	0.11	699	764	0.18	797
686	-0.01	701	766	0.03	799
688	-0.12	704	768	-0.10	802
			770	-0.23	804
			772	-0.36	807
			774	-0.40	809
			776	-0.30	812
			778	-0.24	814
			780	-0.31	816
			782	-0.42	819

3. Richmond and Fullerton (1986) use the Lava Creek B tephra layer, dated 620 ka (K-Ar & fission-track; G.A. Izett, U.S. Geological Survey, oral commun., 1987) to define this boundary. This tephra is widespread in the western U.S. This is the approximate age of the boundary between oxygen-isotope stages 15 and 16 (Fig. 2).

4. The Matuyama-Brunhes (M/B) geomagnetic Chron boundary is now proposed by an international body as marking the boundary between the lower and middle Pleistocene (INQUA Subcommission on boundaries of subdivisions of the Pleistocene, 1987).

The age of the M/B Chron boundary cannot be ascertained directly; this age (like all paleomagnetic ages) must be determined by proxy, by dating closely underlying and overlying strata by independent means (isotopic, fission-track, or other methods) at many localities. The best approximation of the age of this Chron boundary appears to be about midway between the estimates of Mankinen/Dalrymple (1979), Imbrie and others (1984), and Johnson (1982) (respectively, 730±11, 734±5 and 788 ka) for the following reasons:

(1) Johnson's (1982) date of 788 ka is somewhat too old, because it does not allow enough time between the M/B Chron boundary and the end of the Jaramillo Subchron (well-dated at 0.89 Ma), as evinced by deposition rates in many deep-sea cores (G.J.Kukla, personal commun., 1989). [Nevertheless, Richmond and Fullerton (1986) accept Johnson's date as a provisional age for the M/B boundary.]

(2) Both the Mankinen/Dalrymple and Imbrie and others ages clearly are too young because they disagree with the re-determination of the age of the Bishop Ash by Glen Izett (U.S. Geological

Survey, personal commun.,1988) as 738±3 ka, obtained as a weighted mean of 14 dates (K-Ar on sanadine and fission-track on zircon). This normal-polarity tephra layer lies 3.5 m above the M/B boundary in a Lake Bonneville (Utah) sequence cored at the southern edge of Great Salt Lake, and a strongly developed paleosol lies just below the Bishop Ash; the M/B Chron boundary is estimated (by deposition rate and disregarding time for soil development) to be at least 15 ka older than the Bishop Ash (i.e., at least 753 ka) (Eardley and others, 1973, Fig. 1 and p. 212).

In two borehole cores near Bakersfield, California, the M/B boundary was identified (in lacustrine clay deposited during a major deglaciation) 3.7 and 4.9 m below the Bishop Ash; the average deposition rate including gaps is 11.7 cm/1000 yr, making the approximate age of the M/B boundary about 775 Ma (using 738 ka as the age of the Bishop Ash; Davis and others, 1977).

<u>Because of the above considerations, the Matuyama-Brunhes Chron boundary is tentatively dated 750-770+ ka in this volume</u>.

The Bishop tephra layer lies <1 m to rarely >3 m above this boundary in remnants scattered widely over the western U.S. (Chapters 5, 6, 7, 9, 10, 13, 14 and Plate , this volume).

5. Two quite different stratigraphic horizons/ages currently are being proposed for the Pliocene-Pleistocene boundary:

(A)<u>The end of the Olduvai normal-polarity subchron, dated 1.64-1.65 Ma</u>. This is the provisional boundary selected in 1981 by joint resolution of the Working Group of the International Geological Correlation Program Project 41 (Neogene-Quaternary Boundary) and the International Union for Quaternary Research (INQUA)

Subcommission 1-d on the Pliocene-Pleistocene Boundary (International Commission on Stratigraphy Working Group on the Pliocene-Pleistocene Boundary).

Nevertheless, THIS CANDIDATE FOR AN INTERNATIONAL STRATOTYPE FOR A GEOLOGIC PERIOD BOUNDARY IS SERIOUSLY UNSUITABLE, for these reasons:

(i) The proposed stratotype area in southern Italy is much deformed and faulted, with many tectonic and erosional hiatuses; even the proposed stratotype, the "Vrica section", is truncated.

Aguirre and Pasini (1985) propose that the international stratotype for the Plio-Pleistocene boundary be designated as the top of the Olduvai normal-polarity Subchron in the Vrica section. However, its paleomagnetic, tephrochronologic, biostratigraphic, and chronologic data are ambiguous and may be in serious error (Kukla, 1987, p. 214-216). Identification of the Olduvai Subcron here is questionable; the normal-polarity strata may represent an older Subchron such as the Reunion (Tauxe and Opdyke, 1981; Arrias and Bonnadona, 1987).

(ii) The relatively short Olduvai Subchron cannot be identified paleomagnetically in many Pliocene-Pleistocene sequences, marine and terrestrial-- and even less frequently, the precise position of its upper boundary.

(iii) <u>The Olduvai Subchron does not mark a substantial climatic event on a global basis, and therefore is not a world-wide distinctive litho- or biostratigraphic unit</u>.

Published comments adverse to placing the Plio-Pleistocene boundary at the top of the Olduvai Subchron include:

(1) From Richmond and Fullerton (1986, p. 186):

"...there are no criteria by which the Pliocene-Pleistocene boundary thus defined can be located accurately in the stratigraphic sequences in the U.S.A."

Also, "The Pliocene-Pleistocene boundary thus defined has no significance in the stratigraphic and chronologic framework of glaciation in the United States. ...It has no significance with respect to the dispersal of microtine rodents ...or other vertebrate faunas...that distinguish the North American land mammal ages; ...no clear significance with respect to climatic or environmental changes in North America based on biotic criteria."

(2) G. I. Smith (Chapter 11, this volume) observes regarding the deep-core record at Searles Lake, California:

"...the 1.6 Ma "beginning of Quaternary time" falls near the middle of a virtually uninterrupted intermediate hydrologic regime that lasted about 0.75 m.y."

(3) Kukla (1987) comments that the proposed Pliocene-Pleistocene boundary has no lithostratigraphic or biostratigraphic representation in the loess sequences of China.

(4) The Olduvai Subchron lacks distinctive features (other than paleomagnetic) in deep-sea-core records (Fig. 1; Jenkins, 1987, p. 41).

(B) <u>The Gauss-Matuyama Chron boundary, currently dated 2.48 Ma</u>.

This paleomagnetic boundary should become the internationally accepted boundary between the Pliocene and Pleistocene Epochs (Tertiary and Quaternary Periods) because:

(i) It is a widespread global stratigraphic marker horizon approximately coeval with the initiation of moderate-sized ice sheets in the Northern Hemisphere, between 2.5 and 2.4 Ma. Throughout the early Pliocene, climate in the Northern Hemisphere, even at high latitudes, was consistently warmer than

Pleistocene climates; the climatic cycles had much smaller amplitudes than those of the Pleistocene and never became colder than the Pleistocene interglacials. The striking climatic shift (Figure 1) that occurred close in time to the Gauss-Matuyama Chron boundary -- the true beginning of the "Great Ice Age" -- is recorded in marine deposits by marked decrease in percent $CaCO_3$ (along with a similar increase in ice rafting and delta ^{18}O) in cores from the subpolar North Atlantic and the Labrador and Norwegian Seas (Backman, 1979; Shackleton and others, 1984; Zimmerman and others, 1985; Ruddiman and Kidd,1986; Eldholm and others, 1987; Arthur and others, 1987; Ruddiman and Wright, 1987). This catastrophic change is recorded on land in middle latitudes of the Northern Hemisphere by the start of loess deposition (Kukla, 1987, 1989).

(ii) Furthermore, the Gauss-Matuyama polarity reversal can be identified widely and unambiguously in terrestial and marine sequences throughout the world.

<u>Some proposals for Pliocene-Pleistocene boundary stratotypes</u>: A suitable stratotype for placing this important period boundary at 2.4-2.5 Ma has not yet been officially proposed. I have several candidates:

(a) <u>Loess sections at either Xifeng or Luochuan, China</u>. The loess sequences of north-central China surpass those anywhere else in the world in depth of exposure (>200 m) and stratigraphic detail, as documented by intensive sedimentologic and magnetostratigraphic study (Kukla, 1987; Kukla and An, 1989; Liu, X.M., 1985; Liu, T.S. and others, 1985). The exposures provide excellent, well-accessible potential holo- or parastratotypes for this period boundary. The Gauss-Matuyama boundary (and the earliest loess) are exposed in the uppermost part of the Pliocene Red Clay Formation, at a depth of about 180 m in Xifeng and 135 m in Luochuan (Kukla and others, 1988).

(b) The Pliocene-Pleistocene sequence (Pico Formation, etc.) in the Ventura basin, California. This sequence is in a long-active tectonic depocenter and has an exceptionally complete, thick, detailed, chiefly marine record (including eight tephra layers, many foraminiferal biozones, the Olduvai Subchron, and extending far below and above the Gauss-Matuyama boundary (Yeats, Chapter 7, this volume). Also, it is well-exposed, explored extensively in depth by drillhole coring, and intensively studied by micropaleontologists, sedimentologists, tephrochronologists, structural and other geologists. Thus, it can be correlated, chiefly via magnetostratigraphy and tephrochronology, with other important terrestrial sequences, ranging from Clear Lake to Lake Tecopa (see Chapters 7 and 10).

(c) The Hueso and Vallecito members (Woodard, 1963) of the Palm Springs Formation in the Vallecito-Fish Creek basin, on the west side of the Salton Trough about 60 km northwest of El Centro, California. This section, several hundred meters of chiefly Colorado River deltaic sediments, is well exposed due to strong deformation and deep badland-type erosion. Its magnetostratigraphy is well studied and indicates that the Hueso and Vallecito members range from 2.8 to 0.9 Ma (Johnson and others, 1983; Johnson, 1985); both the Olduvai Subchron and G/M Chron boundary have been identified, as well as several tephra layers. Winker (Chapter 11, this volume) states: "this section ... contains the most precisely located Plio-Pleistocene boundary in the Salton Trough." The Hueso and Vallecito members also yield a diverse vertebrate fauna of Blancan to Irvingtonian age (White and Downs, 1961; Woodard, 1963; Downs and White, 1968).

6. The Miocene-Pliocene boundary currently is dated 5.0-5.5 Ma (Odin, 1982).

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Appendix B-IV

Excerpts from Progress Report on the Lake Tecopa Project for fiscal Year 1987 - 1988
06 November 1988
by R. B. Morrison.

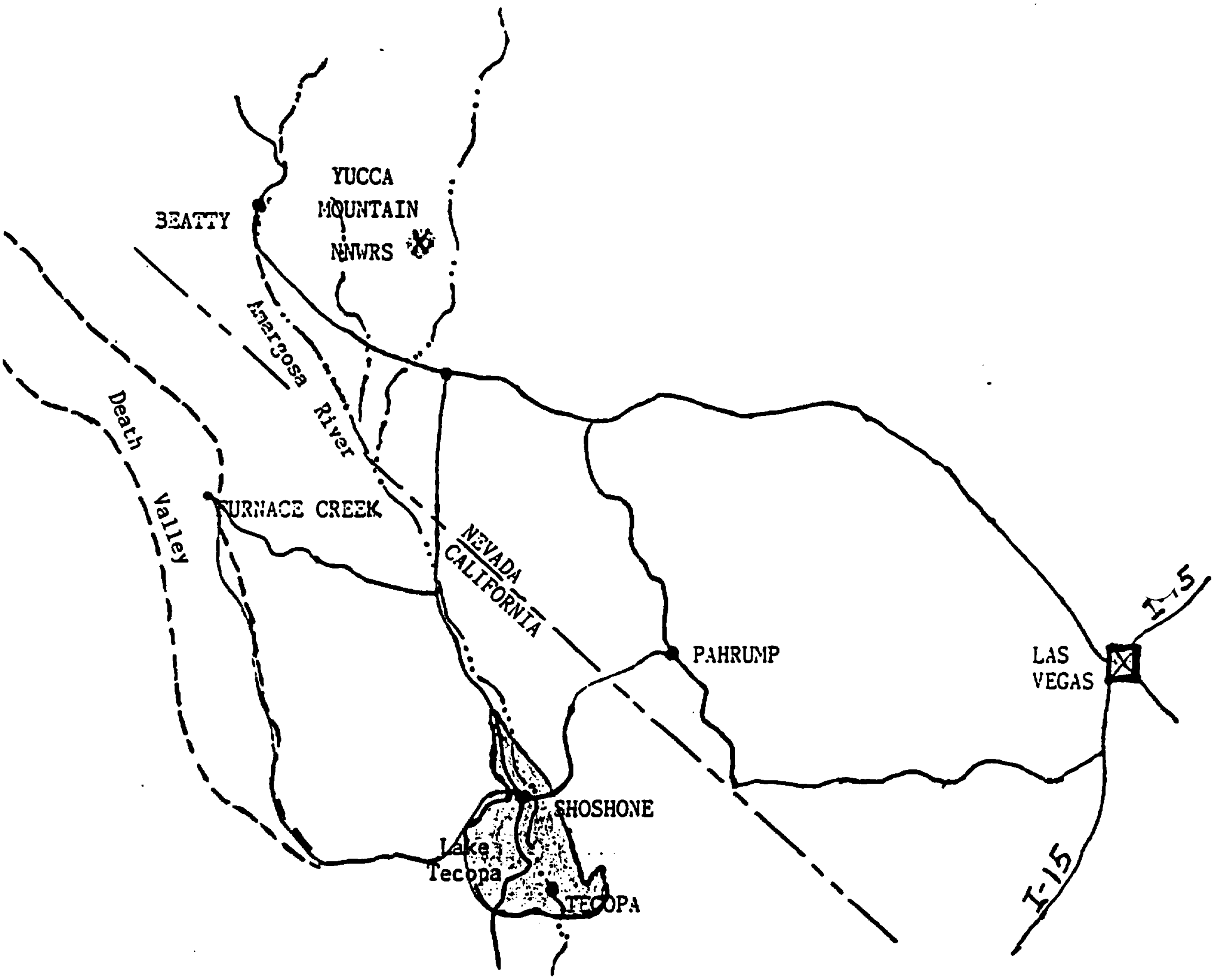


Figure 1. Location map.

1:1 million scale; 1 mm = 1 km

more intensively measured/sampled/studied stratigraphic sections. The various transects utilize the best-available badland exposures throughout the Lake Tecopa basin, that range in age from beyond 2.0 Ma (late to middle Pliocene) to Holocene (see Appendices A, B, C).

Background data

Ancient Lake Tecopa, at its highest stages, covered about 235 sq km near the towns of Tecopa, Tecopa Springs, and Shoshone, in Inyo County, California. "Lake Tecopa" is the name for a long series of alternating lacustral and desiccation episodes, that began about 2.5 Ma and ended sometime in latest middle Pleistocene (about 0.25 Ma), after the lake basin became breached and completely drained by the Amargosa River. Thus, for at least two m.y. Lake Tecopa was the sump for about 6000 sq km of the upper drainage basin of this river, including a large part of the Yucca Mountain area.

Subsequent dissection of the barrier that enclosed Lake Tecopa (a massive late Tertiary fan-gravel complex at the southern end of the Lake Tecopa basin) provides fine exposures of a partly lacustrine, partly playa/subaerial stratigraphic sequence, about 150 m in total exposed thickness. This sequence, from middle Pliocene through lower and most of middle Pleistocene, is one of the longest and most complete exposed "pluvial-lake" records in the western U.S. It contains at least 15 separate tephra, including several dated ones: the Lava Creek B (~0.62 Ma), Bishop (0.735 Ma), Glass Mountain G (1.0-1.1 Ma), and Huckleberry Ridge (~2 Ma) tephra layers (Sarna-Wojcicki et al., 1984 and in press). The tephra layers facilitate regional correlation between Lake Tecopa and other sites with important long-ranging paleoclimatic records, such as Manix Lake, Searles Lake, Salton trough/Anza-Borrego, Ventura/ South Mountain/Balcom Canyon, San Joaquin Valley/Tule Lake, Clear Lake (all in California), and Lake Lahontan (Nevada).

A superb fluvial record complements the lacustrine record. The fluvial record is partly contained in tongues of alluvium intercalated with Lake Tecopa's lacustrine sediments, and also in alluvial units that mantle four well-defined erosion surfaces that developed during and after the draining of Lake Tecopa.

The late-Pliocene/Pleistocene climatic record preserved in Lake Tecopa strata is important not only because it is the best-exposed long record in this region but also because it lies in a critical paleoclimatic zone. This climatic region is one of fluctuation of the boundary between the north-temperate and north-subtropical-arid climatic zones. This boundary probably fluctuated north and south as much as 900 km with the various interglacial and glacial climatic episodes of the later Pliocene and Pleistocene, with big effects upon stream flows, lake levels, watertables and ground-water piezometric surfaces in this region. The migrations of this boundary from the last glacial through the Holocene are becoming fairly well known (Spaulding, 1985; Spaulding et al., 1983; Van Devender and Spaulding, 1979), but almost nothing is known about earlier changes and their effect upon hydrogeologic regimes.

SIGNIFICANT RESULTS FROM THIS PROJECT

The most important results to date from the Lake Tecopa project are:

1) Determined the basic pattern of the complex stratigraphy of deposits in the Lake Tecopa basin -- a >2 m.y.-long series of alternating playa to deep-lake deposits that intertongue with alluvial and some eolian and spring/seep sediments, with many changes in lithology from basin margins to basin interior, as well as local faulting and tilting. Chiefly studied were deposits younger than the Bishop Ash (735 ka), particularly those younger than the Lava Creek B Ash (620 ka), because the younger part of the Lake Tecopa record is most relevant to concerns about NNWR. (See Appendices A to E for details on stratigraphic procedures and findings).

2) On the basis of information from (1), determined the basic outlines of the following histories:

a) Paleohydrologic--the long history of changing lake levels, with many alternations from playa to shallow- to moderate- and deep-lake levels before Lake Tecopa became drained (Appendix Figure F-1). Also determined the history of the four chief post-Lake Tecopa cycles of stream erosion and deposition.

b) Paleohydrogeologic--the groundwater history, of fluctuations in water table and piezometric surface (Appendix Figure F-2). This is particularly relevant to NNWRS because it pertains chiefly to changes in the piezometric surface of a complex artesian aquifer system that is widespread in southern Nevada and adjoining California.

c) Paleoclimatic--the history of the climatic changes that controlled the hydrologic and hydrogeologic histories (Appendix Figure F-3.)

d) Neotectonic--the history of faulting and warping during and after Lake Tecopa's >2 m.y. life, including the locations of intra- and post-Lake Tecopa tectonic features (Appendix Figure H-1). Much more neotectonism has occurred in this basin than has been recognized by USGS workers (Dohrenwend, 1985; Hillhouse, 1987).

3) Prepared a provisional correlation chart, correlating the Lake Tecopa sequence with the Amargosa Desert, Searles Lake, and Lake Lahontan stratigraphic records (see below and Appendix Figure G-1).

PREVIOUS STUDIES OF LAKE TECOPA

Notwithstanding the paleoclimatic importance of the long and well exposed Lake Tecopa sequence in a key part of the southwestern U.S., the history of the repeated deep-lake and desiccation episodes of Lake Tecopa remained completely unknown until this project was started.

Also unknown until this project was how the lacustrine history correlates with the above-lake, chiefly fluvial, erosional and depositional history. Such a correlation is a basic need if a regional paleoclimatic synthesis is to be achieved.

Also unknown was a great deal of striking evidence on marked changes in groundwater conditions: episodes of strong spring discharge (chiefly artesian) alternated with times without such discharge.

For about seventy years preceding 1986, Lake Tecopa received various reconnaissance studies that recognized it as an unusual "pluvial lake" and determined its general outline and lithology (Noble, 1926; Thompson, 1929; Blackwelder, 1936; Sheppard and Gude, 1968; Starkey and Blackmon, 1979). The more intensive studies were directed toward finding commercially useful minerals from the lake beds; none of them attempted to decipher the intricate lake history. Only recently has its approximate age range been determined correctly, by tephrochronology (Sarna-Wojcicki et al., 1984, 1985, and in press).

The recent (Hillhouse, 1987) USGS map of the late Cenozoic deposits of the Lake Tecopa basin was a big step forward toward understanding the complex stratigraphy of this basin. It is helpful for showing most of the exposures of three chief tephra layers, Tuff A (Lava Creek B, 0.62 Ma), Tuff B (Bishop, 0.738 Ma), and Tuff C (Huckleberry Ridge, ~2 Ma); also a few paleomagnetic data; also it is the best published attempt at documentation of exposures of Lake Tecopa and related deposits. However, Hillhouse did not attempt anything approaching a detailed, comprehensive study of the stratigraphy of the Pliocene and Quaternary deposits in the Lake Tecopa basin, nor an interpretation of Lake Tecopa's history (not even unambiguous indication of its highest strandline). Also, his map has many deficiencies (see Appendix I for a detailed analysis).

SUMMARY DESCRIPTION OF THE LATE CENOZOIC DEPOSITS IN THE LAKE TECOPA BASIN AND OUTLINE OF LAKE TECOPA'S HISTORY

(See also Appendices A, B, C, and F.)

Beneath the lacustrine and subaerial deposits comprising the Lake Tecopa Allogroup are hundreds of meters of Pliocene and Miocene sediments, chiefly fan gravel units that are moderately consolidated to strongly cemented, with many paleosols. These deposits and older Tertiary to Precambrian rocks are exposed in places at the periphery of the Tecopa basin, and also in Tecopa Hills and small areas elsewhere within the basin.

The deposits of Lake Tecopa, here collectively called the Lake Tecopa Allogroup, cover a roughly triangular area 18 x 24 km below the highest strandline at about 550 m altitude (1800 ft); the lowest exposures are at about 396 m (1300 ft), at the Amargosa River outlet at the south end of the former lake basin. They include shallow to deep-lake sediments and intercalated alluvium and other subaerial deposits. In most places they are nearly horizontal, rarely sloping as much as one degree basinward; however, in some fault blocks they are tilted, usually only a few degrees but occasionally to high angles, including vertical.

Lake Tecopa has a long <u>lacustrine</u> history, of many shallow to deep-lake cycles (not just high-water-table/paludal conditions), interspersed with many desiccation episodes. Until about 900 ka playa to shallow-lake conditions prevailed, with slow sedimentation rates (Appendix Figures F-1 and F-4). Then began a gradual (but irregular) trend of generally rising lake levels and higher sedimentation rates. This trend accelerated after deposition of the Bishop Tuff (738 ka). Lake Tecopa's highest lake level was reached close to the end of its long history, probably between 300 and 200 thousand years ago (a tentative age estimate based on 30-45 m of chiefly lake sediment that overlie the Lava Creek tephra layer, dated 620 ka (Morrison, 1986-1988 field data; Hillhouse, 1987). At its all-time maximum Lake Tecopa is estimated to have been between 45 and 90 m deep, based on various projections/extrapolations from remnant exposures near its margins.

<u>Pre-Huckleberry Ridge (Tuff C) deposits and history, ~2.5-2 Ma</u>

Exposed pre-Tuff C sediments (Spanish Trail Alloformation) are limited to a few sq km in the southern part of the Lake Tecopa basin, below 440-420 m. [The term "alloformation" is the fundamental unit in a new category of stratigraphic classification (North American Commission on Stratigraphic Nomenclature, 1983). An allostratigraphic unit is a mappable stratiform body of sedimentary rock that is defined and identified on the basis of its bounding discontinuities, rather than by content. Its boundaries are laterally traceable discontinuities.] These deposits have not yet been studied intensively for this project. Our reconnaissances found them to be at least 20 m in maximum exposed thickness and mostly moderately to well-indurated clay and silt (claystone and mudstone), in places with a few thin interbeds of silty very fine to fine sandstone, and perhaps a few paleosols--chiefly playa and playa-margin sediments, with some shallow-lake and distal piedmont to basin-interior alluvium. Nearly all these strata are more or less completely recrystallized by authigenesis except in small upfaulted blocks a few miles NE of Tecopa.

The age of the lowest exposed beds in the Spanish Trail Alloformation (AF) is unknown, but at least 2.5 Ma (late-middle Pliocene) and perhaps [if the sedimentation rate was the same as that between the Huckleberry Ridge and Glass Mountain G tephra (Appendix Figure F-4)] to around the Miocene-Pliocene boundary. Thus, this unit records a few hundred thousand to several million years of playa to occasional shallow-lake conditions, but apparently no deep lakes. At this time, global climatic circulations were quite different from now: The amplitude of interglacial-glacial-type climatic oscillations was much smaller than in the Quaternary (Ruddiman and Wright, 1987). Also, the interface between the North-Temperate and North Subtropical-Arid zones probably was farther north and its north-south fluctuations smaller and slower. In addition, very important for this region, the Sierra Nevada were much lower than now (Huber, 1981; Morrison, in press; Smith and others, 1983), allowing much more moisture to reach the desert areas to the east.

<u>Huckleberry Ridge Tuff to Bishop Tuff sediments (Greenwater Fan Alloformation) and history, ~2 to 0.735 Ma</u>

Deposits of this ~1.3 m.y. interval, about 15 to more than 30 m thick, are well exposed in the badlands near and south of Shoshone, below the Bishop Ash, which ranges in altitude from 445 to 495 m. They generally resemble those of the Spanish Trail Alloformation but are more widely and commonly better exposed. They are chiefly monotonous sequences of moderately to well-indurated clay and silty clay (mudstone) and silt and sandy silt (siltstone), grading to siltstone and fine-grained sandstone toward the basin margins. They appear to have been deposited chiefly in playa and shallow-lake environments, therefore toward the basin margins the Greenwater Fan AF includes increasing amounts of alluvium, even paleosols.

This unit also has not yet been studied in detail for this project. Preliminary interpretation is that its depositional environment was relatively monotonous on a nearly flat basin-interior plain. Its sediments indicate mostly playa, playa-margin, and distal piedmont (fine-grained alluvium) deposition, but also occasional brief shallow-lake episodes. No deeper lakes are apparent--until shortly before deposition of the Bishop Tuff. Wave-ripplemarks in this tephra layer and closely associated fine sandstone beds at several localities at about 450 m altitude in the southwestern part of the basin testify to a lake 15-20 meters deep at this time.

Bishop to Lava Creek B Ash sediments (Shoshone Springs Alloformation) and history, 735-620 ka

Sediments of the Shoshone Springs AF, about 8 to 20 m thick, are widely exposed except north of Shoshone, where they disappear beneath the flood plain of the Amargosa River. They are commonly less indurated and altered than the older deposits. In the northern part of the Lake Tecopa area this unit is chiefly alluvium and loessial deposits, but southward it grades through fluctuating-strandline sandy sediments into 2 to 7+ meters of deep-lake clayey silt and clay in the southwestern part of the basin.

Thus, this ~115 k.y. interval started with a lake about 15-20 m deep, in the southern part of the basin. This lake undoubtedly fluctuated considerably, but during the later part of this interval it was commonly 20 to perhaps occasionally 30 m deep, while alluviation and some loessial eolian deposition continued in the northern part of the Lake Tecopa area. The interval ended with a lake standing at about 480-490 m (present) altitude, on the basis of wave-ripple-marked beds in the Lava Creek tephra layer at several localities, and other evidence of strandline deposition.

Lake Tecopa sediments younger than the Lava Creek B Ash (Amargosa Alloformation) and their history, 620 to ~200 ka

Sediments younger than the Lava Creek Ash have received the most intensive study because their record is most relevant to NNWRS concerns. Erosion after Lake Tecopa was breached has entirely removed them from the central part of the lake basin, but remnants are preserved in many places close to the margins of Lake Tecopa. The remnants are chiefly in ridges capped by pediment gravel of the older post-Lake Tecopa pediments--but unfortunately these pediments slope basinward at an angle considerably greater than the dip o these strata; thus the pediments progressively truncate these deposits basinward. Fortunately, two large areas in the northern part of the basin were not pedimented; both preserve impressive chiefly lacustrine but partly alluvial sequences that rise to or nearly to the highest Lake Tecopa strandline.

The Amargosa Alloformation, commonly 25 to 35 and about 45 m maximum thickness, records two main deep-lake periods, here called lake megacycles. Its lower member (in the northern part of the basin) records a lake megacycle (whose trend started shortly before deposition of the Bishop Ash, but accelerated after Lava Creek Ash time) that peaked about 500 ka at about 520 m altitude, Then came lake regression to below 440 m. The upper member records another lake megacycle that rose with oscillations to Lake Tecopa's all-time maximum at about 550 m, with a maximum depth of 45-90 m. (This altitude varies from place to place about the former lake periphery because of small-scale faulting and tectonic warping since the ultimate lake maximum.) Thus, Lake Tecopa, close to the end of its >2 m.y. life, had two successive all-time-high lake maxima that went above 500 m altitude.

Amargosa AF sediments were deposited on a flat to very gently sloping plain, that sloped generally less than 1 degree at the northern and mountain margins toward a level interior. This is indicated by the horizontal to sub-horizontal strata (where not later deformed) and the fact that along the ancestral Amargosa River northward from Shoshone, fluvial scour/fills rarely exceed 1 m in depth. Deposits of this AF, in the northern 1/3 of Lake Tecopa and marginal to the Sperry Hills/Tecopa Peak are chiefly small-pebble gravel, sand, and silt, with minor clay, marl, limestone, and calcareous siltstone and sandstone. They represent chiefly near-shore, strandline, and deltaic deposits with fluvial intercalations. In contrast to older units, they typically are poorly consolidated to unconsolidated and little altered by authigenesis. However, locally they are moderately to well-cemented and include travertine to tufa-like beds (see below). I found several new proven or probable tephra layers in this unit.

The Amargosa AF is especially rich in carbonate deposits of several genetic modes. The northern part of the basin, particularly within 5 km of Shoshone, displays an ancient "carbonate delta" of the Amargosa River. The carbonate delta is conspicuous (compared to drab sediments elsewhere in the Lake Tecopa area) by predominant white to very pale gray strata, clay to fine sand (stone), whose light tones are due chiefly to fine-grained carbonate. This carbonate likely is a chemical precipitate formed in the zone where relatively lower pH water of the Amargosa River mixed with high pH water of Lake Tecopa (Shepard and Gude, 1968).

The chief other genetic mode of unusual degree of carbonate deposition in this AF is local carbonate-cemented siltstone, sandstone, and pebble gravel, and marl to travertine (chiefly due to spring/seepage discharge in basin-interior to near-offshore lake environments; Mifflin and Wheat, 1979; Quade, 1986). Such deposits occur throughout the Lake Tecopa basin, but are individually very localized (commonly in linear orientation as if along fracture zones), and most common within 20 m of the highest strandline of Lake Tecopa. My present interpretation is that this class of carbonate deposits was deposited from artesian upwelling carbonate-charged water, probably moving first along bedrock fault/fissure zones and then more diffusely through the mostly poorly consolidated Amargosa AF.

Another genetic class of carbonate deposit is tufa that seems to have been deposited by algal action on strandlines (at and within several meters below lake level). These deposits are preserved in only locally, especially at sites prone to strong wave action. Samples currently are being studied.

The uppermost stratigraphic remnants of the Amargosa AF are preserved only locally in the highest strandline zone, due to post-Lake Tecopa erosion. They consist of lacustrine pebble gravel, sand, and silt intercalated with varying amounts of alluvium--also local marl to travertine "tufa mound" deposits that grade into carbonate-cemented sandstone and gravel, likely formed at sites of artesian groundwater discharge. The uppermost lacustrine tongues are much thinner than the main lacustrine units in this alloformation and suggest two or three very brief rises to the high-shore level at the end of Amargosa time. Apparently Lake Tecopa had a rapid demise; no deposits from this final lake regression seem to be preserved.

[Parenthetic note about the Amargosa AF:]
An ambiguity is apparent in the earlier part of the lacustrine record from this unit, between the northern and southern parts of the Lake Tecopa basin. In the northern part, widespread exposures of strandline and offshore deposits above the Lava Creek Ash evince a major lake cycle with lake levels above present 500 m altitude lasting at least several tens of thousands of years. On the other hand, in the southwestern part of the basin at about 465 m altitude, 8 to 10 m of silty and fine-sandy silt beds overlie the Lava Creek Ash, indicating that here playa and playa-margin conditions existed at what is now a lower altitude than the lake to the north. Perhaps tectonism has lowered the southwestern area with respect to the northern; both areas have faults that were active during Amargosa Alloformation time; these faults are particularly numerous in the southwestern area.

Post-Lake Tecopa alluvial deposits and history

Four main fluvial erosion-deposition surfaces developed during and after the draining of Lake Tecopa. They are chiefly pediments that toward the periphery of the basin digitate into strath terraces along principal washes. Typically they bear a veneer 1 to several meters thick of alluvial cobble to pebble gravel with some pebbly sand locally; however, the youngest surface commonly bears much finer (sand to clay) sediments in the lower parts of the basin interior. These post-Lake Tecopa surfaces and their alluvial veneers are here designated numbers 1 (oldest) to 4 (youngest)(see Appendix B).

NOTE: Dohrenwend (1985) gave names for three erosion surfaces in this basin, pre- to post-Lake Tecopa: Sperry (chiefly Pliocene and early Pleistocene, pre-Lake Tecopa maximum), Greenwater, and Amargosa (Holocene)]. His descriptions of these surfaces are so over-simplified and inexplicit (no real definitions or type localities are given) that his nomenclature ought to be abandoned; I do not use it.

The #1 and #2 surfaces/deposits seem to be close in age and will be discussed together. Their remnants are the relatively few highest ridges (between major washes) on the piedmonts o this basin. The alluvial veneers likely are ancient channel-bed deposits of principal washes These narrow mesa-like remnants have a veneer of <1 to rarely >2 m of "pediment gravel". Their surfaces are strongly desert-varnished, nearly smooth (have lost original fluvial irregularities), and their alluvium bears a very strongly developed paleosol. John Rosholt (Chief of Branch of Isotope Geology, USGS) obtained a uranium-trend date of about 160 ka from the relict paleosol on the pediment surface at the Shoshone town dump, which is either the #1 or #2 surface (likely the former; its correlation is uncertain due to faulting).

The #3 surface is a lesser one, expressed chiefly by strath terrace remnants.

NOTE: The #1, #2, and #3 surfaces (my classification) all correspond to Dohrenwend's (1985) "Greenwater Surface", the only post-Lake Tecopa, pre-Holocene surface that he recognized.

The #4 (youngest) surface is equivalent to Dohrenwend's "Amargosa Surface". This surface includes moderately widespread pediments in the southern part of the basin-- surprisingly extensive considering their youth. I believe that this surface formed during both the later Wisconsin and Holocene [not just in the Holocene, as Dohrenwend (1985) believes], on the basis of soil development on the higher remnants of its alluvial veneer in many places throughout the basin.

CORRELATIONS WITH AMARGOSA DESERT (ASH MEADOWS), SEARLES LAKE, LAKE LAHONTAN, AND THE SIERRA NEVADA

Correlation of the Lake Tecopa Allogroup with middle Pliocene deposits of the Amargosa Desert

The Amargosa Desert (Amargosa Flat-Ash Meadows area) is noted for its middle Pliocene deposits of high-magnesium clays and carbonate rocks that are overlain unconformably by much younger Quaternary fluvial and eolian sediments (Denny and Drewes, 1965; Papke, 1970, 1972; Pexton, 1984). The clay-rich Pliocene beds are estimated to be about 4 to 2 Ma on the basis of their relations to dated basalts and tuffs (Hoover, 1985; Pexton, 1984).

Two tephra layers, the Nomlaki, near the base of the exposed section, and the Huckleberry Ridge, close to its top, are dated 3.2-3.4 and 2.0 Ma, respectively (Sarna-Wojcicki and others, in press). Therefore, on a tephrochronologic basis, the middle Pliocene deposits in the Amargosa Desert may range older than those exposed at Lake Tecopa, but likely overlap with the lowermost exposed Lake Tecopa strata (all of the Spanish Trail Alloformation and perhaps the lower part of the Greenwater Fan Alloformation).

Correlation with the Searles Lake record

Lake Tecopa has a stratigraphic/climatic record superior to that of Searles Lake in several respects (see Appendix K).

The Searles Lake record is based chiefly on core data; its exposed record is relatively meager, disjunct, and ambiguous, and goes back not much farther than the last interglacial. The lacustrine part of the 930-m "long" core from Searles Lake begins about 3.2 Ma (Smith et al., 1983; Smith, 1984), perhaps older than the lowest exposed deposits of Lake Tecopa and comparable to the oldest exposed deposits in the Amargosa Desert.

Preliminary comparisons indicate considerable differences in the interpretations of the history of lake fluctuations between Lakes Tecopa and Searles. The following summary for Lake Searles is based entirely on Smith's interpretation of the long core at Searles (Smith, 1986), and ends at 0.25 Ma, because Tecopa's lacustrine history ends before the more detailed short-core and exposed-deposit history at Searles (Appendix Figure G-1):

(a) Between 3.2 and 2.5 Ma, was a series of deep lakes. At ca. 2.5 Ma is a transition from deep-water to playa sediments.

(b) Between ~2.5 and ~2 Ma, low lake levels appear to have alternated with desiccation episodes at Searles Lake. [This part agrees with the Lake Tecopa record.]

(c) At Searles Lake, between ~2 and ~0.6 Ma,"intermediate" to "wet" conditions prevailed, with a series of perennial lakes (lasting 10 ka or longer) that rose to intermediate or high levels. Wet conditions peaked between 1.3 to 1.0 Ma.
[In contrast, Lake Tecopa appears to have had playa to shallow-lake conditions during the earlier part of this interval, changing to intermediate lake conditions about 0.75-0.8 Ma, and remained at intermediate (not high) levels to 0.6 Ma.]

(d) There was a long dry interval at Searles Lake between about 0.57 and 0.31 Ma. [In contrast, at Lake Tecopa two major deep-lake megacycles (with a moderate recession between them) occupied this interval, and Lake Tecopa reached its all-time lake maximum near the end of the second megacycle--and became breached at or soon after the end of this interval.]

(e) From 0.3 Ma to 10 ka intermediate to wet conditions prevailed at Searles, with desiccation between 130 and ~100 ka..

Correlation of Lake Tecopa with Lake Lahontan

Pluvial Lake Lahontan was 335 to 675 km north of Lake Tecopa and definitely in the North-Temperate climatic zone. Lahontan's stratigraphic record is one of the very best exposed records in the western U.S., in terms of stratigraphic completeness, range (from well beyond 1 Ma thru Holocene), detail of exposed record, and unambiguity. There is little controversy about intra-Lahontan basin stratigraphic correlations, much less than for the Lake Bonneville basin, partly due to better exposures and partly because more than 50 different tephra layers facilitate correlations within the Lahontan basin (Morrison and Davis, 1984a, 1984b and Appendix Figure G-1).

The lower part of Lake Lahontan's exposed sequence overlaps the upper part of Lake Tecopa's sequence, probably as follows:

The Lovelock Alloformation of Lake Lahontan contains the Bishop Ash in its upper part and is younger than the 1.0 Ma Glass Mountain G Ash. It represents several hundred thousand years when the Lahontan basin was nearly to completely desiccated, but dozens of strong paleosols testify to mild semiarid climate. It likely is equivalent to the upper part of the Greenwater Fan AF and the lower part of the Shoshone Springs AF.

The Rye Patch AF of Lake Lahontan has the Lava Creek Ash near the top of its upper lacustrine member. This AF records two moderately deep lake cycles separated by a brief but moderately deep lake recession. It likely is equivalent to the upper part of the Shoshone Springs AF and the lower part of the Amargosa AF, on the basis of tephrochronology. This signifies significant diachronism between the deep-lake history of Lakes Lahontan and Tecopa, an asynchroneity of more than 100,000 years in ages of respective lake maxima. Lahontan had two deep-lake cycles chiefly before the Lava Creek Ash (Rye Patch AF), but Tecopa's first deep lake cycle came after this tephra (Appendix Figure G-1).

The Paiute AF of Lake Lahontan records a long desiccation period between Rye Patch and Eetza time. It contains the 400 ka Rockland Ash near its top. Likely it correlates approximately with the desiccation interval represented by the subaerial member in the middle of the Amargosa AF, although it may represent twice as long a time interval. [Flash! A previously unknown moderate lake cycle (maximum below 1260 m) within the Paiute AF was discovered this summer (J.O. Davis, oral communication, Oct 1988). Its relation to the Rockland Ash still is uncertain.]

The Eetza AF of Lake Lahontan probably ranges in age from about 350 to 130 ka -- and its lower part likely correlates with the upper part of the Amargosa AF (Appendix Figure G-1).

Sierra Nevada glaciations

Sierra Nevada glaciations have been highly controversial as to number of significant glaciations and especially as to their chronology. Appendix Figure G-1 (Sierra Nevada) is based on the important synthesis by Fullerton (1986), which is by far the best analysis and summary to date.

Again, significant diachronism appears at all age levels, from Wisconsin to mid-Pliocene. One example: the Sherwin Glaciation (~780 - ~900 ka), one of the biggest on basis of end moraines, appears to have taken place during Lovelock AF time in the Lahontan basin, and near the end of Greenwater Fan AF time at Lake Tecopa--but the Searles and Tecopa basins held only shallow lakes probably alternating with playas.

Note also that a major glaciation is postulated between 0.9 and 2.3 Ma, a time interval when the Lakes Searles and Tecopa usually were playas.

Conclusion about correlations with the above areas:

Significant diachronism is demonstrated among the long-histories of these key areas; these histories show both (1) at times more-or-less in-phase relations -- but also and commonly (2) lacustral, glacial, and climatic phenomena that are significantly out-of-phase, by as much as the 100,000-year magnitude.

The indicated diachronism between beginnings, maxima, and endings of pre-late Pleistocene lake megacycles in the three "pluvial-lake" areas is impressive. This diachronism, commonly in the order, of hundreds of thousands of years, is much greater (by 10^2 order of magnitude) than that demonstrated among the late Wisconsin lake maxima in the Great Basin [1 to 5 ka between Lake Bonneville and Lakes Lahontan and Mono (Morrison, in press)].

PALEOCLIMATOLOGY NEAR LAKE TECOPA FROM 3 MA TO THE PRESENT

This section purposely is not called "regional paleoclimatology" because of the concerns about long-term asynchoneity of climatic changes between various parts of the Mojave Desert-Great Basin during Quaternary time, that were raised in the preceeding section.

3.2 to 2 Ma

For this middle Pliocene interval, the paleoclimatic analysis of Hay and others (1986) of conditions in the Amargosa Desert is most relevant to conditions at Lake Tecopa (the Amargosa Desert exposed record also ranges somewhat older than that at Lake Tecopa).

According to Hay and others (1986), the climate was substantially wetter than at present, likely because the Sierra Nevada and Transverse Ranges were much lower than now (Huber, 1981; Winograd and others, 1985), permitting more moisture to travel eastward into the Great Basin. Climate also may have been at times cooler than now, because a gastropod occurs in the mid-Pliocene deposits that lives in seasonal ponds and marshes farther north and at elevations higher and cooler than the Amargosa Desert today (Taylor, 1983). They apparently (p.1502) found evidence of a change from wetter to drier climate about 2.5 Ma, as also was found at Searles Lake (Smith and others, 1983; see "Correlations" above). [Interestingly, a major global shift to cooler climate and increased ice volume also is recorded at about 2.5 Ma in the oxygen-isotope records in deep-sea cores (Ruddiman and Wright, 1987).]

Spring discharge was much more abundant and widespread than at present, much of it coming from Paleozoic rocks to the east of the chief present-day springs, as well as along the western margin of the basin, indicating generally higher piezometric surface and watertable conditions.

Greenwater Fan AF to Shoshone Springs AF time, 2 Ma to 620 ka

In this project, no quantitative data have yet been obtained about temperature and precipitation conditions at specific times during Greenwater-Shoshone Springs AF time in the Lake Tecopa area. Following are qualitative conclusions from our preliminary reconnaissance observations.

At Lake Tecopa this long interval was a time of continued low effective precipitation, with low stream flows and playa to occasional shallow-lake conditions, until near the end of Greenwater Fan time, when somewhat increased effective precipitation caused lake level to rise to about 450 m present altitude, shortly before the Bishop Ash was deposited. Effective precipitation continued to increase slightly during Shoshone Springs time, as documented by slightly higher lake level in the southern part of the Tecopa basin.

Spring and high-water-table deposits are lacking to rare in the exposed Greenwater Fan sediments, suggesting that piezometric surfaces and watertables then were too low for more than local artesian discharge at a few large springs. However, such deposits occur in places in the upper part of the Shoshone Springs AF, notably near Shoshone, indicating a rise in piezometric-water-table levels with the start of the mega-pluvial that caused the first Amargosa deep-lake period, shortly before deposition of the Lava Creek Ash.

In contrast, at Searles Lake Smith and others (1983) postulate from the "long" core data an intermediate to deep-lake period between 2.0 to 0.6 Ma! (Appendix Figure G-1)

Amargosa AF time, 620 to about 250 ka

Amargosa time was marked by two mega-pluvials (mega-deep-lake cycles) separated by a moderate lake recession (Appendix Figure F-1). Obviously, effective precipitation was greater, the highest in Lake Tecopa's history (Appendix Figure F-3). The fan-delta of the Amargosa River at the head of Lake Tecopa (north of Shoshone) has copious pebble-cobble river gravel (interbedded with high-level lake sediments), testifying to augmented river discharge. Likewise, widespread spring and groundwater seepage activity took place in many places in the basin, in places to the highest strandline zone. Stratigraphic evidence shows that commonly spring/seepage deposition slightly preceeded lake deposition at a given altitude, and also continued for a short time after lake level had fallen below this elevation (Appendix Figure F-2).

APPENDIX B.

PROPOSED ALLOSTRATIGHRAPHIC UNITS IN THE LAKE TECOPA AREA

LAKE TECOPA ALLOGROUP
(lacustrine and subaerial sediments of Lake Tecopa age, middle Pliocene to late-middle Pleistocene)

Amargosa Alloformation

Lacustrine and subaerial sediments above the base of the Lava Creek B tephra bed (Tuff A), up-section to the youngest Lake Tecopa deposits.

Upper lacustrine allomember:

Upper unit (fluctuating high and regressive lake stands; small-pebble gravel and small-pebbly sand).

Middle unit (chiefly lacustrine sand, silt, some clay, some sandy small-pebble gravel lenses locally).

Lower unit (transgressive; lacustrine small-pebble gravel and small-pebbly sand).

Middle subaerial allomember (upper "yellow zone"):

Lower lacustrine allomember

Lava Creek B tephra layer (Tuff A), ~0.62 Ma.

Shoshone Springs Alloformation

Upper lacustrine allomember

Middle subaerial allomember (lower "yellow zone")

Lower lacustrine allomember

Bishop tephra layers/complex (Tuff B), ~ 0.735 Ma.

Greenwater Fan Alloformation

Subaerial allomember(s)/tongues

Lacustrine allomembers/tongues

Huckleberry Ridge tephra layer (Tuff C), ~2.1 Ma.

Spanish Trail Alloformation

Post-Lake Tecopa alluvial units

#1 PLT alluvial complex

Cobble (rarely sm bldr) gravel to cobble-pbl gravel on pediments, discontinuously preserved, chiefly at margins of LT basin. Several meters above #2 surface. Class 2+ surface parameters. Intermediate in age between Dohrenwend's (1985) Greenwater and Sperry surfaces [although perhaps youngest members of the Sperry complex (which is chiefly pre-Lake Tecopa) may overlap into this unit].

#2 PLT alluvial complex

Cobble and pebble gravel veneer chiefly on pediments (preserved mostly on narrow mesa-like ridges in the interior of the LT basin), tonguing up side washes into strath-terrace gravels. (1985) "Greenwater Surface". Class 2 surface parameters.

#3 PLT alluvial complex.

Pediment and strath-terrace gravels of all side-washes; strath-terrace gravel of AR. Late-middle Pleistocene. Several meters above #4 surface (top of #4 unit). Bears relict (surface) paleosol with moderate Bt and stage 2+ Bk development. Class 3 surface parameters (desert-varnish development and levelling of swale morphology plus relict paleosol development). Intermediate between Dohrenwend's (1985) "Amargosa" and "Greenwater" surfaces.

<u>#4 PLT alluvial complex</u>. Chiefly Holocene but probably in part Wisconsin; equivalent to "Amargosa Surface" of Dohrenwend (1985). Underlies moderately extensive pediments on LT sediments both E and W of Tecopa Hills, and the Holocene flood plain of the Amargosa River; also wide young "flood plain" embayments along larger side washes, as well as flood plains of all minor washes.

Silt and clay, commonly sandy, near Amargosa River in S part of basin, to sandy pebble-cobble gravel, rarely boulder gravel, along Amargosa River and all the side washes.

Soil and desert-varnish development: nil to trivial (very weak).

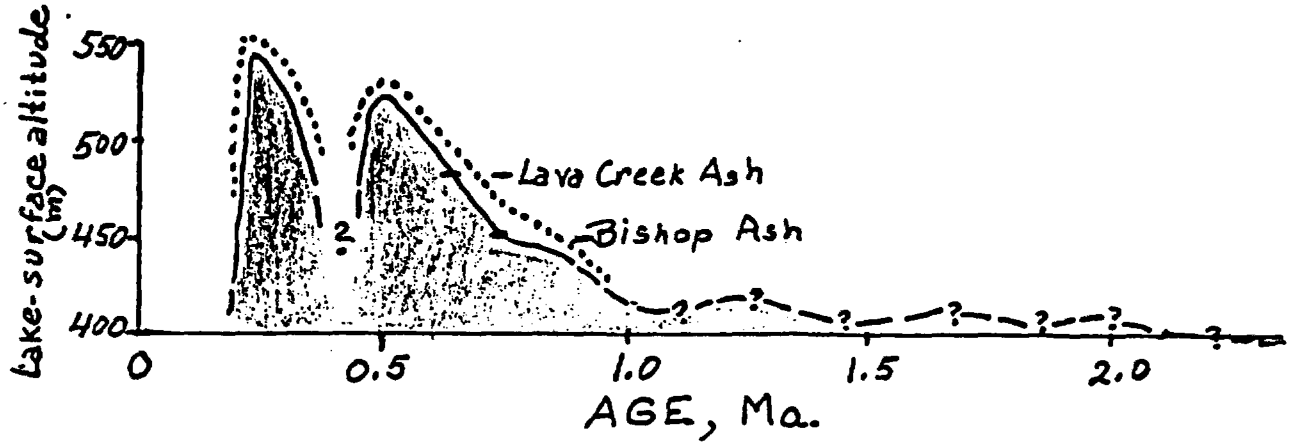
APPENDIX C.

Examples of diagrammatic measured stratigraphic sections
[See Figures C-1 to C-14]

Explanation

1) Vertical scale: 1/2-inch = 1 meter (starting from left columns)

2) See Appendix D for explanation of symbols used in all columns.



Appendix Figure F-1 (black solid line) Changes in lake level in the Lake Tecopa basin between 2.2 and 0.2 Ma

Notes: (1) This curve is smoothed and does not show the many small-scale brief oscillations in lake level in this closed lake basin. The portion from 2.2 to 0.75 Ma is particularly generalized because our present data provide only a general history for this time interval; more intensive stratigraphic research on its deposits, including reliable dating of key strata, will be necessary to find out details on elevations and timing of specific lake fluctuations.

(2) Our present stratigraphic data from exposed deposits, however, show clearly that Lake Tecopa remained at low levels and at times was a playa from 2.2 to probably between 1 and 0.8 Ma. A trend of gradual rise in lake level commenced somewhat before Bishop Ash time (0.735 Ma), that attained about 450 m and then about 480 m when the Bishop and Lava Creek tephra layers, respectively were deposited. Thus began the early part of the first deep-lake megacycle of Lake Tecopa. This megacycle culminated at about 520 m altitude probably around 0.5 Ma. It was followed by a deep lake recession to at least as low as 440 m, that probably lasted at least a few tens of thousands of years. Next came the second and final deep-lake megacycle, which rose to about 550 m altitude--the all-time maximum for Lake Tecopa. Breaching and commmencement of draining of this lake seems to have occurred at the end of this maximum, probably between 0.2 and 0.3 Ma.

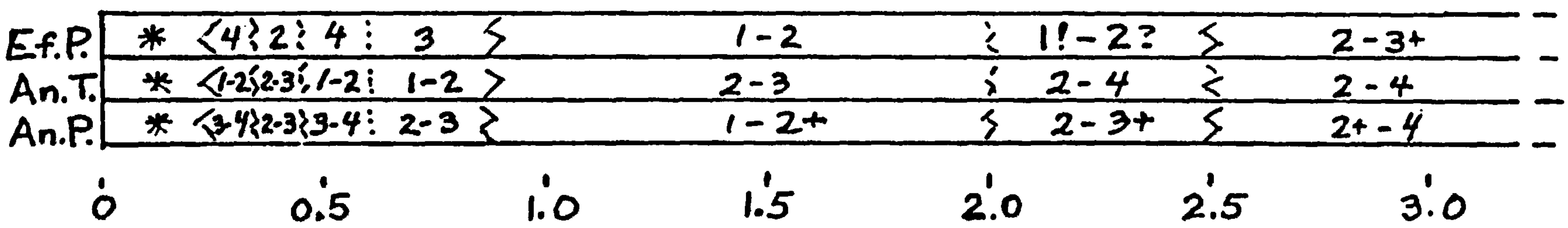
(3) The portion of the curve from 0.4 to 0.62 (Lava Creek Ash time) Ma is from the north part of the Lake tecopa basin, because in the southwestern part lake levels were anomalously lower perhaps due to tectonism.

Appendix Figure F-2 (dotted line) Changes in altitude of piezometric surface and watertables, inferred from exposures of spring /seepage carbonate cementation, travertine, and tufa at and within 1-2 m of the original landsurface.

Note that during the lake transgressions the piezometric surface/watertable rose faster than lake level; conversely, during lake regressions, it fell more slowly than the lake level.

APPENDIX FIGURE F-3

INFERRED PALEOCLIMATIC HISTORY OF THE LAKE TECOPA AREA FROM 3.2 TO 0.2 MA



EXPLANATION

Ef. P. = effective precipitation.

An. T. = annual temperature.

An. P. = annual precipitation.

<u>Relative-value numerals in the figure:</u>
1: Minimal, less than present values in this area.
2: Low-intermediate, values about like now.
3: High-intermediate, values somewhat higher than now.
4: Maximal, values appreciably greater than now.

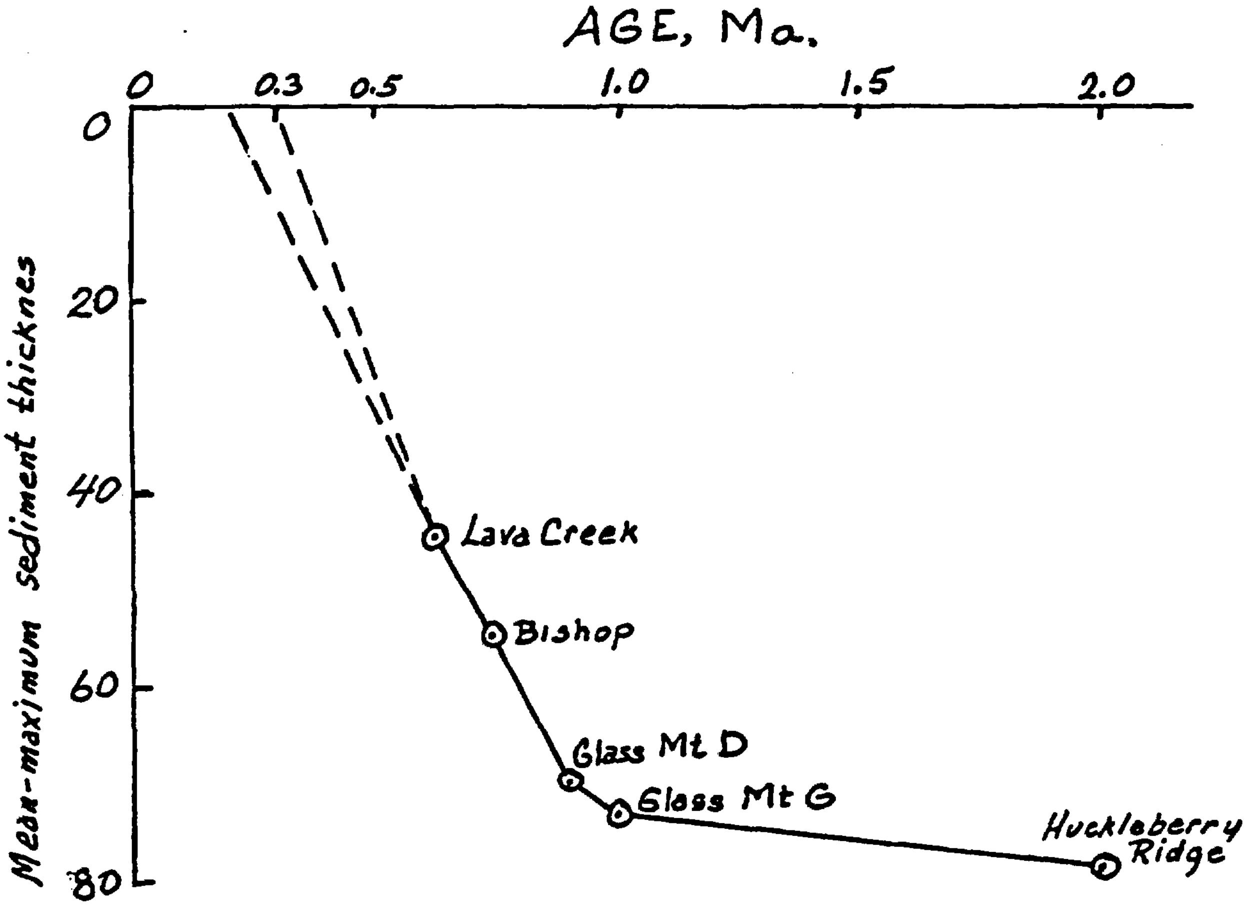
* After breaching of Lake Tecopa, four major erosion surfaces were formed. Each started with strong downcutting by streams, then lateral stream planation, followed by alluviation and then a time of landscape stability and soil development [erosion-deposition-stability (EDS) cycles (Morrison, 1987); the post-Lake Tecopa cycles correspond to Morrison's meso- to macro- EDS cycles]. These EDS cycles were induced by marked cyclic changes in effective precipitation through later Illinoian, Wisconsin, and Holocene time in this area.

At present, our climatic data are relatively crude and qualitative, pending inputs from various specialists who are analyzing samples collected from key horizons (particularly from deposits younger than the Bishop Ash). We hope to have more quantitative information about climatic conditions during specific episodes in Lake Tecopa's history as we get more climatic and chronometric data from our sampling program. The interpretations in this diagram are based chiefly on the lacustrine and fluvial history (lake levels and stream runoff) as determined from many measured stratigraphic sections throughout the Lake Tecopa area.

Data for the 2.5 to 3.2 Ma interval are from Hay and others (1986).

APPENDIX FIGURE F-4.

DIAGRAM OF SEDIMENTATION RATES IN THE LAKE TECOPA AREA



Depth in the Lake Tepoca sequence (Lake Tecopa Allogroup) versus age, from about 0.2 to 2 Ma. Age control is from well-dated tephra layers (Sarna-Wojcicki and others, 1987). Depths are my mean-maximum thicknesses down to the Bishop Ash, and from Sarna-Wojcicki and others (1987) below this tephra layer. The two diverging lines above the Lava Creek Ash show the probable uncertainty as to time of breaching of Lake Tecopa.

APPENDIX FIGURE G.

CORRELATIONS OF THE LAKE TECOPA SEQUENCE WITH THE STRATIGRAPHIC RECORDS FROM SEARLES LAKE, LAKE LAHONTAN, AND THE SIERRA NEVADA

Appendix Figure G-1, Explanation and Comments:

Horizontal scale is Ma for all 4 diagrams.

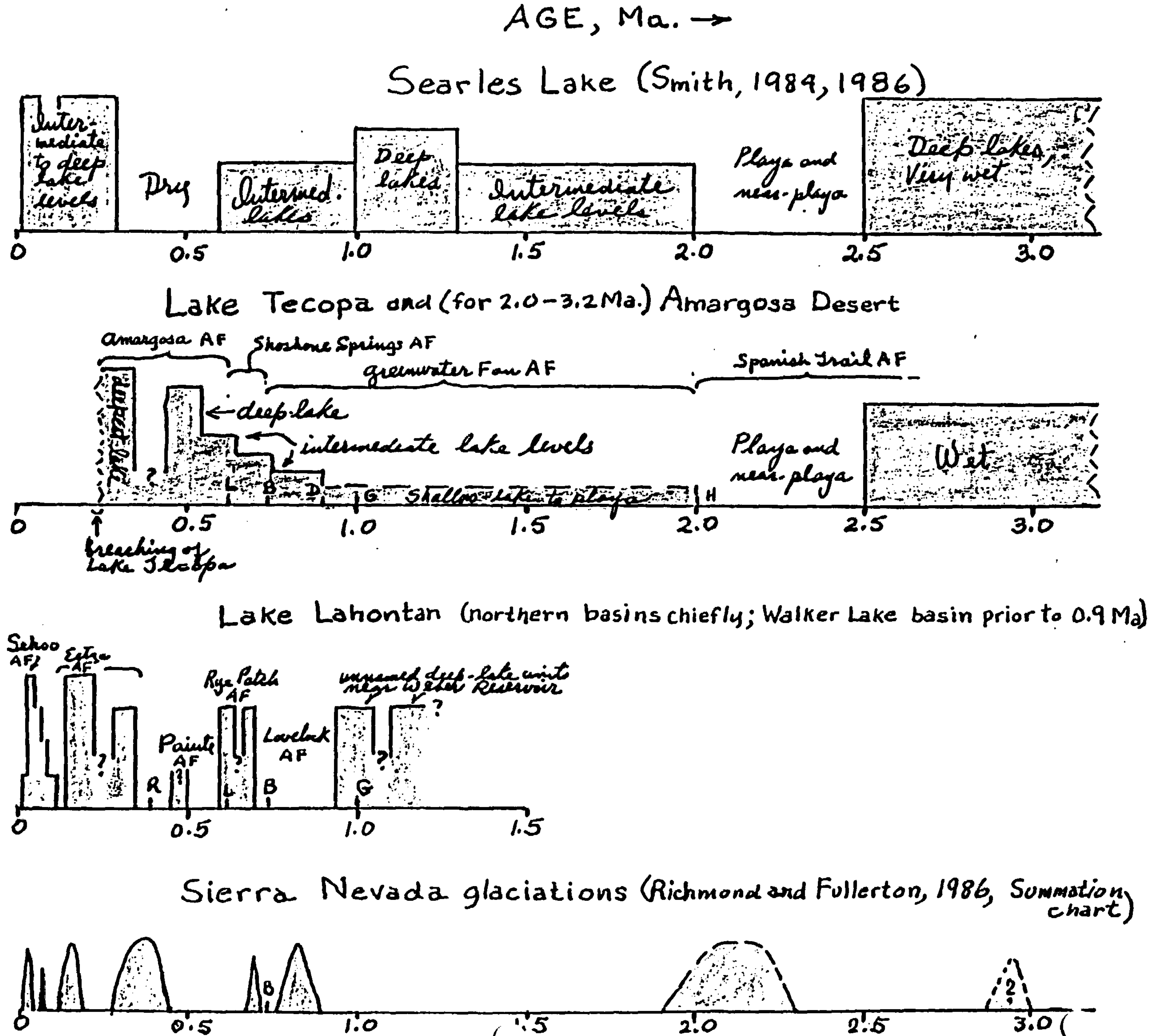
Vertical scale is schematic.

Capital letters just above age lines indicate positions of tephra layers: R = Rockland (400 ka); L = Lava Creek B (620 ka); B = Bishop (738 ka); D = Glass Mountain D (0.9 Ma); G = Glass Mountain G (1 Ma); H = Huckleberry Ridge (2 Ma).

For discussion, see text section "Correlations with Amargosa Desert (Ash Meadows), Searles Lakes, Lake Lahontan, and the Sierra Nevada".

Lake Tecopa interpretation is based on my own stratigraphic field studies, 1986-1988; Amargosa Desert data are from Hay and others, 1986. Lake Lahontan interpretation is chiefly from my own field studies (Morrison, 1964, 1965; Morrison and Frye, 1965; Morrison and others, 1965; Morrison and Davis, 1984a, 1984b; and unpublished field data), supplemented by tephrochronologic and stratigraphic data from J. O. Davis (oral and written communications, 1984-1988). Searles Lake data are from Smith (1979, 1984, 1983) and Smith and Street-Perrott (1983). A.M. Sarna-Wojcicki (and colleagues, 1984, 1985, 1987, and in press) supplied tephrochronologic control for all these areas.

APPENDIX H. NEOTECTONIC MAP OF THE LAKE TECOPA AREA
[Figure H-1, in preparation]



APPENDIX FIGURE G-1. CORRELATIONS OF THE LAKE TECOPA SEQUENCE WITH THE STRATIGRAPHIC RECORDS FROM SEARLES LAKE, LAKE LAHONTAN, AND THE SIERRA NEVADA

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Appendix B-V

Progress Report -Groundwater Discharge Deposits by J. Quade.

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PROGRESS REPORT - Ground-Water Discharge Deposits

by J. Quade

Well-exposed fine-grained deposits abound in the valleys of southern Nevada. However, for reasons of age or poor exposure, only a few are appropriate for detailed study, though nearly all contain useful paleohydrologic information in some form. Geologic mapping and sampling has therefore been pursued at two scales: reconnaissance and detailed. Both scales contribute to construction of a regional paleohydrologic framework for the last "full" pluvial roughly 18,000 years ago. Detailed studies, in addition, should supply a more quantitative picture of the ground-water flux passing through the last full pluvial hydrologic system.

Reconnaissance fieldwork Several of these types of study, which entail several days of mapping and sampling, and weeks of laboratory follow-up have been completed or added to in the past 18 months:

Piute Valley--southern Clark County, Nevada
Valley Wells-- San Bernadino County, Calif.
Diatomite of Lathrop Wells--Nye County, Nevada
Coyote Springs Valley--deposits in the southern end of the valley (Clark County) and the northern end (Lincoln County).
Chicago Valley-- Inyo County, California

Detailed fieldwork Only a few valleys have proven to contain deposits of appropriate age or sufficient exposure for detailed work. This fieldwork entails several weeks to months of mapping, and description and sampling of all known major exposures. Mapping was conducted on 1:62,500 scale black and white aerial photographs, and then transferred to orthophotos on the completion of each area. All paleofauna sample sites were described in detail and often photographed, as were localities containing datable materials.

The following areas were completed or added to in the past 18 months:

Corn Creek Springs (Clark County, Nevada)
Indian Springs (Nye and Clark Counties, Nevada)
Pahrump Valley (Nye County, Nevada and Inyo County, California)
Sandy Valley (Clark County, Nevada)

Laboratory Work

Faunal samples About 250 samples have been processed in the past eighteen months. Processing has entailed disaggregation of sample matrix, sieving, and handpicking of each for mollusks. These are then forwarded for analysis to Dr. W. L. Pratt at the Natural History Museum in Las Vegas. Some samples have been found to contain diatoms as well. Eleven of these are being examined by Dr. L. Burckle at Lamont-Doherty Laboratories, Palisades, New York. Ostracodes from a few samples have been isolated; no analyses are planned.

Amino-Acid Analyses Large faunal samples from key localities were picked and cleaned; forty-five were submitted for amino acid dating, most of which have been completed.

Radiocarbon analyses Ten samples have been pretreated for analysis in the Utah laboratory in the past 18 months. Others pretreatments were handled by the University of Arizona, which is performing all of the dating.

Pollen analysis Eight samples were isolated for pollen, and sent to Dr. O. Davis at the University of Arizona for counting.

RESULTS

Piute Valley Fine-grained deposits are located on the west side of the Pauite Valley just over the California-Nevada border about 80 kilometers south of Boulder City, Nevada. Relative to other areas they fairly limited in extent, covering about 4 km^2. They are nonetheless of interest, being (1) the southernmost deposits studied, (2) not immediately adjacent to any major mountain range, and (3) situated in alluvium dominated by volcanic clasts. In the last two respects the Piute Valley deposits are closely analogous to the Diatomites of Lathrop Wells near Yucca Mountain. Mollusks are not abundant. Sample PteVF87-1 (Table 1) indicates locally ponded conditions, and PteVF87-4 the surrounding moist terrestrial habitat. Fluvial silt and mudstone are more common than ponded units, which are not laterally continuous. Several paleosols were mapped within the deposits. Diatomite is abundant and was sampled at six localities. No identifications are completed. In overall aspect, the deposits in Piute Valley are consistent with a ground-water discharge, not lacustrine setting.

Megafaunal remains, particularly camel and mammoth teeth, are very common, and indicate a mid-Pleistocene age (B. Reynolds, San Bernadino County Museum, pers. comm., 1988). This is consistent with amino-acid ratios on *Gyraulus* sp. (Table 2, PteVF87-1) which are largest--and therefore oldest--of any sample taken thus far in southern Nevada, except for perhaps the ratios on clams from Chicago Valley. No Wisconsin-age deposits are present.

Two north-south trending lineaments bound the eastern, downslope extent of the deposits. It is quite likely that these structures have in some manner localized discharge upslope, either by juxtaposition of impermeable layers against a gravel aquifer, or by infilling of the fault with impermeable cements. Other examples of tectonic control on paleodischarge can be found in many valleys described below.

Valley Wells Valley Wells (or Shadow Valley) is located near the California-Nevada border in San Bernadino County, California, about 70 km west of Piute Valley. Fine-grained deposits cover about 4.5 km^2.

Deeply-incised bluffs end abruptly downslope against several north-south trending lineaments.The bluff exposures contain a long history of spring discharge in the area. Amino-acid ratios (Table 2, VWF87-5 and 9) on pond snails indicate they are slightly younger than Piute Valley snails. Irvingtonian-age megafauna found by B. Reynolds are also consistent with a mid-Pleistocene age. Black mats from thin deposits inset into the older bluff units yielded a radiocarbon age of 10,250±160 (Table 3, A-4899). Artifacts were found eroding from the mat, and mammoth teeth are common in the underlying pale-green clays clays.

The older bluff deposits are mainly composed of bedded pale-brown silts and sands which are dominantly fluvial in character. Green clay pond units increase downslope, although they remain thin and difficult trace laterally. All mollusk samples are consistent with a ponded setting and fringing wet meadow environments (Table 1, VWF87-1,4,5,6,7, and 9). The younger, late Wisconsinan deposits are inset into the bluffs along at least one drainage. As such, they are of rather limited extent. Pale-green clays and organic mats entirely compose them. Habitats indicated by mollusks are similar to those of the bluff deposits. In all, pond, wet meadow, and phreatophyte flat settings account for the long history of sedimentation in the area. Several stands of phreatophytes (cottonwood and mesquite) attest to ongoing high water table in the area of the fine-grained sediments.

Like Piute Valley, at least three north-south trending lineaments bound the downslope extent of the three adjacent areas of fine-grained deposits. They likely localized former and modern discharge along the upslope side. It is interesting that the deposits are the highest in elevation at 1,100 m of any identified in southern Nevada. The Clark Mountains, reaching over 2,400 m, bound the east side of the valley. This nearby recharge source, and the faults likely account for the fine-grained deposits at such a high elevation.

Chicago Valley Chicago Valley is located in Inyo County, California, about 110 km west of Las Vegas. The valley opens onto the Tecopa Basin at its south end. A fairly broad expanse (5.8 km^2) of low-lying sediments cover the lower piedmont areas on the east-central side of the valley. At least two lineaments bound the downslope extent of the two adjacent expanses of deposits. As in other valleys, these faults likely served as a barrier to ground-water flow, damming water at depth and forcing it to the surface. Twelve Mile Spring still discharges from along the upper lineament. Mesquite is extensive in washes cut into the fine-grained deposits and over the small flats in the valley floor.

Poor-exposure limits what can be said about the deposits. As in other areas, the deposits appear to be dominantly fluvial, and are accompanied by extensive nodular carbonate. In other areas this material is of ground-water origin. Ponded units are very limited; previous descriptions of the deposits as lacustrine do not appear to hold up. The few faunal samples (Table 1, CV-mol. 1 a-1 and 2) obtained attest to ground-water discharge well upslope from the active springs . The spring mollusks show strong affinities with presettlement faunas in Ash Meadows springs. Amino-acid racemization dates on freshwater clams indicate an age at least equal to the Piute Valley deposits, i.e. mid-Pleistocene. No late Wisconsinan spring deposits were located, but this may well be the result of poor exposure given that ground water is so close to the surface even in the modern climate.

The Chicago Valley is bordered on the east and west by the Nopah and Resting Springs Ranges, respectively. Neither exceeds 2,000 m, which raises the question of a recharge source for the modern and Pleistocene springs in the valley. One distinct possibility is that underflow through the Nopah Range from neighboring Pahrump Valley has and is occurring. The low point in the adjacent Pahrump Valley playa is about 90 m higher than Twelve Mile Springs. Moreover, the Chicago Valley ground-water discharge deposits are found only on the east side of the valley, the right location if underflow from the east is occurring.

Coyote Springs Valley Exposures of fine-grained sediments are very extensive in the Coyote Springs Valley, located immediately east of the Sheep Range. Description will begin with the relatively restricted deposits in the northeast part of the valley and end with the more widespread ones in the south.

The North Coyote Springs Valley deposits cover about 8 km^2. In many respects these deposits are similar to those in Valley Wells. At least two lineaments bound the downslope extent of the deposits. Deeply-incised bluffs expose over 12 m of alternating pale-brown to green silts and mudstones. Inset into the bluffs are much younger, likely late Wisconsin age units. Mesquite chokes most of the main washes cutting through the deposits. Several active seeps occur along the lineament.

The age of the bluff beds remains unknown, but a very thick, dense caliche layer capping them belies their antiquity. A few poorly-preserved mollusks were found. Standing water is indicated by the faunas but the greenish clays containing them are neither thick nor laterally extensive. Several paleosols are also present.

The inset deposits contain abundant mollusks, green clays, and black mats. The green clays are laterally very discontinuous and generally follow the local wash gradient. This makes substantial extent to standing water unlikely. This is supported by identified mollusks (Table 2, NCySF-2,3,5,8,9, and 11) which are typical of wet meadows and very localized ponding. Dating of the mats is in progress at the

University of Arizona. Some of the spring deposits contain artifacts, suggesting a Holocene as well as Pleistocene component to discharge.

The south Coyote Springs deposits cover about 17 km^2. Work in this large area is in progress and results presented here are preliminary. The deposits almost certainly represent a spectrum of ages. Muddy Creek age deposits, probably late Miocene in age, are exposed in large bluffs on the east side of the valley. Much younger deposits crop out all along the west side, including one small area containing an organic mat and mammoth teeth almost certainly late Wisconsin in age. Organics from the mat are now with the Arizona radiocarbon lab. Other units are tilted up to 10 degrees, and clearly antedate the Wisconsin. The age of the majority of the fine-grained beds is unclear, and may be anywhere from early Pleistocene to late Pleistocene. Earlier this year three key localities were sampled for amino-acid racemization dating. These mollusks are now with the Amherst lab.

The deposits are dominantly fluvial pale-brown silts and occasional gravels. Green mudstones accompanied by dense caliche caps are also common toward the basin center. The facies pattern is similar in most respects to ground-water discharge systems described elsewhere. SCySF-1, the only sample counted thus far, contains a typical "wet meadow" faunal suite. Other mollusks examined in the field are entirely consistent with this setting and with fringing moist terrestrial environments. No marsh fauna, such as are found in the Tule Springs, Corn Creek, and to a lesser extent in the Pahrump Valley deposits, have been found. Ponding must therefore have been quite limited throughout the history of deposition.

The Pleistocene age ground-water discharge deposits are all concentrated on the west flank of the valley, probably because the high Sheep Range bounds that side of the valley and was certainly a principle recharge source for the valley. The deposits are cut by several small faults which have uplifted several small horsts of older material. These horsts were subsequently beveled and capped by dense caliche. The deposits are abruptly truncated in the valley center by the extension of the Arrow Canyon Range bounding fault. To the east, only Muddy Creek age deposits crop out. As in other valleys, this structure may have dammed subsurface aquifers, forcing flow to the surface and producing the large area of ground-water discharge deposits we observe today on the west side.

DETAILED MAPPING AND SAMPLING

Four valleys contain deposits of late Wisconsin age that are sufficiently well exposed to warrant detailed mapping and sampling: Indian Springs Valley, Pahrump Valley, Corn Creek Springs Valley, and Sandy Valley. Except for the Pahrump Valley, the intent is to construct as detailed a picture as possible of the whole full-pluvial ground-water discharge environment. This then will serve as a basis for a semi-quantitative estimate of paleodischarge in each area. The Pahrump Valley deposits, because of their complexity, do not lend themselves well to this kind of analysis. Nonetheless, a long and well-exposed history of deposition has made the Pahrump Valley a focus of much detailed work. The Indian Springs Valley deposits have already been described in a series of other reports; journal publication of these results will be in *Quaternary Research* sometime in the first half of 1989.

Sandy Valley Also known as Mesquite Valley, this basin sits astride the California-Nevada border immediately south of the Pahrump Valley. The mapped deposits are concentrated in the northeast corner of the valley, and cover about 5 km^2. They are separated from similarly appearing units in the south end of the Pahrump Valley by only a few kilometers.

The deposits are mostly late Wisconsin in age. This is based on generally weak induration of the deposits, thin carbonate caps, well-preserved mollusks, and common organic mats. Five of the mats are currently being dated. Amino-acid ratios (SVF-14, 16, and 22) are generally consistent with late Wisconsin mollusks from other valleys. The one determination inconsistent with a late Wisconsin age comes from a sample that may have experienced very high surface temperatures.

Pale-green to white mudstones are widespread and contain abundant mollusks. These units grade into pale-brown to white silts on the upslope margins of the deposits. Nineteen mollusk samples (Table 1, SVF and SAV series) have been counted. Nearly all the samples contain *Gyraulus parvus*, which in these systems generally inhabits small ponds. However, no open-water marsh forms were observed. Several samples also contained *Pyrgulopsis* sp., which favors fast-flowing fresh water generally proximal to spring-discharge points. Nearly all samples contained terrestrial mollusks in some percentage, as is typical of these systems, indicating the very discontinuous nature of the standing water. Both the sedimentology and and fauna indicate a very wet overall environment with ponding, and fringing wet meadows covering most of the 5 km^2 area.

The deposits wrap around the southern nose of the low-lying Black Hills and then spread into a triangular-shaped area downgradient. The hills may well have intercepted and dammed the water table as it sloped away from the adjacent Spring Mountains. Beyond the hills, the triangular area of deposits are bounded on its downslope side by two parallel faults which are extensions of the Black Hills bounding fault. As in other valleys, they clearly have localized discharge on their upslope side. Even today, mesquite and associated coppice dunes clog drainages in the immediate vicinity of the faults, although no surface discharge is occurring. A 1,300 $\pm$ 50 yrs B.P. age (Table 3, A-4860) was obtained on hearth charcoal deep within one coppice dune.

Corn Creek Springs Valley This valley is actually a sub-basin of the Las Vegas Valley, occupying its upper northwest end. The high Spring and Sheep Ranges bound the basin on the west and east sides, respectively. Fine-grained deposits in the valley center are well exposed and cover about about 40 km^2. As almost all the exposed sediments are late Wisconsin in age, this is the second largest exposure of such deposits in southern Nevada after those in the Las Vegas Valley.

The Quaternary geology of this area has already been the subject of one publication by the author. Subsequent to that, several months of additional fieldwork and many months of labwork have considerably refined the stratigraphic and depositional history of the deposits. About half of the 100 additional mollusk samples have been counted but results could not be tabulated in time for this report. A few additional radiocarbon dates have been completed, with many more pending at Arizona.

Additional radiocarbon analyses do not significantly alter the basic stratigraphy presented in Quade (1986). All (Table 3, A-44861, 4862, 4901) fall within the latest Pleistocene to earliest Holocene. This fits with the stratigraphic position of the dated horizons near or at the top of the late pluvial ground-water discharge deposits. A single analysis on marsh snails underlying these horizons produced a date of $28{,}420^{+1080}_{-950}$ yrs B.P. (Table 3), consistent with the full-pluvial position of the sample. Amino acid ratios from Corn Creek Flat (Table 2, CS85-5,17, 20 and CSF-15, 27, 65, 79) confirm that the majority of the deposits are late Wisconsin in age. They also corroborate (CSF-22 and 33) the existence a few outcrops of a pre-late Wisconsin beds on lower Corn Creek Flat and next to Corn Creek Station.

A revised preliminary map of the full-pluvial setting of a part of Corn Creek Flat is given in Mifflin and Quade (1988). An additional map of the sedimentology and fauna is being compiled as analyses come in. Sedimentologically, most of the fine-grained deposits are pale-brown fluvial silts. White to pale-green mudstones cover a much smaller area, mainly at the southern end of the valley, along a narrow belt on the valley's east side, and in three small patches on the west side. The overall impression of the full-glacial setting is that the majority of the 16 km^2 exposed area was covered by a phreatophyte flat in which no direct flow discharge occurred. However, a belt of springs discharged along the east side of the valley. These and two small spring complexes on the west side supported a series of small ponds on the upper flat along the valley axis, as well as a marsh at the bottom of the flat. The marsh covered about 1.5 km^2. A narrow marshy stream complex in turn fed out of the marsh through some narrows into Tule Springs Flat downvalley.

The aerial extent of all the major facies, including wet meadows and phreatophyte flats form the basis for quantitative estimates of the amount of discharge occurring in the valley during the full-pluvial climate. Such estimates of discharge appear to be possible to established for Corn Creek Flat, Indian Springs, and Sandy Valley, and will be the subject of further work.

Pahrump Valley The Pahrump Valley contains the longest and the best exposed record of ground-water discharge of any valley studied in the southern Great Basin. However, the outcrop is so extensive and the stratigraphic relations are sufficiently complex that many years could be spent in their characterization. Efforts to date have focused on identifying deposits associated only with the last full-glacial. Deposits related to the waning phases of that pluvial period, from about 11,500 years B.P. to present are relatively easy to map and characterize. However, units related to the full-pluvial, i.e., ca. 18,000 have not been successfully differentiated from the many other ground-water discharge units antedating the last full-glacial climate. As in other valleys, organic matter does not preserve well beyond about 15,000 years, and so the deposits cannot be identified by dating alone. And stratigraphic relations in all but a few areas are too complex to confidently reconstruct the full-pluvial setting. For these reasons, Pahrump Valley ground-water discharge can not be as confidently used in estimating pluvial maximum discharge. Considerable effort has been expended in deciphering its rich history of ground-water discharge.

Tilting and faulting of fine-grained beds has exposed over 150 m of section in several areas in the center of the valley. They are composed of alternating fluvial siltstones, paleosols, white to pale green mudstones, and occasional gravels. One major ridge in the lower third of the tilted section is composed of massive travertines which include textbook examples of flowstones and ripplestones over a large areas. No such travertine is associated with modern spring discharge in the valley. No mollusks have been found preserved in the sediments after a careful search. However, the sedimentary patterns observed in these beds are consistent with those of later periods of clear ground-water origin.

Untilted beds exposed in deeply incised bluffs stretching for kilometers along the valley axis constitute the next generation of sediments. A dense caliche caps the bluffs in most areas. Stratigraphy is often not traceable from one major wash exposure to the next. The beds are dominantly pale to medium brown silts and sands interrupted by many paleosols and erosional disconformities. Pale-green mudstones are common but tend to be laterally discontinuous. Mollusks and occasional megafaunal remains have been observed. Amino-acid dates (Table 2, PV Mol. 31) on pond snails and clams suggest in both cases an age younger than the Valley Wells, Chicago Valley, or Piute Valley deposits, but older than late Wisconsin. The samples counted to date from the green mudstones suggest wet meadow and pond environments. No open-water fauna such as typify lower Corn Creek Flat in the full-pluvial have been located.

Two major drainages in the southern half of the valley contain a well exposed and basically concordant record of latest Wisconsin deposition. These are deeply incised into the older bluff sediments described above. Sometime before about 11,300 years B.P. both the Hidden Valley and the Stump Springs drainages began to fill with sediment. Broad wet meadows at the heads of the drainages coalesced into flowing streams with marshy borders. The wet areas were never wider than 30 or so meters in the drainages, and the sediments associated with them generally lapped against but never entirely over the adjacent bluff sediments. Fauna is extremely abundant, including moist terrestrial, flowing stream, and pond snails (Table 1, Pah. Mol. series) to tens of mammoth molars. The wet meadows persisted along these two drainages from 11,200 to at least 8,500 years B.P. (Table 3, A-4590 to 4595, 4606, and 4607), after which discharge decreased dramatically. Though both drainages are filled with mesquite, the only spring discharge in the area up to the 1920's was a few gallons per minute from Stump Spring.

Exposure of the beds end abruptly in a series of major faults running along the north-south axis of the valley. West of the faults no fine-grained ground-water discharge deposits are exposed but a moderately sized dry playa is present in the valley bottom. Cuttings from three 24 ft. hand augured boreholes were extracted from the playa in order to ascertain the pre-Holocene environment. Two cuttings profiles revealed a full 24 ft of brown silt such as is being deposited on the playa today. A third cutting profile contained pale-green clays starting at 14 ft. Pond snails from the clays have been submitted for amino-acid racemization dating. The appearance of the clays and the overlying thickness of brown silt suggest that the clays antedate the Wisconsin. The preferred interpretation is that little or no ground-water discharge was occurring in the playa area.

Brown Spring, now dry but which in historical times discharged 20 or more gallons per minute, is located on the main north-south lineament of the valley along which the oldest beds are uplifted and tilted. A dead cottonwood marks the spot. Massive incision in the last few decades has exposed an excellent stratigraphy. Debris and midden left by pioneers (the spring is on the old Santa Fe Trail) form the uppermost exposed beds and aboriginal artifacts occur in neighboring dunes. Pleistocene and Holocene discharge spread several hundred meters down from the present site of the cottonwood. Artifacts in the outflow facies date to 8,510 $\pm$ 190 years B.P. (A-4609). Several meters of spring deposits underlie this dated layer.

Many square kilometers of fine-grained beds occurs in the northern part of the valley. The exposed ones, which include three separate areas are clearly associated with faults on their downslope sides. Two paleospring areas have been identified. One ceased to flow at about 10,920 $\pm$ 160 yrs. B.P. (Table 3, A-4609). Other paleospring areas may exist in the beds, but the vast majority of these exposures are composed of monotonous brown silts, likely deposited in a phreatophyte flat. The existing exposures become buried by Holocene silts toward the valley center, probably obscuring a very extensive paleoground-water discharge system. This northern area is the focus of most modern discharge in the valley. It is probable that this was also true of the Pleisotocene, but the extent can not be mapped.

REFERENCES

Mifflin, M.D. and Quade, J., 1988, Paleohydrology and hydrology of the carbonate rock province of the Great Basin (East-central to southern Nevada): Geological Society of America Guidebook no. 12 (Centennial national meeting, Denver), p. 305-336.

Quade, J., 1896, Late Quaternary geology of the upper Las Vegas Valley: Quaternary Research v. 26, p. 340-357.

Mollusk Samples

Species	CV-mol-1a	CV-mol-2	NCySF-11	NCySF-2	NCySF-3	NCySF-5	NCySF-8	NCySF-9	PteVF-1
Assiminea sp.	3.4	2.2							
Catinella	12.2	2.9		19.2	11.4		14.6	5.9	0
Deroceras			4.8	1.4			1.2		
Discus cronkhitei									
Euconulus fulvus									
Fossaria modicella							0.6		
Fossaria parva	1.69	0.4	3.2	1.4				3.2	
Gastrocopta pellucida			6.3				0.6		
G. tappaniana			6.3	49.3	32.9	6.3	76	66.2	
Gyraulus parvus						31.3	0.6		
G. circumstriatus	0.8	0.4							100
Hawaiia sp.			3.2	8.2			1.8	0.6	
Oxyloma sp.			3.2						
Physa gyrina	1.2								
P. virgata									
Pisidium casertanum	1.3	0.4	73	4.1		62.5		4.6	
P. rotundatum				2.7					
Pupilla hebes									
P. muscorum				1.4					
Pupoides sp.									
Pyrgulopsis av.							1.2	1.3	
Pyrgulopsis mi.	59.1	82.5							
Pyrgulopsis sp.					55.8		3.5	0.6	
Stagnicola caperata									
S. elodes									
S. montanensis									
S. pilsbryi	1.69	0.7							
Succinea									
Tryonia v.	3.4	8							
Vallonia cyclophorella									
V. gracilicosta				6.8					
Vallonia sp.									
Vertigo berryi	15.2	2.5		5.5				17.5	

mollusks/kilogram sediment

TABLE 1

Mollusk Samples

Sample no.

Species	PteVF-4	SAV-carb-1	SCySF-1	SV87-6	SVC-1	SVC-2	SVC87-3	SVF87-16	SVF87-1
Assiminea sp.									
Catinella gabbi	62.5	13	39.7	27.7	16.1	18.7	27.8	48.6	0.5
Deroceras		0.5	0.5		1.1	0.4		1.9	
Discus cronkitei									
Euconulus fulvus		0.5		0.3		0.4			
Fossaria modicella			7.5						
Fossaria parva		14.1		14	29.9	13.5	8.3	7.2	2.6
Gastrocopta pellucida	12.5								
G. tappaniana		6.5		0.3	12.6	18.7			
Gyraulus parvus		14.6	8	7.4		15.9	8.3	6.5	0.5
G. circumstriatus		17.3		13.7		8.8		9.2	0.5
Hawaiia sp.									
Oxyloma sp.						0.4			0.5
Physa gyrina									
P. virgata				0.6		3.6			1.5
Pisidium casertanum		6.5	0.5	7.1	23	0.8		2.7	25.5
P. rotundatum		5.4			17.2				4.1
Pupilla hebes									
P. muscorum		0.5	17.1	12.9			27.8	6.5	
Pupilla sp.									0.5
Pupoides albolabris	25								
Pyrgulopsis av.									
Pyrgulopsis mi.									
Pyrgulopsis sp.		0.5				2.4			63
Stagnicola caperata									
S. elodes									
S. montanensis									
S. pilsbryi								0.9	
Succinea									
Tryonia v.									
Vallonia cyclophorella									
V. gracilicosta		7							
Vallonia sp.									
Vertigo berryi		13.5	26.3	16.1		16.3			

mollusks/kilogram sediment

Species	SVF87-4	SVF87-5	SVF87-7	VWF87-1	VWF87-4	VWF87-5	VWF87-6	VWF87-7	VWF87-9
				Sa[illegible] Samples					
Asaminea sp.									
Catinellidae	9.8	40.5	16.7	1.1	57.1	17	28.5	11	7.7
Deroceras		1.1				1.1	2.7		0.5
Discus cronkitei									
Euconulus fulvus									0.5
Fossaria modicella									
Fossaria parva		5.6		18		4.6			
Gastrocopta pellucida									
G. tappaniana				68.5		0.4	3.7		
Gyraulus parvus	17.6	3.5		2.2			2.7		1.9
G. circumstriatus		2.1		1.1		41.9	5.9	5.2	49
Hawaiia sp.									
Oxyloma sp.									
Physa gyrina									
Physa sp.							0.5		
P. virgata									
Pisidium casertanum	9.8	2.1			21.4	3.1			
P. rotudatum	52.9	9.1				0.4			
Pupilla hebes									
P. muscorum		6.7	50	1.1		20.8	15.2	2.1	1.4
Pupoides sp.									
Pyrgulopsis av.									
Pyrgulopsis mi.									
Pyrgulopsis sp.		2.1							
Stagnicola caperata							26.9	2.1	29.3
S. elodes									4.8
S. montananesis									
S. pilsbryi		3.5							
Succinea									
Tryonia r.									
Vallonia cyclophorella						4.6	7.5	8.9	1.4
V. gracilicosta								11	
Vallonia sp.								58.6	
Vertigo berryi	9.8	23.7	33.3	7.9	21.4	6.2	6.4	1.2	3.4
mollusks/kilogram sediment									

Mollusk Samples

sample #

Species	SVF87-11	SVF87-13	SVF87-14	SVF87-17	SVF87-2	SVF87-22	SVF87-23	SVF87-24	SVF87-28
Assiminea sp.									
Catinellidae	19.8	33.3	38.2	22.7	1.5	60.1	31.4	31.6	27.2
Deroceras				2			2.8		
Discus cronkhitei									
Euconulus fulvus	2.9			1				0.7	
Fossaria modicella			4.3	3		1			
Fossaria parva	9		4.9	5	11.9	3.4	1.1	13.6	3.7
Gastrocopta pellucida									
G. tappaniana	3.3		1.2	3.5		1.5	2		7.6
Gyraulus parvus	1.7	33.3	22.8	13.6	13.4	1		4.3	1.6
G. circumstriatus	3.3		6.2	7.1	1.5		17.6	9.3	7.6
Hawaiia sp.									
Oxyloma sp.	0.4				1.5	1.1			
Physa gyrina									
P. virgata				0.5	4.5	0.5		1.4	
Pisidium casertanum	19.8	33.3	8	5.6	34.3		7.4	5	2.8
P. rotundatum				4.5	10.4	1		1.4	0.9
Pupilla hebes									
P. muscorum	17.7		1.9	4		10.8	10.2	17.2	19.6
Pupoides sp.									
Pyrgulopsis ar.									
Pyrgulopsis mi.									
Pyrgulopsis sp.	3.3				11.9				
Stagnicola caperata									
S. elodes									
S. montanensis									
S. pilsbryi						2		0.7	
Succinea									
Tryonia v.									
Vallonia cyclophorella	0.4								
V. gracilicosta						2	1.1	6.5	1.6
Vallonia sp.									
Vertigo berryi	18.5		12.3	27.3	4.5	16.7	25.2	8.5	27.5

mollusks/kilogram
…diment

usk Samples

Species	Sample # Pah. Mol. 1	Pah. Mol. 2	Pah. Mol. 3	Pah. Mol. 4	Pah. Mol. 5	Pah. Mol. 6	Pah. Mol. 7	Pah. Mol. 9	Pah. Mol. 17
Asaminea sp.									
Catinellidae									
Deroceras									
Discus cronkitei		7.7		7.1					
Euconulus fulvus									
Ferrissia californica			1.2	2.4					
Fossaria modicella									
Fossaria parva	6.7		6.1					7.4	
Gastrocopta pellucida									
G. tappaniana			1.2					13.1	
Gyraulus parvus									
G. circumstriatus			4.9	2.4	56.5	56.1	44	0.6	93.6
Hawaiia sp.				2.4				28.6	
Oxyloma sp.									
Physa gyrina			2.4						
P. virgata									
Pisidium casertanum	53.3	23.1	19.5	16.7	6.5		36	20.6	
P. rotundatum									
Pupilla hebes									
P. muscorum									
Pupoides sp.									
Pyrgulopsis ar.									
Pyrgulopsis mi.									
Pyrgulopsis sp.	13.3	61.4	58.5	42.7		2.4		2.9	
Stagnicola caperata				11.9	27.4	31.7	16		
S. elodes									
S. montanenesis									
S. pilsbryi									
Succinea	26.7	7.7	2.4	4.8	8.1	7.3	4	4.6	6.5
Tryonia r.									
Vallonia cyclophorella				4.8					
V. gracilicosta			1.2	4.8				15.4	
Vallonia sp.									
Vertigo berryi			2.4		1.6	2.4		6.9	
mollusks/kilogram sediment									

TABLE 2 AMINO ACID RATIOS ON SOUTHERN NEVADA MOLLUSKS

SAMPLE #	GENUS	AMINO ACID RATIOS FREE	TOTAL HYDROLYSATE
CS85Mol.20	*Gyraulus*	0.188	0.133
CS85Mol.5	*Gyraulus*	0.189	0.131
CSF87-17	*Gyraulus*	0.202	0.114
CSF87-15	*Gyraulus*	0.23	0.175
CSF87-22	*Gyraulus*	0.241	0.172
CSF87-27	*Gyraulus*	0.169	0.107
CSF87-33	*Gyraulus*	0.326	0.257
Pah. Mol.5	*Gyraulus*	0.191	0.112
PY Mol. 31	*Gyraulus*	0.267	0.195
Piute Valley 87-1	*Gyraulus*	0.367	0.256
CY Mol. 2	*Gyraulus*	0.338	0.214
SYF87-22	*Gyraulus*	0.198	0.118
SYF87-16	*Gyraulus*	0.191	0.111
YWF87-5	*Gyraulus*	0.291	0.183
YWF87-9	*Gyraulus*	0.295	0.197
CS85-17	*Pisidium*	0.212	0.156
CS85Mol.5	*Pisidium*	0.227	0.154
CS85Mol. 20	*Pisidium*	0.21	0.146
CSF87-15	*Pisidium*	0.266	0.179
CSF87-22	*Pisidium*	0.296	0.196
CSF87-27	*Pisidium*	0.156	0.128
CSF87-33	*Pisidium*	0.378	0.274
CSF87-79	*Pisidium*	0.236	0.158
CY Mol. 1a	*Pisidium*	0.422	0.318
CY Mol. 2	*Pisidium*	0.409	0.277
PY Mol. 29	*Pisidium*	0.264	0.214
PY Mol. 66	*Pisidium*	0.177	0.134
PY Mol. 81	*Pisidium*	0.243	0.178
PY Mol. 31	*Pisidium*	0.375	0.293
SYF87-16	*Pisidium*	0.229	0.183
SYF87-22	*Pisidium*	0.207	0.166

INCOMPLETE OR NON-LINEAR RESULTS

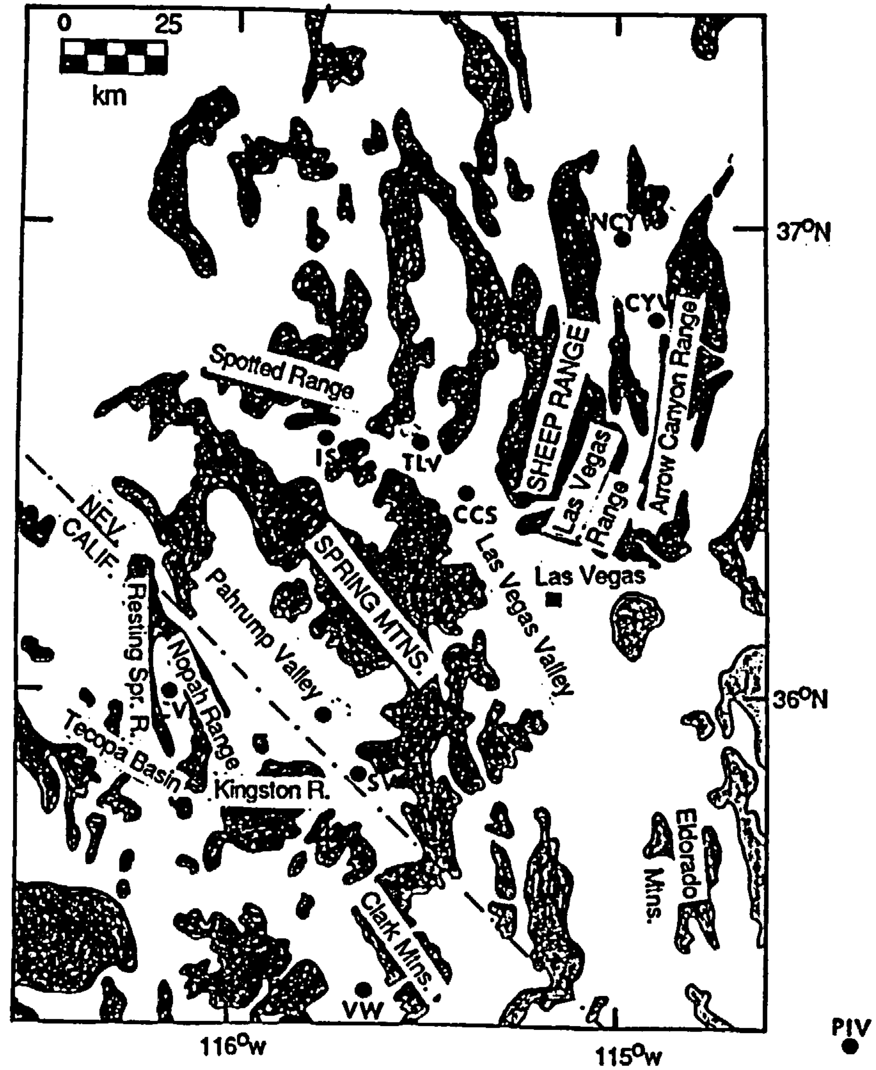
SAY. Mol. 2	*Pisidium*	0.271	0.193
Pah. 85 Mol. 16	*Gyraulus*	0.292	0.19
SYF87-14	*Pisidium*		0.215
SYF87-14	*Gyraulus*		0.147

Note: CS = Corn Creek Flat; SY = SAY = Sandy Valley; PY = Pah. = Pahrump Valley; CY = Chicago Valley; YW = Valley Wells

Radiocarbon Results

A-Number	Sample Description	Conventional Date	Del C-13
4859	Pah.85 Carb.23a - charcoal	880 +/- 50	-24.6
4860	SYC 87-4a	1300 +/- 50	-24.4
4861	CS81 Carb. 6b -humates from organic mat	9220 +/- 180	-17.4
4862	CSC87-28 - carbonized wood	11,570 +/- 240	-22.8
4897	Pah. Carb 29 (follow-up) -carbonized wood	(very small sample)	
4898	YWF87-1 - Organic mat	10,250 +/- 160	-25
4899	CSC87-25 - Shell	(result expected soon)	
4900	PYC87- 42 -carbonized wood	(only 300 mg. carbon)	
4901	CSC87-8 -carbonized wood	11,870 +/- 200	-28.2
4606	PY86-Carb.35b -Organic matter with carbonized wood	9120 +/- 110	-24.3
4607	PY86-Carb.26b - Organic matter	10,090 +/- 100	-26.3
4608	PY86-Carb.10b - Carbonized wood	8510 +/-190	-26.8
4609	PY86-Carb.39b - Carbonized wood	10,920 +/- 160	-25.1
4590	PY86-Carb.15 - Stump Spring	8570 +/- 170	-25.7
4591	PY86-Carb37 - Hidden Valley Ranch	8480 +/- 160	-26.4
4592	PY86 Carb 31b - Hidden Valley Ranch	11,190 +/- 210	-26.6
4593	PY86 Carb 33 - Hidden Valley Ranch	10,940 +/- 390	-25
4594	PY86 Carb11b - Stump Springs	10,380 +/- 380	-21.4
4595	PY86 Carb 34	8600 +/- 170	-25.6
4537	CS81 Carb. 13b -Corn Creek Spring Black organic mat	10,220 +/- 210	-26.1
4538	PYCarb.29a - Charcoal	8610 +/- 150	-28.8
4539	PYCarb. 7b - Carbonized wood	10,090 +/- 200	-28.5
4540	PYCarb. 21b - Pure humates from carbonized wood, after pretreatment	8120 +/- 210	-25.4

TABLE 3



0
25
km
37°N
36°N
116°W
115°W
NCY
CYV
Spotted Range
SHEEP RANGE
Arrow Canyon Range
Las Vegas
Range
IS
TLV
CCS
NEV.
CALIF.
SPRING MTNS.
Las Vegas Valley
Las Vegas
Resting Spr. R.
Pahrump Valley
Nopah Range
Tecopa Basin
Kingston R.
SV
Eldorado
Mtns.
Clark Mtns.
VW
PIV

Appendix B-VI

Late Wisconsin Ground-Water Discharge Environments of the Southwestern Indian Springs Valley, Southern Nevada by J. Quade and W. L. Pratt.

LATE WISCONSIN GROUND-WATER DISCHARGE ENVIRONMENTS OF THE SOUTHWESTERN INDIAN SPRINGS VALLEY, SOUTHERN NEVADA

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ABSTRACT

Badland exposures in the southern Indian Springs Valley, southern Nevada contain evidence of widespread spring and seep discharge at and before about 9400 yr B.P. The stratigraphic position and appearance of most of these deposits suggests correlation with late Wisconsin (30,000 to ca. 10,000 yr B.P.) marsh deposits up to 60 km to the southwest in the Las Vegas Valley, at Tule Springs and on Corn Creek Flat. Sedimentologic and faunal evidence indicate that during the late Wisconsin, a fine-grained subaerial flat probably vegetated by phreatophytes surrounded areas of moist grassland or "wet meadow" containing at least one perennial pond and creek. This reconstruction was facilitated by comparison with active analog environments in Steptoe Valley in northeast Nevada. Elsewhere in Indian Springs Valley, such as around Indian Springs itself and on the playa below, poor exposure has prevented characterization of the late Wisconsin environment.

INTRODUCTION

Dissected fine-grained deposits blanket much of the Las Vegas Valley bottom from the urban areas of Las Vegas in the southeastern valley to Indian Springs, about 70 km northwest of Las Vegas (Fig. 1). This large expanse of mainly late Wisconsin sediments, in places underlain by genetically similar sedimentary sequences of greater age, has long been of paleontological and archeological interest (Spurr, 1903; Harrington and Simpson, 1961; Shutler and Shutler, 1962). Up to the mid-sixties, the deposits were interpreted as "lakebeds". As with geologists and nongeologists alike, the lakebed interpretation is often applied indiscriminately to any continental basin deposit that is fine grained, light colored, and that contains aquatic mollusks. This has been the case with late Pleistocene deposits in the Las Vegas Valley (Hubbs and Miller, 1948; Maxey and Jameson, 1948; Snyder *et al*, 1964; Longwell *et al*, 1966). Haynes (1967) was the first to describe the deposits in detail with his work at the Tule Springs archeological site 12 km north of Las Vegas (Fig. 1), and in adjacent spring areas. Haynes recognized the stratigraphic record as dominantly fluvial, while he also established the presence of a shallow, tule-fringed lake or marsh --'Pluvial Lake Las Vegas'-- at the archaeological site during the full-glacial (Unit D). Although Haynes's Unit D interpretation was locally correct, the shallow lacustrine setting has not proved representative of most Unit D age fine-grained deposits studied since then. Mifflin and Wheat (1979) first suggested that deposition of Unit D was largely related to vigorous ground-water discharge, and not to a valley-wide lacustrine setting. Detailed stratigraphic studies of Quade (1986) lent strong support to this interpretation, and extended it to late Wisconsin deposits along the length of the upper Las Vegas valley. However, interpretation of many sedimentologic features in Unit D recognized by that study remained uncertain. This report presents the results of a comparative study between the sedimentologic and faunal evidence from late Wisconsin sediments in the Indian Springs Valley, 70 km northwest of Las Vegas, and existing ground-water discharge environments of the Steptoe and Butte Valleys in northeastern Nevada.

In particular, the analog as a model addresses several curious features of the late Wisconsin fine-grained deposits which taken together set them apart from lacustrine deposits:

(1) the presence of a sharp coarse-to-fine (gravel to sandy silt) transition on the valley flank, as described by Quade (1986). This textural transition, although previously interpreted as possibly shoreline related, sedimentologically shows no typical shoreline features. Also, the transition does not follow elevation contours in a bathtub-ring fashion, but rather parallels the gentle slope of the valley axis.

(2) the presence of a kilometer-wide (or less) subaerial sand flat which separates gravels higher on the alluvial fan from marsh deposits in the basin center.

(3) the presence of white to green clayey sediments containing terrestrial, semi-aquatic, and aquatic mollusks in close association.

(4) the presence of sediments deposited in apparent standing water in settings with significant slopes, often within basins with little or no hydrographic closure.

Methods

Mapping was conducted on a 1:24,000 black-and-white aerial photographic base.

Organic matter sampled for dating was subjected to standard acid (6N HCl) and base (2% NaOH) pretreatment. The base soluble (humate) fraction was then precipitated by acidification with HCl, and collected over silica filter paper. This portion was dated, and results appear in the text. Base insoluble residue, largely devoid of organics after base treatment, was discarded.

Each faunal sample was collected from a single exposure within a single sedimentary unit. The amount of sediment collected was determined by the abundance of shell material, but generally averaged one to two kilograms. Mollusks were sieved and dried over mesh screens The presence or absence of ostracodes was also noted. Well-indurated samples were in some cases boiled in water mixed with Calgon and Na_2CO_3 to facilitate disaggregation. The shells were then sorted into species lots under a dissecting microscope, and the lots were identified, counted, and stored individual vials.

The basic references used for mollusk identification are Pilsbry (1939-1948) for land snails, Burch (1982) for the aquatic snails, and Burch (1972) for bivalves. Baker (1928), Bequaert and Miller (1973), Harrington (1962), and Hibbard and Taylor (1960) are supplementary sources for some taxa. Taylor (1975) proved useful as an entry to the literature on particular problem species.

Very little has been published regarding habitat selection by Great Basin mollusks *per se*, but most of the species involved are widespread, and habitat data are available from a variety of sources, including the authors' personal studies. Important among published studies are Bequaert and Miller (1973), Chamberlin and Jones (1929), Henderson (1924, 1929, 1936a, 1936b), Hibbard and Taylor (1960), Hubricht (1985), and Russell (1971).

