WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: USGS-WRI-84-4267

DOCUMENT: Waddell, R.K., Robison, J.H., and Blankennagel, R.K., 1984, Hydrology of Yucca Mountain and Vicinity, Nevada-California--Investigative Results Through Mid-1983. U.S.G.S. Water Resources Investigations Report 84-4267, Denver, 72 p.

REVIEWER: Williams & Associates, Inc.

DATE REVIEW COMPLETED: May 28, 1986

ABSTRACT OF REVIEW: APPROVED BY: Roy E Williams

The report under review presents investigative results for Yucca Mountain and vicinity through mid-1983. Conceptual models for flow in the saturated zone are presented. These conceptual models are modified after the original models presented by Winograd and Thordarson (1975). Conceptual models presented in the report under review include data not available to Winograd and Thordarson (1975). Conceptual models for flow in the unsaturated zone are not presented in detail because investigations up to mid-1983 were concerned primarily with potential high level waste disposal within the saturated zone.

BRIEF SUMMARY OF DOCUMENT:

Introduction

The purpose of the report under review is to present the USGS hydrology contributions to the site characterization report of the Yucca Mountain area. A companion report (U.S. Geological Survey, 1984) presents the geology of the Yucca Mountain area. These reports include data collected and analyzed through mid-1983. The report under review describes the hydrology within the "candidate area" prescribed by the Nuclear Regulatory Commission. The candidate area refers to the area contained within a 100 km radius of Yucca Mountain.

Surface-Water Hydrology

The candidate area includes most of the Death Valley Basin Hydrographic Region of California-Nevada and a small part of the Central Hydrographic Region of Nevada. These hydrographic regions are divided into smaller units called hydrographic areas. The Yucca Mountain site lies on the boundary between Crater Flat and Fortymile Canyon-Jackass Flats hydrographic areas.

The report describes briefly the data available pertaining to flood potential in the vicinity of Yucca Mountain. According to the report, past severe flooding indicates that occasional severe floods probably will occur in the future within southern Nevada. and may occur at Yucca Mountain. The report under review presents the following conclusions based on an investigation of flood potential in Topopah Wash by Christensen and Spahr (1980):

1. The 100 year flood-prone areas closely parallel most main channels.

2. The five-year flood would exceed the discharge capacity of all stream channels except Topopah Wash and some upstream reaches of a few tributaries.

3. The "maximum potential" flood would inundate most of Jackass Flats.

Squires and Young (1984) studied the downstream part of Fortymile Wash. According to the report under review, Squires and Young (1984) concluded that:

1. The 100 year, 500 year, and "regional maximum" floods would stay within the confines of the wash.

2. Crested Butte Wash and Drill Hole Wash would have estimated flood-water depths from 0.3 to 1.2 m in the stream channel during the 100 year flood. The 500 year flood would exceed bank capacities at several reaches of the washes. The "regional maximum" flood would inundate all central flat-fan areas in the two watersheds.

3. The 100 year, 500 year, and "regional maximum" floods within Yucca Wash would stay within the steep-side-slope stream banks that contain the floodplain.

According to the report, most of Yucca Mountain is well above expected flood levels; however, areas that are close to channels or within the lower terraces of Fortymile Wash are subject to flooding.

Regional Groundwater Hydrology

Discussion of the regional groundwater hydrology begins with a description of the basic hydrogeologic units that occur within the candidate area. These hydrogeologic units from oldest to youngest are: the lower clastic aquitard, the lower carbonate aquifer, the upper clastic aquitard, the upper carbonate aquifer, granite, volcanic rocks, and valley fill aquifer. A general description of each of these units is presented in the report.

According to the report, recharge areas were estimated based on the potentiometric map (Plate 3 of the report) and the distribution of precipitation. Areas of high precipitation were considered to be the primary groundwater recharge areas. These recharge areas include the Spring Mountains, and the Sheep, Pahranagat, and Belted Ranges.

According to the report, groundwater discharge areas within the candidate area are characterized by rocks of relatively lower hydraulic conductivity that occur downgradient from the discharge areas. The report suggests that a steep potentiometric gradient across the low hydraulic conductivity rocks causes the water table to intersect land surface whereupon groundwater discharge areas are created. Plate 4 of the report shows the locations of springs within the candidate area. Major discharge areas are located along the Ash Meadows spring line, and at Alkali Flat (Franklin Lake), the Furnace Creek Ranch area, and Oasis Valley. Minor discharge areas from the regional aquifers are believed to occur also at Indian Springs and Cactus Springs. According to the report, numerous perched springs of minor and variable discharge are present throughout the area.

The candidate area is located within the Death Valley groundwater basin. The authors of the report divide the Death Valley groundwater basin into three groundwater subbasins. These subbasins are: Oasis Valley, Ash Meadows, and Alkali Flat-Furnace Creek Ranch. According to the report, a subbasin consists of recharge areas and flow paths to a major discharge area. A description of each of the three subbasins is presented in the report. However, it should be noted that the actual boundaries of each subbasin are not well defined. The boundaries of the subbasins are defined based on the locations of aquifer outcrops, the distribution of precipitation, and topography. Essentially no hydraulic head data are available upon which to delineate the actual locations of the boundaries.

A brief discussion of the isotopic and regional hydrochemistry is presented in the report. The data indicate that most of the groundwater samples collected to date have highly variable compositions. According to the report, mixing of waters from carbonate and tuffaceous sources is indicated by the chemistry of waters in parts of Ash Meadows and Alkali Flat-Furnace Creek Ranch groundwater subbasins; mixing is evident especially beneath the southern Amargosa Desert and near the Furnace Creek Ranch. According to the report, chemistry of the water beneath Yucca Mountain probably is derived solely by reaction with tuffaceous rocks.

Carbon-14 ages for samples taken from test holes UE-29a#1 and UE-29a#2 in upper Fortymile Canyon are given as 4,100, 3,800, and 2,280 years. According to the report, these carbon-14 ages suggest that recharge has occurred relatively recently along major drainages. Most of the hydrogen and oxygen isotopic data presented in Plate 5 of the report indicate that recharge water probably was derived from melting snow.

Yucca Mountain Hydrogeologic System

According to the report, two series of test holes were drilled to depths greater than a few hundred meters. In one series, small diameter core holes were drilled to obtain stratigraphic, structural, and physical-property data (UE-25a#1, UE-25b#1, USW G-1, USW G-2, USW G-3/GU-3, and USW G-4). A second series of test holes was drilled to obtain hydrologic data. A small amount of core was obtained from test wells USW H-1, USW H-3, USW H-4, USW H-5, and USW H-6. According to the report, test holes UE-25b#1 and USW G-4 were cored and then reamed to allow for hydrologic testing. Four piezometers were installed at different depths in test well USW H-1 to measure the vertical head gradients within the test hole.

According to the report, concepts on water movement within the unsaturated zone are not well developed, in part because early hydrologic studies of Yucca Mountain concentrated on the saturated zone. According to the report, additional data are needed to answer the following questions (p. 47):

1. What is the rate of recharge, and how does it vary spatially and temporally?

2. Do the effects of capillary barriers inhibit movement of water from porous tuffs through fractures; if so, what potential gradients are necessary to initiate flow in fractures in densely welded tuffs?

3. If water moves in fractures, how far can it travel before being drawn into the matrix?

4. Does perched water occur in the unsaturated zone at Yucca Mountain?

5. What would be the effect of increased recharge that might accompany a return to pluvial climatic conditions on movement of water within the unsaturated zone? In particular, what effect would there be on travel time from a repository to the saturated zone?

The report notes that both matrix and fracture hydraulic conductivity occur in the volcanic rocks in the vicinity of Yucca Mountain. According to the report, a zone of relatively intense fracturing and faulting on the southeastern and eastern sides of Yucca Mountain has been mapped. Another feature indicated by surface mapping is that fracture density is less intense in the northern part of Yucca Mountain, where displacement and the number of faults are less than in the southern part. The report notes that aquifer test data are being analyzed to estimate insitu hydraulic conductivity of rocks in the saturated zone; however, the report notes also that the data analyses are incomplete in part because a single unifying theory for analyzing aquifer tests in fractured rocks has not been developed sufficiently.

The report describes the distribution of groundwater recharge in the vicinity of Yucca Mountain as a function of the amount and distribution of precipitation, type of precipitation, conditions at time of snow melt (if a snowpack is present), lithology and moisture content of soil, vegetation, and topography. The report notes that data on the distribution of recharge at Yucca Mountain do not exist. The report suggests that more recharge may occur beneath the washes than beneath the surrounding ridges, because water is concentrated in washes during runoff events. According to the report, the arid environment at Yucca Mountain and the absence of large drainage basins indicate that recharge is very small. The report notes that data from Yucca Flat suggest that long-term average recharge rates probably are less than 5 mm/yr. Heat flow analyses in test well UE-25a#7 suggest that recharge may occur in pulses rather than at a constant rate over a long period of time.

Figure 8 of the report is a preliminary potentiometric surface map of the vicinity of Yucca Mountain. According to the report, measured head values used to construct the potentiometric map represent composite water levels. The potentiometric map indicates that the hydraulic gradient is low in western Jackass Flats (Fortymile Wash area) and in the Amargosa Dessert. The potentiometric map indicates that the gradient is high in volcanic rocks north of Yucca Mountain and across northern Yucca Mountain. The report notes that the potentiometric data collected in conjunction with injection testing generally are not adequate to define vertical head gradients.

The report suggests that the potentiometric levels mav be used to indicate the general directions of groundwater flow; consequently the general directions of the movement of radionuclides from a repository beneath Yucca Mountain should be obtainable from the map. The report suggests that flow beneath Yucca Mountain probably is toward the southeast into the Fortymile Wash area and then to the south toward the Amargosa Desert and Alkali Flat, then toward Furnace Creek Ranch. The report notes however that the actual flow path that a particle of water would take may be much different from that indicated by the potentiometric map due to heterogeneity and anisotropy.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

The report under review presents a summary of the results of hydrogeologic investigations conducted by the USGS in the vicinity of Yucca Mountain. The report summarizes the results of hydrogeologic investigations completed through mid-1983.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The report under review represents the USGS contribution to the hydrology portion of a site characterization report for the Yucca Mountain area. The report presents general descriptions and analyses of the hydrogeologic data collected at the Yucca Mountain site. The report is not a highly technical discussion of the hydrogeology of Yucca Mountain, but rather a general description in layman terms of the basic USGS understanding of the hydrogeology.