MODERN SPRING DISCHARGE ENVIRONMENTS

Steptoe Valley is located about 450 km north-northeast of Indian Springs Valley. It receives roughly twice as much annual precipitation (23 cm) as the Indian Springs Valley, while mean annual temperature is about 10°C lower (Eakin *et al*, 1967). The shallow phreatic zone and ground-water discharge environments present in Steptoe Valley are thought to be a reasonable analog to late Wisconsin conditions in southern Nevada. This valley was also selected because no pluvial lake was present during the late Pleistocene due to lack of hydrographic closure (Mifflin and Wheat, 1979). The surface geology is therefore uncomplicated by exposures of older lacustrine deposits. Spring discharge areas in adjacent Butte Valley were also briefly surveyed and sampled. In a later section of the report, the surface sedimentologic and faunal patterns in these active ground-water discharge environments are compared to those in late Wisconsin deposits in the Indian Springs Valley.

Steptoe Valley (northeast Nevada)

The area of study encompasses the west side of the northern Steptoe valley between about Indian Ranch and Murphy Ranch (Fig. 2). Goshute Lake occupies the bottom of this portion of the valley. Although generally a playa and intermittant playa lake, in the recent high runoff years Goshute Lake has not dried completely during the warm months. When full the lake is about 8 km long and 1 to 3 km wide.

The northern Steptoe Valley is bordered on the west side by the Cherry Creek Range. The range exceeds 3000 m in elevation in places, and serves as the principal recharge source to this segment of the valley. Over seventy piedmont springs and seeps are present in this portion of the valley on the west side. The east side of the valley is bordered by only several small ranges. As a result, no springs are present on that side between the range fronts and Goshute Lake.

Little surface runoff from the ranges appears to reach the lake most of the year, probably because the range is dominated by permeable carbonate rocks. In this respect, the ranges are analogous to those in southern Nevada. Goshute Creek is the only perennial creek in the area. In late July of 1985, flow in the creek was comparable to only that of a single medium-sized spring on the west side.

In this area the valley axis slopes gently to the north, except along the playa where the gradient is nearly flat. The elevation of the highest piedmont springs also decreases to the north, although adjacent the playa the gradient is as little as 0.2 m/km (Eakin et al, 1967). Thus the elevations of springs vary in general as function of the intersection of the water table with the gentle south-to-north sloping valley gradient. In places, small faults localize spring discharge.

Three distinct vegetation zones occur in the valley lowlands. Because these zones exercise significant control on grain size of valley alluvium, vegetation was mapped on a reconnaissance level, as described below.

Big sage - greasewood - rabbitbush zone

A sharp lineament is visible on aerial photographs that runs most of the length of the west side of the valley just above the highest piedmont springs. The lineament marks the sharp vegetation transition between drought-tolerant black sage (*Artemisia tridentata nova*) and shadscale (*Atriplex convertifolia*) upslope, and big sage (*Artemisia tridentata tridentata*), greasewood (*Sarcobatus vermiculatus*), and rabbitbush (*Chrysothamnus nauseous*) below the lineament (Fig. 2). The elevation of this transition decreases downvalley (south to north), like the elevation of the highest piedmont springs. This correlation suggests that the transition marks plant root's first penetration of the capillary fringe as it approaches the ground surface above and between springs (Miller et al, 1982).

On aerial photographs, the trend and position of this vegetation lineament, and the coarse-to-fine facies transition in late Pleistocene sediments fringing valleys in southern Nevada are remarkably similar. The reason for this similarity can be seen in the impact of the vegetation changes on surface sedimentology. Above the transition, the vegetation is small and widely spaced, and the alluvium is gravelly. In contrast, below the transition, live plants and deadfall are much denser. Hydraulic roughness is evidently sufficiently increased by these factors to cause unconfined surface flow to drop most of its coarse load about 50 to 100 m downslope of the transition. Thus, most of the big sage-greasewood- rabbitbush zone is underlain by sandy silt alluvium.

Springs and wet meadows

Over seventy springs and seeps discharge on the piedmont zone of the west side of this portion of the valley. Depending on local gradient and discharge rate, either a marshy seep or a small flowing stream form at the point of discharge. If the springs are closely spaced, as in the case of the clusters around Cordano and Murphy Ranches, then a more continuous marshy area forms as spring discharge coaleses downslope. Where the springs are widely spaced, then big sage and rabbitbush cover intervening areas. Thus the big sage zone is not continuous in that springs intersperse the entire zone. The transition of this zone to the coalescing wet meadows below is also irregular, depending on the extent of local discharge (Fig. 2).

A detailed look at the morphology of spring disharge areas and associated wet meadows is instructive in that it offers an explanation for the mixed terrestrial/aquatic mollusk assemblages so common in the southern valleys in the Pleistocene. Where the gradient is high, a flowing stream issues from the point of spring discharge. *Pyrgulopsis*(*Fontelicella* of Quade, 1983, 1986, and previous authors) was observed everywhere in watercress in the margins of the clear, oxygenated flowing water(Table 1). A band of marsh vegetation composed mostly of blade and wire grasses as well as several types of wild flowers often fringes the stream. This area can be saturated, depending on the time of year. But by July, efflorescent salt gives the dried surface a white appearance on aerial photographs.

Where gradients are lower, a marshy seep or "wet meadow" instead of a stream forms at the point of discharge. One such typical seep covered 300 m by about 75 m. Most of the area was covered by tufts of grass interspersed with standing water 20 to 40 cm deep. Two small ponds were also present. Water was deeper and sediment sandier where spring water was roiling from the ground in several hollows. Mollusks were collected from each of the environments (Table 1). The small ponds and sluggish flowing water are dominated by *Gyraulus parvus* and *Pisidium casertanum* (Table 1, SY-3 and other unlisted samples).The grass tuft areas contained various terrestrial mollusks like *Vallonia gracilicosta* and *Pupilla muscorum*. Sediment samples (SY-4 and 5) from the small streams feeding out of the base of the seep area contained most of the forms found alive in the seep area, as well as *Fossaria parva*, a semiaquatic snail, *Pyrgulopsis*, and several additional terrestrial forms (*Vertigo ovata, Catinella* sp.).

The seep sediment is largely composed of strongly reduced clay. Local subaerial exposure turned the sediment white (10 YR 8/1 - dry), but pockets remained black perhaps due to lack of oxidation locally. The small streams produced well-sorted sand where flow was strong but mostly poorly sorted clay, angular pebbles, and sand.

Downgradient the spring seeps coalesce into flowing streams, or where discharge is large, into continuous wet meadow with local ponds. Both scenarios occur in the Steptoe Valley. It is important to note that clay-dominated environments produced by springs on the valley flanks may or may not grade into marshy sediments below. In the case of the north end of the valley, large areas below the elevation of the marshy seeps are subaerially exposed sand and silt covered by big sage and rabbitbush.

Discharge from most major springs reaches the playa margin (or Goshute Lake in the case of the 1985 study). Seasonal contraction was visible on the lake margins in July, 1985. No permanent marsh vegetation, such is present in the Ruby Marsh in the Ruby Valley, was visible in this ephemeral lake. No mollusks were found in water on the margins of the lake.

Butte Valley (northeast Nevada)

Two sediment samples (Table 1, BV-2 and 3) containing mollusks were collected along a small perennial creek at the north end of the valley. The creek drains a large (several km^2) wet meadow. The meadow is fed by several large springs about a kilometer from the sample sites. The mollusks samples constitute thanatocenoeses accumulated in muddy channel sediment..

Both samples contain a mix of aquatic and terrestrial mollusks that reflect quite faithfully the local stream setting borbered by marshy banks and wet meadow. Interestingly, *Pyrgulopsis* is present in nearby springs tributary to the stream, but is scarce or absent in the channel sediment samples. Moreover, mollusks favoring a seasonal moisture regime are absent. Evidently, mollusks undergo little transport after death in the spring-wet meadow setting.

STRATIGRAPHY AND SEDIMENTOLOGY OF LATE WISCONSIN DEPOSITS IN S. NEVADA

Indian Springs and Cactus Springs lie in the south end of the Indian Springs Valley, located 70 km northwest of Las Vegas (Fig. 1). The valley is the highest of a series of sub-basins connected by one continuous northwest-southeast trending structural basin (Las Vegas Shear Zone) that includes Las Vegas Valley along its southern extent. The hydrographic sub-basins were created by encroachment of large alluvial fans from adjacent ranges across the valley axis. Both Indian Springs Valley and adjacent Three Lakes Valley lie in closed sub-basins divided by low sills. Southeast into the Las Vegas valley, Corn Creek Flat and Tule Springs Flat (just north of Las Vegas) are tributary to the Colorado River.

Fine-grained, late Quaternary deposits are nearly continuously exposed from Las Vegas northwest to Indian Springs Valley. Haynes (1967) established the basic stratigraphic framework for these deposits in his work at the Tule Springs archeological site near Las Vegas. Quade (1983,1986) extended most of that stratigraphy to Corn Creek Flat, between the site and Indian Springs. Similar appearing deposits are also exposed around Three Lakes Valley, which have not been studied.

The Indian Springs Valley has a backwards "L" shape. A playa occupies the longer, north-south portion valley, while Indian and Cactus Springs, and a wash that feeds into the extensive playa to the north, occupy the east-west trending foot of the valley. The origin of fine-grained deposits exposed along that wash and around the springs is the main topic of this report. The playa and surrounding bajada are undissected.

The use at Indian Springs of Haynes's stratigraphic nomenclature from the archeological site is loose: three radiocarbon dates, stratigraphic position, and lithologic similarity are the basis of correlation between the two areas. Briefly, Haynes recognized two principle marsh phases at Tule Springs: Unit B_2, which fell beyond the range of ^{14}C dating, and the more widespread Unit D (30,000 to 15,000 yr B.P.). A period of marsh contraction (Unit E_1-E_2) following 15,000 yr B.P. ended by about 7000 yr B.P. with the attainment of near modern effective moisture conditions. After 7000 yr B.P., widespread dissection of fine-grained deposits began, and this continues today.

The fine-grained deposits of the Indian Springs Valley range in age from modern to probably beyond the range of ^{14}C dating. The emphasis in this paper is on Unit D and Unit E, the two units spanning the last pluvial period (30,000 to ca. 7000 yr B.P.). The rest of the column will be dealt with only briefly below.

Pre-Unit B

Several areas are covered by pre-Unit B age fine-grained deposits. Most important are some prominent white bluffs cropping out upslope from Cactus Springs. The bluffs sediments are well-indurated and are capped by up to 75 cm of dense caliche, a degree of development much greater than that characteristic of Unit B orD. The exposed section is largely fluvial (Fig. 3), but contains several thin horizons with a mix of terrestrial and aquatic mollusks similar to those of later periods described below.

Units B and C and Soil S_3

North of Cactus Springs, deep dissection has exposed horizons older than the pale-green mudstones belonging to Unit D-E. The older horizon is entirely brown fluvial silt (Fig. 3, Unit B-C) capped by a well-developed soil (Soil S_3), and then by Unit D-E. Haynes recognized two entirely fluvial units (Unit B_3 and Unit C) at Tule Springs underlying full-glacial Unit D. Soil S_3 occurred on top of Unit B_3. Similar physical appearance and stratigraphic position were there- fore the basis for correlating the brown silts at Cactus Springs with Unit B or C, and the soil above it with Soil S_3.

Stratigraphic relations are best exposed in the central portion of the badlands (Fig. 4, Section 25). Unit B-C is not confined to that one area, but poor exposure prevents mapping its complete extent with confidence. This uncertainty is expressed on the geologic map by designating several areas as Unit B to lower Unit D undifferentiated (Fig. 5).

Unit D and E

Age

Pale green clay and mudstone mixed with secondary carbonate occur just below the top of the fine-grained valley fill over broad areas around Indian and Cactus Springs. This is also the stratigraphic position and basic composition of Unit D (30,000 to 15,000 yr B.P.) and Unit E_1 (14,000 to 11,800 yr B.P.) in the lower Las Vegas Valley, and thus a correlation with one or both is strongly suggested. Furthermore, a similar appearing thin brown alluvial unit caps the clays in both areas. In the lower Las Vegas Valley, the brown alluvium generally correlates with all or part of upper Unit E_2 (ca. 10,000 to 7200 yr B.P.).

Pale green clay crops out within 30 m downslope of the caliche-capped bluffs above Cactus Springs. The clays are inferred to be inset into the older caliche-capped sediments (pre-Unit B) although no outcrop actually exposes this relationship. The clays are much less indurated and are greener (5 Y 6/2 dry) than the older sediments (10 YR 8/1-8/2 dry). The exposure shown in Figure 6 summarizes the stratigraphic succession in the younger green clays around Cactus Springs, and also shows the position of two radiocarbon-dated samples.

USGS-2211 is disseminated carbonized wood from the green clays (Fig. 6). Carbonized wood is charcoal-like in appearance. But unlike typical charcoal, it is soluble in basic (2% NaOH) solution. Its field occurrence and chemical behavior led Haynes (1967) to conclude it was probably nonpyrolized wood. Both Haynes (1967) and Quade (1983) concluded that the material yielded reliable radiocarbon dates.

USGS-2211 yielded a date of $42,600^{+1600}_{-1300}$ (Table 2). This age on the clays is probably too old since the wood occurs about a meter below two early Holocene organic layers (see below). No disconformities are evident between the samples, and the clays and organic layers are similarly indurated. The wood is therefore tentatively concluded to be redeposited. Haynes (1967, p. 73) encountered similar anomalies at Tule Springs in the vicinity of paleospring orifices. More radiocarbon samples are being sought in the clays.

One and in places two dark gray (10 YR 4/1.5 dry), organic-rich layers overlie the green clay in most exposures around Cactus Springs. The humate fraction from two separate samples of the organic layer yielded 9680±100 yr B.P. (Table 2, USGS-2212) and 9460±70 yr B.P. (Table 2, USGS-2213). The humate fraction date should reflect a mean residence time for the organics in the layer. Pieces of a mammoth molar were discovered eroding from the top of the underlying green clays. This position relative to the organic layers is consistent with a late Rancholabrean age for the molar.

Lithology and distribution

Similar to observations at Corn Creek Flat and Tule Springs Flat (Quade, 1986), Unit D undergoes regular sedimentologic and faunal changes from valley margin to center. Gravels of the surrounding bajada surfaces grade abruptly (<100 m) to brown silty alluvium, which downslope grades to the white and pale green clay and mudstone already mentioned (Fig. 4 and Fig. 7). Fine-grained deposits below the textural transition are generally devoid of gravel. As seen elsewhere, the coarse-to-fine transition gently increases in elevation westward parallel to the length of the valley, such that the highest fine-grained deposits at the west end of the valley are about 120 m above the playa (elev. 919 m). Moreover, within the east-west "foot" or extension of the valley, the coarse-to-fine transition averages 30 m higher in elevation on the Spring Mountain (south) side than the Spotted Range (north) side.

Figure 8 shows the distribution of the three facies of Unit D-E mapped in the Cactus Springs area. They are best seen in the extreme west end of the 'foot' of the valley. Briefly, the facies from valley center to margin are:

(1) *green clays* -- pale green (5 Y 7/2 dry) very hard clay to silty clay; very sticky, very plastic; strong, medium to coarse prismatic structure; calcareous with dispersed to continuous layers of nodular secondary carbonate; locally mixed with angular pebbles; MnO_2 and FeO coatings in certain horizons; generally lacking in sedimentary structures; mollusks common.

(2) *white silty clays* -- white (10 YR 8/1 dry) hard to very hard; sticky, plastic;

weak, coarse prismatic structure; secondary carbonate as nodules or as massive ledges; MnO_2 stains and mollusks common.

(3) *sand - silts* --pale brown (10 YR 7/2-7/4 dry) interbedded sand and silt showing well-preserved planar and cross-ripple laminations; slightly hard; slightly sticky, slightly plastic; weak crumb structure to silts; rare gravel lenses; cicada and other insect burrows; rare mollusks; rare secondary carbonate; large bone fragments.

The facies scheme above is similar to that used at Corn Creek Flat (Quade, 1986). The differences are that a calcareous sand-silt facies mapped at Corn Creek is poorly preserved or exposed at Indian Springs and has therefore been lumped into the sand-silt facies. Also, the white silty clay facies was combined with the calcareous green clays at Corn Creek for mapping purposes.

There is some uncertainty in correlating of green clays over such a large area. Around Cactus Springs, where the clays underlie the dated earliest Holocene organic layers, they are moderately to strongly prismatic, and very hard when dry. Identically appearing green clays crop out in the extensive exposures west of Cactus Springs along the main valley wash. No organic layers are present in that area, but the overlying pale-brown sand and gravel is just as at the Cactus Springs exposures. These similarities make correlation between undated sequences reasonable.

The nature of late Pleistocene deposition on Indian Springs playa remains unknown due to lack of exposure. The presence of the described marshy deposits on the valley flanks suggests that possibly more than ephemeral surface runoff reached the playa at that time. However, as pointed out by Mifflin and Wheat (1979), lack of paleostrandlines rules out the existence of "Pluvial Indian Springs Lake" of Hubbs and Miller (1948).

Faunal Distribution

Eighteen mollusk/ostracode samples were collected from the area (Table 3); locations are given in Figure 9. By combining data sets, the relationship between facies and fauna can be summarized as follows:

(1) All the green clays contain ostracodes. Most aquatic mollusks present favor standing water that experiences seasonal drying (e.g. *Stagnicola caperata, Stagnicola montanensis, Gyraulus circumstriatus*). *Fossaria parva,* a semi-aquatic snail, lives in moist areas bordering permanent water. Only two samples(Table 3, CACSPR-10 and -17) contain *Gyraulus parvus,* which requires permanent standing water. These two samples are also the only ones from the area which contain less than about 20% terrestrial mollusks, although they are still represented. It is doubtful that the terrestrial forms were washed from a distance into the sample locality since there are no indication that the clays were reworked.

(2) The white silty clays lack ostracodes, but locally can contain mollusks. Terrestrial mollusks such as *Pupilla muscorum, Catinella* sp., and others dominate (Table 3, CACSPR-1 and CACSPR-9). *Fossaria parva, Gyraulus circumstriatus,* and *Pisidium casertanum* are also present in CACSPR-1. They are semiaquatic to aquatic but none require permanent water to survive.

(3) The sand-silt facies lacks ostracodes and mollusks except for occasional terrestrial forms (*Vallonidee*). Mammal bones, and borrowing produced by cicadas (*Cicadidae*), a terrestrial insect, are common.

Depositional Setting

Although the fauna collected from the Indian Springs Valley indicate that standing water was present, the sedimentologic and faunal pattern is not typical of a lacustrine setting. As Figures 4 and 8 show, green clays occur upslope from at least one area of white silty clays, the reverse of that expected were standing water to extend over the area continuously. Continuous standing water can be dismissed by physical constraints alone, since the highest clays rest nearly 120 m above the basin threshold. Furthermore, all but one of the mollusk assemblages contains terrestrial forms, suggesting a close proximity to unsubmerged ground.

The pattern of sedimentation and the types of mollusks are sufficiently similar between the Steptoe Valley and Pleistocene strata in the Indian Springs Valley to allow the reconstruction given in Figure 10. This figure was constructed by cross-referencing sediment type with fauna composition in the Pleistocene sediments, and based on the analog setting in northeastern Nevada, assigning an environment.

The coarse-to-fine (gravel to sand-silt) transition in Unit D-E probably resulted from the surface hydraulic effects of the nonphreatophyte to phreatophyte transition, as is visible in Steptoe Valley today. Below this transition, sandy silts were entrapped by dense, phreatophytic vegetation on slopes between 0.3 and 0.8 degrees, as is occurring in Steptoe Valley now. Cicades, whose burrows are common in this facies, are known to favor unsaturated, sagebrush-covered environments in the northern Great Basin (Hughie and Passie, 1963). The former presence of sagebrush in the valley is attested to by pollen spectra from the archeological site (Mehringer, 1967), and by pack-rat midden evidence (Spaulding, 1983). Spaulding also found rabbitbush in a nearby hillslope midden (Point of Rocks #2) dated at 14,800 yr B.P. The presence of large mammal bones, particularly where this facies grades into the white silty clay facies, suggests proximity to but not inundation by water. Paucity of gravels in the sand-silt facies indicates that little perennial surface flow was reaching the valley bottom from the surrounding upper fans and ranges. This phreatophyte zone surrounded all of the Indian Springs Valley wet meadows, as well as those on Corn Creek Flat (see Fig.4 in Quade, 1986) and on Tule Springs Flat.

The white silty clay facies downslope from the sand-silts probably coincides with moist grassland and typically is dominated by terrestrial mollusks (Table 3, CACSPR-1 and 9). *F. parva* and *G. circumstriatus* are also sometimes present, implying marshiness and local seasonal stands of water.

Pale green clays containing a mix of terrestrial and semi-aquatic mollusks were probably produced in the more continuously saturated seep areas, which combines subaerial (grass tufts) and shallow subaqueous microenvironments over broad areas. However, seasonal drying is impled by those assemblages dominated by the various *Stagnicola* (except *S. eloides*) and *G. circumstriatus*. These types are notably absent from the Steptoe Valley assemblages. Perhaps they were actually present in the area but were not sampled because by July seasonal water has dried and such mollusks would be dormant in muds of the unsampled wet meadows. Pale-green clays containing *G. parvus* are interpreted to represent those portions of the wet meadow environment that didn't experience seasonal drying, such as the ponds, springs, and perennial channels. *Pyrgulopsis* is notably lacking in the Cactus Springs samples while it is common at Tule Springs and Corn Creek. Fast flowing (stream or spring), well-oxygenated waters that *Pyrgulopsis* favors were evidently not widely present in the area during Unit D time. Deeper, permanent water mollusks (e.g. *Lymnaea stagnalis, Planorbella subcrenata, Stagnicola elodes,* etc.,) found in modern Ruby Marsh (unpub. data), and in Unit D on lower Corn Creek Flat (Quade, 1986) and at Tule Springs (Taylor, 1967) are not present in any of the Cactus Springs samples.

The overall setting was therefore: spring or seep discharge along gentle slopes on the valley flanks, an intervening dry area crossed by perhaps a sluggish, perennial stream immediately below the springs, and finally emergence of wet meadows and ponds at lower elevation. This pattern is not uncommon in the Steptoe Valley. Wet meadow stood higher in the valley on the Spring Range side (south) than the Spotted Range (north) side, as seen on a larger scale in Steptoe Valley.

Poor exposure and/or preservation in several areas hampers reconstruction of all potential discharge areas of the Indian Springs Valley during the late Pleistocene. Pale green clays are present in a few outcrops around Indian Springs, as well as sandy silts. But urban development has destroyed most evidence of Pleistocene discharge in that area. A few isolated outcrops of fine-grained sediments are visible on the Spotted Range side of the valley, but they remain uninvestigated. A playa or intermittant playa lake, permanent marsh , or combination of the three environments were all possibly present during the late Pleistocene in the area now occupied by Indian Springs playa, judging from modern analogs in northeast Nevada.

Unit E_2 and Soil 5

Upper Unit E_2 rests directly atop the organic layer at Cactus Springs (Fig. 6), although the organic layer is not present in the more extensive badland exposures to the west. The unit is largely pale-brown (10 YR 7/3 dry) silt with local mixed sand and gravel. It averages 1.5 to 2 m in thickness. One weak soil (Soil 5a) sometimes occurs within Unit E_2, while a stronger one is usually found on top(Soil 5b)(Figs. 3 and 6). A tightly packed desert pavement with darkly varnished clasts (10 YR 3/2) mantles the surface. Cicada burrows are common in upper Unit E_2. Their presence indicates persistance of moist, sagebrush-covered steppe in the area after 9400 yr B.P. (Hughie and Passie, 1963; Quade, 1986). The thickness of upper Unit E_2 and the weak development of Soil 5a suggests that dissection of the fine-grained deposits began within a few thousand years after 9400 yr B.P. Similar dissection began to the southeast in Las Vegas Valley at about 8000 to7000 yr B.P. (Haynes, 1967: Quade, 1986).

Unit FG

Following dissection of older fine-grained deposits beginning around 8000 to7000 yr B.P., gravelly alluvium flooded into the valley bottom. Several distinct geomorphic surfaces and deposits inset into the fine-grained deposits are visible, but no attempt will be made to discuss them here. For mapping purposes, these deposits were lumped under Unit FG (Fig. 5).

CONCLUSIONS

The stratigraphic column first established by Haynes (1967) at Tule Springs has been shown to apply to Corn Creek Flat (Quade, 1986), and is herein extended to the Indian Springs Valley. Limited radiocarbon dating and physical similarity of units support the correlations. Continuity of stratigraphy between these areas is noteworthy as the Indian Springs and Tule Springs areas are over 60 km apart and lie within hydrographically separate sub-basins. Shared climatic controls on paleohydrology and associated depositional and erosional events best explain the apparent uniformity of the stratigraphy.

Detailed examination of active phreatic discharge environments in northeast Nevada has allowed reconstruction of similar late Wisconsin environments in southern Nevada. In all, the sedimentology and fauna of the two areas have proved, with few exceptions, to be remarkably similar. It is unlikely that basin depositional environments were lacustrine in southern Nevada during the late Wisconsin as has been suggested by some previous workers. Instead, fine-grained deposits at Indian Springs and in the Las Vegas Valley were deposited in a complex mosaic of hydrologic environments. Of the valleys adjacent to the Spring Mountains studied thus far, the Indian Springs area manifests the least valley discharge. Wet meadows with only a few perennial pools characterize the area. Downvalley on Corn Creek Flat, greater discharge is in evidence in the form of widespread wet meadows and a small perennial marsh at the lower end of the valley (Quade, 1986). The Tule Springs area shows the largest discharge with the development of a shallow, tule-fringed marsh in the area (Haynes, 1967). Sedimentologic evidence from all areas suggests that water reached the valley primarily through springs, not as surface runoff.

The most southerly pluvial lakes in the Great Basin identified by Mifflin and Wheat (1979)(excluding those supported by runoff from the Sierra Nevadas and the San Gabriel Mountains) are Kawich and Groom Lakes, located 100 km north of Indian Springs. South of these former lakes, localized occurrences fine-grained deposits very similar to those described in this report are now under study outside the Las Vegas Valley. Valleys which include similar deposits are include Coyote Springs (Nevada), Pahrump and Mesquite (Nevada-California), and Chicago and Shadow Valleys (California). Recently, Hay *et al* (1986) reported on a similar ground-water discharge origin to Plio-Pleistocene fine-grained deposits in the southern Amargosa Desert, 60 km west of Indian Springs. The apparent extent of these fluvio-paludal deposits in the southern Great Basin suggests that vigorous spring discharge resulting in local marshy areas was the principal surface hydrologic expression of increased recharge associated with the last pluvial period.

ACKNOWLEDGMENTS

Dr.M. Mifflin provided much needed guidance during this work, as well as reviewed the manuscript. Tom Hurst and Grace Tao drafted the figures. This project was primarily supported by State of Nevada, Agency for Nuclear Projects, Nuclear Waste Project Office. The U.S. Geological Survey supplied the radiocarbon dates.

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TABLE 1 COMPOSITION (IN %) OF MOLLUSK SAMPLES FROM STEPTOE AND BUTTE VALLEYS, NORTHEAST NEVADA

TAXON	Sample No. SV-5	SV-4	SV-3	BV-2	BV-3
Aquatic clams					
Pisidium casertanum	14	48	2	2	9
Pisidium rotundatum				51	34
Aquatic snails					
Valvata humeralis		0.5			
Pyrgulopsis	84	8	2		1
Fossaria parva	0.5	2		2	3
Fossaria modicella			4		
Gyraulus parvus	2	0.5	92	19	37
Land snails					
Vallonia gracilicosta		6		15	5
Pupilla muscorum		11		7	10
Vertigo ovata		18		3	
Catinella sp.		6		1	1
Deroceras sp.		0.5			
Total number of mollusks in sample	216	176	51	239	131

Note: SV = Steptoe Valley, see Fig. 2 for locations; BV = Butte Valley, in main creek at north end of valley

TABLE 2 RADIOCARBON DATES FROM THE CACTUS SPRINGS AREA

Sample no.	Date (^{14}C years B.P.)	Material	Comments
USGS-2211b	$42{,}600^{+1600}_{-1300}$	carbonized wood, humate fraction	probably redeposited
USGS-2212b	9680±100	organic layer, humate fraction	
USGS-2213b	9460±60	organic layer, humate fraction	same layer as USGS-2212b, but taken 200 meters laterally

TABLE 3 COMPOSITION (IN %) OF MOLLUSK SAMPLES FROM LATE WISCONSIN DEPOSITS IN THE CACTUS SPRINGS AREA, SOUTHERN NEVADA

TAXON	Sample No. (CACSPR-)										
	1	4	5	7	8	9	10	11	15	17	18
Aquatic clams											
Pisidium casertanum	3	3	5	4	41		70	15	9	44	14
Pisidium rotundatum										15	
Aquatic and semi-aquatic snails											
Fossaria parva	6	3	9	3	3	6	6	8			6
Stagnicola caperata									10	10	
Stagnicola montanenesis							5				
Stagnicola pilsbryi				0.5	1						
Gyraulus parvus			0.5				3			15	
Gyraulus circumstriatus	29			13	24		15	14	63	2	17
Land Snails											
Vallonia cyclophorella										1	
Vallonia gracilicosta		22	9	0.5		17		6			3
Gastrocopta tappaniana	6		20		1	0.5		7			3
Pupilla muscorum	10	50	9	38	3	54		12		2	
Vertigo berryi	16		26	23	17		1	11	12	0.5	9
Catinella sp.	26	22	21	14	10	21	2	20	6	10	11
Euconulus fulvus	3		2	4				1			
Deroceras sp.			0.5								37

Total mollusks in sample	31	32	305	193	242	321	87	260	163	181	35

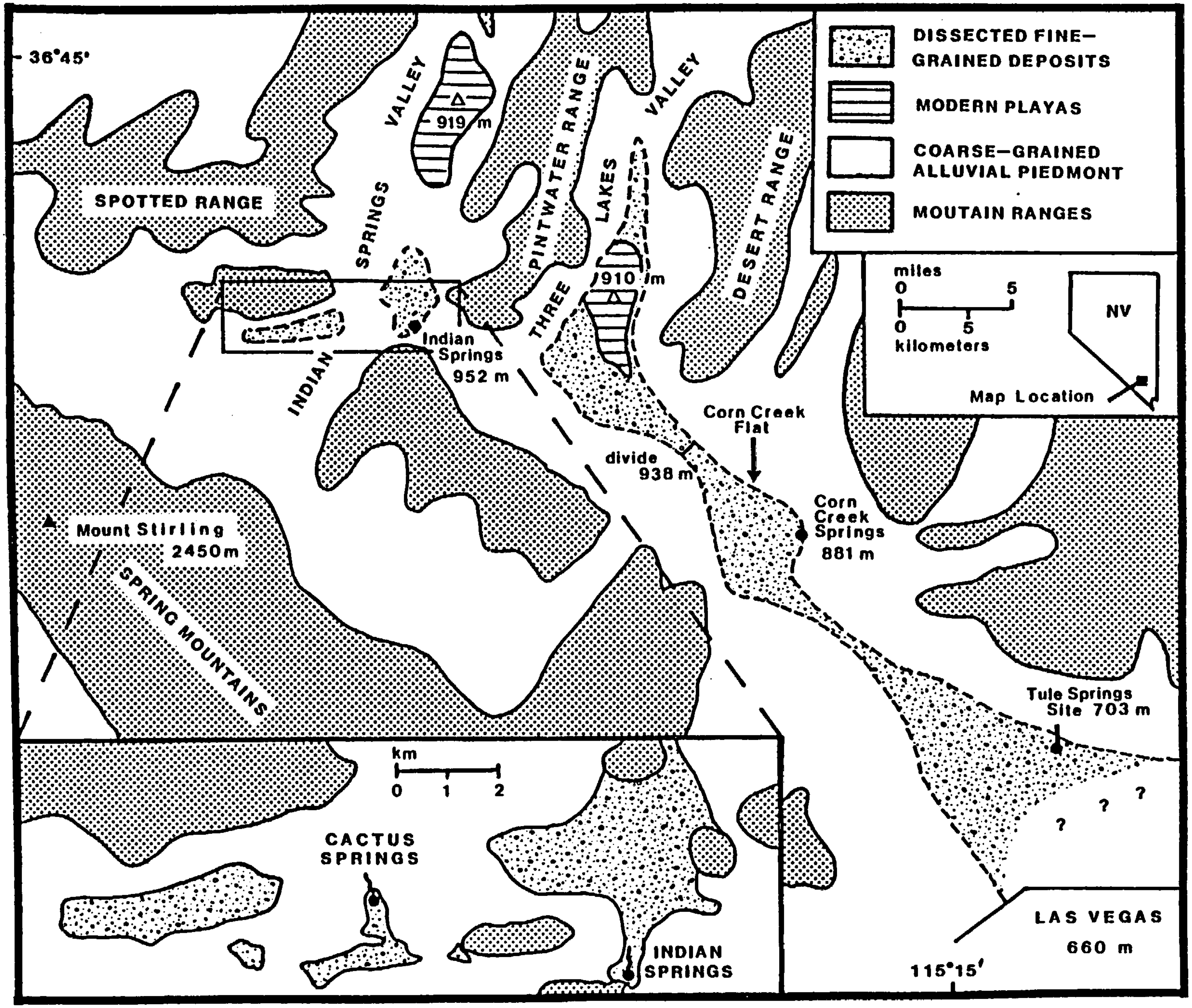
Note: see Figures 4 and 9 for sample locations.

List of Figures

Fig. 8 Distribution of lithologic facies for Unit D-E. in the Cactus Springs area. See Figure 5 for the full map key.

Fig. 9 Locations of fossil fauna, and their surface hydrologic implications, Cactus Springs area. See Figure 5 for the full map key.

Fig. 10 Late Wisconsin depositional environments in the Cactus Springs area. See Figure 5 for the full map key.



36°45'
DISSECTED FINE-GRAINED DEPOSITS
MODERN PLAYAS
COARSE-GRAINED ALLUVIAL PIEDMONT
MOUTAIN RANGES
VALLEY
919 m
PINTWATER RANGE
VALLEY
SPOTTED RANGE
SPRINGS
LAKES
DESERT RANGE
910 m
THREE
Indian Springs
952 m
INDIAN
miles
0
5
0
5
kilometers
NV
Map Location
Corn Creek Flat
divide
938 m
Corn Creek Springs
881 m
Mount Stirling
2450m
SPRING MOUNTAINS
Tule Springs Site 703 m
km
0
1
2
CACTUS SPRINGS
INDIAN SPRINGS
LAS VEGAS
660 m
115°15'

Fig. 1

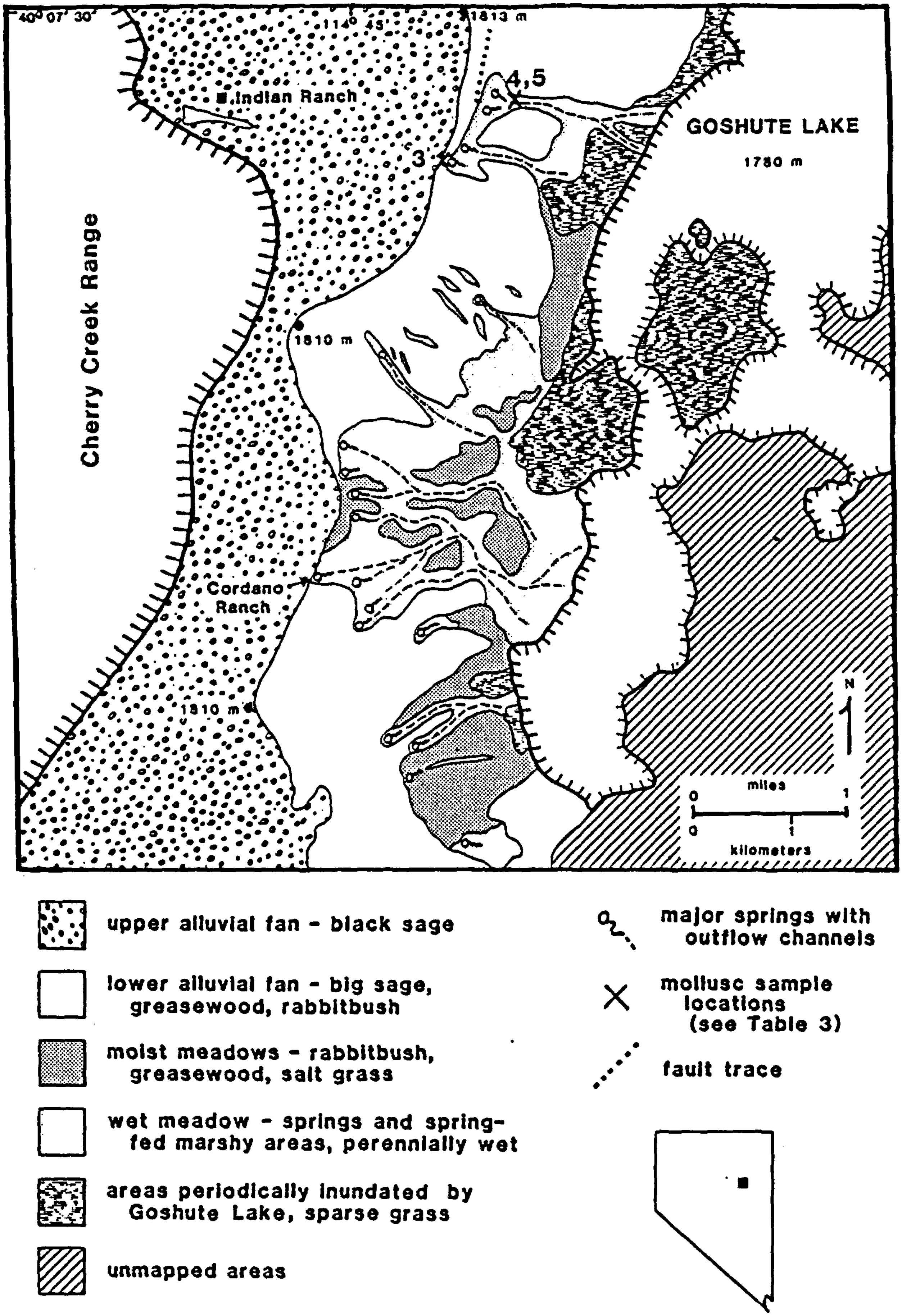
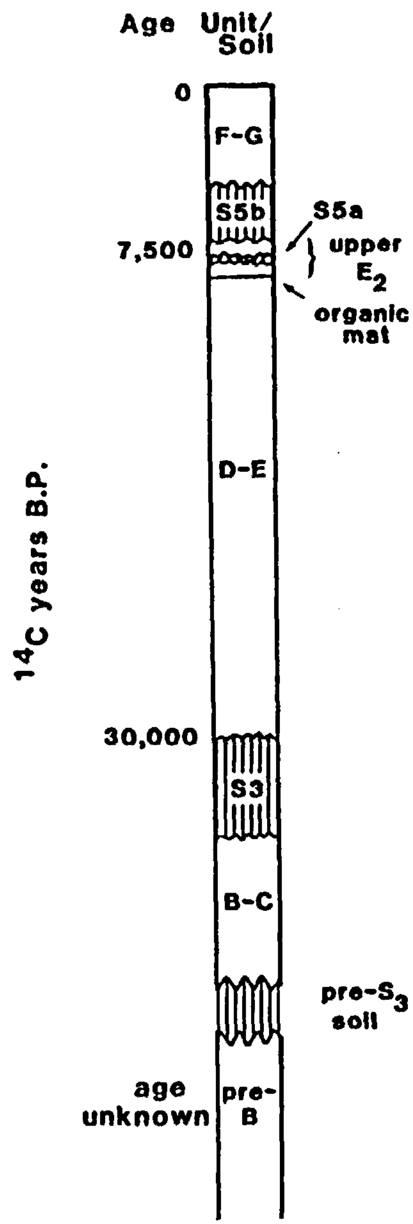

40° 07' 30"
114° 45'
1813 m
4,5
Indian Ranch
GOSHUTE LAKE
1780 m
3
Cherry Creek Range
1810 m
Cordano Ranch
1810 m
N
miles
0
1
0
1
kilometers
upper alluvial fan - black sage
lower alluvial fan - big sage, greasewood, rabbitbush
moist meadows - rabbitbush, greasewood, salt grass
wet meadow - springs and spring-fed marshy areas, perennially wet
areas periodically inundated by Goshute Lake, sparse grass
unmapped areas
major springs with outflow channels
mollusc sample locations (see Table 3)
fault trace

Fig. 2



Description

Unit F-G: Sand and gravel, mainly limestone cobbles but some reworked secondary carbonate; mainly inset into older units as alluvial sheets and terraces.

Soil S_{5b}: weak cambic horizon (10 YR 7/4d, 5/4m) at base of vesicular horizon; weak Stage II calcic horizon in gravelly alluvium; generally relict, with tightly packed, well-varnished pavement capping erosionally inverted Pleistocene sediments.

Upper Unit E_2: Alluvial silt pale brown (10 YR 7/3d) at base, separated by weak soil (5a) from overlying gravel and sand. The silt is soft, lacks molluscs or secondary carbonate, and is bioturbated by cicadas.

Soil S_{5a}: mostly eroded, truncated cicada burrows, dispersed carbonate coatings on rootlet molds.

Unit D-E: Locally capped by dark gray (10 YR 4/1.5 dry) organic layer(s) containing dispersed molluscs.

Three facies:

(1) sand-silt facies: soft, pale brown (10 YR 7/3 dry); local gravel lenses, no molluscs or secondary carbonate.

(2) white silty clay facies: slightly hard to hard, white (10 YR 8/1 dry); silt to silty clay, bioturbated secondary nodular carbonate, terrestrial and semi-aquatic molluscs, common vertebrate remains.

(3) pale green clay facies: hard to very hard, pale green (5 Y 7/1 dry); strong prismatic structure, bioturbated, sparse to abundant secondary carbonate, terrestrial and aquatic molluscs.

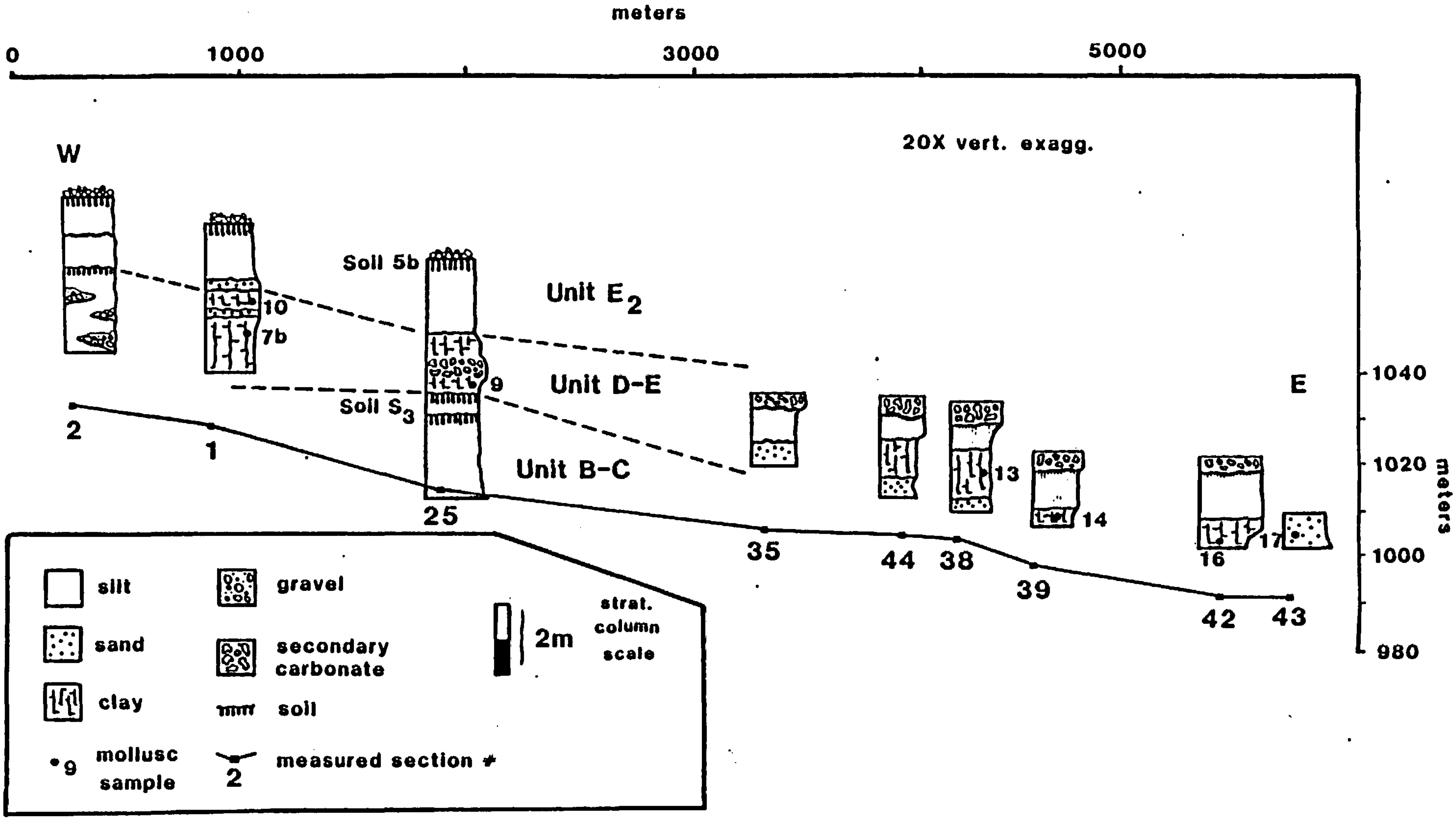
Soil S_3: generally buried, strong cambic horizon (10 YR 6/4 dry); strong, medium prismatic; Stage II calcic horizon in fine-grained alluvium.

Unit B-C: Silt, pale brown (10 YR 7/3d); very hard, weakly prismatic; locally sandy, dispersed secondary carbonate nodules, MnO_2 as coatings on rootlet molds.

Pre-S_3 soil: relict, 50-75 cm of dense caliche, more dispersed downwards; no extant B horizon.

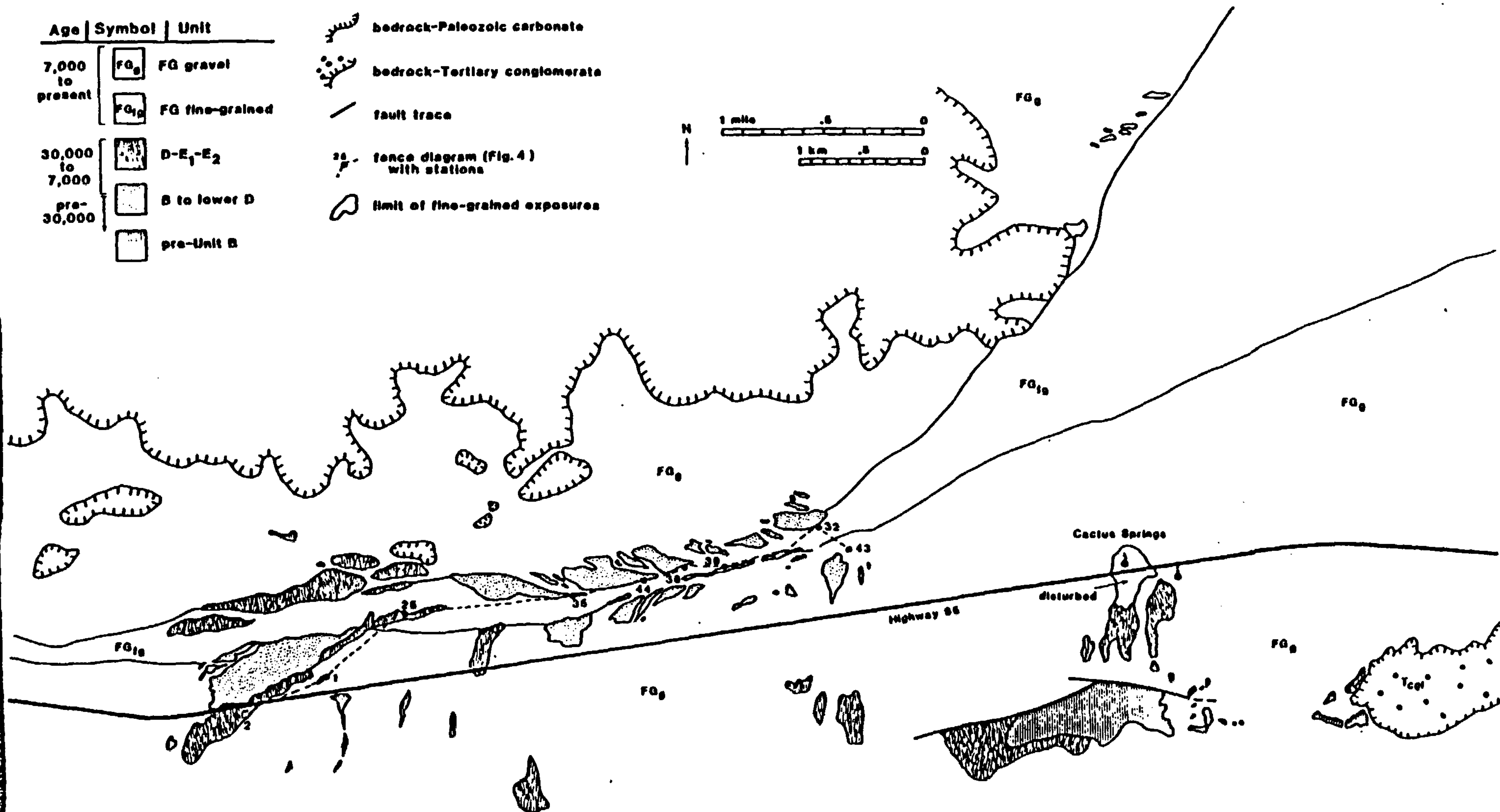
Pre-Unit B: Silt to clayey silt, pale brown (10 YR 7/2-7/3 dry); very hard, coarsely prismatic; local gravelly sand layers; several possible weak soils; strong MnO_2, FeO stains, secondary carbonate; dispersed terrestrial molluscs.

Fig. 3



meters
0
1000
3000
5000
20X vert. exagg.
W
E
Soil 5b
Unit E2
10
7b
9
Unit D-E
Soil S3
Unit B-C
13
14
17
16
2
1
25
35
44
38
39
42
43
1040
1020
1000
980
meters
silt
sand
clay
mollusc sample
gravel
secondary carbonate
soil
measured section #
2m
strat. column scale

Fig. 4



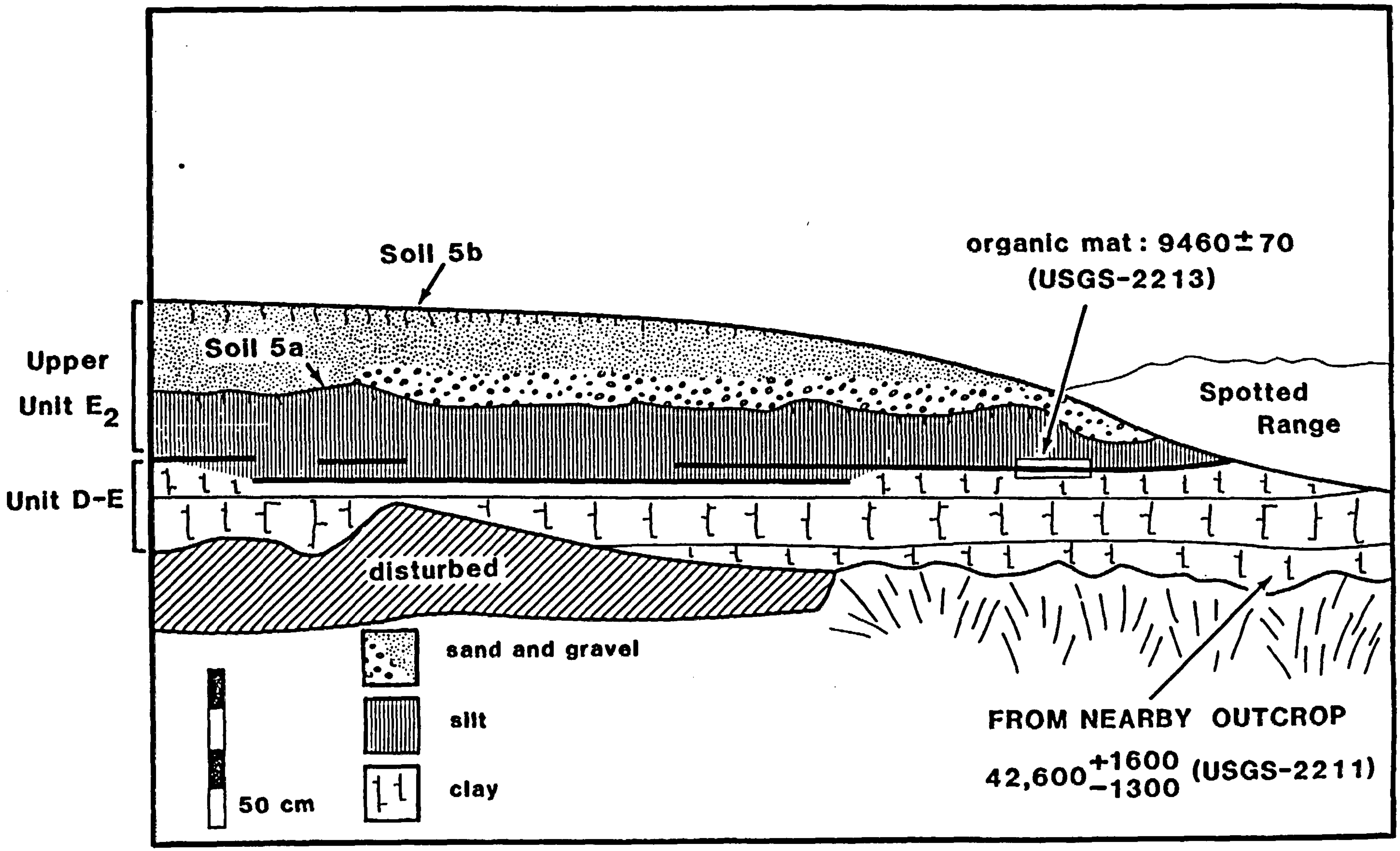
Age | Symbol | Unit
7,000 to present
FG gravel
FG fine-grained
30,000 to 7,000
D-E1-E2
pre-30,000
B to lower D
pre-Unit B
bedrock-Paleozoic carbonate
bedrock-Tertiary conglomerate
fault trace
fence diagram (Fig. 4) with stations
limit of fine-grained exposures
N
1 mile .5 0
1 km .5 0
Cactus Springs
disturbed
Highway 95

Fig. 5

Fig. 6 ----- Line drawing and photograph

photograph

line drawing



Soil 5b
organic mat : 9460±70
(USGS-2213)
Upper
Unit E2
Soil 5a
Spotted
Range
Unit D-E
disturbed
sand and gravel
silt
clay
50 cm
FROM NEARBY OUTCROP
42,600 +1600 −1300 (USGS-2211)

Fig. 6 Part 1

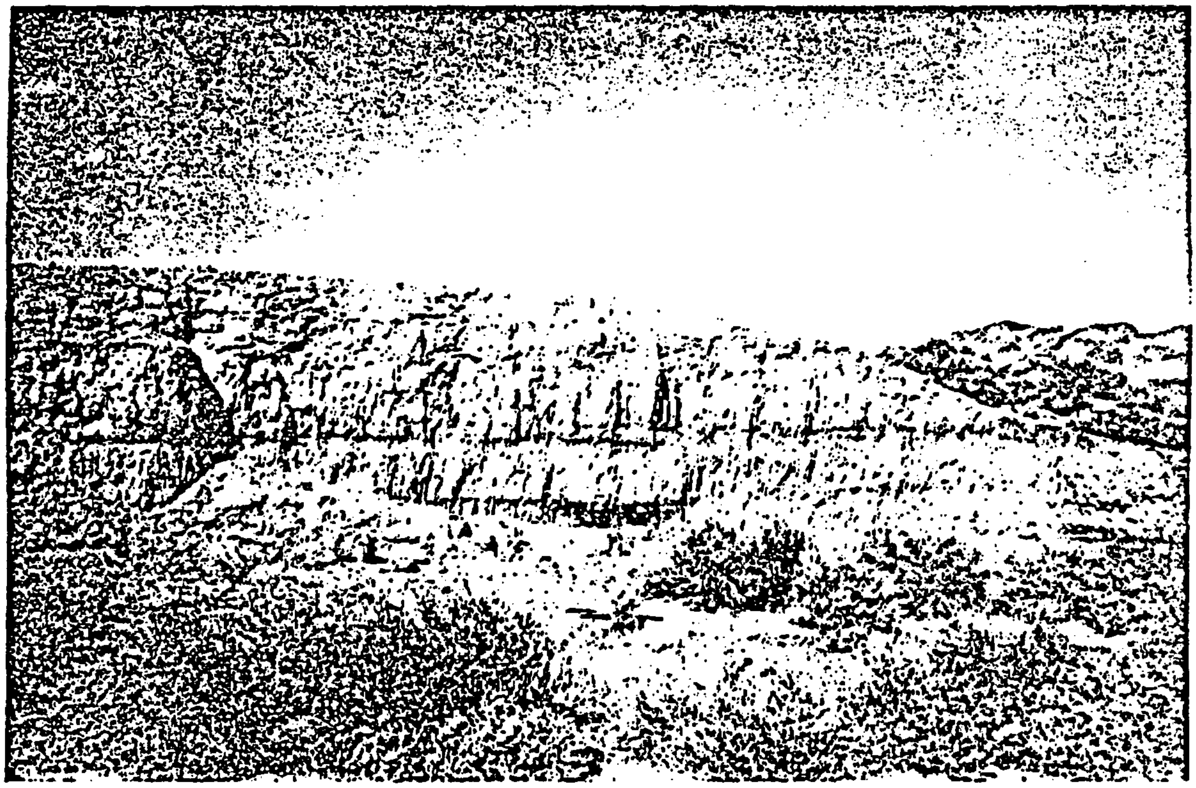


Fig. 6 Part 2

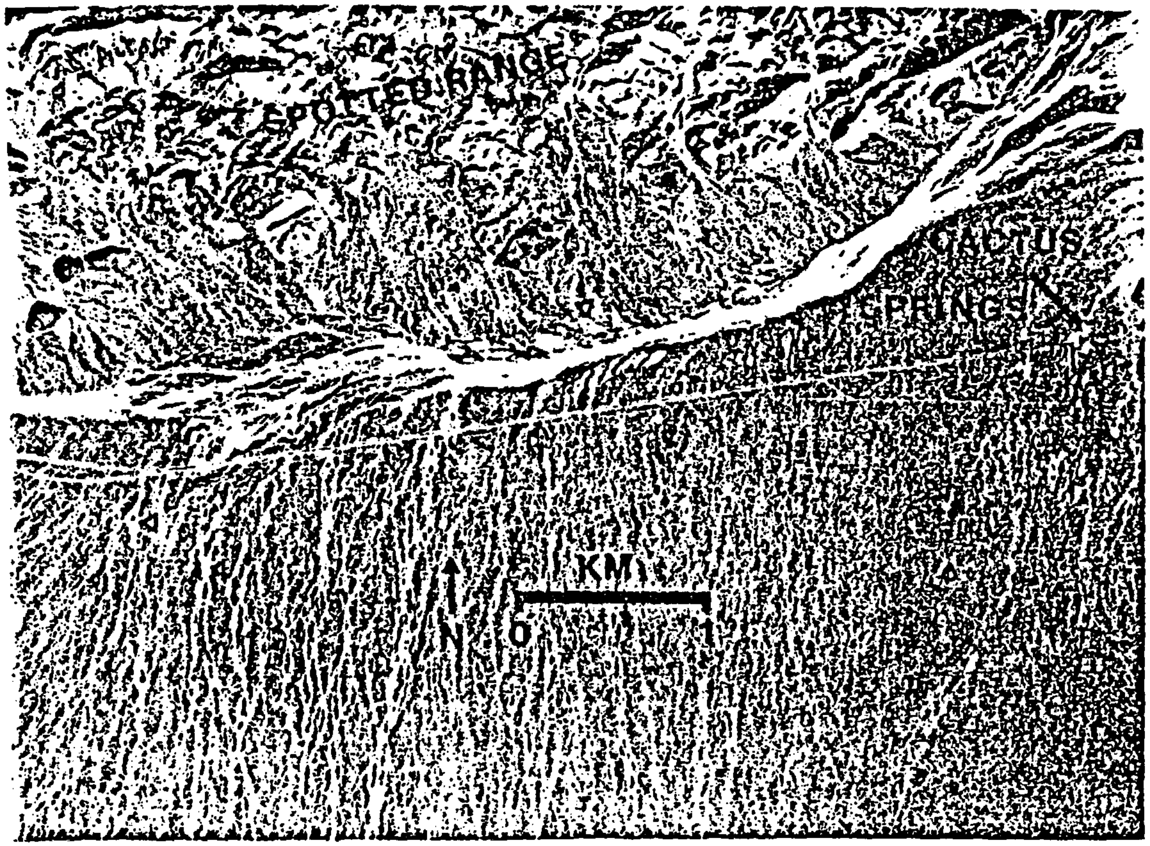


Fig. 7

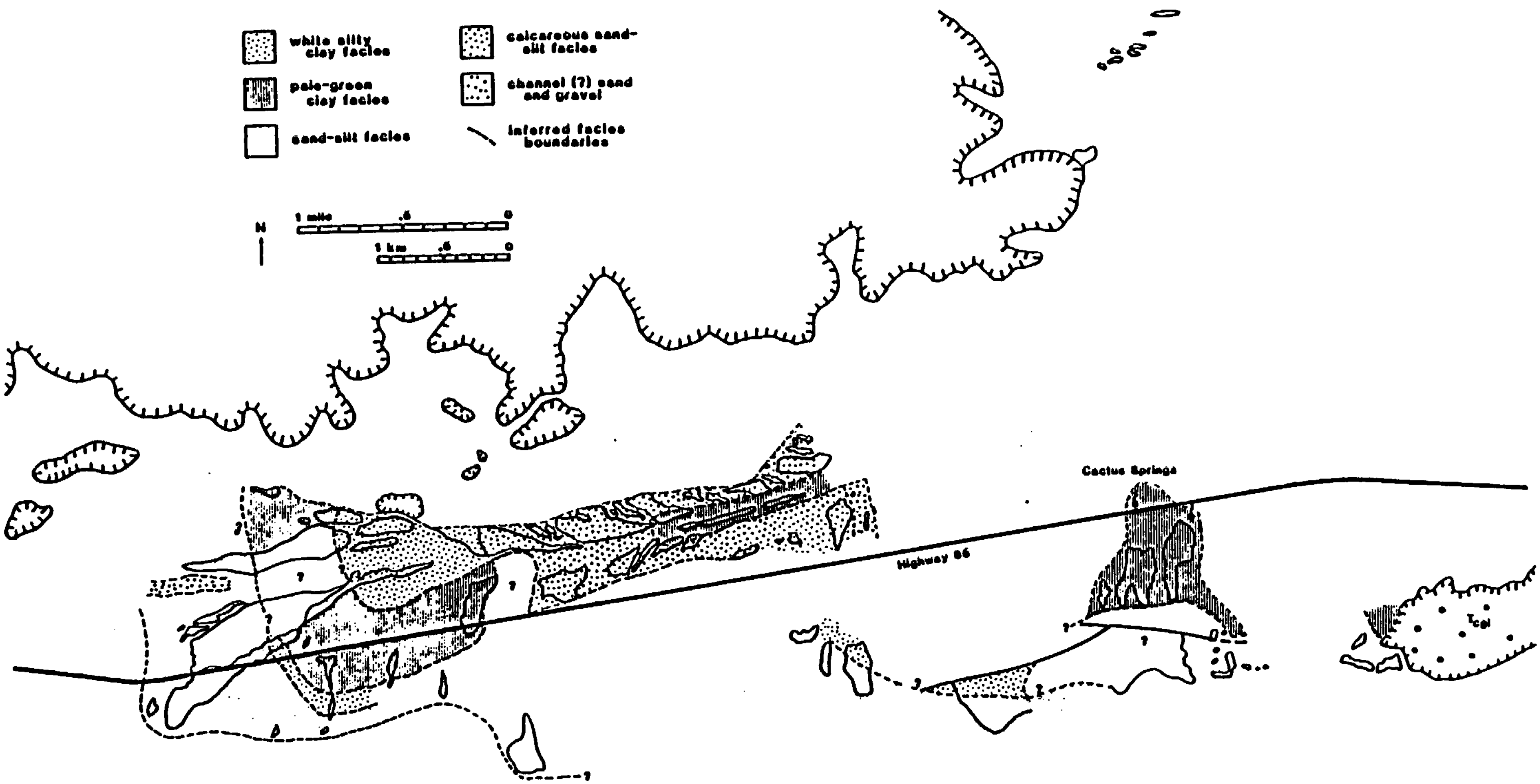

white silty clay facies
calcareous sand-silt facies
pale-green clay facies
channel (?) sand and gravel
sand-silt facies
inferred facies boundaries
N
1 mile .5 0
1 km .5 0
Cactus Springs
Highway 95
T_{cgl}

Fig. 6

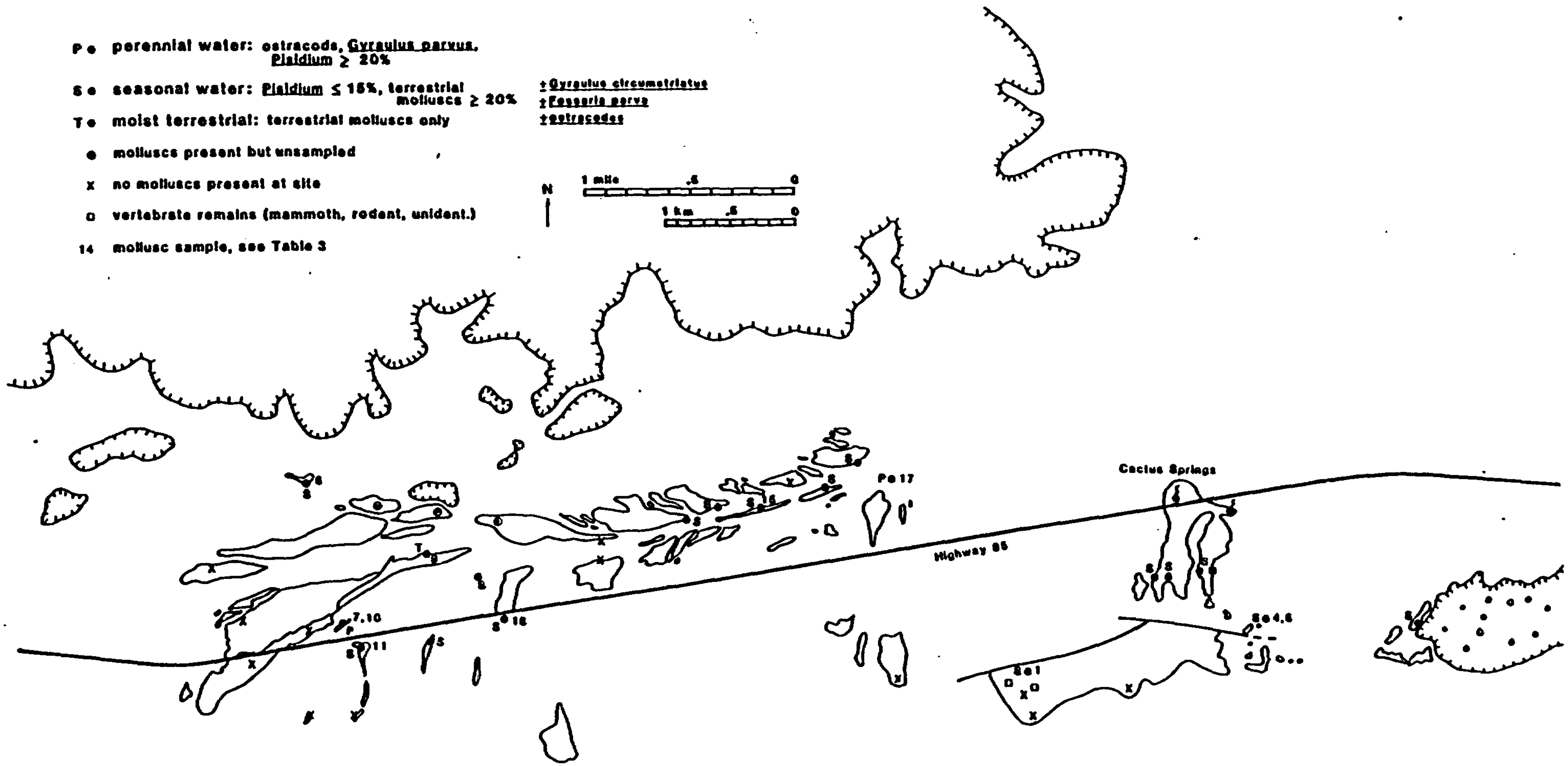
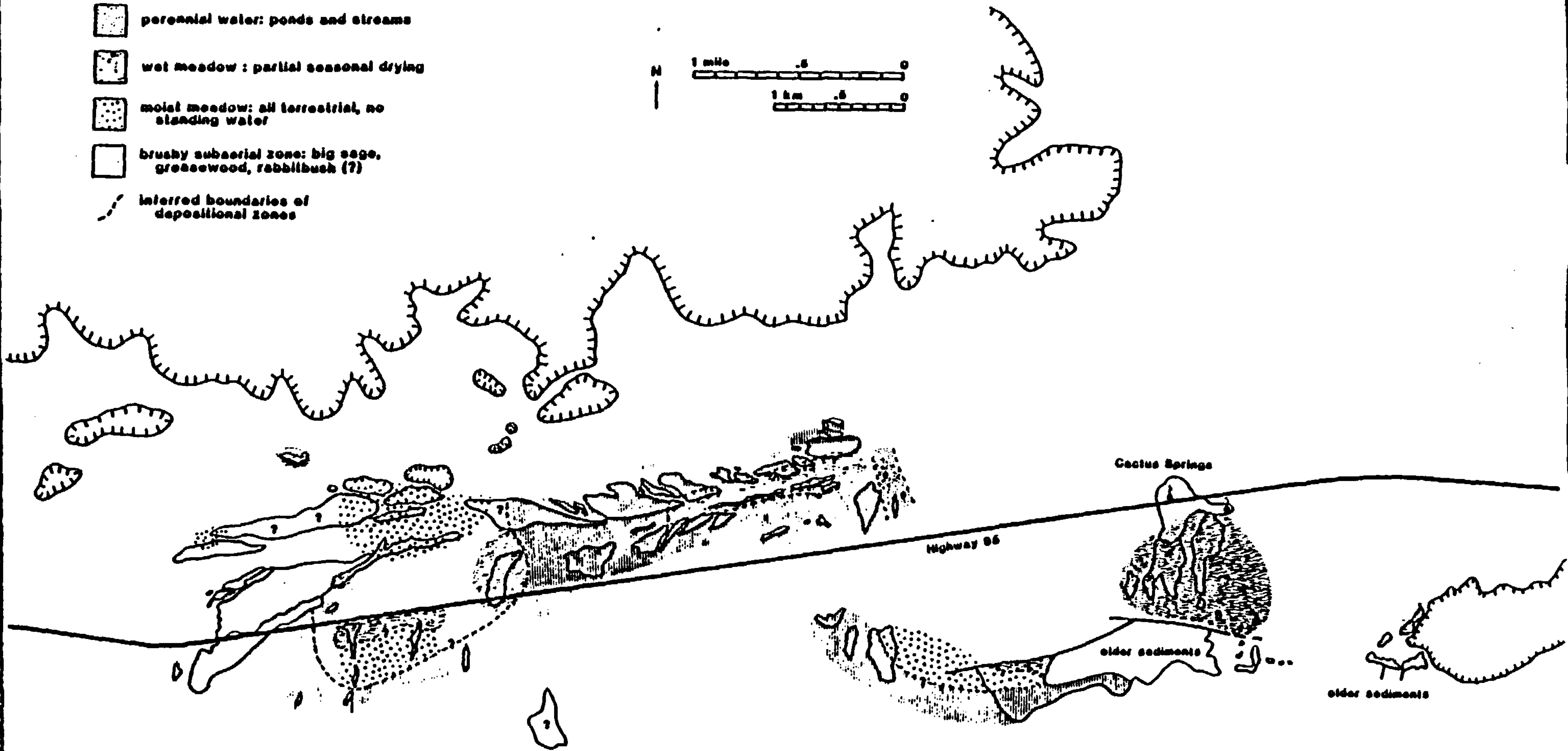

P ● perennial water: ostracods, Gyraulus parvus, Pisidium ≥ 20%
S ● seasonal water: Pisidium ≤ 15%, terrestrial molluscs ≥ 20%
T ● moist terrestrial: terrestrial molluscs only
● molluscs present but unsampled
x no molluscs present at site
o vertebrate remains (mammoth, rodent, unident.)
14 mollusc sample, see Table 3
± Gyraulus circumstriatus
± Fossaria parva
± ostracodes
N
1 mile .5 0
1 km .5 0
Cactus Springs
Highway 95
Pe 17
Se 1
Se 4,6
7,10
11
18

Fig.9



perennial water: ponds and streams
wet meadow : partial seasonal drying
moist meadow: all terrestrial, no standing water
brushy subaerial zone: big sage, greasewood, rabbitbush (?)
inferred boundaries of depositional zones
N
1 mile .5 0
1 km .5 0
Cactus Springs
Highway 95
older sediments
older sediments

Fig 2

Appendix B-VII

Systematic variations in del^{13}C and del^{18}O of soil carbonate along elevation transects in the southern Great Basin, USA by J. Quade and T. Cerling.

Systematic variations in $\delta^{13}C$ and $\delta^{18}O$ of soil carbonate along elevation transects in the southern Great Basin, USA

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ABSTRACT

Stable carbon and oxygen isotope variations in recent soil carbonates were examined along several elevation transects in the southern Great Basin, USA. Our intent was to study the relationship between the stable isotopic composition of soil carbonates and climate, ecological variations, differences in parent material, and soil depth. $\delta^{13}C$ varies by about 12 per mil over a 2440 meter elevation change, being enriched in ^{13}C at the lowest elevations. The slope of $\delta^{13}C$ versus elevation is very similar for soils developed on carbonate and on non-carbonate parent materials, being depleted by 4.6 per mil per 1000 meters increase in altitude between 300 to 2740 meters above mean sea level for the localities studied. This similarity indicates that little if any carbon in soil carbonates is inherited from the dissolution of limestone. $\delta^{18}O$ values are also higher at lower elevations, due in part to the more positive $\delta^{18}O$ values for meteoric waters at lower elevations.

$\delta^{13}C$ of soil carbonate decreases with soil depth, reflecting a decrease in the ratio of atmospheric to plant-derived CO_2 downprofile. $\delta^{18}O$ is heaviest shallow in the soil, probably due to evaporative enrichment.

INTRODUCTION

Pedogenic carbonate is an important component in many soils, yet relatively little is known about the systematics of its stable isotopic geochemistry. Although the isotopic composition of soil carbonate has been used to estimate the degree of recrystallization of carbonate in soils (e.g., Magaritz and Amiel, 1980, 1981; Amundson and Lund, 1987) and to study paleoclimatology and paleoecology (Margaritz *et al.*, 1981; Cerling, 1984; Schlesinger, 1985; Cerling and Hay, 1986), few systematic studies of isotopic variations in modern soils have been made.

It has been suggested previously that the isotopic composition of soil CO_2 is controlled by the proportion of surface plant biomass using the C-3 or C-4 photosynthetic pathway (Cerling, 1984), which have average organic carbon $\delta^{13}C$ values of about -27 per mil and -13 per mil, respectively (Deines, 1980; Cerling, 1984). Considerations of typical carbonate dissolution reactions show that inherited carbon from parent material is significant in the dissolution step of carbonates (Salomons, 1986):

$$CaCO_3 + CO_2 + H_2O = Ca^{++} + 2\,HCO_3^-$$

Because the rate of new soil carbonate accumulation is small (10^{-7} to 10^{-6} mole·cm^{-2}·yr^{-1}) compared to the CO_2 respired flux (10^{-3} to 10^{-5} mole·cm^{-2}·yr^{-1}), Cerling (1984) suggested that the isotopic composition of soil carbonate will be controlled by the isotopic composition of soil CO_2 and that the inherited carbon from any dissolved carbonates would be insignificant. In this paper we compare soil carbonates formed on parent materials approaching pure limestone with soil carbonates formed on a parent material with little to no detrital carbonate. Comparison of the carbon isotopic composition of soil carbonates formed from the two different parent materials should show if any carbon is inherited from the dissolution of detrital limestone clasts.

Soil carbonates were studied along elevation transects in the basin and range setting because it was expected that large changes in the $\delta^{13}C$ value of soil carbonates should occur over several thousand meters elevation change as a function of changes in the type of plant cover at various sites. At low elevations, the $\delta^{13}C$ values should be highest. This is because they are most likely to have a high proportion of C-4 biomass, since plant utilizing the C-4 photosynthetic pathway are adapted to conditions of high water stress. In addition, low elevation sites are likely to have lower net respiration rates than higher elevation sites. Therefore, low elevation sites are more likely to have a significant atmospheric component, which happens to have an isotopic value very similar to that expected for a pure C-4 biomass (+4 per mil and + 2 per mil for soil carbonate produced from a pure atmospheric and pure C-4 component, respectively, using the three component model of Cerling, 1984). For comparison, soil carbonate formed from a pure C-3 biomass with an insignificant atmospheric component should have a $\delta^{13}C$ value of about -12 per mil. This should allow us to assess the affect of inheritance of ^{13}C from the dissolution of carbonates. In addition, these transects allow us the study the $\delta^{18}O$ variations of soil carbonates as a function of altitude, since the $\delta^{18}O$ value for meteoric water is progressively depleted with increase in elevation (Dansgaard, 1964 ; Smith *et al*, 1979).

METHODS

The sites studied were from the Spring Mountains facing the Las Vegas Valley, Titus Canyon, and from the nearby Grapevine, Panamint, and Pine Valley Mountain Ranges, all in the southern Great Basin (Fig. 1). In order to insure that sampled soils were post-early Holocene in age, we selected terraces immediately adjacent to and therefore recently abandoned by active washes. Quade (1986) has shown that such terraces in the Las Vegas Valley are younger than 7000 B.P. We also confined ourselves to terrace settings because significant vegetation changes occur between the active channels and the nearby ridge tops, the latter being much drier with a more xeric vegetation.

We sampled seven sites in the Spring Mountains and in Titus Canyon (Fig. 1) where the parent material was composed almost entirely of limestone clasts. These sites varied from 300 to 2740 meters above mean sea level. For comparison with non-calcareous parent material, seven sites were selected in the Grapevine, Panamint, and Pine Valley Ranges. For the Grapevine and Pine Valley sites, Tertiary volcanic rocks entirely compose the alluvium; at the Panamint Range site, alluvium is dominated by non-calcareous metamorphic clasts (schists, phyllite and quartzite). In all soils, a small amount of carbonate could be present due to the deposition of aeolian dust, particularly in vesicular horizons found in soils at lower elevations in the region (McFadden et al., 1987).

We sampled two or three separate profiles at each site. All the samples used to construct the transects are from 50±10 cm depth, unless otherwise noted. We chose this depth since Cerling (1984) showed that significant variations in the isotopic composition of soil CO_2 are expected shallow in soil profiles. To examine this depth dependency, we sampled one profile in detail in which soil carbonate was present at all levels. All carbonates sampled show weak to mature Stage 1 morphology (Gile *et al*, 1966). Relatively pure encrustations of soil carbonate were scraped from alluvial clasts under a binocular microscope, taking care not to include any carbonate from the host clast itself, or from older carbonate cement.

Soil carbonates were baked under vacuum at 450 °C for one hour prior to reaction with 100% phosphoric acid. Results are reported in the δ (per mil) notation where:

$$\delta\,(\text{per mil}) = \left(\frac{R_{sample}}{R_{standard}} - 1\right) 1000$$

and R_{sample} and $R_{standard}$ refer to the $^{13}C/^{12}C$ or $^{18}O/^{16}O$ ratios in a sample or standard, respectively.

Climate varies considerably along these transects. For example, Las Vegas, Nevada, with an elevation of 640 m, has a mean annual temperature of 19.5°C and mean annual precipitation of 10 cm/yr. Based on temperature (0.54°C/100 m) and precipitation (12 mm/100m) lapse rates calculated by Barbour (?) for the Spring Range, the highest soil station on the transect has a mean annual temperature of 8.5°C and mean annual precipitation of about 33 cm /yr. Broadly, five vegetation zones are recognizable along these climatic gradients. They are: creosote-burrobush, blackbush, sage, pinyon-juniper-sage, and fir-pine. Vegetation lists were compiled at each locality in April, 1987 although additional observations were made in August, 1986, and January, 1987. Plant density and species diversity was measured along 60-meter long line transects.

RESULTS AND DISCUSSION

The $\delta^{13}C$ value for soil carbonates (Table 1) decreases systematically with elevation (Fig. 2) for soils formed on carbonate or non-carbonate parent materials. Both suites of samples decrease by 4.6 per mil per 1000 meters increase in elevation, although the best fit lines are offset by about 1.7 per mil. The $\delta^{13}C$ relationship to elevation for the two transects are:

$\delta^{13}C = 3.59 - 4.60\times10^{-3} \times Z$ for the carbonate transect ($r^2 = 0.93$)

$\delta^{13}C = 1.86 - 4.61\times10^{-3} \times Z$ for the non-carbonate transect ($r^2 = 0.86$)

where Z is the elevation above mean sea level in meters.

Inheritance of carbon from the dissolution step

The isotopic composition of soil CO_2, dissolved HCO_3^-, and newly precipitated soil carbonate are related by the fractionation factors between these species and the kinetics of exchange and precipitation. The CO_2 composition of soil gas can be described by diffusion equations that include a term for the production of CO_2 in soil (Kirkham and Powers, 1972). Cerling (1984) previously suggested that the isotopic composition of soil gas can be described by applying diffusion equations to account for $^{12}CO_2$ and $^{13}CO_2$ produced by soil respiration in the soil and mixing with atmospheric $^{12}CO_2$ and $^{13}CO_2$. That model estimated endmember soil carbonate in equilibrium with C-3, C-4, and the atmospheric components to be about -12, +2, and +4 per mil, respectively. Marine limestone has an isotopic composition of about 0 per mil. Thus, any inheritance of carbon derived from dissolution of marine limestone should result in a mixing line between the marine value and one of the other endmembers. The dissolution equation given above shows that half of the carbon in the dissolution step of carbonate is derived from pre-existing carbonate. Therefore, if total exchange with soil CO_2 does not occur, carbonates with very negative $\delta^{13}C$ values (high C-3 component) would be shifted more than those with a high $\delta^{13}C$ value (high C-4 or atmospheric component). The similarity of the slopes for soil carbonate formed in a carbonate-rich parent material compared to a non-carbonate parent material (Fig. 2) suggests that virtually no carbon is inherited by the newly precipitated soil carbonate. This implies virtually complete exchange of soil CO_2 with the soil solution containing dissolved HCO_3^- prior to soil carbonate precipitation.

Complete exchange with soil CO_2 means that the carbon isotopic composition of soil carbonates is related to the isotopic composition of soil CO_2, which in turn is related to the proportion of C-3 and C-4 biomass present as well as the total soil CO_2 respiration rate with resultant mixing of atmospheric CO_2 (see discussion below). This has important implications for ^{14}C studies of soil carbonate because it implies that no "dead" carbon appears to be inherited from the dissolution of limestone. The limitations of ^{14}C studies of soil carbonate are more likely to be with detrital contamination and sample size. Those problems will be greatly reduced by using very small sample sizes, which can be achieved by measuring ^{14}C with accelerator mass spectrometry.

Origin of the decrease in $\delta 13C$ of soil carbonate as a function of elevation

The precise $\delta^{13}C$ value of soil carbonate in the transects is also of interest. Modern vegetation in the region has a considerable fraction of C-4 biomass (Table 2). A higher abundance of C-4 plants is observed at lower elevations. However, the fraction of C-4 biomass in the modern vegetation is not sufficient to explain the high $\delta^{13}C$ values observed for soil carbonate. There are two possible explanations for this: 1] that the modern vegetation is not in isotopic equilibrium with the soil carbonate, and 2] that the soil carbonates have a significant atmospheric component due to low soil respiration rates. The first is very likely to be the case because considerable vegetation changes due to overgrazing are evident at the lower elevations. Overgrazing can select against desert C-4 plants, particularly shrubs like saltbush (*Atriplex canescens* and *A. confertifolia*). In grasslands, overgrazing often selects against C-4 grasses in particular (Madson, 1982). In addition, our survey of vegetation shows that numerous non-indigenous plants such as Brome grasses (*Bromus rubens*, *Bromus tectorum*), storksbill (?), and various mustards have invaded the area. This makes modern vegetation surveys of dubious value in estimating the proportion of C-4

prior to the impacts of livestock grazing which began in the late 1800s.

biomass for pre-settlement times. In any case, such surveys are further complicated because grasses and forbs are not woody and may be underrepresented by above ground plant surveys. Dorn and DeNiro (1985) and Dorn *et al* (1987) have shown that the most recent period of desert varnish formation in the lower elevations of the Mohave is dominated by C-4 organic material, although the modern vegetation is not dominantly C-4. This provides evidence that post-settlement vegetation changes have taken place in the region.

It is also possible that soil carbonates formed in these desert soils formed under conditions of very low soil respiration. Cerling (1984) showed that soil CO_2 at relatively low pCO_2 (lower than $10^{-2.5}$) has a significant atmospheric component. Low pCO_2 in soils occurs when the soil respiration rate is relatively low; in the Great Basin, such low respiration rates are to be expected even during the height of the growing season (e.g., Parker *et al*, 1983; Quade, unpublished data). Soil carbonate precipitated in isotopic equilibrium under such conditions will have a high atmospheric component, which would result in $\delta^{13}C$ values more positive than expected for CO_2 derived only from soil respiration.

We suspect that both causes contribute to the lack of correlation between the $\delta^{13}C$ value for soil carbonates and the fraction of C-4 biomass. It is certain that the modern vegetation differs from that present more than 150 years ago in the region, and it is likely that some C-4 plants have been selectively grazed out. Also, low CO_2 respiration rates of desert soils make it probable that significant CO_2 invasion from the atmosphere occurs. This causes an increase in the isotopic composition of soil CO_2 and the soil carbonate precipitated in isotopic equilibrium with it. It is thus possible that some of the trend observed in this study is due to a respiration gradient as well as a change in the isotopic composition of the soil respired CO_2 (and hence the fraction of C-4 biomass). Unfortunately, high proportions of C-4 plants and low soil CO_2 respiration rates both result in high $\delta^{13}C$ values for soil CO_2. Therefore, both of these processes, which are related to high moisture stress conditions, could result in higher $\delta^{13}C$ values for soil carbonates we have observed.

The slight offset observed between the two trends is probably due to a systematic shift in the vegetation and soil respiration that results from the suites of samples having different parent materials. Soils at the same elevation but developed on the two parent materials display slight systematic differences in soil texture, moisture, or nutrients.

Relationship between the oxygen isotopic composition of soil carbonate and elevation

changes?

The oxygen isotopic composition of soil carbonate decreases markedly with increasing elevation in both suites of samples (Fig. 3), although there is more scatter in the data than was observed for carbon. The relationship between $\delta^{18}O$ and elevation is:

does not decrease — δ changes $\delta^{18}O$!

$$\delta^{18}O = -3.78 - 3.4\times10^{-3} \times Z \qquad (r^2 = 0.74)$$

where Z is the elevation in meters. The relationship of meteoric water to elevation is complicated in the Great Basin and Mojave Desert region by rain shadow effects of the Sierra Nevada and other mountain ranges. However, Smith *et al.* (1979) have found that in the Mojave Desert and the adjacent Sierras the isotopic composition of δD decreases by 33 per mil/ 1000 m, which would be equivalent to a change of 4.3 per mil for $\delta^{18}O$ per 1000 m. This gradient is similar but not identical to that observed in this study.

$\delta^{18}O$ values for soil carbonate show more scatter (r^2=0.74) than for $\delta^{13}C$ (r^2=0.96 and 0.84). We suggest three possible explanations for this. First, in areas of high plant density where most water loss is through evapotranspiration it is possible that little isotopic enrichment of the soil water occurs. However, Allison *et al.* (1984) have shown that isotopic enrichment is large when bare soil is present. Thus, it is possible that soil water at our soil sites, which all have some bare ground (Table 2), have undergone isotopic enrichment with respect to oxygen as a result of evaporation. A second possible explanation is that $\delta^{18}O$ values for storms have been observed to vary substantially both individually and seasonally (Smith *et al.*, 1979; Jack Hess, 1987, pers. comm.). This isotopic heterogeneity might result in variable $\delta^{18}O$ values of soil carbonate such as we observe. Finally, because all of the sites studied are in or near active channels, it is possible ~~likely~~ that some of the water infiltrating at each site originally fell at a higher elevation where precipitation was isotopically lighter.

have you another table?

Isotopic gradients as a function of soil depth

Cerling (1984) modeled the variation of $\delta^{13}C$ of soil CO2 versus soil depth as a function of different soil respiration rates. As has been described, the

$\delta^{13}C$ of soil CO2 should reflect the admixture of two sources: atmospheric CO2 at the top of the profile, and increasing plant-derived CO2 with depth. Atmospheric CO2 is heavier (-7 per mil) than plant-derived CO2 (C-3 plants= -22 per mil and C-4 plants = -8 per mil). Therefore, the model predicted an exponential decrease with depth in the $\delta^{13}C$ of soil CO2, from -7 per mil at the surface to some lighter value more reflective of the C-4/C-3 plant ratio at the site. In turn, carbonate precipitated at the soil surface in equilibrium with atmospheric CO2 should average about +3 per mil, and should decrease with depth. The rate and extent of that decrease depends on (1) the soil respiration rate, and (2) the proportion of C-4 to C-3 plants at the site.

In order to test Cerling's model, we sampled soil carbonate with depth at one site on the Spring Mountain transect (Site SM-2, elevation 1550 m). $\delta^{13}C$ of soil carbonate does in fact decrease exponentially with depth (Fig.4). Carbonate from the first 5 cm of the profile averaged + 3.7 per mil, reflecting isotopic equilibrium with atmospheric CO_2 as predicted by Cerling (1984). Values decrease evenly with depth and appear to level off below 30 cm at about -7 per mil. As already discussed, this value may reflect a C-4 to C-3 plant proportion no longer present at the site due to overgrazing, or an admixture of atmospheric CO_2 with plant-derived CO_2 throughout the profile, or both. The depth dependency of $\delta^{13}C$ of soil carbonate suggests that values useful for intra-site comparison in ecologic reconstruction must be taken below 30 cm, as was done in this study.

$\delta^{18}O$ of soil carbonate also decreases systematically with depth (Fig. 5). We interprete this to be the result of evaporative enrichment of near surface soil solution. The lighter isotopic values evident with depth probably represent precipitation in equilibrium with larger, more deeply penetrating (and therefore less evaporated) rainfall/runoff events. If true, the values below 30 cm should be most representative of the average annual $\delta^{18}O$ compostion of rainfall at the site. We conclude that depth dependency should be kept in mind when interpreting the ecological meaning of both the $\delta^{13}C$ and $\delta^{18}O$ composition of soil carbonate.

CONCLUSIONS

Measurements of the carbon and oxygen isotopic composition of post early-Holocene soil carbonates from the Great Basin and Mojave Desert show a strong dependence on elevation. Comparison of the carbon isotopic composition of soil carbonates on carbonate and non-carbonate parent materials suggest that virtually no carbon is inherited from the parent carbonate. This suggests that complete isotopic exchange of soil CO_2 with the dissolved bicarbonate in the soil solution occurs prior to soil carbonate formation. This in turn implies that the carbon isotopic composition of soil carbonates is directly related to the isotopic composition of soil CO_2, which itself is controlled by the fraction of C-3 and C-4 biomass present and soil CO_2 respiration rates. If this isotopic signal is preserved in paleosol carbonates, the $\delta^{13}C$ value of paleosol carbonates could prove to be a valuable tool in paleoecologic studies. Furthermore, complete exchange means that ^{14}C dates on soil carbonate should reflect true ages of carbonate precipitation, assuming that only short intervals are sampled, and that there is no detrital contamination present.

Comparison of the $\delta^{13}C$ value of soil carbonates in this study with that expected from the observed modern vegetation implies that major ecologic changes have recently taken place as a result of post-settlement grazing and related activities. Many of the observed species present at lower elevations are not native to the region, and we have reason to expect that C-4 plants are selected against by grazing. It is also probable that there is a significant amount of invasion of atmospheric CO_2 by diffusion resulting from low soil CO_2 respiration rates. The latter is not unexpected since mathematical modeling of the isotopic composition of soil CO_2 shows that atmospheric invasion is likely at low soil CO_2 respiration rates (Cerling, 1984).

$\delta^{18}O$ shows a systematic decrease in the soil carbonates with increasing elevation. This results from the changes in the average annual isotopic composition of meteoric water with elevation. Within-site variability in $\delta^{18}O$ may be due to differential evaporation of soil water, to short-term isotopic variation in rainfall, or to runoff from higher elevation sites. Preservation of the oxygen isotopic value in paleosol carbonates may make them a useful paleoenvironmental indicator, as well.

Finally, the strong depth dependency of both the $\delta^{13}C$ and $\delta^{18}O$ composition of soil carbonate must be kept in mind in interpreting the ecological implications of isotope results.

ACKNOWLEDGEMENTS

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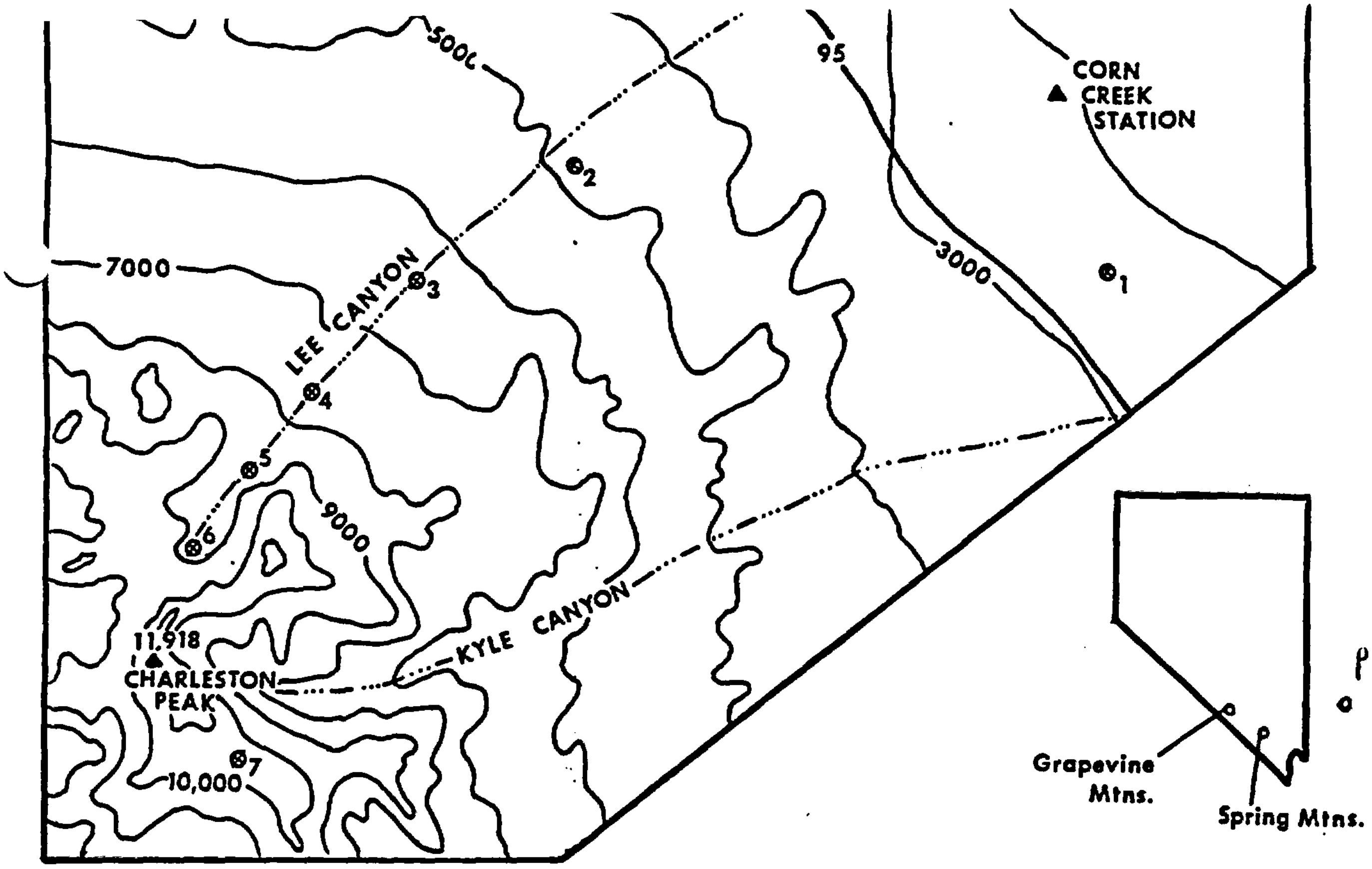


Pine Mts

⊗ = sample sites

0 5 10 miles

C.I. = 1000'

Figure 1a. Map of the Spring Mountains showing soil sample sites

Also need Pine Mt. site location map.

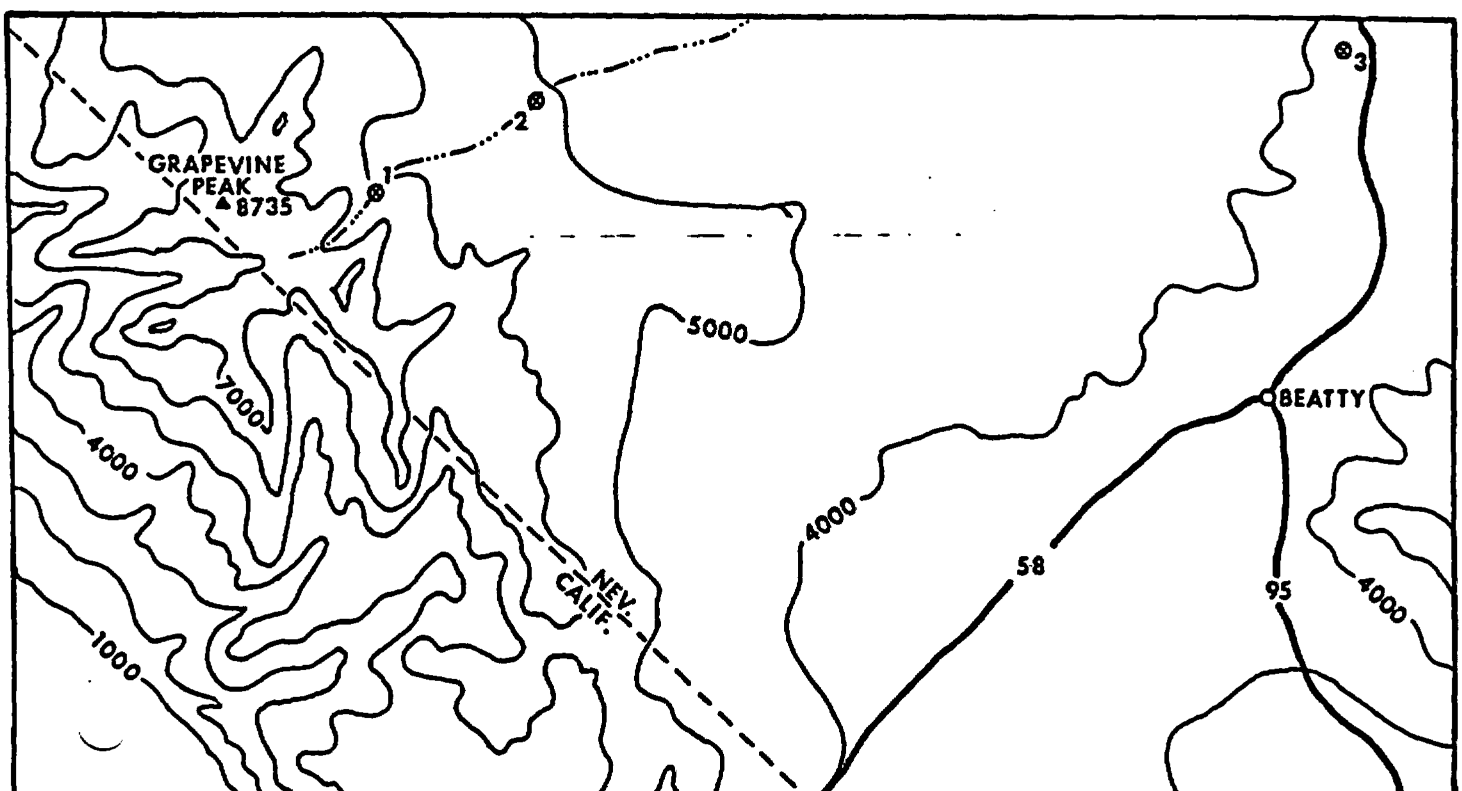


Figure 1b. Map of the Grapevine Mountains showing soil sample sites.

Figure ~~1~~ 2

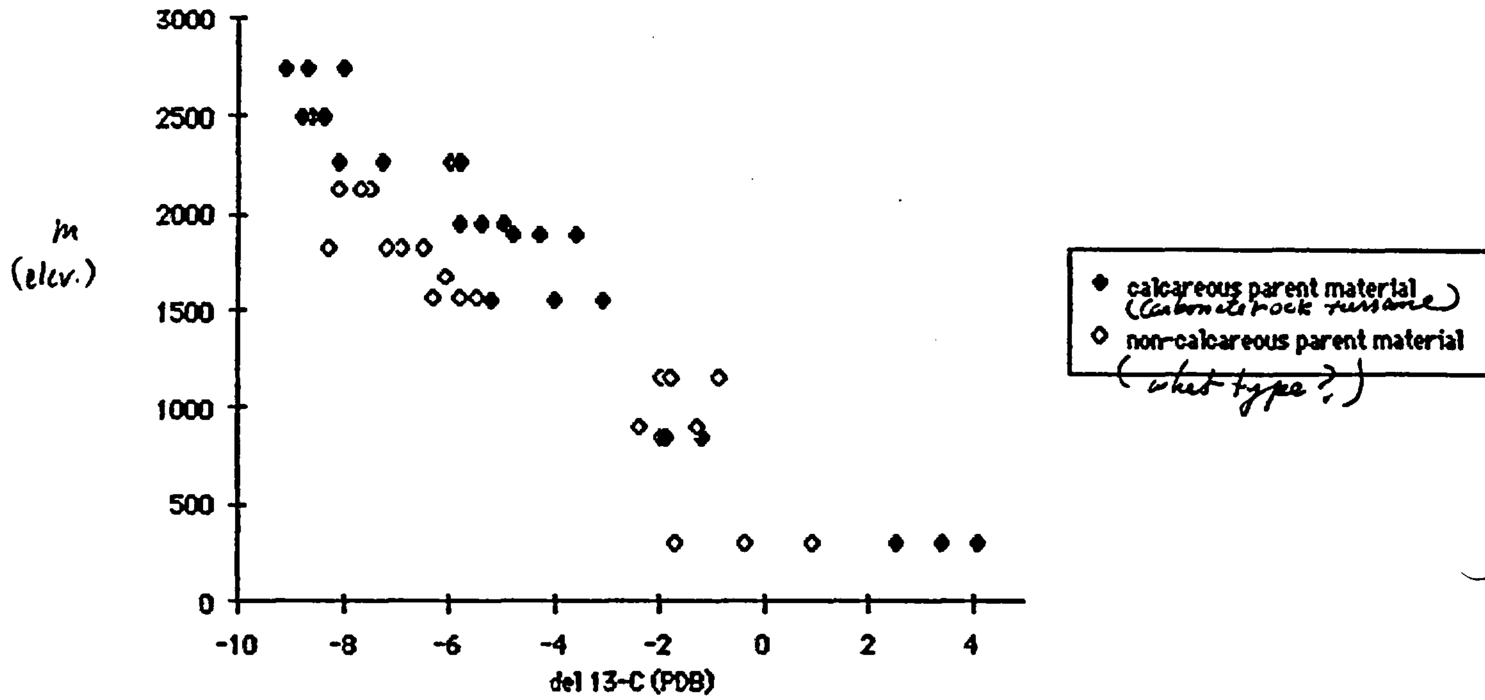
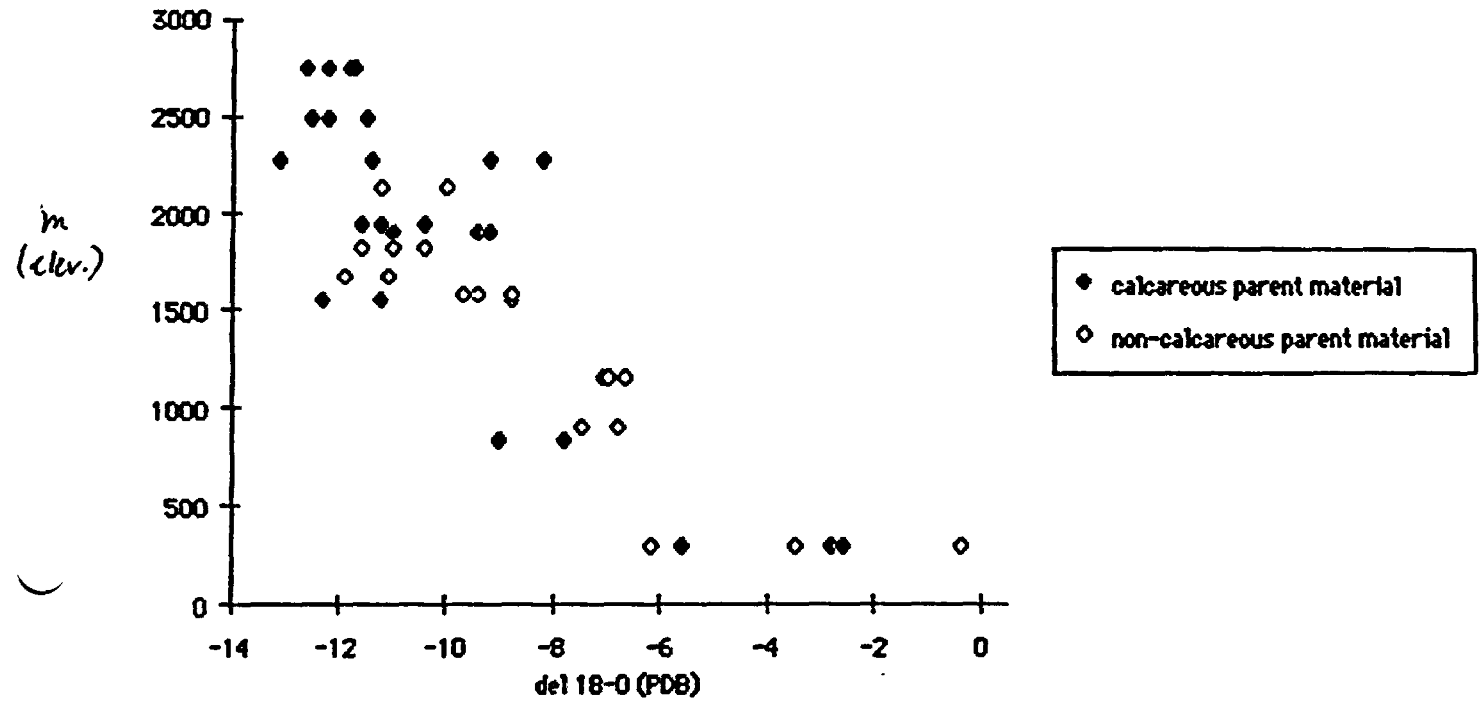

m
(elev.)
3000
2500
2000
1500
1000
500
0
-10
-8
-6
-4
-2
0
2
4
del 13-C (PDB)
calcareous parent material
(Carbonate rock terrane)
non-calcareous parent material
(what type?)