REFERENCES CITED:

Christensen, R.C., and Spahr, N.E., 1980, Flood Potential of Topopah Wash and Tributaries, Eastern Part of Jackass Flats, Nevada Test Site, Southern Nevada. USGS Open File Report 80-963, 22 p.

Squires, R.R., and Young, R.L., 1984, Flood-plain Analysis of Fortymile Wash and Its Southwesternmost Tributaries, Nevada Test Site, Southern Nevada. USGS Water Resources Investigations Report 83-4001, 33 p.

U.S. Geological Survey, 1984, A Summary of Geologic Studies Through January 1, 1983, of a Potential High-Level Radioactive Waste Disposal Site at Yucca Mountain, Southern Nye County, Nevada. USGS Open File Report 84-792, 103 p.

Winograd, I.J., and Thordarson, J.W., 1975, Hydrogeologic and Hydrochemical Framework, South-Central Great Basin, Nevada-California With Special Reference to the Nevada Test Site. USGS Prof. Paper 712-C, 126 p.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: USGS-WRI-84-4272

DOCUMENT: Thordarson, William, Rush, F.E., and Waddell, S.J., 1985, Geohydrology of Test Well USW H-3, Yucca Mountain, Nye County, Nevada. U.S. Geological Survey, Water Resources Investigations Report 84-4272, Lakewood, CO.

REVIEWER: Williams & Associates, Inc., James L Osiensky

DATE REVIEW COMPLETED: September 17, 1987

ABSTRACT OF REVIEW: APPROVED BY: Roy E Williams

The report under review presents interpretations of hydraulic tests conducted within the saturated zone in test well USW H-3. Hydraulic tests conducted in the test well consisted of pumping tests, injection tests, and swabbing tests. Interpretations of the data presented in the report are highly subjective due to the poor type curve matches for many of the tests.

BRIEF SUMMARY OF DOCUMENT:

The report under review presents hydrogeologic interpretations of test data collected from test well USW H-3. The data used for the interpretations presented in the report are presented in Thordarson and others (1984).

Test well USW H-3 is located on the southern portion of Yucca Mountain near its crest. The test hole was rotary drilled with an air-foam drilling fluid. The drilling fluid consisted of air, detergent, and water obtained from well J-13. The rocks penetrated by test well USW H-3 consist primarily of ash flow tuff, plus "four thin, poorly lithified, bedded, or reworked tuffs at the bases of several stratigraphic units." Table 1 of the report presents a generalized lithologic log of the test well. The test hole was drilled to a total depth of 1,219 meters; it penetrates the Paintbrush Tuff, the Calico Hills, the Crater Flat Tuff, and bottoms in the Lithic Ridge Tuff.

Sixteen different geophysical logs were recorded in the well. The report explains that a summary of the geophysical logs is presented in Thordarson and others (1984). Figure 2 of the report presents a graph of the distribution of porous rock in the well as interpreted from the geophysical logs. A television camera log showed water to be seeping from fractures above the static water level at a depth of 277 meters.

A borehole flow survey using a radioactive tracer (iodine 131) was conducted to measure vertical flow rates in the well while water was pumped into the well at a rate of 2.7 L/s at a constant head. The flow survey was conducted between the depths of 792 m and 1219 m. According to the report, the interval between 809 m to 840.9 m received 63 percent of the injected water. This interval is in the upper part of the Tram Member. The interval between 1060 m and 1120.4 m received 30 percent of the flow. This interval extends from the lower part of the Tram Member into the upper part of the Lithic Ridge Tuff. The remaining part of the injected water entered the tuffs between 840.9 m to 933 m. This interval also is in the Tram Member. The borehole flow survey data are significant in that the authors of the report use these data in conjunction with the results of hydraulic tests to assign values of transmissivity and hydraulic conductivity to the saturated portion of the rocks penetrated by the test well. The results of the borehole flow survey are presented in figure 3 of the report.

Water level measurements were made during the drilling period, during hydraulic tests, and after testing was completed. A packer was installed at a depth of 1,190 m to obtain information on the vertical distribution of hydraulic head in the well. According to the report, on November 3, 1983, the hydraulic head in the rocks above the packer was 732.9 m above mean sea level (MSL); below the packer, the hydraulic head was at 754.0 m above MSL and rising slowly toward static conditions. These data indicate that the zone below the packer had a composite head at least 21.1 m higher than the zone above the packer. These results are significant because they suggest that an upward vertical hydraulic gradient (vertically upward flow) exists in this portion of the test well.