Figure 3



m
(elev.)
3000
2500
2000
1500
1000
500
0
-14
-12
-10
-8
-6
-4
-2
0
del 18-O (PDB)
calcareous parent material
non-calcareous parent material

Fig. 4

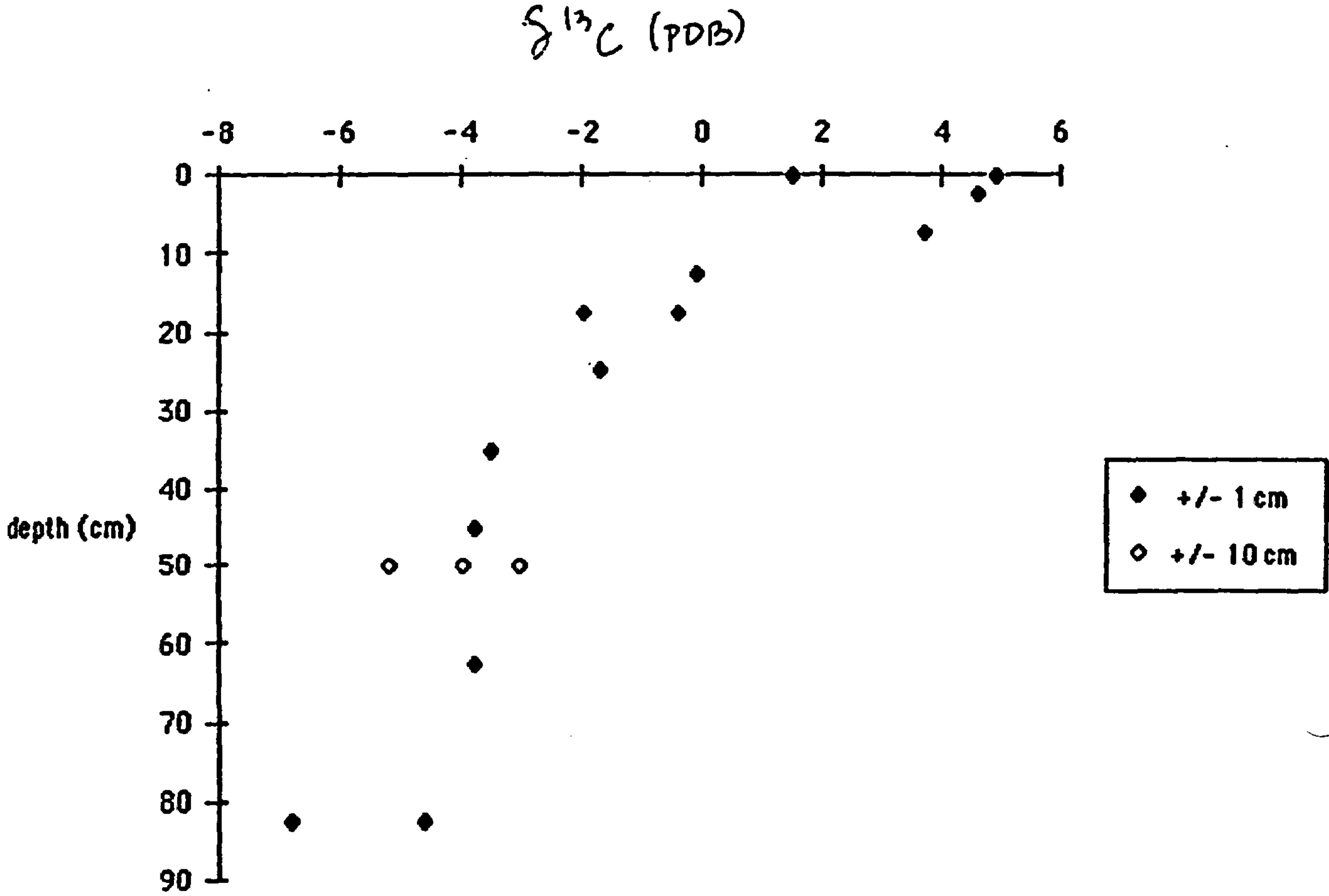
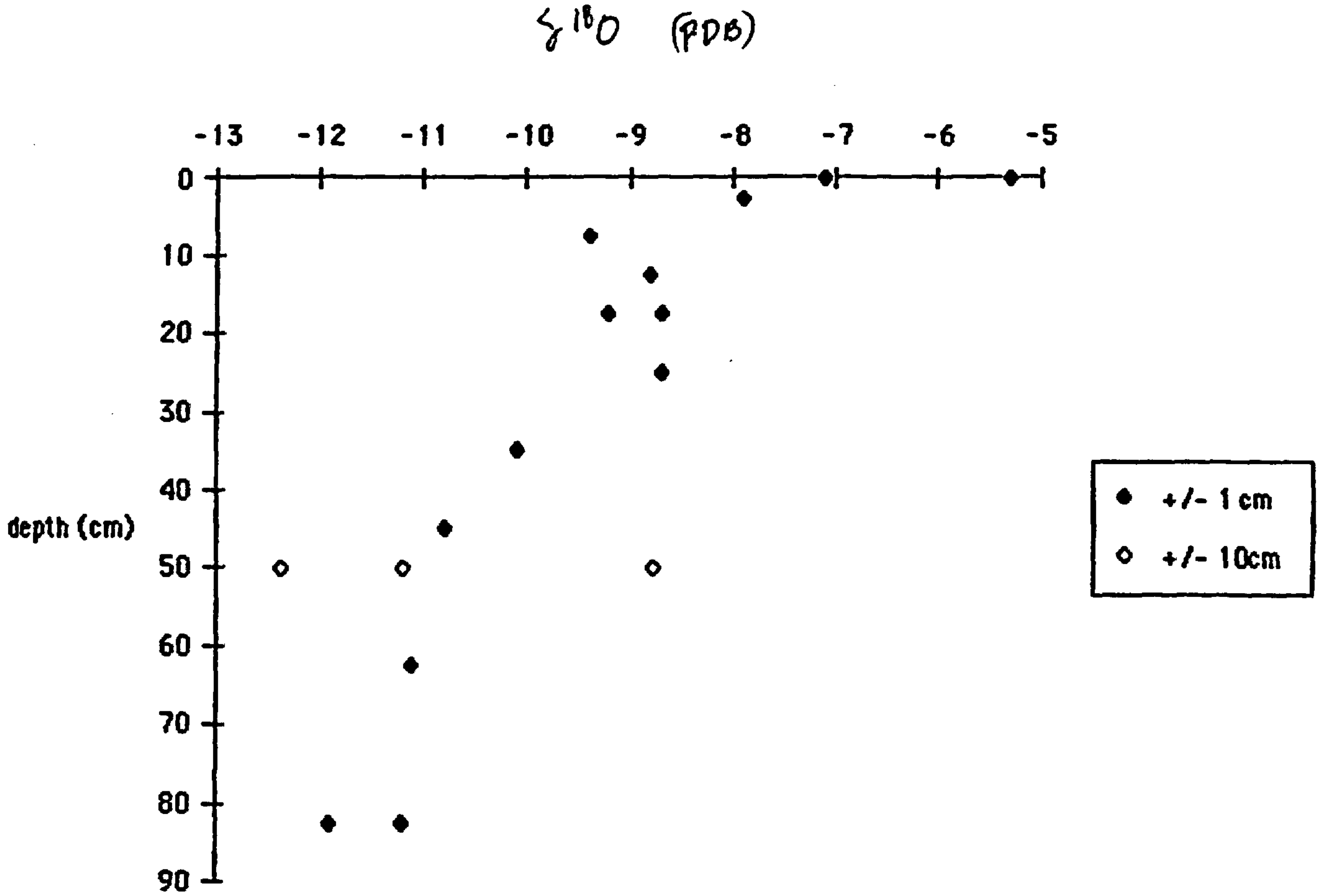


Fig. 5



δ18O (PDB)
-13
-12
-11
-10
-9
-8
-7
-6
-5
depth (cm)
0
10
20
30
40
50
60
70
80
90
+/- 1 cm
+/- 10cm

Table 1 Isotopic data from southern Great Basin soil sites

sample no.	elevation (m)	del 13-C (PDB)	del 18-O (PDB)
SM-1a	840	-2	-9
SM-1b	840	-1.9	-7.8
SM-1c	840	-1.2	-7.8
SM-2b	1550	-3.1	-8.8
SM-2b	1550	-4	-11.2
SM-2c	1550	-5.2	-12.3
SM-3a	1950	-5.4	-11.2
SM-3b	1950	-5	-11.6
SM-3c	1950	-5.8	-10.4
SM-3(B)a	1900	-4.3	-11
SM-3(B)b	1900	-3.6	-9.4
SM-3(B)c	1900	-4.8	-9.2
SM-4a	2270	-8.1	-13.1
SM-4b	2270	-6	-8.2
SM-4c	2270	-5.8	-9.2
SM-4d	2270	-7.3	-11.4
SM-5a	2490	-8.62	-12.2
SM-5b	2490	-8.4	-12.2
SM-5b-rerun	2490	-8.4	-12.5
SM-5c	2490	-8.8	-11.5
SM-6a	2740	-9.11	-12.2
SM-6b-1	2740	-8.08	-11.8
SM-6b--2	2740	-8.7	-12.6
SM-6c	2740	-8	-11.7
TC-1a	300	3.4	-2.8
TC-1b	300	4.1	-2.6
TC-1c	300	2.5	-5.6
GM-1a	1830	-8.3	-11
GM-1a--1m	1830	-6.9	-11.6
GM-1c	1830	-6.5	-10.4
GM-1d	1830	-7.2	-11
GM-2a-90 cm	1575	-6.3	-9.4
GM-2b	1575	-5.8	-8.8
GM-2c	1575	-5.5	-9.7
GM-3a	1160	-2	-6.7
GM-3b	1160	-0.9	-7.1
GM-3c	1160	-1.8	-7
GM-4a	900	-2.4	-6.8
GM-4b	900	-1.3	-7.5
PaM-1a	300	-1.7	-0.4
PaM-1b	300	-0.4	-3.5
PaM-1c	300	0.9	-6.2
PiVM-1a	1675	-6.1	-11.1
PiVM-1d	1675	-6.1	-11.9
PiVM-2a	2130	-8.1	-11.2
PiVM-2b	2130	-7.5	-10
PiVM-2c	2130	-7.7	-11.2

Table 1 Isotopic data from southern Great Basin soil sites

profile	depth (cm)	del 13-C (PDB)	del 18-0 (PDB)
SM-2p(surf. 1)	0	1.5	-7.1
SM-2p(surf. 2)	0	4.9	-5.3
SM-2p(0-5a)	2.5	4.6	-7.9
SM-2p(5-10a)	7.5	3.7	-9.4
SM-2p(10-15a)	12.5	-0.1	-8.8
SM-2p(15-20a)	17.5	-2	-9.2
SM-2p(15-20b)	17.5	-0.4	-8.7
SM-2p(20-30a)	25	-1.7	-8.7
SM-2p(30-40a)	35	-3.5	-10.1
SM-2p(40-50a)	45	-3.8	-10.8
SM-2p(50-75a)	62.5	-3.8	-11.1
SM-2p(75-100a)	82.5	-4.6	-11.9
SM-2p(75-100b)	82.5	-6.8	-11.2

Note: Sample numbers indicate locations as follows:

SM = Spring Mountains
GM = Grapevine Mountains
PaM = Panamint Mountains
PiVM= Pine Valley Mountains
TC= Titus Canyon

Two to three carbonate samples were collected from separate profiles at each transect site; individual profiles are denoted by a letter in the sample number designations (e.g. profile 'a', 'b', etc.). All samples come from 50 cm +/- 10 cm depth unless otherwise designated in the sample number. Small letters in profile sample numbers denote individual pebbles from a given depth interval.

Appendix B-VIII

Paleohydrology and Paleoclimate of the Yucca Mountain Area by W. G. Spaulding.

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QUATERNARY RESEARCH CENTER
LABORATORY OF ARID LANDS PALEOECOLOGY
SEATTLE, WASHINGTON 98195

ANNUAL REPORT TO: Mifflin and Associates
Suite B-13, 2700 E. Sunset
Las Vegas, NV 89120

DATE: 6 JANUARY, 1988

SUBJECT: Paleohydrology and Paleoclimates of The Yucca Mountain Area

FOR PERIOD: June, 1987 though December, 1987

SUBMITTED BY: W. Geoffrey Spaulding
Quaternary Research Center &
Department of Botany
University of Washington

Note: This is a description of research in progress and does not constitute an actual report of research results.

Endorsement: W. G. Spaulding Date: 6 January, 1988

RESULTS TO DATE

Research is focussed on the plant macrofossil and pollen records from three localities in southern Nevada: Fortymile Canyon Locality D, Sandy Valley, and Double Canyon. The first and last are located near major drainages that are now ephemeral, but that might have had a perennial water flow during the last pluvial episode(s). The Sandy Valley locality is near paleospring deposits that are evidence of former increased discharge, presumably during former plúvials. Thus, the research questions addressed are slightly different for the paleoecological records from the two canyon localities. In their case, it is necessary to prove that there was ever perennial water in those channels. Of course, the absence of such evidence would not mean that they were dry, but positive evidence is required to demonstrate that perennially wet conditions actually existed. For all three localities, paleoecological research is designed to test for the former extent of phreatophytic habitat through the plant macrofossil and pollen records. Important data are also gained on general paleoenvironmental conditions that can be compared to prior paleoclimatic reconstructions for the Candidate Area.

Table 1 presents a summary of the midden sites located and selected for study, and Table 2 provide a list of samples selected for detailed analyses. In Table 1, "distance from target habitat" refers to the distance from the midden site to the edge of the main course of Fortymile or Double Canyons in the case of those two localities, and to the closest evident paleospring deposit in the case of the Sandy Valley locality. These values are important in that the foraging range assigned by most workers to the packrat (*Neotoma* spp.) is 30 m, although values of 50 m and 100 m have also been used. In several cases, macrofossils of phreatophytes have been recovered from sites that are at least 100 m from the target habitat. For example, at the Fortymile Canyon-7 site the edge of the wash is ca. 110 m distant, at the bottom of a steep 70 m slope.

The macrofossils of wet-soil plants in this assemblage indicate that the packrats were either exceeding their nominal foraging range by a considerable amount, or phreatophyte habitat was more widely distributed and(or) closer to the site. The final pollen data will provide information on which case may apply to these sites. They are not discussed in detail here because, unlike the presence-absence data provided by macrofossils, interpretation of pollen data relies on relative percentages and comparisons with modern pollen samples, and such subjective interpretations should not be hazarded until the data are final.

Fortymile Canyon Locality D

The first three packrat midden localities studied in this drainage system were sites developed in Quaternary alluvium in the lower reaches of Fortymile Canyon (950 to 1100 m). All yielded middens of late Holocene age (<1900 yr B.P.), and provided no records of phreatophytic plant taxa. However, substantial retreat of the upper limit of creosote bush occurred as a result of more mesic climatic episodes during the late Holocene, and an increase in flood frequency has been inferred from the remains of disturbance adapted species where they do not occur today (Spaulding, 1987a, b).

A different set of macrofossil records has been obtained from the higher elevation (1250 to 1310 m) sites of Fortymile Canyon locality D. At this elevation the course of the canyon is more constricted as bedrock walls confine its course. The slopes of Tertiary volcanic rocks weather in such a fashion as to afford numerous rock shelters and cavities. Middens in these cavities evidently persist for millennia longer than those in the Quaternary alluvium of localities A through C. Some assemblages (FMC-8A, FMC-11) provide vegetational records of glacial-age woodland or woodland-steppe mosaic characterized by the abundant pollen and macrofossils of sagebrush (Artemisia subgen. tridentatae), curl-leaf mountain mahogany (Cercocarpus ledifolius), and Utah juniper (Juniperus osteosperma)(Table 3). This is the vegetational context of the white fir record (see discussion of phreatophyte occurrences, below), and appears to be the paleovegetation zone below the subalpine-steppe vegetation type recorded at the Eleana Range-2 site (1810 m elevation). At the ER-2 site vegetation was dominated by limber pine, mountain mahogany, and steppe shrubs from at least 17,100 to 13,200 yr B.P. Steppe shrubs and mountain mahogany persist at these lower-elevation Fortymile Canyon sites, but limber pine has given way to Utah juniper. Other assemblages provide probable latest-glacial or early Holocene records of woodland in which mountain mahogany is not recorded and prickly-pear cactus (Opuntia cf. polyacantha) is abundant, sagebrush is much reduced, and pinyon pine (Pinus monophylla) is more common (FMC-7(1); FMC-10). This is similar to the pinyon-juniper-cactus assemblages dated to 11,700 and 10,600 yr B.P. at the Eleana Range-2 site (Spaulding et al., 1984), and is the paleovegetational context of the wild-rose and knotweed occurrences (see discussion of phreatophyte occurrences, below).

Sandy Valley

Middens from the low inselbergs adjacent to paleospring and wet-meadow deposits in Sandy Valley are of general paleoenvironmental interest because the sites were evidently below the lower limit of glacial-age woodland. Desert scrub is recorded by the Sandy Valley assemblages, albeit a different type of desert scrub than that which occupies the sites today. The warm-temperate species that currently dominate the sites are absent. Instead, the vegetation was characterized by a combination of Great Basin shrubs (Chrysothamnus nauseosus, Atriplex confertifolia) and more mesophytic northern Mojave taxa (Buddleja utahensis, Ephedra spp., *Lycium* sp., *Lepidium montanum*-type) (Table 4). This is the vegetational context of the net-leaf hackberry record (see discussion of phreatophyte occurrences, below) and can be compared to the Pleistocene-age desertscrub records from higher elevations in the Amargosa Desert (Spaulding, 1983, 1987a, b). There had been some apparent vegetation change before the deposition of SaV-3(1), the midden deposit containing the remains of mesquite (*Prosopis juliflora*; Table 4; see discussion of phreatophyte occurrences, below). The most mesic upland taxa (e.g. *Symphoricarpos*), are not recorded in this assemblage and thermophiles appear, including rock-nettle (*Eucnide urens*) and tidestromia (*Tidestromia oblongifolia*). The inferred younger age for this assemblage is being tested by radiocarbon dating, but is consistent with the presence of mesquite. Today mesquite reaches its northern limit in the Candidate Area, and it would not be expected during times when winter minimum temperatures were appreciably lower (>1.5°C) than those of today. Its presumed immigration into the region during the latest glacial or early Holocene can provide important paleoclimatic information on minimum temperatures, as well as on the presence of artesian water.

Double Canyon

The Double Canyon midden records more closely resemble the paleovegetation records from the lower Grand Canyon (Phillips, 1977; Mead and Phillips, 1981) than they do those from the Nevada Test Site area. Key taxa that are rare or absent from the glacial-age vegetational records of the Sheep Range and areas northwest include Whipple cholla (*Opuntia whipplei*) and single-leaf ash (*Fraxinus anomala*)(Table 5), species well-represented in the lower Grand Canyon fossil record. This suggests an appreciable east-west gradient of effective moisture during the last pluvial episode(s), perhaps greater than that of today.

PHREATOPHYTIC SPECIES ENCOUNTERED TO DATE AS MACROFOSSILS

Wild rose (Rosa woodsii); thorned twigs, seeds. Recovered from both Wisconsin-age assemblages from Fortymile Canyon-7, the habitat of the species as described by Beatley (1976, p. 251) is "in seepage areas or usually in washes below springs." This characterization is consistent with field observations of this author...wild rose is a facultative phreatophyte and, in the Great Basin climatic regime, it is restricted to perennially wet areas. It was likely growing at the foot of the cliff below the site, on the margins of Fortymile Canyon Wash. The present distance to the edge of the wash from the site is estimated at 110 m. It is unlikely that wild rose was growing on the exposed slopes any closer to the site

White fir (Abies concolor); a single needle. Recovered from the Wisconsin-age Fortymile Canyon-11A(1) assemblage. A possible product of long-distance transport from elsewhere in the vicinity. A single needle is not sufficient evidence that the tree was growing at the site. Eolian transport of pine needles has been observed to carry them as much as 500 m from the nearest tree in the Toquima Range of central Nevada (author's field notes, vol. 11). However, at such a low elevation (1310 m), this montane tree was probably a phreatophyte wherever it occurred in this area. At present its lower limit in a mesic canyon in the Sheep Range is ca. 2070 m elevation; the lowest Wisconsin-age record prior to this find is from a midden in the Sheep Range, at 1570 m elevation. This was also in mesic setting, but in a smaller canyon (the Willow Wash locality; Spaulding, 1981). White fir was not recovered from any of the Eleana Range midden samples; although the ER sites are at a higher elevation (1810 m), they occupy a xeric south slope, and white fir was not detected in the stadial-age limber pine-steppe shrub assemblages (ER-2), or in the interstadial-age woodland assemblages (ER-3; Spaulding et al., 1984; Spaulding, 1985). As such, this is a new and paleoclimatologically significant record for the Yucca Mountain area. Assuming its water requirements were met, its occurrence at this elevational range would have been limited by summer temperature only. This makes certain calculations of summer temperature decline possible (Table 6).

Knot-weed (Polygonum lapathifolium-type);seeds. Recovered from the Wisconsin-age Fortymile Canyon-7(1) assemblage. Only one Polygonum species (P. douglasii) is recorded as being native to the Nevada Test Site area (Beatley, 1976), and its seeds are shaped differently from those of this fossil taxon. These are lenticular and without angles, and their morphology conforms with taxa such as P. pennsylvanicum and P. lapathifolium. This taxonomic assignment is significant because P. douglasii may grow in mesic settings away from water, while those taxa included in P. lapathifolium-type occupy the moist, disturbed soils of wet meadows and stream-sides (Munz, 1968). Like wild-rose, it was likely growing below the site,on the margins of Fortymile Canyon Wash.

Mesquite (Prosopis juliflora): pod fragments and leaflets. Recovered from the latest Wisconsin or early Holocene-age Sandy Valley-3(1) assemblage. The presence of both leaflets and seeds indicates that the species may have been growing within 30 m of the site. In the Candidate Area today it occurs only on perennially moist ground, or in dunes along fault lineaments where it is probably also reliant on artesian water (Quade, pers. comm., 1987)

Net-leaf hackberry (Celtis reticulata): a single seed. Recovered from the Wisconsin-age Sandy Valley 2(3)3 assemblage. The remains of hackberry are rare in the southern Great Basin macrofossil record. The tree is an obligate phreatophye throughout its range in the Great Basin and adjacent areas (Benson and Darrow, 1981). Even in an area such as the Grand Canyon, which receives more average annual and summer precipitation than does the Candidate Area, net-leaf hackberry is restricted to perennially moist sites (Phillips et al., 1987). Like the white fir needle discussed above, this macrofossil represents probable long-distance transport. However, because the seed is encased in a berry, it could have been transported a considerable distance in the gut of an animal, to be excreted near the site and then the feces incorporated into the midden. Such is the presumed manner of origin of all other Celtis records in the Candidate Area, with the exception of the Deadman Canyon- 2 site (see below).

Prior Records of Phreatophytic or Hydrophyllic Species in The Candidate Area

Skeleton Hills- 2(2): Ondatra sp. (muskrat); A single tooth identified by C.A. Repenning, U.S.G.S., Denver. Likely from a carnivor scat or raptor "pellet", it is associated with a radiocarbon date of 8710 ± 100 yr B.P. (Spaulding, 1987a, b).

Skeleton Hills- 1B(2): Celtis reticulata; A single seed from this site, at 910 m elevation in the Amargosa Desert, is associated with a radiocarbon date of 9160 ± 140 yr B.P. (Spaulding, 1987a, b).

Deadman- 2: Celtis reticulata; Abundant seeds indicating the presence of this tree at 2075 m near the mouth of Deadman Canyon, presently an ephemeral drainage on the west side of the Sheep Range. The seeds yielded a radiocarbon date of 9560 ± 180 yr B.P. (Spaulding, 1981).

Flaherty Shelter: Celtis reticulata; A single seed from stratified sediments in a rockshelter at 1650 m elevation on the east site of the Sheep Range. Designated "early Holocene" (10,000 to 8000 yr B.P.) on the basis of an overlying radiocarbon date of 6950 ± 320 yr B.P. (Spaulding, 1974).

CONCLUDING COMMENTS

The radiocarbon samples have been submitted for dating and all midden samples have been processed for analyses. While some conjecture as to the age of certain assemblages has been made for the heuristic sake of testing prior paleovegetational reconstructions through inferences based upon them, the results of dating tests are not desired until the macrofossil and pollen analyses are completed. In this manner we may avoid any interpretational bias introduced by knowing the age of a particular series of samples before its macrofossil and pollen flora is completely analyzed.

An additonal benefit from these studies will be the records of climatically sensitive plant taxa near what was their lower (or upper) elevation limit during the last glacial age. By applying estimated elevation depression values and lapse rates, we may derive a more secure notion of what the climatic parameters of the Candidate Area are during a pluvial episode. Coupled with specific information on the near-surface hydrologic impact of those climatic events, this research is developing a broad-based understanding of the climatic causes and hydrologic effects of paleoenvironmental change in the area.

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Table 1. Packrat midden sites included in this research project.

Site name and no.	N. lat.	W. long.	Elev. (m)	Dist. (m) from target habitat	Substrate	Site's primary habitat Type	Orientation	Area	Secondary habitat Type	Orientation	Area	Tertiary habitat Type	Orientation	Area
FORTYMILE CANYON, NEVADA TEST SITE, NYE COUNTY														
Fortymile Canyon-7	36°56'42"	116°22'21"	1250	110	Tfv	lj,tc	260°	60%	rtp	-	30%	cl	260°-300°	10%
Fortymile Canyon-8	36°56'49"	116°22'46"	1240	100	Tfv	stc	38°	70%	lj, rtp	-	30%			
Fortymile Canyon-9	36°56'49"	116°23'01"	1200	400	Tfv	cl,lj	340°-180°	60%	ts,lj	15°-25°	40%			
Fortymile Canyon-10	36°56'57"	116°22'39"	1230	< 50	Tfv	ts	193°	40%	lj,rtp	-	30%	cl,lj	245°	30%
Fortymile Canyon-11	36°56'49"	116°23'27"	1310	500	Tfv	lj,tc	332°	70%	cl,lj	340°-180°	30%			
Fortymile Canyon-12	36°56'26"	116°22'35"	1240	100	Tfv	lj,cl	85°	50%	cl,lj	20°-60°	25%	lj,ts	90°-200°	25%
BIG SANDY (MESQUITE) VALLEY, CLARK COUNTY														
Sandy Valley-2	35°52'40"	115°42'28"	935	450	Pzc	lj,ts	45°	60%	rtp	135°	15%	stc	160°-90°	25%
Sandy Valley-3	35°52'40"	115°42'25"	885	200	Pzc	lj,tc	230°	50%	rtp,lj	-	40%	alf	190°	10%
COYOTE SPRINGS (PAHRANAGAT) WASH, DOUBLE CANYON, ARROW CANYON RANGE														
*Double Canyon-1	36°47'05"	114°53'04"	660	< 50	Pzc	ts,lj	40°-65°	80%	cl,lj,tc	45°-90°	20%			
*Double Canyon-2	36°46'50"	114°52'51"	670	150	Pzc	lj	90°-110°	65%	stc	95°	25%	stc	25°-90°	10%
*Double Canyon-4	36°46'50"	114°52'53"	690	200	Pzc	lj	95°-120°	60%	stc	80°-105°	40%			
*Double Canyon-5	36°46'23"	114°52'44"	ca. 680	270	Pzc	PROSPECT SAMPLING ONLY								

*original site name: Coyote Springs Wash

alf, alluvial fan; Cbk, Cambrian Bonanza King dolomite; cl, cliff; lj, bedrock ledges; Pzc, Paleozoic carbonate rocks; rtp, ridge top; stc, stabilized, colluvial slope, tc, rubbly talus chutes; Tfv, welded tuff, the rhyolite of Vent Pass (Orkild and O'Connor, 1970); ts, talus slopes; ws, dry wash.

Note: longitude and latitude values for the Sandy Valley sites are approximate

Table 3 Plant species from the Fortymile Canyon Locality D midden sites

	SITE	Fortymile	FMC-7	FMC-7(1)	FMC-8	FMC-8A	FMC-9	FMC-10	FMC-10A(1)	FMC-10C(2)	FMC-11	FMC-11A(1)	FMC-11A(2)	FMC-12
	ASPECT/AGE	Canyon Wash	W	> 12 KBP	NE	> 12 KBP	N to E	S to W	12>8 KBP	12>8 KBP	N	> 12 KBP	> 12 KBP	NE to S
FAMILY	GENUS AND SPECIES													
Hydrophyllaceae	Nama demissum	x												
	Phacelia mustelina										x			x
	Phacelia sp.						x							
Lamiaceae	Salazaria mexicana				2									2
	Salvia cf. columbariae								1					
	I Salvia dorrii											1	2	
Malvaceae	Sphaeralcea ambigua	x	1		1		1							2
	Sphaeralcea sp.			1					1	1				
Nyctaginaceae	Mirabilis multiflora				1									
	Mirabilis sp.									1				
Papaveraceae	Argemone munita	x												
Pinaceae	I Abies concolor											''		
	I Pinus flexilis											1		
	I Pinus monophylla			3					1	•		''		
Plantaginaceae	Plantago sp.								1					
Poaceae	Aristida cf. longiseta		3		1		1							x
	Bromus rubens		x		x		x	x			x			x
	Bromus tectorum	x			x		x	x			x			x
	Erioneuron pulchellum							1						
	Hilaria jamesii				1									
	Muhlenbergia porteri													
	Oryzopsis hymenoides	x		1								1		
	Poa sp.				1									
	Sitanion hystrix				x		x	x			x			
	Stipa sp.		2				x	x			x			x
	Poaceae undifferentiated					2			2	1		1		
Polemoniaceae	cf. Leptodactylon pungens		3		1		1				x			1
	Gilia sp.								1					x
Polygonaceae	Chorizanthe sp.					1								
	Eriogonum fasciculatum	x	3		2		2	4			x			3
	I Eriogonum heermannii-type			1										
	Eriogonum inflatum	x												
	Eriogonum thomasii													
	Eriogonum sp (perennial)					2					x	1		x
	Eriogonum sp (annual)	x								1				
	I Polygonum lapathifolium-type			1										
	I Polygonum sp.					1								
Polypodiaceae	Pellaea mucronata										x			
Rosaceae	I Cercocarpus ledifolius					2						3	3	
	I Chamaebatiaria millefolium			1		1						1		
	Coleogyne ramosissima				4		1							1
	I Holodiscus microphyllus					1						1		
	Purshia glandulosa	x			1		1		4	4				1
	I Rosa woodsii			1										
Rubiaceae	Galium sp.					1				1				
Rutaceae	Thamnosma montana		x											
Saxifragaceae	I Ribes cf. velutinum											1		
	I Ribes sp.					1								

Table 3 Plant species from the Fortymile Canyon Locality D midden sites

	SITE	Fortymile	FMC-7	FMC-7(1)	FMC-8	FMC-8A	FMC-9	FMC-10	FMC-10A(1)	FMC-10C(2)	FMC-11	FMC-11A(1)	FMC-11A(2) I	FMC-12
	ASPECT/AGE	Canyon Wash	W	> 12 KBP	NE	> 12 KBP	N to E	S to W	12>8 KBP	12>8 KBP	N	> 12 KBP	> 12 KBP	NE to S
FAMILY	GENUS AND SPECIES													
Scophulariaceae	Castilleja chromosa		1											
	Castilleja sp.					1								
	Penstemon cf. palmeri	x												
Solanacea	Datura meteloides	x	1					1						1
	Lycium andersonii				1			2						
Ulmaceae	Celtis reticulata						***							
Zygophyllaceae	Larrea divaricata	x			**									

* in the vicinity of the sites, but more than 50 m distant
** in the vicinity, but more than 100 m from site
*** ca. 200 m distant in wash bottom
' nut shell fragments only
'' one fragment only
I extralocal taxon
x, present; 1, rare; 2, occasional; 3, common; 4, abundant; 5, very abundant.

TABLE 4. Plant species at the Sandy Valley midden sites

	Site and sample no.: SaV-	2 veg.	2 veg.	2(1)1	2(3)3	3 veg.	3(1)	3(2)
	Aspect/age	NE slope	S slope	8-12 K	> 10 K		8-12 K	> 10 K
Family	Genus and species							
Agavaceae	Yucca brevifolia	*	*		1	*	1	
	Yucca schidigera	**	**			**		
Amaranthaceae	Tidestromia oblongifolia						1	
Asteraceae	Ambrosia dumosa	x	3	†		2		
	Amphipappus fremontii	x	1					
	Brickellia arguta	x				2		
	B. microphylla	1						
	Brickellia sp.				2			
	! Chrysothamnus nauseosus				3			1
	Cirsium sp.						1	
	Encelia farinosa	x						
	Encelia sp.			1			1	1
	Gutierrezia microcephala	x			1	3		2
	Peucephyllum schottii	x						
	Pleurocoronis pluriseta					1		
	Stephanomeria sp.					1		
Boraginaceae	Amsinckia sp.			1	1			1
	Cryptantha racemosa	x						
	Cryptantha sp.					x		
Brassicaceae	Lepidium montanum-type			1			3	2
	! Lepidium cf. fremontii				1			
Cactaceae	Coryphantha vivipara	x						
	Echinocactus polycephalus		1		1	1		
	Mammilaria microcarpa						1	
	! Opuntia sp.			1	1		1	1
Caprifoliaceae	! Symphoricarpos cf. longiflorus							3
	! Symphoricarpos sp.			1				
Caryophyllaceae	Scopulophila rixfordii	x		5	4			
Chenopodiaceae	! Atriplex canescens				1			
	Atriplex hymenelytra	**	**			**		
	Atriplex confertifolia		1					
	Atriplex confertifolia-type			1				4
	! Ceratoides lanata							1
Ephedraceae	Ephedra funerea					2		
	Ephedra nevadensis-type							2
	! E. torreyana-type			3				
	Ephedra sp.				2		1	
Fabaceae	Prosopis juliflora						1	
Hydrophyllaceae	Phacelia sp.		x					
Krameriaceae	Krameria parvifolia		2			1		
Hydrophyllaceae	Phacelia sp.			1				
Lamiaceae	Salazaria mexicana	**	**			**		
Loasaceae	Eucnide urens	x					1	1
	Loasaceae undet.							1
Loganiaceae	Buddleja utahensis			3	2	2		3

TABLE 4. Plant species at the Sandy Valley midden sites

Family	Site and sample no.: SaV- / Aspect/age	2 veg. NE slope	2 veg. S slope	2(1)1 8-12 K	2(3)3 > 10 K	3 veg.	3(1) 8-12 K	3(2) > 10 K
Nyctaginaceae	Boerhaavia sp.			1				
	Mirabilis sp.							1
Plantaginaceae	Plantago sp.		x	2			1	1
Poaceae	Aristida adscencionis	x				x		
	Bromus rubens					x		
	Erioneuron pulchellum		x	1		x	1	
	Hilaria rigida	x						
	Muhlenbergia porteri					x		
	Oryzopsis hymenoides							1
	Stipa sp.			1				
	Poaceae undetermined			1	1		2	3
Polemoniaceae	Gilia sp.			1	1			1
	Leptodactylon pungens	x			2	1		
Polygonaceae	Chorizanthe brevicornu	x						
	Chorizanthe brevicornu-type							1
	Chorizanthe rigida		x					
	Eriogonum heermannii	x			1	1		
	Eriogonum inflatum		x					
	Eriogonum thomasii					x		
Polypodiaceae	Cheilanthes feeii	x						
Rosaceae	! Coleogyne ramosissima			1				
Rubiaceae	Galium sp.				1			
Rutaceae	Thamnosma montana	x	1	2	1	1	1	1
Solanaceae	Lycium andersonii	x	2			2		
	Lycium pallidum					1		
	Lycium sp.			2	2		3	3
	Physalis crassifolia	x						
	Nicotiana trigonophylla	x		1		2	2	2
Ulmaceae	! Celtis reticulata				†			
Zygophyllaceae	Larrea divaricata	x	2			1		

† 1 fragment only, a possible contaminant (as with A. dumosa), or long-distance transport (C. reticulata)

* within 1 km of sites but restricted to the alluvial fan

** in the vicinity of the sites, but more than 60 m distant from either

see Table 3 for a key to relative abundance values

Table 5. Plant species from the Double Canyon midden sites

Family	Genus and species	DC-1	DC-1(1)	DC-2	DC-2(1)
Agavaceae	Yucca schidigera	1		1	
Asteraceae	Ambrosia dumosa	2		3	
	Ambrosia acanthicarpa	*			
	Artemisia subgen. tridentatae				1
	Bebbia juncea	1		1	
	Brickellia arguta	2		1	
	! Chrysothamnus nauseosus		1		
	Encelia virginensis	1		1	
	Erigeron sp.				1
	Gutierrezia microcephala	1	1	3	
	Haplopappus sp.				3
	Hymenoclea salsola	*			
	Peucephyllum schottii	1		1	
	Stephanomeria pauciflora			1	
	Xylorhiza tortifolia	1			
Bignoniaceae	Chilopsis linearis	*			
Boraginaceae	Amsinckia sp.	x			
	Cryptantha pterocarya-type		1		
	Cryptantha sp.			x	
Brassicaceae	Lepidium montanum	2		1	
Cactaceae	Echinocactus polycephalus	1			
	Ferocactus acanthodes	1		1	
	Opuntia erinacea	1	1	1	
	! Opuntia whipplei		3		
	Opuntia sp.				2
Caprifoliaceae	! Symphoricarpos cf. longiflorus		2		1
Caryophyllaceae	! Scopulophila rixfordii		2	3	
Chenopodiaceae	! Atriplex confertifolia		1		
Cupressaceae	! Juniperus osteosperma		5		4
Ephedraceae	Ephedra torreyana	1		1	
Fabaceae	Acacia greggii	*		1	
	! Astragalus sp.		1		
Krameriaceae	Krameria parvifolia	1		1	
Lamiaceae	Salazaria mexicana			1	
	! Salvia dorrii		1		
Loasaceae	Eucnide urens	1		2	

Table 5. Plant species from the Double Canyon midden sites

	Site and sample no.:	DC-1	DC-1(1)	DC-2	DC-2(1)
Family	Genus and species				
Loganiaceae	Buddleja utahensis			**	1
Malvaceae	Sphaeralcea ambigua	3			
Oleaceae	! Fraxinus anomala		1		
Plantaginaceae	Plantago sp.	x			
Poaceae	Aristida adscencionis			1	
	Bromus rubens	x		x	
	Erioneuron pulchellum	1			
	Hilaria rigida	2		1	
	Schismus arabicus	x			
	Stipa arida	1			
	Poaceae undetermined				
Polemoniaceae	Gilia sp.	x			
	Leptodactylon pungens				1
Polygonaceae	Chorizanthe rigida	x			
	Eriogonum fasciculatum	2		2	
	Eriogonum heermannii				2
	Eriogonum inflatum	x		x	
	Eriogonum sp. (annual)			x	
Plantaginaceae	Plantago sp.	x			
Rosaceae	! Prunus fasciculata		1		1
Rubiaceae	Galium stellatum	1		1	
Rutaceae	Thamnosma montana	1			
Saxifragaceae	! Ribes cf. velutinum		1		
Solanaceae	Lycium andersonii	2			
	Lycium pallidum	*			
Zygophyllaceae	Larrea divaricata	3		4	
* ca. 70 m from DC-1 site, restricted to Pahranagat Wash					
** within 100 m, but more than 30 m distant from site					

Table 6. Calculations of glacial-age departure of summer temperature in the Candidate Area assuming that the water requirements of species noted are met at their lower limit.

	current lower limit (m)	lowest fossil record (FMC)	minimum displacement (m)	calculation of summer temperature decline - ΔTs with lapse rate of ___°C/100 m				Reference
	-	-	-	0.60	0.65	0.70	0.75	
Abies concolor	2073*	1280	793	4.8	5.2	5.6	5.9	from data in progress
do. adjusted for Merriam effect (+200 m)	2273†	d.o.	993	6.0	6.5	7.0	7.4	from data in progress
Pinus flexilis	2439	1280	1159	7.0	7.5	8.1	8.7	from data in progress
	lower limit (m)	lowest fossil record	minimum displacement (m)					
Juniperus osteosperma	1900	700	1200	7.2	7.8	8.4	9.0	from Spaulding (1985, Table 8)
Pinus flexilis	2650	1585	1065	6.4	6.9	7.5	8.0	from Spaulding (1985, Table 8)

* lower limit in mesic canyon bottom on moderate-size mountain range (Sheep Range)

† adjustment for Merriam effect assumes that on a smaller mountain mass (Yucca Mountain) the lower limits will be higher than on a large mountain mass, such as the Sheep Range

FIELD MAP COPIES

1. Location of Fortymile Canyon Locality D and the Fortymile Canyon-7 site (immediately east of the eastern margin of the Topopah Springs NW, 1:24,000 sheet.

2. Location of the Fortymile Canyon-7 , -8, -9, -10, and -11 sites.

3. Location of the Sandy Valley midden sites, copy of J. Quade field map.

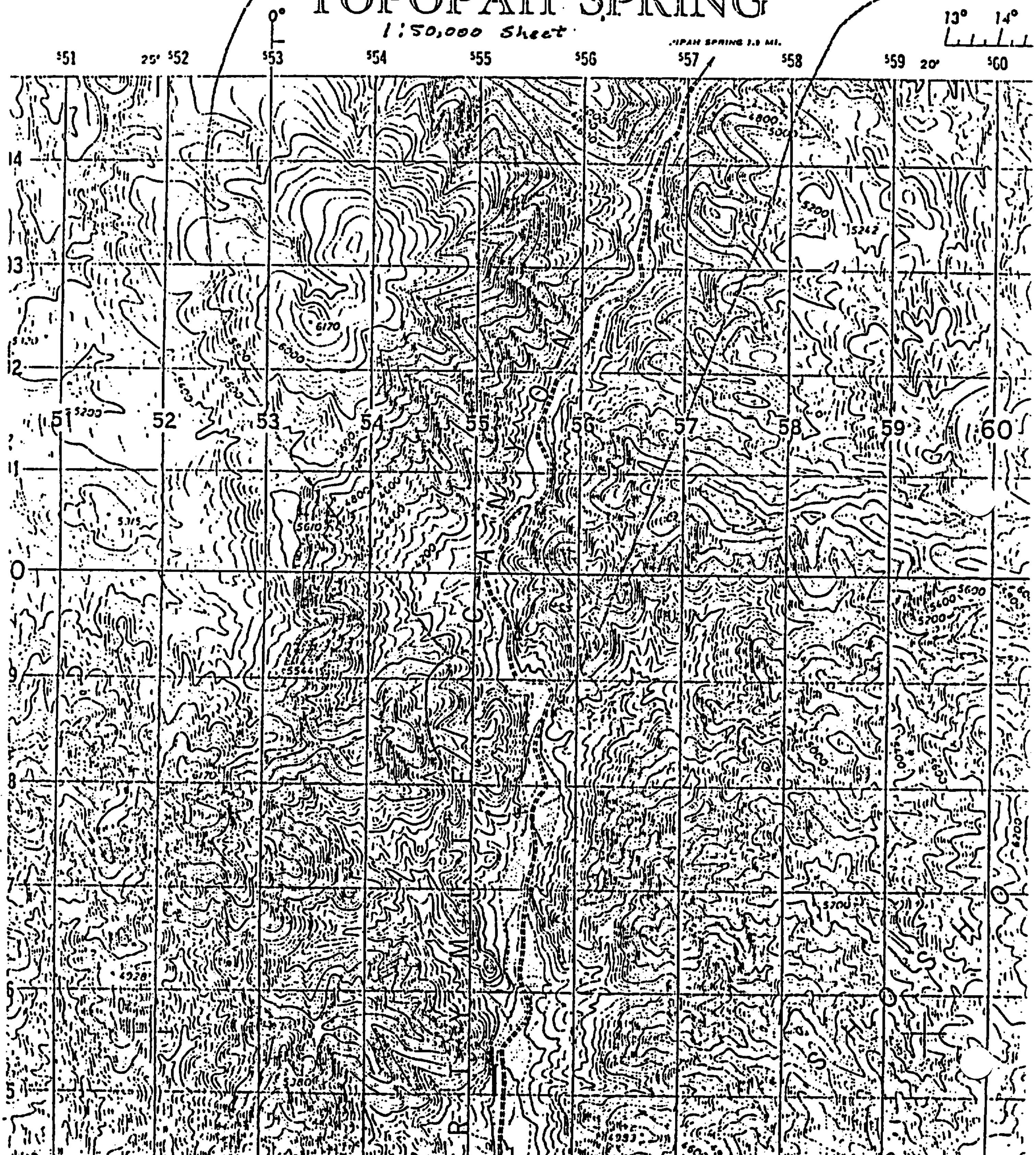
4. Location of the Double Canyon (formerly Coyote Springs Wash [CSW]) sites.

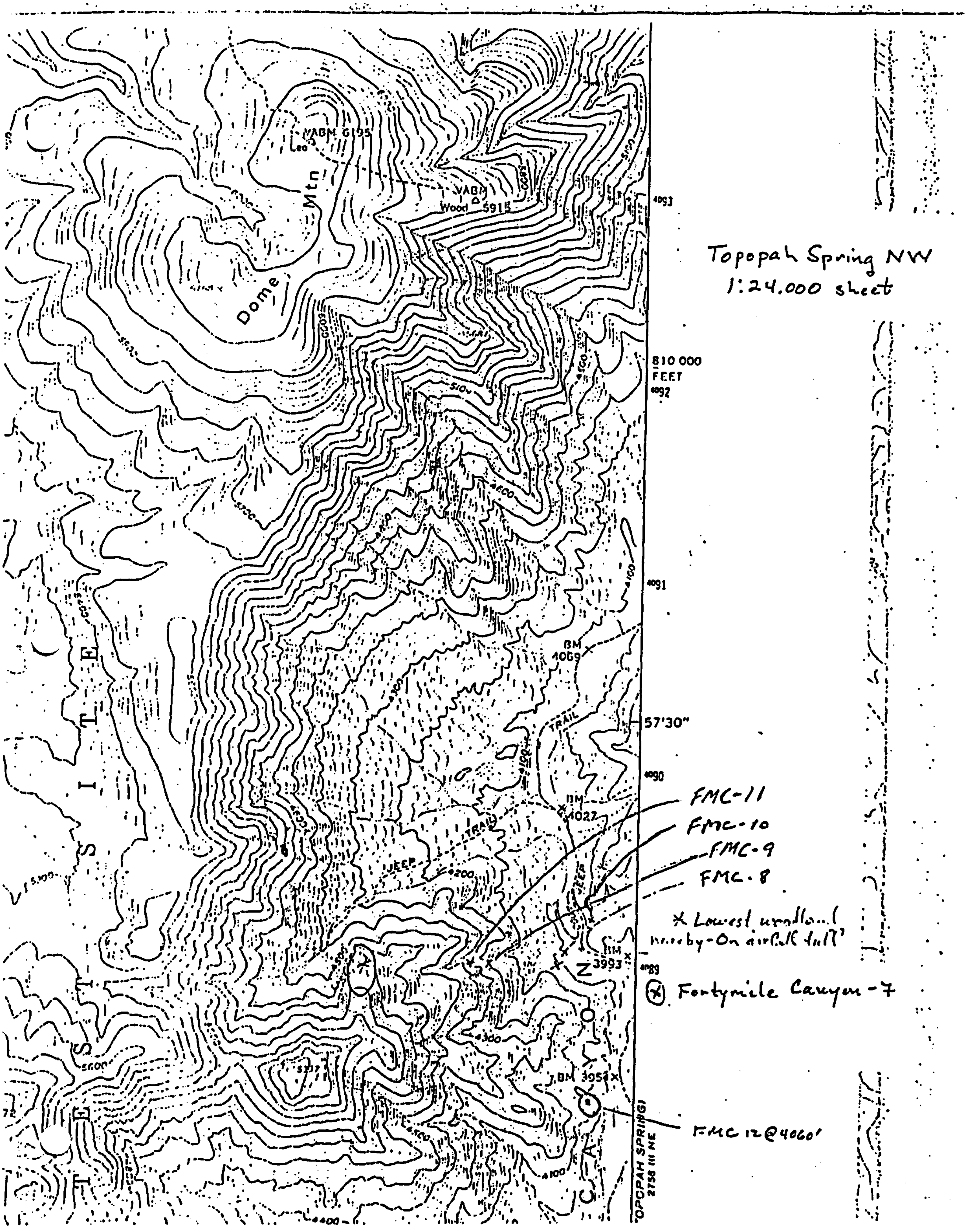
Fortymile Canyon, Locality D

TOPOPAH SPRING

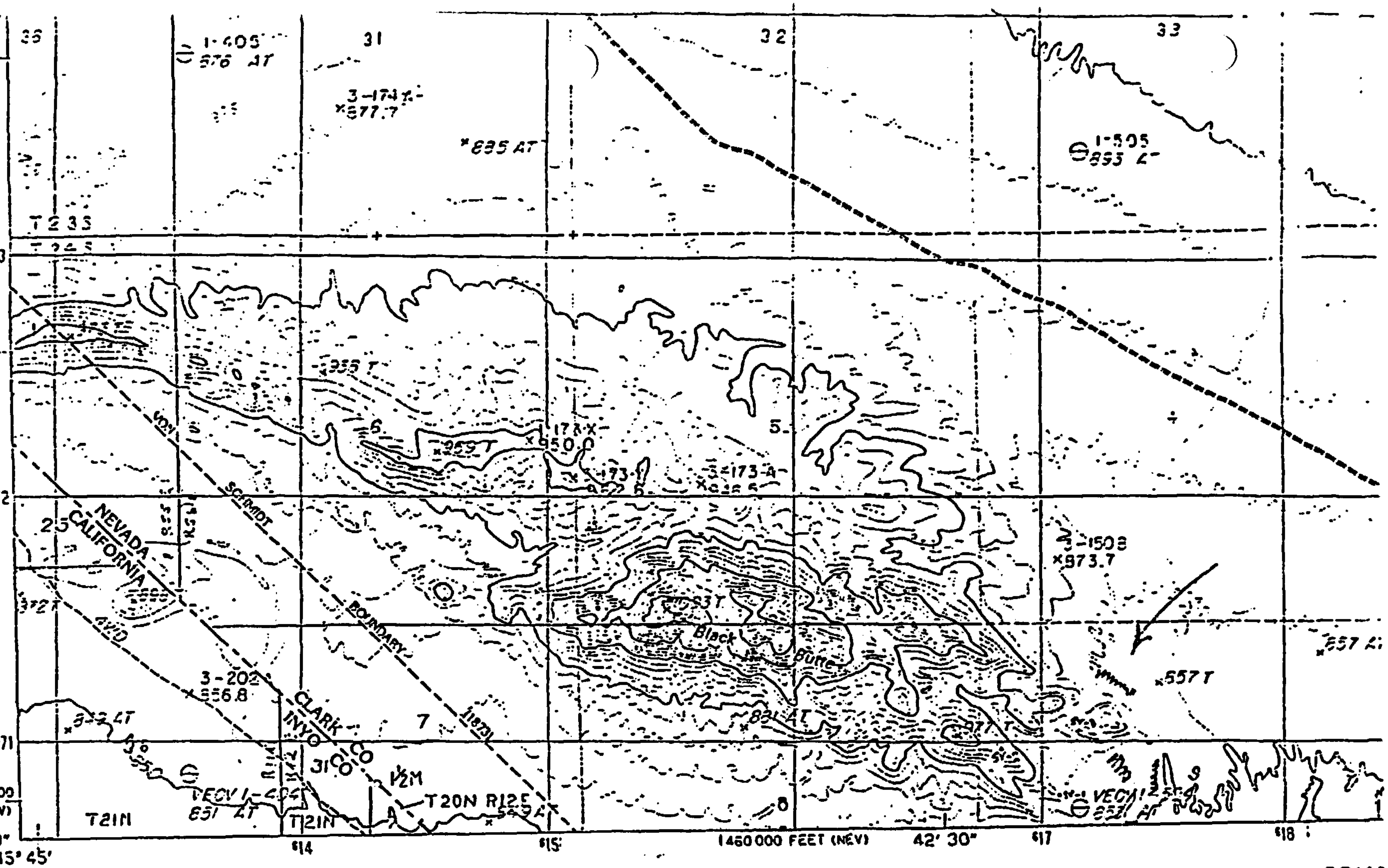
1:50,000 Sheet

Fortymile Cn. 7




Topopah Spring NW
1:24,000 sheet
VABM 6195
Leo
VABM
Wood 5915
Dome Mtn
810 000
FEET
4093
4092
4091
4090
4089
BM 4069
TRAIL
57'30"
BM 4027
JEEP TRAIL
JEEP
FMC-11
FMC-10
FMC-9
FMC-8
3993
Fortymile Canyon-7
BM 3952
FMC 12 @ 4060'
TOPOPAH SPRING
2738 III NE

Sandy Valley (SaV) sites



Green Monster Mine, Nv-Cal

7.5'

PRODUCED BY THE UNITED STATES GEOLOGICAL SURVEY
CONTROL BY .... USGS, NOS/NOAA
COMPILED FROM AERIAL PHOTOGRAPHS TAKEN .... 1976 AND 1978
FIELD CHECKED .... 1980. MAP EDITED 1984
PROJECTION .... UNIVERSAL TRANSVERSE MERCATOR
GRID: 1000-METER UNIVERSAL TRANSVERSE MERCATOR ...... ZONE 11
10 000-FOOT STATE GRID TICKS...NEV., EAST ZONE AND CALIF., ZONE 4
UTM GRID DECLINATION .... 0°46' EAST
1980 MAGNETIC NORTH DECLINATION .... 14°30' EAST
VERTICAL DATUM ... NATIONAL GEODETIC VERTICAL DATUM OF 1929
HORIZONTAL DATUM .... 1927 NORTH AMERICAN DATUM
To place on the predicted North American Datum of 1983, move the projection lines as shown by dashed corner ticks (5 meters north / 76 meters east)
There may be private inholdings within the boundaries of any Federal and State Reservations shown on this map
Certain land lines are omitted because of insufficient data

NORTH

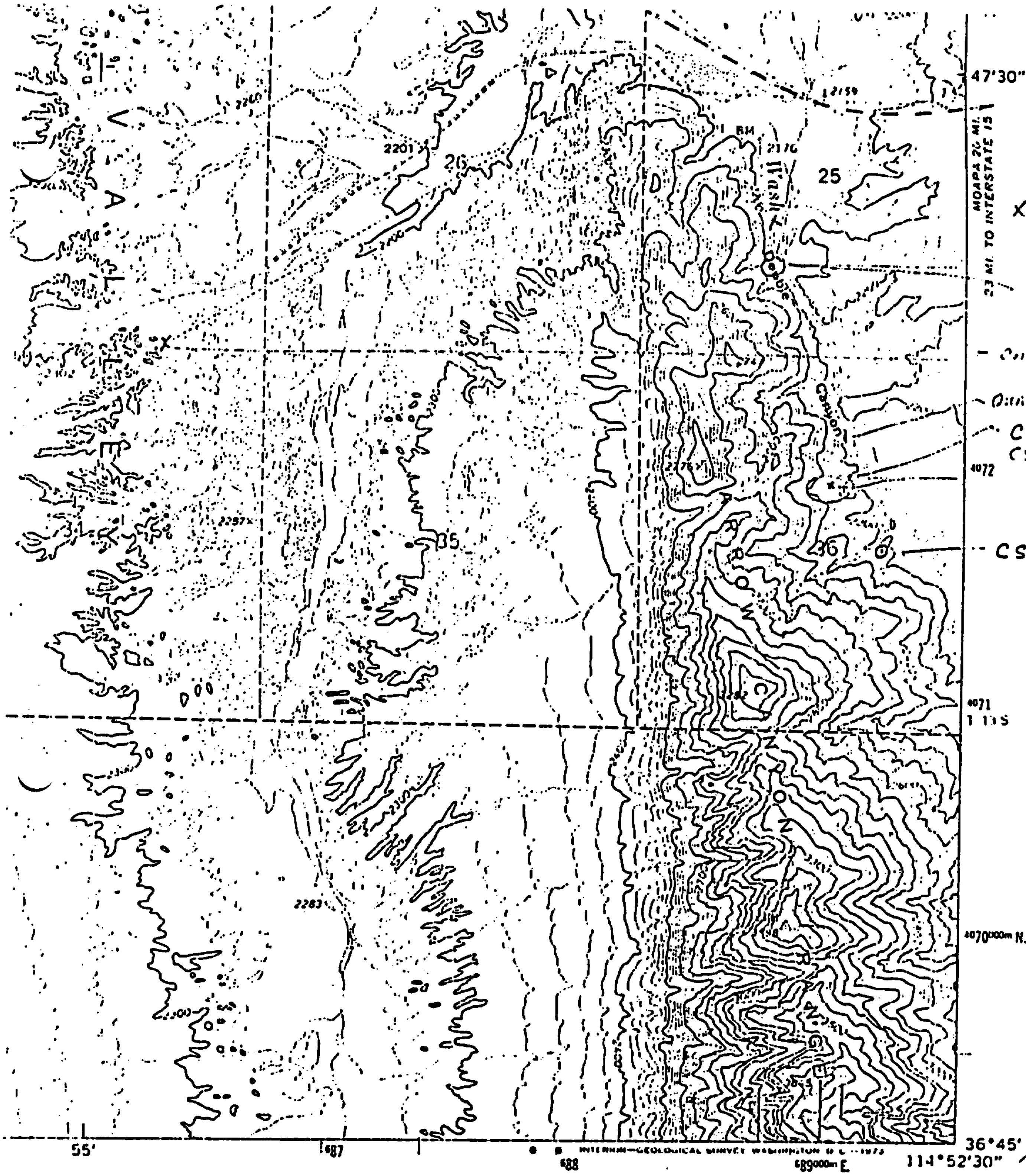
[illegible]m = Sv-1 = modern sample
935m = Sv-2 = [illegible]
855m = Sv-3 = [illegible]

PROVISIONAL MAP
Produced from original manuscript drawings. Information shown as of date of field check. 2

SCALE

CONTOUR INT
10 meter contours
SUPPLEMENTARY CO
CONTROL ELEVATIONS SH
OTHER ELEVATIONS SH
To convert meters
To convert feet to

THIS MAP COMPLIES WITH NAT
FOR SALE BY U.S. GEOLOGICAL SURVEY, DEN



INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D. C.—1973

(ARROW CANYON)
3057 III
1:62 500

ROAD CLASSIFICATION

Primary highway, hard surface	Light-duty road, hard or improved surface
Secondary highway, hard surface	Unimproved road

Interstate Route   U. S. Route   State Route

1 MILE

NEVADA

QUADRANGLE LOCATION

WILDCAT WASH SW, NEV.
N3645—W11452.5/7.5

1969

AMS 3057 IV SW—SERIES V896

. C. 20242

long = .1618'/cm

DOUBLE CH
SITES

WE

Appendix B-IX

The Paleohydrology and Paleoenvironments in the Vicinity of the Proposed Yucca Mountain Nuclear Waste Repository by W. G. Spaulding.

Update Report:

The Paleohydrology and Paleoenvironments in The Vicinity of The Proposed Yucca Mountain Nuclear Waste Respository

Prepared by

Arid Lands Paleoecology Laboratory, Quaternary Research Center, AK-60, University of Washington, Seattle 98195

Endorsement: W. Geoffrey Spaulding Date: 24 June, 1988

W. Geoffrey Spaulding, Research Assoc. Professor
Quaternary Research Center and Department of Botany

Research on the nature of pluvial-age environments in the vicinity of the proposed Yucca Mountain Nuclear Waste Repository (here referred to as the "Candidate Area") has as its primary objective the detection of episodes of increased ground-water discharge in this presently arid region. Increased ground-water discharge in nearby valley bottoms during the Late Wisconsin (Quade, 1986, 1987) provides good reason to further investigate both low-land spring-discharge habitats, and upland drainages. This is a deliberate test of the hypothesis that during some climatic regimes there may be both increased ground-water discharge and increased discharge through presently-ephemeral desert washes. This possibility has exceptional implications for the long-term integrity of a proposed nuclear waste respository because it is resonable to anticipate that pluvial climates will occur again, within the design life of the respository (10,000 to 100,000 yr). On one hand, if no exceptional evidence of increased discharge is found, it would be considered a favorable finding from the point of view of hydrologic stability in this region. On the other hand, if evidence is found for perennial water in currently-dry drainages such as Fortymile Canyon, this would indicate that provisions for substantially increased recharge rates, ground-water travel times, and instability of drainage systems need to be made.

Other means of studying the long-term climatic and hydrolgic stability of the Candidate Area include general paleovegetation reconstructions, since the same data base can be used for both, and because former paleoenvironmental reconstructions in the region need to be related to ongoing research. This provides the basis for testing the results of former studies that found relatively dry climatic conditions prevailing through late Wisconsin time in the Candidate Area (Spaulding, 1985), and evidence for a monsoonal period during the Wisconsin-Holocene transition (Spaulding and Graumlich, 1986).

The data for these studies are derived from radiocarbon dated plant macrofossil and pollen assemblages from ancient packrat middens. The sampling strategy of this research is to collect middens at localities that, on geologic and geomorphic grounds, could have been near stream-side or spring environments. Such riparian habitats have a distinctive flora composed of plants adapted to the constant presence of near-surface water. In the rugged terrain of the Candidate Area it is possible to locate midden sites near canyon-bottoms and paleospring sites. Today these habitats are, almost without exception, dry water courses or barren valley-bottom inselbergs. However, at certain times in the past, conditions were quite different.

RESULTS OF RADIOCARBON DATING

The results of ^{14}C dating on middens collected in June of last year are generally consistent with the predicted ages of the samples (Table 1). These predictions were made on the basis of floristic composition of the macrofossil assemblages recovered from the packrat middens, and on the basis of curves that establish the tendency for ancient middens from a given geographic area to cluster in particular age ranges (Fig. 1).

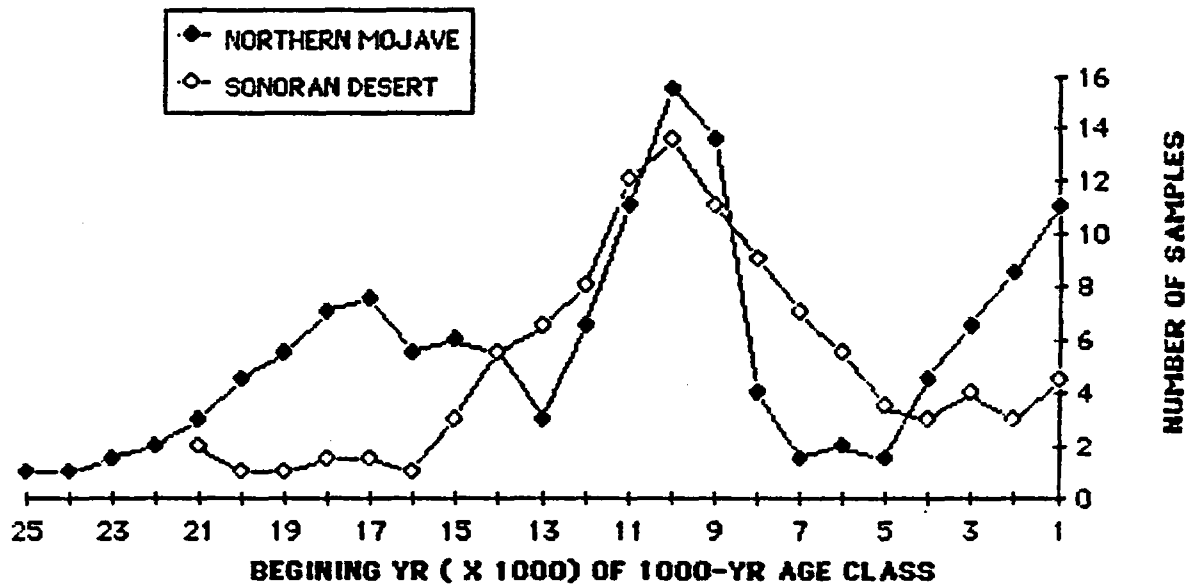


Figure 1. Age distribution of radiocarbon dates on packrat middens from two separate regions in the American southwest. Note the absence of a Wisconsin-maximum peak in sample abundance from the southerly, Sonoran region, and the bundance of samples from the terminal-Wisconsin-early Holocene (ca. 12,000 - 8,000 yr B.P.) in both regions The data are smoothed by a two-level moving average and include all published radiocarbon dates available before July, 1987.

In the northern Mojave Desert, most middens date to the last 4,000 yr, to the period 8,000 to 12,000 yr B.P., or to the period from ca. 14,000 to 21,000 yr B.P. These new sample dates fall into those periods (Fig. 2), with the exception of two from the Fortymile Canyon- 7 site that are considerably older (Table 1). As

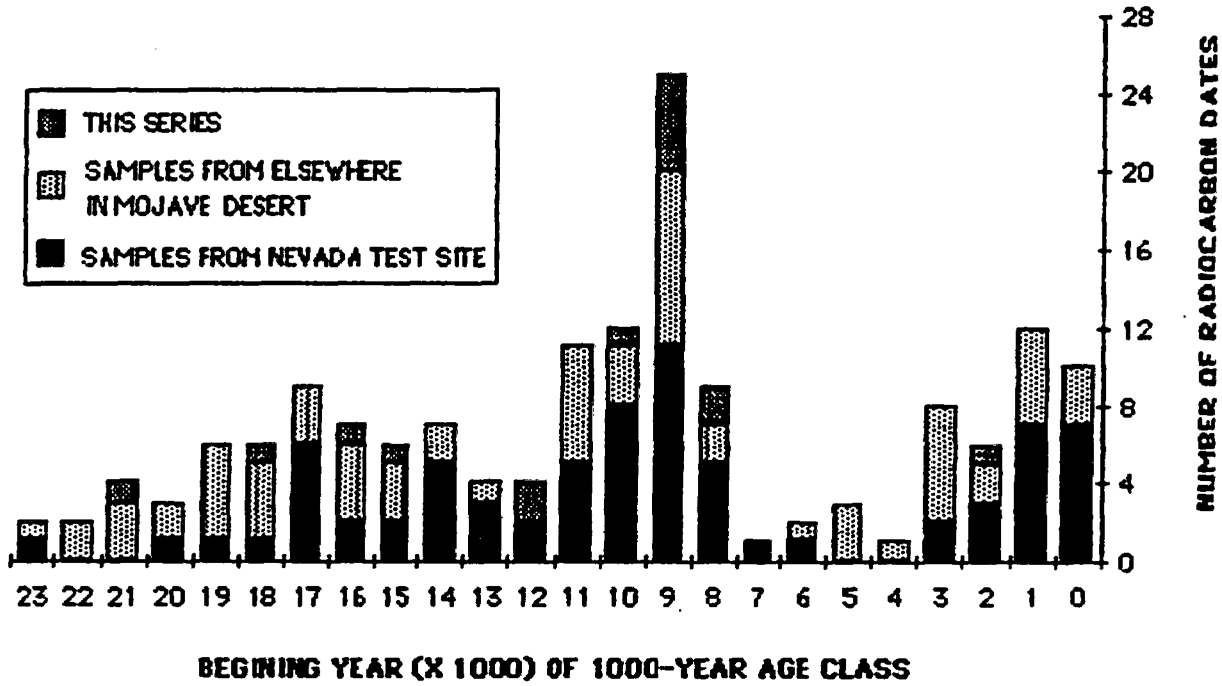


Figure 2. Age-distribution of radiocarbon dates on packrat middens from the northern Mojave Desert, including the new series discussed in this report (Table 1).

discussed in prior reports, there is reason to believe that (1) midden accumulation rates are higher during periods of increased effective moisture and (2) middens deposited during the full-glacial may, in some areas, have been destroyed by excessive moisture during subsequent pluvial episodes. The former hypothesis is supported by the tendency for midden abundance peaks to correlate with other paleohydrologic records of increased effective moisture (Fig. 3). The latter is supported, at least circumstantially, by the general absence of full-glacial records from the Sonoran Desert; a region that may have been characterized by a particularly intense, terminal-Wisconsin monsoonal pluvial (Spaulding and Graumlich, 1986). This idea is relevant in assessing the dating results from the most southerly locality in Big Sandy (Mesquite) Valley.

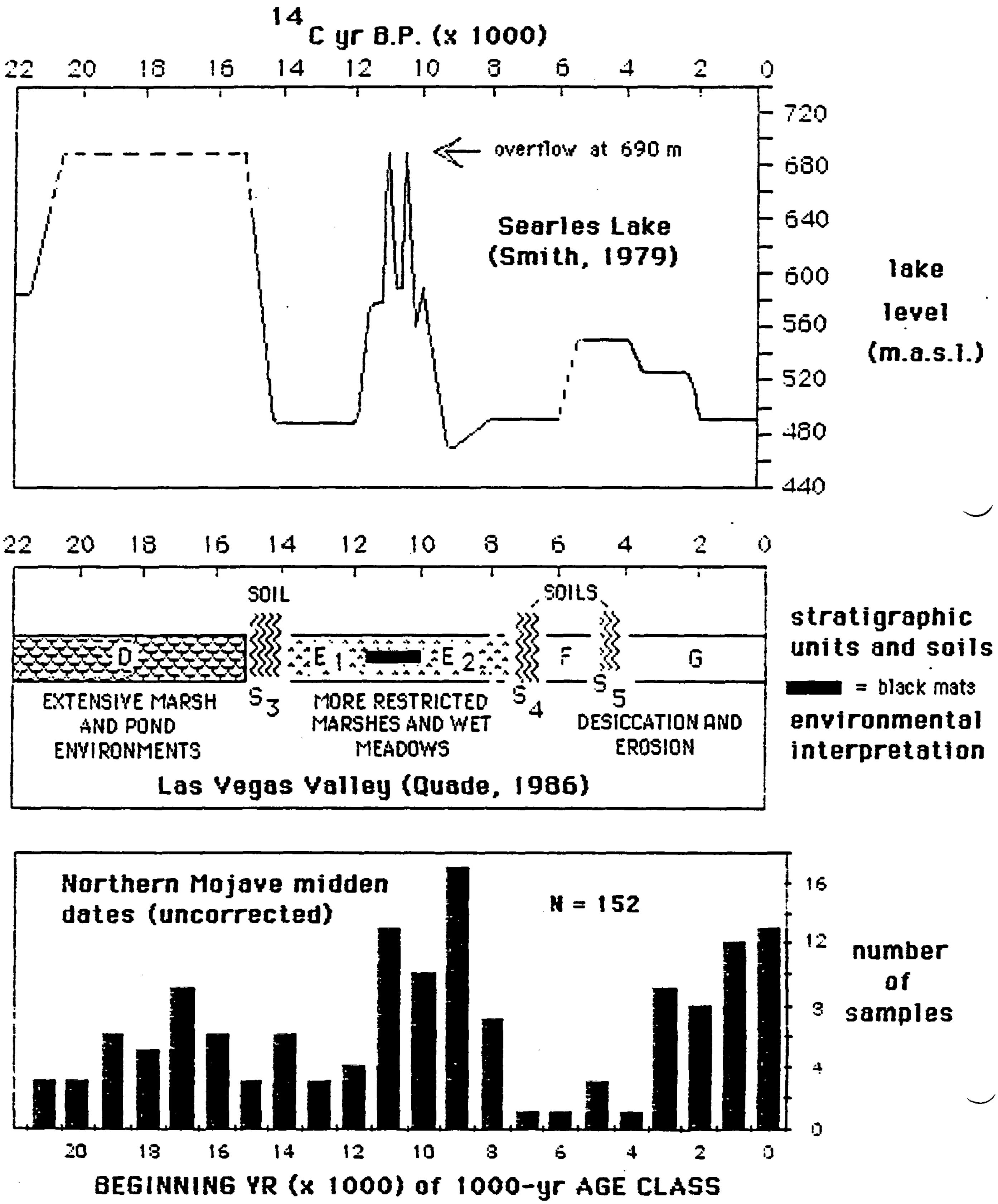
Age of The Big Sandy Valley Middens

Inselbergs of Paleozoic carbonate rocks occur in the vicinity of paleospring deposits in Big Sandy Valley, and these rocks contain abundant shelters and small caves ideal for the preservation of ancient packrat middens. In the search for middens from this locality, emphasis was placed on collecting those deposits which appeared to be of the greatest age, and therefore offered the best chance of yielding fossil evidence of pluvial climatic conditions.

Despite the ideal setting and the scores of individual cavities that were checked, only two middens of any great antiquity were discovered. A large midden deposit, Sandy Valley- 2 (SaV-2), contained multiple units that appear to have been deposited within a millennium, from ca. 9400 to ca. 8800 yr B.P. (Table 1). A

Figure 3 (following). Comparison of age-frequency distribution of radiocarbon dates on packrat middens from the northern Mojave Desert and two independent sources of evidence for variations in effective moisture in the region.

LATE WISCONSIN AND HOLOCENE



smaller deposit from a separate shelter, SaV-3, also dates to the early Holocene (ca. 8500 and 9400 yr B.P.). Due to the thoroughness of the field search and emphasis on the oldest assmeblages recovered, the absence of full-glacial middens from this locality appears not to be an artifact of sampling procedure. The Sandy Valley locality is not in the northern Mojave bioclimatic region. At 35°53' N lat., it is closer to the Sonoran Desert (Rowlands et al., 1982). The fact that dating results indicate a clustering of samples during the early Holocene suggests that whatever mechanism served to obliterate full-glacial records in the Sonoran Desert (Fig. 1) may have also operated here. In other words, there is the possibility that a particularly strong south-north gradient of decreasing effective moisture existed in this region during the latest Wisconsin and early Holocene.

Age of The Fortymile Canyon Middens

Farther north near the current northern limit of the Mojave Desert, at 36°53' N lat., rock shelters from the bedrock narrows of Fortymile Canyon do yield middens of full-glacial age, as well as those that date to the early Holocene (Table 1). Also recovered was a deposit of Middle Wisconsin age, the Fortymile Canyon- 7 midden (FMC- 7), with ^{14}C dates on the top and bottom units of 47,200 ± 3000 yr B.P. and >52,000 yr B.P., respectively. Of the five other midden samples judged to be older than 12,000 yr B.P., four yielded dates ranging from 21,830 ± 110 to 15,870 ± 70 yr B.P., satisfying the prediction based on the age-frequency curves (Fig. 1) that there is an abundance of full-glacial deposits in the region. A fifth sample, from the FMC-11B(1) midden, yielded an age of 12,870 ± 50 yr B.P. This falls near or in the apparent "dead zone" between full-glacial and latest glacial midden abundance, and will provide valuable clues to the nature of climate during this period.

The general chronology of vegetation change during the Late Wisconsin in the vicinity of Yucca Mountain is well enough known that macrofossil assemblages of terminal Wisconsin or early Holocene age could be identified from their component plant species. Samples from the FMC-10 site fall into this category. Two separate middens from this rock shelter yielded similar radiocarbon ages of 9470 ± 40 and 9390 ± 40 yr B.P. A final sample, thought to be younger than 4000 yr B.P., yielded a radiocarbon date of 2770 ± 30 yr B.P. (Table 1).

Age of The Pahranagat Wash Middens

Pahranagat Wash Locality A is at the north end of the Arrow Canyon Range, where the wash has incised a narrow canyon into Paleozoic carbonate rocks. Preliminary dating of two of the best deposits, from the Double Canyon-1 and -4 sites (DC-1, DC-4) revealed that both were of terminal Wisconsin age. The sample from DC-1, dated at 12,060 ± 70 yr B.P. falls close to the northern Mojave hiatus of ca. 15,000 to 12,000 yr B.P.(Figs. 1-3). Many more middens dating from ca. 14,000 to 12,000 yr B.P. have been recovered from the Lower Grand Canyon (Fig. 4; Phillips, 1977), less than 100 km east of this locality, than have been recovered from the Candidate Area. Although these samples are receiving full analysis, a subsequent field trip to this drainage has been made to collect middens that are more likely to be of full glacial age, and that lie closer to the floor of Pahranagat Wash.

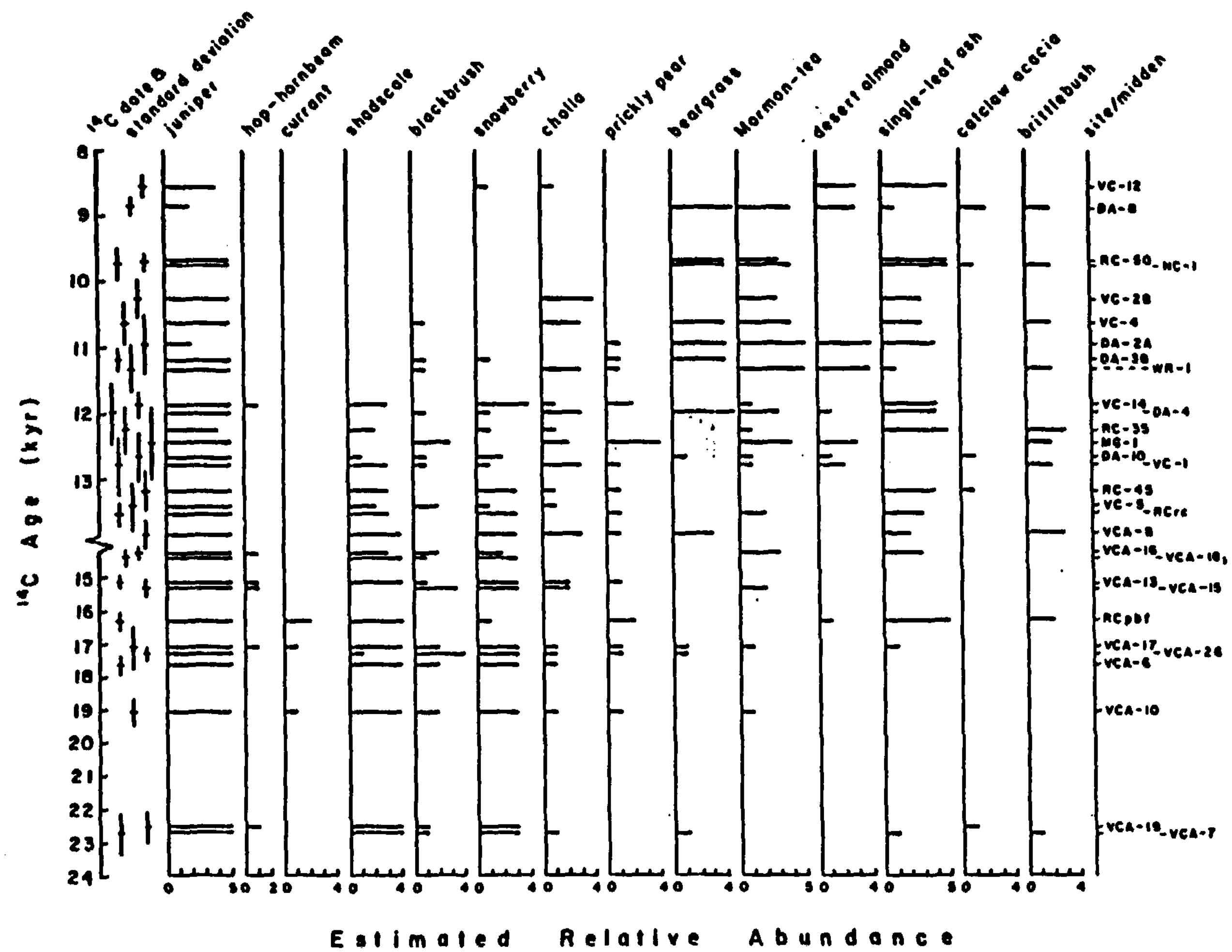
PALEOENVIRONMENTS OF FORTYMILE CANYON

The six midden sites from the middle reaches of Fortymile Canyon provide plant macrofossil and pollen data that allow relatively detailed reconstructions of glacial and early Holocene conditions. All macrofossil assemblages dated to these periods reflect Utah juniper (Juniperus osteosperma) woodland, but with substantial changes in associated dominants and secondary components, depending on age and site characteristics.

Wisconsin-age Records

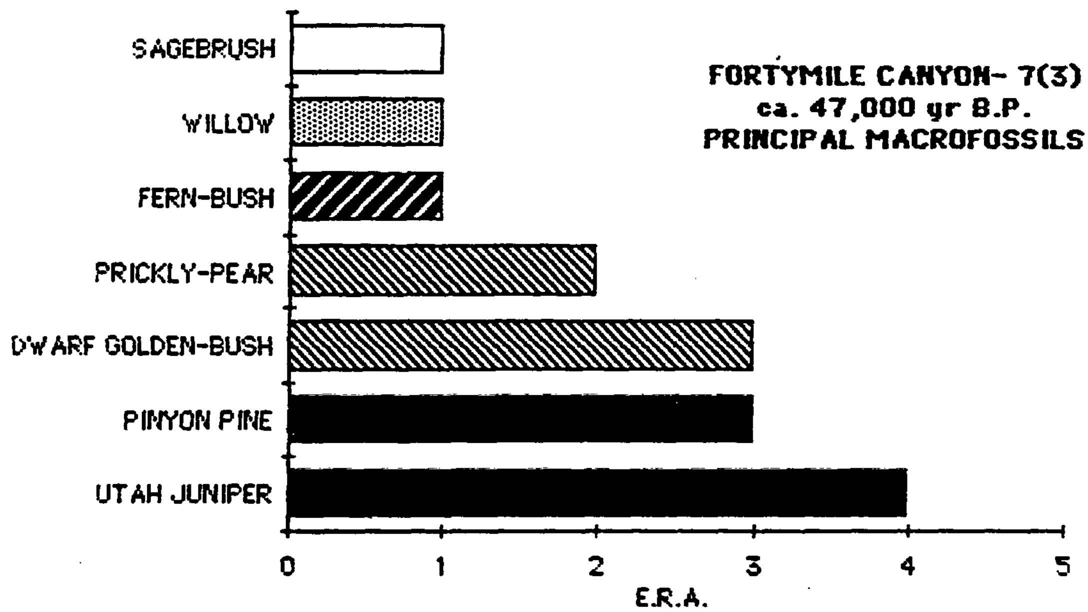
The Fortymile Canyon -7(1) [FMC-7 (1)] midden sample, dated at 47,200 ± 3000 yr B.P., is the only assemblage containing common pinyon pine (Pinus monophylla)(Fig. 5). Plains prickly-pear (Opuntia cf. polyacantha) and dwarf goldenbush (Haplopappus nanus) are other important components of this assemblage; today both are

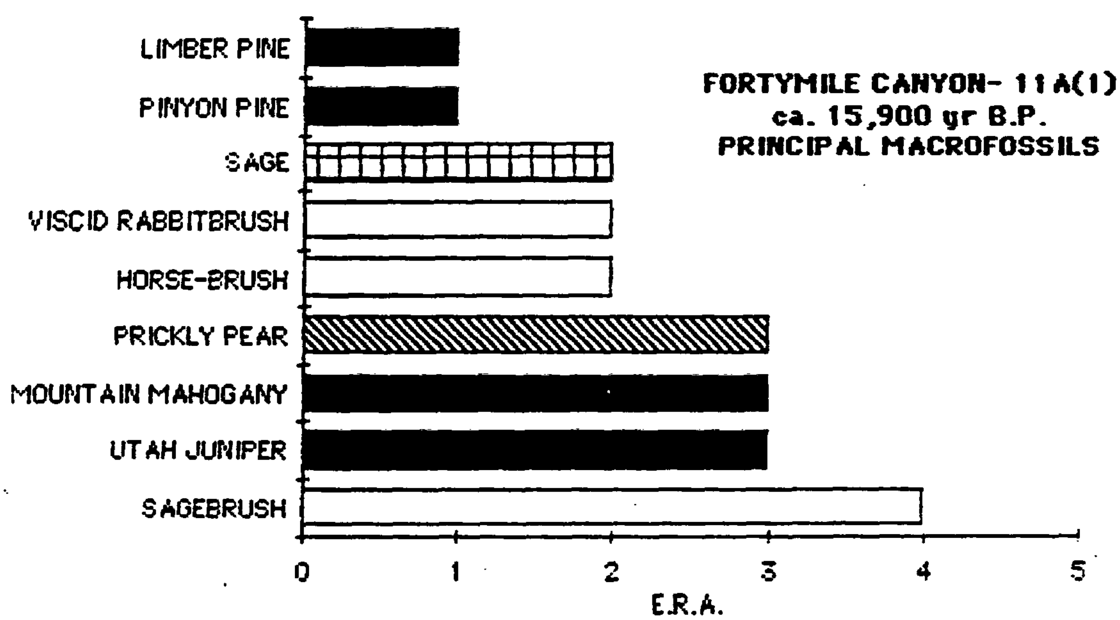
Figure 4 (following). The estimated relative abundance of selected plant taxa in Late Wisconsin and early Holocene middens from the Lower Grand Canyon, Arizona. Site abbreviations are : DA, Desert Almond; MG, Muav Gate; NC, Needle-eye Canyon; RC, Rampart Cave; VC, Vulture Canyon; VCA, Vulture Cave; WR, Window Rock. Data from Phillips (1977), Mead and Phillips (1981). Figure from Spaulding (1988).



14C date & standard deviation
juniper
hop-hornbeam
currant
shadscale
blackbrush
snowberry
cholla
prickly pear
beargrass
Mormon-tea
desert almond
single-leaf ash
catclaw acacia
brittlebush
site/midden
14C Age (kyr)
Estimated Relative Abundance
VC-12
DA-8
RC-50
NC-1
VC-2B
VC-4
DA-2A
DA-3B
WR-1
VC-14
DA-4
RC-35
MS-1
DA-10
VC-1
RC-45
VC-5
RCrc
VCA-8
VCA-16
VCA-13
VCA-15
RCpbf
VCA-17
VCA-26
VCA-6
VCA-10
VCA-19
VCA-7

Figure 5 (following). Summary macrofossil diagrams for the Fortymile Canyon-7(1) and Fortymile Canyon-11A(1) packrat midden samples. E.R.A., estimated relative abundance where: 1, present but rare; 2, occasional; 3, common; 4, abundant; 5, very abundant.


FORTYMILE CANYON- 7(3)
ca. 47,000 yr B.P.
PRINCIPAL MACROFOSSILS
SAGEBRUSH
WILLOW
FERN-BUSH
PRICKLY-PEAR
DWARF GOLDEN-BUSH
PINYON PINE
UTAH JUNIPER
0
1
2
3
4
5
E.R.A.

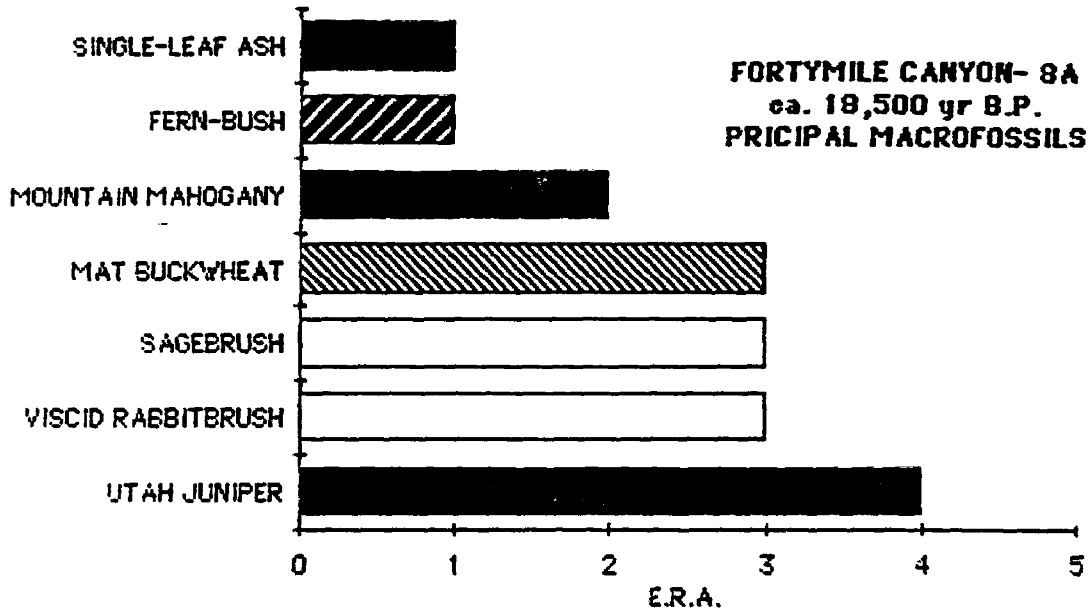

FORTYMILE CANYON- 11A(1)
ca. 15,900 yr B.P.
PRINCIPAL MACROFOSSILS
LIMBER PINE
PINYON PINE
SAGE
VISCID RABBITBRUSH
HORSE-BRUSH
PRICKLY PEAR
MOUNTAIN MAHOGANY
UTAH JUNIPER
SAGEBRUSH
0
1
2
3
4
5
E.R.A.

associated with open woodland habitats. Fern-bush (Chamaebatiaria millefolium), however, occurs in more mesic woodland and montane settings. Willow (Salix sp.) is present in this assemblage, although the distance from the FMC-7 site to the bottom of Fortymile Canyon is greater than 100m. Sagebrush (Artemisia subgen. tridentatae) is but rare, in contrast to those assemblages of full-glacial age.

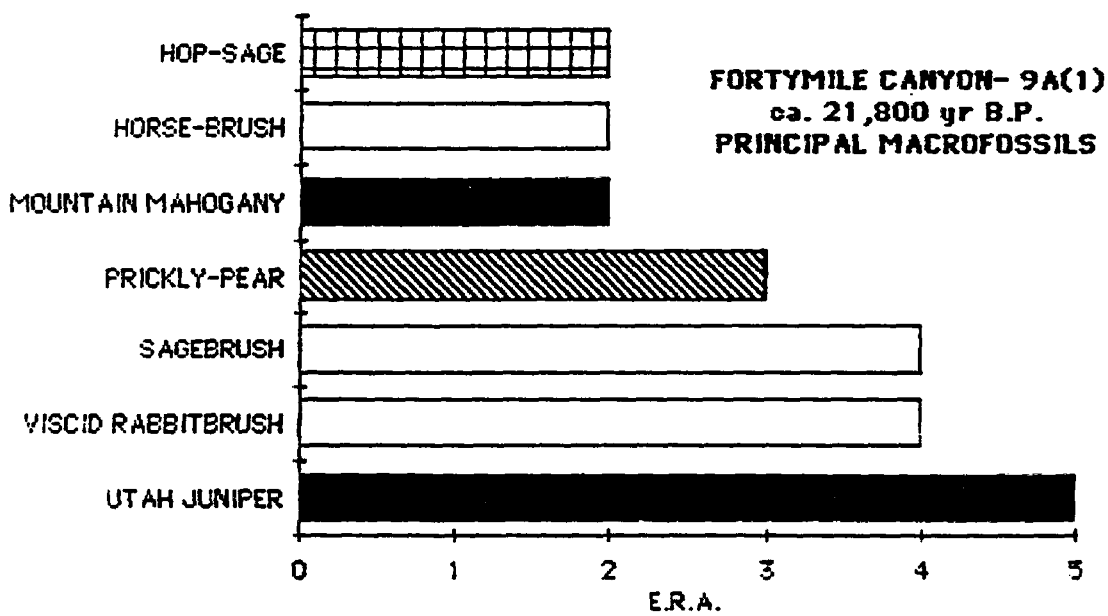
Macrofossil assemblages that date to about the full-glacial contain abundant Utah juniper and, moreover, common to abundant steppe shrubs (sagebrush, viscid rabbitbrush [Chrsothamnus viscidiflorus], horsebrush [Tetradymia canescens-type]; Figs. 5, 6). The association of woodland plants (juniper, fern-bush, mountain mahogany [Cercocarpus ledifolius]) with shrubs typical of Great Basin steppe is a common feature of stadial-age vegetation in southern Nevada (Spaulding et al., 1983). The importance of sagebrush, relative to juniper, in these samples suggests considerable open habitat. Sagebrush is a heliophile and its abundant pollen (Fig. 7) is consistent with the interpretation of an open woodland. The climatic implications of such woodland-steppe shrub associations have been discussed by Spaulding (1985). They conform to the interpretation of a semi-arid climate with winter temperatures $\geq 6°C$ lower than present, strong winter-seasonality of precipitation, and only a modest increase ($\leq 40\%$) in average annual precipitation.

Macrofossil assemblages from the Fortymile Canyon-8, -9, and -11 sites, dating from ca. 21,800 to 15,900 yr B.P. (Table 1), show

Figure 6 (following). Summary macrofossil diagrams for the Fortymile Canyon-8A and Fortymile Canyon-9A(1) packrat midden samples. E.R.A., estimated relative abundance where: 1, present but rare; 2, occasional; 3, common; 4, abundant; 5, very abundant.



FORTYMILE CANYON- 8A
ca. 18,500 yr B.P.
PRICIPAL MACROFOSSILS
SINGLE-LEAF ASH
FERN-BUSH
MOUNTAIN MAHOGANY
MAT BUCKWHEAT
SAGEBRUSH
VISCID RABBITBRUSH
UTAH JUNIPER
0
1
2
3
4
5
E.R.A.



FORTYMILE CANYON- 9A(1)
ca. 21,800 yr B.P.
PRINCIPAL MACROFOSSILS
HOP-SAGE
HORSE-BRUSH
MOUNTAIN MAHOGANY
PRICKLY-PEAR
SAGEBRUSH
VISCID RABBITBRUSH
UTAH JUNIPER
0
1
2
3
4
5
E.R.A.

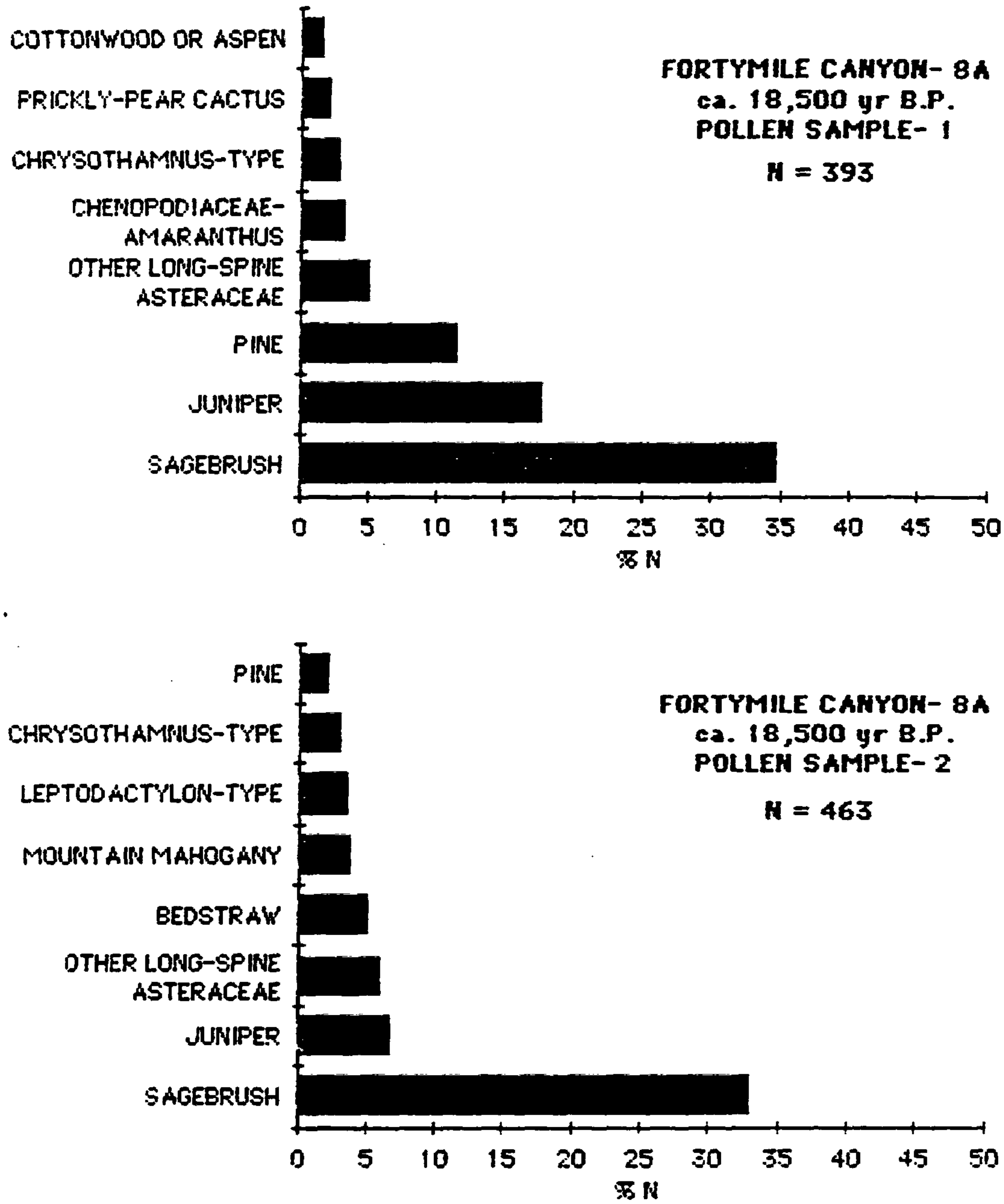


Figure 7. Summary pollen diagrams for samples from the FMC-8A packrat midden sample. N, total number of pollen grains encountered.

variations in composition that may be attributable to local variations in effective moisture. Of interest in this regard is the occurence of hop-sage (Grayia spinosa) in FMC-9A(1)(Fig. 6). A desert shrub in the Chenopodiaceae family, its presence here suggests relatively xeric conditions at this exposed site. The occurence of limber pine (Pinus flexilis) in FMC-11A(1) is consistent with the fact that this midden was from a mesic, north-facing alcove near a stream bed. At ca. 1310 m, this subalpine conifer was likely near its lower elevational limit at this site during the full glacial. Limber pine is the principal arboreal component of a higher elevation (1810 m) vegetation sequence in the Eleana Range (Spaulding et al., 1984), showing that the full-glacial vegetation zonation in the vicinity of Yucca Mountain was from higher elevation subalpine-steppe shrub communities to juniper-steppe shrub vegetation at lower elevations.

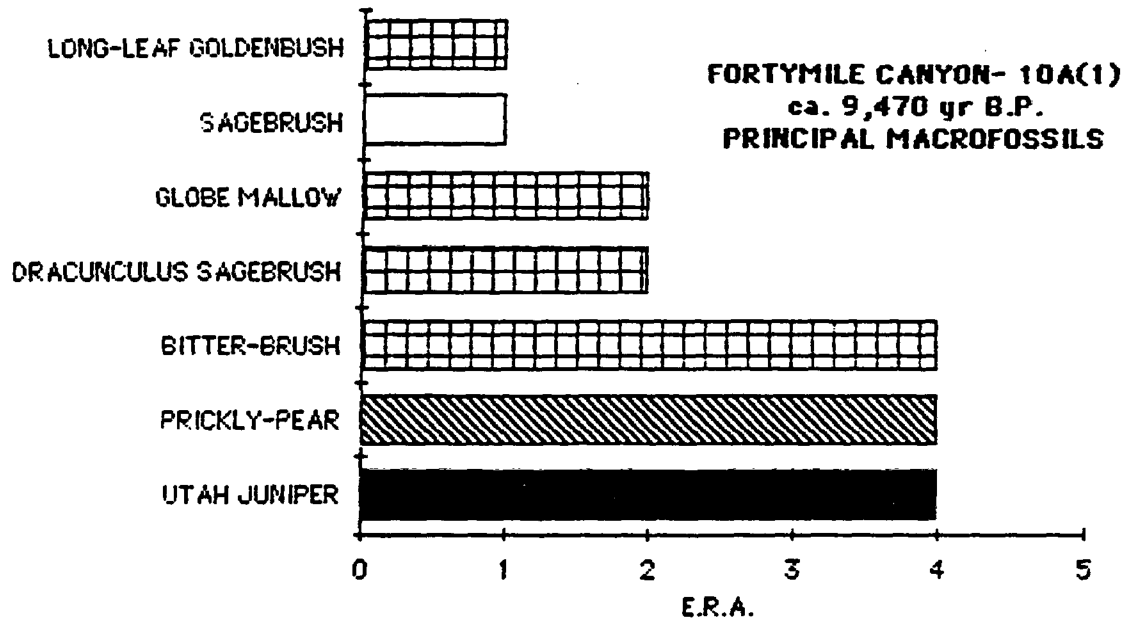
The occurence of single-leaf ash (Fraxinus anomala) in several full-glacial samples from this locality is of biogeographic significance (e.g. Fig. 6; Table 2). Known from only a few localities in the Mojave Desert today (Grapevine Mountains, Panamint Range), it is a shrub common in lower-elevation woodlands in the Colorado Plateau. Like limber pine and several other plant species discovered in these middens (Table 2), it is not known to occur today anywhere in the Yucca Mountain-Pahute Mesa-Belted Range highland complex (Beatley, 1976).

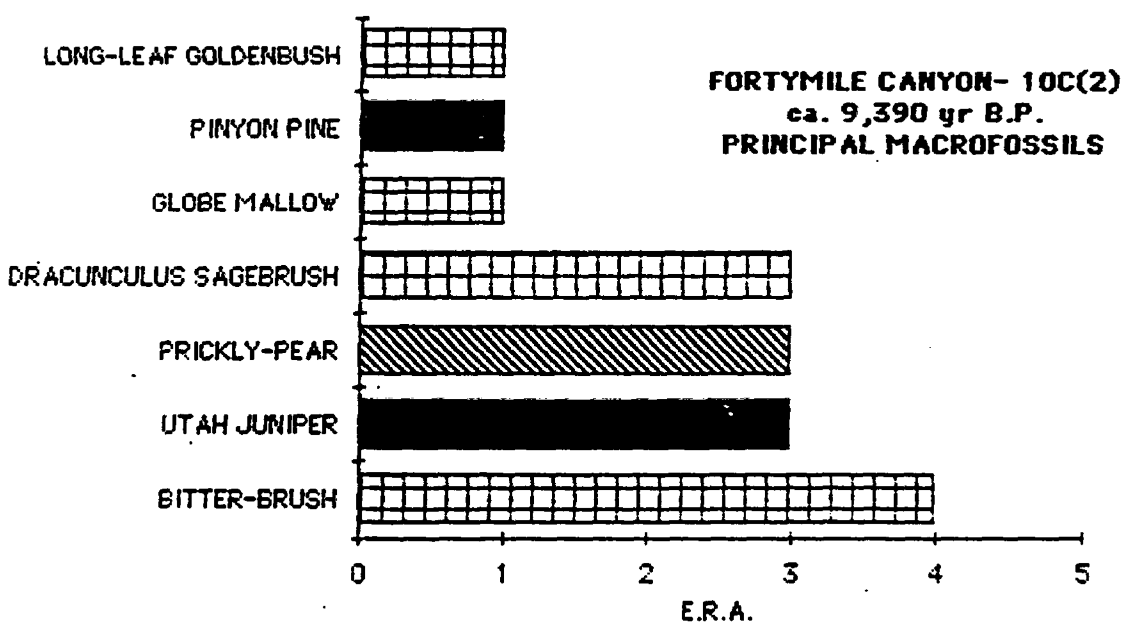
Early Holocene Records and Contrasts With Wisconsin-age Conditions

While juniper woodland evidently persisted into the early Holocene, as it did in many mid-elevation localities in the region (Van Devender, 1977), macrofossil assemblages from the FMC-10 middens show substantial differences with Wisconsin-age samples. Shrubs important in current desertscrub at the loaclity are well-represented for the first time; species such as globe mallow (Sphaeralcea ambigua), bitter-brush (Purshia glandulosa), and dracunculus sagebrush (Artemisia dracunculus)(Fig.8) Steppe shrubs are rare or absent, consistent with a change to warmer winters and decreased importance of winter precipitation (Spaulding and Graumlich, 1986).

Values of Nts (number of tree, shrub, and succulent taxa) for these early Holocene samples (11 and 13) are lower than those for the Wisconsin-age assemblages (15 to 18). The younger FMC-10 assemblages also contain 25% and 32% extralocal (not occurring within the area) or extralimital (not occurring in the Yucca Mountain-Pahute Mesa-Belted Range highland complex) taxa, as opposed to values between 41% and 63% for glacial-age samples (Table 2). The apparent reduction in shrub and tree species in the early Holocene therefore appears to have been due to the extinctions of taxa that today occur farther north, at higher

Figure 8 (following). Summary macrofossil diagrams for samples from the Fortymile Canyon-10A and Fortymile Canyon-10C packrat middens, located in the same rock shelter. E.R.A., estimated relative abundance where: 1, present but rare; 2, occasional; 3, common; 4, abundant; 5, very abundant.


FORTYMILE CANYON- 10A(1)
ca. 9,470 yr B.P.
PRINCIPAL MACROFOSSILS
LONG-LEAF GOLDENBUSH
SAGEBRUSH
GLOBE MALLOW
DRACUNCULUS SAGEBRUSH
BITTER-BRUSH
PRICKLY-PEAR
UTAH JUNIPER
0
1
2
3
4
5
E.R.A.


FORTYMILE CANYON- 10C(2)
ca. 9,390 yr B.P.
PRINCIPAL MACROFOSSILS
LONG-LEAF GOLDENBUSH
PINYON PINE
GLOBE MALLOW
DRACUNCULUS SAGEBRUSH
PRICKLY-PEAR
UTAH JUNIPER
BITTER-BRUSH
0
1
2
3
4
5
E.R.A.

elevations, or in wetter habitats. This and the failure of some modern elements to immigrate to the site by the beginning early Holocene led to lower species richness values, in a manner predicted by Cole's (1985) model of vegetational inertia. The immigration of many modern, thermophilous taxa was delayed for millennia, resulting in depressed species richness values following terminal-Wisconsin climatic change.

With this idea in mind, it is interesting to examine species-richness values for herbaceous plants and grasses. They appear to display a behavior inverse to that of the woody taxa, being more abundant in the early Holocene samples (54% of N in both assemblages), compared to the glacial-age middens (21% to 41%; Table 2). Part of this appears to be due to the appearance of annual species larely dependent on late spring and summer rains, such as pig-weed (Amaranthus sp.), lambs-quarters (Chenopodium sp.), spurge (Euphorbia cf. serpyllifolia), six-weeks gramma (Bouteloua barbata), and spectacle-pod (Thysanocarpus curvipes; Table 2).

Paleohydroligic Implications

Plant species useful in paleohydrologic reconstructions can be placed in four classes, with abbreviations as used in Table 2:

1) The obligate hydrophiles, or phreatophyes (H). These include such species as willow, cottonwood (Populus sp.), and cat-tail (Typha sp.).

2) The facultative phreatophyes (h). Species restricted to spring margins and the banks of perennial streams in the Great Basin, but that occur over a broader range of habitats elsewhere in the western United States. Examples include wild rose (Rosa woodsii) and hackberry (Celtis reticulata). Also included here are plants usually restricted to perennially-moist habitats near their lower elevational limits, such as white fir (Abies concolor).

3) Plants associated with riparian habitats in the Nevada Test Site area by Beatley (1976)(aH). These are forbs such as dock (Rumex cf. salicifolius) and Scouler's heliotrope (Plagiobothrys cf. scouleri) collected in pereniallly moist habitats but not necessarily dependent on constant moisture.

4) Desert riparian plant species (DR). Riparian desertscrub is a distinctive community type typical of ephemeral drainages (Bradely and Deacon, 1967), and there are plant taxa that are found only in these communities. These are desert shrubs well-adapted to habitats characterized by episodic floods and sandy, poorly developed soils.

Only one macrofossil assemblage analyzed to date contains unequivoval evidence of a riparian habitat, FMC-7(1), dated at 47,000 ± 3000 yr B.P. Four hydrophilic taxa and two desert-riparian species were encountered in this sample. Plants such as willow, wild rose, and knotweed (Polygonum lapathifolium-type) indicate perennial water within packrat foraging distance of the site. The remains of arroyo bursage (Ambrosia cf. acanthicarpa) and dock (Table 2) suggest that the canyon-bottom habitat was accessible from the FMC-7 site, and the vegetation sampled by the packrat was probably not that of a perennial seep on the canyon-side. The question of whether the packrat(s) were collecting plants from the bottom of Fortymile Canyon or from a seep somewhere nearer the site is an important one because, at present, the site is ca. 110 m from the canyon bottom. However, if there was more alluvium in Fortymile Canyon, its bed would be elevated and the canyon-bottom habitat would be closer to the site. In other words, it is possible that the canyon was not as deeply incised during the Middle Wisconsin, and the hydrophilic and riparian species present in FMC-7(1) are there because they occurred within the packrat's normal foraging distance of 30 to 50m. This would imply that incision of Fortymile Canyon has occurred in latest Quaternary times.

In contrast to this assemblage, those from other middens collected thus far have yielded few macrofossils of riparian plants. The possible remains of velvet ash (cf. Fraxinus velutina) in FMC-9A, a single white fir needle in FMC-11A(1), and the seeds of Scouler's heliotrope in FMC-11A(2) are all equivocal indicators of perennial water from ca. 21,800 to 15,900 yr B.P. (Table 2). The macrofossils of hydrophilic taxa have not been identified in the early Holocene FMC-10 assemblages, despite the proximity to the margin of Fortymile Canyon Wash (<50 m), and the occurrence of the desert-riparian shrub scale-broom (Lepidospartum latisquamum) in both assemblages (Table 2). Scale-broom indicates that packrats did forage down to the wash, and that the absence of riparian species in the FMC-10 assemblages would be consistent with the absence of perennially moist ground near this site.

CURRENT ACTIVITIES

This research represents a new approach to paleoenvironmental reconstruction using ancient packrat middens, and the particular aspects of research activities that affect the quality and reliability of these results have been identified. The taxonomic diversity of the macrofossil assemblages under study represents one challenge. Unidentified macrofossil types may represent riparian plant taxa seldom encountered in the normal course of field work in the southern Great Basin. Pains must be taken to identify these because, in some cases, they are indeed important paleoenvironmental indicators. The identification of willow in FMC-7(1) and Scouler's heliotrope in FMC-11A(2) represents one man-day of work for the Principal Investigator, and verifications of those identifications at the University of Washington Herbarium will require a minimum 2 hours of additional work.

The diversity of pollen types and tendency for packrat-midden pollen assemblages to be swamped by endogenous pollen (pollen originating from the flowers transported to the midden by the packrat) represents another challenge. Just as thousands of plant macrofossils must be sorted in a single plant macrofossil assemblage, pollen tallies must be high in order to assure that the pollen of such plants as willow or cat-tail are not important components of, say, the full-glacial pollen rain.

These then are current activities at the Quaternary Research Center's Laboratory of Arid Lands Paleoecology:

(1) The final validation of the taxonomic status of the plant macrofossil types that comprise the radiocarbon dated assemblages from Fortymile Canyon, Big Sandy Valley, and Pahranagat Wash.