The conceptual model used in the analysis of the hydraulic test data is based on the assumption that "sufficiently dense fracture spacing probably results in the fractured ash-flow tuffs functioning in a hydraulically similar fashion to a granular porous medium." Based on this conceptual model, the authors of the report suggest that homogeneous porous media solutions can be used to define the general hydrogeologic coefficients in fractured media, using late time test data to define the dual porosity system that exists in the tuffs at Yucca Mountain. The report notes, however, that "data used for computing apparent transmissivity for all types of tests in this well probably are early time data, as concluded by Rush and others (1984) for test well USW H-1, and therefore apply only to the fractured part of the system." The magnitude (small, moderate, and large) of the departures from ideal conditions for each test is described in table 2 of the report. It should be noted that the magnitudes of the departures listed in table 2 are subjective in nature.

Several different aquifer tests were conducted to evaluate the hydrogeologic coefficients for the tuff penetrated by test well USW H-3. The initial pump test conducted in the well consisted of pumping the well at a rate of "several liters per second." According to the report, the well could not sustain the initial pumping rate so the pump test was converted to a cyclical test. The well was pumped and allowed to recover several times during the test. Figure 4 of the report presents the semi log plot of the second cycle of pumping. These data were analyzed by the Jacob straight line method of analysis. Figure 5 of the report presents a graph of drawdown and recovery for the entire aquifer test. These data were analyzed using Brown's method for a cyclically pumped well. Brown's method is described by Ferris and others (1962, p. 122).

According to the report, "a long-term, small-discharge-rate pumping test" was conducted within the interval between 822 m to 1219 m. The discharge rate was about 0.16 L/s for a 20,520 min pumping period. A log-log graph of drawdown versus time for this aquifer test is presented in figure 6 of the report. Figure 6 shows that drawdown data deviate from the theoretical Theis curve after approximately 2,000 min of pumping. The authors of the report attribute the deviation to leaky aquifer conditions, a recharge boundary, or the transition from early time to late time in a dual porosity system.

Six injection tests were conducted within selected depth intervals by using inflatable packers in the well to isolate the test zones. The injection test data were analyzed by the Jacob straight line method, by the slug test method of Cooper and others (1967), and by the slug test method of Papadopulos and others (1973). Data for the injection tests are plotted in figures 13 through 18 of the report. According to the report, data plotted in these figures are affected significantly by wellbore storage and fracturing. According to the report, hydraulic fracturing probably occurred during the early parts of the injection tests because of the large hydraulic head exerted. The effects of wellbore storage and fracturing are most obvious during the early time data during the first 5 to 7 min of each test.

Values of storage coefficient calculated from injection test data range from $4x10^{-6}$ to $7x10^{-6}$. According to the report, these values of storage coefficient are very small, but probably are reasonable. However, a calculation by Williams and Associates suggests that the calculated storage coefficients probably are too small by as much as one order of magnitude. The values of storage coefficients calculated by the authors suggest that the aquifer is completely incompressible (storativity attributed to expansion of water only) and that values for porosity range between 0.006 and 0.02. According to table 2 of the report, departure from ideal conditions during the injection tests range from moderate to large for calculation of the storage coefficients.

Swabbing tests were conducted in the open uncased part of the well between two inflatable straddle packers. According to the report, the swabbing tests consisted of multiple swabbing runs. Data for the swabbing tests were analyzed by the authors by using the Jacob straight line method. Analyses of two of the swabbing tests are presented in figures 19 and 20 of the report. Results of the swabbing tests are presented in table 2 of the report.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

The report under review is significant with respect to understanding the hydrogeologic characteristics of the tuff in the saturated zone in the vicinity of test well USW H-3. According to the results of the hydraulic testing, the "apparent horizontal transmissivity" of the section of tuff penetrated by the test well is about 1 m^2/day. Hydraulic conductivity generally ranges between 10^{-2} and 10^{-4} m/day.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The primary limitation of the report under review is that data from several of the hydraulic tests produce type curves that deviate significantly from ideal curves, thereby precluding reliable curve matches. As an example, only four data points for the injection test of the interval from 1,063 to 1,124 m fall on the type curve for slug testing. This poor type curve match is reflected in the very low value for the storage coefficient (7×10^{-6}) that was calculated for this particular test. The values of hydrogeologic coefficients calculated from the test data are questionable. However, interpretations of the data are limited because the field curves deviate from the ideal curves. This is not a limitation of the report; it is a limitation of the data base.

SUGGESTED FOLLOW-UP ACTIVITIES:

No follow-up activities are suggested at the present time. However, data presented in this report may prove to be important with respect to characterization of the saturated zone beneath Yucca Mountain.

REFERENCES CITED:

Cooper, H.H., Jr., Bredehoeft, J.D., and Papadopulos, S.S., 1967, Response of a finite-diameter well to an instantaneous charge of water. Water Resources Research, v. 3, no. 1, p. 263-269.

Ferris, J.G., Knowles, D.B., Brown, R.H., and Stallman, R.W., 1962, Theory of aquifer tests. U.S. Geological Survey Water-Supply Paper 1536-E, 174 p.

Papadopulos, S.S., Bredehoeft, J.D., and Cooper, H.H., Jr., 1973, On the analysis of "slug test" data. Water Resources Research, v. 9, no. 4, p. 1087-1089.

Rush, F.E., Thordarson, William, and Pyles, D.G., 1984, Geohydrology of test well USW H-1, Yucca Mountain, Nye County, Nevada. U.S. Geological Survey Water-Resources Investigations Report 84-4032, 56 p.

Thordarson, William, Rush,, F.E., Spengler, R.W., and Waddell, S.J., 1984, Geohydrologic and drill-hole data for test well USW H-3, adjacent to Nevada Test Site, Nye County, Nevada. U.S. Geological Survey Open-File Report 84-149, 28 p.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: USGS-WRI-84-4328

DOCUMENT: Spaulding, W.G., Robinson, S.W., and Paillet, F.L., 1984, Preliminary Assessment of Climate Change During Late Wisconsin Time, Southern Great Basin and Vicinity, Arizona, California, and Nevada: USGS Water Resources Investigations Report 84-4328.

REVIEWER: Williams & Associates, Inc., James L Osiensky

DATE REVIEW COMPLETED: February 25, 1987

ABSTRACT OF REVIEW: APPROVED BY: Roy E. Williams

The report under review presents an evaluation of paleoclimatic conditions based on plant macrofossils from the Eleana Range-2 packrat midden on the Nevada Test Site. The report suggests that a major warming trend occurred between about 16,000 and 12,000 years before present (B.P.). The average annual precipitation in the vicinity of the Eleana Range-2 packrat midden is believed to have peaked at more than 100 percent greater than present precipitation by about 12,000 to 9,000 years B.P. The report is significant in that it helps to define the maximum potential long-term precipitation in the vicinity of Yucca Mountain.

BRIEF SUMMARY OF DOCUMENT:

The report under review describes the results of an investigation of paleoclimatic changes in the vicinity of the Nevada Test Site over the last 16,000 years. The investigation consisted primarily of the evaluation of stratified accumulations of plant debris and packrat feces within the Eleana Range on the Nevada Test Site. The primary packrat midden under investigation was designated the Eleana Range-2 packrat midden. This midden consists of a stratified accumulation of plant debris and packrat feces, about 1.2 m high and 2 m wide. According to the report, samples for macrofossil analysis were collected along a single vertical column, cut 100 to 200 mm into the deposit, from the exterior face. These samples were prepared by soaking them in warm water for 3 to 5 days to dissolve the cementing amberat. The disaggregated samples were washed and passed through soil sieves to separate the various materials. According to the report, plant macrofossils were sorted from the mass of organic debris, identified, and counted or weighted.

The analysis of the paleoclimatic conditions presented in the report is based on the presumption that the plant species present in the midden represent paleovegetation that was common or abundant in the immediate vicinity of the midden. According to the report, studies of modern packrat middens indicate that packrats normally are indiscriminant collectors, and gather whatever plant species are most readily available near the midden site.

Selected samples from the Eleana Range-2 packrat midden were radiocarbon dated during the investigation.. These samples were pretreated by washing with hot distilled water and diluted potassium hydroxide prior to radiocarbon analysis. Table 1 of the report lists the samples and radiocarbon dates from the Eleana Range-2 packrat midden. The estimated radiocarbon ages of these samples range from 17,100 to 10,620 years B.P.

According to the report, the oldest macrofossil assemblages from the Eleana Range-2 packrat midden provide evidence for vegetational conditions toward the end of the Wisconsin (glacial period) maximum. The report notes that these assemblages contain abundant limber pine. According to the report, limber pine does not occur in the Eleana Range or in the adjacent highlands at the present time. The occurrence of limber pine at the present time is restricted to high altitude sub-alpine woodlands in the Great Basin.

The report suggests that between approximately 13,200 and 11,700 years B.P. a pronounced alteration of vegetation occurred in the vicinity of the packrat midden. The packrat midden data suggest that by 11,700 years B.P. sub-alpine woodland gave way to thermolphilous woodland typified by Utah juniper, pinon pine, and prickly pear cactus.

According to the report, the pinon-juniper woodland of the latest Wisconsin differs from the woodland that exists currently at the Eleana Range locality. The primary change that occurred during the last 10,600 years consists primarily of changes in the composition of the understory. Evidence for these differences exists in the comparison between macrofossil assemblages of the Eleana Range-2 packrat midden with the composition of the modern Eleana Range-4 packrat midden.

The report suggests that climate was the forcing mechanism behind vegetational change in the vicinity of the Eleana Range-2 packrat midden. The report suggests also that "local change toward an increasing xerophytic plant association and an effectively dryer climate probably was gradual and not pronounced at first, followed by as much as 4,000 years by a relatively abrupt change to vegetation dominated by thermolphiles.

According to the report, paleoenvironmental records from other areas offer additional evidence of the climatic change that began during the late Wisconsin. Stratigraphic and surficial evidence of the fluctuations in the water level of Searles Lake suggests significant changes in effective runoff from the late Wisconsin to the present time. Searles Lake consists presently of a salt pan in the Mohave Desert of California; this area was covered by a large lake during part of the late Wisconsin. The report suggests also that chronostratigraphic and packrat midden studies at the Rampart Cave in the Lower Grand Canyon provide detailed data on the timing of biotic change at the close of the last ice age.