(2) The continuing analysis of pollen samples from those middens in order to have individual pollen counts that exceed 400 identified grains per sample, and the assessment of intersample variability of pollen spectra in key midden samples.

(3) The continuing analysis of new samples from Pahranagat Wash in order to gain better understanding of paleohydrologic conditions on the eastern boundary of the Candidate Area.

Table 1. Results of radiocarbon dates on packrat midden samples from Fortymile Canyon, Coyote Springs Valley, and Double Canyon (first batch)

Site name and no	N. lat.	W. long.	Elev. (m)	SAMPLE NO.	Predicted age (yr B.P.)	14-C date (yr B.P.)	Standard deviation (±)	Laboratory number (QL-)	wt (g)	MATERIAL
FORTYMILE CANYON, NEVADA TEST SITE, NYE COUNTY										
Fortymile Canyon- 7	36°56'42"	116°22'21"	1250	FMC-7(1)	> 12,000	47,200	3,000	4,218	8.6	Neotoma pellets and Utah juniper twigs and seeds
				FMC-7(3)	> 12,000	>52,000	-	4,233	11.5	Neotoma pellets and Utah juniper twigs and seeds
Fortymile Canyon- 8	36°56'49"	116°22'46"	1240	FMC-8A	> 12,000	18,530	80	4,219	15.9	Neotoma pellets and sagebrush wood
Fortymile Canyon- 9	36°56'49"	116°23'01"	1280	FMC-9A(1)2	> 12,000	21,830	110	4,220	16.2	Neotoma pellets
Fortymile Canyon- 10	36°56'57"	116°22'39"	1230	FMC-10A(1)	12,000 > 8,000	9,470	40	4,221	16.4	Neotoma pellets
				FMC-10C(2)	12,000 > 8,000	9,390	40	4,222	16	Neotoma pellets
Fortymile Canyon- 11	36°56'49"	116°23'27"	1310	FMC-11A(1)	> 12,000	15,870	70	4,223	16.2	Neotoma pellets
				FMC-11A(2)1	> 12,000	16,410	70	4,234	16.3	Neotoma pellets
				FMC-11B(1)1	> 12,000	12,870	50	4,224	16.1	Neotoma pellets
Fortymile Canyon- 12	36°56'26"	116°22'35"	1240	FMC-12B	< 4,000	2,770	30	4,225	16.7	Neotoma pellets
BIG SANDY (MESQUITE) VALLEY, CLARK COUNTY										
Sandy Valley- 2	35°52'40"	115°42'20"	935	SAV-2(1)1	12,000 > 8,000	8,790	80	4,226	7.6	Neotoma pellets and undifferentiated twigs
				SAV-2(3)2	12,000 > 8,000	9,250	60	4,235	12.7	Neotoma pellets and undifferentiated twigs
				SaV-2(3)3	> 10,000	9,400	90	4,227	16	Neotoma pellets
Sandy Valley- 3	35°52'40"	115°42'25"	885	SAV-3(1)	12,000 > 8,000	8,490	120	4,236	8.5	Undifferentiated midden debris
				SaV-3(2)	> 10,000	9,430	60	4,237	4.1	Undifferentiated midden debris
COYOTE SPRINGS (PAHRANAGAT) WASH, DOUBLE CANYON, ARROW CANYON RANGE										
Double Canyon-1	36°47'05"	114°53'04"	660	DC-1(1)	> 10,000	12,060	70	4,228	11.8	Neotoma pellets and undifferentiated twigs
Double Canyon-4	36°46'50"	114°52'53"	690	DC- 4(2)	> 10,000	10,400	60	4,238	8.7	Undifferentiated midden debris

Table 2 Significant macrofossil records from the Fortymile Canyon packrat middens. These are only species of special environmental or biogeographic significance. See Appendix 1 for complete species lists for these assemblages.

FAMILY	GENUS AND SPECIES	AFFINITY	FMC-7(1)	FMC-8A	FMC-9A(1)	FMC-10A(1)	FMC-10C(2)	FMC-11A(1)	FMC-11A(2)1
	SITE AND SAMPLE:		FMC-7(1)	FMC-8A	FMC-9A(1)	FMC-10A(1)	FMC-10C(2)	FMC-11A(1)	FMC-11A(2)1
	APPROXIMATE 14-C AGE:		47,200	18,530	21,830	9,470	9,390	15,870	16,410
TREES, SHRUBS, SUBSHRUBS, AND SUCCULENTS									
Asteraceae	Ambrosia cf. acanthicarpa	DR	1						
	Brickellia californica	I			1		1		
	Chrysothamnus albidus-type	I					1		
	Chrysothamnus nauseosus	I	1						1
	Chrysothamnus paniculatus	DR							
	Chrysothamnus cf. parryi	I							1
	Lepidospartum latisquamum	I, DR				1	1		
	Tetradymia canescens-type	I	1	1	2			1	2
Cactaceae	Opuntia cf. polyacantha	I	2	1	3	4	3	1	3
Caprifoliaceae	Symphoricarpos sp.	I	1						
Cupressaceae	Juniperus osteosperma	I	4	4	5	4**	3	4	3
Elaeagnaceae	cf. Shepherdia argentea	II, M/S		1					
Fabaceae	Lupinus argenteus-type	I, mW		1				2	1
Lamiaceae	cf. Monardella	I, M/S							1
	Salvia dorrii	I	1					1	2
Oleaceae	Fraxinus anomala	II		1					
	cf. Fraxinus velutina	I, H			1				
Pinaceae	Abies concolor	II, h, M/S						**	
	Pinus flexilis	II, M/S						1	1
	Pinus monophylla	I	3		1	**	1	1	1
Polygonaceae	Eriogonum heermannii	I	1		1				
Rosaceae	Cercocarpus ledifolius	I		2	2			3	3
	Chamaebatiaria millefolium	I, M/S	1	1	1			1	1
	Holodiscus microphyllus	I, M/S		1	1			1	1
	cf. Rubus sp.	II, M/S	1						
	Rosa woodsii	I, H	1						
Salicaceae	Salix sp.	I, H	1						
Saxifragaceae	Ribes velutinum	I						1	
	Ribes sp.	I	1	1					
Solanaceae	cf. Nicotiana attenuata	I		1					

Table 2 (continued)

FAMILY	SITE AND SAMPLE: / APPROXIMATE 14-C AGE: / GENUS AND SPECIES	AFFINITY	CHARACTER	FLOWERING	FMC-7(1) 47,200	FMC-8A 18,530	FMC-9A(1) 21,830	FMC-10A(1) 9,470	FMC-10C(2) 9,390	FMC-11A(1) 15,870	FMC-11A(2)1 16,410
HERBS, FORBS, AND GRASSES											
Amaranthaceae	Amaranthus sp.		an.	June - Nov.				1	1		
Boraginaceae	Cryptantha barbigera-type	II	winter an.	May - June				1	1		
	Plagiobothrys cf. scouleri	II, aH	an.	June						1	1
Brassicaceae	cf. Athysanus pusillus	II	-	-				1			
	Thysanocarpus curvipes	?I	an.	Apr. - May				2	2		
Chenopodiaceae	Chenopodium sp.		an.	May - Oct.			1				
Euphorbiaceae	Euphorbia cf. serpyllifolia		summer an.	Sept. (July-Oct.)				1	1		
Hydrophyllaceae	Phacelia hastata-type	?I	peren.	l. May - July						1	1
Loasaceae	Mentzelia veatchiana-type	?I	winter an.		1	1	1				
Papaveraceae	Argemone munita	DR	peren.	l. May - Aug.							
Poaceae	Bouteloua barbata	?I	summer an.	Aug. - Sept.					1		
	Bromus carinatus	DR	peren.	May - July					1		
Polygonaceae	Polygonum lapathifolium-type	I, H			1						
	Rumex cf. salicifolius	DR, aH	peren.	l. Apr. - Sept.	1						
OTHER REMAINS											
	Ochotona fecal pellets (tally)	II, M/S									2
SUMMARY DATA											
	Nts (tree, shrub, and succulent taxa)				18	17	16	11	13	15	17
	N-Nts (herb, forb, and grass taxa)				9	12	9	13	15	4	7
	(N-Nts) as % of N				33%	41%	36%	54%	54%	21%	29%
	N (total number of taxa)				27	29	25	24	28	19	24
	Extralocals and extralimitals				15	12	11	6	9	11	15
	Extralocals/limitals as % of N				56%	41%	44%	25%	32%	58%	63%
	Hydrophillic taxa				4	0	1	0	0	1	1
	Desert riparian taxa				2	0	0	1	1	0	0

Key to occurence symbols:
* in the vicinity of the sites, but more than 50 m distant
** in the vicinity, but more than 100 m from site
*** ca. 200 m distant in wash bottom
† nut shell fragments only
†† one fragment only
††† two species
*† observed in fecal pellets

Key to affinity symbols
DR- desert-riparian taxon
H- obligate hydrophile or phreatophyte
h- facultative hydrophile or phreatophyte
aH- Noted by Beatley (1976) as occurring in wet meadows or stream-side habitats
M/S- montane or subalpine taxon
mW- mesic woodland taxon
I- extralocal species
?I- probable extralocal species
II- extralimital species

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PRELIMINARY
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OCT 6 1989

YUCCA MOUNTAIN PROJECT

A Summary of Technical Support Activities

January 1987 to June 1988

By:

Mifflin & Associates, Inc.
Las Vegas, Nevada

Submitted to:

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Agency for Nuclear Projects
Nuclear Waste Project Office
Carson City, Nevada

May 1989
Volume 2

Section C

Geochemistry and Mineralogy Program

Geochemistry and Mineralogy Program

Introduction

The activities in the Geochemistry and Mineralogy section of our program support three independent and interrelated subject areas which are:

1. Geochemical retardation/transport of radionuclides to the accessible environment.

2. Site-specific mineralogy and geophysical studies to establish the hydrogeology of the vadose zone.

3. Past climate and related genesis of authigenic desert carbonates and silicates.

Within the classification of these three licensing issues, there are a total of ten intensive review and research activities that have been performed. These activities are distributed in the following manner.

1. Geochemical Retardation:

   a. An assessment of the potential for radionuclide sorption as a function of authigenic mineral stability with respect to thermodynamic properties of zeolites, clays, and associated silicates and oxyhydroxides.

   b. Determination and characterization of the behavior of authigenic zeolites, clays, and transition metal oxyhydroxides during sorption and desorption of radionuclides (and proxies) under laboratory-imposed repository conditions.

   c. An assessment of volcanic glass stability with respect to magnetic and paramagnetic primary minerals included in the volcanic glasses of Yucca Mountain.

   d. An assessment of the geochemical and mineralogical stability of rhyolitic glass at Yucca Mountain with respect to authigenic mineral production and its relation to geochemical retardation of radionuclides.

   e. An assessment of desert varnish dating to determine its utility with respect to determining the rates of authigenic mineral formation from rhyolitic glass at Yucca Mountain.

2. Site-Specific Hydrogeology:

   a. Utilization of tritium, carbon-14, and iodine concentration exchanged into zeolite supercages to determine the relative age of last vadose waters of exposure, to assess the rate of fracture flow in vadose-zone liquid transport.

   b. To determine the magnetic stratigraphy for Yucca Mountain for use as a drilling control during sample collection and search for vadose water.

3. Past climate and desert carbonates:

   a. Characterization of diagenetic events at Lake Tecopa for the resolution of hydrostratigraphic events as they relate to past climate in the region of Yucca Mountain.

   b. An assessment of genesis of desert carbonates with respect to the interpretation of past climate events as they can be resolved from trenches and ground-water discharge deposits.

c. Characterization of opaline and carbonate deposits with specific reference to Trenches 14, 17, 1, and the sand ramps.

The basic design and focus of the geochemical retardation/transport section of the program is to address the ability or inability of the natural environment to isolate radioactive waste from the accessible environment after repository closure. In order to accomplish this task, it has been necessary to assess the thermodynamics of the vadose-zone system with respect to vadose-water chemistry, mineralogy, and temperature (see Appendix C: Bowers, T. J. and R. G. Burns, 1988). These information can be utilized to ascertain sorptive mineral stability under repository conditions. However, predictive value is only as good as input data provided. In this particular case, there is a serious void in good vadose-water chemistry and therefore until this void is filled, the thermodynamic calculations must remain tenuous.

In a parallel study, the sorption behavior of single-crystal zeolites are being assessed (see Appendix C: Wood, V. J., et al., 1988). Crystallographic orientation, initial supercage composition among a host of other parameters, affect the sorption capacity of Yucca Mountain type zeolites such as clinoptilolite and heulandite. These studies will provide a predictive baseline of radionuclide behavior with respect to zeolite crystal chemistry and allow us to move into whole-rock studies in the future. This overall base of information will provide an ability to address our ultimate goal which is the retardation capacity of fracture surfaces, the Topopah Springs Member of the Paintbrush Tuff and the Calico Hills formation. With respect to the Calico Hills formation, there is concern with regards to glass and authigenic mineral stability. This issue is being addressed with the glass studies that are described in this report (see Appendix C: Blundy, J., et al., 1987, 1988).

Site-specific hydrogeology issues that are being addressed in our studies involve drilling and obtaining fracture and matrix samples that contain zeolites. Utilizing a tandetron in Toronto, we are developing procedures to analyze for gases such as C-14 to determine the age of the water of last exposure. These information will give us a better understanding of the fracture flow mechanism at Yucca Mountain.

Past-climate geochemical studies are primarily support-type studies assisting in the interpretation of stratigraphic events (see Appendix C: O'Hara, P. F., et al., 1988). In addition to these, specific studies regarding authigenic carbonates and opal are aiding interpretation of hydrologic and paleoclimatic events and processes for the Yucca Mountain trenches and surrounding desert region.

Appendix C contains abstracts of papers presented at professional symposia and other technical documents that are offshoots of our efforts.

Geochemical Retardation/Transport of Radionuclides to the Accessible Environment.

The capacity for Yucca Mountain tuffs to provide radionuclide retardation for the limitation of radionuclide transport to the accessible environment is an extremely complex issue. It deals with the identification of: the most likely paths of travel, potentially sorptive mineral availability along those paths, crystal orientation, chemical composition, mineral and glass stability under natural and imposed conditions, colloid formation, precipitation, and diffusion. The following efforts explore various aspects of the issue of the natural retardation barrier at Yucca Mountain to assess the capability of that barrier to provide meaningful retardation.

Geochemistry and Mineralogy

ISSUES:

Can potentially sorptive minerals such as clinoptilolite, mordenite, smectite, and other authigenics provide retardation of radionuclides to the extent that credit can be taken by the DOE for isolation of the radioactive waste from the accessible environment after closure in accordance with the requirements set forth in 40 CFR Part 191, 10 CFR Part 60, and 10 CFR Part 960? Will these potentially sorptive minerals remain actively stable and capable to provide sorption even under near-field and far-field repository conditions?

Characterization Issues:

Can we construct activity diagrams for clinoptilolite to provide sufficient data relative to the susceptibility of this zeolite to further diagenetic reactions?

Can we construct activity diagrams for mordenite?

Can we construct activity diagrams for the smectites?

Can we obtain sufficient in situ chemical data concerning vadose-water chemistry to be able to construct activity diagrams for the authigenic minerals situated in the vadose zone?

Can we obtain sufficient in situ ground-water chemical analysis to be able to construct activity diagrams for authigenic minerals in the saturated zone?

GENERAL OBJECTIVE:

Develop activity diagrams for authigenic mineral stability relating to the geochemistry of the aqueous fluids and temperatures in the near and far fields, so as to be able to predict their stability under repository conditions and thereby assist in understanding the role of these minerals during potential retardation of radionuclides.

Specific Objectives:

Review the DOE water-chemistry literature to obtain basic chemical conditions that might be used for constructing activity diagrams.

Review the open literature for the same purpose, since the DOE literature is incomplete and potentially inaccurate.

Review the open literature for basic thermodynamic properties of clinoptilolite and associated minerals.

Construct multicomponent activity diagrams for clinoptilolite on the basis of aluminosilicate activity and temperature.

ACTIVITY SUMMARY:

The stability limits of clinoptilolite and its vulnerability to changes in ground-water chemistry relative to well J-13 have been assessed, by constructing activity diagrams for clinoptilolite solid solutions in the system Ca-Na-K-Mg-Fe-Al-Si-H_2O employing available thermodynamic data for relevant oxide and aluminosilicate phases (see Appendix C: Bowers, T. J. and R. G. Burns, 1988, and R. G. Burns and T. J. Bowers, 1988).

FINDINGS:

The results of our investigations have been submitted to the American Mineralogist for publication (see Appendix C for a copy of the paper. Significantly, it appears that authigenic minerals such as clinoptilolite modify and are modified by ground-water compositions. We have been unable to acquire vadose-water compositions to date and therefore can make no comments concerning zeolite stability in the vadose zone.

INTERPRETATION OF FINDINGS:

The following observations are made:

The coexistence of clinoptilolite with opal correlates with its calculated wide stability field in aqueous solutions saturated with amorphous silica.

Clinoptilolite-smectite assemblages indicate that the zeolite crystallized from ground water with dissolved Al concentrations lower those saturation values with respect to gibbsite.

Calcime clinoptilolite associated with calcite are consistent with crystallization from fracture-flow ground water containing Ca^{+2} and HCO_3^- derived from incipient dissolution of microcrystalline devitrified tuffs. Alkali-rich clinoptilolites correlate with ground water having elevated Na^+ and K^+ but depleted Ca^{2+} concentrations which are associated with altered vitric tuffs.

The clinoptilolite stability field diminishes appreciably between 25°C and 100°C, correlating with burial diagenetic reactions; but, confirming doubts about the thermal stability of clinoptilolite when exposed to repository conditions.

ADDITIONAL WORK REQUIRED:

Obtain vadose-water chemical data and recalculate clinoptilolite stability using these information.

Calculate stability fields of the other zeolites and clays that might provide sorption retardation for radionuclides.

Previous research into zeolite and clay stability will be utilized more heavily in future analytical efforts.

RECOMMENDED PROGRAM:

To continue the existing program of activities and to collect in situ data using our own drilling technology. These new data could then be utilized to calculate authigenic mineral stability more accurately than the present analytical efforts.

Principal Investigator:

Dr. R. G. Burns (MIT) with Dr. T. Bowers (MIT) are Co-Principal Investigators on the project.

Geochemistry and Mineralogy

ISSUES:

To what extent, if any, can the DOE take credit for radionuclide sorption by zeolites, clays, and oxyhydroxides? Can credit be taken for key radionuclides whose travel time and concentration limits might otherwise exceed the established limits?

Characterization Issues:

How do clays and zeolites behave during sorption/desorption? To what extent do they favor certain radionuclides? How does temperature affect sorption, sorption rates, desorption, and desorption rates? How do radionuclide concentrations affect sorption and desorption? How does zeolite crystal orientation affect sorption and desorption?

How do transition-metal oxyhydroxides respond to actinide transport as colloids? To what extent if any do transition-metal oxyhydroxides provide sorption? If sorption is provided, by what mechanism does this occur?

Review Issue:

Does the sorption/desorption work done by the DOE contractors cover the significant issues and are their methods of analyses sound to the extent that they report conservative values?

GENERAL OBJECTIVE:

Determination and characterization of the behavior of authigenic zeolites, clays, and transition-metal oxyhydroxides during sorption and desorption of radionuclides (and proxies) under repository near-field and far-field conditions.

Specific Objectives:

Review the sorption/desorption literature provided by the DOE contractors and determine the value of those data with respect to providing a comprehensive understanding of the retardation parameters for the Yucca Mountain site. Determine whether these parameters are conservative and are focused towards obtaining realistic in situ approximations.

Provide basic laboratory analyses on single crystal (pure mineral) sorption/desorption studies using a variety of proxies for radionuclides. Utilize co-calibrated equipment to insure reproducibility of the results.

Through the experiments with pure minerals, provide an understanding of the efforts of variation in temperature, crystal orientation, time of exposure, crystal size, radionuclide (proxy) concentrations, competing cations, sieving effects and other parameters that may be important with respect to predicting in situ Yucca Mountain sorption/desorption reactions.

Provide an understanding on an atomic/molecular basis on how, where, and why sorption/desorption take place with respect to each mineral and radionuclide in the potential reaction, so that there is a sound theoretical basis for future postclosure predictions of potential retardation.

Provide similar basic information as explained in the previous objectives for minerals in fractures and compare these data to similar information collected for minerals in pores.

ACTIVITY SUMMARY:

Constant temperature bath exchange solutions have been utilized to explore single crystals of known composition (by electron microprobe [EM], scanning electron microprobe [SEM], and ion microprobe analyses [SIMS]). Single crystals of clinoptilolite, mordenite, and analcime have been studied. After experimental exposure, SEM, EM, and SIMS analyses of each crystal with respect to its crystallographic orientation is performed. These experiments are run with variations in both solutions (proxies for radionuclides) and variations in temperatures (see Appendix C: Wood, V. J., M. S. Hubbard, and R. G. Burns, 1988).

Magic angle NMR studies are made on exchanged crystals to determine the sites of sorption by the radionuclide proxies.

Clay minerals and oxyhydroxides have not been utilized as yet during the experiments.

Sorption/desorption data have been reviewed as has been provided by the DOE program.

FINDINGS:

Magic angle studies are beginning to indicate where in the clinoptilolite and heulandite structures various exchanged ions are located. These information are preliminary and more work is needed to resolve this basic issue.

Analcite is not a very good exchanger, primarily because of its tight structure; consequently, it will be insignificant with respect to acting as a sorbing barrier to radionuclide escape from the repository.

Both heulandite and clinoptilolite are relatively good exchangers and both show crystallographic influences for Cs (clinoptilolite shows less of an influence than heulandite). The Cs concentration of the (010) face of heulandite is considerably lower than those of the other two faces, demonstrating that Cs readily enters the heulandite structure along the open channel [100] and [001] direction. The Cs concentrations of the heulandite (100) and (001) faces are comparable or slightly greater than corresponding faces of clinoptilolite which conflicts with older literature which states that the cation exchange properties of heulandite and clinoptilolite are quite dissimilar (see Appendix C).

Since the ground water flowing through Yucca Mountain is likely (chemistry unknown at present) to be dominated by Na, HCO_3, and Cl ions, these were included in some of the experiments. The results of these analyses indicate a slight enrichment of Na and a depletion of K occurred in the Na-loaded crystals (clinoptilolite). The presence of NaCl, however, decreases the uptake of Cs into clinoptilolite and heulandite (see Appendix C).

Clinoptilolite crystals have been mounted on their (010) faces and reacted with 50 ml aliquots of CsCl solutions ranging in concentration from 1 M to 0.0001 M. The amount of Cs exchanged into clinoptilolite crystals decreases with increasing dilution of the CsCl solutions. The efficiency of removal of Cs uptake by the (010) crystal faces increases from 1 M CsCl to 0.0001 M CsCl. Heulandite shows similar effects of CsCl dilution to clinoptilolite (see Appendix C).

INTERPRETATION OF FINDINGS:

The findings of our experiments indicate that various major sorption issues are not being addressed by the DOE subcontractors. Among these issues are the effects of crystal orientation and crystal size. The mineralogy investigators working for the DOE do not report crystal orientation for minerals described from the fractures, therefore, it is not feasible at present to determine potential sorption in the fracture system.

We have concluded that of the zeolites present clinoptilolite, heulandite, and mordenite have the potential to be good sorbing exchangers. Temperature, crystal size, crystal orientation, vadose-water chemistry, concentrations of competing cations, interactions with competing exchangers, initial cations within the supercage of the exchangers, among other controlling parameters greatly affect the potential sorption ability of the natural environment. Unless these issues are fully addressed, the predictability of natural barrier sorption for Yucca Mountain is virtually impossible.

ADDITIONAL WORK REQUIRED:

Reestablish our program using magic angle NMR.

Continue our standards exchange single-crystal bath studies.

Start oxyhydroxide studies with actinide proxies.

Start clay exchange, ion filtration studies.

Analyze key pore and fracture horizons which may provide the bulk of the potential sorption effort at Yucca Mountain.

Build a predictive model using the field and laboratory data collected.

RECOMMENDED PROGRAM/EXISTING PROGRAM:

Objective:

To respond to our Key and Characterization Issues relative to licensing issues.

Activity:

To continue our efforts as outlined in Additional Work Required.

EXISTING PROGRAM:

The existing program is moving ahead with very satisfactory progress. It will be necessary to obtain in situ samples from Yucca Mountain to bring this research in line with licensing issues.

Principal Investigator:

Dr. R. G. Burns (MIT) is the Principal Investigator of this project.

Geochemistry and Mineralogy

ISSUE:

Will glass instability above and below the proposed high-level nuclear waste repository jeopardize the isolation or assist in the isolation of radionuclides from the accessible environment?

Characterization Issues:

To what extent do iron oxides, titanium oxides, and oxyhydroxides as microphenocrysts provide chemical information regarding geochemical-environmental parameters during the diagenetic hydration of acid volcanic glass.

To what extent do the iron oxides and oxyhydroxides contribute to volcanic-glass stability? Instability? In this respect, do they contribute to elevated hydration rates of the glass, and if so, by what reaction mechanism?

How can these information be used to assess sorption chemistry, colloid formation, and neomineralization of smectites and zeolites?

GENERAL OBJECTIVES:

Determination and identification of magnetic and paramagnetic microphenocrysts in volcanic glass in tuffs at Yucca Mountain.

Specific Objectives:

Identify micromineral phenocrysts in volcanic glass at Yucca Mountain.

Describe their distribution, magnetic properties and crystal structure.

Describe and identify these minerals with respect to their stratigraphic position above and below the proposed repository horizon.

Collect similar data from fresh and altered (hydrated) glasses to acquire data on iron mobility.

ACTIVITY SUMMARY:

Samples have been collected from the Tiva Canyon and upper portions of Topopah Springs Member of the Paintbrush Tuff. Sample collection has been made during magnetic stratigraphy investigations (see Appendix C: Schlinger, C. M., 1989).

Laboratory data using Transmission Electron Microscopy (TEM) and magnetics have been acquired.

FINDINGS:

The iron-oxide phases appear to be mostly magnetite-maghemite microphenocrysts. Euhedral microphenocrysts of silicate phases have been found to be present in the upper Topopah Springs Member. It appears that the upper Topopah Springs Member has undergone remagnetization (CRM) which suggests that the time stratigraphic depositional history may be correct. This period of remagnetization probably has occurred during the emplacement of the Tiva Canyon Member (see Appendix C).

INTERPRETATION OF FINDINGS:

Magnetic and paramagnetic microphenocrysts are subject to diagenetic alteration changing their magnetic properties and therefore the paleomagnetic signature of the host rock. The geochemical interaction of these components with the host glass is not yet understood as changes in funding have not allowed for this line of research.

ADDITIONAL WORK REQUIRED:

Additional TEM and probe data must be acquired to resolve the geochemical interaction of volcanic glass and oxyhydroxide phenocrysts.

RECOMMENDED PROGRAM:

Objective:

To respond to our Key and Characterization Issues.

Activity:

To continue our efforts by accomplishing the additional work that we stated is required.

EXISTING PROGRAM:

Status of Previous Research:

Although our preliminary results indicate that significant geochemical reactions have taken place and are probably taking place, we have not followed through to analyze the significance of these reactions with respect to repository performances. Future work is scheduled to accomplish our goals.

Principal Investigator:

Dr. C. M. Schlinger (University of Utah) is the Principal Investigator of the project. After the TEM work is completed, Dr. R. G. Burns will become the Principal Investigator dealing with the mineralogy and geochemistry problems.

Geochemistry and Mineralogy

ISSUES:

Can the stability (chemical and physical) of volcanic glass above and below the repository horizon at Yucca Mountain affect the postclosure performance of the proposed repository?

Can the chemical stability of volcanic glass at the desert surface act as an analog for past and future geochemical reactions within the vadose zone?

Characterization Issues:

To what extent will there be an evolution of heat from hydrating volcanic glass below the proposed repository and to what extent might heat ponding affect repository performance?

To what extent is volcanic glass from Yucca Mountain chemically stable or unstable with respect to forming authigenic minerals in the recent past?

Can rates of volcanic-glass hydration be determined from soil samples?

If volcanic glass is not chemically stable under repository conditions, how might this change water chemistry and thereby affect authigenic-mineral stability and radionuclide retardation?

Might additional authigenic minerals be formed from future volcanic glass hydration?

The potential future hydration of volcanic glass might change the physical properties of the vitrifier below the proposed repository. How might this affect potential future transport of radionuclides, in particular, travel-time estimates?

Review Issue:

The DOE has stated in their EA that they do not expect dissolution and that volcanic glass that could be altered has already been altered. To what extent can their statements be supported by our research into glass stability?

GENERAL OBJECTIVES:

Assess the geochemical and mineralogical stability of rhyolitic volcanic glass at Yucca Mountain under present conditions and under proposed repository conditions, so as to be able to predict the rates of authigenic-mineral formation, the chemistry of fracture flow and pore-water liquids and whole-rock stability.

Specific Objectives:

Obtain geochemical data relative to the hydration reactions of volcanic glass at Yucca Mountain.

Obtain mineralogical data for neomineral formation and authigenic-mineral stability.

Obtain rates of potential reactions that are presently occurring at Yucca Mountain.

Assess statements made by the DOE in the literature, which appear to be unfounded based upon lack of supportive evidence.

Assess authigenic mineral production to assist in resolving issues relative to the genesis of Trench 14 deposits.

Obtain basic information as to the heats of reactions for glass hydration, so as to be able to predict future repository conditions.

ACTIVITY SUMMARY:

Bedded tuff cobbles and pebbles acting as clastics have been studied geochemically and mineralogically. Literature produced by the DOE has been reviewed.

FINDINGS:

Rain-water acting on bedded tuff cobbles at the surface have a tendency to replicate diagenetic and textural features of similar lithologies at depth in Yucca Mountain, such as in the Calico Hills formation. Opal formed as a consequence of glass-hydration reactions appear similar to opal observed from Trench 14 (see Appendix C: Blundy, J., et al., 1987, 1988).

INTERPRETATION OF FINDINGS:

Our findings at present raise fundamental questions concerning future diagenetic reactions within Yucca Mountain. We find that contaminated fluids leaking from the proposed repository may not pass through highly sorptive zeolite-rich tuffs altered 11 million years ago, but along fractures lined with more recently formed authigenic minerals containing nonsorptive calcite and silica assemblages. We find evidence to suggest that volcanic glass at Yucca Mountain is very reactive and that reaction rates are relative to the availability of water and affected dramatically by increasing temperatures. A manuscript with some of our results has been submitted to Earth and Planetary Science Letters for publication (a copy is included in Appendix C).

ADDITIONAL WORK REQUIRED:

Obtain the actual rates of reaction of surface-glass hydration and authigenic-mineral production.

Obtain basic geochemical and mineralogical data from glass at depth at Yucca Mountain.

RECOMMENDED PROGRAM/EXISTING PROGRAM:

As a result of funding cuts, this program has been temporarily suspended until the 1989-1990 funding period. It is recommended that this program be reactivated as soon as possible.

STATUS OF PREVIOUS RESEARCH:

We are presently awaiting the publication of our last manuscript.

Principal Investigator:

Dr. R. G. Burns (MIT) is the Principal Investigator assisted by Dr. M. Morgenstein and Dr. J. Blundy (Oxford).

Geochemistry and Mineralogy

ISSUES:

Can the rates of vadose-zone chemical reactions be determined to the extent that we understand the roles of these reactions in providing retardation of radionuclides, thereby establishing isolation of the radioactive waste from the accessible environment after closure in accordance with the requirements set forth in 40 CFR Part 191, 10 CFR Part 60, and 10 CFR Part 960?

Characterization Issues:

Can desert-varnish dating by cation-ratio techniques be used to determine geologic ages of terraces in the Yucca Mountain area?

Can desert-varnish dating by cation-ratio techniques be used to determine rates of authigenic mineral formation from rhyolitic glass at Yucca Mountain?

Can desert-varnish dating by cation-ratio techniques assist in resolving Trench 14 problems and sandramp problems?

Review Issue:

Can the desert-varnish dating by cation-ratio techniques utilized by the USGS be reproduced with similar results?

OBJECTIVES OF ACTIVITY:

Make an independent assessment of desert-varnish dating cation-ratio technique by doing the following:

Review the cation-ratio dating literature and determine the methods employed.

Reproduce this established methodology and assess the results relative to those data which have been reported in the literature.

If the results do not match, determine the reason(s).

Provide support data for the work completed.

ACTIVITY SUMMARY:

The following techniques have been scrutinized with respect to cation-ratio dating of desert varnish:

Backscatter Electron Microscopy (BSE).

Electron Microprobe (EM).

Scanning Electron Microscope with Energy Dispersive Analyses (SEM/EDX).

PIXE element analysis.

The literature generated by Dorn, Harrington, and Whitney have been reviewed.

Samples of desert varnish have been examined by the various techniques from various locations in Nevada and South Mountain, Arizona.

FINDINGS:

Preliminarily, there appears to be various serious problems with the established methods of investigation. Element concentrations and element/element ratios show extreme variability. Potassium, calcium, K+Ca, and K+Ca/Ti do not consistently decrease with varnish age (depth of the varnish layer) as the cation ratio dating method implies. Using EDX analysis, as was done by Harrington and Whitney (1987), Ba in the varnish interferes with the Ti signal, suggesting that all previously reported cation ratio dating values are effectively K+Ca/Ba+Ti instead of K+Ca/Ti. Since Ba, like K and Ca, is a mobile element, the accuracy of the cation ratio dating technique is compromised. The PIXE method used by Dorn has the same problem as the EDX method used by the USGS. Finally, the oldest varnish on a rock specimen, due to its location in hollows and fractures, makes up only a small percentage of the total varnish and is biased against sampling (PIXE) on analysis (SEM/EDX) (see Appendix C: Krinsley, D. and S. Anderson, 1989).

INTERPRETATION OF FINDINGS:

At present, we do not understand why the established cation-dating method appears to give usable minimum ages. We do not know if the method as is or as possibly modified will provide accurate chronological information. On these basis, we have been unable to respond to our Key Issue or Characterization Issues. With respect to our Review Issue, we find that the results of our investigation to date do not match the USGS data.

ADDITIONAL WORK REQUIRED:

Analyze desert varnish using a variety of techniques including SEM/WDX (wave length dispersive which appears to distinguish between Ba and Ti).

Analyze desert varnishes for two major locations previously analyzed by Dorn.

RECOMMENDED PROGRAM/EXISTING PROGRAM:

Objective:

To respond to our Key and Characterization Issues.

Activity:

To continue our efforts by accomplishing the additional work that we stated above.

STATUS OF PREVIOUS RESEARCH:

Although our preliminary results indicate serious problems with the cation-dating method for desert varnish dating, we must stress that more work is required prior to obtaining reliable conclusions. The information we presently have is not publishable without additional supportive data which needs to be collected.

Principal Investigator:

Dr. D. Krinsley (ASU) is the Principal Investigator on this Project.

Site-Specific Mineralogic and Geophysical Studies to Establish the Hydrogeology of the Vadose Zone.

The complex and essentially unknown hydrologic conditions in the vadose zone and general absence of demonstrated investigative techniques that are powerful enough to characterize this environment with confidence have stimulated several alternative investigative approaches. The following efforts explore possibilities that have been recognized as potentially useful in drilling investigations and in establishing indirect evidence of ephemeral fracture flow.

Geochemistry and Mineralogy

ISSUES:

Is there a method, that complements hydrogeologic observations (water sampling and moisture monitoring), such as utilizing the geochemistry of authigenic zeolites, that will provide an understanding of fracture flow in the vadose zone? If such a method is developed, to what extent does it predict the motion of vadose-zone water? And how would data obtained using such a method affect radioactive waste isolation?

Characterization Issues:

Can the tandetron (accelerator mass spectrometer, or AMS) identify the presence of carbon-14, tritium, and/or iodine in single zeolite crystals? And, if so, can a technique be developed to do this on a routine basis?

Will this technique be able to distinguish between liquid flow and vapor flow?

Can we distinguish between authigenic zeolites in fracture and matrix with respect to their exposure to relatively "young" waters?

GENERAL OBJECTIVES:

Utilize AMS (tandetron) technology to develop a new technique whereby tritium, carbon-14, and iodine can be analyzed in single crystals of zeolites to determine the relative age of last waters of possible exposures within the zeolite supercage. This will make an assessment of the role of fracture flow in vadose-zone liquid transport possible.

Specific Objectives:

Develop an ability to utilize more than one key ion so as to strengthen the dating ability of this technique (such as carbon-14 and tritium).

Once developed, test this technique to insure its utility with respect to licensing issues.

Utilize this technique on a survey of fractures and matrix in situ materials obtained from Yucca Mountain to make a determination of the depth of penetration of "young" water through the vadose zone.

ACTIVITY SUMMARY:

Utilizing the tandetron facility at the University of Toronto, we have been successful in developing a laboratory technique to measure carbon-14 in single crystals of clinoptilolite. These results indicate that ^{14}C (as CO_2) are exchangeable into clinoptilolite. The fractionation factors are being worked out for the exchange reaction. Consequently, we should be able to distinguish the relative activity of vadose fracture flow if and when we are able to obtain Yucca Mountain samples.

We are progressing with iodine and tritium techniques so that we would be able to use these in conjunction with ^{14}C when in situ samples become available.

FINDINGS:

We are optimistic about the relevance of this approach since we now have the capability to obtain the ages of the water of last exposure to zeolites in the vadose zone. If actual liquid samples are not obtained from Yucca Mountain, then whole-rock samples may prove useful in deciphering the relative importance of fracture flow in the vadose zone.

INTERPRETATION OF FINDINGS:

At present, we are unable to make an interpretation of our findings since we have not had the opportunity to obtain Yucca Mountain samples to apply our laboratory results. With an appropriate drilling program, we will be in a position to be able to distinguish the potential flow paths to the accessible environment and the mechanism of that transport.

ADDITIONAL WORK REQUIRED:

Continuation of our laboratory efforts in development of techniques utilizing the Tandetron.

Acquisition of Yucca Mountain whole-rock samples for pore and fracture analyses.

RECOMMENDED PROGRAM:

Objective:

To respond to our Key and Characterization Issues.

Activity:

To continue our laboratory efforts and to expand our efforts into a field/laboratory program specific to Yucca Mountain materials.

EXISTING PROGRAM:

The existing program is moving ahead very slowly due to constraints with funding, and obtaining in situ samples from Yucca Mountain. The design aspects of the program with respect to the development of new techniques have been extremely satisfying.

Principal Investigator:

The Principal Investigator of the program is Dr. J. C. Rucklidge (University of Toronto, Canada). Dr. R. G. Burns (MIT) is assisting with respect to issues in mineralogy.

Geochemistry and Mineralogy

ISSUE:

Will the geologic barriers isolate the radioactive waste from the accessible environment after closure in accordance with the requirements set forth in 40 CFR Part 191, 10 CFR Part 60, and 10 CFR Part 960?

Characterization Issue:

Can magnetic stratigraphy of the volcanic units at Yucca Mountain be used to fingerprint time stratigraphic units, thereby aiding the control of depth of drilling stratigraphy?

GENERAL OBJECTIVE:

Determination of magnetic stratigraphy for Yucca Mountain for use as a drilling control tool.

Specific Objectives:

Establish the feasibility for using magnetics to determine stratigraphic position during drilling.

Establish the similarities and variabilities of magnetic properties in a lateral extent per unit.

Establish the similarities and differences of magnetic properties in stratigraphic profiles.

ACTIVITY SUMMARY:

Field-data collection of samples and magnetic data from outcrop samples from Tiva Canyon to the upper beds of Topopah Springs Member have been carefully made. The sampling areas have been carefully mapped and susceptibility and NRM data have been collected. Magnetic-background data have been collected also. Data have been collected from the west side of Yucca Mountain (see Appendix C: Schlinger, C. M., 1989).

Transmission-electron microscopy (TEM) has been used to characterize the size, distribution, and mineralogy of the magnetic minerals.

FINDINGS:

Magnetic-field data collected suggest that there is good lateral continuity and stratigraphic susceptibility anomalies to utilize magnetics as a "fingerprinting" indication of drilling depth (formation stratigraphy).

There appears to be a time stratigraphic problem in the upper Topopah Springs Member of the Paintbrush Tuff where this portion of the unit has NMR characteristics similar to the overlapping unit (Tiva Canyon) and is dissimilar with the Topopah Springs Member below. This may suggest that the emplacement and cooling history of the stratigraphic framework is not well understood or that the top of the Topopah Springs Member has a CRM component (see Appendix C).

INTERPRETATION OF FINDINGS:

The findings thus far suggest that magnetics appears to be a good tool to use to obtain stratigraphic control during drilling. Nevertheless, more field data are required to obtain detailed information not presently exposed. In order to accomplish this, drilling samples must be obtained. It appears that magnetic data can assist in refining time-stratigraphic cooling history of the tuff units and that our present understanding of the parameters are limited and potentially inaccurate.

ADDITIONAL WORK REQUIRED:

Obtain closely-spaced detailed magnetic data from core samples and boreholes.

Compare the magnetic data with petrographic data so that magnetic profiles can be constructed.

RECOMMENDED PROGRAM:

A field-sampling program is recommended to obtain detailed magnetic information.

Objective:

The objective of this program is to establish detailed magnetic stratigraphy of Yucca Mountain to be used in drilling control and to refine our understanding of the time stratigraphic units.

EXISTING PROGRAM:

The existing program has been held on standby due to budget constraints.

Principal Investigator:

The Principal Investigator for this project is Dr. C. M. Schlinger (University of Utah).

Past Climate and Related Genesis of Authigenic Desert Carbonates and Silicates.

There are analytical support activities of a geochemical and mineralogic nature that have been called upon to aid climate-change investigations. These generally seek to establish paleohydrologic conditions of formations based on textures, mineralogy, geochemistry, and other parameters that can only be established by indepth laboratory analyses.

Geochemistry and Mineralogy

ISSUE:

Can authigenic reactions within volcanic ash be sufficiently understood so that these ashes can be correlated across the Tecopa Basin, and be used in obtaining accurate stratigraphic data which then can be utilized for interpretation of past climate and paleohydrologic issues?

Characterization Issues:

Can the history of diagenesis in volcanic ashes in the Tecopa region be of assistance in studying authigenic reactions in volcanic tuffs at Yucca Mountain?

Can the history of diagenesis in volcanic ashes in the Tecopa region be of assistance in understanding the paleohydrology of Lake Tecopa with respect to the last 100,000 years?

GENERAL OBJECTIVE:

Characterize the diagenetic geochemical activities that have taken place in volcanic ashes in Lake Tecopa, to assist in resolving stratigraphic correlation of units and thereby resolving the interpretive hydrogeologic activity of the area, as it may relate to past climate in the region of Yucca Mountain.

Specific Objectives:

Develop an understanding of the variation of volcanic-glass diagenesis and authigenic-mineral production in the Lake Tecopa Basin and margins, with respect to key ash horizons.

Provide geochemical data, which can be utilized to quantify the diagenetic changes across the Tecopa Basin.

Provide these data to the senior Field Stratigrapher, so that he may utilize these information in mapping the sediments of the Tecopa Basin.

ACTIVITY SUMMARY:

Field data and samples have been collected from Lake Tecopa and geochemically analyzed.

Laboratory and field data have been provided to Dr. R. Morrison, senior Field Stratigrapher, to assist him in his efforts.

FINDINGS:

A paper containing our findings has been presented at the Denver GSA meeting in 1988. Tuff B (Bishop Ash) has been found to alter differently depending upon its geographic location. As a consequence, it is assumed at present that there are three fluid sources reacting with the ash:

a. hot springs;

b. hydrothermal fluids (alkali enriched); and

c. carbonate-enriched ground water venting into the lake as cold springs.

The details of these information will assist in the mapping of the Tecopa Beds (see Appendix C: O'Hara, P. F., et al., 1988).

INTERPRETATION OF FINDINGS:

At present, the stratigraphic units in Tecopa are being mapped and each bed is being classified as to the environment of deposition. When this process is completed, a better history of the hydrogeology of the Tecopa Basin will be available. These information will then be utilized to understand the regional past climate and paleohydrology of the southern Great Basin near Yucca Mountain (see Appendix C).

ADDITIONAL WORK REQUIRED:

Additional work required in this program will primarily be in resolving various ages of the ashes located by the principal investigator. Most of the program is designed to support Dr. R. Morrison's work on Lake Tecopa stratigraphy and thus, until more field work is completed, it is difficult to predict the geochemical and mineralogic requirements for the future.

RECOMMENDED PROGRAM:

Objective:

To respond to our Key and Characterization Issues and to assist Dr. Morrison with geochemical and mineralogic sample studies.

STATUS OF PREVIOUS RESEARCH:

The research is progressing at a satisfactory pace.

Principal Investigator:

Dr. D. Krinsley (ASU) is assisting Dr. R. B. Morrison in obtaining basic geochemical and mineralogic data.

Geochemistry and Mineralogy

ISSUES:

Carbonates, as sedimentary precipitates forming on the desert surface, in fracture fillings, and as K horizons in desert soils, have distinguishing characteristics with respect to the environment of deposition (geochemical and biogeochemical precipitation). If the environment of deposition is affected by the past climate and paleohydrology, desert carbonates could prove of importance with respect to resolving licensing issues. Can sufficient paleohydrological information be acquired from desert carbonates to assist in interpreting the past climate for the past 100,000 years?

Characterization Issues:

Can desert carbonates be distinguished on the basis of petrological and geochemical evidence to the extent that these information impart information concerning the environment of genesis?

To what extent does biological activity such as algal growth promote carbonate precipitation in desert marsh lands, desert lakes, and temporary desert ponds?

To what extent are these deposits different/similar to inorganic-carbonate precipitation? To what extent do biocarbonate deposits inform us of past climate conditions?

How do Trench 1 carbonate sediments compare with modern-day desert-pond sediments?

How do marshland sediments differ from desert-lake sediments?

How variable is the aerosol-carbonate depositional contribution to desert soils in the immediate area of Yucca Mountain? What is the relative contribution between aerosol and in situ biotic transfer carbonate precipitation in the immediate area of Yucca Mountain.

GENERAL OBJECTIVE:

Obtain sufficient baseline information concerning the petrographic, geochemical, and biogeochemical composition of desert carbonates to be able to understand their genesis from the standpoint of environmental parameters.

Specific Objectives:

Be able to distinguish the mechanism and environment of deposition of carbonate sediments including clastic deposition and reprecipitation, biocarbonate precipitation, and evaporite precipitation.

Develop petrological tools for distinguishing varieties of carbonate deposition.

Develop geochemical tools for distinguishing varieties of carbonate deposition.

Utilize these information in interpreting the environments of deposition and thereby the paleohydrology and past climate of the area of deposition.

Utilize these information in interpreting the conditions which promoted sedimentation in Trenches 14, 17, and 1.

ACTIVITY SUMMARY:

Utilizing the SEM, TEM, and electron microprobes determine the fabric and geochemical compositions of desert carbonates from various known and unknown environments of deposition.

Determine whether the information collected are significant in distinguishing various environments and mechanisms of carbonate precipitation from each other. Utilize these information to assist in interpreting past climate conditions and genesis of opal-carbonate deposits.

FINDINGS:

Petrographic and mineral analyses of carbonate sediments from known environments of desert-marsh lands have been completed. Backscatter SEM data have been obtained from Trench 1 samples indicating cool fresh-water environment for carbonate deposition. These information, along with geochemical data which are yet to be collected, will provide the startup data accumulation for this program. Trench 14 and sandramp samples have been collected and are planned for future laboratory analysis. Carbonates from Tecopa have been studied to ascertain the contribution of detrital volcanic glass and these information have been provided to the Tecopa project personnel.

INTERPRETATION OF FINDINGS:

At present, our findings are insufficient to obtain firm conclusions. More samples and more analyses are necessary prior to obtaining usable conclusions.

ADDITIONAL WORK REQUIRED:

Continuation of laboratory efforts in the acquisition of petrographic and geochemical data on carbonate sediments from Yucca Mountain and surrounding areas.

Start comprehensive analyses of Trench 14 samples as soon as we have completed Trench 1 samples.

RECOMMENDED PROGRAM:

Objective:

To respond to our Key and Characterization Issues.

Activity:

To continue our laboratory and field data collection efforts.

EXISTING PROGRAM:

The existing program will expand its efforts as soon as we have completed working on desert-varnish studies.

Principal Investigator:

The Principal Investigator for this effort is Dr. D. Krinsley (ASU) assisted by Mr. J. Quade (University of Utah) and paleontologists (from Columbia University, Lamont-Doherty Geological Observatory).

Geochemistry and Mineralogy

ISSUES:

Silica and carbonate fracture-filling deposits located in Trench 14 are geochemical precipitates from aqueous solutions. To what extent do the aqueous solutions responsible for these authigenic mineral precipitates jeopardize the postclosure performance of the proposed repository at Yucca Mountain, if the conditions responsible for their formation were to reoccur?

Characterization Issues:

What is the genesis of fracture-filling opal in Trench 14?

What is the genesis of fracture-filling carbonates in Trench 14?

What is the immediate source for ash and bioclastic(?) debris in the fracture filling of Trench 14?

Is there geochemical evidence, such as might be obtained from isotope analyses, that might suggest the origin and timing of these deposits?

Are there analog deposits that have known origins that might assist in interpreting the genesis of deposits in Trench 14?

GENERAL OBJECTIVES:

Provide a comprehensive understanding of the genesis of the carbonate and silicate deposits and features within Trench 14 and similar and potentially related structures (such as sandramps and Trench 17), to be able to assess their significance on the postclosure performance of the proposed repository at Yucca Mountain.

Specific Objectives:

Study carbonate and opal deposits of known origin for comparison to Trench 14 deposits.

Analyze Trench 1 deposits from the carbonate characterization study to assess the significance of biological-carbonate production (in situ) in desert fractures and faults.

Obtain field and laboratory data utilizing paleontological, geochemical, and mineralogical techniques so that a reasonable understanding is obtained for the genesis of Trench 14 deposits.

ACTIVITY SUMMARY:

Soil-opal genesis from diagenetic reactions of volcanic glass at Yucca Mountain have been investigated both geochemically and mineralogically. These information indicate that CT opal is presently or relatively recently being formed in the desert soils juxtaposed to Yucca Mountain.

Trench 1 studies indicate that biocarbonate precipitate may be more important than previously recognized and that not all of the desert carbonates are a function of aerosol accumulation.

Field evidence of fracture boundaries indicate that host rocks do not appear to be hydrothermally altered; consequently, the liquids responsible for the deposition of the opal and carbonates may have been ambient in temperature.

SEM backscatter analysis has been determined as a usable tool to distinguish textural carbonate data important to the project.

FINDINGS:

Desert-soil opal formed from the diagenesis of volcanic glass can be partially and possibly wholly responsible for the opal deposits as observed in Trench 14. Additionally, other mechanisms of opal genesis for Trench 14 are certainly possible (see Appendix C: Blundy, J., et al., 1987, 1988).

Biotic-carbonate genesis in desert environments such as ponding water in fractures, may be a fairly significant mode of carbonate production (see Appendix C).

Calcium is released from volcanic-glass hydration reactions at the desert surface. This release of calcium may be partially responsible for carbonate precipitation in desert soils. All of the calcium is not necessarily supplied through aeolian transport and deposition (see Appendix C).

INTERPRETATION OF FINDINGS:

At present, there is insufficient data to resolve the Key and Characterization Issues. Diagenetic reactions in the soil zone and on outcrops may in part provide sufficient source materials to form opaline and carbonate deposits. In addition, aeolian transport may contribute to the supply. Since the timing of these reactions and the relative importance of other variables such as biological precipitation of authigenic minerals are essentially unknown, it is presently too early to establish the genesis of these deposits (see Appendix C).

ADDITIONAL WORK REQUIRED:

To analyze Trench 14 material recently collected during the USGS field trip to Yucca Mountain.

To complete analyses of Trench 1 samples.

To reestablish the volcanic-glass alteration studies and obtain rates of chemical reactions for the desert-surface authigenics.

RECOMMENDED PROGRAM:

Objective:

To respond to our Key and Characterization Issues.

Activity:

To continue our efforts as stated in Additional Work Required.

EXISTING PROGRAM:
Status of Previous Research:

As a consequence of funding cuts, we have been unable to continue our glass-hydration research and have had to slowly schedule Trench 1, 14, 17 and sandramp samples into our laboratory. Consequently, although our research is progressing, it is fairly slow.

Principal Investigator:

Dr. D. Krinsley (ASU) is the Principal Investigator for carbonate research and Dr. R. G. Burns (MIT) is the Principal Investigator for opal research.

Appendix C

Geochemistry and Mineralogy

List of Published Papers, Abstracts, and Manuscripts included in the appendix.

Blundy, J. D. , R. G. Burns, and M. E. Morgenstein, 1987, Authigenic minerals in rhyolite tuff at Yucca Mt., Nevada; diagenesis in a proposed nuclear waste repository: Geological Society of America Annual Meeting, Poster Session, Abstract.

Blundy, J. D., R. G. Burns, M. E. Morgenstein, 1988, Non-sorptive minerals forming in rhyolite tuff at Yucca Mountain, Nevada: diagenesis in a proposed nuclear waste repository: submitted to Earth and Planetary Science Letters, 39 p.

Bowers, T. J. and R. G. Burns, 1988, Activity diagrams for clinoptilolite: susceptibility of this zeolite to further diagenetic reactions: manuscript submitted to the American Mineralogist, 41 p.

Burns, R. G. and T. J. Bowers, 1988, Activity diagrams for clinoptilolite: relevance of zeolitized vitric tuffs at Yucca Mountain, Nevada: Geological Society of America, Abstracts with Program, vol. 20, no. 7, p. A359.

Krinsley, D. and S. Anderson, 1989, Desert varnish: a new look at chemical and textural variations: Geological Society of America Annual Meeting, Poster Session, Abstract.

O'Hara, P. F., Manley, C. R., and Krinsley, D., 1988, Chemical zonation within Bishop Ash, Pleistocene Lake Tecopa, Inyo County, California: Geological Society of America, Annual Meeting, Poster Session, Abstract and manuscript, Poster Session, 22 p.

Schlinger, C. M., 1989, Magnetic Stratigraphy of Ash-flow Sheets at Yucca Mountain, Nevada, Eng. Geol. and Geotech. Eng., Watters (ed.), Balkema, Rotterdam, p. 19 to 24.

Wood, V. J., Hubbard, M. S., and Burns, R. G., 1988, Cesium uptake by clinoptilolite crystals: implications to the immobilization of radionuclides stored at Yucca Mountain, Nevada, Geological Society of America, Abstracts with Program, vol. 20, no. 7, p. A359.

Wood, V. J., Hubbard, M. S., and Burns, R. G., to be published, Cesium uptake by clinoptilolite crystals, manuscript,19 p.

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AUTHIGENIC MINERALS IN RHYOLITE TUFF AT YUCCA MT, NEVADA; DIAGENESIS IN A PROPOSED NUCLEAR WASTE REPOSITORY

№ 136950

BLUNDY, Jonathan D.[1,2], BURNS, Roger G.[1], and MORGENSTEIN, Maury E.[3]
[1]Dept. of Earth, Atmos. & Planet. Sci., MIT, Cambridge MA 02139;
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Cobbles in desert pavement at the base of Yucca Mt derived from bedded tuff above the Topopah Springs Member display prominent geopedal textures in which a leached rind (zone A, 2-4 mm) is separated from core (zone C) by brown vitreous zone B (3-6 mm). This weathering profile is also displayed on outcrop surfaces. Concentration profiles by EMP and SIMS analyses across individual glass shards in the tuffs show uniform Al; losses near margins of Na, Ca, Li, Mn, Fe, and Zr; and gains of K, Rb, and Si. Shards from zones A and B show greater Si and Al relative to zone C, while water (measured by difference) decreases from ~3 wt% (zone C) to ~1% (zone A). Comparisons of zone C glass shards in outcrop surfaces and pavement cobbles reveal that total (mole %) alkali contents remain approximately constant, with higher K and Rb and lower Na, Li, and Ca concentrations in outcrop samples. This indicates a coupled diffusion transport mechanism for these cations in hydrated rhyolite glasses. Suptle variations in Si and Al concentrations correlate with changes of shard surface textures and mineralogy from zone A to C revealed by SEM and XRD. Thus, zone C shards are associated with authigenic smectite and minor clinoptilolite and silica. Shards at the B-C boundary are coated with lepispheres of opal CT and dendritic clinoptilolite, whereas shards at the B-A boundary have crusts of botryoidal opal CT associated with sparry calcite. Therefore, the prominent geopedal zone B corresponds to the boundary between Zones I and II of diagenetic zeolites defined by Iijima (1975). Zone A shards, as well as feldspar phenocrysts, show pitted surfaces indicating the onset of dissolution. They are associated with calcite rhombs, Ca-Mg zeolite, Mn-Fe oxides and evaporite minerals.

The clinoptilolite + opal CT + calcite + smectite phases recorded here resemble mineral assemblages lining fractures throughout the proposed repository and in underlying bedded tuff horizons at Yucca Mt. Thus, diagenetic reactions similar to those between aerated rainwater and rhyolite tuff in desert pavement may be occurring (or have occurred) at depth in the vadose zone throughout the proposed repository.

2 ALL ABSTRACTS—INCLUDING SYMPOSIA ABSTRACTS—MUST be categorized into ONLY ONE of the 35 disciplines below. Do *not* add to the list. Choose the ONE discipline in which peer reviewers would be *best* qualified to evaluate your abstract. This does not necessarily determine the final technical session assigned.

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DETACH FOR MAILING

Non-sorptive minerals forming in rhyolite tuff at Yucca Mountain, Nevada: Diagenesis in a proposed nuclear waste repository

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[Submitted to *Earth and Planetary Science Letters*, December 9, 1988]

Cobbles of desert pavement at the base of Yucca Mt. derived from bedded tuffs above the Topopah Springs Member display prominent geopedal textures in which a leached rind (zone A, 1-2 mm) is separated from core (zone C) by brown vitreous zone B (3-6 mm). This weathering profile is also displayed on outcrop surfaces. Concentration profiles by EMP and SIMS analyses across individual glass shards in the tuffs show uniform Al and Mg; losses near margins of Na, Ca, Li, Mn, Fe, and Zr; and gains of K, Rb, Ba, and La. Shards from zone A have highest Si contents, and water (measured by difference) decreases from ~ 4 wt.% (zone C) to <3% (zone A). Comparisons of zone C glass shards in outcrop surfaces and pavement cobbles reveal that total (mole %) alkali contents remain approximately constant, with higher K and Rb and lower Na, Li, and Ca in outcrop samples. This indicates a coupled diffusion transport mechanism for these cations in hydrated rhyolite glasses. Suptle variations in Si and Al concentrations correlate with changes of shard surface textures and mineralogy from zone A to zone C revealed by SEM and XRD measurements. Thus, zone C shards are associated with authigenic smectite and minor clinoptilolite and silica. Shards at the zone B-C boundary are coated with lepispheres of opal CT and dendritic clinoptilolite, whereas shards at the zone B-A boundary have crusts of botryoidal opal CT associated with sparry calcite. Therefore, the authigenic minerals in geopedal zone B correspond to assemblages occurring in diagenetic Zone II of buried pyroclastic deposits (Iijima, 1975). Zone A shards, as well as feldspar phenocrysts, show pitted surfaces indicating the onset of dissolution. They are associated with calcite rhombs, palygorskite, Mn-Fe oxides, and evaporite minerals. The clinoptilolite + opal CT + calcite + smectite assemblages recorded here resemble mineral deposits lining fractures throughout the proposed repository for underground storage of high-level nuclear waste and in underlying bedded tuff horizons at

Yucca Mt. Thus, diagenetic reactions similar to those between aerated meteoric water and rhyolite tuff in desert pavement may be occurring, or have occurred, in the vadose zone throughout the proposed repository, producing non-sorptive calcite and opal coatings which may retard cation exchange reactions of clinoptilolite and clay silicates.

1. Introduction

Located on the southwest border of the Nevada Test Site, 120 km northwest of Las Vegas, Yucca Mountain consists of a sequence of rhyolitic lavas, ash-flow tuffs and bedded tuffs which exceeds a thickness of 1800 m and ranges in age from 16 to 11 million years [1,2]. Yucca Mountain is the site of a proposed repository for the underground storage of high-level nuclear waste materials [3]. The candidate repository horizon is located approximately 400 m below the surface in the vadose zone some 170 m above the present-day water-table in densely welded tuff of the Topopah Springs Member of the Miocene Paintbrush Tuff unit [4-7]. Numerous drill-core samples taken from widespread locations through Yucca Mountain indicate that secondary minerals, including clay silicates, zeolites, opal and carbonate, have formed by alteration of rhyolitic glasses in certain tuffaceous horizons [8,9]. Zones of zeolitization occur in tuffs now located both above and below the present-day water table. Such zones are commonly discordant with bedding and thicken to the northeast. These observations led to the proposition [9] that extensive zeolitization occurred during elevated heat-flow associated with caldera development approximately 11 Ma ago and pre-dates tectonic tilting of the Yucca Mountain sequence. However, detailed studies of authigenic mineral chemistry through the Yucca Mountain section [9,10] have revealed that significant modifications to zeolite compositions have occurred through interaction of zeolitized tuff with groundwater subsequent to 11 Ma.

Furthermore, zeolites occur along fractures throughout the compacted tuff units, including the level immediately underlying the proposed repository horizon, where glass is parially altered to smectite and calcic clinoptilolite-group minerals [11]. Opal and calcite coatings on fractures have also been observed in the vadose zone [7,11,12] yielding radiometric ages between 300,000 and 30,000 years [13,14]. This evidence, that post-Miocene groundwater interactions have modified pre-existing zeolite compositions and locally precipitated non-sorptive silica and carbonate phases raises questions about future diagenetic trends at Yucca Mountain and the long-term sorptive capacity of the repository host-rocks. In order to assess the nature of vitric tuff/water interactions at Yucca Mountain under present-day conditions, and their influence on ancient tuff-water interactions, a suite of clastic pebbles and outcrop surface samples of tuff from Solitario Canyon adjacent to Yucca Mountain were selected for detailed geochemical and scanning-electron microscope (SEM) studies. The results summarized here suggest that zeolitized vitric tuffs adjacent to the proposed repository are vulnerable to continuing diagenetic reactions.

2. Samples

Solitario Canyon is a prominent fault-bounded depression west of Yucca Mountain developed subsequent to fault movement about 30,000 years ago [15]. The canyon floor is littered with clastic detritus derived from erosion of the Yucca Mountain fault scarp. Particularly prominent amongst this detritus are pebbles of non-welded bedded tuffs derived from horizons between the Tiva Canyon and Topopah Springs Members of the Paintbrush Tuff unit, including vitric tuffs from the Pah Canyon Member, which crop out near the crest of Yucca Mountain above the proposed repository horizon [15,16]. These non-welded bedded vitric tuff units have a characteristic orange-brown coloration and abundant yellow-gray pumice clasts defining a weak bedding fabric [4,5]. In petrographic and compositional characteristics, portions of the Pah Canyon Member resemble the tuffaceous beds of Calico Hills unit which underlies the Topopah Springs Member throughout Yucca Mountain [4,5]. These tuffaceous beds were deposited on 13.6 Ma-old Crater Flat Tuff units as a sequence of sixteen non-welded vitric ash-flows, with thin air-fall and reworked tuffs separating each of the ash flows [15,16]. The interlayered nature of the Calico Hills unit indicates that successive surface layers were exposed to atmospheric weathering between each eruptive event over a 500,000 year interval before they were covered by ash-flow tuffs of the Topopah Springs Member 13.1 Ma ago [2]. Resemblances to the tuffaceous beds of Calico Hills unit make non-welded bedded tuffs below the Tiva Canyon Member a suitable analogue material for the study of progressive diagenetic processes affecting vitric tuffs at Yucca Mountain.

Cobbles of the bedded tuff unit occurring in desert pavement at the base of Solitario Canyon and in outcrop on the west flank of Yucca Mountain display conspicuous weathering rinds resulting from interaction of the tuff with rainwater since pavement and outcrop formation. In pavement cobbles these alteration rinds have a geopedal configuration relative to the desert surface (Figure 1), confirming their origin by *in situ* diagenesis. The alteration rinds are designated as zones A, B, C, and D. The cobble surface develops a vinear of red-brown desert varnish characteristic of arid-climate weathering. The outermost alteration zone A, 1-2 mm thick, effervesces and is readily leached when treated with dilute HCl, indicating the presence of calcite. The conspicuous zone B, 3-6 mm wide, is darker in color, has a vitreous luster, and is only affected by acid in its outer portion. Zone C, representing the bulk interior of the sample, is unaffected by acid and resembles fresh samples of the bedded tuff unit collected at outcrop on Yucca Mountain. Zone D is similar to zone C, but lies below the sediment surface. Two such clastic tuff specimens, designated as samples PC1 and PC4, were among cobbles and pebbles collected in Solitario Canyon from a stable desert pavement (PC4) and an active erosion scarp (PC1) at the foot of Yucca Mountain. In addition, two specimens of bedded tuff were collected at outcrop on the western flank of Yucca Mountain adjacent to the location of drill-core USW G-3 [7]. Sample PC5 was taken close to the base of the bedded tuff horizon, while sample PC6 was collected some 20 cm below the basal vitrophyre of the Tiva Canyon Member. Both outcrop samples have developed alteration rinds on their exposed surfaces resembling the geopedal zones in clasts described above.

3. Analytical Procedures

3.1. Petrology

Thin-section petrographic examination revealed a similarity between the interior portions of outcrop samples PC5 and PC6 and central zone C of the clastic samples PC1 and PC4. Both comprise non-welded vitric tuff in which fresh glass shards (0.15-1 mm long) and welded vitric clasts (1-3 mm) are set in a matrix of argillaceous glass fragments, disseminated fine-grained iron oxides and scarce 5-10 μm plates of a yellow-brown clay silicate. The shards are commonly yellow in color although the vitric clasts and larger shards may have a brown core. Some glasses show perlitic fractures. Phenocrysts (up to 2 mm long) comprise sanidine, plagioclase, biotite, and quartz, and constitute less than 10 volume % of the samples. Pumice clasts up to 1 cm in diameter are invariably altered to fine-grained aggregates of zeolite, clay, and opaque oxide. There is a weakly transitional contact towards zone B marked by the local coalescence of the clay silicate platelets to form irregular lathe-like patches of zeolite, identified as clinoptilolite by X-ray diffraction (XRD) and scanning electron microscopy (SEM) measurements described later, having diameters of up to 50 μm and partially enclosing the glass shards. Within zone B these zeolitic masses increase in abundance but disappear suddenly at the contact with zone A. The interstices in zone A are filled instead by a cryptocrystalline isotropic colorless phase identified as opal CT by XRD and SEM measurements.

3.2. Electron Microprobe

Concentrations of major elements were obtained from electron microprobe (EMP) analyses of individual mineral and glass shards in polished thin sections using a four-spectrometer JEOL 733 Superprobe with full on-line computerized matrix correction and data reduction procedures [17]. In measurements of rhyolitic glasses, a 15 kV accelerating voltage and 10 nA beam current were used with counting times of 20 seconds for all elements except Na, which was analysed first and counted for only 10 seconds in order to minimize loss through volatilization. Loss of volatiles was further reduced by using a defocussed beam of approximately 10 microns diameter to analyse the glass shards. However, a more finely-focussed beam was necessary to analyse the thin zeolite coatings on shards in zone B. To improve precision of elements present in low concentration (e.g. Fe), counting times were increased to 40 seconds. Calibrations were made against analysed standards, such as diopside(65%)-jadeite(35%) glass (providing Ca, Mg, Na, Al, and Si), aenigmatite (Fe, Ti, Na, Si), orthoclase glass (K), and rhodonite (Mn). Precision values to one standard deviation (1 σ) in the EMP analyses of glasses, which are limited by counting statistics, were as follows: SiO_2 0.3%; Al_2O_3 0.5%; CaO 0.5%; K_2O 1.4%; Na_2O 1.1%; FeO 4.8%. Overall accuracy of the EMP-determined concentrations was assessed by analysing the standards as unknowns during and after an analytical session.

3.3. Ion Microprobe

Trace element concentrations were determined by secondary ion mass spectrometry (SIMS) on a Cameca IMS 3F ion microprobe using a primary beam of O^- ions with a net energy of 12.61 KeV and ion current of about 0.1 nA. Spot size was 5-8 microns in diameter. An energy filtering technique [18] was used to reduce molecular ion interferences. Representative isotopes measured relative to ^{28}Si included ^{7}Li, ^{23}Na, ^{39}K, ^{40}Ca, ^{47}Ti, ^{55}Mn, ^{56}Fe, ^{85}Rb, ^{89}Y, ^{90}Zr, ^{93}Nb, ^{138}Ba, and ^{139}La. Element ratios against ^{28}Si were calculated from the background and deadtime corrected intensities, and an individual correction was made for isotopic abundances. Calibration was made by establishing empirical working curves [19] relating relative intensities and absolute concentrations for fused pellets of USGS granite standards G-2 and GSP-1. Precision limits (to 1 σ) based on counting stastics were as follows: Li 2.3%; Na_2O 0.5%; MgO 4%; K_2O 0.4%; CaO 1.4%; TiO_2 2.5%; FeO 1.3%; Rb 2.5%; Y 3.3%; Zr 2.9%; Nb 4.2%; Ba 6.2%; La 10%. Overall accuracy of the SIMS analyses were evaluated by measuring element concentrations in G-2 and GSP-1 run as unknowns at the end of an analytical session. Comparison of SIMS and EMP analyses for K_2O on glass shards revealed a relative discrepency of only 2%. H_2O contents were obtained by subtracting total oxides (including major elements analysed by EMP and trace elements obtained from SIMS analyses) from 100% [20,21].

3.4 Scanning Electron Microscope Measurements.

The JEOL 733 Superprobe used to obtain EMP data was employed as a scanning electron microscope with a reduced condenser aperture and accelerating voltages of 15-25 kV. Typical beam currents were of the order of 150 pA. Semi-quantitative analyses were made by energy dispersive analysis (EDS) with counting times of 20 to 40 seconds.

4. Results

4.1. EMP and SIMS Data

Electron- and ion- microprobe profiles were made across several glass shards in each of the clastic and outcrop specimens, including the different weathering zones A through C of PC1 and PC4. Analyzed shards were generally vesicle- and fracture-free. Table 1 lists representative average compositions of analysed centers of glass shards in different samples, which resemble published analyses of volcanic glasses in drill-core samples from vitric tuffs at Yucca Mountain [9,10], including specimens from the tuffaceous beds of Calico Hills unit. The close resemblance of glass compositions between vitric tuffs from surface deposits and drill-core samples vindicates the importance of studying present-day surface alteration processes in order to understand diagenetic reactions currently, or historically, operating at depth. Average trace element concentrations of a glass shard analysed by SIMS are also given in Table 1. Note the excellent correspondence between EMP and SIMS values for K_2O, CaO, TiO_2, and MgO, testifying to the mutual consistency of these two analytical methods. The relatively high H_2O contents (~4 wt.%) of the glass shards listed in Table 1, which are significantly higher near perlitic fractures, are comparable to values reported for other naturally-occurring [20,21] and experimentally-hydrated [22,23] rhyolitic glasses. Such high H_2O contents largely represent post-erruptive water of hydration, since fresh volcanic glasses in pyroclastic rocks rarely exceed 1 wt.% [24] but undergo hydration rapidly [25,26]. The high water contents of glasses in drill-core samples [9,10], inferred from differences of total oxides from 100%, suggests that post-erruptive hydration of vitric tuffs has been pervasive throughout Yucca Mountain.

Typical concentration profiles of major and minor elements across a glass shard are shown in Figures 2 and 3. These analytical data illustrate major and minor element variations generally observed across glass shards from zone C interiors of clastic and outcrop vitric tuff samples, which include: roughly constant Al, Mg and Si; losses near margins of Na, Ca, Li, Zr, Mn and Fe; and gains near margins of K, Rb, Ba and La. Compositional variations between glass shards from outcrop and clast samples are illustrated in Figure 4. While all analyzed glasses contain approximately constant molar proportions of K_2O plus Na_2O, K_2O concentrations tend to be higher and Na_2O concentrations lower in outcrop samples PC5 and PC6. Furthermore, glasses in stable pavement PC4 cobbles have higher K_2O and lower Na_2O contents than glasses from the active erosion slope PC1 sample. Contours of equal molar alkali concentration in Figure 4 confirm the strongly coupled alkali-exchange trend associated with glass hydration [20,27,28]. The correlation between the extent to which this exchange has proceeded and the sample provenance (pavement or outcrop) suggests that, although initial glass hydration may have been a relatively early event accompanying tuff emplacement [19], alkali-exchange through interaction of glass with vadose water is still actively occurring at the desert surface. Such exchange reaches its greatest extent in PC6 and least in PC1.

4.2. SEM Observations.

Textural features and secondary mineralization associated with glass shards in zones A-C of freshly fractured rock chips of clastic samples are demonstrated by the SEM photographs in Figures 5-8. Glasses in zone A, as well as feldspar phenocrysts, were observed to show extensive pitting indicative of dissolution, in contrast to zone C in which both phases have smooth fresh surfaces. Calcic smectite accompanies glass in zone C, occurring both as interstitial platy aggregates and as honeycomb texture [29] surface coatings (Figure 5). Similar textural features were reported [30] in vitric tuff sequences above zones of clinoptilolite crystallization at Rainier Mesa 50 km north-northeast of Yucca Mountain. Towards the zone C-B contact, shard surfaces develop mammiform protruberances (Figure 6A), which become increasingly spherical and develop into lepispheres of silica (identified by XRD as opal-CT and shown in Figures 6B and C) in inner zone B (designated later as zones B_3 and B_2). The same silica phase takes the form of botryoidal crusts in outer zone B (zone B_1). Compositionally, the botryoidal crusts are nearly pure SiO_2, whereas the opal-CT lepispheres contain appreciable Al, K and Na. The opal lepispheres in inner zone B (zone B_2) are associated with sheaf-like aggregates of dendritic clinoptilolite (Figures 6D and 7). Electron microprobe analyses of the zeolite phase in zone B summarized in Table 2 show that the clinoptilolite crystallites contain higher atomic proportions of (Ca+Mg) than K and Na, with Si/Al ratios of 4.5-5. Such compositions resemble those reported for clinoptilolites associated with opal in tuffaceous beds of the Calico Hills unit and along fractures adjacent to the proposed repository horizon in the Topopah Springs Member [9-12], particularly to the northeast of the exploration block at Yucca Mountain [9]. Calcite is associated with opal-CT in outer zone B (zone B_1), where clinoptilolite is absent. Two textural associations of calcite and opal are observed: calcite rhombs with opal lepispheres near the zone B_1-B_2 contact (Figure 8C and D); and sparry "dog-tooth" calcite with the botryoidal silica crusts near the zone B_1-A contact (Figure 8A and B). Similar calcite + silica assemblages have been recorded as fracture-coatings from borehole [11,12] and trench [13,31] samples at Yucca Mountain. Calcite also occurs in zone A, where opal-CT is absent, in association with a magnesian clay silicate identified by XRD as palygorskite, which occurs as ovoid concretions up to 10 microns in length. Palygorskite + calcite assemblages are common in desert calcretes [32,33], where they often display a concretionary habit [34,35]. Some concretion surfaces are coated with Cl-bearing salts. Manganese and iron oxides occur in the outermost portions of zone A.

The authigenic mineralogy of the geopedal alteration rinds on clastic pebbles of the bedded tuff unit summarized in Figure 9. The mineral zonation sequence resembles portion of that observed in burial diagenesis of thick pyroclastic deposits [36-38], in which Zone I is zeolite-free and is characterized by glass shards altering to smectite and opal. Diagenetic Zone II is defined by the appearance of clinoptilolite in zeolitized rhyolitic tuffs, which is replaced by analcime in Zone III and by albite in Zone IV. Drill-core samples indicate that each of these diagenetic zones occurs at progressive depths beneath Yucca Mountain [9]. Therefore, the glass alteration and mineral sequences observed in zones C and B of clastic and outcrop samples are analogous to those documented in diagenetic Zones I and II, respectively.

5. Discussion

The microprobe analyses demonstrate that glasses in vitric tuffs have interacted with aqueous solutions, during which dissolution, leaching, cation exchange and hydration reactions have occurred. Some of the water involved in these reactions may have been derived from volatiles originally present in the volcanic debris [38], although the variation in the extent of alkali-exchange with sample provenance (pavement versus outcrop) shown in Figure 4 indicates that glass hydration is still occurring at the desert surface. Hence it is inferred that a significant component of meteoric water is involved in these reactions.

The geopedal configuration of the alteration rinds in clastic pebbles suggests that reactions involved a radial movement of solutions between clast core and surface. Evaporation is an important process in arid-climate weathering [33].

Hence, reactions in clasts are likely to have involved both the influx and efflux of water, and to be accelerated by day-time high temperatures in desert environments. The zonal mineralogy appears to be determined by the relative solubility of the dissolved species, which is typical of low-temperature, kinetically-controlled glass-water reactions [39]. Evaporation-driven efflux of variably saturated pore fluids towards the clast surfaces caused progressive outward migration of the more soluble species (e.g. Ca) while less soluble species (notably Al) are retained in the sample core. Consequently aluminous phases such as Ca-bearing smectite and clinoptilolite occur in zones C, B_3, and B_2, while calcite and palygorskite prevail in zones B_1 and A. The clinoptilolite-opal-calcite assemblage delineating the zone B_1-B_2 boundary in geopedal alteration rinds (Figure 9) is also consistent with equilibrium activity diagrams calculated for clinoptilolite solid-solutions [40]. The Na^+ and K^+ ions are also mobile but are occupied principally in cation-exchange reactions within silicate glass. Nonetheless the salty taste of clast outer surfaces testifies to some precipitation of sodium chloride at the sample surface.

The chemistry of the solutions from which the authigenic phases precipitate during evaporation is made up of rainwater and windblown aerosols together with solutes derived from tuff dissolution. Studies of chemical weathering of the 1980 Mount St. Helens ash-fall deposits [41] have demonstrated the importance of dissolved CO_2, derived from the atmosphere and from plant respiration, in chemical weathering reactions of silicates, during which Na^+, Ca^{2+} and HCO_3^- ions are released. Silica-rich glasses are particularly vulnerable to chemical attack [30]. These solutions percolate into clasts and surface exposures during periods of precipitation. Dissolution may be both congruent (c.f. surface pitting of glass shards and feldspar phenocrysts in zone A) and incongruent (e.g., the losses near shard margins of Na, Ca, Fe, Zr, Li, and Mn; Figures 2 and 3). The aqueous phase as it penetrates the bedded vitric tuff, deposits sequentially calcite, opal, calcic clinoptilolite and smectite phases in a zonal front onto glass shards and transports soluble ions to greater depths in downward-percolating surface waters. Similar glass dissolution, ion migration and mineral deposition might occur deeper in pyroclastic tuff terranes if the aqueous solutions were to migrate along fractures. Therefore, continued diagenetic alteration of buried vitric tuffs induced by meteoric water is possible.

Presumably similar surface weathering reactions occurred when vitric tuffs in the Calico Hills unit were exposed to the atmosphere between 13.6 and 13.1 Ma ago. The numerous ash-fall and reworked tuff sequences constituting the tuffaceous beds of Calico Hills probably represent periods during which hydration of the vitric tuffs and diagenetic alteration to clay silicate-clinoptilolite-opal-calcite assemblages occurred between successive volcanic eruptive episodes within the 500,000 year period prior to burial by the Topopah Spring Member the ash-flow deposits 13.1 Ma ago. Although extensive zeolitization of the vitric tuffs in the Calico Hills unit may have taken place during caldera development to the north of Yucca Mountain 11 Ma ago [2,9], further diagenetic reactions producing mineral zonations of calcic clinoptilolite-opal-calcite assemblages could occur in the presence of bicarbonate-rich fracture-flow groundwater with a high meteoric water component. On the other hand, calcic clinoptilolite and calcite-lined fractures occurring throughout Yucca Mountain probably formed by precipitation from descending surface water rather than from upwhelling groundwater from underlying Paleozoic carbonate aquitards [42].

6. Conclusions

The tendency of present-day reactions between surface rainwater and bedded tuff to replicate diagenetic and textural features of similar lithologies at depth (e.g., tuffaceous beds of Calico Hills [10,11]]), as well as fracture-coatings within the Yucca Mountain sequence [12,13], raises fundamental questions about the agents and mechanisms of future diagenetic reactions within Yucca Mountain. Rainwater under desert conditions is a powerful agent of diagenetic alteration of tuff deposits. Notwithstanding the low precipitation at Yucca Mountain, the presence of such water at depth raise doubts about the long-term sorptive capacity of the host-rock adjacent to the proposed repository for nuclear waste. Contaminated fluids leaking from the repository may pass not through highly sorptive zeolite-rich tuffs altered 11 million years ago, but along fractures lined with more recently formed authigenic minerals containing non-sorptive calcite and silica assemblages which prevent zeolites and clay silicates from immobilizing radiogenic elements in the groundwater.

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Table 1. Average compositions of analysed glasses

Oxide Wt.%	PC1.G1 [C](4)	PC4.G1 [C](15)	PC4.G2 [B](8)	PC4.G3 [B](7)	PC4.G4 [B](1)	PC4.G5 [A](11)	PC4.G2* [B](13)
SiO_2	74.00	73.95	73.72	73.92	73.05	75.10	
Al_2O_3	12.03	12.01	11.89	11.98	12.00	11.86	
TiO_2	0.13	0.13	0.12	0.12	0.12	0.12	0.13
FeO	0.75	0.77	0.81	0.73	0.76	0.71	
MgO	0.05	0.03	0.04	0.03	0.05	0.03	0.033
CaO	0.20	0.14	0.13	0.18	0.09	0.03	0.124
Na_2O	3.92	3.72	3.68	3.19	3.04	3.66	
K_2O	4.67	5.25	5.25	5.50	5.46	5.40	5.36
MnO	0.11	0.10	0.11	0.09	0.08	0.07	
H_2O**	4.15	3.90	4.34	4.33	5.35	2.99	

* Analysis by SIMS. Other minor elements analysed (in ppm) included: Li, 30.6; Rb, 232; Zr, 410; Ba, 27; La, 42

** Determined by difference

[C], etc.: center of glass shard from zone C, etc.
(4), etc.: number of analyses used in the average
PC1.G1: 1.70 mm, pertilic glass shard from zone C
PC4.G1: 0.43 mm. vesicular shard 9 mm from zone B
PC4.G2: 0.84 mm, glass shard at zone C-B contact
PC4.G3: 2.09 mm. pertitic shard at zone B-C contact
PC4.G4: 0.23 mm. glass shard within zone B
PC4.G5: 0.22 and 0.14 mm. adjacent shards in zone A.

Table 2. Microprobe analyses of zeolites on glass shard surfaces

Oxide Wt.%	PC1 Z1 [B] (3)	PC4.Z2 [B] (4)	PC5.Z3 [B] (1)
SiO_2	55.8	58.9	64.0
Al_2O_3	10.4	9.1	11.9
TiO_2	0.1	0.1	0.1
FeO	0.9	0.7	1.4
MgO	1.5	1.9	4.0
CaO	3.4	1.3	1.5
Na_2O	1.5	2.5	2.2
K_2O	2.6	2.4	1.9
Total*	76.2	76.9	86.8

* Low totals reflect the difficulty of analysing thin surface coatings of clinoptilolite on glass shards (see Figure 7).

Captions to Figures

Figure 1. Photograph of a sectioned slab through a clastic cobble of the non-welded bedded tuff unit showing the surfacial alteration rind. The top outermost weathered zone A is separated from the interior zone C by the conspicuous dark vitreous band designated as zone B.

Figure 2. Compositional profiles measured by electron microprobe across a glass shard in zone B of a clastic cobble of non-welded bedded tuff. Water estimated by difference is ~3-4 wt.%.

Figure 3. Compositional profiles measured by ion microprobe across the same glass shard used in Figure 2. The two figures together illustrate the general trends: uniform Si, Al and Mg; losses of Na, Ca, Li, Zr and Fe; and gains of K, Rb, Ba and La towards the margins of the glass shard.

Figure 4. Correlations of K_2O versus Na_2O in interiors of glass shards from zone C of clastic and outcrop samples of the non-welded bedded tuff unit. Contours of constant molar concentration suggest a strongly coupled alkali exchange trend during glass hydration.

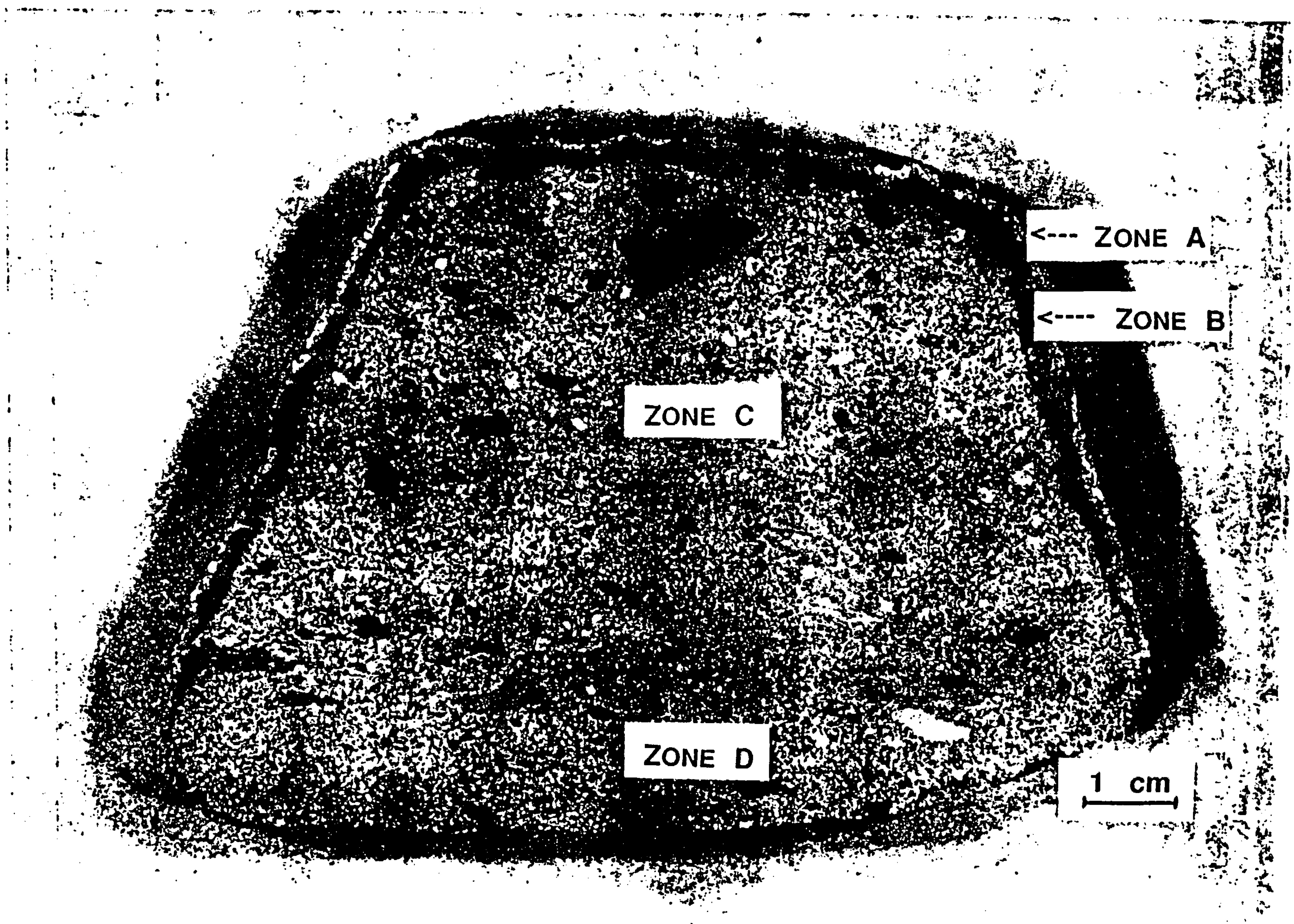
Figure 5. Scanning electron microscope photographs of smectite in Zone C (A,B) coating glass shards; and (C,D) associated with glass in the groundmass. The vertical bar at bottom left of each photograph represents 10 microns.

Figure 6. Scanning electron microscope photographs of surfaces of glass shards near the Zone B-C contact (A) with mammiform protuberances of silica, which become increasingly spherical (B,C) and associated with acicular zeolite crystallites (D).

Figure 7. Scanning electron microscope photographs showing dendritic clinoptilolite crystallites associated with lepisheres of opal CT in Zone B.

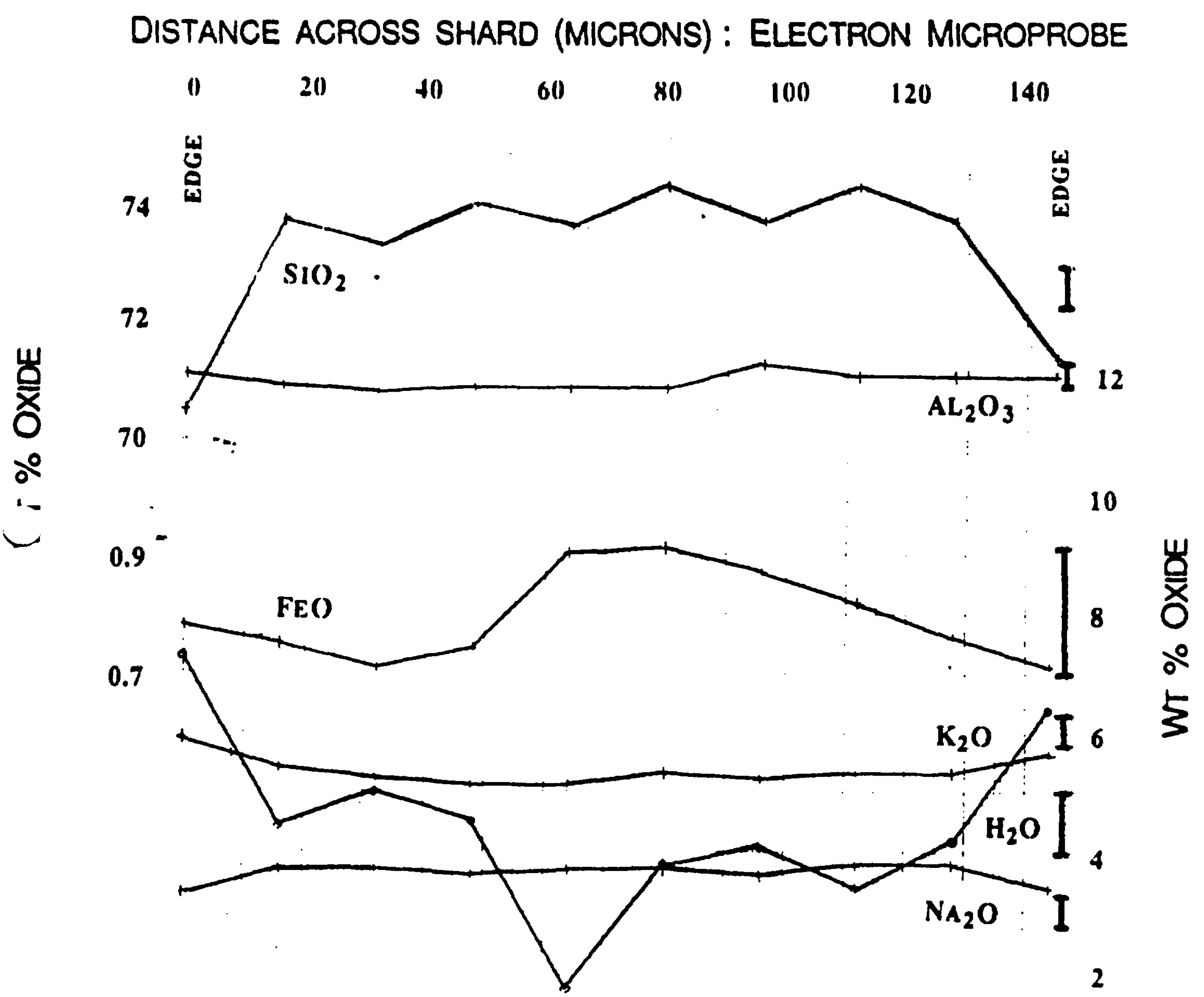
Figure 8. Scanning electron microscope photographs of calcite in Zone B. (A,B) as sparry dog-tooth crystallites with botryoidal silica near the zone B-A contact; and (C,D) as rhombs associated with lepispheres of opal CY near the Zone B-C contact.

Figure 9. Zonal mineralogy patterns observed in alteration rinds on non-welded vitric bedded tuffs. The visual zone B of Figure 1 is subdivided into three subzones B_1, B_2 and B_3, based on mineral assemblages identified by SEM and XRD measurements.



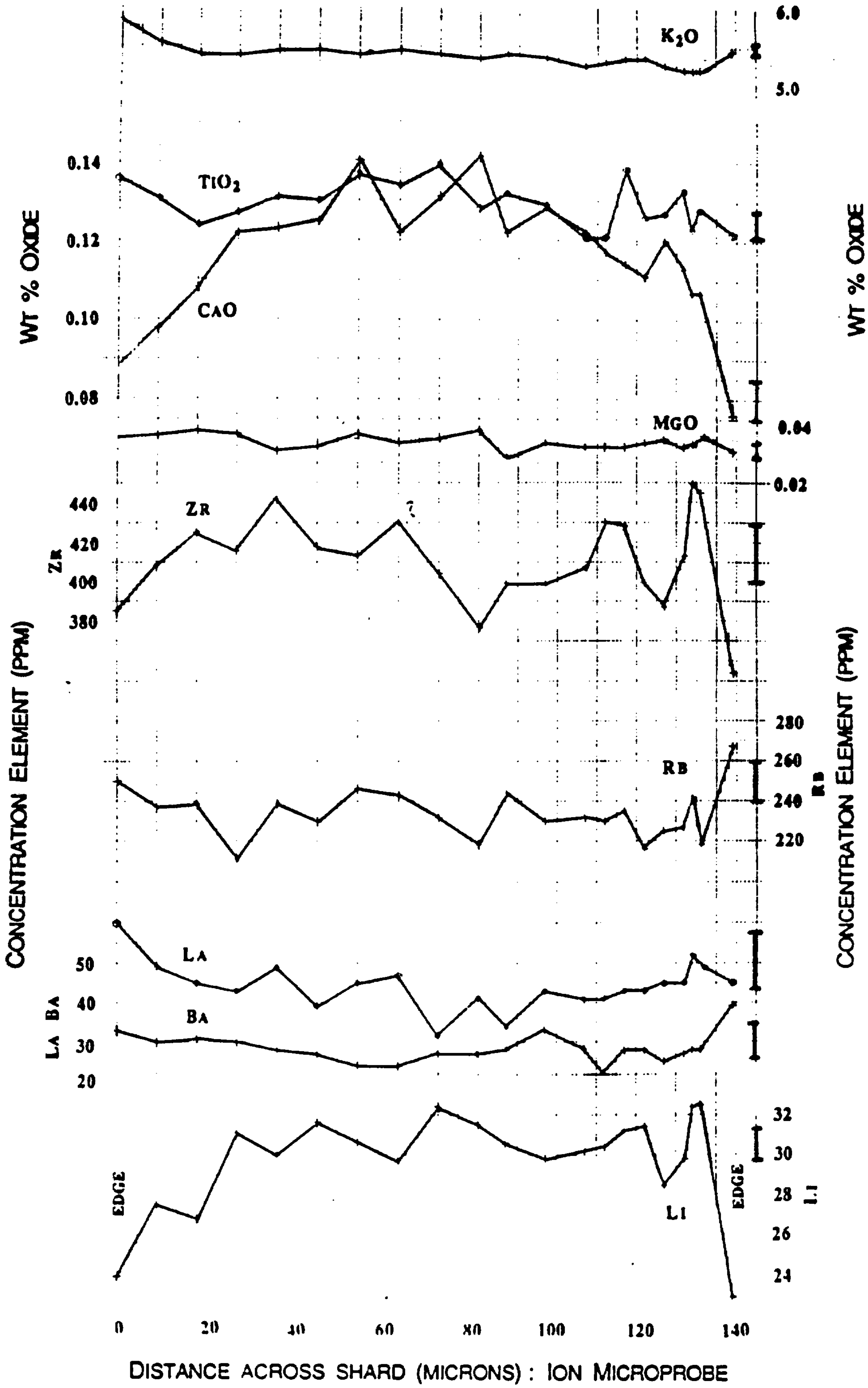
<--- ZONE A
<---- ZONE B
ZONE C
ZONE D
1 cm

(2)



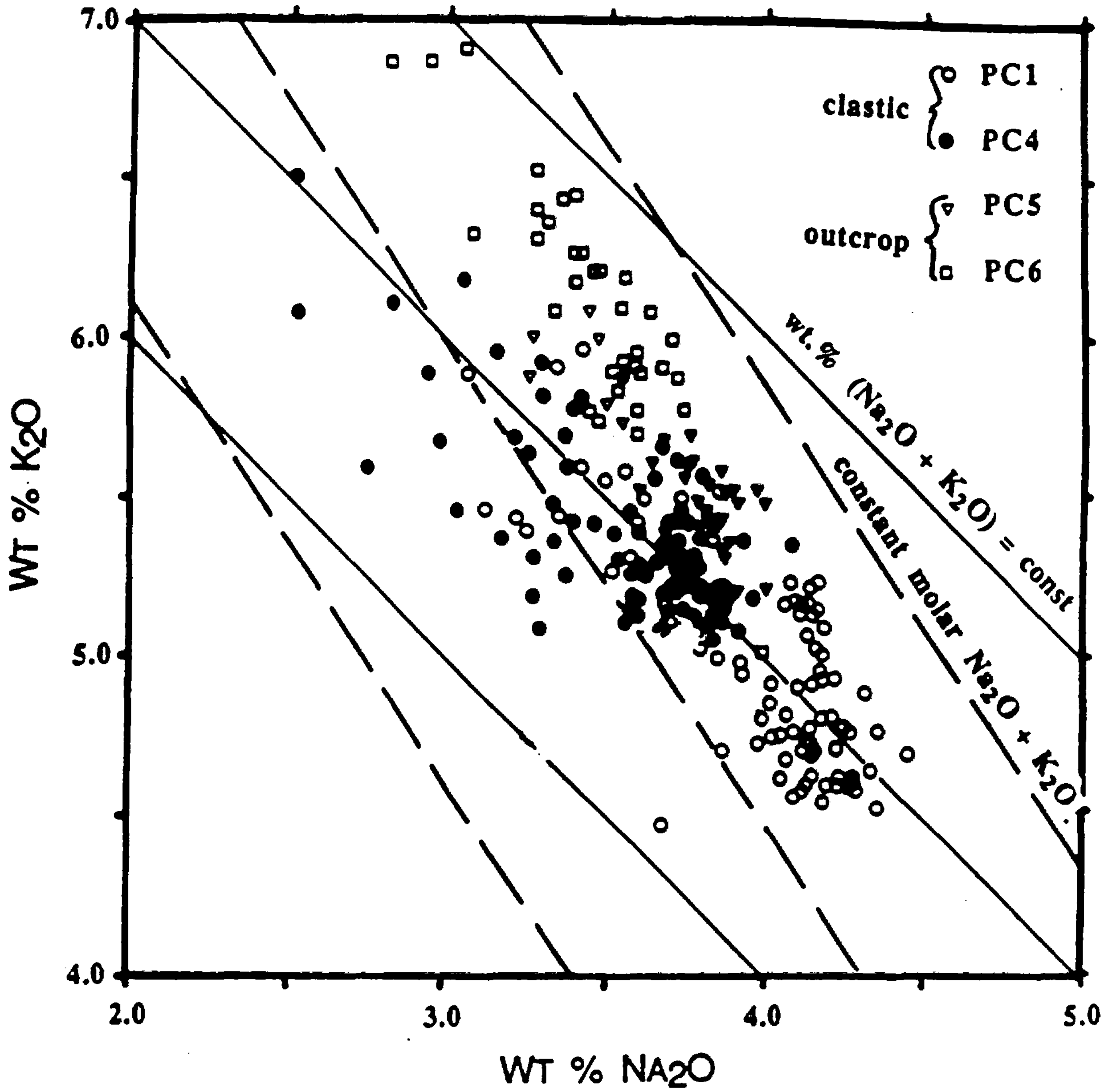
DISTANCE ACROSS SHARD (MICRONS) : ELECTRON MICROPROBE
0
20
40
60
80
100
120
140
EDGE
EDGE
74
72
70
0.9
0.7
SIO2
AL2O3
FEO
K2O
H2O
NA2O
12
10
8
6
4
2
WT % OXIDE

3

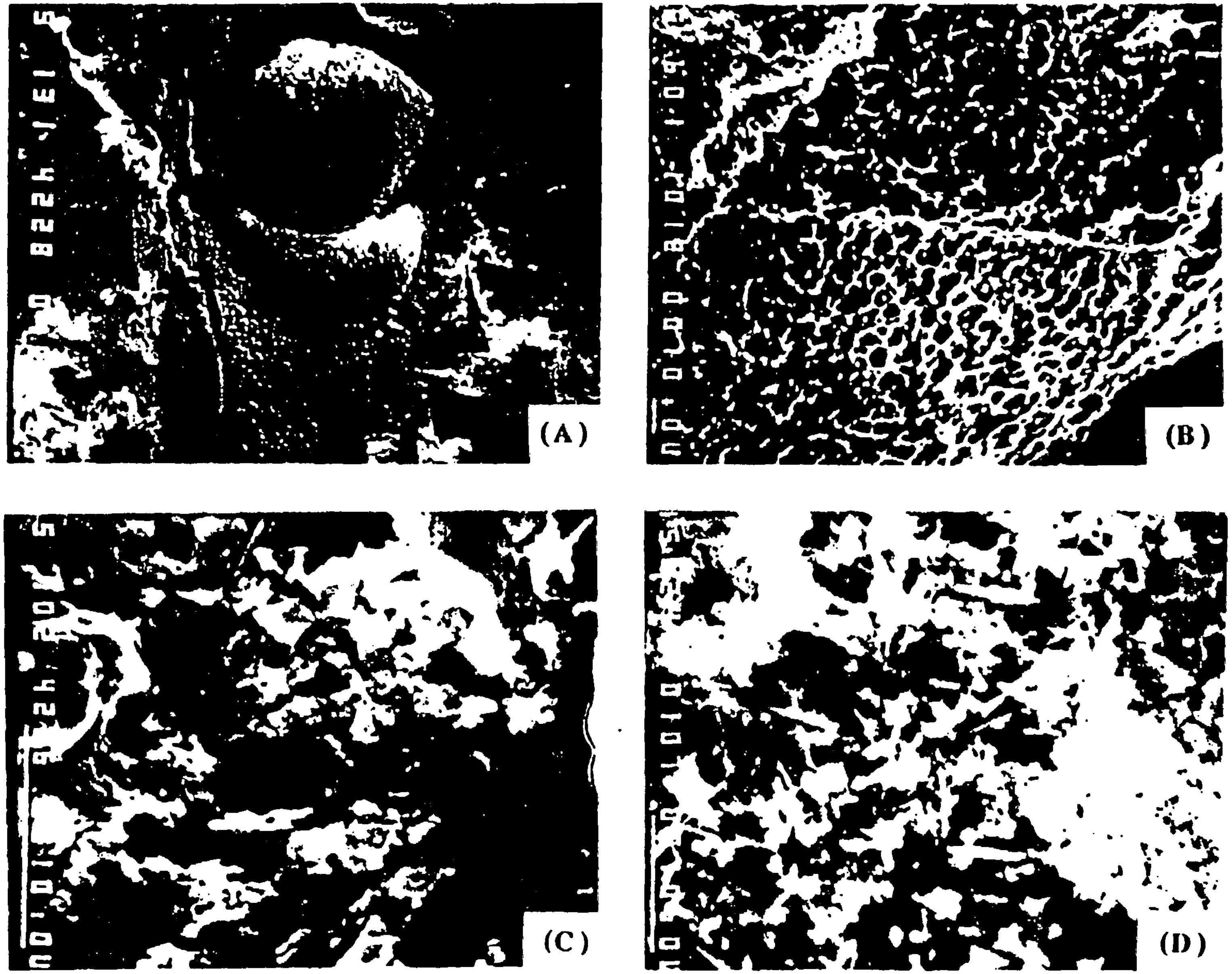


K2O
6.0
5.0
0.14
0.12
0.10
0.08
TiO2
CaO
WT % OXIDE
WT % OXIDE
MgO
0.04
0.02
440
420
400
380
ZR
ZR
CONCENTRATION ELEMENT (PPM)
CONCENTRATION ELEMENT (PPM)
280
260
240
220
RB
RB
LA
BA
50
40
30
20
LA BA
32
30
28
26
24
LI
LI
EDGE
EDGE
0
20
40
60
80
100
120
140
DISTANCE ACROSS SHARD (MICRONS) : ION MICROPROBE

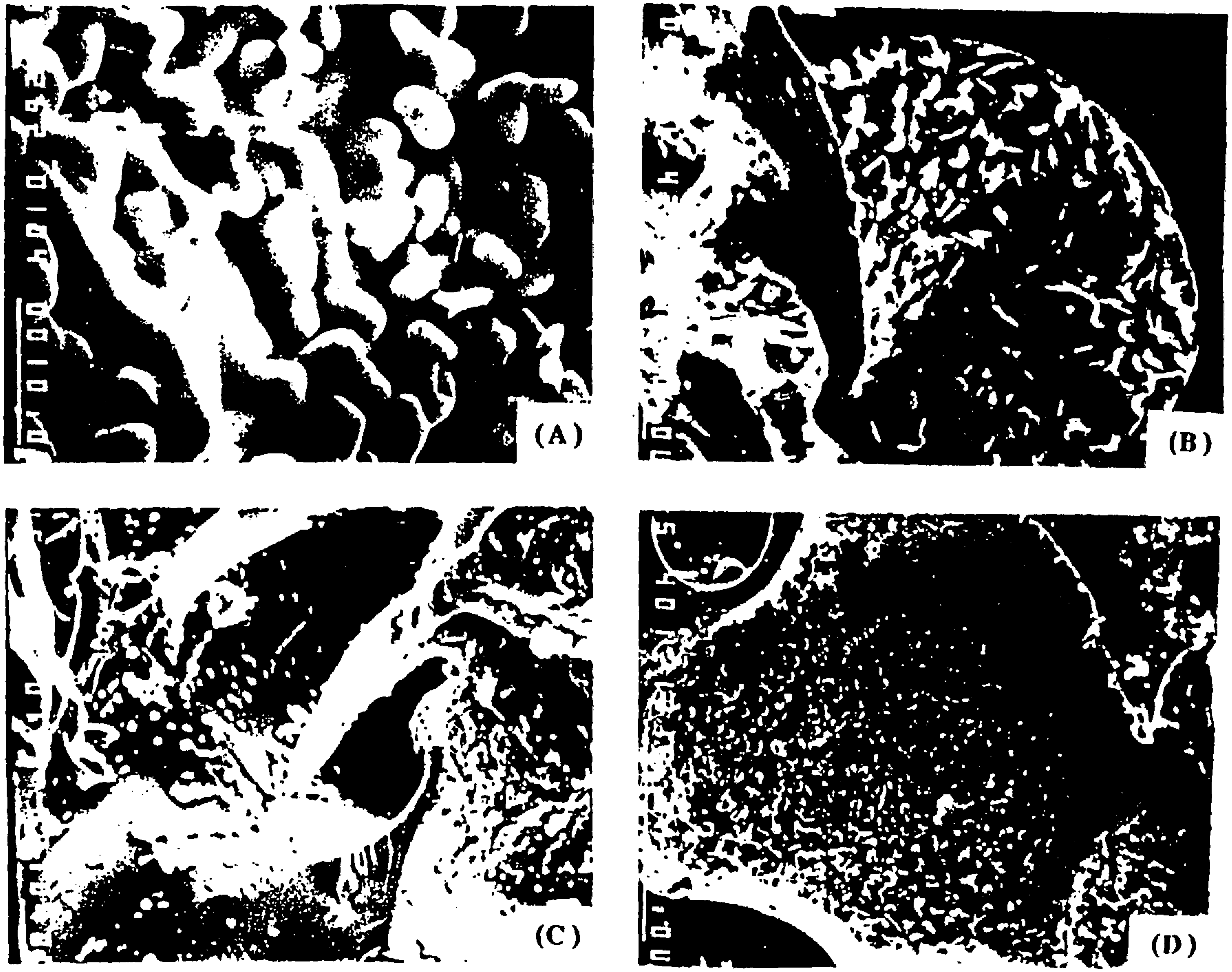
(4)



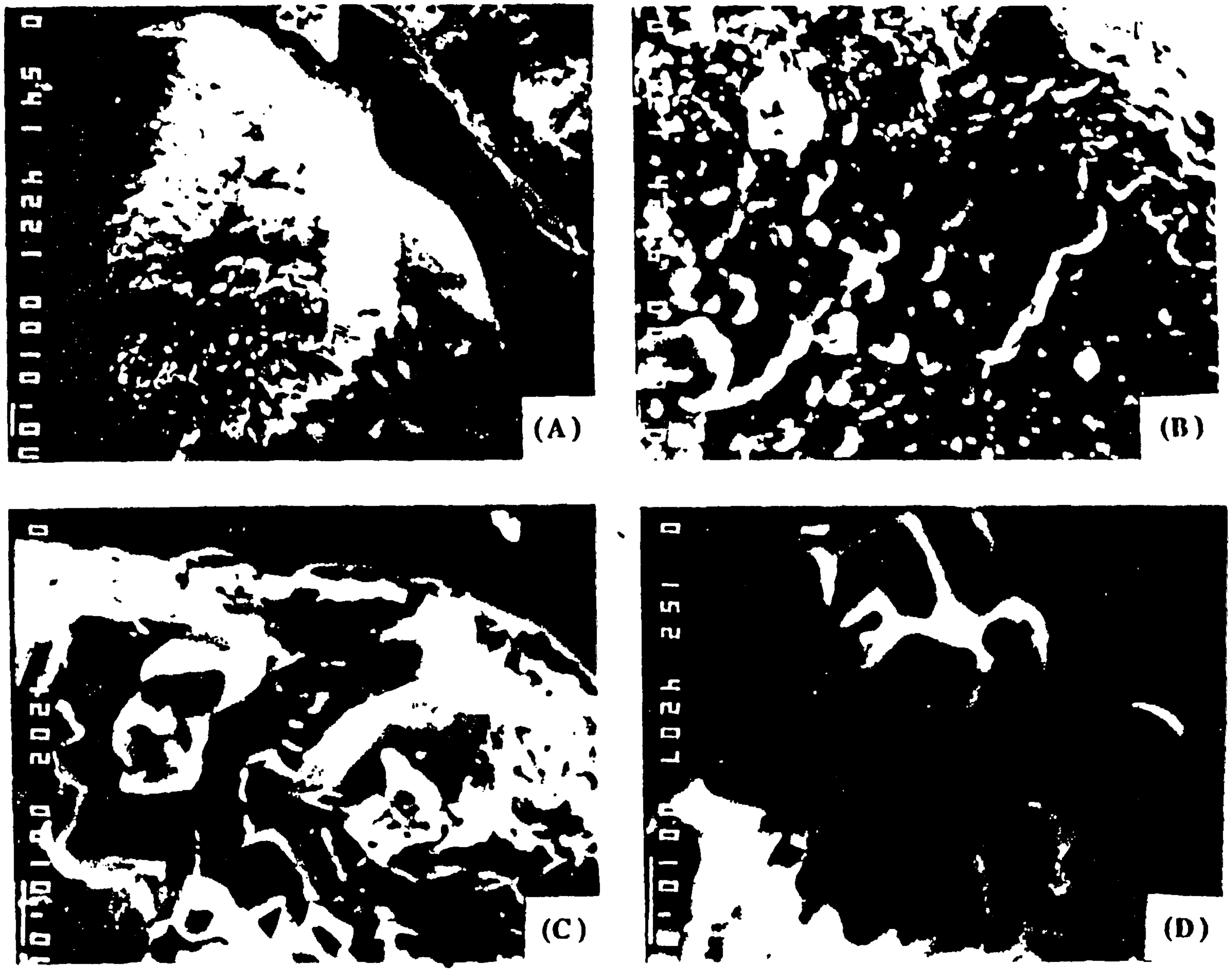
7.0
6.0
5.0
4.0
2.0
3.0
4.0
5.0
WT % K2O
WT % NA2O
clastic
PC1
PC4
outcrop
PC5
PC6
wt. % (Na2O + K2O) = const
constant molar Na2O + K2O



(A) (B) (C) (D)

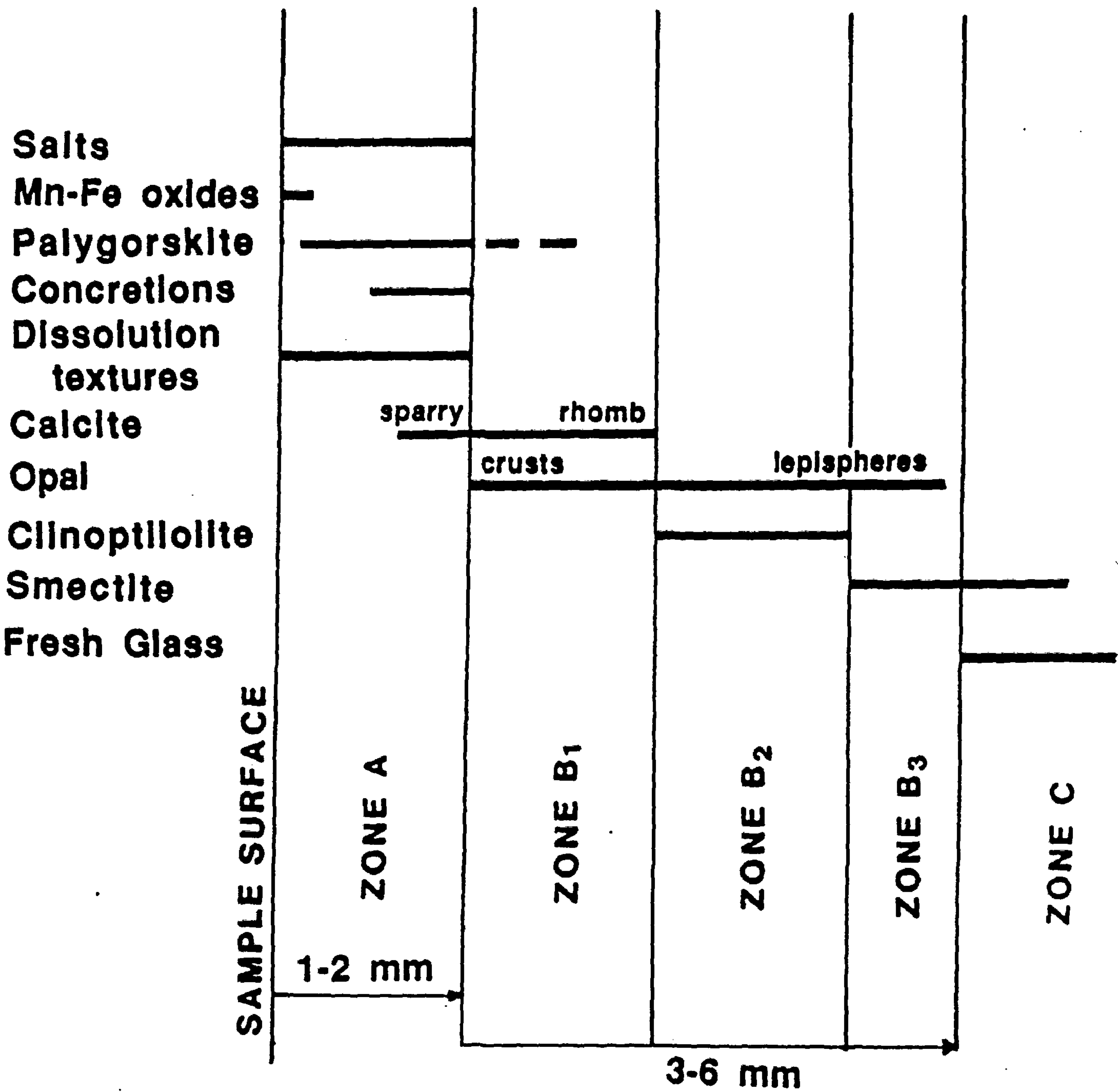

(A)
(B)
(C)
(D)

7



8

(9)


Salts
Mn-Fe oxides
Palygorskite
Concretions
Dissolution textures
Calcite
Opal
Clinoptilolite
Smectite
Fresh Glass
sparry
rhomb
crusts
lepispheres
SAMPLE SURFACE
ZONE A
ZONE B1
ZONE B2
ZONE B3
ZONE C
1-2 mm
3-6 mm

ACTIVITY DIAGRAMS FOR CLINOPTILOLITE: SUSCEPTIBILITY OF THIS ZEOLITE TO FURTHER DIAGENETIC REACTIONS

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ABSTRACT

Clinoptilolite is the predominant zeolite in diagenetically altered volcanic rocks at Yucca Mountain, Nevada, having formed by post-eruptive reactions of groundwater with vitric tuffs in the pyroclastic deposits there. The zeolite, which lines fractures adjacent to the proposed repository for high-level nuclear waste in a densely welded, devitrified tuff unit located in the vadose zone well above the present-day water table, is particularly abundant in underlying vitric to zeolitized non-welded tuffs. Compositional variations of clinoptilolites in the fractures and zeolitized tuffs not presently in contact with groundwater raise questions about the long-term stability of this zeolite to further diagenetic reactions. Equilibrium activity diagrams were calculated for clinoptilolite solid-solutions in the seven-component system Ca-Na-K-Mg-Fe-Al-Si plus H_2O employing available thermodynamic data for related minerals, aqueous species and water. Stability fields are portrayed graphically on plots of $log(a_{Na^+}/a_{H^+})$ versus $log(a_{Ca^{2+}}/(a_{H^+})^2)$, assuming the presence of K-feldspar, saponite and hematite and using ranges of activities for SiO_2 and Al^{3+} defined by the saturation limits for quartz, amorphous silica, gibbsite, kaolinite and pyrophyllite. Formation of clinoptilolite is favored by higher SiO_2 activities than allowed for by the presence of quartz, thus accounting for the coexistence of clinoptilolite with opal CT in zeolitized vitric tuffs. The clinoptilolite stability field broadens with increasing atomic substitution of Ca for Na, K for Ca, and Mg for Ca, reaches a maximum for intermediate activities of dissolved Al, and decreases at elevated temperatures. The thermodynamic calculations show that sodium bicarbonate-type groundwater, such as reference J-13 well-water collected from fractured devitrified tuffs at the adjacent Nuclear Test Site in Nevada, is approximately in equilibrium at 25 °C with calcite and several zeolites including Ca-bearing clinoptilolite. Sodic clinoptilolites are stabilized in groundwater depleted in Ca^{2+} and enriched in Na^+ derived from

altered vitric tuffs. Decreasing Al^{3+} activities results in the association of clinoptilolite with calcite and opal CT observed in weathered zeolitized vitric tuffs at Yucca Mt. The activity diagrams indicate that prolonged diagenetic reactions with groundwater depleted in Al, enriched in Na and heated by the thermal envelope surrounding the nuclear waste repository may eliminate sorptive clinoptilolite.

INTRODUCTION.

Clinoptilolite, ideally $(Na,K,Ca)_{5-6}Si_{30}Al_6O_{72}.24H_2O$, is an abundant natural zeolite that is common in diagenetically altered volcanic rocks where it forms by post-eruptive reactions of saline groundwater with rhyolitic glass shards in tuffaceous ash-fall and ash-flow deposits (Hay, 1966; Hay and Sheppard, 1977; Iijima, 1975, 1980). Such silicic ash-flow tuffs are the predominant lithology at Yucca Mountain, Nevada, the site of the proposed repository for burial of high-level nuclear waste (U.S. Dept. Energy, 1988). The repository horizon there is a densely welded and devitrified tuff unit underlain by vitric to zeolitized non-welded tuffs containing high proportions of clinoptilolite (Broxton et al., 1987). Because of its favorable cation exchange reactions, clinoptilolite is assumed to serve as an agent for immobilizing several of the soluble cations and to be an effective barrier to radionuclide migration should groundwater flowing through the repository cause leakage of fission products in the future.

Clinoptilolites analysed in drill-core samples throughout Yucca Mountain and its immediate vicinity display wide compositional variations, particularly in fractures adjacent to the repository horizon in the Topopah Spring Member of the Paintbrush Tuff unit (Levy, 1984) and in the underlying zeolitized tuffaceous beds of Calico Hills unit (Broxton et al., 1987). In the vadose zone beneath Yucca Mountain, clinoptilolites with high Ca and Mg contents line fractures in the Topopah Spring Member (Carlos, 1985; Broxton et al., 1986, 1987). However, in the underlying tuffaceous beds of Calico Hills unit and deeper zeolitized tuff members, the clinoptilolites display regional and depth variations (Broxton et al., 1986, 1987). On the western side of Yucca Mountain the clinoptilolites are Na-K-bearing and become Na-rich with depth. To the east, the clinoptilolites are Ca-K-bearing and become Ca-rich with depth. Such compositional variations of clinoptilolites not presently in contact with groundwater raise questions about the long-term stability of this zeolite to further diagenetic reactions.

Although the Topopah Springs Member and tuffaceous beds of Calico Hills unit both lie in the undersaturated zone well above the present-day water table beneath Yucca Mountain, the two formations dip to the east so that at the location of the nearest water-supply well, designated J-13 and located 6 km to the east at Jackass Flat on the Nevada Test site, the Topopah Springs Member lies beneath the water table. As a result, the major producing horizon for J-13 well-water is a highly fractured interval within the Topopah Springs Member (Delany, 1985). The chemical composition of the sodium bicarbonate-type groundwater obtained from well J-13 has been monitored for several years (Daniels et al., 1982; Bish et al., 1984; Kerrisk, 1987) and serves as a reference standard in laboratory experiments and geochemical modelling studies for characterizing the Yucca Mountain exploration block (e.g. Oversby, 1985; Delany, 1985; Knauss et al., 1985a,b; Moore et al., 1986). Whether or not J-13 water is of an appropriate composition for prediction of authigenic mineral reactions in the undersaturated zone beneath Yucca Mountain requires critical evaluation.

In order to assess the stability limits of clinoptilolite and its vulnerability to changes of groundwater chemistry relative to the composition of J-13 well-water, equilibrium activity diagrams have been calculated for clinoptilolite solid-solutions in the system Ca-Na-K-Mg-Fe-Al-Si-H_2O employing available thermodynamic data for relevant oxide and aluminosilicate phases. Results reported here indicate that authigenic minerals such as clinoptilolite modify, and are modified by, groundwater compositions.

CALCULATIONS OF ACTIVITY DIAGRAMS

Sources of Thermodynamic Data.

The method for calculating activity diagrams is described in Bowers et al. (1984), who also tabulated thermodynamic data for many of the phases considered here (Table 1). Additional thermodynamic data for zeolites are provided by calorimetric measurements made by Johnson et al. (1982, 1983, 1985) and Hemingway and Robie (1984).

The clinoptilolite measured by Hemingway and Robie (1984) from altered tuffs of the Big Sandy Formation, Mohave County, Arizona (Sheppard and Gude, 1973) was formulated by them as

$$Na_{0.56}K_{0.98}Ca_{1.50}Mg_{1.23}Fe_{0.3}Al_{6.7}Si_{29}O_{72}.22H_2O$$

and, as indicated in Table 2, resembles some of the (Ca + Mg)-rich clinoptilolites lining fractures in the Topopah Spring Member and present in the zeolitized tuff of Calico Hills unit, particularly beneath the north-eastern block of Yucca Mountain (Broxton et al., 1987). However, since Hemingway and Robie (1984) provided only increments to the free energy and enthalpy with no reference points, it was necessary to estimate the standard free energy of formation ($\Delta G^o{}_f$) and enthalpy of formation ($\Delta H^o{}_f$) for clinoptilolite at 25 ^{o}C by a component-summation method, using thermodynamic data for water and related minerals listed in Table 1 (Helgeson et al., 1978; Robie et al., 1978). Thus, the $\Delta G^o{}_f$ and $\Delta H^o{}_f$ values of clinoptilolite that are listed in Table 3 were estimated from data for natrolite, scolecite, K-feldspar, brucite, hematite, gibbsite, quartz, and water. Similarly, the $\Delta G^o{}_f$ for the Ca end-member heulandite was estimated from the value given by Johnson et al. (1985) after correcting for minor Ba, Sr, K and Na components. The $\Delta G^o{}_f$ of Na-phillipsite was estimated from the experimental value for natrolite (Johnson et al., 1983) and data for quartz and water. Values of $\Delta G^o{}_f$ for Ca-phillipsite and epistilbite were estimated in a similar manner from published data for scolecite (Johnson et al., 1983), while the free energy of formation of K-phillipsite was estimated from those of Na-phillipsite, albite and K-feldspar. All estimated data used in this study are listed in Table 3.

Table 4 contains estimated free energies of formation for compositionally variable clinoptilolites. Independent substitutions are allowed of Na for Ca, K for Ca and Ca for Mg, where charge balance is maintained. $\Delta G^o{}_f$ is estimated from the value given for clinoptilolite in Table 3 by a component-summation method using natrolite, scolecite and H_2O for Na-Ca substitution; K-feldspar, anorthite and quartz for K-Ca substitution; and CaO and MgO for Ca-Mg substitution. These correction mechanisms result in lower free energies for Ca over Na, K over Ca and Ca over Mg-rich clinoptilolites.

Composition of Groundwater.

Because the Topopah Spring Member tuff is the major producing horizon for water pumped from J-13 well, it is generally assumed (Oversby, 1985) that the composition of J-13 well-water approximates the prevailing groundwater chemistry of the proposed repository horizon in the same formation at Yucca Mountain even though the Topopah Spring Member there is in the undersaturated zone. As a result, J-13 well-water has been widely used as the reference aqueous phase for calibrating numerous environmental parameters relevant to the Yucca Mountain repository horizon (Oversby, 1985; Delany, 1985; Knauss et al.., 1985a,b; Moore et al., 1986). The chemical composition of J-13 well-water has been monitored for several years (Daniels et al., 1982; Kerrisk, 1987) and typical concentrations of dissolved species in it are summarized in Table 5. Small fluctuations of concentrations with time have been recorded, but the variations are minor compared with other variables in experiments in which J-13 well-water was used (Daniels et al., 1982). However, during experiments in which J-13 well-water was contacted with tuff samples of the Topopah Spring Member taken from a drill core at the appropriate region of main water production of the J-13 well, concentrations of many constituents changed slightly (Table 5), particularly Mg and Al which decreased after 3 weeks at room-temperature (Daniels et al., 1982). Moreover, filtration affected the composition of some elements, particularly Fe, Al and Mg, which were drastically reduced in samples passed through 0.05 micron Nuclepore membranes compared to those obtained from 0.45 micron Millipore filters (Daniels et al., 1982). The Al concentration, for example, decreased from ~40 mg/l (0.45 µm filter) to <0.01 mg/l (0.05 µm filter) (Daniels et al., 1982). Cation concentrations in solutions contacted with vitrophyre samples from the Topopah Springs Member at 152 ^{o}C showed significant increases of dissolved Si, Fe, Al, K and Na and a decrease of dissolved Mg, which were attributed to dissolution of glass and precipitation of clays. A specimen of zeolitized tuff from the tuffaceous beds of Calico Hills unit reacted with J-13 water at the same temperature showed marked dissolution of clinoptilolite and disappearance of mordenite and cristobalite (Daniels et al., 1982). In later experiments, Knauss et al. (1985a,b) studied compositional changes of J-13 well-water after reacting it with crushed tuff and polished wafer samples of the densely-welded, devitrified ash-flow tuff in a drill core taken from the repository level in the Topopah Spring Member. The modal mineralogy of this horizon consists of a ~98% microcrystalline feldspar-cristobalite-quartz and accessory (<2%) biotite-montmorillonite assemblage (Bish et al., 1984). Reactions were performed for 2-3 month intervals at temperatures of 90, 150 and 250 ^{o}C and pressures of 90-100 bars. Results from the 150 ^{o}C experiments are summarized in Table 5, where it can be seen that dissolved SiO_2 concentrations increase and are close to the cristobalite saturation value (Knauss et al., 1985a). Sodium also increased during the experiments, Ca and Mg decreased, and Al and K both increased rapidly and then decreased. These effects were attributed to dissolution of montmorillonite and precipitation of calcite and smectite. The experiments at 90 °C and 250 °C produced similar trends. Phases identified by scanning electron microscopy included illite, Mg-Ca or Fe-rich clays, gibbsite, calcite and a pure SiO_2 phase considered to be cristobalite (Knauss et al., 1985 a,b).

Studies to determine compositional changes of groundwater as it passes through the undersaturated zone in tuffaceous deposits have been conducted at Rainier Mesa located 50 km to the north-northeast of Yucca Mountain (Benson, 1976; White et al., 1980). At Rainier Mesa welded and vitric tuffs overlie zeolitized tuffs, resembling the sequence of ash-flow deposits at Yucca Mountain. Concentrations of Ca and Mg in interstitial waters decreased as a function of depth and were generally lower than in J-13 well-water, whereas opposite effects were observed for Na (Benson, 1976; White et al., 1980). The concentration of dissolved K was lower at depth, and SiO_2 higher, than J-13 water compositions, while Cl^- decreased and HCO_3^- increased with depth. The maximum compositional variations of the interstitial water occurred in alteration zones containing clinoptilolite and montmorillonite (Benson, 1976; White et al., 1980). Water seeping through fractures in tunnels beneath the zeolitized tuffs was HCO_3^--rich, and had lower Ca, Mg and SiO_2 contents, variable K and higher Na concentrations than J-13 well-water (Benson, 1976; White et al., 1980). The clinoptilolites along fractures were Ca-Mg-K-rich, correlating with the depletion of these cations in the groundwater, while the fracture-flow water was enriched in HCO_3^- relative to the more Cl^--rich interstitial water. Comparisons made with dissolution experiments on vitric and crystalline tuffs demonstrated the rapid dissolution of Na and SiO_2 but retention of K in glass-bearing tuffs, whereas dissolution of crystalline tuffs containing sanidine, quartz, biotite and clinopyroxene phenocrysts and sanidine-cristobalite groundmass resulted in solutions rich in Ca, Mg and HCO_3^- (White et al., 1980). White et al (1980) thus concluded that fracture-water compositions, such as J-13 well-water, are dominated by dissolution of vitric tuffs, but are modified by infiltration through zeolitized tuffs.

These results clearly show that zeolitized tuffs affect groundwater chemistry and suggest that compositional variability of clinoptilolites influence, and are influenced by, groundwater compositions.

Representation of Activity Diagrams.

Three- and four-component plus H_2O systems can be readily represented in two dimensions. For example, in the system Ca-Al-Si-H_2O, two components are selected for the x and y axes, a third component is balanced upon, leaving the activity of H_2O to be assigned, commonly equal to unity. A reaction between amorphous silica and epistilbite can be represented by writing a hydrolysis reaction for each mineral:

$$SiO_{2(am)} = SiO_{2(aq)} \qquad [1]$$

$$CaAl_2Si_6O_{16}.5H_2O + 8H^+ = Ca^{2+} + 2Al^{3+} + 6SiO_{2(aq)} + 9H_2O \qquad [2]$$

Combining reactions [1] and [2] such that no $SiO_{2(aq)}$ remains gives:

$$CaAl_2Si_6O_{16}.5H_2O + 8H^+ = 6SiO_{2(am)} + Ca^{2+} + 2Al^{3+} + 9H_2O \qquad [3]$$

A *logk* as a function of pressure and temperature can be calculated from thermodynamic data for this reaction and is expressed as:

$$logk = 2log(a_{Al^{3+}}/(a_{H^+})^3) + log(a_{Ca^{2+}}/(a_{H^+})^2) \qquad [4]$$

If the x and y axes are chosen as $log(a_{Al^{3+}}/(a_{H^+})^3)$ and $log(a_{Ca^{2+}}/(a_{H^+})^2)$, respectively, reaction [4] is the equation of a line with a slope of -2 and a y intercept of *logk* that forms the boundary on an activity diagram between amorphous silica and epistilbite (see Figure 2a discussed later). Similar calculations are performed for all mineral pairs and the resulting intersecting lines form the boundaries of the phases that appear on the stability diagrams presented here.

Four- (or more) component systems plus H_2O are calculated in a similar manner, but with the inclusion of an additional mineral assumed to be at saturation to constrain the fourth component. For example, the system Ca-Na-Al-Si-H_2O might have Ca and Na on the axes, be balanced on Al, and have coexisting amorphous silica, as in reaction [3]. Alternatively, this four-component system could be balanced on SiO_2 and have the Al component constrained by a saturation phase such as gibbsite:

$$CaAl_2Si_6O_{16}.5H_2O + 2H^+ = 2Al(OH)_3 + 6SiO_{2(aq)} + Ca^{2+} + 3H_2O \quad [5]$$

Gibbsite, however, provides a maximum activity of the Al^{3+} component that may not be desirable in all circumstances. Saturation with respect to any Al-bearing mineral in the four-component system can be assumed, although if the chosen saturation phase includes the components plotted on the axes of the diagram it will change the topology of the other fields. At Yucca Mountain, drill core samples in the vadose zone have established the presence of opal and smectite as coexisting authigenic SiO_2 and Al^{3+}-bearing phases, respectively, with some authigenic K-feldspar and minor amounts of cristobalite, quartz, kaolinite, and calcite (Broxton et al., 1987). These phases, together with the composition of J-13 well-water summarized in Table 5, serve to define the ranges of silica and Al^{3+} activities shown in Figure 1 which were used to construct the activity diagrams presented here. Thus, lines labelled D and H on Figure 1 represent the extremes of dissolved silica saturation limits corresponding to quartz and amorphous silica, respectively; cristobalite, a constituent of the welded devitrified tuffs at Yucca Mountain, has an intermediate saturation level approximated by line E; line F corresponds to coexisting kaolinite and pyrophyllite; and line G is the activity of dissolved SiO_2 in J-13 well-water. Similarly, for dissolved Al^{3+}, lines A, B, and C correspond to saturation values for coexisting amorphous silica plus pyrophyllite, coexisting pyrophyllite plus kaolinite, and gibbsite, respectively, while line I represents an arbitrary low value of dissolved Al which, as shown later is consistent with the coexistence of opal, calcite and clinoptilolite. The reported analysis of Al in J-13 well-water (0.012 mg/l) is too high to be equilibrium controlled. The fluid speciation program used to calculate cation activities (EQ3NR of Wolery, 1983) indicates that at the pH of J-13 water (~7.5), dissolved Al occurs predominantly as $Al(OH)_4^-$, with a calculated equilibrium value for $[Al^{3+}]$ of $\sim 2 \times 10^{-11}$M. Using an activity coefficient of ~0.6 gives a value for $log(a_{Al^{3+}}/(a_{H^+})^3)$ of 9.6, in excess of the gibbsite saturation value of ~7.9 (Figure 1). A possible interpretation of this result is that the Al in J-13 well-water includes unfiltered particulate matter passing through membrane filters. In calculating the activity diagrams, the activity of H_2O is taken to be unity, and the calcite boundary is added to appropriate diagrams by assuming a dissolved HCO_3^- content equivalent to that of J-13 well-water (Table 5) and using the 90 °C analytical data in the activity diagrams calculated at 100 °C.

RESULTS

Three-Component plus H_2O Diagrams

A series of three-component plus H_2O diagrams are shown in Figures 2 to 4 for the systems Ca-Al-Si, Na-Al-Si, and K-Al-Si, respectively. All of these diagrams are balanced on SiO_2. Quartz has been suppressed throughout the calculations described here in favor of amorphous silica because opal is reported to be the commonly observed authigenic SiO_2 phase in zeolitized ash-flow tuffs at Yucca Mountain (Broxton et al., 1986, 1987). As a result, all of the three-component diagrams in Figures 2-4 have amorphous silica as the stable phase in the bottom left-hand corner. Amorphous silica occupies a relatively smaller stability field than would quartz had quartz not been suppressed. Figures 2a-c illustrate the changes in mineral phase relations for the system Ca-Al-Si with increasing temperature at 25, 100, and 200 °C with pressures corresponding to the steam saturation curve. Note that the epistilbite field at 25 °C is replaced by Ca-phillipsite at higher temperatures. The scolecite field decreases in size with increasing temperature and this zeolite is no longer stable at 200 °C (Fig. 2c). The Ca-beidellite field apparent at 200 °C may exist at lower temperatures as well, but does not appear in Figs. 2a and b possibly because of inaccuracies in the thermodyamic data for Ca-beidellite or adjacent phases. The stable limits of these and other activity diagrams described later are delineated by the dashed lines labelled gibbsite (or diaspore at 200 °C) and calcite. Higher Al or Ca activities can only result from supersaturation of the fluid with respect to these phases. As noted earlier, J-13 well-water is unconstrained on the Al axis. It is apparent from Figs 2a and b that in the simple Ca-Al-Si system, J-13 well-water is somewhat undersaturated with respect to calcite at 25 °C and slightly oversaturated at 100 °C.

Activity diagrams for the system Na-Al-Si illustrated in Figures 3a and b show that Na-beidellite becomes stable at 100 °C. Figs. 4a and b show similar diagrams for the system K-Al-Si at 25 and 100 °C. J-13 well water plots below any of the Na- or K-rich zeolites in Figs. 3 and 4 and is consistent with equilibrium with respect to feldspar: albite in Fig. 3 and K-feldspar in Fig. 4.

These diagrams indicate that although the activity of Al is unconstrained, calculated cation activities for J-13 well-water are consistent with the formation of Ca-rich zeolites and smectite observed in experimental studies of tuff samples contacted with water at ambient and elevated temperatures (Knauss et al., 1985a,b; White et al., 1980).

Multicomponent Diagrams

The three-component diagrams in Figures 2 to 4 provided simplified reference activity diagrams for comparison with the more complex four- and five-component plus H_2O systems necessary for plotting the stability field of clinoptilolite. Figures 5-8 are activity diagrams for the system Ca-Na-K-Al-Si. Values of $log(a_{Na^+}/a_{H^+})$ and $log(a_{Ca^{2+}}/(a_{H^+})^2)$ are plotted on the x- and y-axes, respectively, in each diagram. Either Al (Figs. 5 and 6) or Si (Figs. 7 and 8) has been used as the balancing component. In each case, two additional components need to be specified. The component K^+ is constrained by assuming the presence of K-feldspar, since it occurs as an authigenic mineral (Broxton et al., 1987) and as a phenocryst and groundmass mineral in the rhyolite tuffs at Yucca Mountain. The other component, Al^{3+} or SiO_2, is assigned the series of values shown in the plot of $log(a_{Al^{3+}}/(a_{H^+})^3)$ versus $log\,a_{SiO_2}$ at 25 ^oC in Figure 1. The activity diagrams in Figures 5a-d are balanced on Al at 25 ^oC and have $log\,a_{SiO_2}$ specified by the lines labelled D, E, F, G and H in Figure 1. The activity diagrams in Figures 6a and b are balanced on Al with amorphous silica and quartz saturations, respectively, at 100 ^oC. Figures 7a-d are balanced on Si at 25 ^oC and have Al^{3+} concentrations constrained by values corresponding to lines labelled I, A, B, and C, respectively, on Figure 1. The 100 ^oC diagrams shown in Figures 8a-c are balanced on Si with Al constrained by pyrophyllite-amorphous silica, kaolinite-pyrophyllite, and gibbsite saturations, respectively. Clinoptilolite is included in these diagrams, where stable, by considering it to be in equilibrium with Ca-saponite (smectite) and hematite to constrain the small amounts of Mg and Fe in the clinoptilolite specimen measured by Hemingway and Robie (1984). On all of the activity diagrams shown in Figures 5 to 8, calcite is plotted with a dashed line by assuming a bicarbonate ion content comparable to J-13 well-water, and the circular symbol labelled J-13 corresponds to Ca and Na activities of this reference groundwater.

By comparing the activity diagrams shown in Figures 5-8 through changing temperature, or for different activities of Al or Si, trends in the relative stability of various zeolite phases may be easily recognized. For example, Figure 5 shows that: mesolite is a stable zeolite at low activities of silica; the mesolite field narrows and then disappears with increasing silica activity; and, clinoptilolite is stable at high activities of silica and increases in size the higher the silica activity.

The effects of temperature can be seen by comparing Figure 5a with Figure 6a (corresponding to amorphous silica saturation) and Figure 5d with Figure 6b (quartz saturation), where it is apparent that both clinoptilolite and mesolite have smaller regions of stability at 100 ^{o}C than at 25 ^{o}C.

The effects of variable Al activity at 25 ^{o}C can be observed in Figure 7. Mesolite has the largest stability field at gibbsite saturation (Figure 7d). Clinoptilolite is not stable at high Al activities corresponding to gibbsite saturation, but appears with decreasing Al activity (Figures 7a-c). Its stability field maximizes in size at an intermediate Al activity constrained by the coexistence of amorphous silica and pyrophyllite (Figure 7b), and then becomes smaller with further decrease in Al activity (Figure 7a). Note that circles representing Ca and Na concentrations of J-13 well-water plot close to the join of mesolite, epistilbite and clinoptilolite in Figures 7b and c. Again, effects of increasing the temperature to 100 ^{o}C may be seen in Figure 8 which shows that the clinoptilolite stability field decreases with increasing temperature and appears only at low Al^{3+} activities.

In Figures 9a and b, the system Ca-Na-K-Al-Si is represented with $log(a_{K^+})/(a_{H^+})$ replacing $log(a_{Na^+})/(a_{H^+})$ on the x-axis and albite replacing K-feldspar as the saturation phase. Figure 9a is balanced on Al and amorphous silica is the saturation phase, whereas Figure 9b is balanced on Si with Al^{3+} activity controlled by coexisting amorphous silica plus pyrophyllite. These two representative activity diagrams based on K^+ activities are very similar to their Na-counterparts except that K-silicate phases replace Na-silicate minerals. The stability field of clinoptilolite is again largest at high silica activities, intermediate Al^{3+} activities, and low temperatures.

Activity Diagrams for Clinoptilolites of Variable Compositions.

Since clinoptilolites at Yucca Mountain occurring in the zeolitized tuffaceous beds of Calico Hills unit vary from Ca-rich compositions in the east to (Na + K)-rich compositions in the west (Broxton et al., 1986, 1987), and are (Ca + Mg)-rich in fractures in the Topopah Spring Member tuff (Levy, 1984; Carlos, 1985; Broxton et al., 1987), activity diagrams were calculated for variable Na-Ca, K-Ca and Ca-Mg contents of the zeolite. The results are shown in Figures 10a-c, respectively. Each activity diagram is related to that shown in Figure 7b in which Si is balanced and Al activities are constrained by the pyrophyllite-amorphous silica (plus K-feldspar) assemblage.

Figure 10a shows that with increasing atomic substitution of Na in clinoptilolite, the clinoptilolite stability field narrows and is displaced to lower calcium activities. Conversely, the clinoptilolite stability field widens for clinoptilolites with higher Ca contents. Clinoptilolites more sodic than $Na_{1.56}Ca_{1.0}$ are no longer in equilibrium with J-13 well-water, suggesting that groundwater with higher Na concentrations, perhaps derived from altered vitric tuffs (White et al., 1980), is necessary to stabilize sodic clinoptilolites.

Potassium has the opposite effect on the clinoptilolite stability field (Figure 10b), which widens considerably with increasing atomic substitution of K for Ca in clinoptilolite. Clinoptilolites less potassic than $K_{0.5}Ca_{1.74}$ would no longer be in equilibrium with J-13 well-water. Magnesium, too, replacing Ca in clinoptilolite widens its stability field (Figure 10c). Clinoptilolites less magnesian than $Ca_{1.7}Mg_{1.03}$ would not be in equilibrium with J-13 well-water, but this effect could be compensated by increased atomic substitution of K into the zeolite. Clinoptillolites less magnesian than $Ca_{2.5}Mg_{0.23}$ do not coexist stably with Ca-saponite under the conditions of the activity diagram shown in Figure 10c.

DISCUSSION

The activity diagrams demonstrate that the formation of clinoptilolite is favored by higher SiO_2 activities than allowed for by the presence of quartz. This is clearly demonstrated by Figure 5 and is achieved, for example, when clinoptilolite coexists with opal in diagenetically alterated volcanic glasses. Such assemblages are commonly observed in vitric tuff samples from drill cores at Yucca Mountain (Benson, 1976; White et al., 1980; Broxton et al., 1987) and from surface desert pavement and outcrop locations (Blundy et al., 1988).

Clinoptilolite has a maximum stability field at some intermediate aluminium activity value, but shrinks with either increasing or decreasing activities of aluminum. This is indicated by Figure 7 in which the clinoptilolite stability field is largest when aluminium activities are controlled by the amorphous silica-pyrophyllite assemblage (Figure 7b). Furthermore, since the composition of J-13 well-water appears to be approximately in equilibrium with respect to calcite, the J-13 Ca^{2+}/Na^{+} points plotted in Figures 5a, 7b and 7c suggest that the aluminum activities lie between the values for kaolinite-pyrophyllite and pyrophyllite-amorphous silica. Such aluminum activities also indicate that J-13 well-water could be in equilibrium with other zeolites represented on the activity diagrams, including epistilbite (Figure 5b) and mesolite (Figure 5c, 7b and 9b), particularly when the stability field of Na-rich clinoptilolites is diminished (Figure 10a).

The clinoptilolite stability field decreases in size with increasing temperature between 25 °C and 100 °C (Figures 6 and 8), and has disappeared by 200 °C. This correlates with hydrothermal experiments (Boles, 1971; Knauss et al., 1985a,b; Hawkins et al., 1978) and observed geological occurrences of clinoptilolite (Hay, 1966; Hay and Sheppard, 1977). Zeolite diagenetic zones have been suggested for alteration of vitric tuffs based on the appearance and disappearance of clinoptilolite in buried pyroclastic deposits (Iijima, 1975, 1980; Smyth, 1982). Zone I, for example, is characterized by large-scale preservation of glass in vitric tuffs above the water table, and incipient alteration of glass shards, particularly in groundmass, to smectite and opal. The Topopah Spring Member at Yucca Mountain, lying well above the water table, falls into Zone I. However, Ca-rich clinoptilolites occur in fractures through lower welded tuff and vitrophyre horizons and may be indicative of groundwater interactions, perhaps with microcrystalline devitrified tuffs which produce relatively high concentrations of dissolved Ca^{2+}, Na^{+} and HCO_3^- in fracture-flow water (White et al., 1980). The 25 °C activity diagrams consistently show that calcic clinoptilolites are stable in the presence of fracture-flow J-13 well-water originating from microcrystalline devitrified Topopah Spring Member tuffs, even though such zeolites have not been observed as fracture-lining minerals at this level in J-13 drill cores (Carlos, 1988). The abundance of drusy quartz coating fractures there (Carlos, 1988) may depress the silica activity below that necessary to crystallize clinoptilolite.

Diagenetic zone II, which characterizes the tuffaceous beds of Calico Hills unit, represents extensive zeolitization of vitric tuffs to clinoptilolite-bearing assemblages, and is promoted by saline groundwater and slightly elevated temperatures (Smyth, 1982). Progressive hydration and dissolution reactions of the rhyolitic vitric tuffs increase the concentrations of SiO_2, Na^+, and ultimately K^+ in groundwater (White et al., 1980) from which clinoptilolite-clay silicate-opal assemblages are derived. The presence of Ca-poor, K-Na-rich clinoptilolites in diagenetic zone II conforms with the activity diagrams which consistently show the clinoptilolite stability field moving away from J-13 well-water compositions at elevated temperatures and for increased Na, but depleted Ca, concentrations in groundwater.

Deeper drill-cores through Yucca Mountain have yielded analcime instead of clinoptilolite which is indicative of diagenetic Zone III, while Zone IV is represented by the breakdown of analcime to albite at greater depths. The Zone II - Zone III boundary appears to be between 100 °C and 150 °C (Smyth, 1982), which again is consistent with the absence or decreased stability field of clinoptilolite in activity diagrams calculated at elevated temperatures. Adverse effects of temperature on the clinoptilolite stability field also indicate the vulnerability of calcic clinoptilolites to thermal decomposition in the vicinity of the heat envelope surrounding stored radioactive waste at Yucca Mountain, particularly if concentrations of dissolved Na were to increase, and Ca decrease, in heated groundwater.

Several observed reactions suggested by phase assemblages in weathered vitric tuffs (Benson, 1976; White et al., 1980; Blundy et al., 1988) can be demonstrated on the activity diagrams. For example the reaction of glass + clay silicates to clinoptilolite plus opal plots at the intersection of amorphous silica + pyrophyllite, albite and clinoptilolite in Figures 5a and 7b, but requires lower calcium activities in the coexisting fluid than that of J-13 well-water. Low Ca and slightly reduced K activities would account for the assemblage glass-opal-clay silicates-authigenic K-feldspar forming on weathered vitric tuffs and outcrop and in detritus forming desert pavement (Blundy et al., 1988). The assemblage of clinoptilolite-calcite-opal also found in weathered vitric tuffs is represented on Figure 7a requiring, however, very low activities of Al.

CONCLUSIONS

The calculated activity diagrams presented here quantify observed field occurrences and verify deductions made about the stability of clinoptilolite in diagenetically altered tuffs. The coexistence of clinoptilolite with opal correlates with its calculated wide stability field in aqueous solutions saturated with amorphous silica. Clinoptilolite-smectite assemblages indicate that the zeolite crystallized from groundwater with dissolved Al concentrations lower than saturation values with respect to gibbsite. Calcic clinoptilolites associated with calcite are consistent with crystallization from fracture-flow groundwater containing Ca^{2+} and HCO_3^- derived from incipient dissolution of microcrystalline devitrified tuffs. Alkali-rich clinoptilolites, on the other hand, correlate with groundwater having elevated Na^+ and K^+ but depleted Ca^{2+} concentrations which are associated with altered vitric tuffs. Although the crystallization of clinoptilolite may be promoted by saline groundwater, the clinoptilolite stability field diminishes appreciably between 25 ^{o}C and 100 ^{o}C, correlating with burial diagenetic reactions but confirming doubts about the thermal stability of clinoptilolite when it is in close proximity to buried radioactive waste.

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TABLE 1: MINERALS AND FORMULAS	
Quartz	SiO_2
Amorphous silica	SiO_2
Gibbsite	$Al(OH)_3$
Diaspore	$AlO(OH)$
Kaolinite	$Al_2Si_2O_5(OH)_4$
Pyrophyllite	$Al_2Si_4O_{10}(OH)_2$
Wollastonite	$CaSiO_3$
Grossular	$Ca_3Al_2Si_3O_{12}$
Prehnite	$Ca_2Al_2Si_3O_{10}(OH)_2$
Margarite	$CaAl_4Si_2O_{10}(OH)_2$
Ca-beidellite	$Ca_{.165}Al_2(Al_{.33}Si_{3.67}O_{10})(OH)_2$
Lawsonite	$CaAl_2Si_2O_7(OH)_2 \cdot H_2O$
Ca-phillipsite	$CaAl_2Si_5O_{14} \cdot 5H_2O$
Scolecite	$CaAl_2Si_3O_{10} \cdot 3H_2O$
Epistilbite	$CaAl_2Si_6O_{16} \cdot 5H_2O$
Heulandite	$CaAl_2Si_7O_{18} \cdot 6H_2O$
Albite	$NaAlSi_3O_8$
Nepheline	$NaAlSiO_4$
Paragonite	$NaAl_2(AlSi_3O_{10})(OH)_2$
Na-beidellite	$Na_{.33}Al_2(Al_{.33}Si_{3.67}O_{10})(OH)_2$
Analcime	$NaAlSi_2O_6 \cdot H_2O$
Natrolite	$Na_2Al_2Si_3O_{10} \cdot 2H_2O$
K-feldspar	$KAlSi_3O_8$
Kalsilite	$KAlSiO_4$
Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$
K-phillipsite	$K_2Al_2Si_5O_{14} \cdot 5H_2O$
Mesolite	$Na_{.676}Ca_{.657}Al_{1.99}Si_{3.01}O_{10} \cdot 2.647H_2O$
Clinoptilolite	$(Na_{.56}K_{.98}Ca_{1.5}Mg_{1.23})(Al_{6.7}Fe_{.3})Si_{29}O_{72} \cdot 22H_2O$
Ca-saponite	$Ca_{.165}Mg_3(Al_{.33}Si_{3.67}O_{10})(OH)_2$
Hematite	Fe_2O_3

TABLE 2: REPRESENTATIVE CHEMICAL COMPOSITIONS AND FORMULAE OF CLINOPTILOLITE				
	[1]	[2]	[3]	[4]
SiO_2	62.78	65.5	68.6	68.1
TiO_2	0.28	0.02	0	0
Al_2O_3	12.33	13.3	12.4	12.2
Fe_2O_3	1.41	0	0	0
MgO	1.99	0.86	0.07	0.09
CaO	3.10	5.19	3.59	1.11
BaO	0.13			0.03
Na_2O	0.63	0.17	1.13	2.84
K_2O	1.67	0.21	3.00	4.20
Total	84.32	85.2	88.8	88.5
Formulae calculated for 72 oxygens				
Si	29	29.2	29.7	29.8
Ti		0.01	0	0
Al	6.7	6.98	6.35	6.28
Fe	0.3	0	0	0
Mg	1.23	0.57	0.04	0.06
Ca	1.50	2.48	1.67	0.52
Ba	0.02	0.00	0.01	0.01
Na	0.56	0.15	0.95	2.41
K	0.98	0.12	1.66	2.35
%K	23	4	16	44
%Na	13	4	31	45
Si/Al	4.33	4.18	4.68	4.75

[1] Hemingway and Robie (1984): Thermodynamic data
[2] Topopah Spring Member fractures; Broxton *et al.* (1987)
[3] Tuff of Calico Hills, eastern YM; Broxton *et al.* (1987)
[4] Tuff of Calico Hills, western YM; Broxton *et al.* (1987)

TABLE 3:

ESTIMATED FREE ENERGIES AND ENTHALPIES

	$\Delta G_f^\circ(298)(cal.)$	$\Delta H_f^\circ(298)(cal.)$
Na-phillipsite	-1,850,051.	-2,002,144.
K-phillipsite	-1,868,183.	-2,022,272.
Ca-phillipsite	-1,860,596.	-2,010,073.
Epistilbite	-2,065,242.	-2,234,763.
Heulandite	-2,321,459.	-2.514,766.
Clinoptilolite	-9,055,456.	-9,809,599.

TABLE 4: ESTIMATED FREE ENERGIES FOR COMPOSITIONALLY VARIABLE CLINOPTILOLITE	
	$\Delta G_f^o(298)(cal.)$
$(Na_{.56}K_{.98}Ca_{1.5}Mg_{1.23})$ $(Al_{6.7}Fe_{.3})Si_{29}O_{72} \cdot 22H_2O$	-9,055,456.
Na-Ca substitution	
$Na_{1.56}Ca_{1.0}$	-9,028,215.
$Na_{2.56}Ca_{0.5}$	-9,000,973.
$Na_{3.56}$	-8,973,732.
$Na_{0.28}Ca_{1.64}$	-9,063,084.
$Ca_{1.67}$	-9,070,711.
K-Ca substitution	
$K_{1.98}Ca_{1.0}$	-9,064,389.
$K_{2.98}Ca_{0.5}$	-9,073,322.
$K_{3.78}Ca_{0.1}$	-9,080,468.
$K_{0.5}Ca_{1.74}$	-9,051,168.
$Ca_{1.99}$	-9,046,702.
Ca-Mg substitution	
$Ca_{0.73}Mg_{2.0}$	-9,049,080.
$Ca_{1.7}Mg_{1.03}$	-9,057,112.
$Ca_{2.0}Mg_{0.73}$	-9,059,596.
$Ca_{2.5}Mg_{0.23}$	-9,063,736.
$Ca_{2.73}$	-9,065,640.

TABLE 5: CHEMICAL COMPOSITION OF J-13 WELL WATER (mg/l)							
	[1]	[2]	[3]	[4]	[5]	[6]	[7]
Li	0.042				0.06	0.05	0.05
Na	43.9	55	58.5	44	45	51	54.1
K	5.11	7.5	5.58	4.4	5.3	4.9	6.4
Ca	12.5	11.5	6.46	13	11.5	14	11
Mg	1.92	1.1	0.315	2.0	1.76	2.1	0.95
Sr	0.035					0.05	0.002
Al	0.012	0.999	1.64		0.02	0.03	0.01
Fe	0.006				0.01	0.04	0.004
SiO_2	57.9	53	148	59	31.87	66	71.6
NO_3	9.6	9.0	9.5	8.7	10.1	5.6	
F	2.2	2.3	2.4	2.2	2.1	2.2	
Cl	6.9	7.2	7.4		6.4	7.5	
HCO_3	125.3	178.8	61.0	120	143	120	
SO_4	18.7	18.3	18.5	19	18.1	22	
pH	7.6	7.27	6.97	7.5	6.9	7.1	

[1] Delany (1985)

[2] J-13 reacted with TS tuff at 90°C; Knauss *et al.* (1985)

[3] J-13 reacted with TS tuff at 150°C; Knauss *et al.* (1985)

[4] Moore *et al.* (1986)

[5] Bish *et al.* (1984)

[6] Daniels *et al.* (1982)

[7] Daniels *et al.* (1982), after J-13 water reacted with TS tuff at 25°C

FIGURE CAPTIONS.

Figure 1. Ranges of dissolved silica and aluminum activities used in the calculations of activity diagrams. Silica activities correspond to amorphous silica (H), J-13 well-water (G), coexisting pyrophyllite-kaolinite (F), cristobalite (E) and quartz (D) saturated solutions. Aluminum activities are those for solutions saturated by pyrophyllite-amorphous silica (A), pyrophyllite-kaolinite (B), and gibbsite (C) assemblages and an arbitrary low value (I).

Figure 2. Activity diagrams for the three-component Ca-Al-Si plus H_2O system balanced on Si (a) at 25 ^oC; (b) at 100 ^oC; and (c) at 200 ^oC and 15.5 bars.

Figure 3. Activity diagrams for the three-component Na-Al-Si plus H_2O system balanced on Si (a) at 25 ^oC; and (b) at 100 ^oC

Figure 4. Activity diagrams for the three-component K-Al-Si plus H_2O system balanced on Si (a) at 25 ^oC; and (b) at 100 ^oC

Figure 5. Activity diagrams for the Ca-Na-K-Al-Si plus H_2O system balanced on Al at 25 ^oC for different silica activities (a) amorphous silica; (b) J-13 well-water; (c) pyrophyllite-kaolinite; and (d) quartz and cristobalite (inset dashed lines). Saturation phases also include K-feldspar, hematite and Ca-saponite.

Figure 6. Activity diagrams for the Ca-Na-K-Al-Si plus H_2O system balanced on Al at 100 ^oC for different silica activities (a) amorphous silica; and (b) quartz.

Figure 7. Activity diagrams for the Ca-Na-K-Al-Si plus H_2O system balanced on Si at 25 ^oC for different aluminum activities (a) low Al activity corresponding to line

I in Figure 1; (b) pyrophyllite-amorphous silica; (c) kaolinite-pyrophyllite; and (d) gibbsite. Saturation phases again include K-feldspar, hematite, and Ca-saponite.

Figure 8. Activity diagrams for the Ca-Na-K-Al-Si plus H_2O system balanced on Si at 100 ^oC for different aluminum activities (a) pyrophyllite-amorphous silica; (b) kaolinite-pyrophyllite; and (c) gibbsite.

Figure 9. Activity diagrams based on K and Ca activities in the Ca-Na-K-Al-Si plus H_2O system at 25 ^oC (a) balanced on Al with silica saturation by amorphous silica; and (b) balanced on Si with aluminum saturation by pyrophyllite plus amorphous silica. Saturation phases include albite, hematite and Ca-saponite.

Figure 10. Activity diagrams for clinoptilolites having variable cation compositions (a) Ca-Na: (b) K-Ca; and (c) Ca-Mg. The calculated 25 ^oC stability fields correspond to aluminum saturation by pyrophyllite plus amorphous silica and are balanced on Si (Fig. 7b).

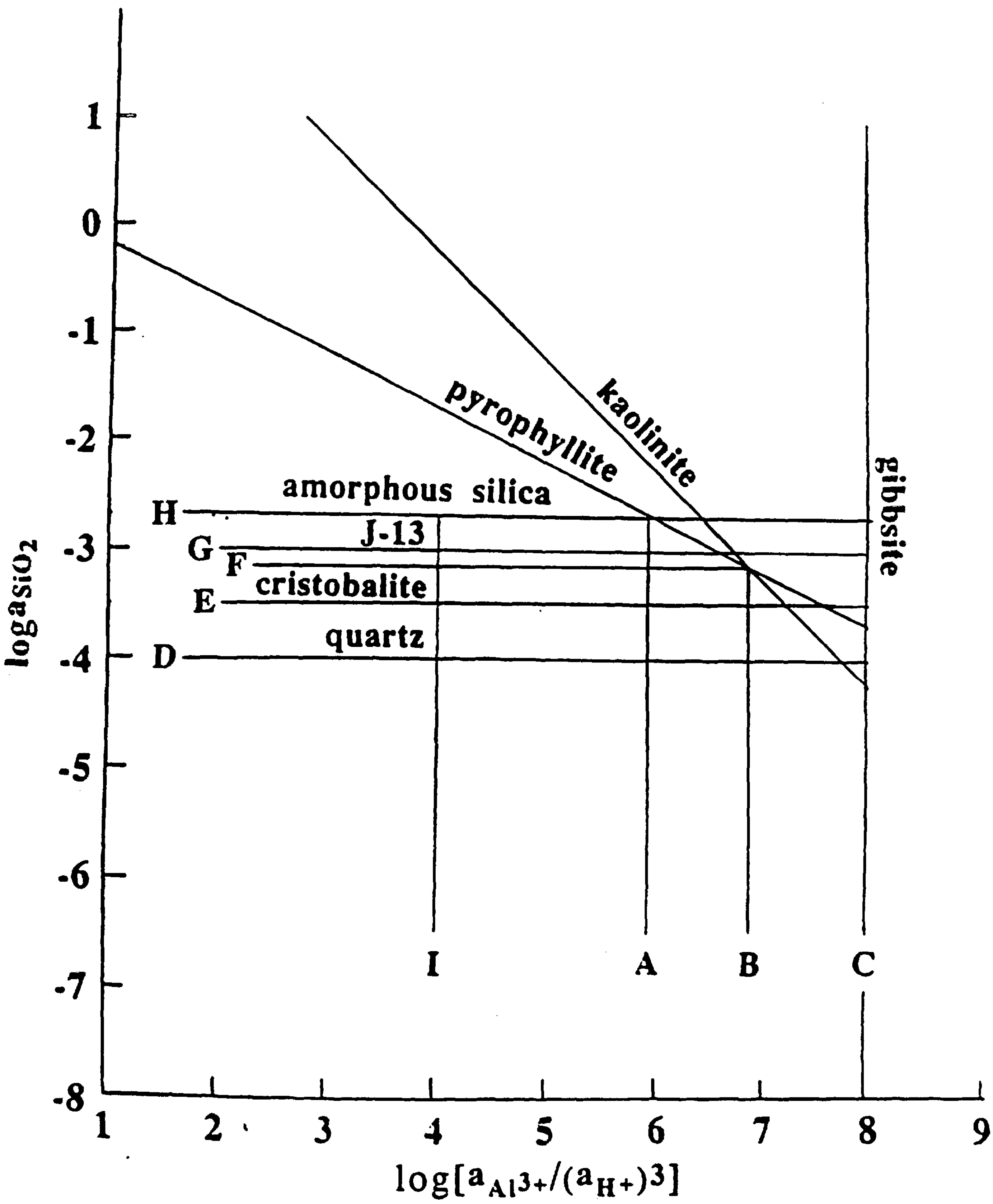

1
0
-1
-2
-3
-4
-5
-6
-7
-8
1
2
3
4
5
6
7
8
9
loga_{SiO_2}
log[$a_{Al^{3+}}/(a_{H^+})^3$]
kaolinite
pyrophyllite
gibbsite
amorphous silica
J-13
cristobalite
quartz
H
G
F
E
D
I
A
B
C

Figure 2

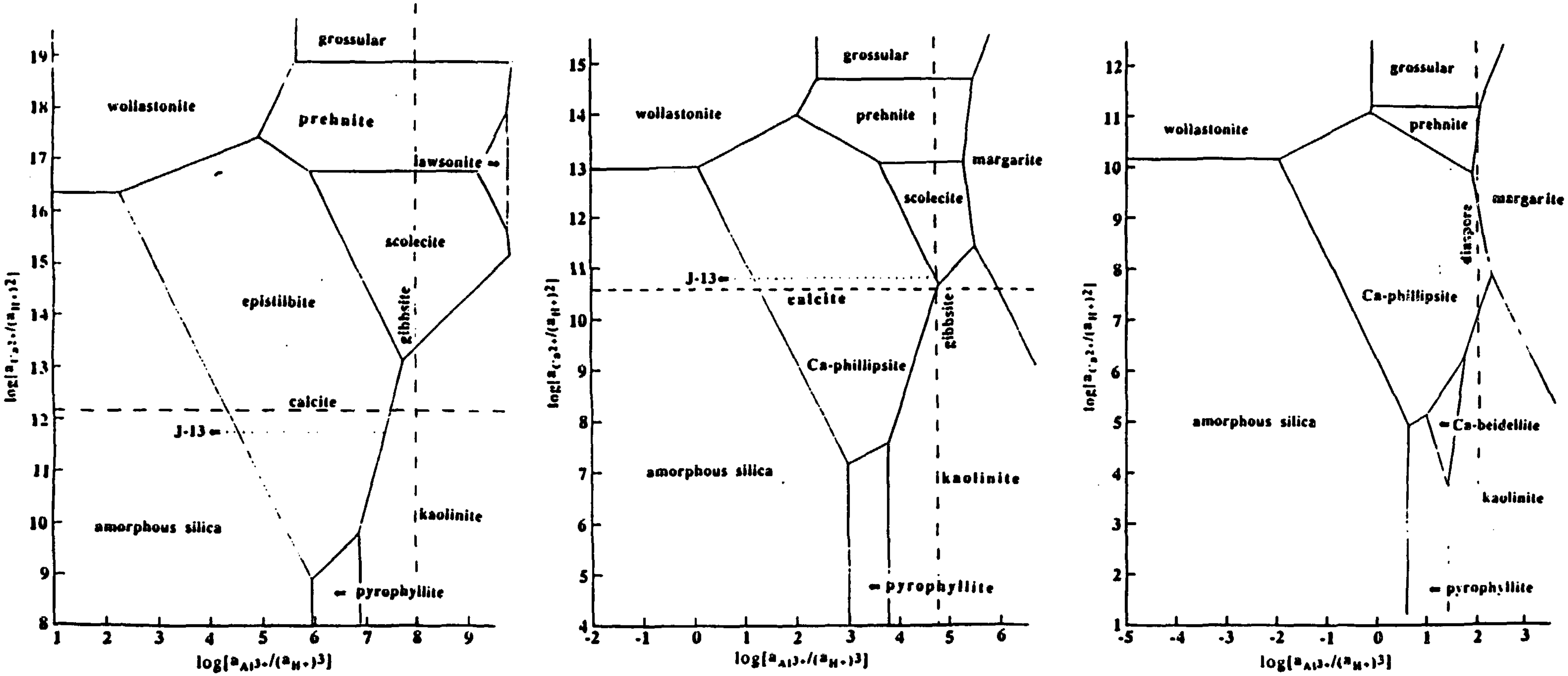
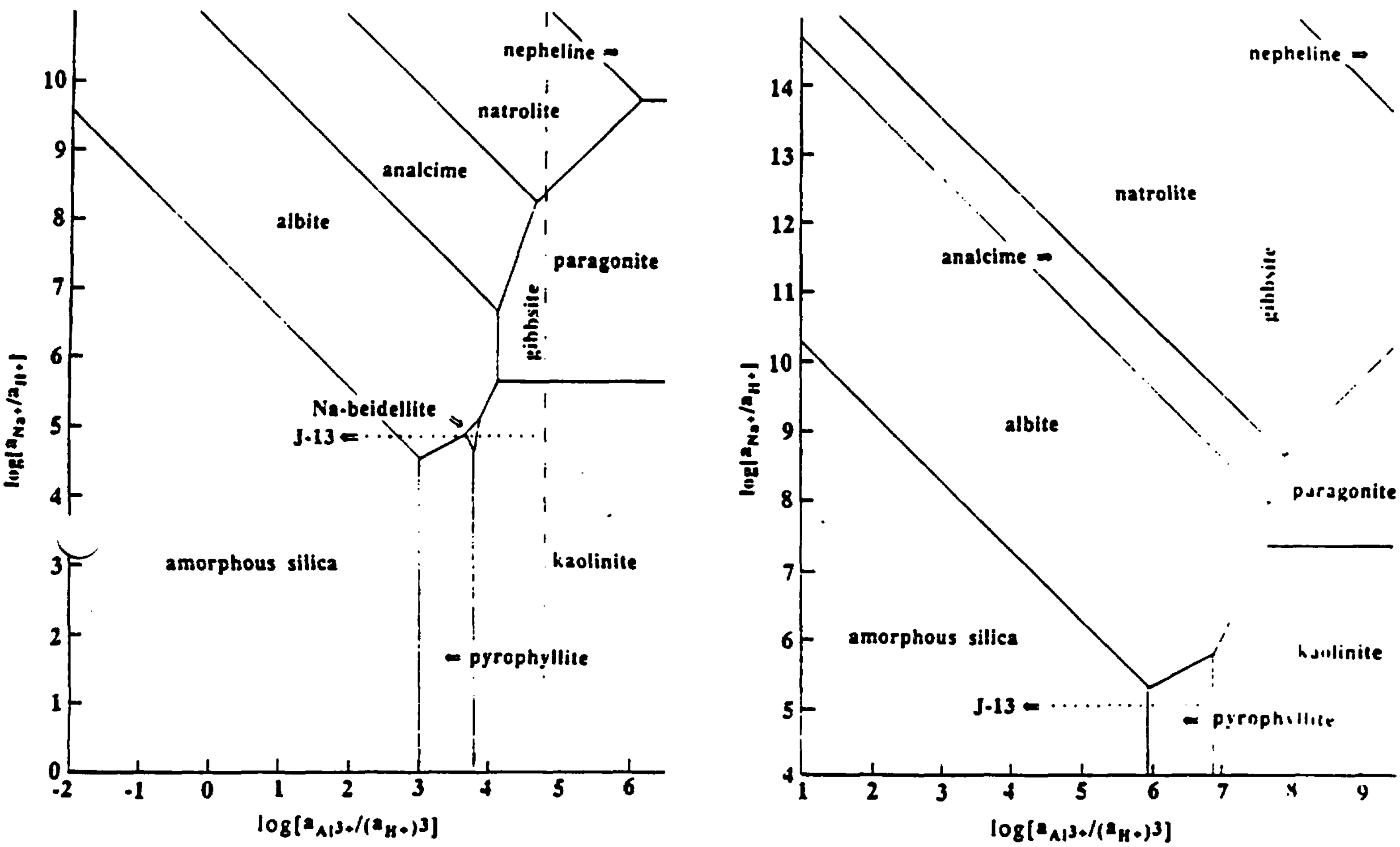
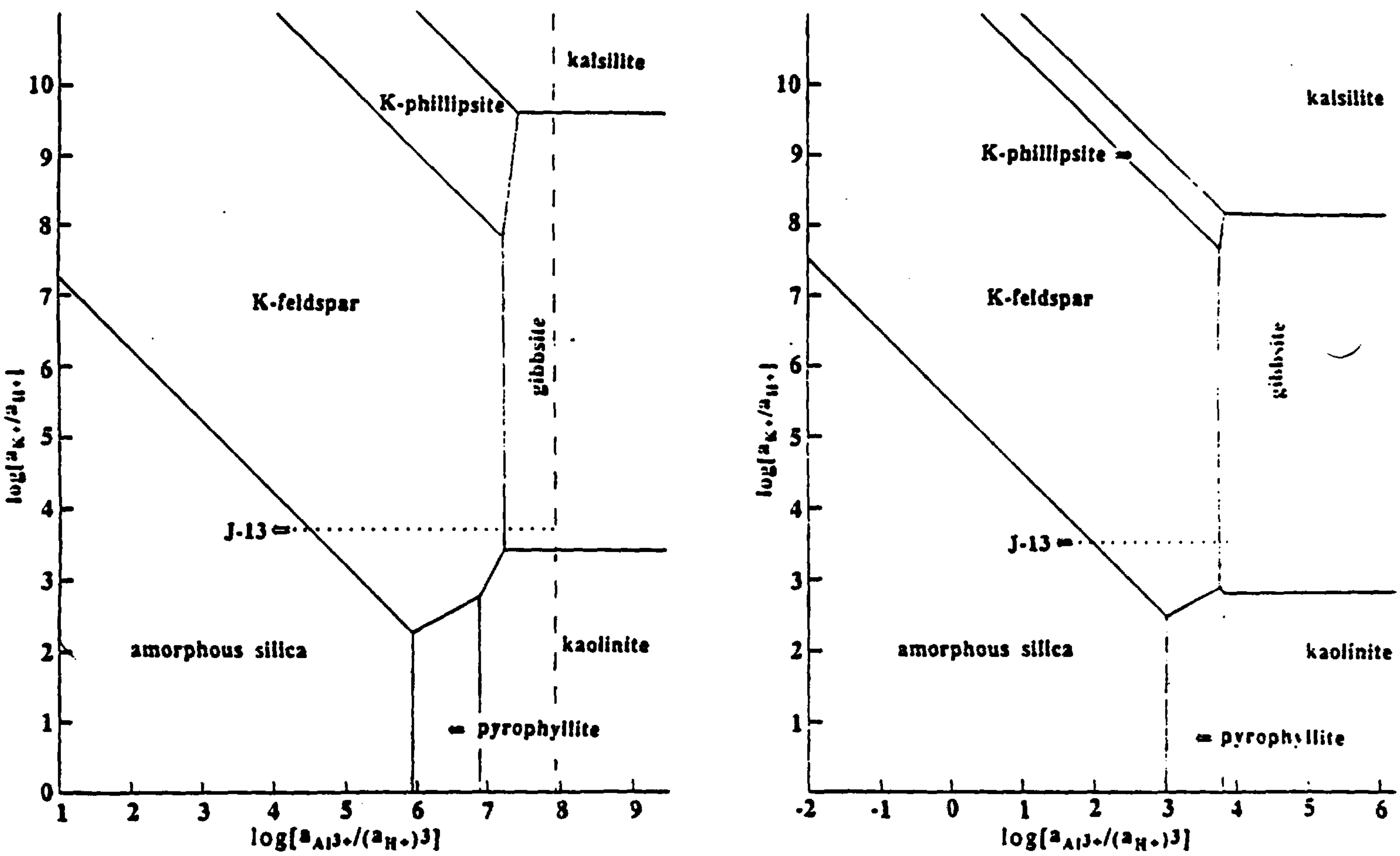

grossular
wollastonite
prehnite
lawsonite
scolecite
epistilbite
gibbsite
calcite
J-13
amorphous silica
kaolinite
pyrophyllite
margarite
Ca-phillipsite
diaspore
Ca-beidellite
$\log[a_{Ca^{2+}}/(a_{H^+})^2]$
$\log[a_{Al^{3+}}/(a_{H^+})^3]$

Figure 3



nepheline
natrolite
analcime
albite
paragonite
gibbsite
Na-beidellite
J-13
amorphous silica
kaolinite
pyrophyllite
log[a_{Na^+}/a_{H^+}]
log[$a_{Al^{3+}}/(a_{H^+})^3$]
nepheline
natrolite
gibbsite
analcime
albite
paragonite
amorphous silica
kaolinite
J-13
pyrophyllite
log[a_{Na^+}/a_{H^+}]
log[$a_{Al^{3+}}/(a_{H^+})^3$]

Figure 4


kalsilite
K-phillipsite
K-feldspar
gibbsite
J-13
amorphous silica
kaolinite
pyrophyllite
log[a_{K+}/a_{H+}]
log[$a_{Al^{3+}}/(a_{H+})^3$]
kalsilite
K-phillipsite
K-feldspar
gibbsite
J-13
amorphous silica
kaolinite
pyrophyllite
log[a_{K+}/a_{H+}]
log[$a_{Al^{3+}}/(a_{H+})^3$]

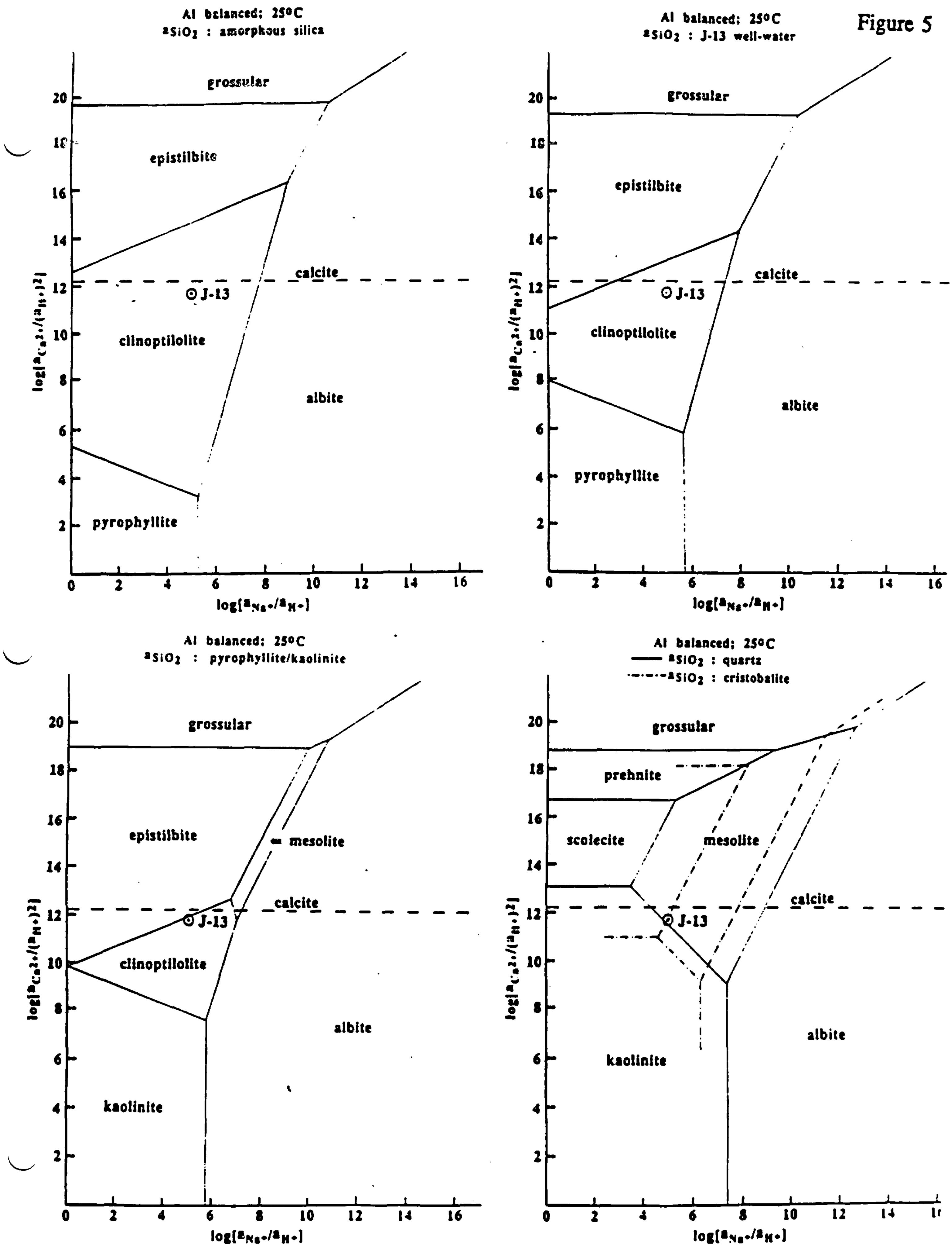
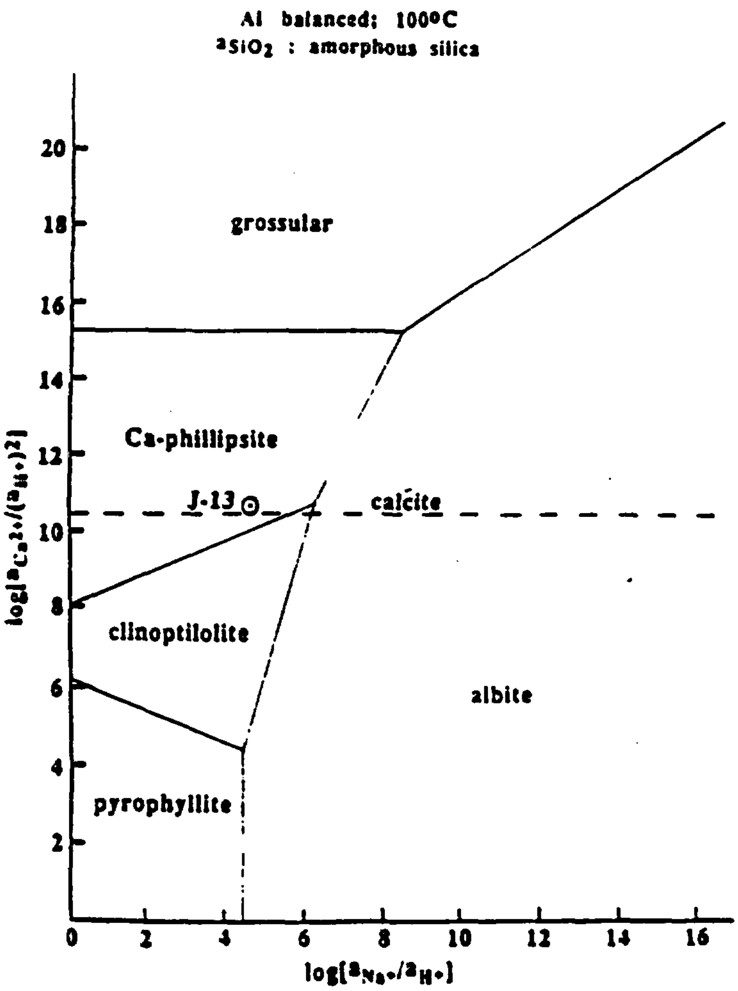
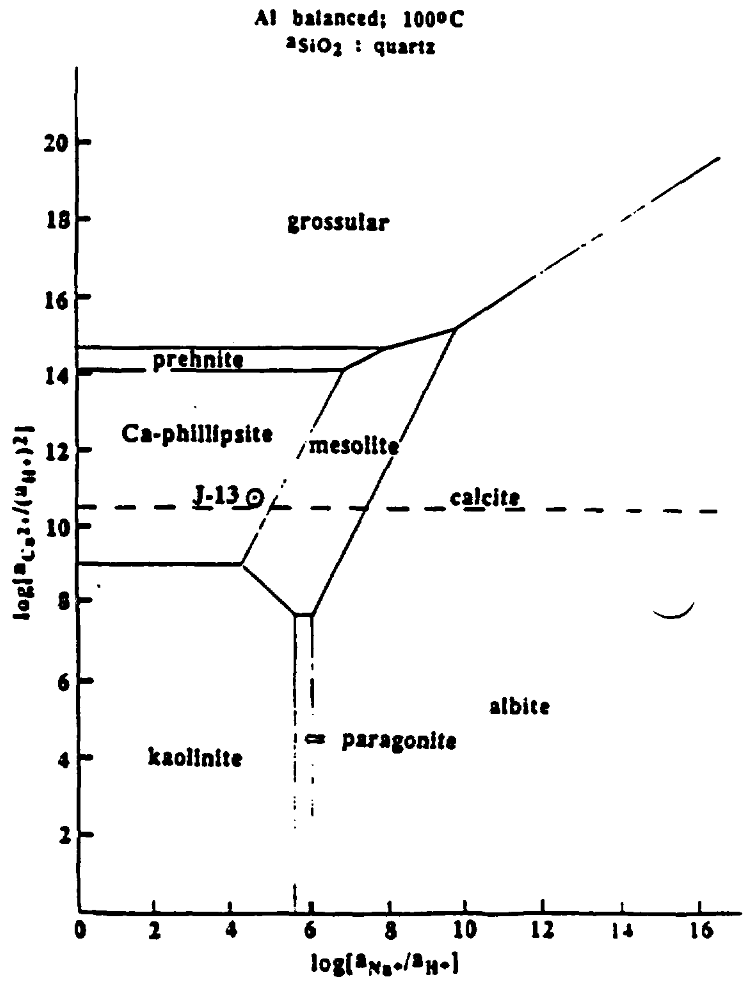


Figure 5
Al balanced; 25°C
aSiO2 : amorphous silica
grossular
epistilbite
calcite
J-13
clinoptilolite
albite
pyrophyllite
log[aCa2+/(aH+)2]
log[aNa+/aH+]
Al balanced; 25°C
aSiO2 : J-13 well-water
grossular
epistilbite
calcite
J-13
clinoptilolite
albite
pyrophyllite
log[aCa2+/(aH+)2]
log[aNa+/aH+]
Al balanced; 25°C
aSiO2 : pyrophyllite/kaolinite
grossular
epistilbite
mesolite
calcite
J-13
clinoptilolite
albite
kaolinite
log[aCa2+/(aH+)2]
log[aNa+/aH+]
Al balanced; 25°C
aSiO2 : quartz
aSiO2 : cristobalite
grossular
prehnite
scolecite
mesolite
calcite
J-13
albite
kaolinite
log[aCa2+/(aH+)2]
log[aNa+/aH+]

Figure 6

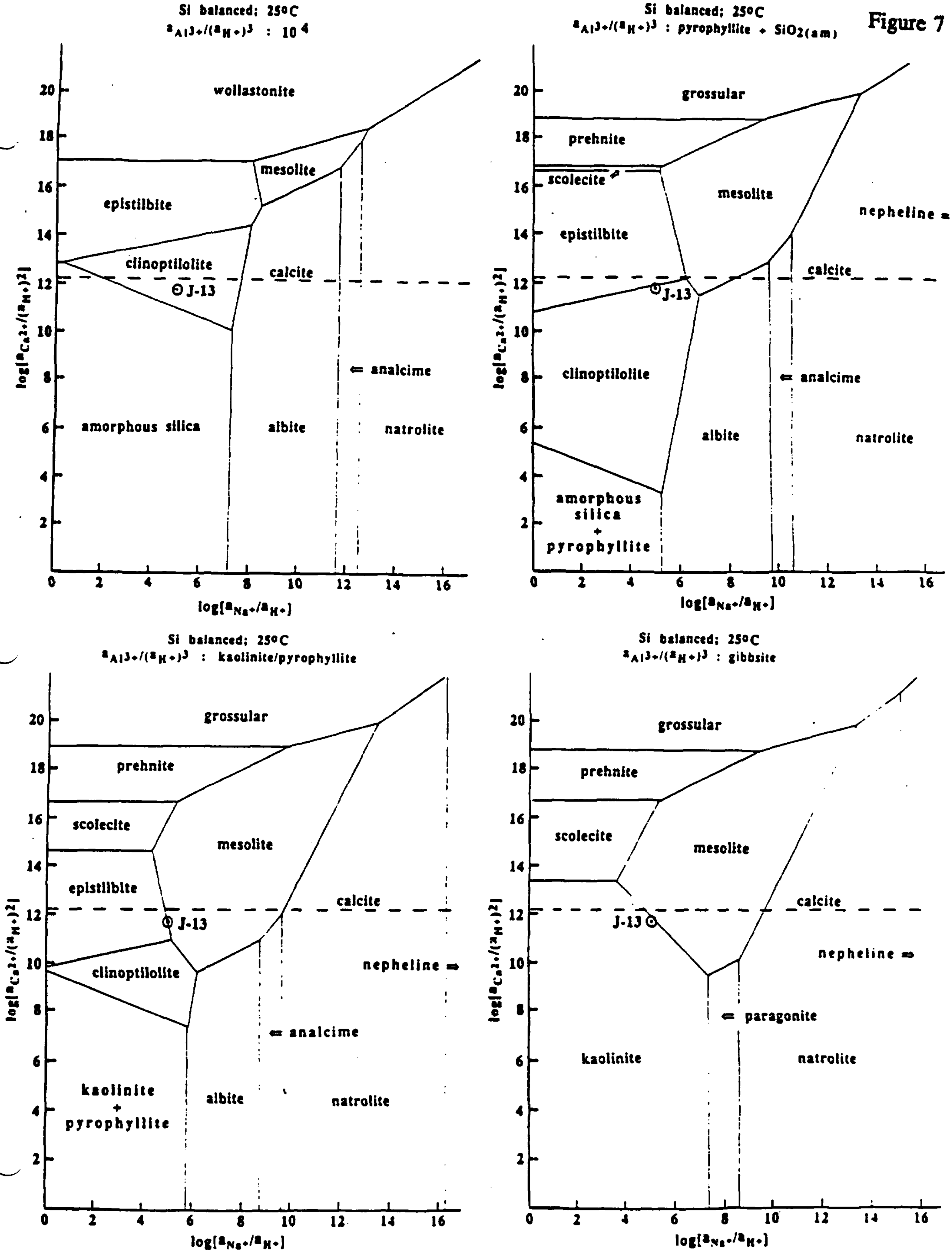


Al balanced; 100°C
a_{SiO_2} : amorphous silica
grossular
Ca-phillipsite
J-13
calcite
clinoptilolite
albite
pyrophyllite
$\log[a_{Ca^{2+}}/(a_{H^+})^2]$
$\log[a_{Na^+}/a_{H^+}]$
0
2
4
6
8
10
12
14
16
18
20



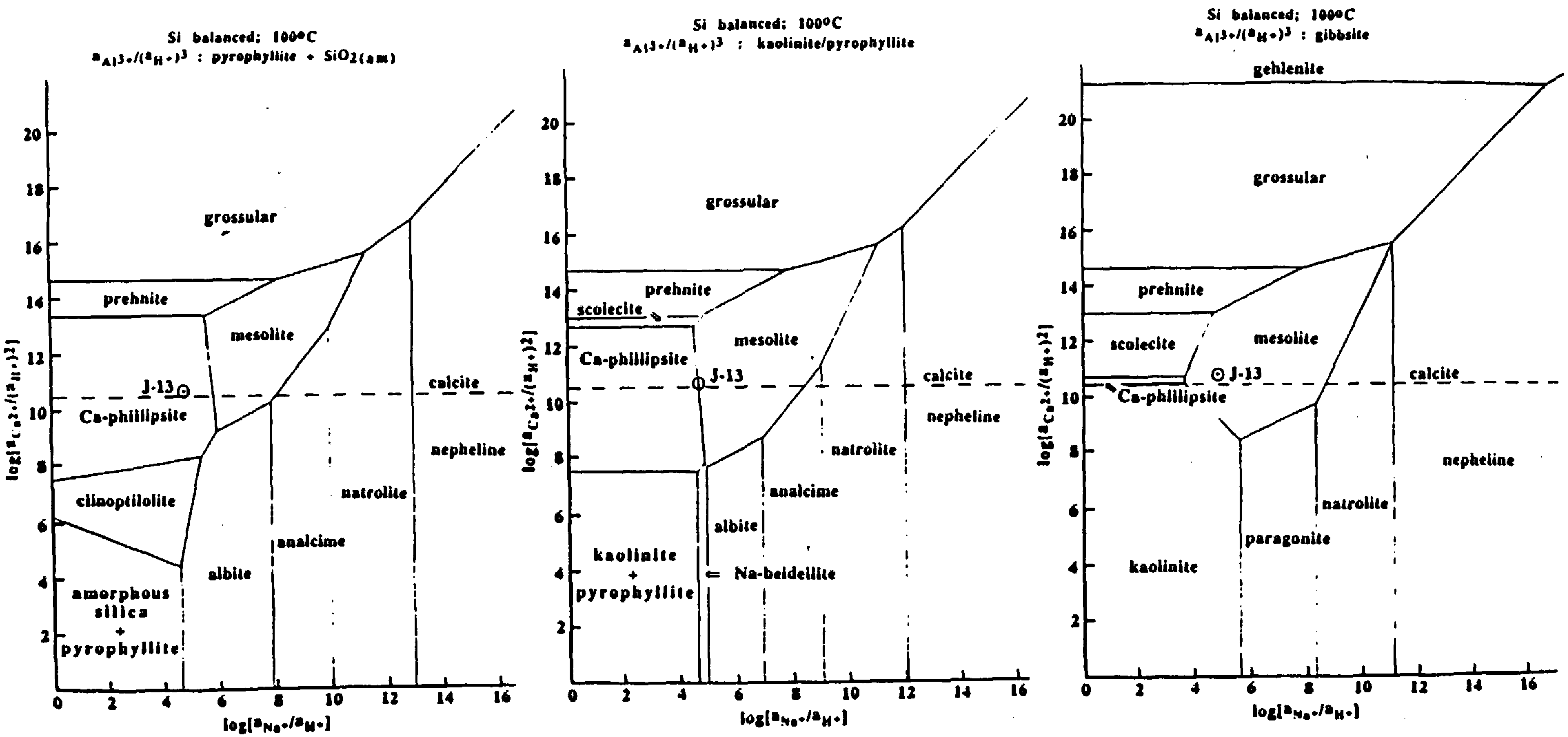
Al balanced; 100°C
a_{SiO_2} : quartz
grossular
prehnite
Ca-phillipsite
mesolite
J-13
calcite
kaolinite
paragonite
albite
$\log[a_{Ca^{2+}}/(a_{H^+})^2]$
$\log[a_{Na^+}/a_{H^+}]$
0
2
4
6
8
10
12
14
16
18
20

Figure 7



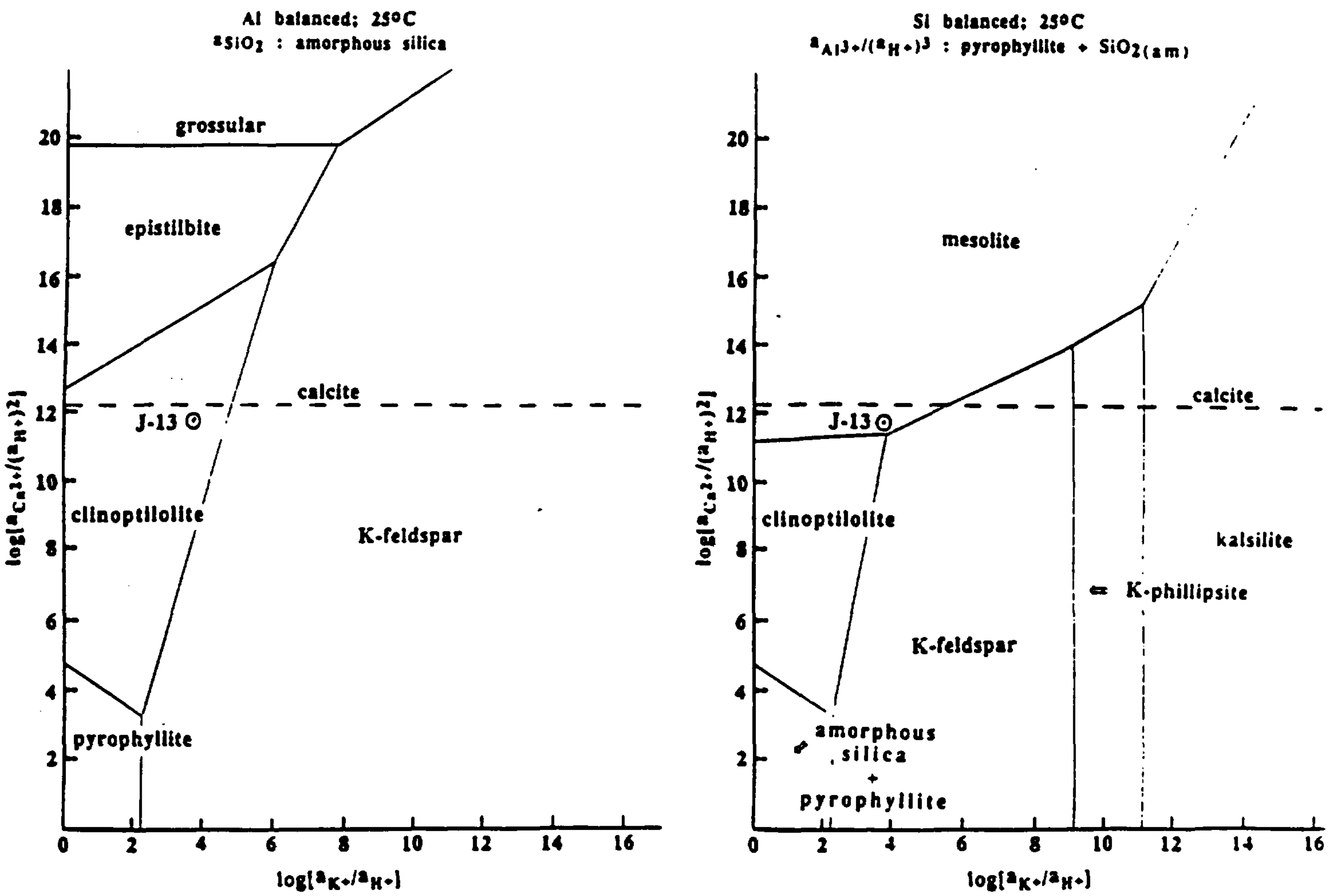
Si balanced; 25°C
$a_{Al^{3+}}/(a_{H^+})^3$: 10^4
wollastonite
mesolite
epistilbite
clinoptilolite
calcite
J-13
⇐ analcime
amorphous silica
albite
natrolite
$\log[a_{Ca^{2+}}/(a_{H^+})^2]$
$\log[a_{Na^+}/a_{H^+}]$
Si balanced; 25°C
$a_{Al^{3+}}/(a_{H^+})^3$: pyrophyllite + $SiO_{2(am)}$
grossular
prehnite
scolecite
mesolite
nepheline ⇒
epistilbite
calcite
J-13
clinoptilolite
⇐ analcime
albite
natrolite
amorphous silica + pyrophyllite
$\log[a_{Ca^{2+}}/(a_{H^+})^2]$
$\log[a_{Na^+}/a_{H^+}]$
Si balanced; 25°C
$a_{Al^{3+}}/(a_{H^+})^3$: kaolinite/pyrophyllite
grossular
prehnite
scolecite
mesolite
epistilbite
calcite
J-13
nepheline ⇒
clinoptilolite
⇐ analcime
kaolinite + pyrophyllite
albite
natrolite
$\log[a_{Ca^{2+}}/(a_{H^+})^2]$
$\log[a_{Na^+}/a_{H^+}]$
Si balanced; 25°C
$a_{Al^{3+}}/(a_{H^+})^3$: gibbsite
grossular
prehnite
scolecite
mesolite
calcite
J-13
nepheline ⇒
⇐ paragonite
kaolinite
natrolite
$\log[a_{Ca^{2+}}/(a_{H^+})^2]$
$\log[a_{Na^+}/a_{H^+}]$

Figure 8



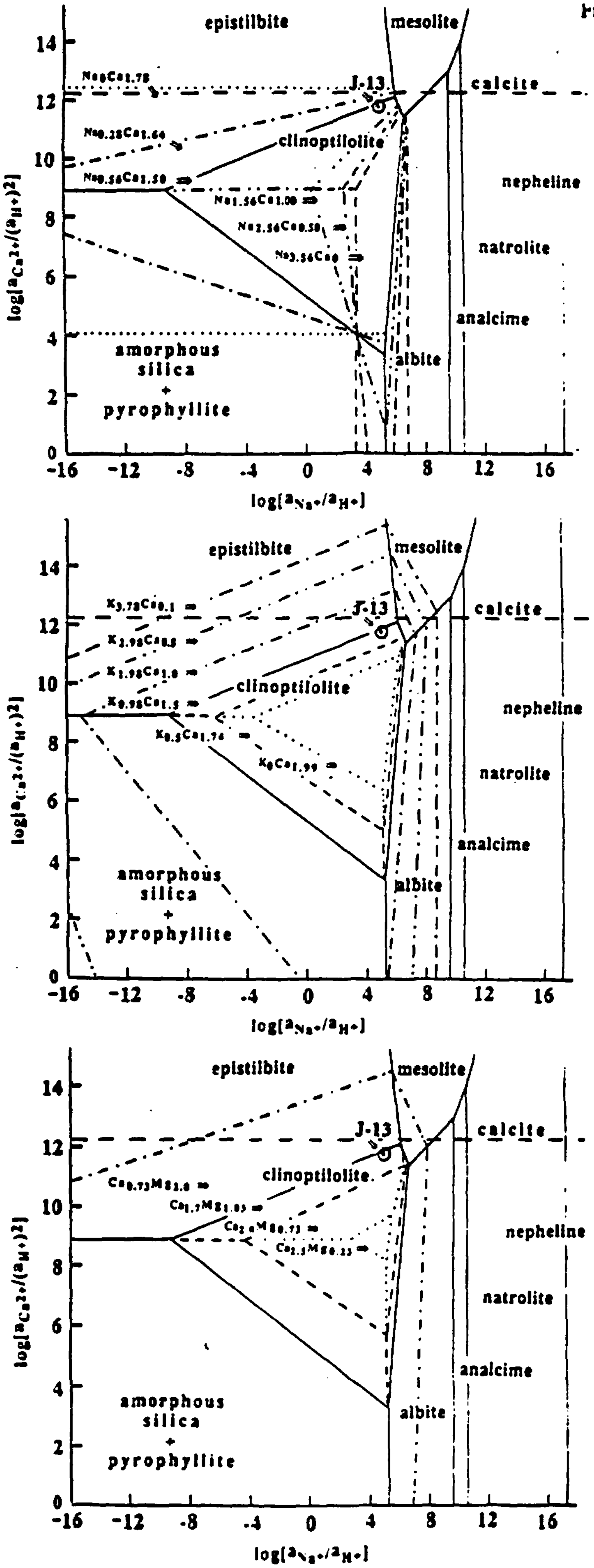
Si balanced; 100°C
$a_{Al^{3+}}/(a_{H^+})^3$: pyrophyllite + $SiO_{2(am)}$
grossular
prehnite
mesolite
J-13
calcite
Ca-phillipsite
clinoptilolite
natrolite
nepheline
analcime
albite
amorphous silica + pyrophyllite
$\log[a_{Ca^{2+}}/(a_{H^+})^2]$
$\log[a_{Na^+}/a_{H^+}]$
Si balanced; 100°C
$a_{Al^{3+}}/(a_{H^+})^3$: kaolinite/pyrophyllite
grossular
prehnite
scolecite
mesolite
Ca-phillipsite
J-13
calcite
nepheline
natrolite
analcime
albite
kaolinite + pyrophyllite
Na-beidellite
$\log[a_{Ca^{2+}}/(a_{H^+})^2]$
$\log[a_{Na^+}/a_{H^+}]$
Si balanced; 100°C
$a_{Al^{3+}}/(a_{H^+})^3$: gibbsite
gehlenite
grossular
prehnite
scolecite
mesolite
J-13
calcite
Ca-phillipsite
nepheline
natrolite
paragonite
kaolinite
$\log[a_{Ca^{2+}}/(a_{H^+})^2]$
$\log[a_{Na^+}/a_{H^+}]$

Figure 9

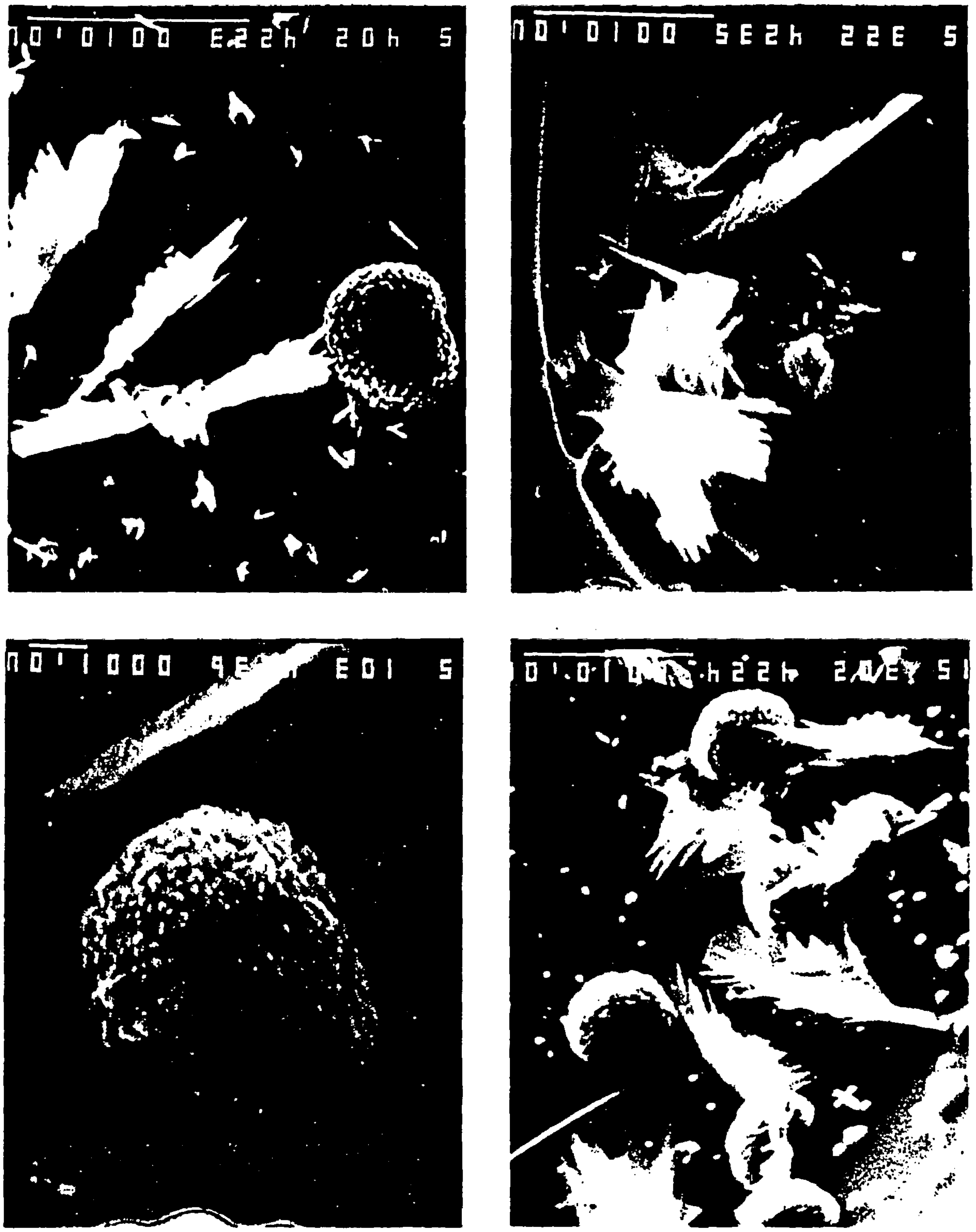


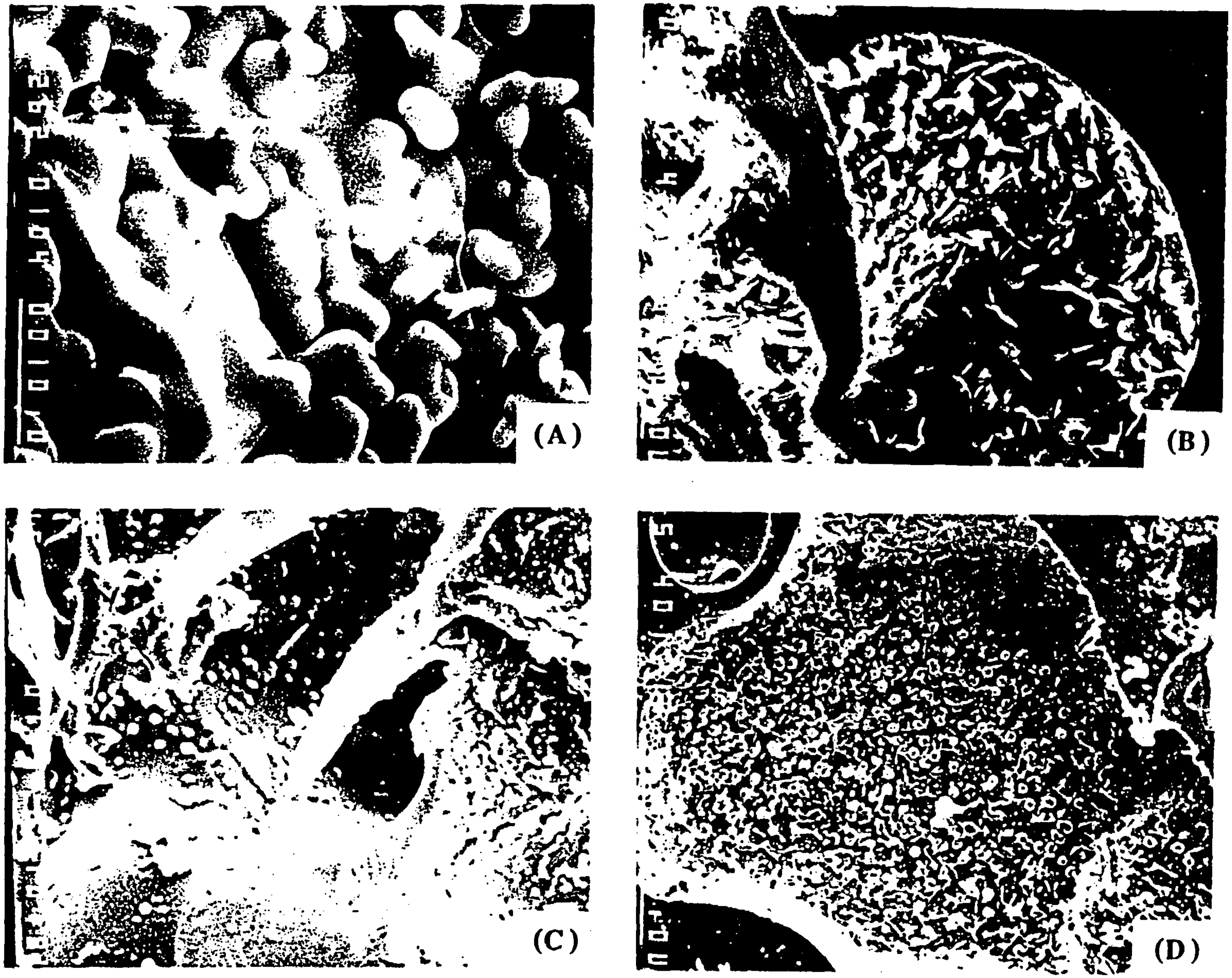
Al balanced; 25°C
a_{SiO_2} : amorphous silica
grossular
epistilbite
calcite
J-13
clinoptilolite
K-feldspar
pyrophyllite
$\log[a_{Ca^{2+}}/(a_{H^+})^2]$
$\log[a_{K^+}/a_{H^+}]$
Si balanced; 25°C
$a_{Al^{3+}}/(a_{H^+})^3$: pyrophyllite + $SiO_{2(am)}$
mesolite
calcite
J-13
clinoptilolite
kalsilite
K-phillipsite
K-feldspar
amorphous silica + pyrophyllite
$\log[a_{Ca^{2+}}/(a_{H^+})^2]$
$\log[a_{K^+}/a_{H^+}]$

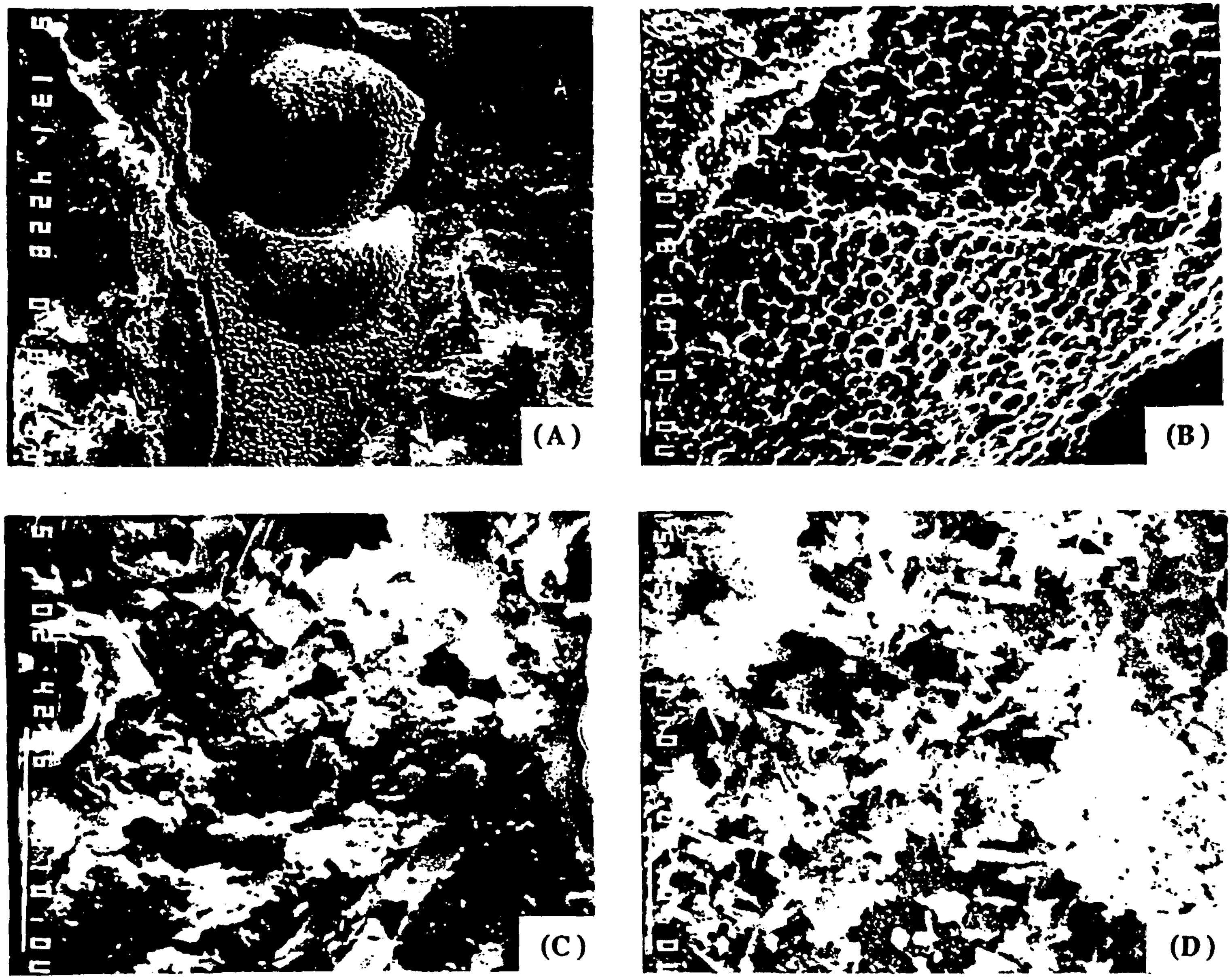
Figure 10



epistilbite
mesolite
calcite
J-13
clinoptilolite
nepheline
natrolite
analcime
albite
amorphous silica + pyrophyllite
log[$a_{Ca^{2+}}/(a_{H^+})^2$]
log[a_{Na^+}/a_{H^+}]




(A)
(B)
(C)
(D)


(A)
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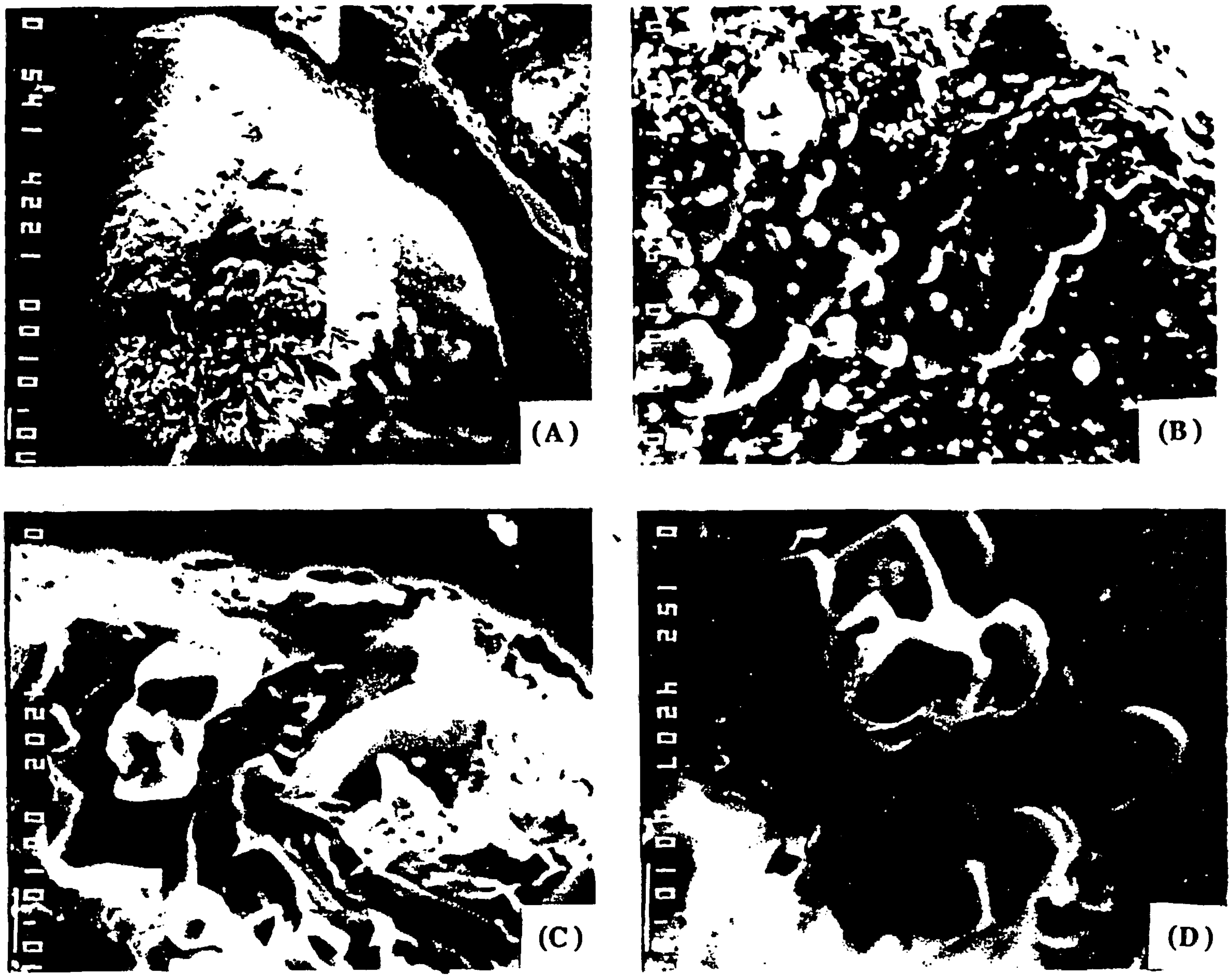
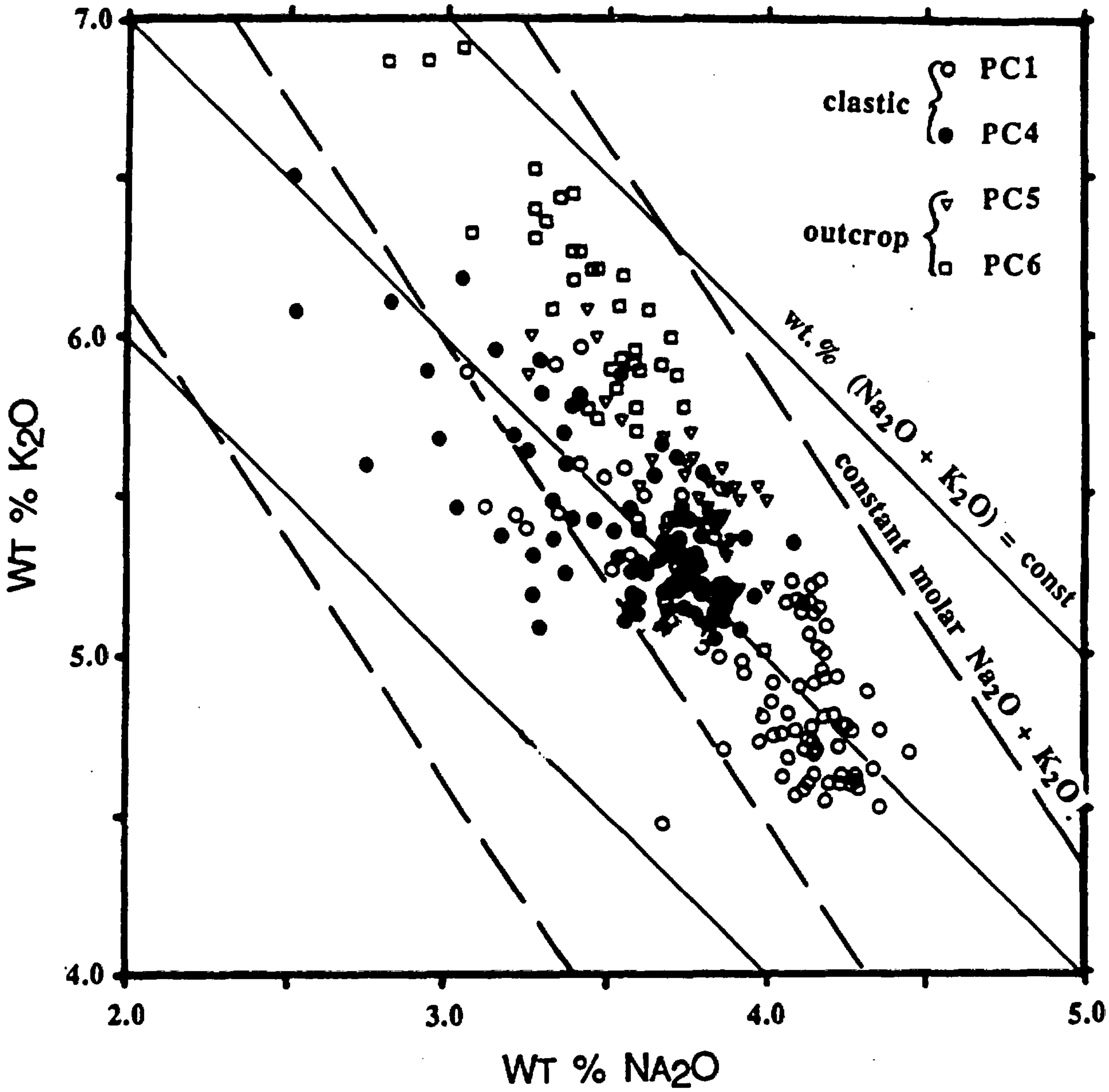
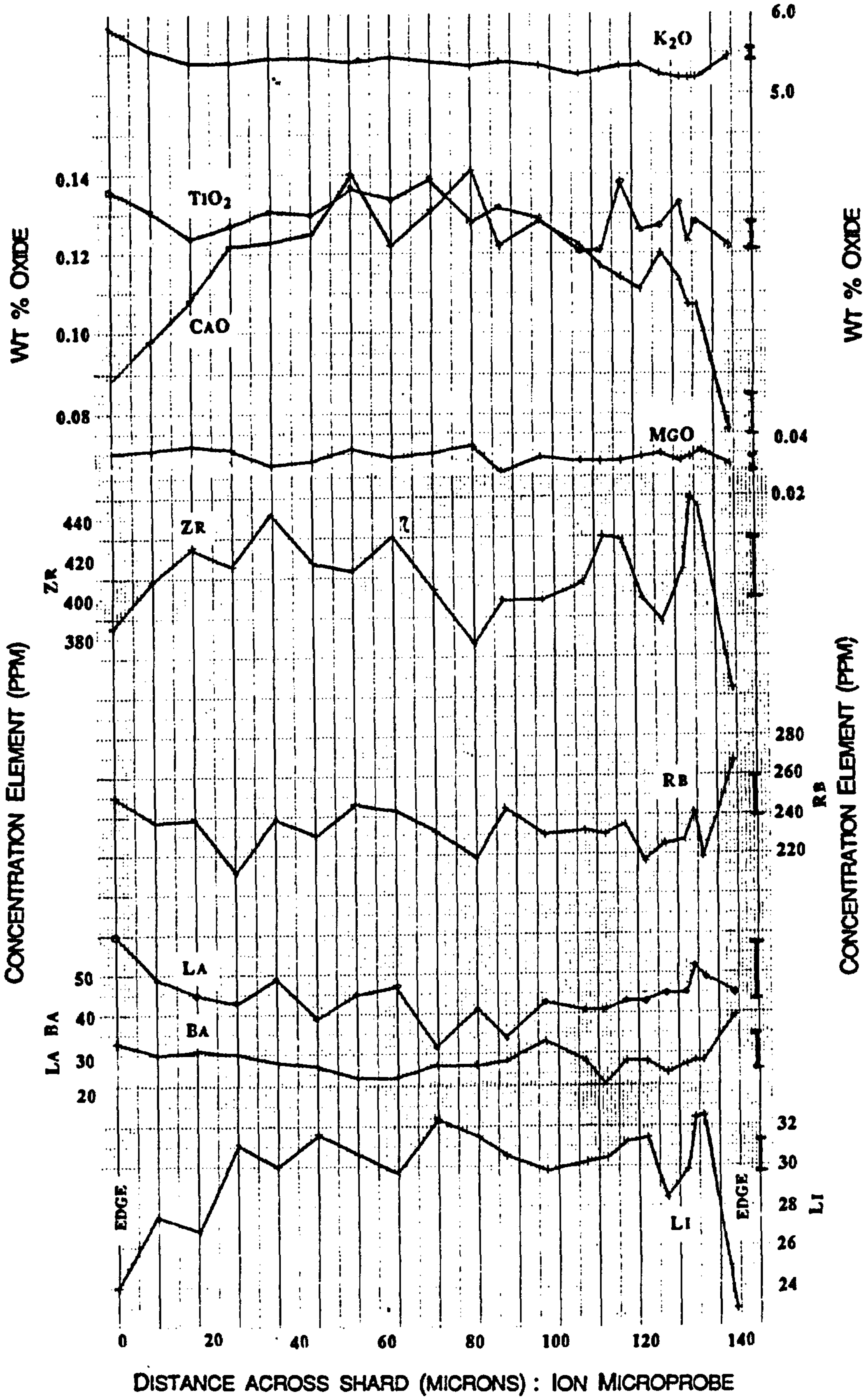

(A)
(B)
(C)
(D)

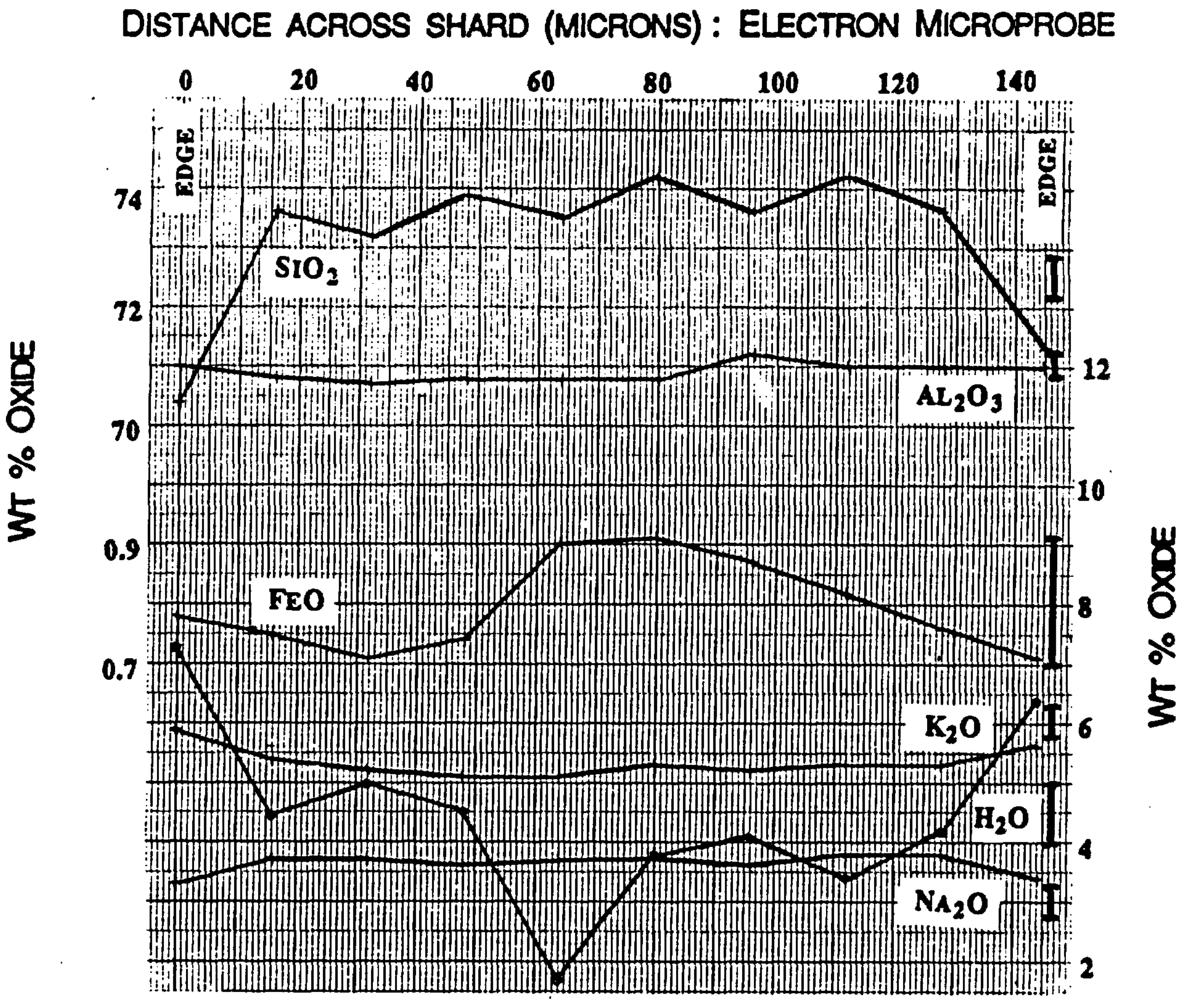


7.0
6.0
5.0
4.0
2.0
3.0
4.0
5.0
WT % K2O
WT % NA2O
clastic
PC1
PC4
outcrop
PC5
PC6
wt. % (Na2O + K2O) = const
constant molar Na2O + K2O.