Fluctuations in the water level of Searles Lake were controlled primarily by variations in the inflow from the Owens River. The report suggests that the lake level fluctuations reflect overall changes in the regional hydrologic budget, and that these changes were climatically controlled. The report suggests that stratigraphic and geochemical evidence exists for a drying trend beginning about 16,200 years B.P. The data suggest that climatic change caused a significant shrinkage of Searles Lake more than 1,000 years before a significant biotic change occurred at the Eleana Range-2 packrat midden site.

Biostratigraphic data from packrat middens in Rampart Cave indicate that ground sloths occupied Rampart Cave between 14,800 and 13,140 years B.P. The report suggests that abandonment of the cave by ground sloths at the close of the middle Wisconsin and a subsequent reoccupation of the cave after the close of the full glacial episode was due to climatic change. Plant-macrofossil assemblages from Rampart Cave suggest that a progressive change in vegetation began about 16,300 years B.P.

Based on data from the Eleana Range-2 packrat midden, studies of Searles Lake and Rampart Cave, and stable-isotope studies of groundwater in the Amargosa Desert, the authors of the report conclude that the trend toward collectively dryer conditions in the Southern Great Basin began about 16,000 B.P. Evidence suggests that temperatures began to increase about 16,000 B.P.; however, the report suggests also that the climate was wetter than present between approximately 12,000 and 8,000 years B.P. The report suggests that winter precipitation was dominant prior to 16,000 years B.P., but by about 12,000 years B.P. as much as one half of the annual precipitation may have occurred during the summer. According to the report, "summer rainfall in the Southern Great Basin during the latest Wisconsin may have exceeded present quantities by more than 50 percent." In addition to higher summer rainfalls, the authors suggest that winter temperatures and winter precipitation may have been greater than present conditions. The report suggests that these estimated conditions may correlate with a period of significant groundwater recharge in the Amargosa Desert between about 15,000 and 9,000 years B.P. (Claassen, 1983).

The authors of the report under review conclude based on the information evaluated during their study that two distinct pluvial climates probably occurred in the Southern Great Basin. The report suggests that after the full-glacial climate ended about 16,000 years B.P., temperatures increased rapidly resulting in radical alteration of seasonal precipitation regimes. It is suggested that by 12,000 to 9,000 years B.P. annual precipitation may have exceeded present precipitation by more than 100 percent.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

The report under review discusses the evidence in support of significant climatic change during the late Wisconsin time in the Southern Great Basin and vicinity. Based primarily on the vegetational content of packrat middens, the authors of the report suggest that precipitation rates in the vicinity of the Eleana Range-2 packrat midden may have exceeded present precipitation by more than 100 percent. This information is significant with respect to the prediction of potential precipitation during future pluvial periods. While additional work is needed to refine estimates of potential precipitation during pluvial periods, the report under review provides a basis for which estimates of flux in the unsaturated zone at Yucca Mountain can be made.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The report under review presents an interpretation of paleovegetation with respect to climatic conditions that existed during the life-cycle of that vegetation. Unique interpretations of the data are not possible. For example, the hypothesis that average annual precipitation may have been more than 100 percent greater than present precipitation represents a significant change from an earlier estimate (Spaulding, 1983) that annual precipitation during the late Wisconsin exceeded present precipitation by 10 to 20 percent.

The report under review presents an evaluation of climatic conditions based on paleovegetation. Estimates of annual precipitation are subjective and cannot be verified.

SUGGESTED FOLLOW-UP ACTIVITIES:

Independent analysis of this report is beyond the expertise of hydrogeologists.

REFERENCES CITED:

Claassen, H.C., 1983, Sources and Mechanisms of Recharge for Groundwater in the West-Central Amargosa Desert, Nevada--A Geochemical Interpretation. USGS Open-file Report 83-542, 66 p.

Spaulding, W.G., 1983, Vegetation and Climates of the Last 45,000 Years in the Vicinity of the Nevada Test Site, South-Central Nevada. USGS Open-file Report 83-535.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: USGS-WRI-84-4344

DOCUMENT: Czarnecki, J.B., 1984, Simulated Effects of Increased Recharge on the Groundwater Flow System of Yucca Mountain and Vicinity, Nevada-California. U.S. Geological Survey prepared in Cooperation with the U.S. Department of Energy.

REVIEWER: Williams & Associates, Inc.

DATE REVIEW COMPLETED: August 26, 1986

ABSTRACT OF REVIEW: APPROVED BY: Roy E. Williams

The effect of increased recharge on the groundwater flow system beneath Yucca Mountain was investigated. A 100% increase of precipitation was assumed to increase the recharge 14 times. The finite element code FEMODE was used for simulation, which showed that the water table would rise to no less than 130 m from the repository. A weakness of the analysis is that an empirical relationship which may or may not be valid is used to relate recharge to the precipitation.

BRIEF SUMMARY OF DOCUMENT:

This study was conducted to evaluate the potential effects of possible changes in climatic conditions on the groundwater flow system at Yucca Mountain. Such changes in precipitation could cause increased recharge rates resulting in higher groundwater elevations and possible flooding of the repository.