K2O
6.0
5.0
TiO2
CaO
MgO
0.14
0.12
0.10
0.08
0.04
0.02
Wt % Oxide
Wt % Oxide
Zr
440
420
400
380
Rb
280
260
240
220
La
Ba
50
40
30
20
Li
32
30
28
26
24
Edge
Edge
Concentration Element (ppm)
Concentration Element (ppm)
0
20
40
60
80
100
120
140
Distance across shard (microns) : Ion Microprobe

Fig. 1. Missing —
no extra
prints left
R



Geological Society of America, Abstracts with Program, vol. 20, no. 7, 1988, p. A359.
(Paper presented in session: "Geochemistry VI: Layered Silicates and Zeolites/Mineralogy/Crystallography II)

№ 23742

ACTIVITY DIAGRAMS FOR CLINOPTILOLITE: RELEVANCE TO ZEOLITIZED VITRIC TUFFS AT YUCCA MOUNTAIN, NEVADA

BURNS, Roger G., and BOWERS, Teresa S.: Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139.

Clinoptilolite, e.g. $(Na_{0.56}K_{0.98}Ca_{1.50}Mg_{1.23})(Si_{29}Al_{6.7}Fe_{0.3})O_{72}.22H_2O$, occurs as a secondary mineral in zeolitized vitric tuffs and is considered to be a prime candidate for immobilizing certain soluble radionuclides (e.g. ^{135}Cs, ^{90}Sr) contained in fission products to be stored in the proposed repository for high-level nuclear waste at Yucca Mt. Clinoptilolites, occurring in the undersaturated zone above the water table there, show regional variations of Na and Ca, which raise questions about the vulnerability of the zeolites to further diagenetic reactions with groundwater. Therefore, equilibrium activity diagrams were calculated for clinoptilolite solid-solutions in the seven component system Na-K-Ca-Mg-Fe-Al-Si plus H_2O, employing available thermodynamic data for relevant oxide and aluminosilicate phases. Stability fields were portrayed graphically on plots of $log(a_{Na^+}/a_{H^+})$ versus $log(a_{Ca^{2+}}/a_{H^+})^2$, assuming the presence of K-feldspar, saponite and hematite and using ranges of activities for SiO_2 and Al^{3+} defined by the saturation limits for quartz, amorphous silica, gibbsite, kaolinite and pyrophyllite. Formation of clinoptilolite is favored by higher SiO_2 activities than allowed for by the presence of quartz, thus accounting for coexistence of clinoptilolite with opal CT in zeolitized vitric tuffs. The clinoptilolite stability field broadens with increasing ratio of Ca to Na, reaches a maximum size for intermediate Al^{3+} activities, and decreases at elevated temperatures. In the absence of analytical data for vadose-zone water at Yucca Mt., the water composition of the nearest producing well (J-13 at the adjacent Nuclear Test Site) was used as reference. The thermodynamic calculations show that sodium bicarbonate-type J-13 well-water is approximately in equilibrium with calcite and several zeolites, including clinoptilolite. Decreasing Al^{3+} activities results in the association of clinoptilolite with calcite and opal CT observed in some zeolitized vitric tuffs at Yucca Mt. This suggests that prolonged diagenetic reactions with groundwater depleted in Al and heated by the thermal envelope surrounding the repository may eliminate sorptive clinoptilolite.

ABSTRACT FORM FOR ALL GSA MEETINGS IN 1989

Complete all sections [3] through [7] below

[1] TYPE ABSTRACT within blue lines — they're absolute! Mail flat, reinforced.

№ 6647

DESERT VARNISH: A NEW LOOK AT CHEMICAL AND TEXTURAL VARIATIONS

KRINSLEY, David, and ANDERSON, Steven, Geology Department, Arizona State University, Tempe, AZ 85287

We have combined several analytical techniques and used them to acquire chemical and textural information from rock varnish samples. Polished sections of varnish and underlying rock material were photographed at both low and high magnification (up to 15,000X) using scanning electron microscopy (SEM) in the backscattered electron mode (BSE). Photomosaics show the relations between the varnish and the underlying rock, including textural variations and chemical differences within the varnish layers. Sections were analyzed with the electron microprobe to obtain major element distributions. Water content and trace element data on the same section were then acquired using the ion microprobe. Chemical analyses were related to depth in the varnish layers, overall varnish thickness, and structure within the varnish. The percentage of water at a number of points in cross section was compared to chemical composition and texture.

BSE microphotography has shown that the contact between the varnish and the rock substrate is very sharp and distinct, with no evidence of chemical weathering. This suggests that either the rock to which the varnish adheres is resistant to chemical weathering, or varnish accretion begins soon after the rock has become mechanically stable; the latter is probably more likely. There also does not appear to be chemical exchange between rock and varnish. In addition, porosity decreases with depth, and 1-2 micron lamellae are concentrated at the bottom of the varnish near the rock-varnish interface.

Preliminary analysis of ion and electron microprobe data from South Mountain, Arizona and Coso volcanic field, California varnish samples has revealed a highly varied chemistry. Major elements, trace elements, water contents, and the cation ratios (Ca+K/Ti) do not show any clear trends with depth.

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- ☐ 3 economic geology
- ☐ 4 engineering geology
- ☐ 5 environmental geology
- ☐ 6 general geology
- ☐ 7 geochemistry
- ☐ 8 geology education
- ☐ 9 geomorphology
- ☐ 10 geophysics
- ☐ 11 geoscience information
- ☐ 12 glacial geology
- ☐ 13 history of geology
- ☐ 14 hydrogeology
- ☐ 15 marine geology
- ☐ 16 micropaleontology
- ☐ 17 mineral./crystal.
- ☐ 18 oceanography
- ☐ 19 paleontology/paleobot.
- ☐ 20 petroleum geology
- ☐ 21 petrology, experimental
- ☐ 22 petrology, igneous
- ☐ 23 petrology, metamorphic
- ☐ 24 petrology, sedimentary
- ☐ 25 planetary geology
- ☐ 26 Precambrian geology
- ☐ 27 Quaternary geology
- ☐ 28 remote sensing
- ☐ 29 sedimentology
- ☐ 30 stratigraphy
- ☐ 31 structural geology
- ☐ 32 tectonics
- ☐ 33 tectonics/geophysics
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ONLY if your abstract has been formally invited by a Symposium Convener, write the name of the symposium on the blank line then skip to item [4]. When your abstract is ready, send original + 5 photocopies direct to your Convener to arrive on or before July 19, 1989.

______

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If this is a volunteered abstract, complete item (1) or item (2) below—but not both.

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(Check below)

- O ☐ ORAL: Check here if you want an oral presentation in a regular session, organized by discipline.
- P ☒ POSTER: Check here if you want a presentation by display of graphic materials in a booth which you attend.
- E ☐ I've checked ORAL or POSTER, but I'll accept a change of session type (ORAL ↔ POSTER) if necessary.
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[6] SPEAKER'S IDENTITY AND MAILING ADDRESS:

Speaker's Name: Steven Anderson
Address: Dept. of Geology
Address: Arizona State University
City/St/ZIP: Tempe, AZ 85287-1404
Country ______
Office Telephone (602) 965-6236
Home Telephone: (602) 829-7812
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Denver Meeting

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№ 26427

CHEMICAL ZONATION WITHIN BISHOP ASH, PLEISTOCENE LAKE TECOPA, INYO COUNTY, CALIFORNIA

O'HARA, Parick F., Kaaterskill Exploration, 691 Robinson Dr., Prescott, AZ 86303; MANLEY, Curtis R., KRINSLEY, David, Dept. Geology, Arizona State Univ., Tempe, AZ 85287

Tuff B (Bishop Ash) is a LREE enriched, corundum normative calc-alkaline rhyolite, which crops out within the mudstones of the Late Teritary Lake Tecopa basin, and is present in the fresh glass, zeolite, and K-feldspar diagenetic facies of Sheppard and Gude (1968). Because airfall tuff has a nearly fixed chemical composition during deposition, lateral elemental variation (31 elements) is used to deduce changing geochemical processes and patterns.

Samples of fresh glass are enriched in F, Mo, W and Y, but these elements are depleted in all samples of recrystallized tuff. Two zones enriched in alkalis and depleted in U are present in the altered tuff. An As + B trace element association is found in a six sample zone where the most anomalous samples containing alkali enrichment, U depletion and high Cu + Ba concentrations exist. Anomalous Pb and U flank this zone.

Zones of both As + B and alkali depletion flank corresponding zones of high concentrations, suggesting potential paths of fluid flow. Both fresh glass and recrystallized tuff facies locally contain high calcite + Mn concentrations. Three fluid sources are inferred: 1) hot springs which added high concentrations of B + As and associated elements, 2) alkali enriched fluid, which might be associated with hydrothermal fluids, and 3) carbonate-enriched groundwater venting into the lake as cold springs.

Lack of correlation between these chemical zones and the diagentic mineral assemblages may preclude a direct relation between the fluid and diagenetic phases. The Bishop Ash could have been open to chemical exchange prior to diagenesis.

[2] CATEGORIZE ALL ABSTRACTS —Check ONE discipline below in which reviewers would be best qualified to evaluate this abstract.

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- ☐ 8 geology education
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- ☐ 10 geophysics
- ☐ 11 geoscience information
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Speaker's name DR. PAT O'HARA

Address 691 Robinson DRive

Address ____________

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CHEMICAL ZONATION WITHIN BISHOP ASH, PLEISTOCENE LAKE TECOPA, INYO COUNTY, CALIFORNIA

O'HARA, Patrick F., Kaaterskill Exploration, 691 Robinson Dr., Prescott, AZ 86303; MANLEY, Curtis R., KRINSLEY, David, Dept. Geology, Arizona State Univ., Tempe, AZ 85287

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fluid, which might be associated with hydrothermal fluids, and 3) carbonate-enriched groundwater venting into the lake as cold springs.

Lack of correlation between these chemical zones and the diagenetic mineral assemblages may preclude a direct relation between the fluid and diagenetic phases. The Bishop Ash could have been open to chemical exchange prior to diagenesis.

INTRODUCTION

Pleistocene lake beds in Lake Tecopa formed as a result of the damming of the ancestral Amargosa River. Surface flow in the Amargosa River was a direct result of higher groundwater levels and associated increase in groundwater flow. Either at the time of lake sediment distribution or at some later date, rock-fluid reactions have changed the chemistry and mineralogy of the lake deposits. This study is a preliminary attempt to explain the spacial distributions, timing and physiochemical processes associated with these changes.

Lake sediments may have several sources; therefore, they probably have a high degree of chemical variance. For this reason it would be difficult to model chemical variation caused by alteration. However, because felsic volcanic ash of fixed initial chemical composition exists within the basin, these rocks can be used to model chemical and mineralogical changes due to groundwater discharge and alteration, hotspring alteration and diagenetic reactions.

PREVIOUS WORK

Field studies of Lake Tecopa (Map 1) have delineated the areal distribution of lake sediments (Hillhouse, 1987) and the zonation of diagenetic facies using mineral assembleges from felsic ash beds (Sheppard and Gude, 1968; Sheppard, 1985). Currently Roger Morrison, is mapping the distribution of sedimentary rock units and tuffs within the lake beds in order to generate a model of sedimentary facies within Lake Tecopa.

OBJECTIVES

The Bishop Ash is present in all diagenetic facies of Sheppard and Gude (1968) and crops out throughout the Lake Tecopa basin. Textural relationships indicate that the mineral assemblages, which make up the diagenetic facies (Figure 1) change progressively as discontinuous reactions from fresh glass to zeolites and then from zeolites to potassium feldspar (Sheppard and Gude, 1968). Because a felsic ash airfall approximates a fixed composition at the time of deposition, the Bishop Ash can be used to model chemical change caused by rock fluid reactions which occured after deposition. Therefore, initial hypotheses can be generated which can be tested at a later date with more precise methods.

In order to explain chemical variance within the Bishop Ash, multi-element geochemical analyses and x-ray diffraction data are used in conjunction with multivariate statistical analysis. This data is then used to generate hypotheses concerning the geochemical processes of rock-fluid reactions within alkaline lake deposits. The use of the SEM-EDS system allows petrographic testing of the initial hypotheses and the determination of the timing of each processes (textural analysis). Once all this information is evaluated, an inclusive model can be generated which summarizes rock-fluid reaction processes in alkaline lake deposits.

GEOCHEMISTRY

Fifty-two elements were analysed for thirty-two samples of Bishop Ash. Table I summarizes the elements analysed, detection limits, extraction techniques and method of analysis. Thirty-one of these elements were used in the statistical analyses. The remaining elements were rejected because the samples were mostly below detection limit or had extremely low variance. (Table 1). Each variable was $\log_{10}$ normalized in order to compare skewness between the arithmetic and $\log_{10}$ normalized data. The use of either the arithmetic or $\log_{10}$ normalized variable was based upon the data set that had a skewness value closer to zero.

PRELIMINARY STATISTICAL RESULTS

Initial factors (table 2) derived from the database suggest that seven processes are responsible for changes in chemistry within the Bishop Ash. Fresh samples are enriched in a lithophile element suite containing high concentrations of Mo, W and Rb with depleted concentrations in Ba. This data suggests that during alteration Mo, W and Rb are leached out of the ash and that Ba is added to the ash, preferentially partitioning into the new alteration phases. Locally within the altered rocks alkali addition occurs along with a weak tendency towards U depletion. A strong B, As association is noted and high concentrations of this suite is inferred to be associated with hydrothermal activity. The presence of a "chert" in the Bishop Ash locally within the area of B, As enrichment leads credence to this hypothesis. Because the "chert" is fairly dirty (contaminated with many components) it is unclear whether it is formed by replacement of ash by SiO_2 (silicification), formed by silicification of sediments immediately above the Bishop Ash, or is an exhalative rock which is contaminated by an ash or sediment component. Further petrographic and geochemical work is needed to test these possibilities. Carbonate addition is present in many samples and is associated with an increase in Mn. Detailed field and petrographic studies will be needed to determine whether these carbonate enriched rocks are formed by a precipitation type chemical reaction within local beds by groundwater, as tuffa mounds or as exhalative zones.

Two sets of associated elements are present within the altered Bishop Ash, which may be related to mineral reactions during alteration or diagenesis.

1. Fe, Ti concentrations
2. MgO, F, Li concentrations

ZONATION WITHIN THE BISHOP ASH (Figures 3 through 9)

Relative zonation of elemental associations is observed by plotting the samples within the highest factor scores for each elemental association on a map. Figure 1 is a map generated by computer use of coordinates arbitrarily devised for this data set. The east-west axis is exaggerated in order to enhance the differences between samples. Figure 2 summarizes the original data set's distribution. Fresh samples are located in the northeast while all other samples are variably altered. Two zones of alkali addition are present, while the southern zone is associated with hydrothermal (B, As) activity. Comparison with the diagenetic facies map (Figure 1) of Sheppard and Gude (1968) indicates that many of these processes may have occurred before diagenesis, while some may be related to diagenetic reactions. Future petrographic work with SEM-EDS should help unravel the timing of these events.

FACTOR ANALYSIS

Principle component and factor analysis are designed to represent complex relationships between a large number of variables, measured on a set of objects by similar relationships among fewer variables. This reduction should make complex relationships more comprehensible. Various mathematical procedures are performed to describe the objects in terms of a small number of new variables. These new variables are linearly related to the original measured variables by rotation in space and should explain most of the sample variance in far fewer variables than originally measured (Till, 1974).

R-mode factor analysis proceeds in four steps, namely:

1. Correlation matrix is computed
2. Factor extraction
3. Rotation
4. Factor scores computed (optional)

Once the correlation matrix is computed, principle components analysis is used to estimate the initial factors. Principle components analysis is a mathematical procedure which calculates the number of eigenvectors and associated eigenvalues which explain the largest percentage of variance in the database. The first principle component is the combination of variables which accounts for the largest amount of variance in the sample. The second principle component accounts for the next largest amount of variance and is uncorrelated with one another. It is possible to compute as many principle components as there are variables. If all principle components are used, each variable can be exactly represented by them, but nothing has been gained because there are as many factors (principle components) as variables. When all factors are included in the solution, all the variance of each variable is accounted for, and there is no unique factor in the model. The proportion of variance accounted for by the common factors (communality) is 1.0 for all variables (Norusis, 1984).

In order to determine how many factors are needed to represent the data, the percentage of total variance which is explained by each factor must be examined. The procedure which is used in this report for determining the number of useful factors in the model is the "eigenvalue 1.0" technique. This model suggests that only factors which account for variance greater than 1.0 should be included, because factors with a variance less than 1.0 are no better than a single variable (communality = 1.0 by definition).

Once the number of usable factors is chosen it is important to determine how well the factor model describes the variances of the original variables. First, the total percentage of variance explained by the chosen factors is calculated. Because the factors are uncorrelated the total percentage of variance, which has been determined, is the sum of the variance explained by each factor. Second, the percentage of variance of the original variables, which is explained by the factor model, is calculated and is presented in table form as the communality of the variable. Communalities can range from 0 to 1.0 with 0 indicating that all the chosen factors explain none of the variance, and 1.0 indicating that all of the variance is explained by the chosen factors.

During state 2 (factor extraction) factor loadings are generated for each of the chosen factors and all the original variables. These loadings are difficult to analyse and interpret because they are generally all quite high. In order to maximize or minimize the loading of each variable within an individual factor, the factors are mathematically rotated (varimax rotation). The goal of rotation is to transform complicated matrices into simpler matrices (stage 3). The rotation matrix is then calculated and new loadings determined. It is in this format that the data is used for interpreting geochemical processes. Factor loadings of each variable are considered significant if their values fall between 0.55 and 1.0. The closness of the value of the coefficient to 1.0 (positive or negative) indicates the relative degree of influence an element has in the factor.

TABLE 1

CHEMICAL ANALYSIS
by
BONDAR - Clegg; Denver, Colorado

ELEMENT	LOWER DETECTION LIMIT	EXTRACTION	METHOD	
A1203	0.01 PCT	BORATE FUSION	PLASMA EMISSION SPEC	*
Ca0	0.01 PCT	BORATE FUSION	PLASMA EMISSION SPEC	*
FE203	0.01 PCT	BORATE FUSION	PLASMA EMISSION SPEC	*
L01	0.01 PCT		GRAVIANTRIC	*
K20	0.01 PCT	BORATE FUSION	PLASMA EMISSION SPEC	*
Mg0	0.01 PCT	BORATE FUSION	PLASMA EMISSION SPEC	*
Mn0	0.01 PCT	BORATE FUSION	PLASMA EMISSION SPEC	*
Na20	0.01 PCT	BORATE FUSION	PLASMA EMISSION SPEC	*
P205	0.01 PCT	BORATE FUSION	PLASMA EMISSION SPEC	*
S102	0.01 PCT	BORATE FUSION	PLASMA EMISSION SPEC	*
T102	0.01 PCT	BOARTE FUSION	PLASMA EMISSION SPEC	*
Au	5 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	
Sb	0.2 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	
B	50 PPM	MULT ACID TOT DIG	D.C. PLASMA	*
Ag	1 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	*
Ba	100 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	*
Br	1 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	
Cd	1 PPM	MULT ACID TOT DIG	D.C. PLASMA	
Ce	10 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	*
Cs	1 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	
Cr	50 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	
Cu	1 PPM	MULT ACID TOT DIG	D.C. PLASMA	*
Co	10 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	
Eu	2 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	
F	20 PPM	101 HYDROXIDE FUSION	SPECIFIC ION	*
Hf	2 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	
Lr	100 PPB	NOT APPLICABLE	IND. NEUTRON ACTIV.	
La	5 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	*
Lu	0.5 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	
Li	1 PPM	MULT ACID TOT DIG	D.C. PLASMA	*
Mo	2 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	*
Pb	5 PPM	MULT ACID TOT DIG	D.C. PLASMA	*
NI	1 PPM	MULT ACID TOT DIG	D.C. PLASMA	*
Rb	10 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	*
Sm	0.1 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	*
Sc	0.5 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	
Se	10 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	
Ag	0.5 PPM	MULT ACID TOT DIG	D.C. PLASMA	
Ta	1 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	
Tn	20 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	
Tb	1 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	
Th	0.5 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	*
Sn	200 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	
W	2 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	*
U	0.5 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	*
Yb	5 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	
Zn	1 PPM	MULT ACID TOT DIG	D.C. PLASMA	*
Zr	500 PPM	NOT APPLICABLE	IND. NEUTRON ACTIV.	
Sr	5 PPM		X-RAY FLOURESCENCE	*
Nb	5 PPM		X-RAY FLOURESCENCE	*
V	5 PPM		X-RAY FLOURESCENCE	*

TABLE 2

PRELIMINARY RESULTS OF STATISTICAL ANALYSES OF BISHOP ASH SAMPLES

FACTOR ANALYSIS

FACTOR	EIGENVALUE	PCT OF VAR	CUM PCT
1	8.99753	29.0	29.0
2	5.75474	18.6	47.6
3	3.45885	11.2	58.7
4	3.28152	10.6	69.3
5	2.10266	6.8	76.1
6	1.73358	5.6	81.7
7	1.62365	5.2	86.9
8	1.06045	3.4	90.4

VARIABLE	COMMUNALITY
AL203	.93758
CAO	.95609
FE203	.97706
LOI	.98011
K20	.96308
MGO	.95873
MNO	.90565
NA20	.92039
P205	.84802
ST02	.94326
TT02	.93632
LB	.95217
LAS	.90764
LBA	.85746
LCE	.87833
CU	.85993
LF	.95300
LA	.95259
LLI	.92472
LMO	.90581
PB	.85928
NI	.85065
LRB	.94059
SM	.93140
TH	.76246
LW	.89476
U	.85786
LZN	.86382
SR	.91479
NB	.85710
LY	.87236

ROTATED FACTOR MATRIX:

	FACTOR 1	FACTOR 2	FACTOR 3	FACTOR 4	FACTOR 5	FACTOR 6	FACTOR 7	FACTOR 8
AL203					-.71			
CAO					.88			
FE203		.81						
LOI	-.77							
K20						.56		
MGO			.95					
MNO					.74			
NA20						.69		
P205								
SI02			-.61			-.56		
TI02		.85						
LB							.84	
LAS							.88	
LBA		.72						
LCE				.91				
CU								.88
LF	.67		.69					
LA				.90				
LLI			.85					
LMO	.80							
PB		-.75						
NI								
L[illegible]	.88							
S[illegible]				.66				
TH								
LW	.70							
U						-.86		
LZN								
SR			.61					
NB		-.67						
LY	.64							

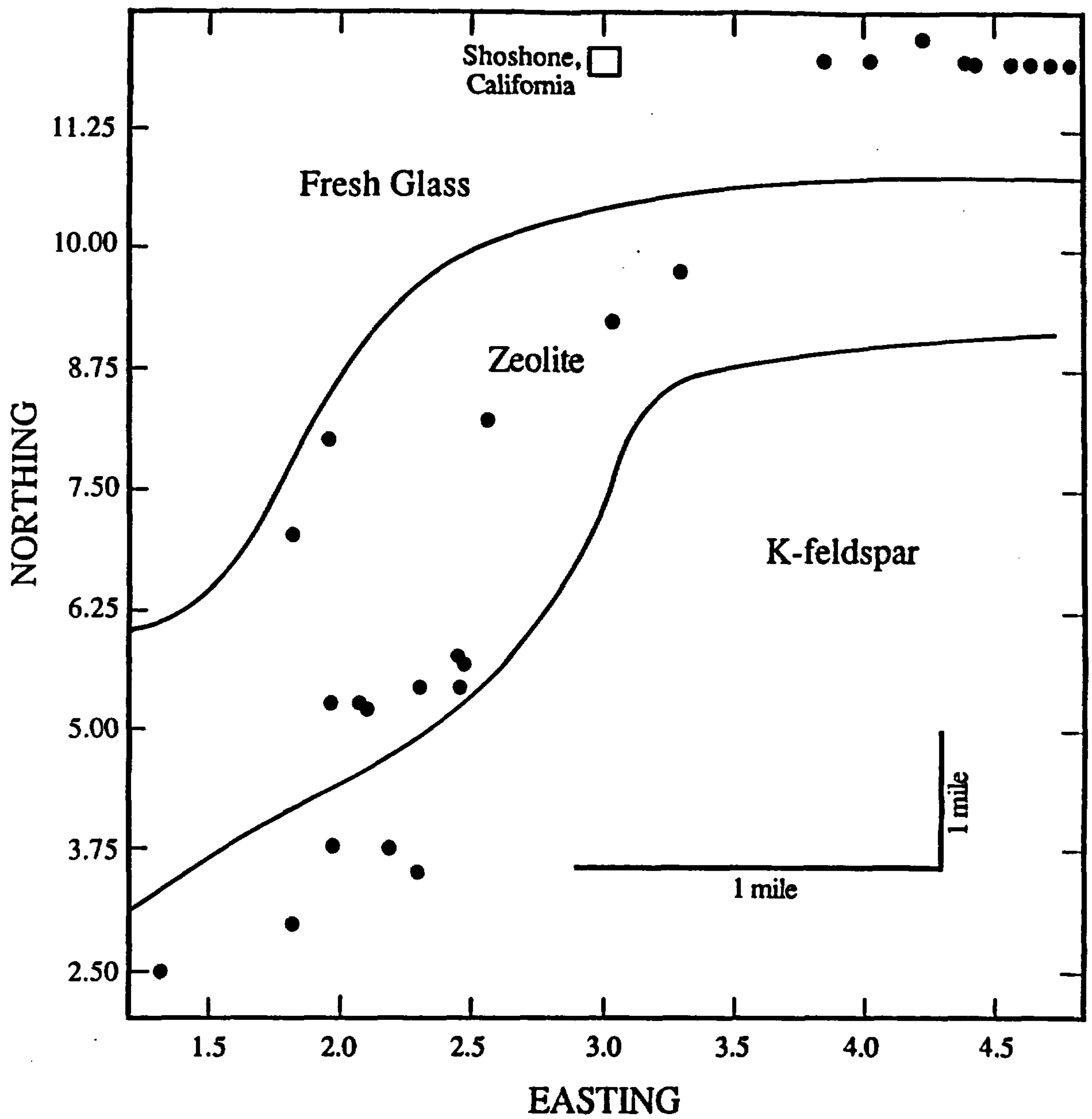
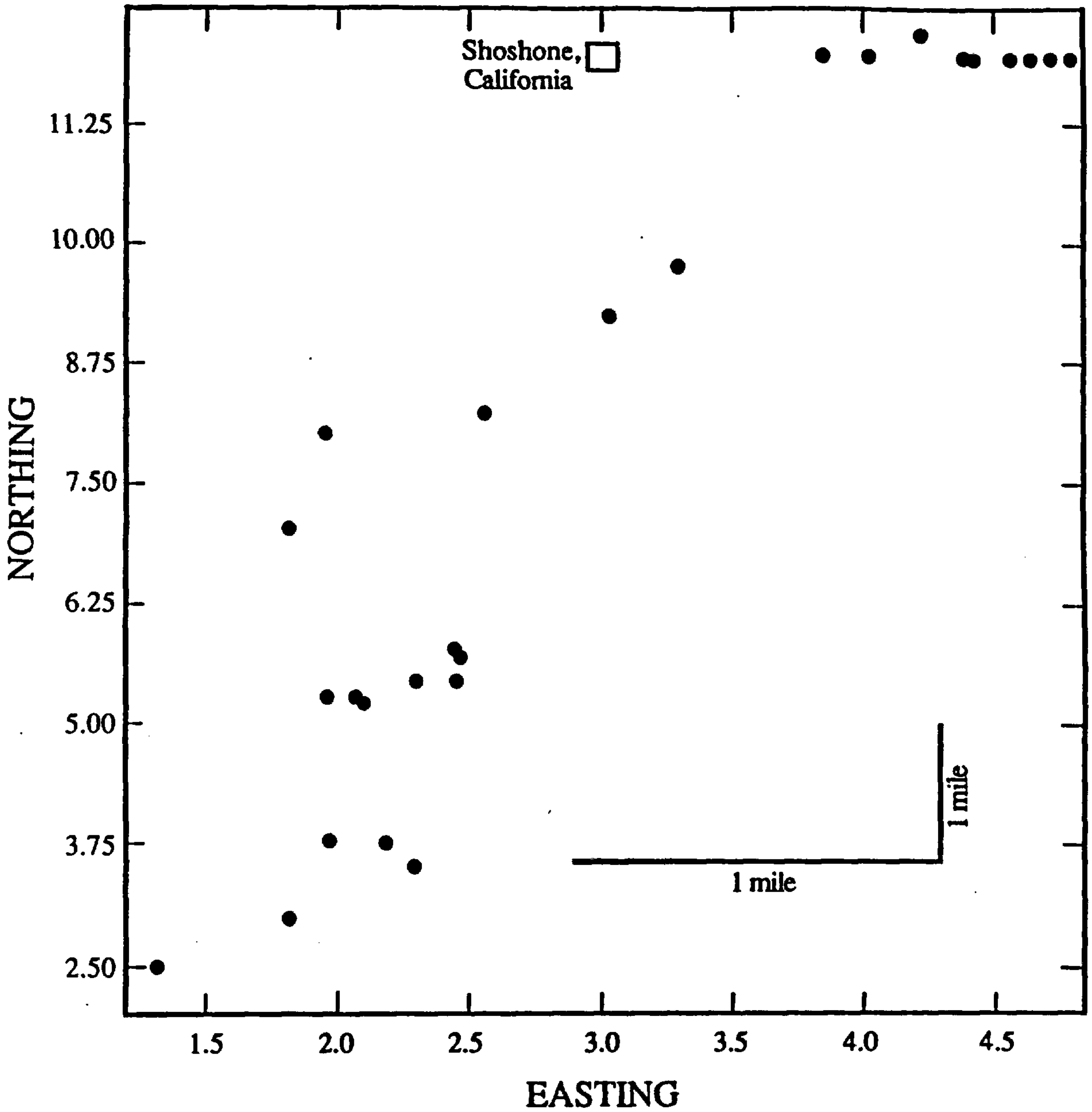


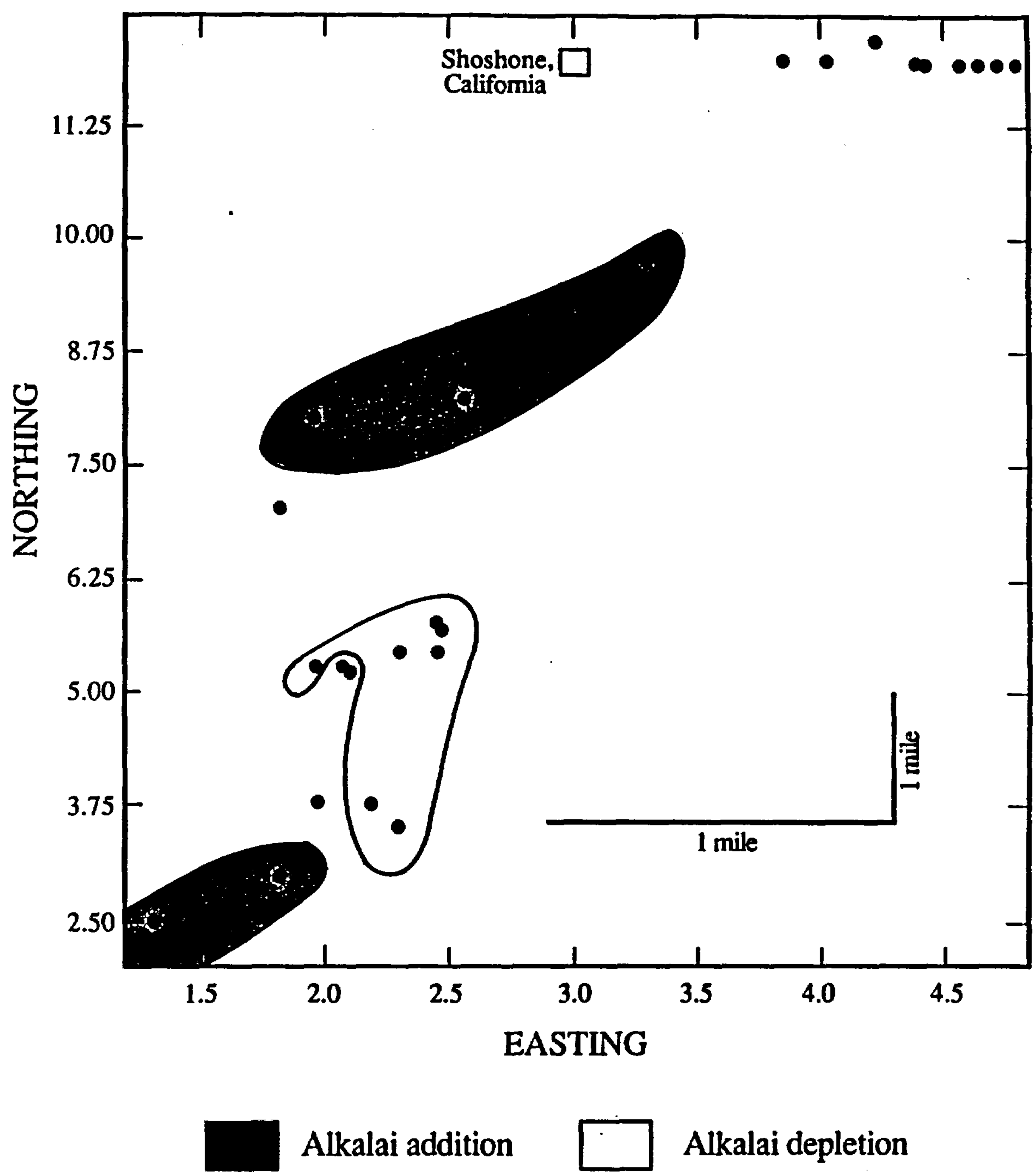
FIGURE 1

Diagenetic facies boundaries for Bishop Ash (Sheppard and Gude, 1968).



Shoshone, California
11.25
10.00
8.75
7.50
6.25
5.00
3.75
2.50
NORTHING
1 mile
1 mile
1.5
2.0
2.5
3.0
3.5
4.0
4.5
EASTING

FIGURE 2



Shoshone,
California
NORTHING
11.25
10.00
8.75
7.50
6.25
5.00
3.75
2.50
1.5
2.0
2.5
3.0
3.5
4.0
4.5
EASTING
1 mile
1 mile
Alkalai addition
Alkalai depletion

FIGURE 3

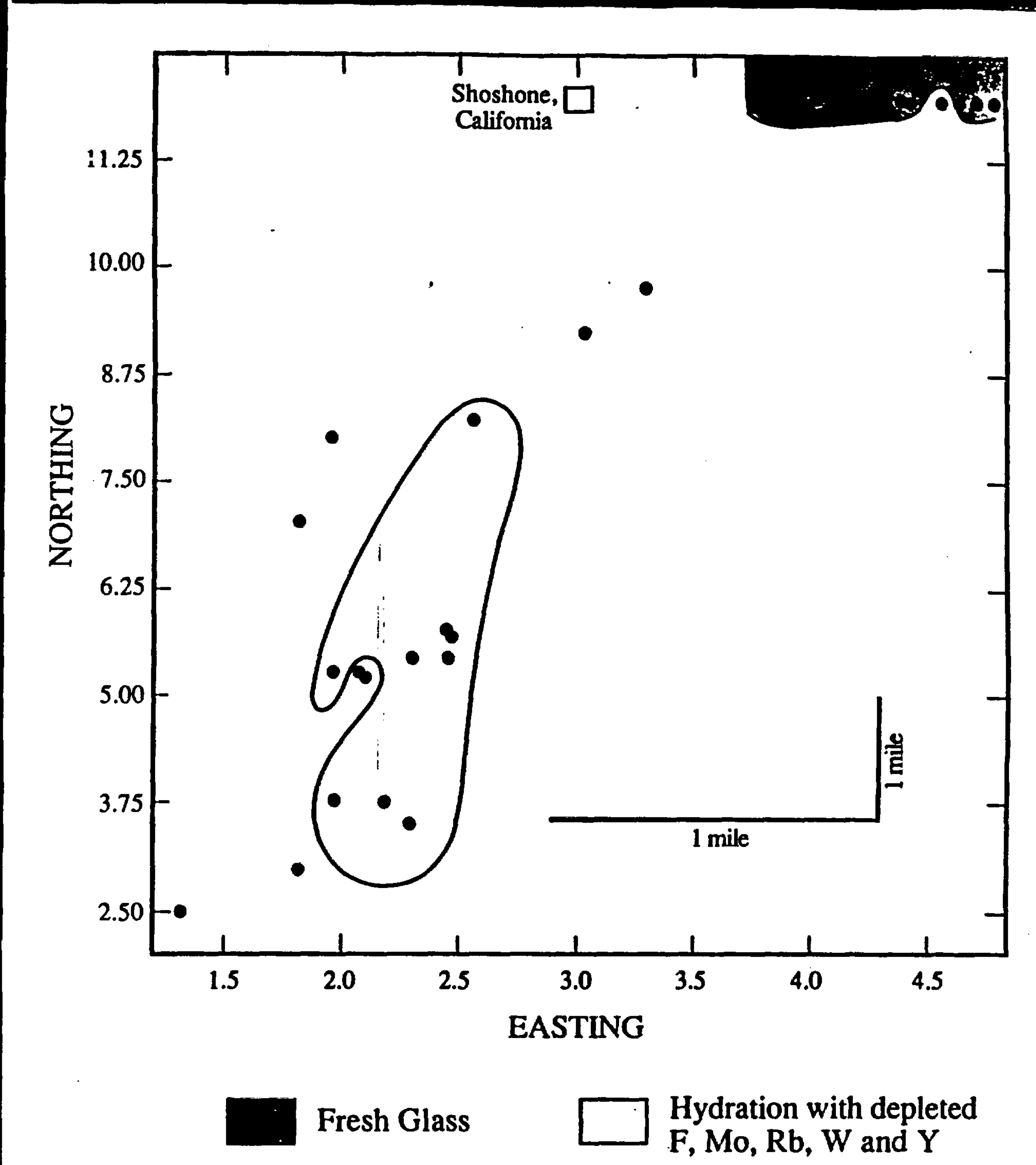

Shoshone,
California
11.25
10.00
8.75
7.50
6.25
5.00
3.75
2.50
NORTHING
1.5
2.0
2.5
3.0
3.5
4.0
4.5
EASTING
1 mile
1 mile
Fresh Glass
Hydration with depleted
F, Mo, Rb, W and Y

FIGURE 4

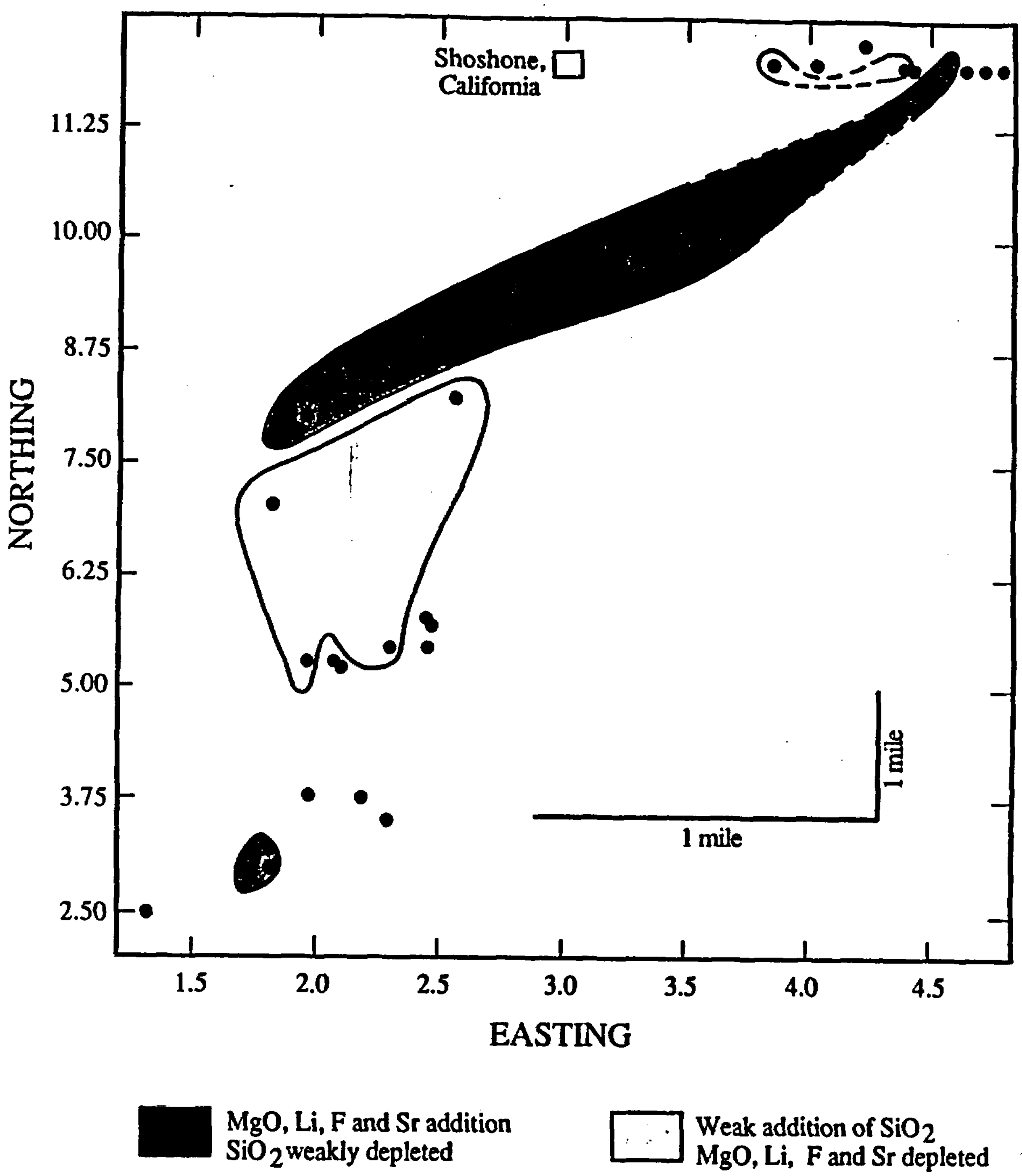

Shoshone, California
11.25
10.00
8.75
7.50
6.25
5.00
3.75
2.50
NORTHING
1.5
2.0
2.5
3.0
3.5
4.0
4.5
EASTING
1 mile
1 mile
MgO, Li, F and Sr addition
SiO_2 weakly depleted
Weak addition of SiO_2
MgO, Li, F and Sr depleted

FIGURE 5

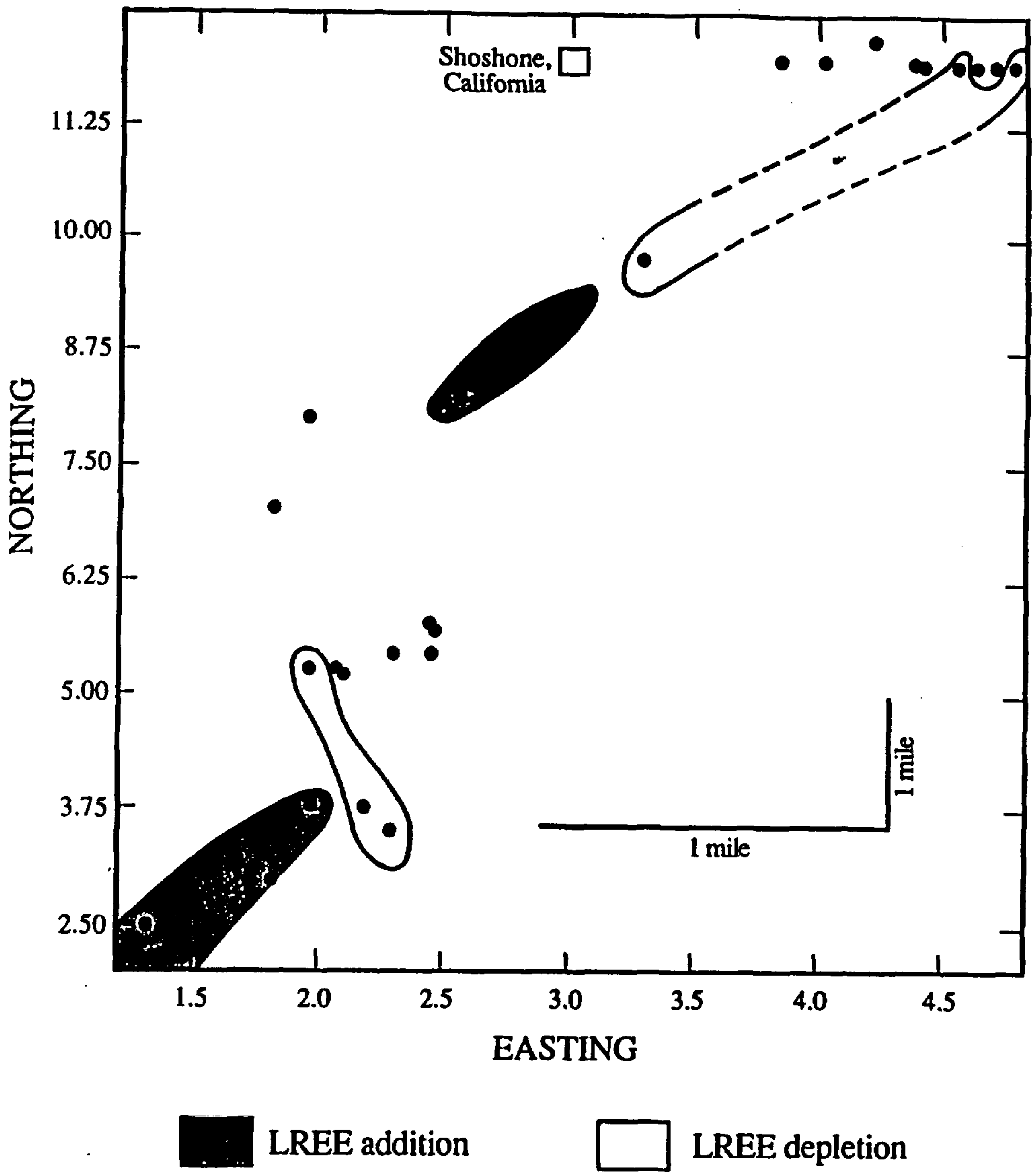
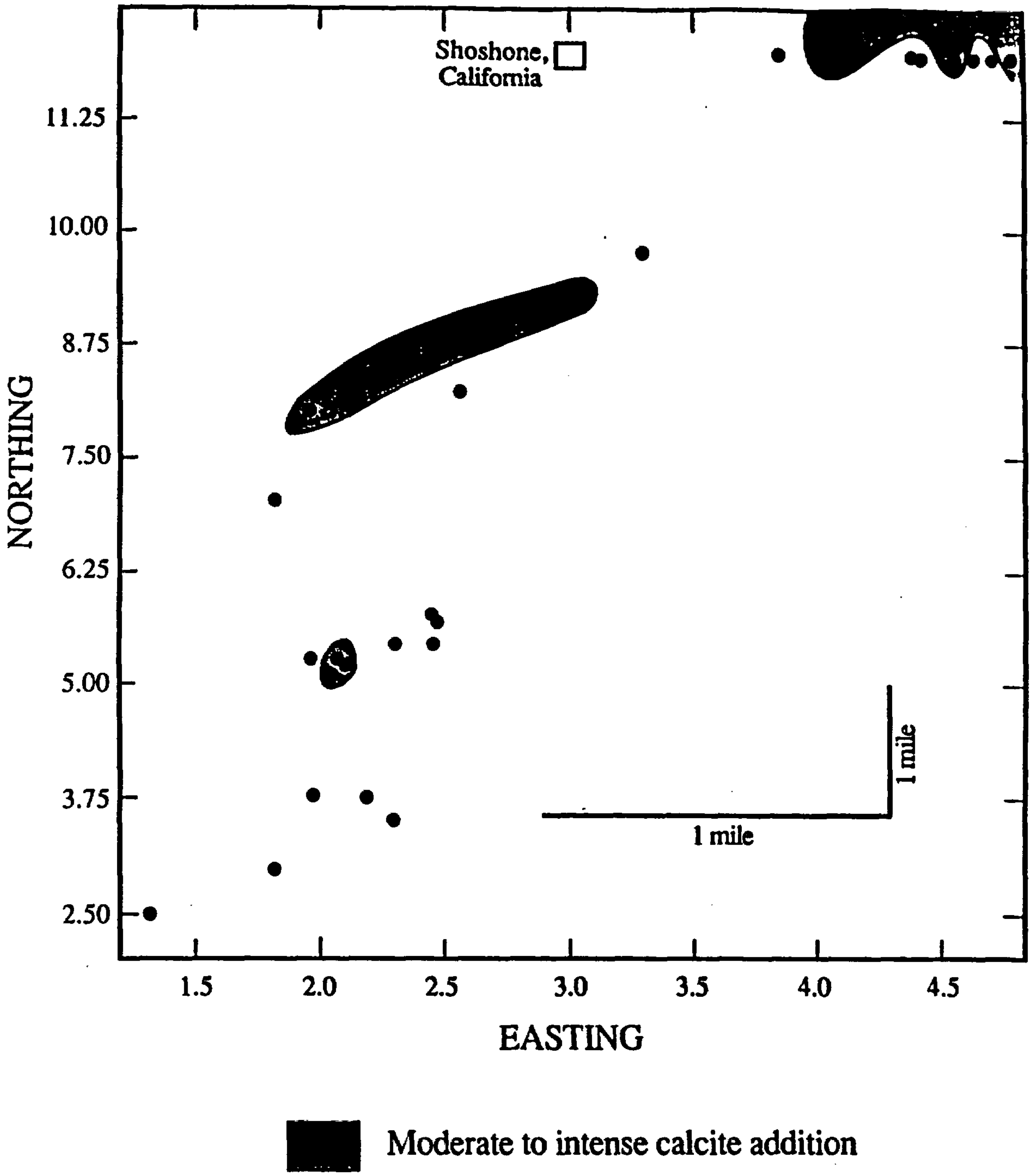
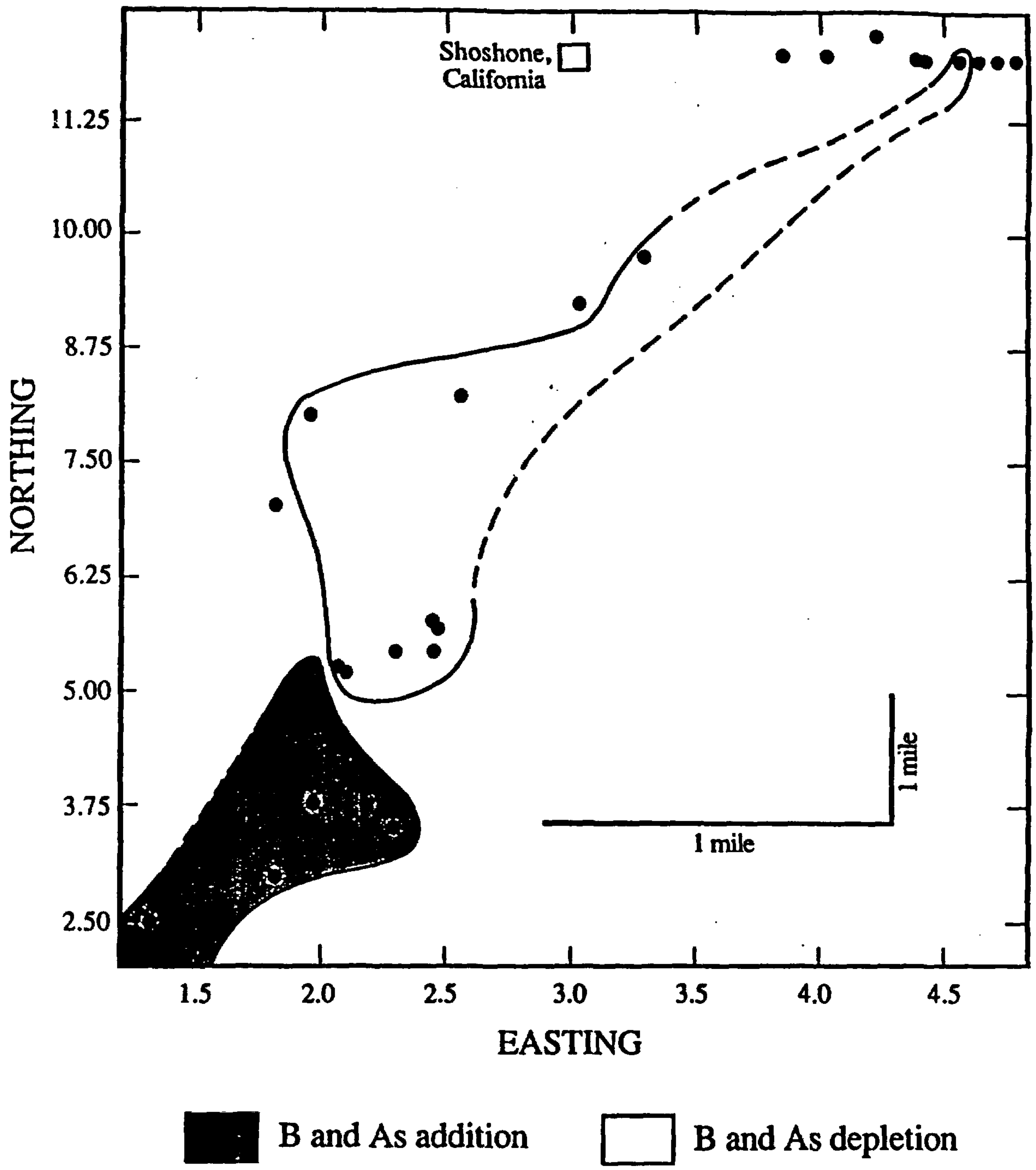

Shoshone, California
NORTHING
11.25
10.00
8.75
7.50
6.25
5.00
3.75
2.50
1.5
2.0
2.5
3.0
3.5
4.0
4.5
EASTING
1 mile
1 mile
LREE addition
LREE depletion

FIGURE 6



Shoshone, California
11.25
10.00
8.75
7.50
6.25
5.00
3.75
2.50
NORTHING
1.5
2.0
2.5
3.0
3.5
4.0
4.5
EASTING
1 mile
1 mile
Moderate to intense calcite addition

FIGURE 7



Shoshone, California
NORTHING
11.25
10.00
8.75
7.50
6.25
5.00
3.75
2.50
1.5
2.0
2.5
3.0
3.5
4.0
4.5
EASTING
1 mile
1 mile
B and As addition
B and As depletion

FIGURE 8

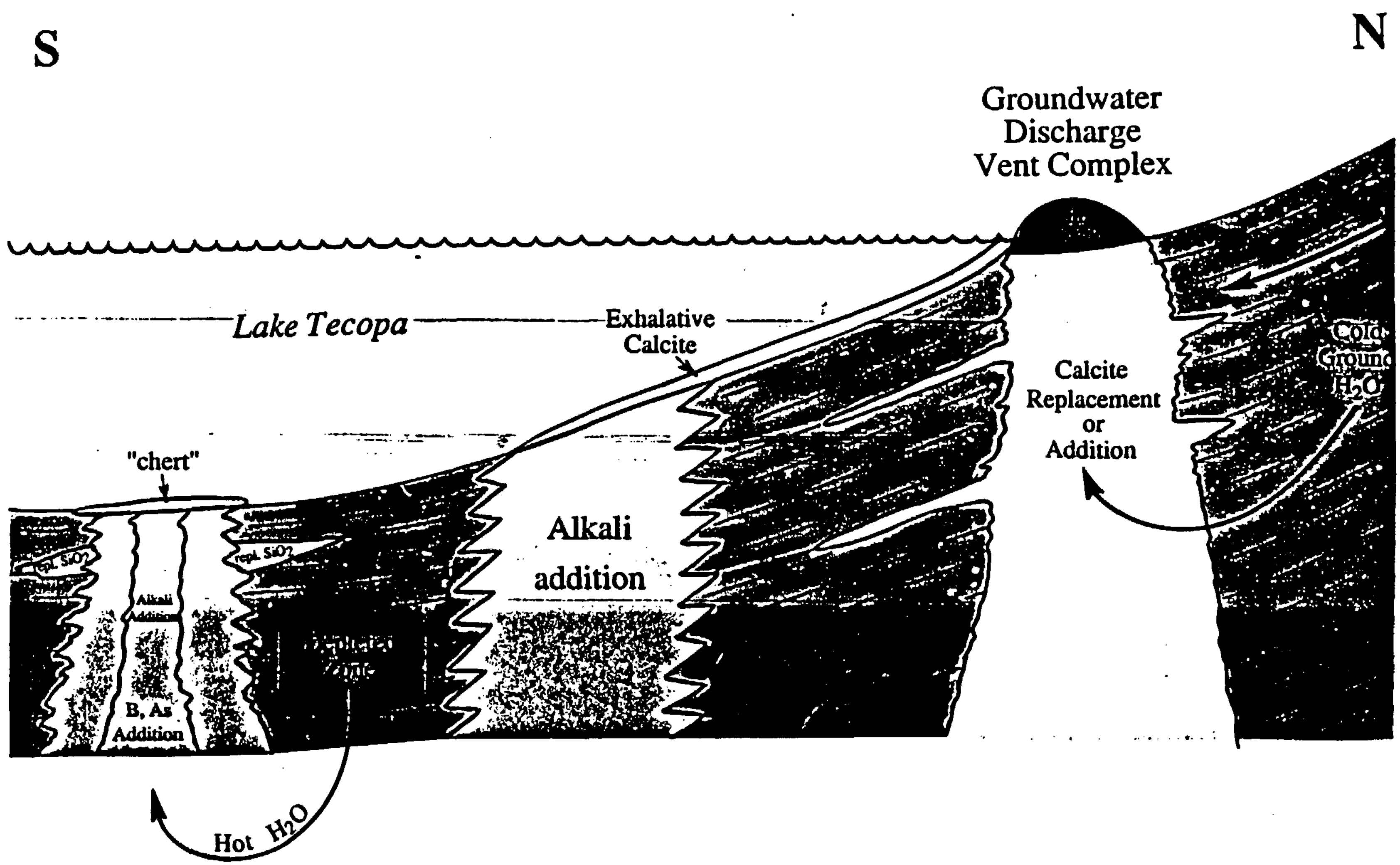


FIGURE 9

Highly schematic N-S cross section through Lake Tecopa at the time of Bishop Ash Emplacement. Potential exhalative processes producing "chert" and or calcite would occur immediately after deposition of the ash. Alternative and diagenetic changes could form any time after deposition.

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Magnetic stratigraphy of ash-flow sheets at Yucca Mountain, Nevada

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ABSTRACT: Ash-flow sheets are widely distributed in the geological record, both spatially and temporally. A variety of engineering studies of these volcanic rocks can take advantage of borehole measurements of magnetic susceptibility for stratigraphic correlation and control in faulted terrain. The magnetic 'stratigraphy' of ash-flow sheets is especially useful because the cooling of ash-flow sheets has a profound impact on rock magnetization, which can be readily observed by measurement of magnetic susceptibility and remanent magnetization. As part of a larger study we have obtained magnetic susceptibility profiles for portions of the Tiva Canyon and Topopah Spring Members of the Paintbrush Tuff using a hand-held susceptibility meter. The results provide a calibration of susceptibility to known geology and underscore the feasibility of the proposed borehole method. The susceptibility measurements were located spatially using an electronic theodolite and electronic distance meter. Maxima and minima in susceptibility measured along the profiles at Yucca Mountain, Nevada, are observed to be reliable stratigraphic markers within the Tiva Canyon and Topopah Spring Members of the Paintbrush tuff. The minima and maxima exist over the 8 km of section examined. Maxima in susceptibility correspond either to magnetic Fe-oxide precipitates that nucleated and grew in volcanic glass subsequent to eruption, or to an abundance of magnetic Fe-Ti oxide phenocrysts. Minima in susceptibility are indicative of: precipitates that grew too large to have high susceptibility; alteration of magnetic Fe-Ti oxide phenocrysts (or precipitates) to weakly magnetic or nonmagnetic phases; or an absence of magnetic minerals altogether. The size and mineralogical variations of precipitated Fe-oxide in volcanic glass of outcrop samples, which have been established using both the transmission electron microscope and the petrographic microscope, are consistent with variations in susceptibility measured at the outcrop. Susceptibility variations in these rocks are readily detectable with borehole instruments, although existing instrumentation could benefit from improvements.

INTRODUCTION

Magnetic susceptibility is a material property that has been used in numerous instances to outline geological variations in outcrop and borehole environments, where petrologic or mineralogic changes can be related to fluctuations in the amount, size and mineralogy of magnetic minerals. Often the applications have been economic (Glenn and Nelson, 1979; Hood et al., 1979), however, a variety of other investigations have taken advantage of susceptibility measurements (e.g., Hearst and Nelson, 1985; Rosenbaum and Snyder, 1985; Thompson and Oldfield, 1986; Balch et al., in press). In addition, engineering and geotechnical problems commonly involve layered soil and rock materials that may be suitable for study and characterization by means of magnetic susceptibility measurements. Examples of such layered media would be ash-flow tuffs at Yucca Mountain, Nevada, in the Basin and Range Province of the western United States.

Yucca Mountain is the proposed site of a national nuclear waste repository; consequently the region has been the subject of numerous engineering and scientific investigations. Past, ongoing and future studies of this site can take advantage of whatever stratigraphic and structural control might be established there. The geology consists of normal-faulted ash-flow tuff layers, or ash-flow sheets as they are known, which have been mapped and sampled at the outcrop and by means of boreholes. For borehole studies, the identification of units and determining their lateral extent and structural disruption by faulting can possibly be accomplished by means of painstaking geochemical and petrographic studies. However, in lieu of rapid methods for geochemical and petrographic analyses, an easier, less-time-consuming and less-expensive geophysical method is desirable. Even in situations where such a geophysical investigation cannot supplant other studies, the results of such a study may be of use for unequivocal interpretation of data from analytical investigations.

Recent magnetic studies of volcanic glasses, including samples from boreholes at Yucca Mountain (Schlinger et al., 1988a, 1988b), have shown that magnetic susceptibility variations in volcanic glasses are often a consequence of Fe-oxide that nucleated and grew (precipitated) in volcanic glass at high-temperatures, subsequent to eruption. These results suggest that cooling history-dependent variations should exist in most ash-flow sheets. Furthermore, it is known that the phenocryst content of ash-flow sheets varies with stratigraphic position and this variation can also influence susceptibility. Early work on the magnetic properties of U.S. Geological Survey (U.S.G.S.) drill core from Yucca Mountain (Rosenbaum and Snyder, 1985; Rosenbaum and Spengler, 1986; data also presented by Schlinger et al., 1988) provided good evidence for the existence of magnetization (including susceptibility) variations. Typically the spatial sampling interval for these studies was large, on the order of 3 meters, which raised questions about relatively abrupt variations in susceptibility, which would not have been detected with this relatively large measurement spacing.

A high-spatial-resolution record of susceptibility variations was deemed essential for studies of magnetic precipitates in ash-flow sheets, and as part of ongoing research we measured magnetic susceptibility along 5 profiles through exposed sections of the two most voluminous ash-flow sheets of the Paintbrush Tuff at Yucca Mountain. The profile data give us a good indication that quantitative and qualitative variations in susceptibility, which are observed moving vertically through the section, exist over a large strike distance (Schlinger and Rosenbaum, 1988). At the same time, we have sought to understand the geological origin and significance of these variations with position in the section (Schlinger et al., 1988a, manuscript in preparation).

In this paper the susceptibility data are presented and discussed. The vertical variations and the lateral continuity of these variations, observed at the outcrop, offer convincing evidence in favor of susceptibility measurements for assessments of lateral extent and structure of ash-flow sheets, especially where they are hidden in the subsurface and can be accessed only by means of boreholes.

GEOLOGICAL SETTING

Miocene-aged volcanic rocks of the Paintbrush Tuff are exposed at Yucca Mountain, a volcanic plateau in Nye County, Nevada (Figure 1). The geology of the area has been discussed by Lipman et al. (1966), Byers et al. (1976), and Christiansen et al. (1977). Lithologic descriptions of the outcrop at Yucca Mountain have been given by Scott et al. (1983). Scott and Castellanos (1984) discussed the lithologies as encountered in U.S.G.S. boreholes, and a geological map of the area has been published by Scott and Bonk (1984). The source of the Paintbrush Tuff is believed to have been the Claim Canyon cauldron (outline shown on Figure 1). Two compositionally-zoned compound-cooling ash-flow tuffs, the Tiva Canyon Member and the Topopah Spring Member, make up the majority of the thickness of the Paintbrush Tuff (about 100 m and 300 m, respectively). In the vicinity of Yucca Mountain the volcanic layers are sub-horizontal in attitude, with dips typically less than 15° (Scott and Castellanos 1984).

SUSCEPTIBILITY MEASUREMENTS

During the Fall of 1987 we gained access to Yucca Mountain through Bureau of Land Management property. Magnetic susceptibility was measured at the outcrop, along profiles that took us up and down the west flank of Yucca Mountain, through the section exposed there. Measurements were obtained along 5 distinct profiles. These profiles were spaced nonuniformly over approximately 8 km (between VABM 'Mile' and VABM 'Iron' on the U.S.G.S. 7.5 minute quadrangle map "Busted Butte, Nevada"). Due to a lack of outcrop exposure, detailed sampling of susceptibility with measurement spacings as small as ~10 cm was restricted to the lower part of the Tiva Canyon Member, the top of the Topopah Spring Member, and the intervening Bedded Tuff. We used an EDA K-2 hand-held susceptibility meter for our work. This meter has a resolution of 10^{-5} c.g.s. dimensionless Gaussian units.

In order to spatially locate the susceptibility measurements, selected measurement points along these 5 profiles were periodically surveyed using an electronic theodolite with an electronic distance meter. This surveying effort was designed to maintain both absolute and relative positioning (tied to USGS brass cap bench mark and VABM control points, and surveyed neutron-log and water-table borehole locations). The locations of measurements made between the surveyed points were linearly interpolated. In anticipation of this, efforts were made during the course of the survey to obtain equal spacing of measurements between surveyed measurement points. All measurements points were assigned an x-y-z location in the Nevada State Plane Coordinate system. The 5 profile locations in this coordinate system are given in Figure 2.

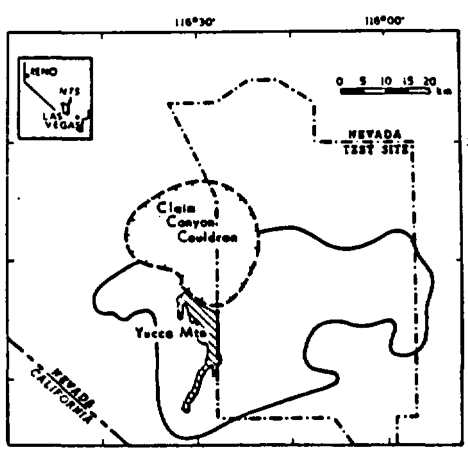

Figure 1. Location map for Yucca Mountain, Nevada. The approximate lateral extent of the Paintbrush Tuff is indicated by the solid line. After Rosenbaum (1986).

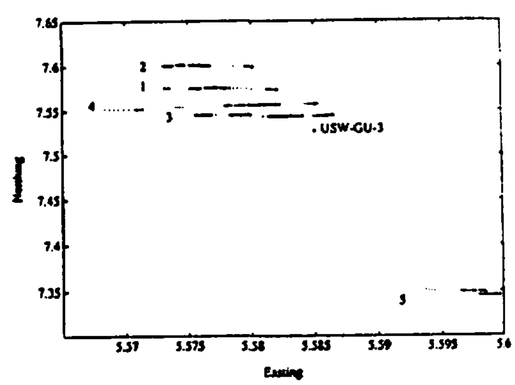

Figure 2. Location map for magnetic susceptibility profiles at Yucca Mountain. The location of U.S.G.S. drill hole USW GU-3 is indicated. All distances (northings and eastings) are in units of 10^5 feet. The horizontal scale on this map is exaggerated by a factor of 10, relative to the vertical scale.

The magnetic susceptibility (c.g.s.) of outcrop along these five profiles is shown in Figure 3. The lowest susceptibilities correspond to measurements in the pumice-rich unit of the Bedded Tuff (bt on profiles in Figure 3) which lies below the Tiva Canyon Member and above the Topopah Spring Member. Near the base (labeled bz, for basal zone, on profiles in Figure 3) of the Tiva Canyon Member there is a horizon that has the highest susceptibility within the member. A similar susceptibility maximum is found near the top of the Topopah Spring Member, within a thin black vitrophyre (i.e., a stratum that is largely glass, formed by high-temperature 'welding' of what was once mostly glass fragments and pumice) that is on the order of a meter or less in thickness. This maximum is labeled c, for caprock, on profiles in Figure 3. Wherever the susceptibility of the columnar zone of the Tiva Canyon Member was measured, it was uniformly about 2×10^{-4}. This zone is a thick basal vitrophyre and is labeled as in Figure 3. Note that the sus-

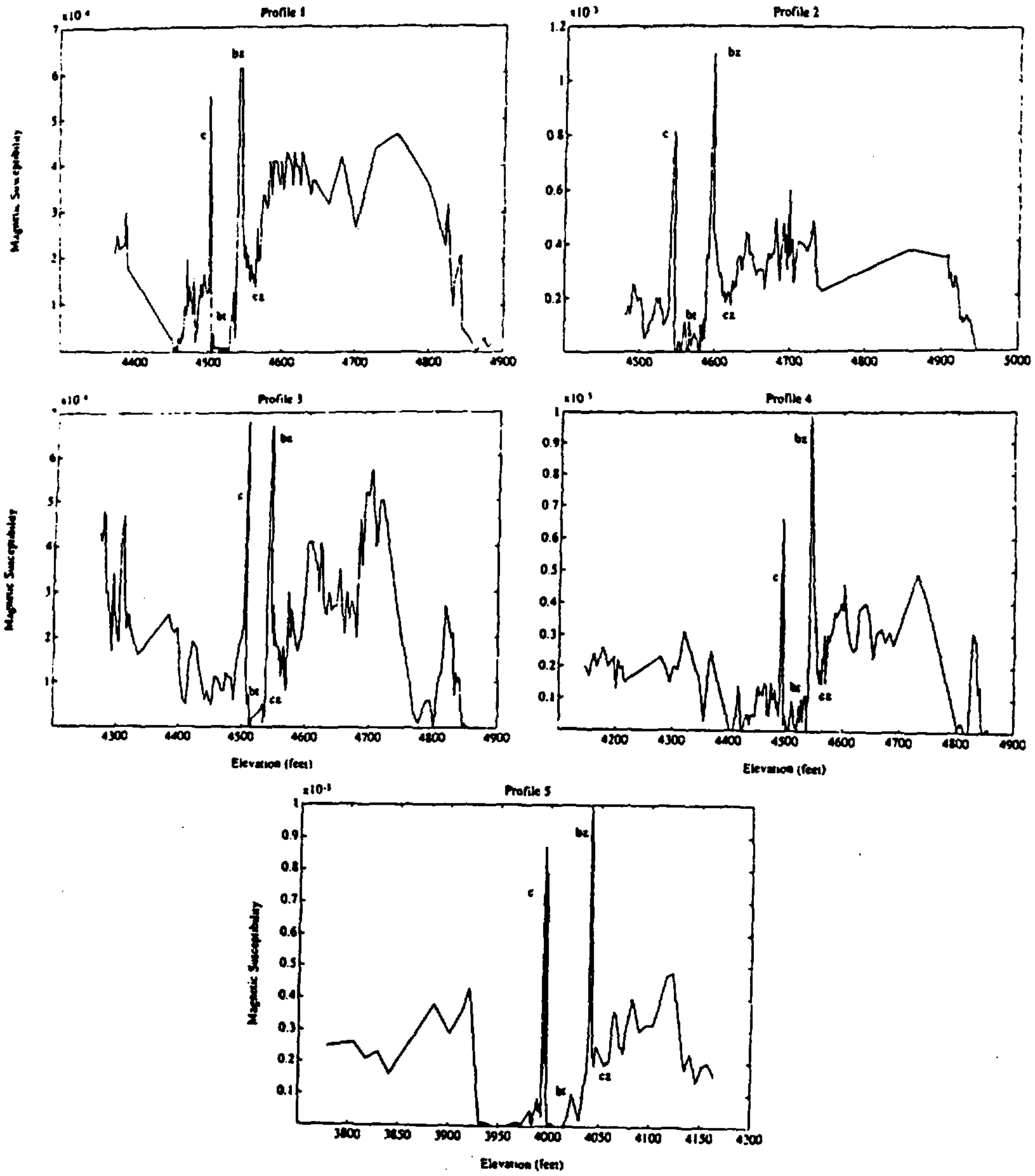

Figure 3. Magnetic susceptibility along profiles 1 to 5. bt is Bedded Tuff, cz is columnar zone and bz is basal zone (Tiva Canyon Member), c is caprock portion of Topopah Spring Member. Susceptibilities are given in c.g.s. dimensionless units; to convert to SI units multiply c.g.s. values by 4π.

ceptibility maxima and minima can be observed, in both a quantitative and qualitative sense, on each of the 5 profiles, which sample the two members of the Paintbrush Tuff over a strike distance of 8 km. There is some structure in the narrow susceptibility peaks on these profiles that needs to be explained. The relatively broad nature of the peak labeled 'c' on Profile 1 is a result of a lateral movement along the side of Yucca Mountain during susceptibility sampling (necessitated by intermittent outcrop exposure). Since the sheets have some tilt we ended up with a duplicate measurement of the high susceptibility horizon at a different elevation after a lateral move. A similar lateral move accounts for the apparent structure in the peak labeled 'c' on Profile 5.

DISCUSSION

Interpretation of susceptibility maxima and minima

The origins of the magnetic susceptibility variations that can be seen in the outcrop profiles shown in Figure 3 deserve some attention. The susceptibility maximum near the top of the Topopah Spring Member ('c' in Figure 3) is indicative of a large modal abundance of what appears to be titanomagnetite phenocrysts (Figure 4). Above and below

Figure 4. Reflected light photomicrograph of a titanomagnetite phenocryst in a sample with high magnetic susceptibility from near the top of the Topopah Spring Member.

this horizon, which is a thin black vitrophyre, the titanomagnetite has been altered to Fe-Ti oxide intergrowths that are only weakly magnetic. Incipient alteration is evident as light colored regions in this crystal, which presumably are martite (hematite after magnetite). The susceptibility maximum at the base of the Tiva Canyon Member ('bz' in Figure 3) exists due to the presence of magnetic Fe-oxide precipitates within volcanic glass, which nucleated and grew at high-temperature, subsequent to emplacement of this member (Schlinger et al., 1988a, manuscript in preparation). At the level of this maximum these precipitates are only a few hundred Ångstroms long. High susceptibilities at this crystal size are a consequence of superparamagnetic behavior of single domains. Above this horizon the susceptibility drops abruptly, which reflects the fact that the precipitates grew too large to have high susceptibility; instead they carry intense remanent magnetization. A representative transmission electron microscope image of representative remanence-carrying precipitates is shown in Figure 5. In this particular image, one can see long thin crystals of cubic Fe-oxide (magnetite/maghemite) that nucleated on a yet longer microcrystal of what is probably a pyroxene. The aggregate resides in a matrix of volcanic glass.

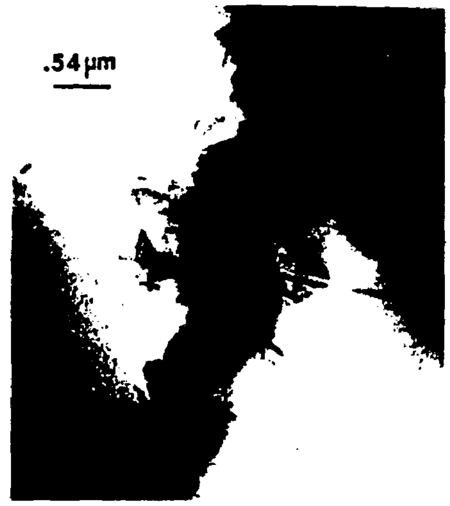

Figure 5. Transmission electron microscope image of precipitated Fe-oxide microcrystals in glass from the basal vitrophyre (columnar zone) of the Tiva Canyon Member.

The low susceptibility of the Bedded Tuff ('bt' in Figure 3) is indicative of an absence of precipitates and an absence of phenocrystic titanomagnetite. We have not had an opportunity to explore other less-pronounced susceptibility variations at other stratigraphic levels that also might prove useful as marker horizons.

Application to borehole susceptibility investigations

From our observations of susceptibility variations with vertical position in ash-flow sheets, it is clear that distinctive and laterally-persistent susceptibility marker horizons exist in ash-flow sheets of the Paintbrush tuff. This is because Fe-oxide mineralogy, amounts, and grain size vary so markedly in ash-flow sheets of this tuff. This is probably true for other ash-flow sheets as well. Since magnetic susceptibility is a physical property that is easily measured in the borehole, it can be useful for assessments of lateral variations in the subsurface, which may come about due to faulting, inhomogeneous deposition, or alteration of these ash-flow sheets. Past geological investigations at Yucca Mountain have in numerous instances focussed on boreholes and drill core. With these new results on susceptibility variations in hand, the application of borehole susceptibility measurements to questions of lateral extent and the subsurface structure of these sheets at this site can be explored.

Assessing the lateral extent of a given ash-flow sheet in a limited geographic area may be relatively straightforward, since one is not especially concerned with the position in space where a unit is found, provided that it exists. This is

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a rudimentary form of stratigraphic correlation. If one chooses to consider a large geographic area, lateral variations in deposition must be taken into consideration. Traditionally, remanent magnetization has been used for stratigraphic correlation of ash-flow tuffs (Hildreth and Mahood, 1985). However, its application requires the use of numerous oriented samples, due to directional dispersion of remanent magnetic moments, and magnetometers for measuring these remanent moments. Additionally, while remanent magnetization may be used for correlation, the interpretation of the relevant data is subject to a number of assumptions that may be difficult to justify (for example, that a given sheet is normally or reversely magnetized throughout). Plastic deformation during cooling (Rosenbaum, 1986) and tectonic rotation(s) can further complicate the interpretation of remanent magnetization directional data. Assessing lateral extent using magnetic susceptibility circumvents most of these problems simply because susceptibility is a scalar quantity that depends on petrologic history alone.

Determining whether or not faulting has occurred in these ash-flow sheets is a much different problem. In this case absolute positions of susceptibility maxima or minima in space, combined with any information on attitude (strike and dip), must be quantified in order to delimit structural discontinuities. Furthermore, since ash-flow sheets drape over pre-existing topography, a structural interpretation will hopefully be constrained by independent stratigraphic information, which might be established with drill cuttings or drill core. Additionally, other geophysical information, such as a seismic reflection profile, acquired in a manner appropriate for volcanic lithologies (which has often proven to be a problem with an elusive answer) may be of use.

Finally, from geological mapping of ash-flow sheets it is known that sheet thicknesses vary laterally, and this will produce lateral variations that reflect cooling history. These will probably be manifested as quantitative and qualitative variations in susceptibility maxima and minima due to magnetic precipitates, which must be taken into account during the interpretation process.

For magnetic susceptibility logging of formations such as the Paintbrush Tuff, a number of borehole susceptibility meters are commercially available. The continuous record of a susceptibility log makes it especially attractive (versus the discrete and non-uniform sampling obtained in this study of outcrop). General characteristics of all are: relatively thin diameter sondes (40 mm to 50 mm); sensing over a distance vertical distance of 20 cm to 40 cm; advertised resolutions of ~5 to 20×10^{-6} c.g.s. units. These sonde geometries do not favor faithful resolution of thin ~ 5 to 10 cm-thick layers of relatively low or high susceptibility material (e.g., the high susceptibility layer at the base of the Tiva Canyon Member). To alleviate this problem, sensing coils could be shortened, however, with other parameters remaining fixed this cannot be done without some loss of sensitivity (M.T. Hämäläinen, personal communication, 1988).

Thus, it seems that borehole susceptibility meters could benefit from some modifications that would improve their response to thin layers, which in the case of the Tiva Canyon Member, and possibly other lithologies elsewhere, turn out to be diagnostic marker horizons. Otherwise, one runs the risk of taking a short-spatial-wavelength high-amplitude signal and smearing it out towards longer wavelengths and smaller amplitudes. In this case signals of interest may be hidden amongst less easily interpretable or less correlatable features in the overall borehole susceptibility record. In other geological environments, including volcanic settings, thin diagnostic horizons might be characterized by low susceptibilities; faithful response to thin layers seems essential. An additional improvement would be thermal stabilization of the sonde, since temperature drift degrades the resolution of the instrument. However, one can make efforts to characterize drift effects, measure temperature in the sonde, and apply a correction (e.g., Balch et al., in press).

Within the Paintbrush Tuff we have found that the susceptibility maxima may be indicative of either relatively coarse-grained Fe-Ti oxide phenocrysts (the thin vitrophyre above the caprock of the Topopah Spring Member) or relatively fine-grained Fe-oxide precipitates in the basal zone of the Tiva Canyon Member). These maxima, similar in appearance to one another ('c' and 'bz' in Figure 3), could in all likelihood be distinguished from one another by measuring susceptibility at two (or more) frequencies. This would take advantage of the fact that the susceptibility of tiny superparamagnetic crystals (the precipitates in glass at the base of the Tiva Canyon Member) probably has a different frequency dependence than that of coarse-grained Fe-Ti oxide phenocrysts (Thompson and Oldfield, 1986). Variable-frequency susceptibility meters are available for laboratory work, however, to my knowledge, this option has not been incorporated into existing borehole instrumentation.

While borehole measurements of magnetic susceptibility at Yucca Mountain remain at this time only a future objective, we find that a geological calibration can be obtained by means of outcrop measurements; were no outcrop available, the calibration could be made using continuous drill core, or possibly with cuttings.

CONCLUSIONS

- Over a strike distance of 8 km at Yucca Mountain, the Tiva Canyon and Topopah Spring members and the Bedded Tuff have a marked lateral uniformity in measured values of magnetic susceptibility, even though the thickness and outcrop appearance of the units may vary from place to place. Furthermore, the variations in susceptibility with vertical position in the geologic column persist laterally.
- Spatial variations in physical properties, e.g., magnetic properties, can often be understood in terms of the geological history of a given formation. This investigation of outcrop susceptibility has demonstrated the existence of magnetic marker horizons in ash-flow sheets, which can be understood in terms of Fe-Ti oxide mineralogy and grain size. In the case of the ash-flow sheets of the Paintbrush Tuff, grain size and mineralogical variations, acquired mostly subsequent to emplacement, define the marker horizons that we see. A suitable calibration of physical property variations to mineralogy and petrology is essential before measurements of magnetic properties in boreholes can be interpreted in a constrained manner.

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№ 23744

CESIUM UPTAKE BY CLINOPTILOLITE CRYSTALS: IMPLICATIONS TO THE IMMOBILIZATION OF RADIONUCLIDES STORED AT YUCCA MOUNTAIN, NEVADA

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At the proposed repository for high-level nuclear waste at Yucca Mtn, densely welded tuff is underlaid by zeolitized vitric tuffs containing microcrystalline clinoptilolite and mordenite. These zeolites are assumed to be capable of immobilizing dissolved, long-lived radionuclides (e.g. ^{137}Cs and ^{135}Cs) should leakage occur. Euhedral clinoptilolite crystals with habits dominated by coffin-shaped (010) cleavage faces also line fractures throughout the repository, the most probable conduits for groundwater which may be of the sodium bicarbonate-type. To assess the efficiency of clinoptilolite for removing cesium from such groundwater, Cs-exchange experiments were performed on polished mounts of several specimens, using both 1 mm clumps of microcrystalline samples and single crystals oriented parallel to (010), (001), (100) and (101). Reactions at 60°C (simulating groundwater permeating the heat envelope of the repository) with CsCl solutions (1M, 0.01M and 0.001M, with and without $NaHCO_3$) were performed for 1 to 4 weeks in a shaking water bath. Cesium selectively exchanges with other cations in the order Na>K>Ca≥Mg. Electron microprobe analyses of reacted surfaces reveal that microcrystalline clinoptilolite attains higher Cs concentrations in shorter time periods than do mounted single crystals, which are often compositionally zoned possibly due to stacking faults. The Cs is initially least in (010) faces, the one direction (parallel to the *b* axis) along which channels do not exist in the tetrahedral framework of the clinoptilolite structure. However, after a month the Cs contents of all mounted cystals are still inhomogeneous but approach those of microcrystalline samples. The uptake of Cs into all clinoptilolite samples diminishes with CsCl dilution (e.g. ~22 and ~ 6 wt. % Cs_2O for 1M and 0.001M CsCl, respectively, on (010) faces) and in the presence of dissolved Na^+ particularly when added as $NaHCO_3$(e.g. a decrease to ~1.3 % Cs_2O for 0.001M CsCl + $NaHCO_3$. We conclude that clinoptilolite crystals dominated by large surface areas of (010) faces, either lining fractures or cemented in zeolitized vitric tuff, may be inefficient at mobilizing radiogenic Cs in $NaHCO_3$-bearing fracture-flow groundwater when it permeates leaking fission products stored at Yucca Mtn.

(Second Draft)

CESIUM UPTAKE BY CLINOPTILOLITE CRYSTALS

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INTRODUCTION

Clinoptilolite is renouned for its desirable ion exchange properties, which have been investigated more intensely than those of any other natural zeolite (Vaughan, 1978). This zeolite, ideally $(Na,K,Ca)_{5-6}Si_{30}Al_6O_{72}.24H_2O$ and formed by the alteration of rhyolitic glasses in aqueous environments, is widely used for the treatment and disposal of industrial pollutants and hazardous materials (Mercer and Ames, 1978), including scavanging of ammonium ions from municipal waste streams and removal of radiogenic cesium from high-level nuclear waste. The occurrence of potentially highly sorptive clinoptilolite in zeolitic bedded tuffs at Yucca Mountain is one of the factors influencing the selection of this locality in Nevada adjacent to the Nuclear Test Site as the primary geological repository for the long-term storage and disposal of high-level radioactive waste (Vieth, 1984; U.S. Dept. of Energy, 1986).

The high cation-exchange selectivity of clinoptilolite for cesium, and to a lesser extent strontium, was demonstrated by Ames (1960, 1961, 1962a,b,c, 1963, 1964, 1965) and other investigators (Howery and Thomas, 1965; Chelishchev et al., 1974) in radioactive tracer experiments which involved measurements of radionuclides either absorbed by powdered zeolites in an exchange column or removed from spiked aqueous solutions emerging from the ion-exchange column. Little attention was paid in these experiments to the chemical composition and homogeneity of individual zeolite crystals involved in the cation exchange experiments. Euhedral clinoptilolite crystals occur along joints and fractures in densely welded tuffs throughout Yucca Mountain (Carlos, 1985), particularly in the vicinity of the proposed nuclear waste repository (Levy, 1984). Since these clinoptilolite-bearing openings are the most likely conduits for groundwater flowing through the repository and may transport leakages of fission product buried there in the future, we undertook an electron microprobe study of the cesium uptake by single crystals of clinoptilolite and related zeolites in order to assess effects of crystallographic orientation on kinetics, cation selectivity, capacity and homogeneity of Cs-exchanged zeolites.

BACKGROUND

Cation Exchange Measurements.

The high selectivity and capacity of clinoptilolite for cesium were discovered by Ames (1959,1960, 1961, 1962a,b,c; 1963, 1964, 1965). Most of Ames's measurements centered on clinoptilolite in a zeolitized vitric tuff from Hector, California, composed of microcrystalline lamellae (Mumpton and Ormsby, 1978) and 5-15% unaltered glass, quartz and feldspar impurities. He used aqueous salt solutions labelled initially with ^{137}Cs (Ames, 1960, 1961) and later with ^{134}Cs (Ames, 1962a,b,c; 1963, 1964, 1965), and measured concentrations of radiogenic Cs removed in shallow beds of clinoptilolite packed in an exchange column or in the spiked solutions emerging from the columns. Ames (1960) showed that particle sizes of cemented aggregates of the Hector clinoptilolite crystallites affected the Cs capacity, increasing significantly for clumps smaller than 1 mm. In the presence of competing cations, usually involving 1M salt solutions containing 0.01M CsCl, clinoptilolite was shown to have a high selectivity for Cs, leading to the well-known (Vaughan, 1978) replacement series Cs>K>Na>Li and Ba>Sr>Ca>Mg. Cesium capacities increased with decreasing concentrations of CsCl, but were lowered by increasing concentrations of NaCl. Changing the sodium salt from chloride to SO_4^{2-} or NO_3^- did not influence the Cs capacity (Ames, 1960), but it was suggested later (Ames, 1964) that dissolved carbonates might influence cation exchange equilibria. Reactions performed at elevated temperatures decreased the Cs capacity, the concentation exchanged into clinoptilolite dropping by about one-third between 25°C and 60°C. Kinetic measurements of diffusion coeficients (Ames, 1962a,b) showed that the efficiency of Cs to exchange into clinoptilolite increased with temperature, decreased with dilution, and varied inversely with particle size. Ames (1963) suggested that zeolitic altered tuffa, being cemented aggregates of crystallites that rarely exceeded a few microns in diameter, would require a much shorter equilibration time than more coarsely crystalline zeolite assemblages. The Cs capacity of clinoptilolite was found (Ames, 1964) to be influenced by composition differences, being smaller in more the more silicic Hector clinoptilolite than in more calcic clinoptilolite from the John Day formation having a lower Si/Al ratio.

Crystal Structure Determinations.

Clinoptilolite and heulandite are isostructural and have the basic zeolite structure consisting of a three-dimensional framework silicate in which all four oxygens of individual $(Si,Al)O_4$ tetrahedra are mutually shared to form secondary rings of corner-sharing tetrahedra (Gottardi and Galli, 1987). The different linkages of these secondary ring systems define different zeolite groups. The clinoptilolite and heulandite structures (Merkle and Slaughter, 1968; Bartl, 1973; Alberti, 1972,1975; Koyama and Takeuchi, 1977) contain complex 4- and 5-ring systems arranged in a sheet-like array parallel to (010) connected by relatively few oxygen bridges, with the result that clinoptilolite crystals display characteristic platey or lamellar habits and basal (010) cleavage. Linkages between the tetrahedral ring systems along the *b* axis, as well as the *a* axis, define cages which are open and form channels through the clinoptilolite structure. The channel systems in clinoptilolite consist of one set parallel to the *a* axis formed by 8 tetrahedra rings with free-aperture dimensions 4.0 x 5.5 Å (designated as the *C* channels by Koyama and Takeuchi, 1977) and two sets parallel to the *c* axis formed by 10 and 8 rings (the *A* and *B* channels, respectively) with corresponding free apertures of 4.4 x 7.2 Å and 4.4 x 4.4 Å. It is important to note that no channels exist along th *b* axis in clinoptilolite and heulandite.

Cations and water molecules are located in specific sites along the channels. In heulandite there are two cation sites, $M(1)$ and $M(2)$, each in one of the two main channels, *A* and *B*, respectively, parallel to the *c* axis. Both are coordinated to water molecules in the channels and to framework oxygens on one side only of the tetrahedral rings. Calcium alone occupies the $M(2)$ site, and monovalent (Na) cations, when present, occur in $M(1)$ sites with Ca (Gottardi and Galli, 1987). The same two sites also occur in clinoptilolite, again with relative enrichments of Na and Ca in the $M(1)$ and $M(2)$ sites, respectively, in specimens from two localities studied by Koyama and Takeuchi, 1977), comprising a clinoptilolite from Agoura, California which contained higher K and lower Ca contents than crystals from the other locality in Kuruma, Japan. The $M(1)$ site located in channel *A* is coordinated by two framework oxygens and five water molecules, giving for the coordination polyhedron an average $M(1)$-oxygen distance of 2.69 Å (range 2.32-2.85 Å) for the Kuruma clinoptilolite and 2.75 Å for the Agoura specimen. The $M(2)$ site located in channel *B* has neighbors consisting of three framework oxygens and five water molecules with average $M(2)$-oxygen distances of 2.58 Å (Kuruma, range 2.38-2.75 Å; Agoura, average 2.57 Å). The $M(3)$ site is located in the C channels parallel to the a axis and is coordinated by six framework oxygens and three water molecules, giving a mean $M(3)$-oxygen distance of 3.06 Å (Kuruma, range 2.71-3.20 Å; Agoura, average 3.05 Å). The clinoptilolite $M(3)$ site is occupied preferentially by K, which is believed to be responsible for the increased the thermal stability of clinoptilolite relative to heulandite. A fourth site, $M(4)$ located in the A channels, is coordinated by six water molecules, has an average $M(4)$-oxygen distance of 2.03 Å (Kuruma, range 1.59-2.71 Å; Agoura, average 2.09 Å), and is occupied by Mg. Each of the four cation sites is incompletely filled and generally have <50% cation occupancies (Gottardi, 1978). Some of the paired occupancies are forbidden by the close proximity of the cations to oneanother or to water molecules located in nearby structural positions (Koyama and Takeuchi, 1977).

Water molecules, which may occupy seven distinct positions in the channels, fall into two categories. The first category consists of those water molecules which have a maximum occupancy regardless of changes of cation composition, and include $W(3)$ and $W(4)$ located in the C channel tightly bonded to cations in $M(2)$ or $M(3)$ positions. The second category comprises water molecules with variable and low occupancies, including $W(5)$ and $W(6)$ associated with cations in $M(1)$ and $M(4)$ positions, W(2) associated with $M(1)$ and $M(3)$ cations, $W(1)$ bonded only to $M(1)$, and a poorly defined $W(7)$ water position associated with $M(4)$ cations. The vulnerability of clinoptilolites to dehydration at moderate temperatures (Bish, 1984) may reflect diminished water occupancies of all but the $W(3)$

and $W(4)$ positions. Conversely, prolonged soaking of clinoptilolites in some aqueous salt solutions could induce high populations of the water positions in the crystal structure.

Geochemical Constraints.

Groundwater flowing through volcanic deposits such as those at Yucca Mountain contains dissolved constituents which have been leached from the bedded vitric, devitrified and welded ash-flow tuffs. Concentrations of Na^+, HCO_3^- and Cl^- ions and dissolved SiO_2, reported to lie the range 0.001-0.002 M, are generally an order of magnitude higher than K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, F^-, etc. (White et al., 1980). Groundwater compositions vary with depth and are modified by passage through zeolitized tuffs, with the result that fracture-flow water is generally more HCO_3^--rich than interstitial water containing higher Cl^- concentrations (White et al., 1980). The widely used reference groundwater used in laboratory experiments and geochemical modelling studies relevant to the repository horizon at Yucca Mountain is from well J-13 in the near-by Nevada Nuclear Test site and is sodium bicarbonate-type fracture-flow groundwater (Bish et al., 1984; Delany, 1985; Moore et al., 1986).. Therefore, our cesium exchange experiments were conducted in $NaHCO_3$- or NaCl-bearing solutions.

Heat production during radioactive decay of fission products will elevate the temperature of volcanic rocks surrounding the proposed repository at Yucca Mountain, so that permeating groundwater will be heated perhaps to temperatures exceeding 100°C (Smyth, 1982). To simulate effects of elevated temperatures, we conducted our the majority of our cesium exchange measurements at 60°C but carried out some reactions at 80°C.

EXPERIMENTAL DETAILS.

Zeolite Specimens.

Clinoptilolite and heulandite are isostructural, and a solid-solution series appears to exist (Boles, 1972) between the ideal compositions

$$\underset{\text{clinoptilolite}}{(Na,K)_6Si_{30}Al_6O_{72}.24H_2O} \quad \text{and} \quad \underset{\text{heulandite}}{Ca_4Si_{28}Al_8O_{72}.24H_2O}$$

Three criteria have been proposed to distinguish clinoptilolites from heulandites. The zeolite is named clinoptilolite when: (i) (Na + K) > Ca (Mason and Sand, 1960); (ii) the Si/Al ratio exceeds 4 (Boles, 1972); and (iii) the crystal structure survives (i.e. the x-ray pattern is unchanged) after overnight heating at 450 C (Mumpton, 1960). Conversely, heulandites are defined by (Ca + Sr + Ba) > (Na + K), Si/Al < 4, and thermal decomposition above 450 C. Since microprobe analyses of clinoptilolites from Yucca Mountain exhibit wide ranges of Na, K, Ca (and Mg) and Si-Al contents (Broxton *et al.*, 1986, 1987), it was deemed desirable to study a variety of clinoptilolite-heulandite specimens. Compositions and sources of the zeolites studied here are summarized in Table 1.