Two specific questions to be answered in the report were: 1) would increased recharge cause a rise in the water table sufficient to flood the repository at its primary location and 2) would changes in the position of the water table significantly alter the direction and rate of groundwater flow near the primary repository location?

The author discusses the study of Spalding and others (1984) relative to the possible increase of precipitation during climatic changes. The present project was accomplished by use of a finite element computer program called FEMODE, developed by Cooley and Torak (1984). Boundary conditions may be specified as point, line or areally distributed sources or sinks and with either constant flux or constant potential. Flow parameters such as transmissivity and specific storage may be specified for individual elements. Specific storage for this problem was set equal to zero since the solution was not time dependent. A recharge rate of 0.41 m/acre was applied along Fortymile Wash. This value was obtained from the parameter estimation modeling of Czarnecki and Waddell (1984) which also determined that recharge rates in other areas were insignificant. The value of evapotranspiration would increase if the water table rose such as during wet periods, and could even rise to the point that there would be new areas of groundwater discharge. The transmissivity values were obtained from Czarnecki and Waddell (1984).

The land surface was divided into three zones of precipitation. Zone 1 was from 6 to 10 inches per year; Zone 2 was 3 to 6 inches per year; and Zone 3 was less than 3 inches per year. The estimated recharge rate for these regions under present conditions varied from 0 to 2.8 mm/yr. These rates gave an estimated recharge total over the entire area of simulation of approximately 6,000 acre/ft/yr. The method used to estimate recharge under a wetter climate is based on the percentage of recharge increasing with increased precipitation. For a 100% increase of precipitation, the recharge would increase approximately 14 times. The maximum water table rise near the repository is predicted to be 130 m, less than the minimum distance between the base of the repository and the present-day water table. The direction of flux beneath the repository would change very little, but the magnitude of flux would approximately double.

To quote a portion of the conclusions:

> Results of this investigation provide a preliminary basis for estimating the potential effects of possible climatic changes on the groundwater system near a potential site for a nuclear waste repository. However, one of the major assumptions made in this study is that the empirical relationship between increased precipitation and consequent increased recharge is valid. Little basis exists for this assumption. Additional work is needed to document recharge mechanisms and rates and to establish analytical expressions between precipitation rate and associated groundwater recharge rates.

It should be noted that this report does not discuss the recharge through Yucca Mountain which is an important parameter in determining the time of travel between the repository and the saturated zone. The analysis in the present report simply determines the water table elevation that may occur under wetter climates.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

For the adequate design of the repository it is necessary to know the effect of climatic changes on the groundwater flow systems beneath Yucca Mountain. The report under review presents a preliminary analysis of such changes.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The use of an empirical relationship between rainfall and recharge is a deficiency of this report. At the present time this is the only available method; however, if field data on recharge are obtained during characterization it may be possible to improve on this analysis.

SUGGESTED FOLLOW-UP ACTIVITIES

The effect of increased precipitation on recharge should be investigated by field studies during characterization.

REFERENCES CITED

Cooley, R.L., and Torak, L.J., 1984, referenced in text as written communication.

Spalding, W.G., and others, 1984, Preliminary Assessment of Climatic Change During Late Wisconsin Time, Southern Great Basin and Vicinity: U.S. Geological Survey Water-Resources Investigations Report 84-4328, 40 p.

Czarnecki, J.B., and Waddell, R.K., 1984, Finite-Element Simulation of Groundwater Flow in the Vicinity of Yucca Mountain, Nevada-California: U.S. Geological Survey Water-Resources Investigations Report 84-4349, 38 p.

1.0 INTRODUCTION

WWLNUM:	3
DOCUMENT NO.:	USGS-WRI-84-4345
TITLE:	"Conceptual Hydrologic Model of Flow in the Unsaturated Zone, Yucca Mountain, Nevada
AUTHORS:	Parviz Montazer and William E. Wilson
PUBLICATION DATE:	1984
REVIEWER:	Water, Waste & Land, Inc.
DATE REVIEW COMPLETED:	March 20, 1986
DATE APPROVED:	L.A. Davis 3/21/86

Mark J. Logsdon, NWC Project Manager 3/21/86

2.0 SUMMARY OF DOCUMENT AND REVIEW CONCLUSIONS

2.1 Summary of Document

A conceptual model describing the flow of fluids through the unsaturated zone at Yucca Mountain is proposed. The proposed model considers the following phenomena in the unsaturated region:

- o Flow through fractured rock
- o capillary barriers
- o Infiltration into fractured rock
- o Lateral movement
- o Capillary fringe

The proposed model gives a representation of the flow in the hydrogeologic units and structural pathways at Yucca Mountain. Areas needing further investigation are identified.

The authors state explicitly that the concepts presented are intentionally descriptive and conjectural but, for the sake of simplicity and directness, the model is presented as if it were an expression of the facts. It is important that this perspective be kept in mind when assessing this document.

2.2 Summary of Review Conclusions

The conceptual model presented in this document provides a basis for preliminary assessment of site performance and as a guide to further investigations as it was intended to do. However, because the model is presented as if it were a "true expression of the facts", a casual reader may be left with erroneous impressions concerning the degree of understanding of the hydrology at Yucca Mountain.