Microcrystalline clinoptilolite from Hector, California, was one of the zeolites used by Ames (1960, 1961, 1962a,b,c, 1963, 1964) in early cation exchange experiments. Later, Ames, (1964, 1965) used samples of clinoptilolite from the John Day Formation, Oregon. The Hector clinoptilolite was reported (Ames *et al.*, 1958) to contain 5-15% impurities consisting of unaltered glass, quartz, feldspar and minor clay silicate and carbonate. Scanning electron microscope photographs of the Hector clinoptilolite (Mumpton and Ormsby, 1978) indicate that it consists of plates of euhedral, coffin-shaped crystals dominated by (010) faces only a few microns in diameter. A similar morphology and crystallinity is displayed by the clinoptilolite from Castle Creek, Idaho (Mumpton and Ormsby, 1978) which is virtually 100% pure (Sheppard and Gude, 1983) and was the principal zeolite used by Bish (1984) in his thermal studies of cation-exchanged clinoptilolites. The more coarse-grained clinoptilolite from Agoura, California (Wise et al., 1969), also studied by Bish (1984), was used in crystal structure refinements by Alberti (1975) and Koyama and Takeuchi (1977). Unfortunately, only limited amounts of Agoura clinoptilolite crystals were available to us. Therefore, in our detailed investigations of oriented single crystals, we used samples of the clinoptilolite from Succor Creek, Malheur County, Oregon, which consists of euhedral crystals1-2 mm in diameter . The microprobe data summarized in Table 2 indicate that the Succor Creek clinoptilolite with its rather high Ca content and low Si/Al ratio is close to the (arbitrary) classification boundary between clinoptilolite and heulandite; however, the Succor Creek clinoptilolite resembles compositions of some calcic clinoptilolites occurring in fractures throughout densely welded tuff at Yucca Mountain (Broxton *et al.*, 1986, 1987). Retention of its x-ray pattern after overnight heating at 450 C established the identity of the Succor Creek specimen, *sensu stricto*, as clinoptilolite. In addition to these four clinoptilolites, large single crystals of an Icelandic heulandite were also employed in some cesium exchange experiments, as well as an euhedral analcite from Lake Superior.

Mounted Zeolites.

Polished mounts were prepared of small pieces of the microcrystalline Hector and Castle Creek clinoptilolites and of oriented single crystals of the Agoura and Succor Creek clinoptilolites, Icelandic heulandite and the analcime. The samples were encapsulated in cold-setting epoxy cement in small brass cylinders. The characteristic euhedral coffin-shaped habit of the Icelandic heulandite, as well as the Succor Creek clinoptilolite, enabled individual crystals to be mounted on their (010), (100), (101), and (001) faces. Once orientation effects in cesium exchange reactions had been established, most of the subsequent experiments were carried out using crystals mounted on (010) faces, since these have the largest surface areas and are more easily manipulated, particularly for the Succor Creek clinoptilolite. The specimens were polished, carbon-coated, and analysed by electron microprobe before carrying out cation-exchange reactions.

Microprobe Analyses

Chemical compositions of the zeolites were determined using a four-spectrometer JEOL Superprobe weith full on-line computerized matrix correction and data reduction procedures. Operating beam currents ranged were 10 KeV and 5 and 10 nA, with counting times of 20 seconds for all elements except Na, which was analysed first and counted for only 10 seconds in order to minimize loss through volatilization. Loss of Na and zeolitic H_2O was further reduced by using a defocussed beam of approximately 10 microns diameter. Calibrations were made against analysed standards, such as diopside (65%)-jadeite (35%) glass (providing Ca, Mg, Na, Al and Si), cossyrite (Fe, Ti, Na, Si), and orthoclase glass (K), using the general Bence-Albee standardization procedure. Cesium analyses, using a CsCl crystal as primary standard and a pollucite from Mumford, Maine as a secondary standard, were corrected using the ZAF program of Tracer Northern. Counts were collected for a minimum of 5 secconds to a 60 second maximum or until one standard deviation of the counting statistics was less than 1%.

Cesium Exchange Experiments

After the polished mounts had been analysed, the carbon-coating was removed by gentle polishing with .3 micron corundum powder. The probe mounts were then placed inside individual stoppered flasks and specified volumes of different concentrations of cesium chloride solutions were added. Matching experiments were performed in the presence of CsCl solutions and either 1M NaCl or 1M $NaHCO_3$. Initially 1M CsCl solutions were used, followed by progressively lower dilutions of 0.01M, 0.001M or 0.0001M CsCl (without or with 1M NaCl or $NaHCO_3$ being present). In some reactions, unmounted 1-2 mm clumps f the Castle Creek and Hector clinoptilolites, as well as individual crystals of Succor Creek clinoptilolite and Icelandic heulandite, were exchanged first with CsCl solutions before being mounted, polished and microprobed.

The stoppered flasks were placed in a constant-temperature shaking water-bath set at either 60°C or 80°C, and the exchange reactions were carried out for time periods ranging from 5 days tol month. After each reaction time interval crystal mounts were removed, washed several times with cold distilled water, dried at ambient temperatures, and re-coated with carbon prior to microprobe analyses. After microprobe analyses, carbon-coated surfaces of the mounts were gently removed, and the Cs-exhange reaction continued.

RESULTS

NaCl or $NaHCO_3$ Alone.

Since the groundwater flowing through Yucca Mountain is likely to be dominated by Na^+ and HCO_3^- or Cl^- ions, some mounted crystals of the Succor Creek clinoptilolite were reacted first with 1M NaCl or 1M $NaHCO_3$. The analyses shown in Table 2 (columns -- and --) indicate that slight enrichment of Na and depletion of K occurred in these Na-loaded crystals.

[VALERIE,

To Do: (1) Load mounted clumps of Hector cliinoptilolite 1M NaCl (60°C)

(2) Analyse by microprobe to find out whether K (and Ca?) are depleted.

(3) Load crystals with Ca by reacting Succor Creek and Hector clinoptilolites with 1M $CaCl_2$ (60°C).

(4) Measure by microprobe any increases of Ca (and depletion of Na and K?)

(5) Then React the NaCl-loaded and $CaCl_2$-loaded Succor Creek and Hector clinoptilolites with 1M CsCl (or 0.01M CsCl?) for 7 days and 30 days at 60°C

(6) Analyse for Cs to see if different capacities exist for Na-loaded and Ca-loaded clinoptilolites.

Rationale At Yucca Mt, there regional differences of Na and Ca contents of the clinoptiloles in the zeolitic tuffs of Calico Hills. And, Ca-rich clinoptilolites are found in fractures through and beneath the repository horizon. Does high Ca affect the Cs capacity of clinoptilolite?]

Oriented Crystals.

Individual crystals of the Succor Creek clinoptilolite were mounted onto (100), (101), (001) and (010) faces. Microprobe analyses of these crystals before cation exchange reactions summarized in Table 2 indicate a slightly higher Na concentration for the (010) face, suggesting that sodium is less susceptible to volatilization along the [010] axis because open channels do not exist in this direction in the clinoptilolite structure.

Progressive cesium exchange reactions with 1M CsCl were carried out for accumulated time periods of 5, 10, 17 and 30 days and the Cs concentrations of the crystals after each time interval are plotted in Figure 1. The drop-off of Cs after 10 days resulted from accidental condensation in initially unstoppered reaction flask, which decreased the CsCl concentration from 1M to ~0.5M. Thereafter, continued reactions in stoppered flasks with 1M CsCl for 30 days revealed that each crystal face has a different Cs capacity. The Cs concentrations are highest for the (100) and (001) faces, less for the (101) face, and least for (010), demonstrating that Cs selectively exchanges along the [100] and [001] axes which are the two directions in the clinoptilolite structure where open channels exist.

Heulandite shows a much stronger crystallographic influence on Cs-uptake than does clinoptilolite, which is indicated by Figure 2. The Cs concentration of the (010) face of heulandite is again considerably lower than those of the other two faces, demonstrating that Cs readily enters the heulandite structure along the open channel [100] and [001] directions. Furthermore, the Cs concentrations of the heulandite (100) and (001) faces are comparable or slightly greater than corresponding faces of clinoptilolite, which conflicts with conclusions by Ames (1960) who stated that the cation exchange properties of heulandite and clinoptilolite are quite dissimilar.

Effects of Changing CsCl Concentrations

Weighed Succor Creek clinoptilolite crystals with diameters of 1-2 mm were mounted on their (010) faces and reacted for accumulated 30 day periods with 40 or 50 ml. aliquots of CsCl solutions ranging in concentration from 1M to 0.0001M. The results plotted in Figure 3 show that the amount of. Cs exchanged into clinoptilolite crystals decreases with increasing dilution of the CsCl solutions. These results differ from conclusions drawn by Ames (1960) that decreasing concentrations of CsCl increase the Cs capacity of clinoptilolite. However, efficiency of removal of Cs uptake by the (010) crystal faces, as indicated by the ratio

Cs content of clinoptilolite/Cs remaining in solution

increases from (%) for 1M CsCl to (%) for 0.0001M CsCl.

A measure of the reproducibility of the Cs-exchange data for different crystals of the Succor Creek clinoptilolite mounted in identical (010) orientations is demonstrated by the data for 1M CsCl reacted for 30 days. Figure 3 shows ~21 wt% Cs_2O compared with ~22 wt% Cs_2O in Figure 1. These Cs concentrations are somewhat lower than microprobe measurements of aggregates of the Hector clinoptilolite, also reacted for 30 days, which accumulated ~27 wt% Cs_2O. This high Cs content is comparable to values obtained by Ames (1960, 1961) for the Hector clinoptilolite reacted at 25^{o}C with 0.2M CsCl alone (23.3 wt% Cs_2O, compared with 18.75 wt% Cs_2O for reactions with 0.01M CsCl) (c.f. ~12.34 wt% Cs_2O for reactions with 0.01M CsCl at 60^{o}C in figure 3). Ames (1960) also noted that the effect of increasing temperature is to reduce Cs capacities by ~1/3 between 25^{o}C and 60^{o}C, so that our data for the Hector clinoptilolite compare favorably with his results.

Heulandite shows similar effects of CsCl dilution to clinoptilolite. Thus, the Cs_2O content shown in Figure 4 decreases from ~13 wt% Cs_2O to 3 wt% Cs_2O in 30 day reactions with 1M CsCl and 0.01M CsCl, respectively.

Presence of NaCl

Cesium-exchange reactions of (010)-mounted clinoptilolite crystals with solutions containing 1M NaCl and different concentrations of CsCl are summarized in Figure 5. Again, the Cs content of the zeolite decreases with CsCl dilution. Moreover, the presence of NaCl also decreases the uptake of Cs into clinoptilolite compared to NaCl-free solutions. Our data for reactions with 1M NaCl plus 0.01M CsCl, for example, provided ~7 wt % Cs_2O in clinoptilolite, whereas ~12 wt% Cs_2O entered the zeolite in the absence of NaCl. Ames (1960, 1961) in his measurements of the Hector clinoptilolite, observed a decrease of the Cs capacity from ~18.75 wt% Cs_2O to ~10.3 wt.% in reactions with 0.01M CsCl in the absence and presence, respectively, of 1M NaCl. He also reported ~7.5 wt% Cs_2O in the Hector clinoptilolite after reactions with 0.01M CsCl (alone) at 60°C, in good agreement with our measurements for single crystals of the Succor Creek clinoptilolite. Ames (1961) also measured comparable Cs concentrations in 25°C reactions of the Hector clinopilolite reacted with 0.2M CsCl and either 1M NaCl or 2M NaCl (~8 wt% Cs_2O relative to ~23 wt% Cs_2O in the absence of NaCl), and concluded that clinoptilolite tends to maintain a given Cs distribution between zeolite and solution despite an increasing Na concentration. A similar conclusion may be drawn from our 60°C reactions of the Succor Creek clinoptilolite with 0.01M CsCl and 0.1M CsCl in the presence of 1M NaCl.

[Reactions of heulandite with 1M NaCl and different CsCl concentrations are confusing? Cs uptake in Figure 6 decreases in the order 0.1M CsCl > 1M CsCl > 0.01M CsCl ?]

Presence of $NaHCO_3$

The decreased Cs capacity of clinoptilolite in the presence of Na is further demonstrated by exchange reactions with different concentrations of CsCl in the presence of 1M $NaHCO_3$.. Results summarized in Figure 7 show that the Cs_2O concentrations in the Succor Creek clinoptilolite not only decrease appreciably between 1M CsCl and 0.001M CsCl in the presence of $NaHCO_3$, but also are exchanged into the zeolite in significantly lower concentrations than NaCl-bearing solutions. A Similar trends occur for heulandite exchanged with different concentrations of CsCl in the presence of $NaHCO_3$ (Figure 8). These results suggesting that different anions affect Cs-exchange reactions of clinoptilolite appear to be at variance with observations by Ames (1960) who stated that the use of competing Na cations in solutions with the chloride, nitrate, and sulfate anions made no appreciable difference in their effects on Cs capacity. However, Ames (1964) stated later that if less dissociated carbonate salts were used differences might be expected from chloride salts, but these differences were not specified. Our measurements demonstrate that the presence of HCO_3^- anions lowers the exchange capacity clinoptilolite for cesium ions, which has important consequences for the storage of fission products at the proposed repository for nuclear waste at Yucca Mountain..

(to be continued!}

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Section D

Disturbed Zone Program

Disturbed Zone Program

Introduction

The concept of the disturbed zone is important because the outer boundary of the disturbed zone (away from the repository) is the starting point for the calculation of ground-water travel time to the accessible environment. If this boundary is close in to the mined openings of the repository, more credit can be taken by DOE for travel of the ground water through a larger volume of rock in the vadose zone. Conversely, if the boundary extends a greater distance from the repository, less credit for ground water-travel time can be claimed.

Complicating the concept is the possibility that a generic, fixed-distance boundary might be claimed for the disturbed zone, based only upon the thermo-mechanical effects on the rocks from mining the openings of the repository, such as proposed by the NRC. An alternative is a site specific variable distance boundary that also considers phase changes in the wetting fluid within the vadose zone as well as the pathways these fluids might encounter, such as fractures. Furthermore, dissolution and alteration of the solid phases by water-rock interactions should be taken into account as well because these changes can potentially affect the thermo-mechanical properties of the enclosing rock.

The DOE prefers the first approach, the potentially nonconservative, generic fixed distance boundary from mined repository workings because this approach yields the greater physical distance and thus the greater ground-water travel times. However, this approach may not be completely in keeping with the original definition of the disturbed zone, i.e., that volume of rock adjacent to the repository in which processes resulting from loading nuclear waste canisters into the repository are too complex to be accurately modeled or simulated. If the generic fixed distance boundary is closer to the repository than the site specific boundary the implication is that complex processes occurring in the disturbed zone can be modeled by DOE.

In our review of DOE's Environmental Assessment and the NRC's Draft Generic Technical Position on the Disturbed Zone, we found an incomplete and perhaps even lack of understanding of the complicated processes likely to occur in a disturbed zone within the vadose zone, such as refluxing of aqueous fluids and dissolution/alteration of the rock mass. Thus, the choice of a generic fixed-distance disturbed-zone boundary by DOE and NRC is at best simplification of reality or a nonconservative error in judgment to obtain the greatest possible ground-water travel times for satisfying regulatory requirements (see Appendix D).

Based on this tack by DOE and NRC and our concerns on the reasonableness of this approach to satisfying several key licensing criteria, we have chosen the subject of the disturbed zone for further investigation and evaluation. The issues addressed in this section briefly stated are:

1. Effects of phase changes in the aqueous fluids in the fractures and matrix pores of the host rock on the physical extent of the disturbed zone.

2. Effects of dissolution and alteration of the host rocks on the integrity of the repository with respect to the release of radionuclides to the accessible environment.

3. Should the boundary of the disturbed zone be fixed at some generic distance (presently about 50 meters) from mined openings in the repository host rock or at a site specific variable distance depending upon phase changes in fluids, fluid pathways, and alteration and dissolution of the repository host rock resulting form fluid-rock interaction.

The results of exploratory investigations in this section point to the fact that the integrity of the repository will be affected, and that the boundary of the disturbed zone could be at a greater distance than the currently defined 50 meters from mined openings of the repository because of rapid fluid movement in fractures and fissures and dissolution/alteration which will be induced by the heat from the entombed high-level nuclear waste canisters.

The appendix of this section contains abstracts of papers presented at professional meetings and other technical documents that are offshoots of our efforts. A list of these papers and technical documents precedes the appendix.

Disturbed Zone

ISSUES:

How is the extent of the disturbed zone affected by phase changes in the aqueous fluids in the fractures and matrix pores of the host rock, Topopah Springs tuff, and possibly other surrounding units? The phrase "phase changes in the aqueous fluids" implies boiling of pore and fracture water within the drying out envelope which is in the immediate vicinity of the nuclear waste canisters, and the condensation of water vapor to liquid water at some greater distance from the canister where the rock is below the boiling point of water (altitude corrected).

OBJECTIVES OF ACTIVITY:

Determine by geochemical computer modeling, using (as realistic as possible) vadose-zone water composition: (1) the chemistry of the aqueous and gaseous phases as boiling of vadose water progresses; (2) the degree of precipitation of minerals in the zone of boiling; and (3) the degree of dissolution/reaction of minerals in the condensation zone.

ACTIVITY SUMMARY:

Preliminary calculations of open and closed system boiling of Rainier Mesa vadose water, condensation of boiled gases, and reaction of boiling water with the Topopah Springs welded tuff were completed. Computer codes (CHILLER and SOLVEQ) were modified to improve calculations involving aluminum, for heat addition to calculate volumes of minerals produced or destroyed, and to compute changes in rock porosity. Documentation of the computer codes was completed as part of the quality assurance guidelines.

FINDINGS:

As boiling of vadose-zone water proceeds, the pH of the residual solution increases due primarily to degassing of CO_2 and concentration of the salts. If gas remains in contact with the water and minerals precipitating due to boiling, the system is referred to as closed; otherwise, if the gas is removed incrementally (Rayleigh fractionation) the system is considered open. Open system boiling calculations in which the gas phase escapes consistently produces higher pH's in the residual solutions. The predominant mineral precipitate is calcite.

INTERPRETATION OF FINDING(S):

Calculated boiling of vadose water produces a highly alkaline, saline solution that precipitates several minerals, dominantly calcite. These precipitated minerals would most likely plug pores and fractures above the canisters in the zone of boiling resulting in the formation of a perched water layer due to the gravity and capillary induced return of condensed water vapor and ongoing infiltration of surface water. Residual pockets of highly alkaline saline water plus any water that may penetrate the zone of plugging as the thermal peak wanes may redissolve previously precipitated salts in the zone of complete drying out (between canister and zone of boiling), and may eventually contact the canisters and accelerate corrosion under oxidizing conditions.

ADDITIONAL WORK REQUIRED:

- Significance of calculations would be greatly improved if actual analyses of the compositions of vadose waters from Yucca Mountain were available.

- Calculations should proceed to dryness (all liquid water converted to vapor).

- Investigation of the reaction of condensed water vapor with repository host rock (Topopah Springs tuff).

- Determine or estimate thermochemical properties of phases needed to complete calculations.

RECOMMENDED PROGRAM:

Ultimately the geochemical calculations must be combined with hydrogeological calculations on heat and fluid transport (to establish temperature gradients and mass fluxes) to compute the geochemical interaction of the entire refluxing system (boiling fluids to condensing vapor and all water-rock interactions). The importance of fracture versus matrix flow must also be independently established (by field studies) for these types of modeling computations to be relevant to the disposal of high-level nuclear waste at Yucca Mountain.

EXISTING PROGRAM:

The computer algorithms for the geochemical calculations involving boiling and condensing aqueous fluids are currently under development by Dr. M. H. Reed and colleagues at the Department of Geological Sciences, University of Oregon. Preliminary calculations thus far have involved Rainier Mesa vadose water and Topopah Springs welded tuff for open and closed systems (see published abstract by Reed and Spycher in Appendix D-I).

Principal Investigator:

Dr. M. H. Reed, Department of Geological Sciences, University of Oregon.

Disturbed Zone

ISSUES:

Will dissolution of the host rock impact the postclosure integrity of the repository with respect to release of radionuclides to the accessible environment?

How significant will dissolution be as a result of the refluxing of aqueous fluids that most likely will occur during the thermal pulse (thermal peak is about 50 to 100 years after emplacement of canisters)?

Will the zone of dissolution significantly extend the disturbed zone as defined by the U.S. Nuclear Regulatory Commission?

OBJECTIVES OF ACTIVITY:

Determine the effectiveness of a thermal gradient in promoting mass transfer, dissolution, and alteration of the host rock mineralogy, including those phases thought to sorb radionuclides efficiently, such as clays and zeolites.

ACTIVITY SUMMARY:

A vertical thermal gradient experiment was designed and tested that simulated conditions anticipated in partially saturated Topopah Springs welded tuff after emplacement of waste canisters. The experiment consists of a vertically-operated reactor (PVC or aluminum pipe, 4" O.D. and 24" long) containing the rock sample and a heater assembly at the bottom and a cooling assembly at the top. The power adjustment of the heater at the bottom produces a zone of boiling while adjustment of water temperature and flow rate in the cooling assembly results in a condensation zone above the boiling zone. These adjustments permit the heat flux, and consequently, the mass flux through the reactor to be controlled.

Additionally, a hydrothermal mixed flow reactor has been designed, constructed, and pressure and flow tested. This reactor operates at a constant temperature and is to measure the rates of reaction of minerals important for sorption of radionuclides and dissolution of the repository host rock.

FINDINGS:

A zone of boiling formed at the bottom and a zone of condensation formed directly above it. Almost all the grains showed evidence of leaching with the most extensive dissolution occurring in the zone of condensation. Iron oxyhydroxides globules and opaline silica coatings precipitated throughout the experimental sample. Alteration mineral phases formed on grains near the bottom of the reactor column,and tuff grains at the very bottom of the reactor were tightly cemented by deposits of opaline silica.

INTERPRETATION OF FINDINGS:

The results strongly support the hypothesis that mass transport, dissolution, and mineral alteration/precipitation are greatly enhanced in temperature gradients versus isothermal pseudo-equilibrium conditions. Temperature gradients exist today at Yucca Mountain in the form of the geothermal gradient and those formed after emplacement of waste canisters will certainly be more extreme than the preexisting natural geothermal gradient. Although isothermal experiments provide baseline information that can be interpreted in terms of existing geochemical computer models, processes and interactions in thermal gradients can not be predicted nor interpreted with the current"equilibrium" geochemical algorithms.

ADDITIONAL WORK REQUIRED:

Past experiments have utilized crushed tuff; future experiments would also employ solid cores of Topopah Springs tuff with and without fractures. Realistic vadose-zone water compositions must eventually be utilized for these experiments to be relevant to Yucca Mountain in particular. Other parameters that need to be varied to determine their effect on the rate of mineral alteration and/or dissolution and the rate of mass transfer include the thermal flux and the degree of filling of the vessel (determines the degree of saturation during the experiment).

Authigenic mineral phases need to be identified, physical properties of products determined (porosity and permeability), and analysis of sampled waters during experiments analyzed.

Kinetic experiments in the hydrothermal mixed-flow reactor would commence as soon as possible. Kinetic information on those mineral phases important to the sorption and dissolution issues is sorely needed.

RECOMMENDED PROGRAM:

The ultimate goal of this program is to determine if the nonequilibrium thermodynamics of the situation being simulated by experiments can be predicted (with a reasonable number of quantified experiments), and if it is predictable, can the results of models be scaled up to the repository scale? To achieve this goal, a sufficient number of experiments is required in which the sample type (crushed tuff versus solid core, with and without fractures), thermal flux, water composition, degree of saturation, and physical size of the reactor vessel are varied. The results must be quantified as well for input to a model that is to be developed.

EXISTING PROGRAM:

To date, the existing program has been preliminary and exploratory with the main purpose of demonstrating that the phenomenon of mass transport and mineral alteration/dissolution in a thermal gradient can be a significant factor in the safety of a repository at Yucca Mountain (see published abstract by Newcomb and Rimstidt in Appendix D-II).

Principal Investigator:

Dr. J. D. Rimstidt, Department of Geological Sciences, Virginia Polytechnic Institute and State University.

Disturbed Zone

ISSUE:

The key issue of the disturbed zone is whether the boundary should be fixed at some distance (presently 50 meters) from mined openings in the repository host rock. This 50 meter distance is purportedly based on changes in intrinsic rock properties and not (as we believe) on any changes in multiphase fluid states in the host rock's pores and fractures. As defined, the disturbed-zone boundary distinguishes between processes that are too complex to be modeled (thermal and mass transport and transfer) within the boundary and those processes that can be modeled outside of the boundary.

Should the disturbed-zone boundary take into account the multiphase fluid effects and accompanying mineral alteration/dissolution effects?

OBJECTIVES OF ACTIVITY:

We are attempting to evaluate the scientific reasonableness of the disturbed zone definition, and thus the boundary, on the basis of published data in the open literature, and by obtaining and utilizing public domain and DOE/contractors hydrogeologic and geochemical modeling software on realistic problems associated with the development of the thermal envelope surrounding the loaded repository.

ACTIVITY SUMMARY:

A review was written of the NRC's draft generic technical position on the disturbed zone (see Appendix D-III). Three draft technical progress reports on the disturbed zone were generated (see Appendix D-IV). A preliminary annotated bibliography of references concerning the disturbed zone was prepared. Many hydrogeologic and geochemical software modeling packages (programs) were requested and a few were obtained and evaluated (see Progress Report, Appendix D-V):

TOUGH (hydrogeological, K. Pruess, LBL): obtained, and tested on mainframe and personal computers.

PHREEQE (geochemical, U.S.G.S., Intera version): obtained, debugged on personal computer.

EQ3/6 (geochemical, DOE-LLNL): requested, but not obtained.

SAGUARO (hydrogeological, DOE-SNL): requested, but not obtained.

NORIA (hydrogeological, DOE-SNL): requested, but not obtained.

PETROS (hydrogeological, DOE-SNL): requested, but not obtained.

Princeton Transport Code (hydrogeological, Princeton University): obtained, but not completely debugged on non-IBM personal computers.

FINDINGS:

The existing working definition of the disturbed zone (NRC) is seriously flawed and unrealistic. The disturbed-zone boundary is an extremely complicated concept and existing hydrogeologic and geochemical computer software modeling algorithms are not capable of realistically modeling the situation simultaneously (no one program exists that performs both hydrogeologic and geochemical modeling) or individually. The hydrogeological models must be capable of handling thermal and mass transport of multiphase fluids in matrix and fractures under saturated and undersaturated conditions; geochemical models must have the ability to model mass transfer under nonequilibrium (irreversible thermodynamics) conditions (thermal gradients). However, from a more fundamental standpoint, the basic hydrogeologic and geochemical parameters needed to perform modeling have not been determined to a sufficient degree of detail or accuracy by DOE and their contractors.

INTERPRETATION OF FINDINGS:

These findings strongly suggest that if the extent of the disturbed zone is based on that volume of rock in which processes are sufficiently complex that they can not be modeled, the boundary of the disturbed zone could be at a much greater distance than the currently defined 50 meters from mined openings of the repository.

ADDITIONAL WORK NEEDED:

Computer software modeling packages that have been obtained need further evaluation (debugging and testing) within the full gamut of problems: from simple cases to realistically complex ones. Technical literature, as well as NRC and DOE documents, will be reviewed and evaluated as they become available. New software developed by DOE or their contractors needs to be reviewed and tested in terms of assumptions employed, data utilized, and situations modeled.

RECOMMENDED PROGRAM:

The recommended program has three parts and is similar to that described above:

- Review and evaluation of published technical literature, including that by DOE and their contractors, and the U.S. Nuclear Regulatory Commission (NRC).

- Acquisition of public domain, commercial, and DOE/USGS/NRC - contractor computer modeling software and hands-on testing and evaluation of these codes;

- Generation of progress reports, technical position papers, and/or publications for the State's program regarding the disturbed zone.

EXISTING PROGRAM:

The existing program is essentially similar to the recommended program, except that beginning in July, 1987 there were no funds specifically designated for computer work; thus this aspect of the program is suffering.

Principal Investigators:

Drs. D. L. Shettel, Jr. and C. L. Johnson, of MAI.

Appendix D

Disturbed Zone Program

List of Appendices

Appendix D-I

Reed, M. H. and Spycher, N. F., 1988, Chemical modeling of boiling, condensation, fluid-fluid mixing and water rock reaction using programs (CHILLER and SOLVEQ
Abstract presented at 196th American Chemical Society Meeting, Los Angeles, California.

26. CHEMICAL MODELING OF BOILING, CONDENSATION, FLUID-FLUID MIXING AND WATER-ROCK REACTION USING PROGRAMS CHILLER AND SOLVEQ, Mark H. Reed and Nicolas F. Spycher, Department of Geological Sciences, University of Oregon Eugene, OR 97403

In geothermal systems, waters boil at depth, precipitating ore sulfide and carbonate minerals; boiled gases, including Hg, condense near the surface where they are oxidized, producing sulfuric acid waters that alter host rocks to clays, or back-react with boiled waters to precipitate As, Sb and Au. This example illustrates the type of complex natural chemical system that SOLVEQ and CHILLER model by computing: Phase assemblage; Compositions of the aqueous phase and gas phase, treating CO_2, H_2O, CH_4, and H_2S gases as non-ideal mixtures of real gases; Compositions of solid solutions (ideal or non-ideal); Distribution of heat among phases. Key computational capabilities that make this possible include: An internal enthalpy balance equation that is solved simultaneously with the chemical mass balance and mass action equations; Arbitrary selection of redox couples to provide for calculations over the entire range of natural oxygen fugacities; Re-selection of the phase assemblage during the iterative solution process.

Appendix D-II

Newcomb, W. D., and Rimstidt, J. D., 1988, An experiment to simulate mass transport near the Yucca Mountain High Level Radioactive Waste Repository Geological Society of America Annual Meeting, Poster Session, Abstract.

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№ 22748

AN EXPERIMENT TO SIMULATE MASS TRANSPORT NEAR THE YUCCA MOUNTAIN HIGH LEVEL RADIOACTIVE WASTE REPOSITORY

NEWCOMB, William D. and RIMSTIDT, J. Donald, Department of Geological Sciences, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

A vertical thermal gradient experiment (VTGE) was designed to subject samples of partially saturated Topopah Springs member of Yucca Mountain tuffs to geochemical conditions that will likely result from the burial of heat producing, high level radioactive waste canisters. The reactor consists of a PVC pipe, 4 inches diameter, 24 inches long filled with crushed tuff and enough water to partly saturate the pore spaces. A heating assembly at the bottom and and a cooling assembly at the top of the pipe impose a thermal gradient so that water in the pores of the tuff at the bottom of the reactor boils and travels upward as steam which condenses near the top of the reactor. The condensate dissolves some of the tuff and returns to the bottom of the reactor by gravity flow. The reactor design allows the solution and gas composition, heat flux, percent saturation, and matrix permeability to be varied from experiment to experiment.

Intital experiments of one month duration with 30 and 80% of the pore volume filled with liquid water show significant alteration of the tuff. Scanning electron microscope observation of the run products show leaching and pitting of grains from throughout the entire column, with more extensive damage to samples from the upper 20 cm of the column. Zeolite alteration minerals formed in the middle and bottom of the column. Iron oxyhydroxide formed by the oxidation of ferrous iron leached from the tuff and opaline silica coatings were ubiquitous and extensive throughout the run products. Near the very bottom of the reactor the tuff grains were cemented together by precipitates.

These experiments show that refluxing of water from partly saturated pore spaces in the Yucca Mountain tuffs can result in extensive mineral alteration and transport and that geochemical conditions similar to those found in vapor saturated geothermal systems and epithermal gold deposits may obtain during the early stages of the life of the proposed high level waste repository.

2 CATEGORIZE ALL ABSTRACT —Check ONE discipline below which reviewers would be best qualified to evaluate this abstract.

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- ☐ 26 Precambrian geology
- ☐ 27 Quaternary geology
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- ☐ 30 stratigraphy
- ☐ 31 structural geology
- ☐ 32 tectonics
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Speaker's name W. D. Newcomb

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Address Virginia Tech

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Appendix D-III

Review and recommendations: draft generic technical position: interpretation and identification of the extent of the disturbed zone in the high-level waste rule, by M. Gordon, NRC.

Mifflin & Associates, Inc.

Review and Recommendations:

DRAFT GENERIC TECHNICAL POSITION: INTERPRETATION AND IDENTIFICATION OF THE EXTENT OF THE DISTURBED ZONE IN THE HIGH-LEVEL WASTE RULE (10CFR60)/ M. Gordon, *et al*., NRC, 20 June 1986

Reviewed by:

C. L. Johnson
M. D. Mifflin
M. E. Morgenstein
D. L. Shettel, Jr.

Submitted to:

Carl Johnson

AGENCY FOR NUCLEAR PROJECTS
NUCLEAR WASTE PROJECT OFFICE
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August 1986

Table of Contents:

Authorship Responsibility:

OVERVIEW:

M. D. Mifflin.

SPECIFIC TECHNICAL AREAS:

Mineral and Rock Stability:	M. E. Morgenstein.
Heat Transfer Model:	C. L. Johnson and M. D. Mifflin.
Transport Model:	C. L. Johnson and D. L. Shettel, Jr.

1.0 BACKGROUND:

The NRC Draft Generic Technical Position (Gordon, et al., 1986) on the Disturbed Zone Concept (DGTP) is intended to establish a clarified definition of the inner boundary from which ground-water travel times from High-Level Nuclear Waste (HLW) repositories to the accessible environment are determined. The DGTP restricts the definition of the "disturbed zone" to include only that region where the intrinsic properties of the rockmass (i.e., permeability and effective porosity) are changed as a result of HLW emplacement, admitting that a definition which includes completely the zone of increased temperatures and associated fluid buoyancy effects might include portions of the accessible environment. The motivation for this re-definition of the disturbed zone is the recognized difficulty in using pre-waste-emplacement rockmass properties to predict post-waste-emplacement conditions in the region of intrinsic property changes. In contrast, the effects of fluid property changes that are demonstrably not coupled to the intrinsic properties of the rockmass can be modeled using well developed assessment methods.

2.0 DRAFT GENERIC TECHNICAL POSITION:

The revised disturbed zone definition proposed by NRC establishes the inner boundary from which ground-water travel time is determined, thereby simplifying by omission the effects of the creation of the repository and the heat generated by the waste. Credit towards the 1,000 year pre-waste-emplacement travel time is not considered within the disturbed zone, because of the potential difficulty (46FR35280, 35281, July 8, 1981) in assessing the physical and chemical processes contributing towards waste isolation within that region. Consequently, in order to avoid the potential uncertainties of the characterization process, the disturbed zone was established as the inner boundary from which travel-time calculations are to be made for demonstrating compliance with 10CFR60.113(a)(2).

The DGTP indicates clearly:

> "...that the disturbed zone may be considered to be 1) defined by the zone of substantial thermo- hydro-chemical- mechanical changes in intrinsic permeability and effective porosity caused by underground facility construction or by HLW heat generation and 2) should at least include the portion of the host rock directly adjacent to the underground facility in order that a proper measure of the quality of the geologic setting far from the buried waste may be obtained through application of the groundwater travel time criterion."

and:

> "...a disturbed zone of 5 diameters for circular openings, 5 opening heights for noncircular openings, or 50 meters, whichever is largest, from any underground opening, excluding surface shafts and boreholes, may be the minimum appropriate distance for use in calculations of compliance with the pre-waste-emplacement groundwater travel time criterion (10 CFR 60.113 (a)(2))." "The disturbed zone at a given site may, however, extend further than this distance depending on the site and design characteristics." "The extent of the disturbed zone should be calculated by DOE on a site-specific basis." (Gordon, et al., 1986, page 17).

Further, Gordon, et al. (1986) state that the site specific analyses should account for: anomalous geologic situations; effects of the heterogeneous geologic system; the magnitude of the likely ground-water flux (implying vadose and saturated zone flux); the magnitude of areal thermal loading of the repository; geochemical and hydrogeochemical characteristics of the site; and changes in the configuration of the facility through time. (Gordon, et al., 1986, page 17).

3.0 GENERAL REVIEW AND COMMENTS:

We find the DGTP on the disturbed zone conceptually valid with respect to its recognition that near-field processes will change intrinsic properties of permeability and porosity in an indeterminate manner. However, the DGTP clearly excludes thermal effects on fluids as part of the definition of the disturbed zone, stating that these will be treated during assessment of compliance with the overall system standard (10CFR60.112). We assume that this exception also includes phase changes in fluids, and these are anticipated to be of significant impact in the Yucca Mountain vadose environment. Phase changes in fluids and associated moisture redistribution as the result of the phase changes should be explicitly addressed within the technical position, because such changes will occur in the vadose zone and will constitute the disturbed zone as originally defined.

We believe, however, that even with the simplifying exclusion of fluid responses to thermal effects, the objective "...establishment of generic and easily evaluated guidance on the disturbed zone is desirable in order to allow for the demonstration of compliance with the groundwater travel time criterion (10CFR60.113(a)(2)) consistent with NRC's intent in the criterion..." (Gordon, page 16) will not be realized without additional guidance and specific (if arbitrary) definitions of the word <u>substantial</u>. Even with such a definition, considerable additional characterization effort will be required to confidently judge the thermochemical impact on the rock properties within the thermal envelope produced by the waste at the Yucca Mountain site.

Before the DGTP definition of the disturbed zone can be applied to the Yucca Mountain site, the thermal history envelopes for the site need to be accurately established.

Figure 1 is a "site-specific" thermal envelope model developed for Yucca Mountain for 14.2 W/m^2 spent fuel (SF) with a repository midplane at 390 m (Braithwaite and Nimick, 1984, page 10).* Commercial high-level waste (CHLW), not considered in this example, would produce even higher peak temperatures in a shorter time frame given identical initial thermal loadings. Based on the EA (DOE, 1986) the average depth to the repository horizon will likely be between 250 and 300 m below land surface (see Figure 6-19, EA 10-6-248), rather than the assumed 390 m.

We have added to Figure 1 (which depicts the maximum overburden scenario) the position of the repository zone and the range in position of the basal vitrophyre of the Topopah Spring Member. Also, the relative ranges in position of the landsurface and water table with respect to the repository horizon have been indicated. It is important to note that the figure at best represents uncertain approximations in terms of accurately determined thermal envelopes and relative positions of the important features such as land surface, water table, and basal vitrophyre. The thermal envelopes neglect the effects of convective transport of heat via vapor and water transport in fractures, as well as the more complex issue of possible heat sinks and sources triggered

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* It should be noted that the source document for these thermal envelope studies (Svalstad, 1984) is not referencable, i.e. Sandia National Laboratory (SNL) has not reviewed it for external distribution. Details of parameter estimation, boundary conditions, and key assumptions used in constructing the predicted Yucca Mountain thermal envelopes, all of which constitute baseline information for mineral stability studies, must therefore be considered speculative.

by endothermic and exothermic mineral alteration reactions that may occur due to the thermal envelope and migrating steam and hot water. We emphasize that no site-specific, referencable predictions of convective heat flow are available for Yucca Mountain; a highly preliminary study by Lawrence Berkeley Laboratory (LBL) is being reviewed by Sandia National Laboratory (SNL) at the time of this writing (September, 1986), and is not available for external review or comment.

Our objective in presenting Figure 1 is to lend perspective to the problem of establishing the boundary of the disturbed zone as proposed by the DGTP definition. We anticipate at least a 30° C rise in temperature down to the water table in some areas, and major thermal impact on the basal vitrophyre, with temperatures up to 80° C or more. In some areas, it seems likely that 40 to 50° C temperatures will occur at or near land surface if convective heat transport occurs and CHLW constitutes a supplementary wasteform.

4.0 FACTORS AFFECTING THE COMPLEXITY OF DETERMINING THE "DISTURBED ZONE" BOUNDARY AT YUCCA MOUNTAIN:

4.1 Zeolite Stability:

a. Bish and Semarge (1982) state that clinoptilolite and mordenite are not stable over 80-100° C in Yucca Mountain tuffs. Iijima and Utada (1971) have studied the Niigata Oil Field in Japan which contains buried authigenic facies through zeolite-metamorphic facies mineral associations. Temperatures at the top of the mordenite and clinoptilolite zone are 41-49° C, and at the analcime-albite transition, they are 120-124° C. The alkali clinoptilolite stability zone appears to range from 55-91^{o} C and the calcite-clinoptilolite appears to be stable at 8491^{o} C. If for argument's sake, we ignore the aqueous chemistry (not necessarily a conservative approach), zeolite stability for at least clinoptilolite might be safely placed as Bish and Semarge (1982) did, that is between 80-100^{o} C. The term stability, however, needs to be defined as mineral stability does not reflect the loss of adsorbed water.

b. It has been shown by various students of zeolites that Na and K concentrations in the aqueous media greatly affect the zeolite temperature stability field by reducing the stability of the zeolite below calculated and/or observed zeolite stability temperatures.

c. Zeolite stability may be viewed as its endothermic reaction temperature, which liberates water; and its exothermic reaction temperature which condenses its structure and causes mineral transformation. In the light of Differential Thermal Analysis (DTA) analyses on clinoptilolite, it is reasonable to presume that temperatures above its formational temperature will yield endothermic water loss. Whether or not this loss of water is accompanied by cation escape (from the super-cage) is unknown, as there is a paucity of data on this subject.

d. The transformation of clinoptilolite to analcime has been studied by Boles and Wise (1977) and Boles (1977). They report the reaction of deep-sea clinoptilolite to analcime as follows:

$4.4\ Na^+ + \text{Clinoptilolite} \rightarrow 6.8\ \text{analcime} + 3K^+ + 0.3\ Ca^{++} + 0.4\ Mg^{++} + 15.6\ SiO_2 + 13.2\ H_2O$

where: clinoptilolite composition is:

$$Na_{2.40}K_{3.00}Ca_{0.30}Mg_{0.40}Al_{6.80}Si_{29.20}O_{72} \cdot 20H_2O$$

analcime composition is:

$$NaAlSi_3O_3 \cdot H_2O$$

In addition to pressure and temperature controls, the above reaction would be dependent upon sodium and to a lesser extent other cation and water activities. Gieskes (1976, Table 1) cited in Boles (1977) indicates that sediments sharing the clinoptilolite to analcime reaction have pore fluids with molar Na/K ratios of about 160; whereas clinoptilolite-bearing sediments show average molar Na/K ratios of about 60. Consequently, the presence of analcime may be due to high Na/K ratios.

If vadose water evolved from mineral dehydration (such as smectites) were to tend towards relatively high Na/K ratios the transformation of clinoptilolite to analcime might occur even though the temperature regime of the zone(s) of transformation might be below the 120° C Stage 4 (Iijima and Utada, 1971). This reaction would (on the basis of Boles, 1977, calculation above) evolve significant quantities of water and SiO_2 and could also be responsible for a significant change in overall porosity and/or permeability.

4.2 Smectite Stability:

a. Smectites contain both adsorbed water (as interlayer water between lattice sheets) and high-temperature water (as OH^-) which is an essential portion of the crystal lattice structure. Dehydration curves for montmorillonite are S-shaped. Variations are dependent upon Na, H, and Ca - montmorillonite structures with Na more stable than Ca. Adsorbed water loss is usually indicated below 150-200° C with a flattening of the curve between this and 300° C where high-temperature water is generally evolved and structural transformation is indicated. Any temperatures above formational ambient temperature should provide adsorbed water loss until curve flattening temperatures are reached at 150-300° C. This water loss may be accompanied by cation-loss where the cations are in exchange interlayer sites. Na-bentonites may swell to 8-10 times their original volume upon hydration; comparable volumetric decreases accompany dehydration. Thus, in fluctuating temperature regimes, smectites may act as water (and cation) pumps adsorbing and releasing these constituents depending upon temperature fluctuations.

Since the smectites can accomodate more adsorbed water than the zeolites, and are apparently more sensitive to temperature changes (under 80° C), loss of adsorbed water and cations can be responsible for producing fluids which may lower the effective zeolite stability temperatures. Additionally, porosity, permeability, and hydrofracturing effects may be greatly enhanced by changes in the hydration-structure of the smectite minerals.

b. Perry and Hower (1972) have developed a four stage model for dehydration in deeply buried pelitic sediments based upon smectite and mixed-layered clay associations. Above 80° C (1972, figure 7) they show significant changes in clay stability and mineral associations. These changes may also be somewhat dependent upon aqueous chemistry and burial pressure.

c. Jackson (1956, page 266, figure 5-3) shows a Differential Thermal Analysis (DTA) curve for montmorillonite from 0 to 1,000° C. There are two major endothermic peaks between 0-240° C and 550-700° C indicating water loss. The first peak has a rapid water loss from 0-25° C, a significant water loss from 25 to 100° C and thereafter a sharper decline to about 160° C which is the maximum of the peak. This indicates that there is a significant water loss immediately upon heating. The rate of water loss upon heating at low temperatures (from 0-100° C) will be partially dependent upon isomorphous substitution in the octahedral layer of the montmorillonite (as indicated by Jackson, 1956, page 295). Consequently, the thermal behavior of the smectites at Yucca Mountain will be in part a function of their composition; therefore, detailed field data are required prior to attempting to determine the implications of dehydration due to repository heating.

d. Porrenga (1967) has found that for montmorillonites there is a tendency for Ca and Na in montmorillonite to be replaced by Mg. This exchange of Mg for Na and Ca is extremely important with respect to the evolution of vadose water chemistry and therefore on zeolite stability at elevated temperatures.

4.3 Temperature Rise as a Consequence of Authigenic Reactions:

"Surdam and Boles (1977) calculated that the hydration of andesine to laumontite in a sandstone with density of 2.3 g/cc, to 40% andesine, and an initial temperature of 60° C at 1.5 km of burial would raise the temperature of the rock by 40° C if the heat of the reaction is conserved." (Boles, 1977b). Boles (1977(b), page 129), states that "Zeolitization of volcanic glass should also evolve heat."

Consequently, authigenic reactions, which might take place within the disturbed zone as a consequence of repository heating, may also be influenced by the heat-of-reaction produced during diagenetic hydration and this heat evolved may be outside as well as inside the defined disturbed zone boundary.

If this is a factor to be considered, then the temperature distribution envelope for a proposed repository must not only take into account the repository heating, but also, heat evolved due to authigenic reactions which may be beyond the near-field. The heat of reaction temperatures as postulated by Surdam and Boles (1977) are almost as significant as the repository heating itself if those reactions proceed in a demonstrably rapid fashion.

4.4 Volcanic Glass Hydration:

a. Friedman, *et al.*, (1966) have determined the rate of obsidian (rhyolitic glass) hydration in terrigenous environments exposed to humidity and ground water. Rates determined are not intrinsic and are based upon Fick's Law of Diffusion with experimental evidence derived at 100° C. During the diagenetic transformation of obsidian to perlite (hydrated glass) the rates are approximately five times faster at 100° C than at 70° C, and about one order of magnitude faster at 70° C than at 30° C. Consequently, the hydration rate has been shown to be temperature dependent. Perlite further hydrates to transition metal oxyhydroxides, zeolites, and smectites. The rates of formation of this phase of authigenics is unknown. Other significant controlling parameters relating to the hydration of glass are the alkalinity of both the glass and surrounding fluids, bonding chemistry of the glass, initial water (HOH and OH) composition of the glass, among other parameters (which are less significant). Although it has been shown that diffusivities of glass are related to its viscosity which is a function of the original state of polymerization of the melt (Scholze, 1966; Stolper, 1982) it has also been documented that hydration rates are dependent upon the activity of dissolved alkali metals in the environment. Consequently, glass hydration becomes an effective and rapid mass transition process during elevated temperatures in the presence of high concentrations of dissolved alkali metals.

Hydration proceeds along any exposed glass surfaces, causing increases in volume. Many of the glasses respond to volume increases by tensile fracturing, geometrically providing additional surfaces for hydration. The resultant configuration of the alteration mass is a reticulate pattern of interconnected fractures with expandable and exchangeable authigenic mineral fracture coatings and fillings. Glass vesicles previously segregated from the exposed environment are either filled with authigenic minerals or are associated with fracture surfaces. The permeability is significantly increased even when total porosity changes are negligible due to the relatively small effective porosity of the fractures.

At Yucca Mountain, a vitrophyre is present between 45 and 113 meters below the repository horizon and partly within the 50 meter minimum disturbed zone. Temperature elevation above geothermal-ambience in the presence of high humidity will provide adequate conditions to promote glass hydration. Under these conditions "significant amounts of water" might be construed as 80-100% humidity (not necessarily a situation of liquid saturation).

b. The diffusion mechanism of water entering glass and other solids is poorly understood in fractured media. Although, diffusion appears to follow Fick's Law, when single surfaces are present, it appears that it is anomalous in behavior in fractured media (Anacker and Kopelman, 1984). Consequently, rates of diffusion require empirical observations especially when these reactions may affect obtaining accurate disturbed zone boundaries.

4.5 Temperature Distribution at the Vitrophyre:

In accordance with Figure 1 (Braithwaite and Nimick, 1984, figure 2), on which we have superimposed the vitrophyre (from information presented in the EA, DOE/RW-0073) the following temperature distribution for a 57 kW/acre spent fuel loading is anticipated:

Location	250 years	1,000 years	10,000 years
Top of Vitrophyre	67° C	83° C	70° C
Btm. of Vitrophyre	54° C	78° C	67° C

The depth of the Braithwaite and Nimick (1984) repository is 390 m below surface, which is possibly some 70 m deeper than indicated as an average in the EA. Consequently, temperatures shown are possibly a bit higher than they should be for the "average" repository horizon.

4.6 Summary of Concern:

The anticipated temperature distribution over time for a 57 kW/acre loading raises the temperature for the vitrophyre from the ambient 25° C to 83° C in 1,000 years of exposure, an increase of 58° C. This should, on the basis of heat conduction alone, raise the reaction rate of the vitrophyre glass about 25 fold (from about 8 microns squared to 200 microns squared per thousand years for exposed surfaces). If the hydration reaction is seeded by the repository temperature, then it is feasible for the hydration reaction itself to release heat thereby further raising the temperatures in the vitrophyre and surrounding zeolite zones.

We expect that on the basis of repository heating alone, there should be sufficient reactivity to cause significant permeability increases within the vitrophyre. This is especialy true when considering only a few fracture flow paths would be required to provide a "most likely pathway" for transit between the repository horizon and the water table. "Most likely" in this sense is defined in a similar manner as Browning (1985) has done.

Of further concern are the elevated temperature effects upon smectites and clinoptilolite with respect to dehydrating these authigenic mineral components and providing sodium-enriched waters to the system. This condition could be responsible for:

1. Elevating the rate of glass hydration.

2. Reducing the effective-temperature for clinoptilolite stability.

3. Thereby providing additional pore and fracture fluids for reactions.

Knauss, et al., (1985, Tables 1 and 2) show a significant increase in dissolved alkali metals in water reacted with crushed tuff during a short term experiment (an increase of sodium of about 25% at 90° C in less than 80 days). At this temperature, which is about 7° C higher than the calculated maximum vitrophyre temperature at 1,000 years (fig. 1) what would the increase be for sodium in 250 to 1,000 years? And how might this contribute towards driving various reactions whose ultimate result would be a significant increase in permeability?

In addition to the dissolved alkali metals, Knauss, et al. (1985) show a decrease in pH which would aid in promoting dissolution of glass and other silicate minerals.

5.0 SILICA DISSOLUTION (Appendix B):

It is stated in the DGTP (Appendix B, page 15, paragraph 2) that generic calculations presented in Appendix B indicate that silica dissolution and resultant porosity increase are not expected to be significant beyond the mechanically "disturbed zone." It is also recognized that the distance to the edge of the thermochemically "disturbed zone" is strongly dependent on the thermal loading of the repository and the ground-water flux in the host rock. The following paragraphs offer specific comments on the treatment of silica dissolution in the thermochemically "disturbed zone" presented in Appendix B of the DGTP.

5.1 Heat Transfer Model:

Codell's analysis of silica dissolution is intended to address 'typical to conservative' conditions expected near HLW repositories. However, the assumption that convective heat transfer by flowing ground water is negligible (DGTP, 1986, page B2) is certainly not conservative in our opinion, and the basis for this assumption is contained in an unpublished memorandum. The statement that effects of phase changes are expected to be negligible (DGTP, page B2) should be supported by mineralogical data.

Two errors in the thermal data are noted: on page B3 the units for heat capacity of rock, Cp, which should be $J/(m^3 {}^oC)$ are incorrectly given as $J(m^3 {}^oC)$. On page B8, the geothermal gradient, which is on the order of 20^o C to 30^o C per 1,000 m (Turcotte and Schubert, 1982), is incorrectly given as "on the order of" 5^o C per 1,000 m and neglected on this basis.

5.2 Transport Model:

The transport model is unconvincing, because of: the choice of a conceptual model based on total silica in the rock rather than a surface area to fluid mass ratio; the exclusion of convective heat transport, although convective solute transport is treated explictly; the exclusion of geothermal gradient from the analysis: and the exclusion of kinetic effects. The rate of silica dissolution is fast on a geologic time scale, but should be considered on the time scale (1,000 years) of the heating of a repository and vicinity. An important aspect that effects silica kinetics is the solid-surface area to fluid mass ratio. Higher surface areas to fluid mass ratio yield faster dissolution rates, and therefore, a quicker approach to equilibrium. This ratio varies widely for different porosity models.

Dissolution rates of silica are also affected by flow velocity. Faster moving water has less time to equilibrate with rock and less material is dissolved. Thus, marked differences in dissolution rates of silica would be expected between matrix flow and fracture flow, if fracture flow velocities are relatively high.

The inclusion of kinetic effects will result in a smaller amount of silica dissolution than the equilibrium model. However, the distribution of the dissolution sites may be somewhat different. Codell's model indicates "that silica dissolution is greatest where the temperature gradient is steepest." (Codell, 1986, page B9). Areas of the repository with the steepest temperature gradients are likely to have the shortest residence time for aqueous fluids and thus little resulting dissolution. The maximum amount of dissolution may ensue when the thermal envelope around the repository is fully developed and the fluid has the longest residence time to approach equilibrium with the rock. This could be in a halo of saturated fractures beyond the zone of vaporization of water. Dissolution will then be maximized in the hottest areas.

In summary, other porosity models need to be considered, and kinetic affects of silica dissolution need to be considered if flow rates are expected to be significant.

A sign error is present in Table B2; the b-coefficient for quartz should be -2.028×10^{-3} (Rimstidt and Barnes, 1980).

6.0 SUMMARY:

The disturbed zone as defined by NRC is that zone which responds to repository thermal and construction activities by producing substantial (significant) changes in intrinsic permeability and effective porosity. The terms "substantial" and "significant" require clarification as they are subjective.

The DGTP has stated the NRC objective:

> "...establishment of generic and easily evaluated guidance on the disturbed zone is desirable in order to allow for the demonstration of compliance with the groundwater travel time criterion (10CFR60.113(a)(2)) consistent with NRC's intent in the criterion..." (Gordon, et al., page 16).

In our opinion, before site characterization, highly complex sites such as Yucca Mountain do not yield to confident determination of the disturbed zone boundary as attested to by our preceeding discussions of possible distribution of thermochemical and physical effects. Closely associated with these discussed effects are the fluid phase changes and heat and moisture redistributions, which are more complex than bouyancy effects. These interrelated complexities are reasonable to anticipate considering the strength of the HLW heat source and the associated disruption of the ambient thermal regime. There are at least three alternative approaches in dealing with the determination of the disturbed zone:

1. NRC could stand by the original definition of the disturbed zone.

2. NRC could proceed with the proposed draft generic technical position.

3. NRC could restrict the boundary of the disturbed zone to arbitrary but stated distances.

The ramifications of these alternatives briefly are as follows when viewed from the Yucca Mountain Site perspective:

1. The original NRC definition precludes confident pre-site characterization determination of the disturbed zone and therefore travel time.

2. The proposed draft generic position appears to also preclude confident pre-site-characterization determination of the "disturbed zone" boundary and therefore travel time.

3. The arbitrary distance boundary approach allows for pre-site characterization travel <u>distances</u> to be established. However, the intent of confident determination of the travel-time objective may not be realized due to the other uncertainties with respect to fracture and matrix flow conditions prior to in-depth site characterization.

In our opinion, the Yucca Mountain site provides a useful test of the NRC generic position on the disturbed zone. After careful consideration of site-specific conditions, we have come to the conclusion that the DGTP does not simplify the determination of an inner boundary from which travel-time calculations begin. The complexity of the site and the general absence of experience and data in such fractured rock environments in the vadose zone combine to greatly reduce the general level of confidence in "modeled" conditions. Such are presently based on sparse field data and limited knowledge of physical and chemical processes.

We have also noted that, should the disturbed zone boundary be established through an arbitrary distance criterion, site complexities and processes uncertainties still do not lend themselves to confident travel-time determinations. In summary, we think that considerably better site characterization results than currently exist will be necessary before a confident pre-waste-emplacement travel-time estimate can be realized.

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Appendix D-IV

Draft technical position on determination of dissolution reactions and kinetics for the proposed Yucca Mountain high-level nuclear waste repository.

Progress report on a technical position on the disturbed zone.

Draft technical position on the determination of the disturbed zone at Yucca Mountain proposed high-level nuclear waste repository.

Draft Technical Position on Determination of Dissolution Reactions and Kinetics for the Proposed Yucca Mountain High-Level Nuclear Waste Repository.

1.0 Purpose:

This document presents site-specific objectives and approaches for determining the extent of dissolution reactions and kinetic effects in welded and nonwelded tuffs of and adjacent to the repository horizon of Yucca Mountain in support of licensing requirements.

2.0 Regulatory Framework:

The Nuclear Waste Policy Act of 1982 (NWPA, 1983, Public Law 97-425) requires the Department of Energy (DOE) to establish guidelines for the recommendation of sites for nuclear waste repositories (high-level waste and spent fuel) in geologic formations, select sites, perform site-characterization studies, construct and operate approved repositories for the disposal of nuclear waste, and close and decommission such repositories. The Environmental Protection Agency (EPA) has the responsibility for developing standards for offsite release limits of radionuclides to the environment. The Nuclear Regulatory Commission (NRC) is responsible for establishing technical procedures and criteria that will apply in approving or disapproving applications for licenses and authorizations for construction of high-level nuclear waste repositories and for closure and decommissioning of such repositories.

Under the multiple barrier concept for isolation of high-level nuclear waste in a permanently closed repository, the geologic setting of Yucca Mountain, as well as the engineered barrier system and the shafts, boreholes, and their seals, should have the capacity to retard the transport of long-term and short-lived radionuclides, and thus assure that releases of radioactive material to the accessible environment conform to established EPA standards (NRC: 10 CFR60.112 - Overall system performance objective for the geologic repository after permanent closure).

The postclosure technical guidelines for dissolution (section 960.4-2-6) consist of one qualifying condition, one favorable condition, one potentially adverse condition, and one disqualifying condition.

Section 960.4-2-6 Dissolution.

(a) Qualifying condition. The site shall be located such that any subsurface rock dissolution will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in section 960.4-1. In predicting the likelihood of dissolution within the geologic setting at a site, the DOE will consider the evidence of dissolution within that setting during the Quaternary Period, including the locations and characteristics of dissolution fronts or other dissolution features, if identified.

(b) Favorable Condition. No evidence that the host rock within the site was subject to significant dissolution during the Quaternary Period.

(c) Potentially Adverse Condition. Evidence of dissolution within the geologic setting--such as breccia pipes, dissolution cavities, significant volumetric reduction of the host rock or surrounding strata, or any structural collapse-- such that a hydraulic interconnection leading to a loss of waste isolation could occur.

(d) Disqualifying Condition. The site shall be disqualified if it is likely that, during the first 10,000 years after closure, active dissolution, as predicted on the basis of the geologic record, would result in a loss of waste isolation."

Section 960.4-1 referred to above is the qualifying condition for the system guideline:

<u>Section 960.4-1</u> System Guideline.

(a) Qualifying Condition. The geologic setting at the site shall allow for the physical separation of radioactive waste from the accessible environment after closure in accordance with the requirements of 40CFR Part 191, Subpart B, implemented by the provisions of 10CFR Part 60. The geologic setting at the site will allow for the use of engineered barriers to ensure compliance with the requirements of 40CFR Part 191 and 10CFR Part 60..."

Section 121 of NWPA directs the EPA to "promulgate generally applicable standards for the protection of the general environment from offsite releases from radioactive materials in repositories" and the EPA has published high-level radioactive wastes standards (50CFR38066). Section 121 further specifies that the NRC regulations "shall not be inconsistent with any comparable standards promulgated by [EPA]." Published NRC rules which established procedures and technical criteria for disposal of high-level radioactive waste in a geologic repository by DOE are 10CFR Part 60, 46FR 13980, and 48FR 28204.

The applicable section of the proposed EPA rules (40CFR Part 191, Subpart B - Environmental Standards for Disposal), Section 13, sets forth containment requirements. It specifies that disposal systems for high-level and transuranic wastes shall be designed to provide reasonable expectation that 10,000 years after disposal: (a) "reasonably forseeable releases of the waste to the accessible environment are projected to be less than quantities calculated according to Table 1 (Appendix A)"[Table 1: Release Limits for Containment Requirements; units: curies/1,000 MTHM for various radionuclides]; (b) "very likely release of waste to the accessible environment are projected to be less than 10 times the quantities calculated according to Table 1." Applicable definitions are: Accessible environment: includes the atmosphere, land surfaces, surface water, oceans, and parts of the lithosphere that are more than 10 km in any direction from the original location of radioactive waste in the disposal system (NRC has proposed reducing distance to 5 km); reasonably foreseeable releases: releases of radioactive waste to the accessible environment that are estimated to have more than one chance in 100 of occurring within 10,000 years; very unlikely releases: releases of radioactive waste to the accessible environment that are estimated to have between one chance in 100 and one chance in 10,000 of occurring within 10,000 years; disposal: isolation of radioactive waste with no intention of recovery; and disposal system: any combination of engineered and natural barriers that contain radioactive waste after disposal.

3.0 Dissolution Issue:

The Yucca Mountain site has been recommended as one of three sites for characterization in accordance with the Nuclear Waste Policy Act of 1982 (NWPA, 1983) and the Environmental Assessment utilizing the DOE siting guidelines (10CFR Part 960) was the basis for that nomination.

The DOE objective for evaluating dissolution is to ensure that dissolution processes will not adversely affect the nuclear waste isolation capabilities of the Yucca Mountain site. The primary concern is that dissolution of the host rock will compromise the waste isolation capabilities of the site by creating new pathways for radionuclide migration to the accessible environment. However, the evaluation of dissolution processes is based on the evidence of dissolution in the geologic setting of the Yucca Mountain site during the Quaternary Period. The DOE considers the question of dissolution to be of no concern at Yucca Mountain because: (1) no evidence of dissolution (breccia pipes or solution cavities) have been found to date, and (2) rock types present are "considered insoluble."

The manner in which the dissolution guidelines are phrased render them more appropriate for preclosure repository considerations than postclosure. Postclosure dissolution guidelines must consider the effects of repository emplacement on potential dissolution processes. Therefore, the issue of dissolution has been inadequately treated in the Environmental Assessment of Yucca Mountain by DOE due to:

1. uncertainty in the enhancement of existing pathways for radionuclide transport to the accessible environment by dissolution versus the creation of new pathways;

2. the uncertainty of utilizing the geologic past as a basis for evaluating a perturbation to the environment, namely the emplacement of a nuclear waste repository, that apparently has not occurred at any time in the geologic past, including the Quaternary Period;

3. the extremely simplistic and incorrect notion of considering silicate rocks, volcanic glass, and minerals insoluble;

4. a poor understanding of the metastability of volcanic glasses and authigenic minerals;

5. a poor understanding of the kinetics of dissolution of volcanic glass and associated minerals;

6. the uncertainty of future physical and geochemical conditions at the site due to emplacement of nuclear waste; and

7. the uncertainty of applying equilibrium (isothermal) relationships to processes (dissolution reactions and kinetics) that are more likely irreversible (nonequilibrium).

These uncertainties have been ignored in the site- selection process and form a series of basic concerns with respect to licensing issues. These issues are now best addressed during the site-characterization process.

4.0 Statement of Position:

It is the position of the State of Nevada that evaluation of dissolution must be based on a combination of laboratory experiments, in situ field observations, and theoretical modeling which establish the present extent of dissolution and possible range of future dissolution for a given loading of nuclear waste in the repository. Equilibrium and kinetic constants for dissolution reactions, as well as the extent of nonequilibrium processes, can be obtained during site characterization through a site-characterization program strategy which:

1. Characterizes vadose-zone hydrology including climatically induced changes, specifically fluid flux rates in fractures (lateral and depth extent of interconnectivity, aperture width, roughness, and filling mineral distribution) versus matrix;

2. Characterizes vadose-zone hydrogeochemistry: pH, Eh, concentrations of dissolved cations, anions, including organics, colloids, and particulates; and depth variation;

3. Characterizes the chemistries and physicochemical stabilities of the solid phases: volcanic glass, authigenic minerals, and mineral products of devitrification;

as a function of temperature, aqueous fluid pressure, aqueous fluid composition (including organics), pH, and Eh;

4. Characterizes the stabilities of artificial materials (shot-crete, stainless steel, soft steel of roof bolts and meshing, and epoxies used to coat and cement roof bolts, etc.) with respect to the thermal and geochemical regimes expected during the first 10,000 years of repository existence;

5. Characterizes the kinetics of volcanic glass dissolution/hydration/dehydration reactions and dissolution of authigenic minerals, such as clays and zeolites;

6. Characterizes the equilibrium (isothermal) dissolution of natural mineral and artificial phases separately and as a system for the expected variations in temperature, and fluid compositions represented by the range (yet to be determined) of vadose-zone hydrogeochemical analyses to condensed steam under: (a) closed system conditions (static, no flow), and (b) open system conditions with flow rates representative of convective fluid flow rates after repository emplacement;

7. Evaluates uncertainties in thermodynamic data used in equilibrium geochemical modeling of dissolution reactions to obtain conservative estimates of the effects of such processes;

8. Characterizes rocks and minerals for microscopic dissolution features and textures (although large-scale dissolution structures, such as breccia pipes and solution cavities, have not been found to date, megascopic features should be preceded by microscopic dissolution textures);

9. Determines the extent of nonequilibrium (polythermal) dissolution and the rates of reaction of natural minerals present at Yucca Mountain and artificial materials separately and in combination as a system in

experiments scaled to "expected" temperature gradients due to repository emplacement for: (a) closed system (no flow) and (b) open system conditions for representative convective fluid flow rates;

10. Characterizes the post-emplacement concentration gradient of aqueous species in vadose-zone fluids for expected temperature gradients imposed by nuclear waste heating;

11. Determines the importance of thermodiffusion versus convective fluid flow at various stages in the thermal evolution of the repository (Soret coefficients must be known for aqueous species in order to evaluate thermodiffusion);

12. Characterizes effective matrix porosity and permeability changes of volcanic rocks due to equilibrium and nonequilibrium processes;

13. Characterizes effective fracture permeability and transmissivity changes due to equilibrium and nonequilibrium processes affecting volcanic glass, mineral products of devitrification, and authigenic fracture-coating minerals; and

14. Characterizes heat and mass transfer (dissolution/precipitation reactions) expected by convective circulation of aqueous vapor and liquid resulting from nuclear waste emplacement;

Achievement of these objectives may allow bounding estimates to be placed on the extent of dissolution resulting from repository emplacement and its effects on overall repository performance release limits of radionuclides to the accessible environment.

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PROGRESS REPORT ON A TECHNICAL POSITION ON THE DISTURBED ZONE

Background

The potential importance of the hydrothermal effects in the vadose zone of Yucca Mountain due to waste-generated temperatures which exceed the boiling temperature of water is generally unrecognized.* Our analysis indicates marked increases in both vapor and liquid-phase flow should be expected due to the strong thermal envelope generated by the waste. In the fractured-rock environment, the complexity of heat and mass-transfer processes and associated solution-mineral reactions will be greatly increased by the multiphase liquid and vapor-flow environment.

The DOE definition of the disturbed zone to date continues to ignore the presence and importance of multiphase fluid transport. Their current definition is not as defined and intended in 10 CFR 60.2 (46FR35280, 35281, July 8, 1981). Instead of a mechanically disturbed zone of the current DOE definition (measured as extending several meters from the repository horizon) hydrothermal effects may extend many tens of meters downward towards the water table and upward towards the land surface.

The disturbed zone continues to be one important focus of review activities. We find that the zone of difficult-to-understand (and characterize) processes (46FR35280, 35281, July 8, 1981) has been equated conceptually, in a draft technical position by the NRC, to the zone of intrinsic property changes (Gordon, et al., 1986). The central concept of a zone of intrinsic property changes also appears in most, if not all, DOE-sponsored literature that requires a disturbed-zone definition (Langkopf, 1987 and DOE, 1988, Section 8.3.5.12.5, for example). However, even if there were no intrinsic property changes, heat-driven changes in the hydrologic system at Yucca Mountain can reasonably be expected to be profound (and extraordinarily complex from a modeling perspective). The argument that fluid-buoyancy effects can be modeled with "well developed assessment methods" (Gordon, 1986, p. 6) is not applicable to poorly-characterized, subvertical-fracture networks where countercurrent flows of water vapor and liquid water may occur in a partially-saturated environment. These hydrothermal processes can be reasonably expected to occur within 100 years of the beginning of repository loading based on simple calculations using DOE's physical-property values.

Basic Data

Ranges and preferred values for hydrogeologic parameters at Yucca Mountain are summarized by Langkopf (1987, Appendix D). The following data are pertinent to our discussion:

1. Mean and standard deviation of the saturation data for the Topopah Spring welded unit: 65%, 1s = 19%
2. Porosity of Topopah Spring matrix: 0.11
3. Residual saturation of Topopah Spring matrix: 0.08
4. Porosity of Topopah Spring fractures: 18 x 10-5 , derived from (1) apertures reported by

* Langkopf (1987) refers to unpublished modeling studies by J. Gauthier and R. R. Peters communicated to Langkopf in a 1986 internal memorandum (SANDIA). In the modeling study, water redistribution was considered from the repository midline to below the repository . Their reported findings support our scenario of total water expulsion in 100 years as vapor. However, their model assumes the matrix would sorb the displaced moisture.

Peters, et al. (1984) and (2) the assumption that 40 fractures/m^3 reported by Scott, et al. (1983) are all vertical.

5. Residual saturation of Topopah Spring fractures: 0.0395

The fracture porosity in the rock mass above and below the repository horizon is a very important parameter, yet very uncertain. Fracture porosity is the receiving volume into which water vapor, mobilized during repository heating, will be driven into and condensed. Two approaches have been used to calculate fracture porosity. Sinnock, et al. (1984) used bulk-saturated hydraulic-conductivity values from wells J-13 (Thordarson, 1983) and H-1 (Barr, 1984) to obtain effective hydraulic aperture via the cubic law. Peters, et al. (1984) measured the permeability of a planar fracture in a single piece of core (sample G4-2F) from the Topopah Spring welded unit, and used the cubic law to obtain an estimate of its effective hydraulic aperture. Both groups of authors use a fracture density of 40 fractures per cubic meter in the Topopah Spring welded unit (Scott, et al., 1983) to calculate effective porosity as the product of fracture density and aperture. The field-scale approach yields order-of-magnitude larger estimates of fracture porosity, but both methods suffer from a limited understanding of actual aperture geometry and the degree to which adjoining fracture surfaces are in contact.

Multiplying the porosity of the Topopah Spring welded unit matrix (0.11) by its mean saturation (65%), we obtain 0.0715; seven percent (by volume) of the rockmass is water. Langkopf (1987, p. 68) indicates that, with an initial areal power density (APD) of 57 kw/acre, the 100°C isotherm will reach its maximum extent 10 m below the centerline of the waste package 90 years after waste emplacement. Actually, water will boil at 95°C under the ambient atmospheric pressure of 85 kPa at the repository horizon (Weeks, 1987), so the zone of vaporization will extend beyond 10 m from the centerline. Therefore, the zone of vaporization can be conservatively estimated to be 20 meters (65.6 ft) thick.

The CD-SCP (DOE, 1988, p. 6-227) indicates some uncertainty as to the area available and the area needed for the proposed repository at Yucca Mountain. We have selected an area of 2,000 acres for our calculations. A simple volume calculation yields a conservative estimate of the volume of liquid water within the 95°C isotherm during the first 100 years of repository operation:

$$2{,}000 \text{ Acres} \times 65.6 \text{ Ft.} \times 0.0715 = 9{,}381 \text{ Acre-Feet}$$

Possible Worst Case Scenario

The matrix water will entirely vaporize within the 95°C thermal envelope and, as water vapor, migrate away from the 95°C isotherm along the most permeable fracture networks. Most, if not all, of the 9,000 plus acre-feet of matrix water will condense on the walls of the cooler fractures beyond the 95°C isotherm. This condensation could continue until any given fracture is saturated. Perhaps roughly one-half of the vapor would condense to free water above the repository thermal envelope, assuming that fracture permeability is approximately equal above and below the repository thermal envelope. Gravity drainage of condensate in the regions both above and below the repository would occur in the fracture networks on a very large scale. Some condensate trapped above the 95°C thermal envelope could be recycled from vapor to liquid phases many times before draining through the repository horizon. The hot repository zone would likely be continuously penetrated by some returning condensate flow along highly permeable fractures which, in turn, might establish steam explosions and increasingly corrosive fluids in the envelope of hot rock surrounding the repository. An extensive envelope of fracture (and perhaps matrix) saturation totally surrounding the repository horizon seems likely. Recharge flux would also accumulate in the upper zone of saturation as long as the 95°C isotherm existed (assuming that porosity exists to accept the accumulating recharge flux). Upon cooling of the thermal envelope to below 95°C, the repository horizon would eventually be effectively penetrated by the saturation front, and additional fracture flow from the repository horizon to the underlying units would occur.

Significance of Worst-Case Scenario

Licensing criteria would not be met with the above scenario. The disturbed zone could extend upward to near the land surface, which is by definition the accessible environment, and down to the water table. Pre-emplacement ground-water travel time in the saturated zone would be less than the required 1,000 year if the edge of the disturbed zone is at the water table. All travel-time estimates established in the saturated zone are substantially less than 1,000 years.

The presence of extensive fracture saturation above and below the repository from condensing water vapor insures fracture flow and associated rapid travel times to the saturated zone. The invasion of the repository horizon by fracture-flow water during a cool down to below 95°C suggests canister contact with water early in the history of required repository performance. The main attraction of the vadose zone in an arid environment is its presumed dry nature -- the absence of moisture for fracture flow is the postulated waste-isolation attribute. If the thermal envelope changes the environment to one of widespread fracture flow, the postulated waste-isolation attribute of the hydrogeologic environment at Yucca Mountain is lost.

There remains important uncertainties associated with establishing a confident analysis of disturbed-zone behavior. In the preceding scenario, fracture porosity and permeability are key physical properties that are poorly known. In addition, the rate of vapor production/migration in the thermal envelope is uncertain. Configuration of the thermal 95°C envelope, mineral solution, and mineral dissolution rates are also uncertain. Laboratory experiments in conjunction with a much stronger field database would permit a more confident analysis of the extents and rates of development of the hydrothermal effects of the repository.

Progress Summary

Based on a high probability of strong hydrothermal (heat-pipe) effects occurring as the waste heats the surrounding rock matrix to boiling temperature, including a zone of vaporization and upper and lower zones of condensation that could extend upward to land surface and downward to the zone of saturation, we believe that the DOE and NRC have failed to recognize the probable ramifications of the disturbed zone at the Yucca Mountain site. Physical and chemical changes within the zones of vaporization and condensation will be difficult to characterize and accurately predict extents, durations, as well as their effects on intrinsic properties. There is no valid or rational basis for restricting the disturbed-zone definition to some region of intrinsic property changes in the vadose zone.

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Draft Technical Position on the Determination of the Disturbed Zone at Yucca Mountain Proposed High-Level Nuclear Waste Repository.

1.0 Purpose:

The technical position of the State of Nevada on the determination of the disturbed zone boundary is presented as an element of site selection and with the cognizance that licensing issues are dependent upon appropriate site-selection procedures. This document interprets and identifies the "disturbed zone" as it applies to Yucca Mountain and NRC regulations (10CFR Part 60).

2.0 Regulatory Framework:

The Nuclear Waste Policy Act of 1982 (Public Law 97-425) confers responsibility to EPA for developing applicable standards for protection of the environment from off site releases of radionuclides (Section 121): to the NRC for issuing technical requirements and criteria that will apply in approving or disapproving applications for licenses and authorization to construct high-level radioactive waste repositories (Section 121), and for closure and decommissioning of such repositories; and to the DOE for issuing general guidelines for site selection and site characterization, and for construction and operation of the waste disposal facility in accordance with NRC regulations (Section 121).

The NRC has established performance objectives for high-level radioactive waste repositories including performance criteria for both the geologic and engineered barrier systems (10CFR Part 60, Subpart E-Technical Criteria). Within this section, the travel time criteria is stated:

> "The geologic repository shall be located so that the pre-waste-emplacement groundwater travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment shall be at least 1000 years or such other travel time as may be approved or specified by the Commission." (10CFR60.113(a)(2)).

The "disturbed zone" cited in (10CFR Part 60.113(a)(2)) within the travel time criterion has been defined as:

> "That portion of the controlled area the physical or chemical properties of which have changed as a result of underground facility construction or as a result of heat generated by the emplaced radioactive waste such that the resultant change of properties may have a significant effect on the performance of the geologic repository." (10CFR Part 60.2).

Chu, et al. (1983) have suggested that the "disturbed zone" definition requires additional clarification by NRC; and Gordon, et al (NRC) have developed the Draft Generic Technical Position (DGTP) for the Disturbed Zone (1986). Based on extensive comments received by NRC, a revised NRC Generic Technical Position on the Disturbed Zone is anticipated.

3.0 Disturbed Zone Issue:

The disturbed zone, as defined by NRC (10CFR Part 60) is a concept intended to establish a definition of the inner boundary from which ground-water travel times from High-Level Nuclear Waste (HLW) Repositories to the accessible environment are determined.

Credit towards the 1,000 year pre-waste-emplacement travel time objective is not considered within the "disturbed zone" because of the potential difficulty in assessing the physical and chemical processes contributing towards waste isolation within that region. NRC (Gordon, et al., 1986) state that site-specific analyses for determination of the extent of the "disturbed zone" should account for: anomalous geologic situations; effects of the heterogeneous geologic system; the magnitude of the likely ground-water flux (implying vadose and saturated zone flux); the magnitude of areal thermal loading of the repository; geochemical and hydrogeochemical characteristics of the site; and changes in the configuration of the facility through time. (DGTP, page 17).

However, Gordon, et al. (1986) clearly exclude the thermal effects of bouyancy on fluids as part of the definition of the disturbed zone by stating that this will be treated during assessment of compliance with the overall system performance (10CFR Part 60.112). We assume that this exception also includes phase changes in fluids, and we anticipate these to be of significant impact in the Yucca Mountain vadose environment. Therefore, the State of Nevada's position on the "disturbed zone" explicitly addresses phase changes in fluids and associated moisture redistribution as the result of the fluid-phase changes.

4.0 Statement of Position:

It is the position of the State of Nevada that the existing NRC definition of the disturbed zone is appropriate:

> "That portion of the controlled area the physical or chemical properties of which have changed as a result of underground facility construction or as a result

of heat generated by the emplaced radioactive waste such that the resultant change of properties may have a significant effect on the performance of the geologic repository." (10CFR60.2).

Following the above NRC regulation, the "disturbed zone" boundary within the vadose zone of Yucca Mountain may be considered to be:

1) Defined by the maximum extent of thermally-induced fluid (gas and liquid) migrations; and

2) Defined by that part of the thermal envelope within which, changes in the:

a) Abundant* mineral and/or volcanic glass dehydration or hydration states are 10% or greater than the intrinsic values (as non-structural water - determined as water of hydration evolved from ambient temperature to 100°C, inclusive; and

b) Mineral and/or volcanic glass volume changes exceed the yield point of any mineral, glass or whole rock so that tensile failure occurs and results in an increase in intrinsic permeability, effective porosity, and/or a loss of structural strength.

The maximum extent of fluid migration is determined as a function of the maximum extent of 100°C isotherm during the first 1,000 years after waste emplacement, effective fracture porosity within the host rock, total quantity of vadose water (including evolved mineral water) and accumula-

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* Abundant indicates greater than 5 percent for clays and greater than 10 percent for zeolites and volcanic glass.

ted recharge flux. Thermal effects due to hydration reactions should be added to that heat generated by the radioactive waste.

The disturbed zone calculations require laboratory <u>and</u> <u>in situ</u> data acquisition. They will <u>not</u> be considered valid if solely derived from theoretical model studies unsupported or inadequately supported by site-specific data, including fracture network conductivity and effective porosity, fracture and rock matrix water contents, recharge flux, and distribution and concentrations of minerals and volcanic glass which may be hydrated or dehydrated.

5.0 Discussion:

The concept of the disturbed zone was proposed by NRC (10CFR Part 60) as a volume boundary which constitutes the division of highly disturbed host rock due to waste emplacement that is difficult to characterize from host rock which approaches geothermally ambient temperatures and contains metastable and stable mineral and volcanic glass assemblages whose behavior may be modeled or predicted with reasonable confidence. The determination of the location of the disturbed zone boundary is imperative to the proper calculation of travel times, since travel-time calculations commence at the disturbed zone boundary and continue through to the edge of the accessible environment.

The imposition of the proposed repository at Yucca Mountain upon a regional geothermal gradient in the tuffaceous rock mass superposes a thermal regime and radionuclide inventory which abruptly modifies the natural environmental setting. To date, the boundary between the disturbed zone and the apparently less affected and easier to characterize environment has been determined by arbitrary definitions promulgated by changes in intrinsic porosity and permeability, suppositions of mineral stability, such as for clinoptilolite, and technological achievements for approximating kinetic and thermodynamic data into idealized and generic models in addition to the 50 m zone of physically disturbed rock caused by mining.

The DOE has viewed the Yucca Mountain mineral associations as being non-reactive quasi-stable phases under the time and temperatures anticipated during the repository life. These information are treated as conservative estimates: yet, due to limitations in laboratory techniques, thermodynamic variables assumed to control mineral equilibria are limited in their ability to predict the real world (in situ) reactions. Gibb's free energy values, as are used in geochemical models for pure mineral end-members, do not normally have the precision or accuracy required to determine mineral association stabilities in the natural environment. Furthermore, to facilitate modeling, only the end-members of minerals that typically form solid-solution series in nature are considered (such as feldspar, clays, and zeolites). This simplification is thus only an approximation of reality. Consequently, the underlying context for creating the concept of the disturbed zone is valid, however, it is problematic due to the inability to treat its boundary on a site-specific, activity-stability basis.

The thermal envelope produced by the repository is dynamic in its geometric configuration, because heating and cooling events are produced by the thermal load decay rates. Since there is apparent debate on the density and size of the canister load, little of significance has been offered with respect to a precise thermal envelope for the Yucca Mountain site and consequently, peak loading temperatures of the host rock are yet to be reported as a function of both convection and conduction. It seems inappropriate then, to establish a generic distance from the repository center line to the edge of the disturbed zone (50 meters) as a minimum distance requirement. Likewise, it seems premature to establish fixed temperature requirements for the determination of the "disturbed zone" boundary.

There are no radionuclide waste repositories which can offer analog environments for comparison. A presumably reasonable natural analog to the proposed repository system is the hydrothermal alteration of an environment where most of the chemical components can be treated as mobile and reactive variables. In these natural systems, phyllosilicates, aluminosilicates, and tectosilicates tend to be zoned in monomineralogic bands concentric to the zone of hydrothermal fluid introduction. These, attest to systems with very few immobile variables. In the hydrothermal systems, rapidly circulating fluids (as per fracture flow) often increase the temperature locally in prominent paths of fluid transport. Steiner (1968) has observed for Wairakei, New Zealand, that in alteration zones juxtaposed to fissures, a new mineral assemblage is produced adjacent to the pathways of circulating fluids; however, the mineral phases of the general rock series tend to conform to the general trend which is dependent upon the geothermal gradient of the system. In this natural system, a disturbed zone boundary has a strong geometric dependence on fluid phase paths of transport, thermal convection and conduction, and whole-rock petrology (such as mineral associations, grain boundaries, and pore and fracture densities). Although there may be differences in the peak temperatures of hydrothermal analogs and the Yucca Mountain proposed repository, dynamic fluids may produce striking similarities in the dynamic-fractal-thermal envelopes developed in both situations. Thus, a zonation of mineral assemblages is expected for Yucca Mountain as represented by intensive variables of temperature and pressure, and extensive variables such as the mass of fluid, abundances of aqueous solutes, minerals, and glasses. In this context, the most important pathways extending from the repository toward the accessible environments represent, in part or in whole, the fluid migration perturbations surrounding the more general thermal envelope and hence, the disturbed zone boundary as a consequence of fluid movement. In the Topopah Spring Member of the Paintbrush Tuff, near-field reactions should be similar to reactions expected at the zones of fluid perturbation.

Zones of fluid (gas and liquid phases) transport (most likely by fractures) are uniquely complex in their potential behavior due to:

1. Elevated temperatures above geothermal ambience resulting in faster reaction rates;

2. Neoformation of gels and solid phases;

3. Hydration and dehydration reactions uptaking and yielding water of crystallization, respectively;

4. Exchange of cation and anion species resulting in a change in aqueous geochemistry and aluminosilicate and phyllosilicate exchangeable supercage dimensions;

5. Dissolution of stable and metastable phases providing divalent, monovalent, and complex ions into solution; and

6. Providing thermal-chemical-mechanical stresses on the whole rock, mineral and glass phases resulting in tensile failure aiding transport and reducing whole-rock stability.

The State of Nevada views the fracture and joint systems of Yucca Mountain as potential and likely paths of transport, and as potential perturbations of disturbed zone in areas of fluid phase change, and as zonations which are geochemically and physically too complex to characterize.

These zones of fractures and faults should be considered the prominent paths of transport and have the capability of transporting radionuclide species both in solution and as vapor from the repository to the accessible environment. Important vapor transport is accomplished at 100°C or greater, provides outer zones of condensation and fluid convection above the repository, and zones of condensation and transport towards the accessible environment below the repository. Vapor phase escape to the atmosphere above the repository may be sufficient to be taken seriously with respect to licensing criteria.

5.2 Anticipated Diagenetic Events:

5.2.1 Phyllosilicates:

The dominant clay minerals present in the tuffs of Yucca Mountain are montmorillonite - beidellite (10 to 20 Angstrom spacing) and dioctahedral beidellite interstratified with illite. The beidellites are sodium enriched but may be more calcic high in the Yucca Mountain stratigraphy. Sodium montmorillonites have swelling pressures ranging from 10^5 to 10^7 dyne/cm^2 which varies with the water to clay ratios, and basal spacing may vary significantly with very minor changes in temperature and humidity. Minor heating of the clay minerals resulting in concommitant collapse of the basal spacing could release significant quantities of water and result in opening of fractures. Additionally, loss of mineral water could be accompanied by a loss in sodium to the aqueous system. Clay minerals are commonly in abundance as fracture lining and fillings and as fillings between volcanic glass shards. Swelling of these minerals could either be responsible for fracturing of the surrounding rock, sealing small fractures or closing the diffusion pathways between the fracture walls and pores in the tuff.

Any sodium-enriched aqueous fluids evolved from the sodium-montmorillonite dehydration could be responsible for a lowering of the stability temperature of clinoptilolite, thereby reducing the sorption capability of that zeolite. Illite interstratification increases with increasing pressure and temperature thereby reducing the base-exchange capacity of the clay and providing water and sodium to the aqueous system.

5.2.2 Aluminosilicates:

The dominant zeolites associated with the repository horizon are clinoptilolite and mordenite. Clinoptilolites are in a continuous solid-solution series with heulandite (A and B), analcite and albite. The introduction of Cs as an exchange ion coming from the nuclear waste will result in a loss in mineral water in clinoptilolite. Similar ion exchange accompanies changes in the hydration state of the zeolite supercage. Temperature elevations smaller than are required to transform clinoptilolite to analcime also result in water loss to the extent that continuous heating to about 350°C results in a continuous water loss until the dehydrated phase is reached. Water loss both from clay and zeolites can be important relative to glass hydration and aqueous geochemistry. As the alkalic ion concentration in the vadose aqueous system is increased, the rates of glass hydration are increased and the stability of clinoptilolite is decreased. Base exchange (sorption) in clinoptilolite as a means for radionuclide retardation depends upon existing ionic activity in the supercage sites and the composition of the aqueous phases. As these parameters are affected by physico-chemical reactions within the disturbed zone the sorption characteristics of the zeolite becomes variable and difficult to determine.

5.2.3. Volcanic Glass:

Obsidian and its intermediate hydration product perlite are unstable, brittle components in abundance above and below the repository horizon. These glasses have the potential to be affected by both autocatalytic hydration (hydration accompanied by base exchange) and dissolution. Boles (1977) states:

> "The rise in temperature assocated with increasing burial depth may undergo perturbations from hydration reactions involving zeolites. Surdam and Boles (1977) calculated that the hydration of andesine to laumontite in a sandstone with density 1.3 g/cc, 40% andesine, and an initial temperature of 60°C at 1.5 km of burial would raise the temperature of the rock by 40°C if the heat of the reaction is conserved. Zeolitization of volcanic glass should also evolve heat." (Boles, 1977, page 129).

The effects of the loss of heat during the hydration reaction on the repository thermal envelope has not been assessed for Yucca Mountain even though the vitrophyre just below the repository may be subjected to significant hydration effects especially in the light of thermal increases above the geothermal norm. The hydration of glass involves a increase in volume and results in glass fracturing providing additional reactive surface and paths of fracture interconnectivity.

5.2.4 Tectosilicates:

As a consequence of higher rates of dissolution, evolution of mineral water and cations, and increases in environmental temperature, the aqueous system within the vadose zone could potentially contain sufficient components required for opal precipitation. This could be partially responsible for fracture sealing (inhibiting fracture flow). In addition, fracture coatings might be responsible for a reduction in diffusion pore space thus inhibiting the circulation of fluids in the rock matrix and increasing the transport of fluids by fracture flow.

5.2.5 Other Reactions:

Pore fluid chemistry is an important control on mineral reactions in volcanic tuff environments. High CO_2 pressures might favor clay-carbonate assemblages over clinoptilolite-mordenite-analcite assemblages. Changes in the pH and Eh values for the aqueous system will also change the activity of mineral and glass species and will promote either the retardation of radionuclides or their transport to the accessible environment. Effective porosity and permeability changes provide for the transfer of ions between reaction sites and provide variations in the mixing of aqueous fluids by matrix diffusion and fracture flow.

The whole rock and vadose aqueous system should be considered as an interrelated suite of minerals, glass and aqueous phase(s) which are subjected to geologically rapid thermal and chemical changes resulting in a dynamic shift in equilibrium (thermodynamically irreversible processes). The "disturbed zone" concept provides a volume within the geologic system where complex interactions and reactions occurring as a consequence of irreversible thermodynamic processes induced by thermal loading, associated fluid migration, and mechanical effects of repository construction, do not require comprehensive and accurate characterization. This is a reasonable and conservative approach as there is compelling evidence that the "disturbed zone" is probably too complex to obtain the required characterization to meet licensing criteria.

References:

Boles, J. R. Zeolites in Low-Grade Metamorphic Grades (In: Mineralogy and Geology of Natural Zeolites, vol. 4, chapter 6, pages 103 to 135, Mineralogical Society of America, Short Course Notes/ edited by F. A. Mumpton. November 1977.).

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Appendix D-V

Progress report: computer codes and anticipated modeling during intensive review of the disturbed zone.

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PROGRESS REPORT: Computer Codes and Anticipated Modeling During Intensive Review of the Disturbed Zone.

Computer software that will benefit the disturbed zone intensive review falls into two general categories, i.e. programs that simulate mass and energy transport, and those that simulate geochemical reactions. Geochemical reaction models can be further subdivided into reaction path models and mass transfer models. Coupling of a geochemical reaction simulator with a multiphase flow and energy transport code is clearly beyond the state-of-the-art at present (1987), and is considered unlikely to occur during site characterization. It is therefore necessary to model geochemical and transport phenomena as uncoupled processes, using professional judgement to guide feedback between the necessarily separate modeling activities.

In anticipation of the need for review and recalculation of the thermal envelope and host-rock dissolution effects at Yucca Mountain, a number of numerical simulators were added to Mifflin & Associates' code library. These codes will allow for independent assessment of strongly heat-driven flow in partially saturated fractured porous media, consideration of possible reaction paths and mass transfers, and investigation of the significance of highly uncertain parameters and boundary conditions. To our knowledge, only four computer codes presently in existence might solve the problem of heat-driven mass and energy transport in partially-saturated porous media. As outlined below, we either have or expect to have "official" versions of all four of these codes during 1987. There is a much greater variety of geochemical codes from which to choose; we have chosen two that are able to perform all necessary aqueous speciation modeling functions and are able to describe quantitatively the effects of onging geochemical reactions.

The following codes are expected to form the basis of in-house modeling efforts:

TOUGH, by Karsten Pruess of Lawrence Berkeley Laboratory, is a three-dimensional finite-difference program that takes into account most of the physical effects which are important in multi-phase fluid and heat flow. Based on discussions with Pruess, this program is an appropriate tool for studying an environment characterized by gravity drainage of a mixture of recharge and condensate in discrete vertical fractures. The TOUGH code and user's manual were received on March 30, 1987.

NORIA, a finite element computer program for analyzing water, vapor, air, and energy transport in porous media, is expected to be released by Sandia in the near future. NORIA can solve the same types of problems that are solved by TOUGH, but includes Knudsen diffusion and nonlinear binary diffusion. The present status of NORIA is that Sandia has not forwarded it to Argonne's National Energy Software Center, and a DOE mandate requires this formality prior to release of any code. Based on discussions with NORIA'S author, Nathan Bixler, and his supervisor, Dave Gartling, we expect that NORIA will be available to us within a few weeks of this writing (April 1987). We have arranged for release of PETROS, a onedimensinal finite-difference code that solves exactly the same set of equations as NORIA, following disucssions with G. Ron Hadley of Sandia. To complete the transport code picture, Bryan Travis of Los Alamos has indicated that he will send us a copy of WAFE, although the code is being revised to run "much faster" and the documentation is still incomplete.

PHREEQE, by Parkhurst, Thorstenson,and Plummer of the U.S. Geological Survey, is a mass transfer code capable of sumulating a variety on solution-mineral reactions including evaporation and mixing. Johnson and Shettel of MAI both have extensive experience with PHREEQE, and have found it to be relatively efficient and easy to apply compared to other available reaction-path simulators such as EQ3/6. Extreme evaporation will be handled using a modified Pitzer approach that will be set up as a subroutine in PHREEQE. PHREEQE and the Pitzer routine are in our library now (April 1987).

The EQ3/EQ6 software package by Dr. Thomas Wolery of Lawrence Livermore National Laboratory, is a reaction-path model that is presently undergoing extensive revision. Available versions are EQ3.3015U19 of April 9, 1981, and EQ6.3015U93 of March 28, 1981. Since both programs are expected to be superceded in May of 1987 by greatly improved versions, we do not anticipate immediate application of the EQ3/EQ6 package to Yucca Mountain geochemical issues. However, since the new EQ3 will incorporate the Pitzer approach to computing activity coefficients in high-ionic-strength waters, and EQ6 will handle dissolution <u>and</u> precipitation kinetics, these codes will be incorporated into our review process as soon as they are available.

In summary, our collection of transport and geochemical model codes will be adequate in the immediate future for a rigorous review of the predicted thermal envelope and associated geochemical effects, subject to the major hydrogeologic uncertainties at Yucca Mountain. In addition, some intercode comparisons between functionally similar members of the transport and reaction-code families can be expected during 1987.

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Bixler, N. E., 1985, NORIA - A FINITE ELEMENT COMPUTER PROGRAM FOR ANALYZING WATER , VAPOR, AIR, AND ENERGY TRANSPORT IN POROUS MEDIA : Sandia National Laboratories, SAND84-2057.

Hadley, G. R., 1985, PETROS - A PROGRAM FOR CALCULATING TRANSPORT OF HEAT, WATER, WATER VAPOR, AND AIR THROUGH A POROUS MATERIAL : Sandia National Laboratories, SAND84-0878.

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Section E

Review of Technical Documents Program

Review of Technical Documents Program

Introduction

The Technical Review activity was review of selected technical documents in hydrogeologic and related topical areas. Documents reviewed were generally by DOE and NRC (or their contractors), and the open scientific literature. The activity also provided for State of Nevada requests for specific document reviews and attendance at meetings where hydrogeologic, climatic change, and geochemical issues or investigations are discussed. In general, the activity provides ongoing technical review for hydrogeologic investigations, including the following topical or issue areas: vadose-zone hydrogeology, saturated-zone hydrogeology, hydrogechemistry, mineral geochemistry, authigenic mineralogy, climate change, disturbed zone, sorption, and modeling (flow models, transport models, reaction-path models, etc.).

In addition to general technical document review, the most important technical reviews for 1987 and 1988 were DOE Environmental Assessment (EA) and Consultation Draft Site Characterization Plan, Yucca Mountain Site (CD-SCP). The DOE prepared a draft EA (December, 1984) which received public comments and was revised and published as a final EA (May, 1986).

The CD-SCP was released by DOE in January 1988. The CD-SCP is the key document with respect to the manner in which the DOE intends to characterize the proposed Yucca Mountain repository. This document, when considered in the context of existing information and the DOE perspectives established in the EA, made it possible for the State of Nevada to judge the viability of the DOE program with respect to each issue area. Each specific objective of the CD-SCP was judged from the following criteria:

A. Existing database for Yucca Mountain and region
B. Issue and licensing requirements
C. General technical experience/general scientific literature
D. Technical Position of the State of Nevada

The objective of the review was to establish a State of Nevada response with respect to the credibility and acceptability of the SCP for resolution of key technical issues. In those site characterization aspects where credibility or acceptability is absent, the State of Nevada concerns needed to be established and technically justified.

Reviews of the DEA and EA and several draft technical positions established by the NRC prompted the preparation of Technical Position Papers by MAI on behalf of the State of Nevada on the following:

1. Climate change
2. Disturbed Zone
3. Ground-water Travel Time
4. Dissolution
5. Vadose/Saturated zones.

The review section deals mainly with two major technical documents - the Environmental Assessment: Yucca Mountain Site, Nevada Research and Development Area, Nevada, vols. I to III [DOE/RW-0073] (EA) and the Consultation Draft of the Site Characterization Plan : Yucca Mountain Site, Nevada Research and Development Area, Nevada, January 1988 [DOE/RW-0160] (CD-SCP), both by the U.S. Department of Energy. As indicated above other technical documents were reviewed. A list of such documents is provided below.

A. In reviewing the EA, MAI efforts focused on:

1. Identifying and documenting major scientific concerns raised by the EA which warrant scrutiny on the basis of:

   a. Data used;
   b. Methodology used;
   c. Results obtained;
   d. Incompleteness or inaccuracy in reported results; and
   e. Incompleteness or inaccuracy in methodologies used.

2. Identifying and documenting any inconsistencies between scientific results reported in the EA and the results reported in cited literature or open literature.

3. Identifying, documenting, and assessing the support (or lack thereof) within the EA for the DOE nomination and recommendation decision.

4. Providing our expert judgment with respect to assumptions adopted and with respect to whether or not a conservative analysis has been established.

B. In reviewing the CD-SCP, MAI efforts focused on hydrogeology and related activities in terms of:

1. Conceptual completeness and focus;
2. Appropriateness of methodology to accomplish stated objectives;
3. Availability of supportive technology; and
4. Probability of success and/or feasibility.

C. Other technical documents reviewed in addition to the EA and CD-SCP are:

1. Yucca Mountain USGS water-level data.

2. Proposal for new baseline data format for static and aquifer test water level data/Lehman & Associates.

3. Smectite dehydration and stability: applications to radioactive waste isolation at Yucca Mountain, Nevada (LA-11023-MS)/D. L. Bish, Los Alamos National Laboratory (LANL).

4. Draft generic technical position guidance for determination of anticipated processes and events and unanticipated processes and events/U.S. Nuclear Regulatory Commission (NRC).

5. Performance assessment of radioactive waste repositories/ J. E. Campbell and R. M. Cranwell, in Science, vol. 239, p. 1289 to 1392.

6. A preliminary comparison of mineral deposits in faults near Yucca Mountain, Nevada with possible analogs (LA-11289-MS)/ D. T. Vaniman, D. L. Bish, and S. Chipera, LANL.

Appendix E

Review of Technical Documents Program

List of Appendices

Appendix E-I

Technical review comments on the Environmental Assessment: Yucca Mountain site, Nevada Research and Development Area, Nevada, vols. I to III (DOE/RW-0073) by DOE.

Review of Technical Documents

ISSUE:

The technical accuracy of the U. S. Department of Energy Environmental Assessment : Yucca Mountain Site, Nevada Research and Development Area, Nevada : Nuclear Waste Policy Act (Section 112) (DOE/RW-0073), vols. I to III, 1986 (EA).

General Objectives:

Identify and document major scientific concerns raised by the EA which warrant scrutiny on the basis of:

Data used;

Methodology used;

Results obtained;

Incompleteness or inaccuracy in reported results; and

Incompleteness or inaccuracy in methodologies used.

Identify and document any inconsistencies between scientific results reported in the EA and the results reported in cited support literature or open literature.

Identify, document, and assess the support (or lack thereof) within the EA for the DOE nomination and recommendation decision.

Provide our expert judgment with respect to assumptions adopted and with respect to whether or not a conservative analysis has been established.

ACTIVITY SUMMARY:

All of the sections (Vadose Zone, Climate Change, Hydrogeology, Geochemistry, Mineralogy, and the Disturbed Zone) of the final draft of the EA were reviewed taking into consideration certain specific points such as: impact of a plenipluvial climate on repository performance, dissolution, radionuclide retardation by authigenic minerals, the stability of the engineered-barrier system in a chemically reactive ground water in the host rock and Ground-Water Travel Time (GWTT).

FINDINGS:

The following are general conclusions reached after reviewing the preemplacement EA. Excerpts or (where possible) summaries of important sections of our review (important with regard to the postclosure performance of the repository) of the EA are provided immediately after this section and come under "Specific Findings."

We find that there is little scientific evidence available to confidently demonstrate long-term waste isolation at the Yucca Mountain Site.

There is no site-specific data that indicates the lengthy travel times postulated for the vadose zone. Basically the DOE postulates that matrix flow dominates and that recharge is distributed uniformly and is limited by the rock matrix to transmit the flux. We think this is unlikely given the highly fractured rock environment, the manner in which recharge probably occurs in time and space, and suggestive, but unreported evidence of localized saturation within the vadose zone in the proposed repository area. Therefore, we judge the DOE postulated hydrology of the vadose zone unlikely, and their assessments nonconservative.

There is little evaluation or treatment of vapor-phase radionuclide migration in the vadose zone via fracture networks to the land surface, the accessible environment. A conservative evaluation would assume that gas-phase radionuclides migrate very rapidly to land surface if fracture networks are unsaturated.

There is little appropriately developed evidence that important sorption or retardation of the total inventory of radionuclides will occur in the vadose zone. The DOE has placed heavy weight on the concepts of matrix flow and associated retardation and sorption due to abundant authigenic minerals, low flux rates of recharge, and very long travel times. None of these postulates can be demonstrated as valid based on realistic scenarios of postclosure repository conditions and appropriate data bases. In the absence of an appropriate data base, a conservative analysis should recognize the possibility of important fracture flow, significantly larger flux rates, and the thermal envelope's impact on hydrated authigenic minerals and moisture migration in liquid and vapor phases.

There is little fundamental understanding of most species of radionuclides with respect to migration, sorption, and retardation in the anticipated environments of migration pathways. These migration pathways must include the fracture pathways. We think it nonconservative to take important sorption and retardation credit when an indepth review demonstrates the serious weakness of the laboratory data available, and the absence of comparable radionuclide behaviors in natural hydrologic environments.

We find that the vadose-zone environment is subject to marked changes in the hydrologic regimen when the available paleoclimatic information is considered. If the extremely low modern flux rates postulated by the DOE are in error, and larger flux rates are in fact present, major impact on the hydrologic regimen of the vadose zone should be anticipated during a pluvial climate. The majority of recharged flux would be by fracture flow, and we see no mechanism by which long-term retardation of radionuclides could occur in the vadose zone.

We find that the Yucca Mountain Site has not been selected on the basis of conservative scientific assessments of the environment and site-selection criteria, rather the selection is on postulated, but unproven, conceptual arguments.

A number of conceptual models have been treated as scientifically supported fact. There has not been a consistent effort to conservatively evaluate issues of the site selection in view of no data, sparse data, inappropriate or questionably applicable data, unknown or uncertain physical and chemical processes, highly idealized numerical models, etc.

We recognize no case of an overly conservative treatment of uncertain relationships in the EA. We have recognized (and discussed) many cases of nonconservative treatment of issues in favor of meeting site-selection criteria.

We recognize and discuss cases where the general scientific knowledge base has been selectively visited, or ignored, to further the conceptual models favorable to site selection.

We recognize inconsistent and inappropriate use and interpretation of support document findings to further conceptual models favorable to site selection.

We note that some potentially key site-specific data have been ignored in the preparation of the EA and are as published in support documents.

INTERPRETATION OF FINDINGS WITH RESPECT TO OBJECTIVES AND ISSUES:

The following are conclusions based on the above findings. In the "Specific Findings" section which comes later in this report, findings and our comments or conclusions are treated together.

We believe, on the basis of the above observations, that the EA has fallen short of the scientific objectivity desirable in repository site selection. On the basis of our more conservative evaluations of the available data base and general scientific knowledge pertinent to the site performance issues of Yucca Mountain, we find the site highly complex and unlikely to be demonstrated to meet licensing criteria. We find the required waste isolation at the Yucca Mountain Site unlikely to be confidently demonstrated during characterization of the site.

Specific Findings:

Climate:

The EA theme is that great uncertainty exists in the analyses of effects of a change to plenipluvial climate but that the available data indicate no significant impact on repository performance. We believe climate change to a plenipluvial climate (significantly more effective moisture for runoff and recharge) creates repository performance issues of: 1) water-table position; 2) extent of perched water; 3) ground-water travel time in the vadose zone; 4) recharge rates; and 5) in general the ability of the proposed repository to isolate waste. Indepth treatments of these issues within the context of existing data have been avoided in the EA.

We believe repository performance issues during a plenipluvial climate have not been appropriately addressed in the EA nor resolved with respect to the existing paleohydrologic evidence in the region. Available evidence indicates that recharge rates during a plenipluvial climate may greatly exceed the transmissive capacity of the rock matrix, and hence fracture flow may constitute the majority of the recharge flux in the vadose zone and zones of perched water could become extensive. If fracture flow dominates, the ground-water travel time for majority of flux through the vadose zone would be very rapid. In addition, perched zones of saturation, the site-specific position of regional saturation, and the total flux rate of recharge to the thermal envelope all become serious and unresolved repository performance issues.

Dissolution:

The EA's assessment of compliance with the qualifying condition for the dissolution guideline 10 CFR, Part 960.4-2-6 -("The site shall be located such that any subsurface rock dissolution will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in Section 960.4-1." (DOE, 1986, vol. II, p. 6-253).) is based on evidence of dissolution in the geologic setting of the site during the Quaternary Period. As there was no repository in these rocks during this geologic time frame, the potential dissolution effects of placing a thermal source in the vadose zone that is capable of generating steam are unknown.

The EA claims that the "potential host rock at Yucca Mountain has no dissolution features" and that on the basis of the geologic record that "no dissolution is expected during the first 10,000 years after repository closure or thereafter."

We find that the DOE has not provided convincing evidence that: 1) sufficient dissolution would not lead to radionuclide releases greater than those specified in 10 CFR Part 960.4-1, and 2) hydraulic interconnections leading to a loss of waste isolation would not occur because they may in fact already exist.

Further, a thermodynamically unstable mineral assemblage of silica polymorphs is present in the host rock that may be subject to enhanced readjustment (dissolution/precipitation) under expected repository conditions (elevated temperature, convective fluid flux, and above normal geothermal temperature gradients).

Finally, we find that the geologic past at Yucca Mountain is not an adequate basis for evaluating a postclosure technical guideline such as dissolution.

In closing, it appears that the DOE intended the dissolution guideline for those sites containing highly soluble phases, such as halite, and thus treated dissolution in a cursory fashion at Yucca Mountain. However, dissolution/alteration of metastable phases such as volcanic glass and silica polymorphs, zeolites, and clays may be more important to the long-term performance of a nuclear-waste repository at Yucca Mountain than previously thought.

Geochemistry:

The guideline for the Geochemistry Section of the EA contains five favorable conditions, three potentially adverse conditions, and one disqualifying condition. A detailed treatment of each of the conditions of the guideline will not be included in this 18-month report so as to avoid producing a cumbersome volume. What this section contains are therefore excerpts/summaries of points reviewed in the Geochemistry Section of MAI's "Technical Review Comments on the Environmental Assessment: Yucca Mountain Site, Nevada Research and Development Area, Nevada (May 1986, vols. I, II, III [DOE/RW-0073), by DOE, July 1987."

Favorable Conditions:

Favorable Condition 1:

> "The nature and rates of the geochemical processes operating within the geologic setting during the Quaternary Period would, if continued into the future, not affect or would favorably affect the ability of the geologic repository to isolate the waste during the next 100,000 years." (DOE, 1986, vol. II. p. 6-174).

The EA indicates that this condition is present at Yucca Mountain because "sorptive minerals (zeolites) were present in the tuff at Yucca Mountain throughout the Quaternary time; they are still present and are expected to contribute to isolation over the next 100,000 years." (DOE, 1986, vol. II, p. 6-169).

We find that the thermal envelope may seriously jeopardize the potential sorptive capacity of the clays and zeolites. In addition, the thermal envelope may promote the evolution of mineral water affecting mineral dissolution, glass hydration, and increasing effective permeability, thereby inhibiting the geologic repository from isolating the waste during the next 100,000 years.

In summary, we find the conceptual arguments presented in the EA are poorly supported by actual field and analytical data. Consequently, we find that a conservative assessment of the evidence indicates that this favorable condition is not present at Yucca Mountain, as there is little evidence to suggest that authigenics are responsible for sorption, and that these minerals will be stable under imposed thermal conditions, within likely paths of transport of the vadose zone.

Favorable Condition 2:

> "Geochemical conditions that promote the precipitation, diffusion into the rock matrix, or sorption of radionuclides; inhibit the formation of particulates, colloids, inorganic complexes, or organic complexes that increase the mobility of radionuclides; or inhibit the transport of radionuclides by particulate, colloids, or complexes." (DOE, 1986, vol. II, p. 6-176).

The EA indicates that this condition is present at Yucca Mountain because: geochemical properties are expected to promote matrix diffusion; zeolites along flow paths will sorb radionuclides; organic complexes that would increase radionuclide mobility are not present; particulates and colloids may be filtered by tuffs, thereby inhibiting transport.

Many studies concerning waste-glass radiolysis conclude by exclaiming that acid and hydrogen-peroxide production may radically change the vadose-water chemistry at the proximity of the canisters. These chemically dramatic events, favoring colloid production, may be responsible for more than actinide-colloidal formation to the extent that:

1. Other radionuclides may form colloids.

2. Acid attack on silicates may promote dissolution pathways associated with fracture systems favoring fracture flow over matrix flow.

3. The induced high-oxidation potential may not be adequately reduced considering the paucity of transition-metal complexes present (except for canister material itself).
4. The oxidation of canister stainless steel will provide iron and other transition-metal oxyhydroxides, which tend towards colloidal behavior. These complexes may further the colloidal complexation of radionuclides inhibiting authigenic-mineral sorption, and resulting in a reduction of retardation.

In conclusion we do not find sufficient evidence to demonstrate that this condition is present at Yucca Mountain.

Favorable Condition 3:

> "Mineral assemblages that, when subjected to expected repository conditions, would remain unaltered or would alter to mineral assemblages with equal or increased capability to retard radionuclide transport." (DOE, 1986, vol. II, p. 6-192).

The EA indicates that this condition is present at Yucca Mountain because the radionuclide-retardation capacity of tuffs is not expected to degrade due to repository conditions.

We find that retardation capacity as a function of zeolite and clay stability has been inadequately treated in the EA. We find that although volcanic glass likely alters to authigenic minerals with sorption abilities, these minerals may not be stable in the vadose zone to the extent that sorption will have significant capacity for radionuclide retardation. Furthermore, we find that the negative effects of evolution of mineral water may provide increased access for radionuclide escape to the accessible environment. Therefore, we do not find favorable condition 3 present at Yucca Mountain, because when subjected to expected repository conditions, the zeolite/clay assemblage will have a diminished effect in retardation of radionuclide transport, and the presence of these assemblages will likely promote radionuclide escape by providing significant quantities of water of hydration to the system.

Favorable Condition 4:

> "A combination of expected geochemical conditions and a volumetric flow rate of water in the host rock that would allow less than 0.001 percent per year of the total radionuclide inventory in the repository at 1,000 years to be dissolved." (DOE, 1986, vol. II, p. 6-193).

The EA indicates that this condition is present at Yucca Mountain, because expected geochemical conditions and vertical flux of less than 0.5 millimeter (0.02 inch) per year are expected to limit release to less than 0.001 percent per year of total radionuclide inventory at 1,000 years after permanent closure.

We note that the EA does not specifically deal with the reactions or release rates of radionuclides which may occur in gaseous states in the vadose-zone repository environment (^{14}C, ^{3}H, ^{129}I). Gas-phase radionuclides have a potentially short migration path and associated travel time to the accessible environment (land surface) above the repository through the fracture networks. Release of C-14, as CO_2 may be critical as the sealed canisters fail. This aspect continues to be a serious deficiency of both the DEA and EA.

In conclusion, we find that the geochemical setting of Yucca Mountain is not likely to be benign, but rather reactive with respect to waste glass and stainless steel. We find that the flux of vadose water could, conservatively, be up to two orders of magnitude higher than reported in the EA, and we find, therefore, that the waste glass may release considerably greater than 0.001 percent per year of the total radionuclide inventory 1,000 years after permanent closure. Consequently, we do not find that favorable condition 4 is present at Yucca Mountain.

Favorable Condition 5:

> "Any combination of geochemical and physical retardation processes that would decrease the predicted peak cumulative releases of radionuclides to the accessible environment by a factor of 10 as compared to those predicted on the basis of ground-water travel time without such retardation." (DOE, 1986, vol. II, p. 6-198).

The EA indicates that this favorable condition is present at Yucca Mountain because chemical adsorption, low flux, and matrix diffusion are expected to limit radionuclide release by at least a factor 10.

The diffusive retardation factor of 100, which the DOE recognizes, is better attributed to Neretnieks (1980), who has not been offered the opportunity to study Yucca Mountain tuffs. Neretnieks does indicate that for those rocks he studied, accessibility to the rock matrix (pores) is a major determining factor with respect to the magnitude of the potential retardation. There is strong evidence that there are significant differences between diffusion in granites and tuffs. Consequently, until the tuffs at Yucca Mountain are appropriately characterized, it is premature to attribute matrix potential (diffusion) during fracture flow as a mechanism of retardation. Further, if fracture flow is the prime mechanism for radionuclide transport, matrix diffusion will be of minor importance with a diminished capacity in higher velocity flow.

The calculation employed to make the determination that a factor of 11.4 decrease of the cumulative radionuclide release can be attributed to geochemical retardation does not utilize conservative values of flux nor travel times, and consequently does not arrive at conservative site-specific results. The "representative path" from the disturbed zone to the water table which has the mean travel time is not the fastest path and thus is not a conservative numerical evaluation.

As stated in the "Technical Review Comments of the Environmental Assessment: Yucca Mountain Site,..., July 1987, we find that favorable condition 5 has not been demonstrated to be present at Yucca Mountain, due to nonconservative assumptions made with respect to radionuclide-retardation factors, potential sorptive-barrier behavior, vadose-zone flux, and travel-time calculations. Further, we note that in order to obtain accurate travel-time estimates, there needs to be a reasonably defined disturbed-zone boundary which presently has not been accomplished, and site-specific field data which clearly demonstrates that fracture flow does not dominate.

Potentially Adverse Conditions:

Potentially Adverse Condition 1:

> "Ground-water conditions in the host rock that could affect the solubility or the chemical reactivity of the engineered-barrier system to the extent that the expected repository performance could be compromised." (DOE, 1986, vol. II, p. 6-199).

The EA indicates that this condition is not present at Yucca Mountain because "the stainless steel waste disposal container and waste forms are not expected to show detrimental effects due to host-rock water chemistry." (DOE, 1986, vol. II, p. 6-170).

Contrary to DOE assumptions and postulates, there **is no site-specific evidence** that ground-water conditions in the vadose-zone host rock would not jeopardize the repository performance due to the chemical reactivity of the vadose-zone components. General chemical evidence suggests that undesirable effects with respect to oxidation could significantly limit the lifetime of the engineered-barrier system. The reactivity of vadose-zone water therefore is a paramount issue, but it remains totally unstudied at Yucca Mountain. Consequently, we find that potentially adverse condition 1 could reasonably be present at Yucca Mountain. We therefore disagree with the EA conclusions and find the condition present at Yucca Mountain.

Potentially Adverse Condition 2:

> "Geochemical processes or conditions that could reduce the sorption of radionuclides or degrade the rock strength." (DOE, 1986, vol. II, p. 6-202).

The EA indicates that this condition is not present because sorptive zeolites are metastable, but little reaction is expected in the next 100,000 years and because geochemical processes are too slow to affect repository performance through the degradation of rock strength.

Potentially Adverse Condition 2 is directed towards potential changes of the sorption of radionuclides presumably due to a loss or gain of potentially sorbing authigenic minerals and changes in rock strength as a consequence of mineral reactions. The Dibble and Tiller (1981) publication has been inadequately treated in the EA. The kinetic parameters involved in metastable authigenic-mineral transformation towards thermodynamically more stable phases have not been addressed. Reaction rates therefore, on a site-specific basis, given a repository thermal regime and completely uncharacterized vadose-water chemistry, are not determinable. Yet, the EA arrives at certain expectations dealing with reaction rates and related transformation times which appear to be totally unrelated to constructive extrapolation of scientific data.

Consequently, we find that the timing of potential reactions are unknown; and the arguments presented in the EA are totally unsupported.

An underlying assumption in the EA is that the only mode of rock-strength degradation would be the transformation of metastable authigenics to a thermodynamically more stable mineral association; however, we find that reactions such as the hydration of volcanic glass and accompanying volume increases can produce significant changes in structural characteristics (and strength) of the host rock as well as providing significant fracture pathways for radionuclide transport. Dissolution of metastable minerals alters the existing mineral assemblages, rendering them less effective towards sorption. The EA misconception that clinoptilolite must be transformed to an analcime or albite prior to loss of sorption capacity is totally unfounded. Minor changes in the vadose-water chemistry and thermal regime can cause major sorption stability effects.

There are sufficient information available to suggest that both rock strength and sorption capacity could be jeopardized by the thermal load and associated geochemical processes that, in the conservative view, may develop in the host rock of the repository block. Consequently, we find that adverse condition 2 is present at Yucca Mountain.

Potentially Adverse Condition 3:

> "Pre-waste-emplacement ground-water conditions in the host-rock that are chemically oxidizing." (DOE, 1986, vol. II, p. 6-204).

The EA indicates that this condition is present at Yucca Mountain because water is expected to contain dissolved oxygen and be chemically oxidizing (DOE, 1986, vol. II, p. 6-170).

The EA recognizes (DOE, 1986, vol. II, p. 6-204 to 6-205) that:

1. The host rock is in the vadose zone and its pores are partially filled with air and water. Consequently, water can have up to 8.1 ppm oxygen at 25°C.

2. The austenitic stainless-steel waste container should develop a protective oxide film that would limit further corrosion. Therefore, the oxidizing conditions may prolong the lifetime of the waste container.

3. Solubility of spent fuel in an oxidizing environment is greater than in a reducing environment. This could result in larger releases of radionuclides.

4. The lifetime of the zircaloy cladding may be adversely affected if uranium dioxide were to become oxidized and cause stress rupture of the cladding.

5. These conditions could be altered after waste emplacement and are not expected to cause serious problems with respect to the solubility or chemical reactivities of the engineered-barrier system.

We agree with the EA that this condition is present at Yucca Mountain, and believe it may be a more serious condition than is alluded to in the EA. We find no mention of radionuclide-colloid formation due to oxidizing conditions which is a reaction that will tend to inhibit sorption retardation. Further, we underline the fact that the vadose water has not been characterized and that the degree to which these waters are oxidizing is unknown. We believe a scenario of the condensation of water vapor in fractures above the repository horizon, and eventual penetration of these waters by fracture flow to the repository horizon as cooling occurs may set the stage for strongly oxidizing conditions.

We, too, conclude that this adverse condition is present at Yucca Mountain.

Hydrogeology:

Ground-water travel time (GWTT) appears to be the most crucial part of the hydrogeology and ground-water sections of the EA with regard to: calculations on the time radionuclides would be released to the accessible environment. Furthermore, the treatment of GWTT involves a discussion of vadose-zone flux, vadose-zone travel time and saturated-zone travel time. This portion of the 18-month report has therefore been devoted to it.

The GWTT analysis in the EA, is a probabilistic approach that attempts to account for variabilities and (uncertainties?) in the key parameters used for calculating ground-water travel time. Unsaturated (vadose) zone flux, unsaturated (vadose) zone travel time, and saturated-zone travel time are considered separately in the EA and the following comments are structured accordingly.

Vadose (Unsaturated) Zone Flux:

A critical and highly uncertain parameter that is of fundamental importance to ground-water travel-time estimation is the flux of water through the vadose zone. Vadose zone flux at Yucca Mountain has been estimated by two general approaches; the first approach uses a variety of indirect local field and laboratory measurements to provide estimates of flux, while the second method involves extrapolation of an empirical regional relationship between elevation, precipitation, and recharge to the local environment at Yucca Mountain. Flux is considered in the EA to be distributed, that is, not locally concentrated in space by structural features, slope, soil cover, etc., or in time by short-term precipitation events leading to pulses of infiltration and percolation.

Using thermal flux, properties of core and in-situ potential gradients, DOE finds that:

1) 10-7 to 0.2 mm per year of flux could be occurring in the matrix of the Topopah Spring welded unit.

2) All preliminary field and laboratory estimates of moisture flux in the Topopah Spring unit are less than 0.5 mm per year.

3) An upper bound of 0.5 mm per year is consistent with the available information.

Direct measurements of infiltration and recharge have not been made at Yucca Mountain (Montazer and Wilson, 1984, pa. 37). Recent moisture profiles (Hammermeister, et al., 1984) indicate that topography exerts a significant influence on localization of recharge; infiltration from summer storms seems to be most pronounced beneath washes, as opposed to higher ground. Generalizations regarding the distribution of infiltration from winter storms, which seldom generate runoff, are not available. It should be clear from the available data, however, that flux is not uniformly distributed in either time or space.

Calculation Based on Geothermal Gradient:

DOE has used measurements of subsurface temperature gradients to estimate moisture flux in the unsaturated zone at Yucca Mountain. Sass and Lachenbruch (1982, p. 24) calculated a downward vertical flux of 9 mm per year in both the saturated and vadose zones. These authors emphasize, however, that results from Yucca Mountain are inconclusive since only one of the 50 wells studied was completed in the manner required of a confident analysis of the thermal effects of natural ground-water flow (Sass and Lachenbruch, 1982, p. 25). The statement in the EA that "..all preliminary field and laboratory estimates are less than 0.5 millimeter" (DOE, 1986, p. 6-151) is, then, a misrepresentation.

In a referenceable letter to D. L. Veith of DOE/Nevada Operations, W. W. Wilson of the USGS (1985) details the rationale for using 0.5 mm/yr. as a "reasonable and conservative" value of flux beneath the repository horizon at the primary repository area. Geothermal data from USW UZ-1 have been used by Montazer, et al., (1985) to estimate the quantity of water in vapor form that is migrating vertically in the Topopah Spring welded unit. The analysis based on an analytical solution for vertical steady flow of ground water and heat through an isotopic, homogeneous, and fully saturated porous medium (Bredehoeft and Papadopulos, 1965). The interpretation by Montazer, et al. (1985) and Wilson (1985) that temperature profiles are generally convex upward between 91 m and 305 m is open to question; table 1 and figure 12 of Montazer, et al. (1985) reveal that the geothermal gradient can also be interpreted as piecewise linear. The interval from 40 m to 128 m shows a uniform geothermal gradient of 31.45°C per km, and the interval from 128 to 368 m shows a lesser, uniform gradient of 17.50°C/km. Linear regression on temperature-depth data from Montazer, et al. (1985, table 1) results in regression coefficients (r^2) values of 0.99 and 1.00, respectively, for the shallow and deep intervals (Figure 1).

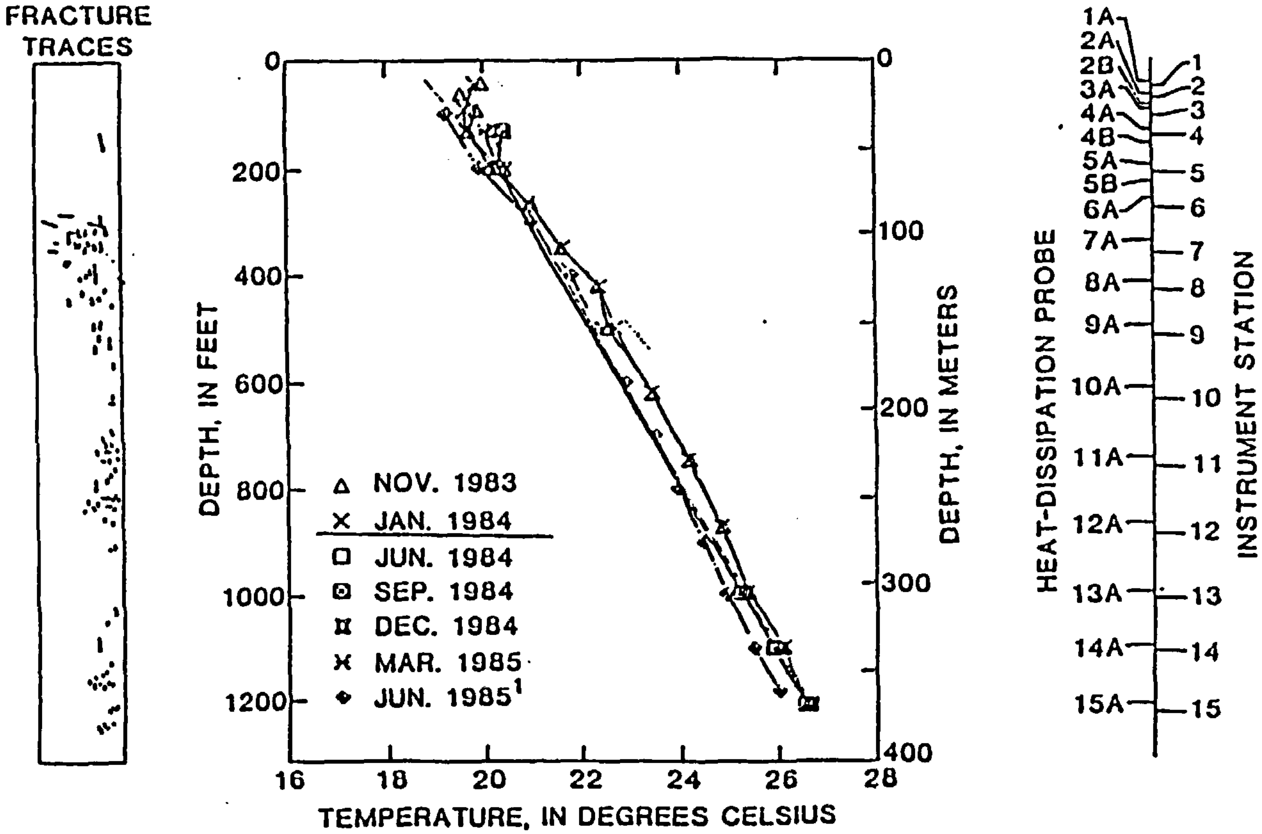


FIGURE 1. (MONTAZER & OTHERS, 1985)

Temperature profiles and distribution of fracture traces at test borehole USW UZ-1. Data for June 1985 from John Sass (U.S. Geological Survey, written commun., 1985).

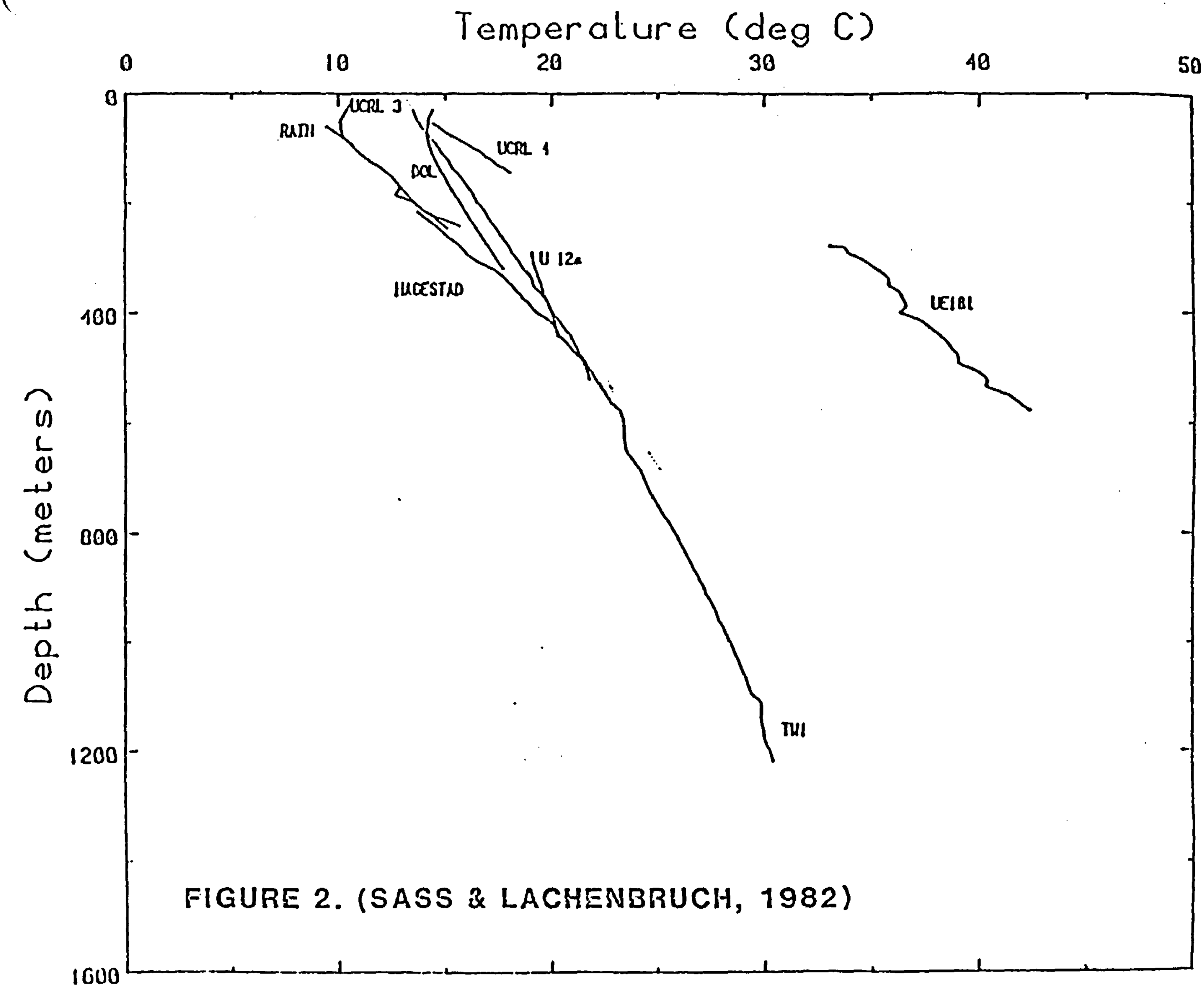


FIGURE 2. (SASS & LACHENBRUCH, 1982)

Composite Temperature Profile for Rainier Mesa & Environs.

Sass and Lachenbruch (1982, figure 5) present a geothermal profile from well TW1 at Rainier Mesa that is similar in shape to that presented by Montazer, et al. (1985) for well USW UZ-1 at Yucca Mountain (Figure 2). The fact that the profile at Yucca Mountain resembles that from an area where seasonal flows from fractures into a tunnel network provides direct evidence of active recharge (Henne, 1982) casts doubt on the utility of the geothermal-gradient-convexity approach to unsaturated-zone flux estimation.

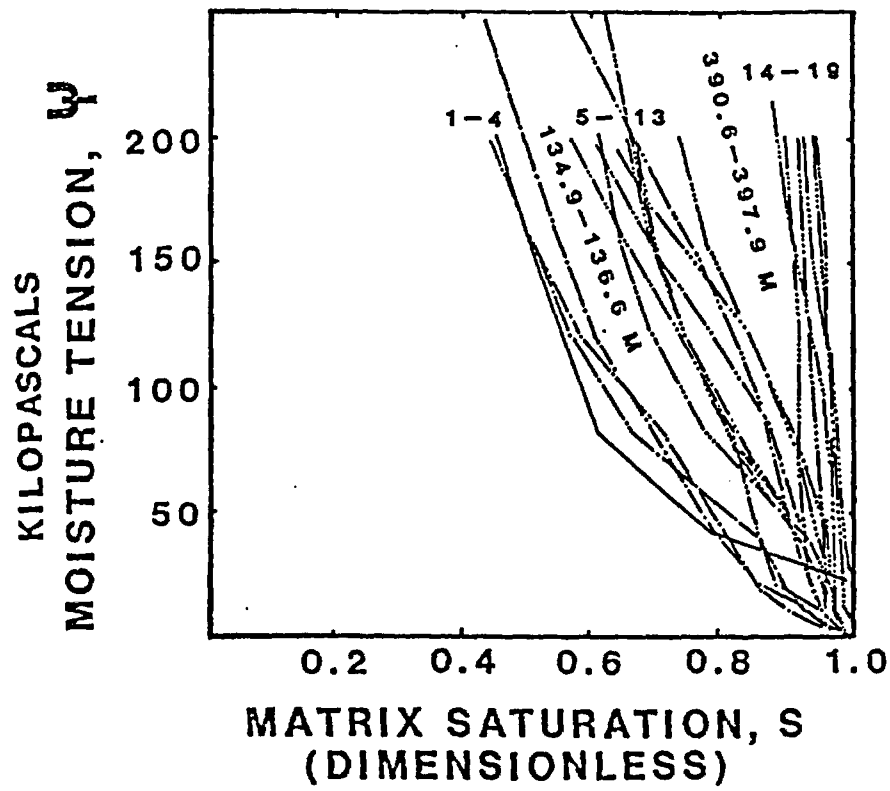
Calculation Based on Properties of Core:

Wilson (1985, p. 2) cites Weeks and Wilson (1984) for an estimated moisture flux of 0.003 to 0.2 mm/yr. in the matrix of the Topopah Spring welded unit. Moisture-characteristic curves relating saturation and moisture tension were developed from results of mercury-injection tests on 19 core samples of unsaturated tuff from test well USW H-1 (Weeks and Wilson, 1984, p. 1). Sixteen of these samples were from the Topopah Spring unit. Relative hydraulic conductivity, defined as the ratio of hydraulic conductivity at a given matrix saturation to that as complete matrix saturation, was estimated from the moisture-characteristic curves (Weeks and Wilson, 1984, p. 12). Only seven of the sixteen samples for the Topopah Spring unit were considered "analyzable", that is, their moisture-characterisitic curves could be fit with an analytical expression that can then be integrated to give an equation for relative permeability as a function of matrix saturations or moisture tension. One value of relative permeability (sample 9) was discarded because "..the porosity of the total sample was much larger than that of the small sample used in the porosimeter" (Weeks and Wilson, 1984, p. 13). Ambient unsaturated hydraulic conductivity was obtained from relative hydraulic conductivity (Weeks and Wilson, 1984) and saturated hydraulic conductivity measurements on core from test well UE25a#1 (Anderson, 1982) which is located 2.0 km east of well USW H-1. One of Anderson's (12981) measurements was discarded because of a visible fracture (Weeks and Wilson, 1984, p. 14). The resulting "effective" hydraulic conductivity values were used with an assumed unit hydraulic gradient to obtain the reported 0.003 to 0.012 mm/yr. vertical water flux through the tuff matrix.

The most noteworthy point regarding flux estimation from core analysis is the systematic exclusion of fractured samples from the analysis. In addition, there could be intentional bias in Weeks and Wilson (1984) toward presentation of their data in a way that minimizes the computed vertical flux through the Topopah Spring unit. For example, sample 8 (Weeks and Wilson, 1984, page 8) was excluded from the calculation of geometric mean relative hydraulic conductivity for reasons quoted in the last paragraph, but sample 9, for which the porosity difference between "small" and "total" sample was higher than sample 8 sample was higher than sample 8 by a factor of four, was included! Furthermore, the calculated geometric mean of the seven values of relative hydraulic conductivity that are considered "valid" (Weeks and Wilson, 1984, page 13) include on very low value from the Paintbrush nonwelded unit. Wilson(1985, page 2) is therefore in error when he cites Weeks and Wilson (1984) for a flux estimated in the Topopah Spring welded unit: their treatment combines nonwelded Paintbrush data with selected Topopah Spring data.

A major uncertainty in the Weeks and Wilson (1984) data is the effect of the air-foam method on measured ambient water content on the core samples. If core samples were subjected to variable amounts of drying during collection and analysis, hydraulic conductivities estimated from laboratory studies would show greater scatter and a lesser magnitude than field values. The importance of wetting or drying effects for this sample set are not known quantitatively.

MOISTURE CHARACTERISTIC CURVES FROM BOREHOLE USW H-1,



PAINTBRUSH NON-WELDED UNIT

——————— 33.5 m below ground level (BGL)

TOPOPAH SPRING WELDED UNIT

—·—·— 128.0 - 134.9 m BGL
—··—··— 136.6 - 143.3 m BGL
—···—···— 219.2 - 225.6 m BGL
—····—····— 390.4 - 405.8 m BGL

CALICO HILLS NON-WELDED UNIT

—·······—·······— 530.7 - 532.8 m BGL

FIGURE 3.

MODIFIED AFTER WEEKS AND WILSON (1984).

Examination of figures 4 through 22 in Weeks and Wilson (1984, p. 17 to 26) reveals three reasonably distinct sets of moisture-characteristic curves from core samples from borehole USW H-1 (Figure 3). The upper (lithophysal?) portion of the Topopah Spring unit is very similar to the Paintbrush nonwelded unit in terms of percent matrix saturation and the shape and position of the moisture-characteristic curves. Matrix saturation in the upper zone of USW H-1 averages 0.50 ± 0.05. The middle portion of the Topopah Spring unit also shows an internal consistency, with matrix saturation averaging 0.71 ± 0.10. Matrix saturation in the lower zone, which includes two samples from the Calico Hills nonwelded unit, is 0.85 ± 0.07. It appears that a stratigraphic inhomogeneity is present in the Topopah Spring unit; and significantly, there is no evidence of a discontinuity in the character of moisture-characteristic curves across the upper and lower boundaries.

Weeks and Wilson (1984) have used geometric mean saturated hydraulic conductivities from Anderson (1981) as a basis for computing "effective" hydraulic conductivities from the "relative" hydraulic conductivities obtained in their own study. The geometric mean of a data set minimizes the effect of extreme values; utilization of geometric mean hydraulic conductivity data is therefore not a conservative approach in the present application.

Calculation Based on In-Situ Potential Gradients and Properties of Core:

Montazer, et al., (1985) report "relatively constant" matric potential in the Topopah Spring welded unit in the 400 to 800 foot depth interval of USW UZ-1. Based on an assumed unit hydraulic gradient, Montazer, et al., (1985) use relative matrix hydraulic conductivities calculated by Peters, et al., (1984) to estimate 0.1 to 0.5 mm/yr. flux through this interval.

It is evident from figures 7, 8, 9, of Montazer, et al., (1985) that there has been considerable drift in the output from thermocouple psychrometers and heat-dissipation probes in USW UZ-1 over the two year monitoring period, and several of the instrument stations have failed. Wetting trends, drying trends, and reversals have occurred at individual stations. The interpretation by Montazer, et al., (1985) that these data, when extrapolated, indicate "relatively constant" matrix potential that represent ambient conditions is judged to be premature.

Rush, et al, (1984, p. 54) indicate that a perched saturated zone is "probably" present in USW H-1 in the depth interval 448 to 458 m; this is based on 45 minutes of airlift water production at flow rates of 1.3 to 1.6 liters/second (21 to 25 gpm) while the well was at a depth of 458 m (Rush, et al., 1983, p. 19). This zone is in the lower portion of the Topopah Spring welded unit.

Similarly, drilling of USW Uz-1 was discontinued at 387 m because a "large' volume of water was encountered, and "the water level could not be lowered significantly." This may represent a naturally occurring perched-water zone, although the water is reported to contain polymer identical to that used in drilling USW G-1, 305 m to the southeast (Whitfield, 1985). However, no analyses of either the encountered water in UZ-1 or drilling water used at USW G-1 have been published.

Prior drilling activities in the vicinity of USW UZ-1 is reported to have introduced large quantities of drilling fluids not the subsurface. Approximately 8,700,000 liters (2,300,000 gallons) of water-based polymer drilling fluid were lost during drilling of USW G-1 (Whitfield, 1985) and over 2,200,000 liters (580,000 gallons) were lost during drilling of USW H-1 (Rush, et al., 1983, p. 20). Locating USW UZ-1 in an area that was proximate to areas perturbed by prior drilling activities was an error in judgment in our opinion.

The vadose-zone saturation encountered in H-1 and UZ-1 may be naturally occurring saturation (perched water) or saturation caused by drilling fluid losses. As chemical analyses of fluid samples for UZ-1 and H-1 (448-458 m zone) have yet to be published, we are not able to judge if the water is only drilling fluid, mixtures of perched water and drilling fluid, or perched water. However, to be conservative, we assume that the fluid encountered is perched water until proven otherwise. The DOE program has, to date, ignored this evidence for perched water in the Topopah Spring Member immediately adjacent to the repository block at approximately the repository-zone depth. Establishing the natural occurrence of perched water is key to site characterization because its presence indicates fracture flow to the depth of occurrence. Instead of following though with an assessment program of the vadose-zone saturation in the area, the water-potential measurement experiment of USW UZ-1 was established. Unfortunately, this effort has yielded so little useful water-potential data that the principal investigators (Montazer, et al., 1985) have treated the widely scattered data as single-valued in terms of fluid-potential gradient! These ambiguous results and the failure to study encountered saturation leaves the vadose-zone flux question totally unresolved at this locality.

The Maxey-Eakin Recharge Method for Flux Estimation:

Another line of "evidence" cited by Wilson (1985) in support of the "conservative" upper-bound flux of 0.5 mm/yr. is a calculation based on the Maxey-Eakin method. In the Maxey-Eakin method, the recharge to a ground-water basin is calculated from specific percentages of the precipitation which is estimated to fall upon several elevation zones on the mountains surrounding that ground-water basin. Without explanation from the original authors, "..the amount of water from the successive zones that reach the ground-water reservoir is estimated as 0, 3, 7, 15, and 25 percent of the precipitation in the respective zones (Maxey and Eakin, 1949, p. 40, cited in Watson, et al., 1976, p. 342).

The Maxey-Eakin method of estimating recharge has not demonstrated validity or utility for determining accurate rates of recharge for localized site-specific hydrogeologic environments such as Yucca Mountain. The basic assumptions necessary for application of the method are: 1) recharge is systematically related to mean annual precipitation, 2) higher percentages of recharge occur from precipitations which falls at the higher altitudes (and usually in greater annual amounts), and 3) the ground-water catchment basins can be delineated. The method also required two other assumptions when originally developed: that the available ground-water discharge estimates were accurate and that the flow systems are in equilibrium (recharge is equal to discharge).

A serious weakness of the Maxey-Eakin method for estimating recharge in a local setting is the general absence of knowledge of the conditions under which recharge occurs, such as the roles varying local hydrogeologic environments and climatic events may play in controlling recharge. It is also undemonstrated that mean annual precipitation is the best parameter of climate from which to estimate recharge. Through trial and error, percentages of mean annual precipitation by zonation have been assumed to equal estimated discharge, and it has been assumed that the higher terrane precipitation is more important and thus more heavily weighted with higher percentages of recharge resulting from the precipitation. There are, however, no studies that have demonstrated unique recharge rates based on percentages of precipitation, and therefore, the Maxey-Eakin recharge estimate derived for a relatively small area like Yucca Mountain has no dependable validity.

In the general absence of knowledge of recharge processes and rates in site-specific environments of the Great Basin, including those at Yucca Mountain, there is little reason to postulate or justify a uniform flux rate in the vadose zone or to believe a method such as the Maxey-Eakin method would accurately characterize the flux rates for travel-time purposes. It is entirely possible, in the climate that prevails at Yucca Mountain, that all recharge is restricted to localized site specific hydrogeologic conditions, such as wash areas underlain by alluvium and fractured rock. It is also possible that in the more arid area, such as Yucca Mountain, much of the recharge may be closely related to "extreme event" precipitation occurrences related to the arid climate. In other words, recharge at Yucca Mountain may be highly localized in both time and space, and travel time estimates for the vadose zone should be so structured to address these possibilities in order to meet the intent of the travel-time objective.

Vadose (Unsaturated) Zone Travel Times:

Vadose-zone travel time estimates in the EA are based on the analysis by Sinnock, et al., (1986). The analysis can be summarized as follows:

1. The disturbed zone was assumed to extend to a a position 560 meters (m) below the midplane of the 45 m thick repository horizon.

2. The region between the disturbed zone and the water table was discretized into 963 vertical prisms, each measuring 76.3 m square; each prism was divided into 3.105 m thick elements.

3. Recharge flux was assumed to be uniformly distributed in time and space; 0.6 mm/yr was adopted as a baseline value.

4. A value of saturated matrix hydraulic conductivity for each element within a particular hydrogeologic unit obtained by statistical sampling methods from a frequency distribution fitted to the matrix hydraulic conductivity data for that particular unit.

5. The randomly selected value of hydraulic conductivity was compared with the value of flux; if the flux value was less than 0.95 times the saturated matrix hydraulic conductivity, it was assumed that the flow within that element was entirely in the porous rock matrix, and a value for matrix effective porosity was then chosen by random sampling from the frequency distribution of porosity values for the appropriate hydrogeologic unit.

6. Water particle velocity for each of the elements for which only matrix flow was assumed to occur was calculated by dividing the flux value by the samples effective porosity, assuming a hydraulic gradient equal to 1.0, then modified to account for partial saturation.

7. If the ratio of flux to the randomly sampled value of saturated matrix hydraulic conductivity was equal to or greater than 0.95, it was assumed that fracture flow occurred for that quantity of flux in excess of 0.95 times the saturated matrix hydraulic conductivity.

8. An effective porosity of 0.0001 was assumed for all fracture flow, and the velocity of flow in fractures for each element was determined by dividing the calculated value for flux in the fractures by 0.0001.

9. The shorter of matrix of fracture flow time was considered to be the "travel time" through any individual element.

10. Ground-water travel time in each of the 963 vertical prisms was calculated as the sum of travel times in all of the 3.06 m thick elements comprising the individual prisms.

11. The procedure was repeated ten times for each prism to provide a representation of the variation in travel time due to the variation in hydraulic parameters.

The selection of a disturbed-zone boundary 40 m below the midplane of a 4 5 m thick envelope containing the underground facilities (Sinnock, et al., 1986, p. 18) is essentially arbitrary. Although the disqualifying condition addressed in the EA applies to pre-waste emplacement conditions, application of the disqualifying condition to a particular site requires that the extent of the disturbed zone during the 1,000 years following waste emplacement be known. Until a quantitative evaluation of convective heat transfer and associated mineral alterations is demonstrated, the approximate extent of the disturbed zone will not be known.

Discretization of the region between the repository horizon and the water table appears to have been guided by convenience rather than a rational choice of element size based on a geostatistically valid correlation length. Since the model does not allow for a nonuniform wetting front (fingering) in individual prisms; this phenomenon is likely to occur on a scale much smaller than the 76.2 m horizontal grid size. The assumed vertical correlation distance is of critical importance in determining the travel time through a vertical prism. This is because the equivalent permeability of a vertical prism is defined by the harmonic mean permeability of the individual layers; the harmonic mean is weighed toward the properties of the least-permeable elements. The greater the number of elements, the greater the probability that a low permeability, but not so low as to require fracture flow) will be assigned to one or more elements in the prism. Sinnock, et al., (1986, p. 58) have concluded that the travel-time distribution is apparently most sensitive to flux, correlation lengths, and spatial variations of saturated matric hydraulic conductivity. Also, "...the sensitivity of the travel times to the correlation lengths suggests how prudent it is to perform a carefully designed testing program for determining the correlation length of all key parameters influencing flow velocities" (Sinnock, et al., 1986, p. 50). A key point is that "...neither the vertical correlation length nor the horizontal correlation length has been determined for the hydrogeological units at Yucca Mountain..." (Sinnock, et al., 1986, p. 15). Vertical correlation length was therefore considered a "free" variable in simulations of unsaturated-zone travel time (Sinnock, et al., 1986, p. 15). If the vertical correlation length is assumed to be at least as great as the thickness of each unit, travel times for approximately two percent of the prisms are less than 1,000 years, even with a flux of only 0.5 mm/yr (Sinnock, et al., 196, p. 48 to 49). The EA states that:

> "This approach yields higher, but probably physically unrealistic, estimates of the probability of continuous fracture flow and rapid matrix flow than the (3.05 - meter) interval sampling method..." (DOE, 1986, section 6.3.1.1, part 6.3.1.1.5, p. 6-150, paragraph 4, lines 11 to 13, and p. 6-162 first partial paragraph, lines 1 to 23),

ignoring evidence such as that presented by Spengler, et al., 1987, p. 25 and 27) that preferred orientations of joints and type and percent of joint fillings in the Topopah Spring Member and the tuffaceous beds of Calico Hills are nearly identical. Vertical correlation lengths may, therefore, be even greater than individual unit thicknesses.

The baseline flux value used for travel-time calculations is 0.5 mm/yr, a value thought by Wilson (1985) to be a "reasonable and conservative" upper bound flux for Yucca Mountain. Using a trial flux value of 1.0 mm/yr, Sinnock, et al., (1986, p. 52) found that a "substantial" proportion of flow paths have travel time of less than 10,000 years. It is emphasized that the nonconservative 3.05 m vertical correlation length was obtained during adjustments of flux; results of simulations that incorporate conservative vertical correlation lengths, and conservative flux rates have not been made available. Given the extreme sensitivity of travel time to flux rate (Peters, et al., 1986, p. 30 to 33) and the very real uncertainty in flux (discussed earlier in this review) we consider the range of flux values utilized in trial calculations of travel time to be incomplete.

Lognormal frequency distributions were fitted to available saturated matrix hydraulic conductivity data from the hydrogeologic units at Yucca Mountain; these distributions were then randomly sampled during each simulation to provide estimates of saturated matrix hydraulic conductivity for each block in the discretized region. Fitting a set of data with a lognormal distribution has two effects; the influence of extremely high values are minimized, and the logarithms take on the characteristics of a normally distribute population. Sinnock, et al., (1985, p. 35) have made a conceptual error by fitting bimodal distributions of saturated matrix hydraulic conductivity data from the Calico Hills vitric unit and Prow Pass welded unit with lognormal distributions.

The assumptions that only matrix flow occurs when the flux rate is less than 0.95 times the saturated matrix hydraulic conductivity is open to question. Skin effects on fractures and hysteresis in the moisture-content dependent characteristics of the rockmass will cause fracture flow to dominate (over matrix flow) earlier and more extensively than otherwise expected (see Montazer and Wilson, 1984, p. 25

for a discussion of hysteresis). As recognized by Montazer and Wilson (1984, p. 25) a secondary hysteresis effect, due to air entrapment in matrix block s during wetting, would further promote fracture flow during recharge events. Hysteresis and skin effects both escape mention in the EA, and the sensitivity of the analysis to the assumed constant relationship between flux an saturated hydraulic conductivity is not addressed.

The concept of relative permeability discussed at length by Weeks and Wilson (1984, p. 12 to 13) appears to have been ignored in the treatment by Sinnock, et al., (1985) and subsequently in the EA. If matrix hydraulic conductivities had been adjusted downward to account for the effects of partial saturation, a proportional increase in fracture flow would result.

Flow velocity through fractures has been obtained from an assumed fracture porosity and an assumed flux excess above the amount transmitted by the matrix. Hydraulic tests on fractured specimens by Peters, et al., (1985, p. 54) indicate fracture apertures up to 67 microns in the Topopah Spring welded unit and 31 microns in the zeolitized Calico Hills unit. Corresponding fracture hydraulic conductivities are 3.78×10^{-3} and 7.9×10^{-4} m/s, respectively; under a unit hydraulic gradient water could move from the repository horizon to the water table in fractures such as these in less than one week! Ogard, et al., (1983, p. 44) report fractures in the Topopah Spring welded unit with apertures exceeding 250 microns.

Saturated Zone Travel Time:

Basic data utilized by the DOE in the calculation of saturated zone travel time at Yucca Mountain is as follows:

1. Potentiometric data from 32 drillholes in the vicinity of Yucca Mountain (DOE, 1986, vol. II, section 6.3.2.2, part 6.3.1.1.5, p. 6-148, fig. 60-3).

2. Fracture effective porosities calculated by multiplying the fracture density from Scott, et al., (1983) by the effective aperture (calculated from a relationship provided by Freeze and Cherry (1979, p. 74).

3. Saturated hydraulic conductivities from tests on wells UE-25b#1 (Lahoud, et al., 1984) and J-13 (Thordarson, 1983).

Sinnock, et al., (1986) are referred to as the source of fig. 56-3 in the EA (DOE, 1986, vol. II, section 6.3.1.1, part 6.3.1.1.5, p. 6-148, fig. 6-3 caption); no similar figure appears in Sinnock, et al., (1985); Robison (1984) is not cited in Sinnock, et al., (19865). A similar figure does appear in Sinnock, et al., (1985, p. 19). No summary of water-level fluctuations in individual boreholes is yet available in the published literature. Although numerous wells are known to be equipped with pressure transducers and data-logging devices.

Fracture effective porosities for the zone of saturation were computed from a theoretical relationship between hydraulic conductivity of the fractured rock, fracture density, and fracture aperture (Snow, 1968, as cited in Freeze and Cherry, 1979, p. 74). This relationship is strictly applicable only to a single set of planar joints with constant aperture. Orientation bias, due to the relative orientation of fractures and the borehole, was accounted for through the relationship:

$$F_c = (\sin A)^{-1} \cdot F_m$$

where: F_c = fractures per cubic meter.

F_m = linear fracture frequency.

A = acute angle between the core axis and an individual fracture set.

This procedure converts all fractures to a single hypothetical set normal to the core axis.

Unfortunately, this simplistic approach to the estimation of fracture parameters does not account for contrasting properties of individual fracture sets, which are likely to differ in preferred orientation roughness, hydraulic aperture, mineral content, etc. The SEM image of a fracture in the lower, nonwelded portion of the Topopah Spring Member (Carlos, 1984, p. 32, fig. 31) illustrates how variable the aperture and roughness of individual fractures are likely to be in the field environment. Analysis that does not account for hydraulic properties of individual fracture sites, connectivities of the fracture sets, and hydraulic significance of fracture intersections markedly increases the uncertainty for the analysis.

Results of hydraulic testing at well J-13 indicate that "850 m^2/day probably is a reasonable maximum value for transmissivity (of the Topopah Spring Member)" (Thordarson, 1983, p. 49). Dividing this transmissivity by the 308./5 m thickness of the tested interval yields a hydraulic conductivity of 2.75 m/day (1,000 m/year). Examination of core recovery data from J-13 (Thordarson, 1983, p. 14) indicates that highly fractured intervals are quite localized, so the hydraulic conductivities of the producing intervals are probably much higher than the average value given above. Recent work by Erickson and Galloway (1984) has resulted in hydraulic conductivity estimates of between 59.56 m/day (21.7 km/year) and 74.3 m/day (27.1 km/yr) for fractured intervals in the Bullfrog and Tram Members of the Crater Flat Tuff. These values contrast sharply with the assumed hydraulic conductivity of 1.0 m/day used in the EA for a calculation of saturated-zone travel time in the indurated tuffs.

ADDITIONAL WORK NEEDED:

Review of the DOE documents which establish site-characterization programs.

RECOMMENDED PROGRAM:

Objective:

Continue to track the DOE site-characterization program in key issue areas, where the database and/or DOE approach is deficient.

EXISTING PROGRAM:

Review of the SCP and work plans.

Appendix E-II

Review of: Consultation Draft of the Site Characterization Plan : Yucca Mountain Site, Nevada
Research and Development Area, Nevada
January 1988 (DOE/RW-0160) by DOE, p. 2 to 28.

Review of Technical Documents

ISSUE:

The technical accuracy of the U.S. Department of Energy Site Characterization Plan : Yucca Mountain Site, Nevada Research and Development Area, Nevada : Consultation Draft : Nuclear Waste Policy Act (Section 113) (DOE/RW-0160), vols. 1 to 8, 1988 (CD-SCP) for Yucca Mountain.

OBJECTIVES OF ACTIVITY:

Review the CD-SCP, especially its hydrogeologically related activity, in terms of: 1) conceptual completeness and focus; 2) appropriateness of methodology to accomplish stated objectives; 3) availability of supportive technology; and 4) probability of success and/or feasibility.

ACTIVITY SUMMARY:

The following elements of the CD-SCP were reviewed in terms of the four points (2a, b, c, and d) listed above:

Geohydrology Program
Geochemistry Program
Rock Characteristics Program
Climate Program
Thermal and Mechanical Rock Properties Program
Waste Package Program
Performance Assessment Program

The review was structured into three basic parts:

Overview Comments - which deals with general impressions;
Issue Resolution Comments - deals specifically with several of the most important hydrogeologic issues; and
Activity Reviews - (Appendix 1) which contains each individual's review of the technical activities.

FINDINGS:

The following comments have been abstracted from the review of the CD-SCP by MAI:

OVERVIEW COMMENTS

GENERAL COMMENTS

The following objectives of the CD-SCP are stated in the Annotated Outline for Site Characterization Plans (DOE, February 1987, p. xii to xiv):

"The purpose of the SCP is to provide a document in which the DOE:

- **Describes the site, design of a repository and engineered barriers** appropriate to the site, waste packages, emplacement environment, and performance analysis **in sufficient detail** so that the planned site characterization program may be understood.

- **Identifies** the uncertainties and **limitations** on site- and design-related information developed during site screening, including **issues** that need further investigation or for which additional assurance is needed.

- **Describes** the detailed programs for additional work, including **performance confirmation**, to (1) resolve outstanding **issues**, (2) reduce uncertainties in the data, and (3) make site suitability findings relative to DOE siting guidelines, 10 CFR 960.

The SCP will provide a vehicle for early NRC, State, Indian tribal, and public input on the DOE's data-gathering and development work so as to avoid postponing **issues** to the point where modifications would involve major delays or disruptions in the program. Early review of the DOE's site characterization plans as presented in the SCP will provide an opportunity for the NRC to evaluate whether the DOE's proposed program is likely to generate data suitable to support a license application." (OGR/B-5, p. xiii).

We find that the CD-SCP substantially, but not completely, meets the above first objective. We find that it does not consistently meet the second and third objectives. **It does not consistently describe the detailed programs** to: 1) resolve outstanding issues; 2) reduce uncertainties in the data; and 3) make site suitability findings relative to the DOE siting guidelines, 10 CFR 960.

We find that the CD-SCP **does not entirely** establish what is known about the Yucca Mountain from site-exploration activities to date. Many if not most aspects and findings are freely and fully discussed, but key findings, such as evidence of perched water within the vadose zone, and important observations of gas-circulation gradients within the vadose zone, are omitted. These omitted observations could prove to be the **most fundamental findings** to date with respect to the site's ability to isolate waste.

We find also, with respect to the above point two objective, that a major issue of fracture flow in the vadose zone has been deemed so unimportant that the resolution activity is to be primarily laboratory experiments. Therefore, we judge the CD-SCP **fundamentally deficient** with respect to resolving the issue by reducing or eliminating the uncertainties about fracture flow in the vadose zone.

We find that, with respect to the above, the CD-SCP often fails to provide enough details in the activity plans to confidently judge the plans.

The following questions are intended to be addressed by the SCP (DOE, OGR/B-5, February 1987):

- Have the important information needs and unresolved issues been identified?

- Does the SCP specifically address these information needs and present program plans to obtain the needed information?

- Are the methods of testing and analysis proposed for the planned site characterization program appropriate?

- Have alternative methods of testing and analysis been identified and evaluated, and has an adequate basis been provided for the selection of the methods to be used?

- Will the data to be collected and the reliability of the collection methods and analysis be of adequate quality to support site selection and a future license application?

- Have the testing plans been based on the performance requirements of the Mined Geologic Disposal System (MGDS) components, and are the tests adequate to enable evaluation of whether or not the MGDS components will perform as required?

We recognize aspects where the CD-SCP is seriously deficient in all of the above points of question. We think that important negative answers can be given for the first five questions when aspects of vadose-zone hydrology are considered. Point six, discussion of whether tests are adequate to enable evaluation of the expected performance of the MGDS, is not recognized in the CD-SCP. We assume that such testing call upon characterizing a combination of dynamic thermal loading and unloading, multiphase water transport, and dissolution processes based on in-situ geochemistry, all acting upon the engineered barriers.

We find the CD-SCP, when judged by the data development/analyses activities, unlikely to create a technical program that will establish viable databases to resolve or answer several of the important issues. The basis for this statement can be further examined in Appendix I reviews. A summary of this appendix reviews is shown in Table 1 (appendix reviews are not included in this report). Many activities are poorly designed and/or focused with respect to available technology. Many others are not feasible with respect to combinations of time, financial resources, and human and laboratory resources. Idealistic approaches, with much modeling in the face of little or no data and marked uncertainties with respect to processes operating, characterize the planned technical program. The CD-SCP is very consistent in calling upon numerical models (using existing, or newly developed, and/or to be developed codes) for the resolution of the characterization issues created by the complexity of the site and the very limited databases.

Our opinion is that the CD-SCP activities need to be carefully screened, focused, and modified into feasible, well-coordinated activity programs that could be completed in five or six years. Each program (investigation, study, and activity) needs the benefit of peer review by experts experienced in both theory and field investigation.

Further, an appropriate SCP would clearly identify and rank the most likely fatal flaws (issues) of the geologic-barrier system of the site to prioritize and coordinate site characterization studies. This has not been done; the CD-SCP generally fails to establish a vadose-zone fracture flow/travel time issue resolution program that will work, and totally ignores the need for a research program to establish the impacts of the thermal envelope, and the associated extent of the disturbed zone with the induced hydrothermal system. Such a disturbed system has major potential to impact waste isolation.

DISCLAIMER

We find the disclaimer printed on the back cover of each volume to be inappropriate to the work presented. It says that the report was prepared as an account of work sponsored by the United States Government, but neither the U.S. Government nor the U.S. Department of Energy, nor employees make any warranty, nor assumes legal liability or responsibility, etc. It also states that the views and opinions of authors expressed herein do not necessarily state or reflect those of the United State Government nor an agency thereof.

The DOE is clearly the author of the CD-SCP, as no authorship is shown other than the U.S. DOE. If the above disclaimer were to be used in an appropriate manner, the majority of the CD-SCP should be backed by specific authorships. Specific authors would be appropriate for the expert opinion and judgment desirable in the planned activities of exploration and research. We find by omitting the specific technical authorship, the DOE may have, perhaps inadvertently, diminished the technical quality of the CD-SCP. We suggest the DOE recognize the scientific and technical challenge of characterizing Yucca Mountain, and appropriately indicate specific authorship on scientific and technical activities in the SCP.

DOE GOALS

A very disquieting presentation characteristic of the CD-SCP is the apparent perception that the given site,Yucca Mountain, in terms of geologic-barrier performance, can be made better or worse, just as an engineered system can be made better or worse by design changes. This conceptual approach has flavored the DOE selection process (Draft Environmental Assessment and Environmental Assessment documents) and continues in the CD-SCP. Explicit examples occur throughout the CD-SCP discussions and in tables, such as Table 8.3.1.5-1 on pages 8.3.1.5-4 and 5. This table, dealing with site performance during a climate change, shows a column of initiating events or processes, and another correlating column entitled "tentative goal", which gives the currently perceived extreme values that would be acceptable. Such a title "tentative goal" would be appropriate for an engineered barrier where engineered design determines performance. **A natural system, the geologic barrier, can not be altered once the site has been selected.** There is no goal, therefore; there is only performance characterization. Geologic and hydrogeologic aspects can only be characterized to varying degrees of accuracy as to how they will perform in waste isolation. Therefore, if the DOE correctly perceived that its mission is to characterize the site to establish if the repository should be built, the many "tentative goal" columns would be better named "performance requirement" or "tentative performance requirement." The term "goal" is widely used in the CD-SCP, and should not be used for the SCP for uncontrollable geologic and hydrologic aspects of the specific site. Performance goals are fine for engineered aspects.

CD-SCP CONTENTS AND TECHNICAL REVIEW

The CD-SCP is so massive and complex in terms of topical scope and objectives that the reader is easily diverted from the true intent of the document. The SCP is the **program of exploration and research, both in the laboratory and in the field.** Therefore, we have focused our review efforts not on the very extensive organizational discussions and rationalizations, but on the descriptions of the programs of exploration and research.

We believe that success or failure in reaching **confident** site characterization will depend heavily on the SCP adopted by the DOE. We base this belief on the following: 1) the choice of a repository-horizon environment that is totally unknown from a hydrogeologic perspective; 2) the ten years of effort already expended on Nevada Test Site (NTS) and the Yucca Mountain characterization; and 3) the continuing high degree of uncertainty with respect to many critical performance aspects of the site. Therefore, the CD-SCP has been reviewed in anticipation of discovering the technical program the DOE would mount to resolve the many issues and performance questions.

Activities are the technical and/or scientific efforts planned for site characterization. The CD-SCP links activities, where there is a usually brief discussion of the planned objectives, methods, and associated elements, to studies, generally composed of one or more activities, to investigations, which are composed of studies, to programs. All have been organized and rationalized with respect to characterization issues from the perspective of licensing requirements. The CD-SCP provides reasonable planning discussions at these levels. However, the **activities** are a better measure of the planned site characterization, and we give, in general, very low marks for the activities.

We have reviewed each activity (Appendix I summary is given in Table 1) in our topical areas of responsibility because we recognize them as the only fundamental investigative activities in the CD-SCP. These activities, when executed, must provide the information to deal definitively with all issues and have the power to characterize the site. **Unfortunately, we have found that many activities are only at the conceptual stage at best, and would be better judged when work plans and technical procedures become available.** In response to this very real problem, we were forced to review the activities from an expert opinion mode, generally reading between the lines and judging the activity from several perspectives.

Technical Review Criteria: The four criteria adopted in the activity reviews: 1) conceptual completeness and focus; 2) appropriateness of methodology to accomplish stated objectives; 3) availability of supportive technology; and 4) probability of success and/or feasibility, warrant brief discussion. There are, however, no detailed **work plans** or **technical procedures** for each activity upon which we can base an in-depth review. Our ability to review conceptual aspects of a given activity is, therefore, better than our ability to review methodology, since the details of methodology are often not complete. **Any activity, if it fails in any of the four categories, fails to establish what is required for site characterization and/or issue resolution.** For example, one might find in a review that conceptual completeness or focus is rated low, and the other three aspects much higher. This would indicate that in our opinion, the activity can be performed in terms of methodology, available technology, and that there are the necessary resources for feasible execution, but it will not likely answer the correct questions. Conversely, we also find many of the activities more or less conceptually appropriate and focused, but unlikely to be successful because of deficiencies in methodology, available technology, or the likely availability of resources (including time).

In the reviews of the activities we find that, out of a total of 190 individual activities, we judge that 163 (about 86%) will not be successful in terms of the site characterization objectives (Table 1). When analyzed by program, we find only in one program (Climate) where there can be some important progress towards site characterization.

Table 1. Summary of MAI Reviews of CD-SCP Activities

CD-SCP PROGRAM	YES	NO	TOTAL REVIEWED
Geohydrology (8.3.1.2)	6(4)	51(47)	57(51)
Geochemistry (8.3.1.3)	4	33(29)	37(33)
Rock Characteristics (8.3.1.4)	1	5	6
Climate (8.3.1.5)	14(12)	15(14)	29(26)
Thermal and Mechanical Rock Properties (8.3.1.15)	2	2	4
Waste Package (8.3.4)	1	14(13)	15(14)
Performance Assessment (8.3.5)			
a. Engineered Barrier System (8.3.5.10)	3	23	26
b. Total System (8.3.5.13)	0	30	30
Total (without duplication)	31(27)	173(163)	204(190)

The DOE has, or could have, at its disposal, the best scientific facilities and cadre of scientists in the nation. Such resources have not been effectively tapped in the development of the CD-SCP. We think it productive to offer the probable reasons for our review findings:

I. The site-selection and licensing criteria demand knowledge about natural systems that is not normally established at the scales of consideration and the levels of confidence required.

II. The DOE has selected an **entirely** undocumented and little studied hydrogeologic environment for the repository at Yucca Mountain. There are few if any useful databases from similar environments in the world, and there are no proven techniques of study with respect to several key issues.

III. Fractured, and somewhat porous rock imposes a well-known but analytically intractable degree of complexity to fluid-flow systems, as does the vadose-zone position of the repository horizon. **It is known that conventional mathematical models and established field-test procedures will not perform adequately in both the saturated and vadose zones of the Yucca Mountain environment.**

IV. The host-rock stability is uncertain due to its origin and composition when subjected to the heat of the thermal envelope.

V. **The primary (and possibly only) waste-isolation attribute of the Yucca Mountain site is its location in an arid climate.** The mechanics and site-specific conditions of recharge are unknown in these arid climates for most classes of terrane, including that represented by Yucca Mountain.

The above factors relate to the thoroughness of the technical questions being asked, the very limited preexisting knowledge, and the complexity of the site. The following, however, relate to the DOE program:

VI. There is little evidence that the DOE has followed the expert advice offered by early peer-review groups. The characterization program continues to be weak in the same areas as the site-selection program (useful field studies lacking, useless models dominating).

VII. There is little evidence of peer review in the development of the majority of the CD-SCP activities. Only one program, climate change, seems to have had the benefit of independent peer review, and we judge half of the activities may succeed, which is a major improvement over all other programs.

VIII. There is ample evidence that many activities have been conceived and written, or perhaps rewritten, by authors with limited experience and training in the topical areas, and that these activities have not been reviewed by experts.

Points six through eight disappoint us. They indicate one or a combination of the following: 1) the DOE management has failed to recognize the complexity of the site (has not taken or used expert advice appropriately); 2) the DOE management has made a determination that careful characterization is not necessary, nor perhaps desirable; and/or 3) the DOE has failed to effectively develop and manage the required scientific program to confidently select and characterize the site.

PERFORMANCE ISSUES

The following sections are discussions and specific comments focused on selected performance issues:

PERFORMANCE ISSUE 1.1

The ability of a mined repository to limit radionuclide releases to the accessible environment is fundamentally dependent on geologic and hydrologic conditions at the site which, combined, establish the degree of the geologic barrier a specific site offers. Intrinsic properties such as permeability provide one general measure of site quality, while the chemistry of the rock-water system determines the mobility of radionuclides as well as the necessary desirable designs for the waste packages. Key Issue I in the Office of Geologic Repositories issues hierarchy relates to whether the mined geologic-disposal system at Yucca Mountain will isolate the radioactive waste from the accessible environment after closure in accordance with the requirements set forth in 40 CFR Part 191, 10 CFR Part 60, and 10 CFR Part 960 (CD-SCP, p. 8.2-2). Performance Issue 1.1, "Will the mined geologic disposal system meet the system performance objective for limiting radionuclide releases to the accessible environment as required by 10 CFR 60.112 and 40 CFR 191.13?" (CD-SCP, p. 8.2-3), dictates information needs 1.1.1 through 1.1.5 of section 8.3.5.13 of the CD-SCP, "Total System Performance":

Information Need (CD-SCP)

1.1.1	Site information needed to calculate releases to the accessible environment.
1.1.2	A set of potentially significant release scenario classes that address all events and processes that may affect the geologic repository.
1.1.3	Calculational models for predicting releases to the accessible environment attending realizations of the potentially significant release scenario classes.
1.1.4	Determination of the radionuclide releases to the accessible environment associated with realizations of potentially significant release scenario classes.
1.1.5	Probabilistic estimates for the radionuclide releases to the accessible environment considering all significant release scenarios.

Geochemistry

8.3.1.7 Overview of Rock Dissolution.....
8.3.1.7.1 Investigation: Rates of dissolution of crystalline and noncrystalline components in tuff.

Comments:

1. The use of the word "investigation" in the title/header is misleading; no investigation is planned.

2. Previous comments (Mifflin & Associates, Inc.) regarding the dissolution section of the EA have been ignored.

3. Specifically, considering the listed conclusions (p. 8.3.1.7-1) regarding dissolution in the EA, restated in the CD-SCP: the second conclusion regarding mineral insolubility is decidedly incorrect and not based on any factual information of which we are aware.

The first part of the fourth conclusion, insolubility of minerals comprising the host rock in and around Yucca Mountain, is incorrect as well; therefore the second part of the fourth conclusion, "significant subsurface rock dissolution is not a credible process leading to radionuclide releases greater than those allowable..." is incorrect information and contradicts current experiments (J. D. Rimstidt, personal communication, 1988) that suggest important mass transport occurs under nonequilibrium conditions (i.e., thermal gradients expected under repository conditions).

8.3.1.7.1.1 Application of Results

In general, there are **no results** when **no investigations** were specifically conducted to consider dissolution. The CD-SCP is illogical when it applies speculative conclusions from the EA to this important site-characterization issue. There are no results, only speculative and totally unsupported conclusions, to address higher-level findings concerning dissolution.

The dissolution question affects favorable conditions 3, 4, and 7 (Table 8.3.5.17-1) and potentially-adverse conditions (Table 8.3.5.17-2) 5, 7, 8, 10, and especially 23 (potential for future perched water bodies that may saturate portions of the underground facility).

Scenarios to characterize potentially-adverse condition [PAC] 5 do not address changes in the hydrologic conditions caused by the heat envelope generated by the repository after a few hundred years.

Scenarios regarding PAC 7 (ground-water geochemistry conditions that could increase solubility or chemical reactivity of the engineered-barrier system) do not address the thermal regime imposed by the waste repository, particularly the hydrochemical and mineralogical reactions that will accompany vaporization and condensation in fractures.

No scenarios concerning PAC 10 (dissolutioning) will be characterized further by DOE because their available information appears adequate to them. This is a serious flaw in the CD-SCP, since the assumption that dissolution will not occur has no basis in fact.

Scenarios regarding PAC 23, the potential for existing or future perched-water bodies that might saturate portions of the repository, do not include any that may result from actual storage of waste canisters in the repository over the several hundred years of perturbing thermal influences. Only the potential for perched-water bodies that may form under present [preclosure] conditions will be considered by the DOE. **This is a serious shortcoming in DOE's site-characterization plans considering the amount of water vapor that will be driven from the rock matrix in the greater than 95°C portion of the thermal envelope.**

If the DOE continues to assume that host rock and minerals are insoluble, then many other CD-SCP activities are inappropriate, such as 8.3.1.3.2.2.1 (History of mineralogic and geochemical alteration...); 8.3.1.3.2.2.2 (Smectite, zeolite, manganese minerals, glass dehydration and transformation); 8.3.1.3.3.2 (Kinetics and thermodynamics of mineral evolution); 8.3.4.2.4.1.1 (Rock-water interactions at elevated temperatures); 8.3.4.2.4.1.7 (Numerical analysis and modeling of rock-water interaction); and 8.3.4.2.4.4.2 (Repository horizon rock-water interaction). The CD-SCP dissolution program is totally deficient. The aforementioned studies and activities need to be integrated into a dissolution program.

General Comments: Geochemistry Section

The following items represent our major concerns regarding the geochemistry program in the CD-SCP. For specific comments, see the activity review sheets and the specific comment section of this review.

1. The continued use of water from well J-13 as a reference water for all experimental work is not justified. Most of the credit taken by DOE for ground-water travel time is postulated to occur in the vadose zone and therefore most of the retardation should also occur in the vadose zone. Thus, obtaining chemical analyses of a vadose-zone water should be of the highest priority in the CD-SCP. The range of vadose-waters compositions should be determined as quickly as possible. As experiments and modeling employing J-13 water may have to be redone, it would be judicious of DOE to suspend those activities utilizing J-13 water until the vadose-water chemistry is characterized.

2. Another serious problem involves extrapolating laboratory sorption data (determination of K_d's and retardation factors) to actual field conditions. Not enough importance is being attached to this subject. It is extremely difficult to envisage how data from experiments employing crushed tuff could be correlated to the field with any scientifically valid confidence. Crushing tuff generates new surfaces with attendant high-surface energies and nonrepresentative sorption characteristics. Furthermore, the mineralogy of the new rock surfaces from a modal standpoint is not known and should not be assumed from modal mineralogy of a whole rock sample. This may partially account for the unexplained scatter in previous experimental work and the differences between crushed tuff and solid core experiments. Highest priority should be assigned to validating the proposed experimental approach through field tests of sorption/retardation before additional resources are wasted in this extensively practiced but totally unproven methodology.

3. A major concern is the undue emphasis placed on modeling before experimental methodology is proven and meaningful field data are collected. Vast resources will apparently be directed to modeling efforts before sufficient information is collected to justify modeling.

4. Samples to be utilized in activities/studies are not clearly identified, nor are sample collection and preservation techniques. Very little is known about the site to date because of sampling difficulties.

5. Analytical methodology is not always indicated.

6. Technical procedures are not determined.

7. There are major inconsistencies in planned activities from one section to another.

8. Incomplete or wrong methodologies are used in many cases to obtain the desired information (See Appendix I Specific comments).

General Comments: Issue 1.1 Resolution Strategy

1. DOE continues to assume that matrix flow predominates over fracture flow in the vadose zone and that the matrix must be saturated for fracture flow to occur. No data exists to support these assumptions; in fact, based on suction-head data for the various rock units, these tuff units are most likely effectively saturated and therefore fracture flow should predominate.

2. DOE continues to assume that the percolation flux is uniformly distributed in space and time. This is highly speculative, not realistic nor conservative, and not supported by any data.

3. The dissolution scenarios (among others) have been ruled "not sufficiently credible to warrant further consideration" (DOE, 1986) by a "panel of experts". The same ruling was incredulously rendered for the bedded and domed salt sites. This ruling was not made by an independent panel of scientifically and/or technically recognized geochemists; but rather it was a DOE panel with, apparently, very limited expertise in the main subject area.

4. The DOE should convene a panel of recognized practicing geochemists and charge these experts with the tasks of evaluation of the rock-dissolution questions, particularly in light of the thermal envelope and the water content of the repository-rock horizon. Then it needs to follow the panel recommendations on appropriate rock-dissolution studies and add these to the SCP, if appropriate.

5. Under "Performance Parameters for Scenario Class C-3 [Table 8.3.5.13-14., p. 8.3.5.13-63] (changes in unsaturated zone rock hydrologic and geochemical properties)", no consideration is

given to the effect of waste emplacement in the repository. Specifically, those changes in rock-water geochemistry and hydrologic properties surrounding the repository level that may result in the formation of a perched-water body in the vadose zone above and below the repository, such as permeability and porosity changes brought about by refluxing of vadose-zone waters due to the thermal pulse of decaying waste.

6. Individual evaluation of topical scenarios for the purpose of eliminating scenarios with insignificant consequences may overlook the coupling that may occur between two or more processes/events that could produce significant consequences for the release of radionuclides to the accessible environment. We think this has occurred: **the DOE has omitted the most obvious scenario of water vapor driven from the thermal envelope condensing in the cooler fractures that surround the repository horizon** and returning to the boiling zone by gravitational forces.

Summary Comments: Issue 1.1 Resolution Strategy

Probabilistic estimates of radionuclide releases to the accessible environment must be based on sound, statistically valid, data and not on unproven DOE assumptions such as:

1. Matrix flow predominates in vadose zone;
2. percolation flux is areally and temporarily uniformly distributed; and
3. batch sorption experiments employing crushed tuff are representative of field conditions;
4. nor on statistically biased data such as were used by Sinnock, et al. (1986).

Until the aforementioned assumptions are proven by site characterization or changed to conservative assumptions, and sound statistical and geostatistical techniques are employed to evaluate data, the resolution of issues will continue to be flawed.

PERFORMANCE ISSUE 1.3:

Important "special" sources of ground water that are in close proximity to a repository should be well-characterized. Key Issue I in the Office of Geologic Repositories issues hierarchy relates to whether the mined geologic-disposal system at Yucca Mountain will isolate the radioactive waste from the accessible environment after closure in accordance with the requirements set forth in 40 CFR Part 191, 10 CFR Part 60, and 10 CFR Part 960 (CD-SCP, p. 8.2-2). Performance Issue 1.3, "Will the mined geologic disposal system meet the requirements for the protection of special sources of ground water as required by 40 CFR 191.16?" (CD-SCP, p. 8.2-3), dictates information needs 1.3.1 and 1.3.2 of section 8.3.5.15 of the CD-SCP, "Ground-water Protection".

Information Need (CD-SCP)

1.3.1 Determination whether any Class 1 or special sources of ground water exist at Yucca Mountain, within the controlled area, or within 5 km of the controlled area boundary

1.3.2 Determine for all special sources whether concentrations of waste products in the ground water during the first 1,000 years after disposal could exceed the limits established in 40 CFR 191.16.

Section 191.16 of 40 CFR Part 191 was added to the final EPA rule to provide protection for those individuals in the vicinity of a disposal system (FR 38072, September 19, 1985). The CD-SCP (p. 8.3.5.15-1) provides the following explanation of EPA water-source designations:

> "An aquifer must meet several criteria to be designated as a special source. The first step in the evaluation is to establish whether the aquifer is a Class I source as defined by the EPA Ground Water Protection Strategy of 1984 (EPA, 1984). The conditions that must be met for designation as a Class I source are (1) that the source is highly vulnerable to contamination because of the hydrologic characteristics and (2) that the source is irreplaceable in that no reasonable alternative is available to substantial populations or that the source is ecologically vital in that it provides baseflow to a sensitive ecological system.
>
> If an aquifer meets the criteria for a Class I source, the next step is to determine whether it qualifies as a special source of ground water. 40 CFR 191.12 defines a special source of groundwater as "those Class I ground waters identified in accordance with the agency's Ground-Water Protection Strategy . . . that: (1) are within the controlled area encompassing a disposal system or less than 5 km beyond the controlled area [the controlled area is the actual area chosen according to the 40 CFR 191.12 definition of the controlled area]; (2) are supplying drinking water for thousands of persons as of the date that the [DOE] chooses a location within that area for detailed characterization as a potential site for a disposal system (e.g., in accordance with Section 112(b) (1)(B) of the Nuclear Waste Policy Act); and (3) are irreplaceable in that no reasonable alternative source of drinking water is available to that population."

A valley-fill aquifer, a tuff aquifer, and a carbonate aquifer are present at Yucca Mountain. DOE states that only the valley-fill aquifer was serving a population of thousands of persons at the time that the site was chosen for characterization (CD-SCP, Section 3.8). DOE also offers a preliminary determination that no potential special sources of ground water are present at the site, below the site, within the boundaries of the controlled area, or within 5 km of the controlled area boundary (CD-SCP, p. 8.3.5.15-6). The hydrologic feasibility of developing the lower carbonate aquifer must consider the possibility of interbasin diversion of baseflow to the Ash Meadows Springs (Section 8.3.1.9.2.). DOE also considers that the Ash Meadows area is part of a different ground-water subbasin (Ash Meadows) from the Alkali Flat-Furnace Creek Ranch ground-water subbasin, which contains Yucca Mountain (Section 3.6).

The content of Section 8.3.1.9.2 (Investigation: Studies to provide the information required on present and future value of energy, mineral, land, and ground-water resources) suggests that the CD-SCP does not intend to refine the very poor understanding of the western margin of the Ash Meadows flow system between Yucca Mountain and Ash Meadows. The projection of this boundary north of Lathrop Wells is entirely speculative. DOE plans an analysis 1.3.1.1. (p. 8.3.5.15-7) to determine whether any aquifers near the site meet the Class I or special-source criteria. This analysis consists of two activities (1.3.1.1.1 and 1.3.1.1.2). These pull hydrologic data from other activities and demographic information into an assessment.

Comments and Discussion

DOE prefers to ignore that the western extent of the Ash Meadows' ground-water flow system is highly uncertain, as well as the carbonate aquifer's uncertain relations with the tuff aquifers of Yucca Mountain and the valley-fill aquifer in Amargosa Valley.

Yucca Mountain overlies the fragmented western extent of a regional-carbonate aquifer (Winograd and Thordarson, 1975), which discharges on the order of 17,000 acre-feet per year of good-quality ground water near Ash Meadows. Structural relationships probably control the extent of the carbonate aquifer in this area. Four major Mesozoic thrust faults that involve the subvolcanic rocks are projected through the Yucca Mountain-Jackass Flats area by Wernicke (1988). From southeast to northwest, these are the Clery-Spector Range Thrust, the Schwaub Peak-Mine Mountain (?) Thrust, an equivalent of the back-facing Panama Thrust, and the Last Chance Thrust. These thrust sheets involve a nearly complete Paleozoic section that is known to include major aquifers in the region. If, as Carr and Monsen (1988) suggest, the breakaway zone for the Fluorspar Canyon Fault is west of Yucca Mountain and faults at Yucca Mountain are genetically related to the Crater Flat graben system, then Paleozoic carbonates could underlie the entire Yucca Mountain-Jackass Flats area. In the absence of large-magnitude Cenozoic extension, the Tertiary section would be expected to be underlain by an allochthonous wedge corresponding to rocks between the Marble Canyon and White Top Thrusts, and equivalents. The Cottonwood Mountains, southern Funeral Mountains, southern Bare Mountain, and Mine Mountain (NTS) offer the best exposures of tectonic elements that could be structurally analogous to those beneath Yucca Mountain. In the Grapevine Mountains, the same structural level of the fold and thrust belt is exposed, but Cenozoic rotation and extensional overprinting have confused relations among pre-Tertiary units there somewhat more than in the other listed areas.

The Mesozoic fold and thrust belt that may underlie Yucca Mountain consists of several discrete thrust sheets with stratigraphic throws of up to 5 km and the full spectrum of brittle through ductile behavior. A key question is whether extensional crustal thinning has removed Paleozoic carbonates from beneath Yucca Mountain, and if the Silurian dolomite in UE25-p#1 is part of the laterally continuous carbonate aquifers which discharges at Ash Meadows. The northwest strike of prethrust normal faults in the Spring Mountains region indicates that hydraulic relations in and beneath the thrust sheets between Yucca Mountain and the northern Specter Range-Ash Meadows area should be explored. Because of the water-resource potential of the regional-carbonate aquifer, an understanding of flow paths within it is needed to resolve performance issue 1.3. The carbonate aquifer serves as a water supply for NTS activities and supports the unique and endangered ecology of the Ash Meadows area, including the Devil's Hole part of Death Valley National Monument. In addition, the major spring areas in Death Valley National Monument are the principal water supply for the Furnace Creek area and may be part of the carbonate-aquifer system.

The available evidence indicates that:

1. The alluvial aquifer is Class 1.

2. The tuff aquifer is Class 1 because it is a prime recharge source to the alluvial aquifer.

3. The carbonate aquifers that discharge at Ash Meadows and at Death Valley are Class 1.

We see that the "special source" designation can only be confidently resolved by determining the flow-system relationships and boundary conditions between the three aquifers known to exist in the vicinity of the controlled area. The CD-SCP has no data collection activities that will produce a definitive database and it therefore offers no useful plan to resolve the ground-water protection "special source" issues.

PERFORMANCE ISSUE 1.6

The statutory requirement for evaluation of ground-water travel time (GWTT) presupposes a need for understanding the geometry and geologic controls on ground-water flow. Key Issue 1 in the Office of Geologic Repositories issues hierarchy relates to whether the mined geologic-disposal system at Yucca Mountain will isolate the radioactive waste from the accessible environment after closure in accordance with the requirements set forth in 40 CFR Part 191, 10 CFR Part 60, and 10 CFR Part 960 (CD-SCP, p. 8.2-2.). Performance issue 1.6, "Will the site meet the performance objective for prewaste-emplacement ground-water travel time as required by 10 CFR 60.113" (CD-SCP, p. 8.2-5), dictates **information needs 1.6.1 through 1.6.5** of section 8.3.5.12 of the CD-SCP, "Ground-water Travel Time":

Information Need (CD-SCP)

1.6.1	Site information and design concepts needed to identify the **fastest path of likely radionuclide travel** and to calculate the ground-water travel time along that path.
1.6.2	**Calculational models to predict ground-water travel times** between the disturbed zone and the accessible environment.
1.6.3	**Identification of the paths of likely radionuclide travel** from the disturbed zone to the accessible environment and identification of the fastest path.
1.6.4	Determination of the prewaste-emplacement **ground-water travel time along the fastest path of likely radionuclide travel** from the disturbed zone to the accessible environment.
1.6.5	**Boundary of the disturbed zone.**

The success of several investigations in the geochemistry program will depend on recognition of ground-water flow paths:

CD-SCP Section

8.3.1.3.1	Investigation: studies to provide information on water chemistry within the potential emplacement horizon and along potential **flow paths**;
8.3.1.3.2	Investigation: Studies to provide information on mineralogy, petrology, and rock chemistry within the potential emplacement horizon and along potential **flow paths**;
8.3.1.3.4	Investigation: Studies to provide the information required on radionuclide retardation by sorption processes along **flow paths** to the accessible environment;
8.3.1.3.5	Investigation: Studies to provide the information required on radionuclide retardation by precipitation processes along **flow paths** to the accessible environment;
8.3.1.3.6	Investigation: Studies to provide the information required on radionuclide retardation by dispersive, diffusive, and advective transport processes along **flow paths** to the accessible environment;
8.3.1.3.7	Investigation: Studies to provide the information required on radionuclide retardation by all processes along **flow paths** to the accessible environment; and
8.3.1.3.8	Investigation: Studies to provide the information required on retardation of gaseous radionuclides along **flow paths** to the accessible environment.

The conceptual framework for calculating ground-water travel time requires identification of "likely" flow paths to the accessible environment, along which travel times are calculated, and a disturbed-zone boundary from which calculations are begun. The original disturbed-zone concept was based on a near-field region of difficult-to-model flow processes (46 FR 35280, 35281, July 8, 1981). Later, the NRC (Gordon, et al., 1986) proposed to restrict the disturbed-zone definition to include only a region of intrinsic-property changes. However, this later proposal has not been formally adopted by the NRC probably because of the large region of hydrothermal (heat-pipe) effects that may develop around emplaced waste, including non-Darcian fracture flow as condensate accumulates. Intrinsic-property changes will probably accompany boiling and condensation of pore fluids, so even if the restricted definition of the disturbed-zone boundary, such as proposed by Gordon, et al. (1986) were adopted by the NRC, the boundary may extend a considerable distance above and below the repository.

Ground-Water Flow Path

It appears that the DOE is approaching the problem of ground-water flow paths from the following perspectives:

1. Calculate flow paths using two-dimensional porous-medium model.
2. Map the intersection of land surface with a composite regional potentiometric surface that rises and falls over geologic time.
3. Determine physical-property conditions that govern fracture versus matrix flow.
4. Investigate apparently steep and apparently flat regions in the composite potentiometric surface by drilling additional WT-holes and by conducting tracer tests.
5. Prepare a plan to investigate the hydrologic significance of the Ghost Dance Fault.

Perspective	CD-SCP Section	Methodology
Calculation based on fluid potentials	8.3.5.12.3.1.2	Numerical Model
Intersection of composite regional potentiometric surface with land surface	8.3.1.2	Reexamine and redate paludal deposits
Determine physical-property conditions that govern fracture vs. matrix flow	8.3.1.2.3	Develop empirical relations from laboratory tests
Investigate steep and flat regions in composite potentiometric surface	8.3.1.2.3.1	Drill WT-holes, hydrology hole, and possibly southern tracer test complex
Investigate steep and flat regions in composite potentiometric surface	8.3.1.2.2.3.3	Solitario Canyon horizontal borehole
Investigate hydrologic significance of Ghost Dance Fault	8.3.1.2.2.6	Develop plan only

Disturbed Zone

DOE proposes to develop a disturbed-zone definition (8.3.5.12.5.2, activity 1.6.5.2), and reevaluate that definition based on saturated and unsaturated-zone system investigations (8.3.1.2.2 and 8.3.1.2.3). We strongly suggest that it would be fundamental for the SCP to include activities that delineate the extent and character of the disturbed zone as now defined.

The disturbed zone is an important focus of State of Nevada review activities. We find that the zone of difficult-to-understand (and characterize) processes (46 FR 35280, 35281, July 8, 1981) has been equated conceptually by the DOE to the zone of intrinsic-property changes. The central concept of a zone of intrinsic-property changes appears in most, if not all, DOE-sponsored literature that requires a disturbed-zone definition (Langkopf, 1987 and CD-SCP, Section 8.3.5.12.5, for example). However, even if there were no intrinsic property changes whatsoever, **heat-driven changes in the hydrologic system at Yucca Mountain can reasonably be expected to be profound** (and extraordinarily complex from a modeling perspective). These hydrothermal processes can be reasonably expected to occur within 100 years of repository loading based on simple calculations using DOE's physical-property values.

The CD-SCP assumes that the NRC draft generic technical position (Gordon, et al., 1986) will be adopted formally by the NRC. The State of Nevada has pointed out to the NRC that that draft position fails to consider the hydrothermal effects of the waste, causing multiphase fluid flow. It is obvious that the more restricted (in space) the disturbed-zone definition, the longer the flow paths in the vadose zone along which travel times are calculated, and the longer the travel times in any flow scenario.

The potential hydrothermal effects in the vadose zone of Yucca Mountain due to waste-generated temperatures which exceed the boiling temperature of water is generally unrecognized[1] in the CD-SCP. Our analysis indicates marked increases in both vapor and liquid-phase flow are expected due to the strong thermal envelope generated by the waste. In the fractured-rock environment, the complexity of heat and mass-transfer processes and associated solution-mineral reactions will be greatly increased by the multiphase liquid and vapor-flow environment. **We estimate that about 10,000 acre-feet of water are present within the volume of rock that is expected to reach boiling temperature within 100 years.**

The CD-SCP definition of the disturbed zone ignores the importance of multiphase fluid transport. The CD-SCP definition is not as defined and intended in 10 CFR 60.2 (46 FR 35280, 35281, July 8, 1981). Instead of a mechanically disturbed zone of the current DOE definition (measured as extending several meters from the repository horizon) hydrothermal effects have the potential to extend downward and upward tens to hundreds of meters from the repository horizon.

Based on our findings of: a) a high probability of field-scale hydrothermal multiphase (heat-pipe) effects occurring during repository loading, and b) the resultant zone of vaporization and condensation that could extend upward and downward significant distances from the repository horizon, we believe that a zone of intrinsic property changes is not conservative as a basis for defining the disturbed zone. Physical and chemical changes within the zone of vaporization and condensation would be difficult to characterize by direct observation, and will be impossible to predict accurately based on initial conditions only. The DOE needs to address and establish a research program to resolve both the thermal and hydrothermal effects in the repository performance in the SCP.

CD-SCP Ground-Water Travel Time Strategy

The DOE recognizes the "reasonable assurance" licensing requirement (10 CFR 60.101(a)(2)) that the ground-water travel time at Yucca Mountain is at least 1,000 years leaves this issue ambiguous as to what constitutes data of sufficient quantity and quality (p. 8.3.5.12-10).

1. Langkopf (1987) refers to unpublished modeling studies by J. Gauthier and R. R. Peters in a 1986 internal memorandum (SANDIA) where water redistribution was considered from the repository midline to below the repository . Their reported findings support our scenario of total water expulsion as vapor in a 100-year period. However, their model assumes the matrix would absorb the moisture.

CD-SCP states (p. 8.0-9):

"The top-level strategy focuses strongly on the investigations of the characteristics of the flow in the unsaturated zone, relying heavily on the current view that the percolation is low and that the water in the unsaturated zone is tightly confined within the rock matrix. If these concepts can be confirmed, then the general objective for the system and for the post closure performance of the engineered and natural barriers are very likely to be met. As part of these investigations, the program will address alternative concepts including flow in fractures, lateral movement of water at rock interfaces in the unsaturated zone, and the effect on the flow of structural features such as faults. The ability of the unsaturated rock to hold water and limit contact of water with the waste packages will also be investigated."

We find that the CD-SCP approach indicated by the above warrants both applause and criticism. The correct issues have been identified, including ground-water travel times, but the characterization approach **is to prove conditions and processes** favorable to waste isolation. This would make good sense if there were established technologies, in-depth understanding of the processes, simple natural systems, and well understood analog environments. This is not the case for the vadose zone at Yucca Mountain. The SCP therefore needs to be structured to **test for the unacceptable conditions**, and for the most part, it fails in terms of the vadose-zone issues.

Vadose-Zone Conceptual Model Comments

The CD-SCP investigation 8.3.1.2.2 entitled "Studies to provide a description of the unsaturated zone hydrologic system at the site" presents the DOE's purpose and objective as "to develop a model of the unsaturated-zone hydrologic system at Yucca Mountain that will assist in assessing the suitability of the site to contain and isolate waste." It is also stated that in developing the model the needed information will be provided through ten studies to characterize the flow and transport through the Yucca Mountain unsaturated zone. The major studies planned to be conducted by DOE during site characterization address the areas of unsaturated-zone infiltration, percolation, gaseous-phase circulation, and hydrochemistry. Appendix I indicates our opinion of the general failure of these investigations to adequately establish site characterization objectives.

The CD-SCP conceptual model of water flow through the vadose zone is generally based on the assumption of steady-state downward flow. A second assumption is that the water flux through the vadose zone is so small that most water flow is through the matrix of the rock and not through fractures. A third assumption is that matrix flow will predominate through the repository horizon (Topopah Spring). This assumption largely depends upon the hypothesis that excess recharge is both diverted away from the repository horizon and retarded by capillary and permeability barriers at the contacts between the Tiva Canyon welded unit and the underlying Paintbrush Tuff nonwelded unit; and between the Topopah Spring welded unit and the overlying Paintbrush Tuff nonwelded unit.

The CD-SCP vadose-zone conceptual model is articulated on p. 3-207 to 3-213. In reviewing the CD-SCP, we have become aware of two important facts. First, the CD-SCP does not seriously consider conservative conceptual models that fit the limited site-specific data and the open-literature data. Second, the CD-SCP conceptual model, amazingly, perfectly satisfies all of the following conditions:

"(i) Low moisture flux in the host rock and in the overlying and underlying hydrogeologic units;

(ii) A water table sufficiently below the underground facility such that fully saturated voids contiguous with the water table do not encounter the underground facility;

(iii) A laterally extensive, low-permeability, hydrogeologic unit above the host rock that would inhibit the downward movement of water or divert downward-moving water to a location beyond the limits of the underground facility;

(iv) A host rock that provides for free drainage; or

(v) A climatic regime in which the average annual historic precipitation is a small percentage of the average annual potential evapotranspiration." (10 CFR 60.122(b)(8)).

The above, of course, are the NRC favorable conditions for a repository in a vadose-zone environment.

We think the CD-SCP conceptual model of flow of water through the vadose zone is not based on nor supported by the available technical data. The estimated downward ground-water flux may be low in the light of published data. Estimates of the downward vertical matrix flux (no fracture flow) through the repository-horizon host rock range from a low value of 0.003 mm/year (based on laboratory determinations on core, Weeks and Wilson, 1984) to a high of 10 mm/yr (Sass and Lachenbruch, 1982) based on the geothermal-gradient analyses. Montazer and Wilson (1984) data from borehole UZ-1 show negative (upward) flux of approximately 1 to 2 mm/yr in the Topopah Spring unit. They also estimated that a downward flux through the same unit to be 1 mm/yr based on geometric mean of the saturated hydraulic-conductivity measurements on core samples assuming a hydraulic gradient of one. However, Montazer and Wilson (1985) reported that the measured hydraulic conductivity of two saturated samples was two-orders-of-magnitude greater than the geometric mean. For the Paintbrush Tuff nonwelded unit, they estimated that a vertical flux of 0.1 to about 100 mm/yr may be occurring. Additional uncertainty on the estimated flux under present conditions is introduced by recharge estimates of 4.5 mm/yr (Rush, 1970) to 5 mm/yr (Waddell, et al., 1984). These estimates of recharge are inconsistent with the postulated 1 mm/yr by the CD-SCP. If the saturated-matrix conductivity of the Topopah Spring unit is limited to a maximum of 1 mm/yr as DOE indicates, then the vadose flux could pass through the repository-horizon host rock (Topopah Spring) as fracture flow.

The CD-SCP conceptual model also assumes by implication that the recharge throughout the proposed repository boundary area is uniformly distributed. In desert terrane such as the Yucca Mountain site, the recharge may be low and variable. However, much of the recharge is certainly concentrated and focused beneath washes, in and through open and exposed fractures, and through faults in the rock matrix of the repository block. It is very likely that most of the recharge occurs through the fractures and in turn gives rise to the flux values that shorten dramatically the ground-water travel times through the vadose zone toward the accessible environment.

The CD-SCP assumption that a capillary barrier exists at the contacts between the Tiva Canyon welded unit and the underlying Paintbrush Tuff nonwelded unit, and between the Topopah Spring welded unit and the overlying Paintbrush Tuff nonwelded unit is unlikely based on the available information provided by DOE. There is no data or evidence that recharge moves laterally down dip at the contact between the fractures networks of the Tiva Canyon welded unit and the matrix of the Paintbrush Tuff nonwelded unit. To date, no field or laboratory data have been published by DOE which indicate that saturated conditions have been observed at or near the contact. It is unlikely that water will move laterally over any significant distance until the tuff is almost saturated.

In addition to the above, the CD-SCP postulates the existence of a capillary barrier between the Paintbrush Tuff nonwelded and the Topopah Spring units. There is no evidence that water is present across this contact or as a general condition across the site. Therefore, there is no basis to assume that "excess recharge" has been stored or that significant lateral flow is occurring within this unit.

The CD-SCP discusses (on pages 8.3.1.2-248 to 250) the use of the geochemical approach to evaluate and determine the flow direction, water flux, and ground-water travel time in the unsaturated zone by isotopic techniques. It also states:

"Pore fluids from the matrix and near fractures will be extracted from exploratory shaft rubble core for chemical and isotope analyses.", "Fracture fluids are expected to permeate the surrounding matrix.", and "Fluids from samples with moisture contents less than 11 percent (including samples that have been squeezed and centrifuged) will be extracted using the vacuum distillation method."

This technique may be useful in estimating and evaluating the ground-water travel times of water **in the matrix.** However, it is not clear from the CD-SCP how water in the fractures, especially the Topopah Spring unit, will be sampled for the geochemical isotopic technique. Nowhere under any activity is it explained how fracture waters will be sampled and analyzed when encountered. There are no activities that address field determination of saturated fractures, or ephemeral fracture flow. Other problems that are not addressed by the CD-SCP are the distributed nature of recharge over the repository block, the scale at which data is developed, the three-dimensional distribution in space of data collection, and the manner in which interpretations of these data will be made. Based on surface mapping and the core data, there are several **million fractures** within the repository block and every one of these is a possible conduit for both liquid and vapor flow. In addition, there are very significant lithologic units and associated facies that can markedly impact matrix-hydraulic conductivities. We find no activities that recognize and deal effectively with these problems.

Vadose Zone Boreholes: The CD-SCP activity 8.3.1.2.3.2 (p. 8.3.1.2-14) entitled "Site vertical borehole studies" describes the DOE investigation which involves dry drilling and coring of nine planned boreholes that will range in depth from 122 to 460 meters below the land surface. **We are surprised by the apparent strategy of the vadose-zone drilling program.** Based on the existing data on moisture in the vadose zone, it could be interpreted that the drilling plan has been designed to **avoid** developing additional data on perched water, or resolving already developed ambiguous data. Specifically UZ-14, near UZ-1, has a design depth of 120 m. Thus, it will avoid encountering known saturation at 387 m, which stopped UZ-1 drilling. Also, it will not provide any data to resolve the ambiguous potential records of UZ-1 in the Topopah Spring.

In addition, all the deep boreholes (UZ-9, UZ-9a, UZ-9b, UZ-2, UZ-3, UZ-10) are useless with respect to evaluating the occurrence and extent of perched water at or below the repository horizon in the repository block. UZ-2 and UZ-3 are shallower than UZ-6 and located very close to UZ-6, hence no new data on the distribution of perched water is likely to be established. UZ-9, UZ-9a, UZ-9b, and UZ-10 are too far from the repository block to be representative of the block conditions. All the rest of the boreholes are too shallow to develop data at or below the repository horizon. Such a plan is unlikely to establish new information on perched water and it can not resolve existing questions about already encountered perched water.

We find that the same two drilling techniques previously used in site-selection studies are planned for all future surface based vadose-zone studies. Both of these drilling methods have serious weaknesses that are well known to DOE from experience, and these weaknesses seriously impact the ability of the DOE to characterize the vadose zone. The ODEX method is slow and has produced a depth maximum of around 400 feet. The reverse-air vacuum produces a large diameter borehole, can not drill through perched water, produces unstable boreholes in fractured tuff, and is **unnecessarily costly.** The moisture data from UZ-1 and UZ-6 are compromised by the large diameter of the borehole and the prolonged drilling time.

Vadose Zone Siting Criteria: The NRC siting criteria set forth in 10 CFR 60.122 consist of two sets of conditions namely, the first set (10 CFR 60.122(b)) encompasses favorable conditions and the second set (10 CFR 60.122(c)) encompasses the potentially adverse conditions. The NRC siting criteria include the requirement that DOE must demonstrate and show by analysis that the potentially adverse conditions, if present at the site, do not affect significantly the ability of the geologic repository to meet the performance objective related to isolation of the waste. The CD-SCP sets out a plan to prove a conceptual model of favorable conditions. In doing so, it fails to provide a **plan of activities that test for unfavorable conditions in the vadose zone.**

The CD-SCP states on p. 3-198:

"Tests are planned to evaluate the conditions under which flow in fractures and faults may occur (Section 8.3.1.2.3), thus aiding in the definition of flow paths in the unsaturated zone."

Also,

"...because of the nearly flat potentiometric surface under parts of Yucca Mountain, specific flowpath directions are currently difficult to define. Furthermore, the degree of anisotropy has not been evaluated. Additional water-table holes and extensive multiple-well and single-well tracer tests may help define anisotropy, hydraulic connections, and probable flow paths in the saturated zone (refer to Section 8.3.1.2.3.1)."

According to a statement on p. 3-105, Section 8.3.1.2 includes studies to reexamine and redate spring and marsh deposits from the south end of Crater Flat and south of Yucca Mountain.

Regarding ground-water flow paths during the Quaternary period, the CD-SCP states on p. 3-107:

"...the occurrence of calcitic veins, tuffs, and marsh deposits kilometers to tens of kilometers upgradient from areas of modern ground-water discharge indicates that flow to points of ground-water discharge were shorter in the past."

Evidence of possible megascale channeling in carbonate rocks of the southern Great Basin has been available in the open literature for over a decade. The CD-SCP reiterates the results of Winograd and Pearson (1976):

"[Winograd and Pearson] have shown a radiocarbon anomaly in Crystal Pool to probably be caused by megascale channeling, with water moving to this discharge point at velocities appreciably greater than those to adjacent springs." (CD-SCP, p. 3-102).

Structural Control on Flow Paths: As stated on p. 8.3.1.17-186, the tectonic synthesis will be applied to information need 1.6.1 (Section 8.3.5.12.1), "site information and design concepts needed to identify the fastest path of likely radionuclide travel and to calculate the ground-water travel time along that path." This is one component of the ground-water travel time issue, as outlined on p. 8.3.5.12-23 in a discussion of interrelationships of information needs. DOE indicates that tectonic synthesis will also be applied to investigations 8.3.1.2.1 (regional hydrologic system) and 8.3.1.4.2 (geologic framework).

We have reviewed the CD-SCP for investigation activities planned to assess the hydrologic significance of geologic structure in the Yucca Mountain region. We looked for evidence that hydrologic test drilling is effectively integrated with geologic-characterization activities. The basis for our review comments is Table 8.3.1.4-2, "Site Characterization Plan Proposed Drilling Requirements," which lists proposed boreholes and associated CD-SCP activities.

Only one activity of the CD-SCP is squarely aimed at characterizing the hydrogeologic significance of a discrete repository-scale geologic structure. **Activity 8.3.1.2.3.1.1, "Solitario Canyon Fault Study in the Saturated Zone,"** will attempt to determine whether the Solitario Canyon Fault is a barrier to eastward movement of ground water through the repository block. Two new WT-holes will be drilled near the Solitario Canyon Fault, plus a new hydrologic test hole (production well) east of the fault on the ridge crest of Yucca Mountain, designated H-7. A long-term pumping test intended to observe pumping response across the Solitario Canyon Fault is planned. We commend this effort but question why similar studies are not planned to evaluate other known structures, such as the Ghost Dance Fault.

Steep hydraulic gradients immediately upgradient of the repository appear to have focused DOE's attention with respect to mission objectives. **Activity 8.3.1.2.3.1.2, "Site Potentiometric-Level Evaluation,"** calls for two water-table drillholes near Drill Hole Wash to obtain additional data on the steep hydraulic gradient in this area, and another two water-table drillholes south and east of the repository site. It is evident from the discussion on p. 8.3.1.2-302 that data from geologic drillhole USW G-5 will be used to help determine the probable cause and nature of the steep hydraulic gradient north of Drill Hole Wash. Conversely, the region inferred to be down the hydraulic gradient receives virtually no attention in terms of possible structural controls and hydraulic connection with underlying and overlying aquifer lithologies.

No plans are given for assessment of preferred flow paths in carbonate rock between Yucca Mountain and Ash Meadows, or refinement of the inferred western boundary of the Ash Meadows ground-water flow system. **Activity 8.3.1.2.3.1.6, "Well Testing with Conservative Tracers Throughout the Site,"** calls for a possible second multiple-well tracer test complex in a location "where the physical rock properties are significantly different from those of the C-hole location" (CD-SCP, p. 8.3.1.2-327). There is no discussion of the many distinct **geologic** controls on fluid flow that might be investigated with tracers, nor is there any elaboration of the role of tracers in developing a hydrologic characterization of structural discontinuities. Most importantly, the building of a statistically meaningful sampling rationale from available data is not evident in the geohydrology program.

Hydrologic Effects of Regional Strain Features: Calcite veins in Pliocene and younger rocks at Ash Meadows strike N40° ± 10°E (Winograd and Szabo, 1986; CD-SCP, 1988). This is approximately at right angles to the direction of regional Cenozoic extension. Although major northeast-trending structures exist in the Yucca Mountain region, the CD-SCP does not appear to address the possibility that they might represent conduits to ground-water flow because of their fundamentally dilational character.

The CD-SCP alludes to the possible, but unknown hydrologic significance of detachment faults in the following statement:

> "If detachment faults exist at depth below the site, their relevance to repository design and performance as potential sources of ground motion, rupture, or hydrologic conduits or barriers hinges on their age, depth, and nature of the intersection of the detachment faults with the steeply-dipping Quaternary normal faults within the site area" (DOE CD-SCP, p. 8.3.1.17-132).

The possible hydrogeologic significance of detachment faults is therefore recognized in the CD-SCP, but no studies are presented for hydrogeologic assessment of detachment faults. The structural studies that focus on particular groups of faults near Yucca Mountain are disjointed from a hydrogeologic perspective, with the exception of Solitario Canyon Fault studies, since they do not include hydrogeologic objectives. One of the stated objectives of activity 8.3.1.17.4.12.1 (Evaluate Tectonic Processes and Tectonic Stability at the Site) is to "...evaluate the regional extent of detachment faults...and evaluate regional extent of Paleozoic rocks known to be aquifers, aquitards, or to provide favored surfaces of detachment or thrusting" (DOE CD-SCP, p. 8.3.1.17-181). The description of this activity given on p. 8.3.1.17-182 of the CD-SCP provides for topical reports on "Quaternary wrench faulting, detachment faulting, normal faulting, and left-lateral strike-slip faulting." Gravity and magnetic maps will be compiled, and "geologic cross sections showing inferred subsurface structural and stratigraphic geometry will be prepared." Nowhere, however, do we find a statement of any clear hydrogeologic objective accompanied by a testing methodology, in these tectonic studies.

We have been unable to judge the merits of DOE's proposed borehole locations since locations given in the CD-SCP are inconsistent and generally unjustified. For example, we note major discrepancies between proposed borehole locations given in Section 8.3.1.2.3.1.2 "Activity: Site Potentiometric Level Evaluation," and Section 8.3.1.4.1 "Investigation: Development of an Integrated Drilling Program." If, as stated on p. 8.3.1.4-18 of the CD-SCP, each proposed drillhole represents a source of data intended to answer a particular requirement of design or performance assessment, then all proposed holes should be precisely located and comprehensively justified. Furthermore, if Figure 8.3.1.4-2 contains a mixture of randomly-located and judiciously-sited holes, they should be clearly distinguished.

The difficulty in defining flow paths in the saturated zone for travel-time calculations is due, as stated on p. 8.3.1.2-295 of the CD-SCP, to the fact that hydraulic tests at Yucca Mountain have failed to identify definitive hydrostratigraphic units:

> "If pervasive fracturing crosses stratigraphic boundaries and accounts for orders of magnitude greater hydraulic conductivity than does the matrix, it may not be appropriate to simulate ground-water flow within a framework of hydrostratigraphic units."

As indicated earlier, only one activity, 8.3.1.2.3.1.1, "Solitario Canyon Fault Study in the Saturated Zone," is focused directly on determining the hydrologic role of a discrete geologic structure. While it is recognized that "...flow down the Ghost Dance Fault could result in concentrated flow in a part of the repository horizon" (CD-SCP, p. 8.3.1.2-255), **a plan to characterize flux in the Ghost Dance Fault has not been presented in the CD-SCP.**

There is no provision in the CD-SCP for hydrogeologic assessment of (discrete) geologic discontinuities in a geostatistically robust (rigorous) fashion. Plans have been made for a limited analysis of the hydrogeologic significance of the Solitario Canyon Fault, and as yet no plan exists for analysis of the Ghost Dance Fault. Activities proposed in the CD-SCP to provide flow-path characterization offer little hope of resolving performance issue 1.6 with respect to flow in the saturated zone. A comprehensive drilling and testing program that includes an assessment of the hydrogeologic character of representative geologic structures (or areas) is absent from the CD-SCP. The CD-SCP fails to focus site-characterization activities on real (as opposed to simulated) flow paths.

INTERPRETATION OF FINDINGS:

The CD-SCP is seriously deficient in establishing a site characterization program that will resolve key licensing issues.

ADDITIONAL WORK REQUIRED:

A comparison of the new SCP (published in December 1988) with our "Review of Consultation Draft of the Site Characterization Plan ... of January 1988".

RECOMMENDED PROGRAM (objectives/activities):

Objective:

Review of the SCP, especially its hydrogeologically related activity, in terms of: 1) conceptual completeness and focus; 2) appropriateness of methodology to accomplish stated objectives; 3) availability of supportive technology; and 4) probability of success and/or feasibility.

EXISTING PROGRAM:

Review of the revised SCP.

Appendix E-III

Technical Meetings/Symposia Attended

Technical Meetings/Symposia Attended

Date	Sponsor	Meeting/Symposia
23 Jan. 1987	US-DOE	DOE Environmental and Socioeconomic Monitoring and Mitigation Plans : Background on Site Characterization Activities.
26 to 28 Jan. 1987	Princeton University	Contaminant Transport Modeling Seminar/Short Course.
10 to 12 Feb. 1987	National Water Well Association (NWWA)	Solving Ground Water Problems with Models.
24 to 28 Feb. 1987	US-NRC	NRC Field Trip in Southern Nevada.
27-30 Apr. 1987	Nuclear Structure Research Laboratory, University of Rochester	Fourth International Symposium on Accelerator Mass Spectrometry.
17-21 May 1987	American Geophysical Union (AGU)	AGU Spring Meeting.
18-21 May 1987	NWWA-Association of Ground Water Scientists and US-EPA-EMSL	First National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods.
27 to 29 May 1987	US-DOE/USGS/SAIC	Peer Review on Calcite and Opaline Silica Deposits Located along Faults Near Yucca Mountain.
15-16 Jun. 1987	Sandia National Laboratory	Uncertainties in Groundwater Travel Time Calculations at Yucca Mountain, Nevada, Second Meeting.
23-26 Jun. 1987	Continuing Education in Engineering, U. C. Berkeley Extension	Aqueous Corrosion - Theory and Analysis.
8 to 9 Jul. 1987	US-NRC	Review of USGS Program.
30 Jul. to 9 Aug. 1987	International Union for Quaternary Research (INQUA)	Congress XII: INQUA.
11 to 16 Sept. 1987	GSA	Paleoenvironmental Interpretation of Paleosols Penrose Conference.
06 to 08 Oct. 1987	Minerals and Geotechnical Logging Society	Second International Symposium on Borehole Geophysics for Minerals, Geotechnical and Ground Water Applications.
03 to 06 Oct. 1987	Colorado Section of the American Institute of Professional Geologists and the Computer Oriented Geological Society	Computer-Aided Methods and Modeling in Geology and Engineering.

18 to 22 Oct. 1987	Clay Minerals Society (CMS)	Clay Minerals Society Meeting.
24 to 29 Oct. 1987	GSA	Geological Society of America Meeting and Short Course.
07 to 10 Dec. 1987	AGU	AGU Fall Meeting.
16 to 18 Feb. 1988	Association of Ground Water Scientists and Engineers	Ground Water Geochemistry Conference.
22 to 26 Feb. 1988	DOE/USGS.	NNWSI-USGS Trench 14, Busted Butte Carbonate/Opal Hydrogenic Deposits Sampling Field Trip.
Feb. 1988	Nevada Water Resources Association	Nevada Water Resources Association Meeting.
29 to 31 Mar. 1988	GSA	GSA Cordilleran Section Meeting.
23 to 26 May 1988	Association of Ground Water Scientists and Engineers and the US-EPA-EMSL.	Second National Outdoor Action Conference on Restoration, Ground Water Monitoring and Geophysical Methods.

MAI Field Trips:

29 May 1987	Crater Flat Preliminary Age Dating Field Studies.
June 1987	Field Mapping at Corn Creek Flat.
June 1987	Reconnaissance Study of the distribution of packrat middens of Pleistocene age in Fortymile Wash, Sandy Valley, Coyote Springs, and L. Pahranagat Valley.
20 and 25 August 1987	Colloid Sampling in Oasis Valley and Ash Meadows.
October 1987	Tecopa Basin field trip
November 1987	Reconnaissance Studies of "Lacustrine Life deposits in Piute Valley, Searchlight, Nevada) and Coyote Springs.
27 to 30 December 1987	Field Trip to Pahrump Valley and Tecopa Valley
February 1988	Tecopa area field trip.
February 1988	Tecopa area field trip.
February to April 1988	Field trip to collect pack rat middens along the White River drainage system.