Several principles of unsaturated flow are discussed in the context of the specific conditions known to exist at Yucca Mountain. These include fracture flow, flow in the matrix, the effect of bedding and textural discontinuities (capillary barriers), and vapor flow. The presentation of these phenomena as generic principles appears accurate and correct. It is the degree to which these phenomena interact to effect the flow at Yucca Mountain that remains in question. We make the following specific points:

a. The tendency for flow to occur preferentially in the fractures or in the matrix is extremely sensitive to the hydraulic properties of both of these flow paths and to the imposed flux (net infiltration). Hard, reliable data on the flux and the hydraulic properties of the fractures are not yet available.

b. The effect of air in the matrix blocks on the tendency for water in the fracture to "diffuse" into the matrix is discussed primarily in terms of inducing hysteresis into the permeability and water retention functions. Because the matrix blocks exhibit low air contents, water movement into the matrix is expected to be retarded more severely than is accounted for by hysteresis and low moisture capacity. The additional retardation will result from very low permeabilities to air at low air contents.

c. The phenomenon of "capillary barriers" existing at textural discontinuities is well known. However, the effect that such discontinuities have on the flow depends strongly on whether the flow is transient or steady-state. At steady-state, the pressure and permeability simply adjust to the conditions required to transmit the imposed flux. If the discontinuity forms a dipping surface, there is also a tendency for streamlines to be refracted at the discontinuity, just as in saturated flow. However, only those streamlines in close proximity to the lateral, bounding faults will be modified sufficiently to result in "lateral flow" to the fault zone. As a consequence, a sloping textural discontinuity may have less influence on the partitioning of total steady discharge into a lateral outflow component and a vertical outflow component than is implied.

On the other hand, the sloping discontinuity will have a relatively greater effect on lateral flow during the transient phase. It seems that the flow at depth is more likely to be approximately steady, thus discounting the importance of textural discontinuity on the partitioning of total discharge into a lateral fraction and a vertical fraction. Thus, the effectiveness of textural discontinuities above the Topopah Springs welded unit in preventing percolation into the repository horizon may be overstated.

d. Upward vapor transport by convection in the fractures is proposed by the authors to provide still another means of reducing the net downward flux of liquid water in the Topopah Springs unit. Certainly the potential for water transport by this mechanism is of the same order as liquid transport. Careful evaluation of this transport mechanism is warranted.

3.0 SIGNIFICANCE TO THE NRC WASTE MANAGEMENT PROGRAM

The conceptual model which is presented in the report is based on extensive geologic information and relatively few hydrogeologic data for the unsaturated zone. The authors have synthesized the available information into a detailed, qualitative model for the processes which possibly govern flow at Yucca Mountain. The authors point out that the proposed conceptual model is general in scope, and that as more data becomes available, modifications and quantification can be incorporated into the model. The conceptual model is a critical portion of the Yucca Mountain high level waste project and provides focus to the needed data collection, laboratory testing, and numerical modeling efforts.

4.0 DETAILED REVIEW (Problems, Deficiencies and Limitations)

4.1 Retardation of flow by capillary barriers

It is considered that the unsaturated zone could be a natural barrier to the migration of the various radionuclides from the potential host repository. Part of the retardation of radionuclide transport would be due to limitation of water flow into the fractured, welded tuffs which contain the repository. Some restriction of water flow is assumed to be caused by natural capillary barriers. A capillary barrier can be formed between a unit containing relatively fine pores or fractures and an underlying unit containing relatively coarse pores or fractures.

The report states that a capillary barrier exists between the matrix of the Paintbrush non-welded unit and the open fractures of the Topopah Spring welded unit. In addition, a capillary barrier is assumed to exist at the contact between the Tiva Canyon welded unit and the underlying Paintbrush nonwelded unit. After a precipitation event, infiltration is thought to flow rapidly down the fractures of the Tiva Canyon unit until reaching the capillary barrier at the top of the Paintbrush nonwelded unit. As a result of the large effective porosity and lesser hydraulic conductivity of the Paintbrush unit, the velocity is significantly decreased and lateral unsaturated flow of water can occur above this contact. The report also states that perching along fault displacements may occur.

The lack of evidence for the capillary barrier makes it difficult to consider such a diversion of water to be a conservative condition. From a broad overview, the specific lack of evidence for the Tiva Canyon/Paintbrush barrier is as follows:

1. No perched water has been observed at the contact in the references.

2. No spring-discharge along the outcrop of the Tiva Canyon/Paintbrush contact has been observed.

Until evidence shows otherwise, the conservative approach to net infiltration reaching the Tiva Canyon welded unit and the Paintbrush nonwelded unit would be to assume there is no capillary barrier to downward flow.

At the contact between the Paintbrush nonwelded unit and the Topopah Spring welded unit, the report states that no matrix to matrix capillary barrier occurs. However, a capillary barrier is stated to exist between the matrix of the Paintbrush nonwelded unit and the open fractures of the Topopah Spring welded unit. In the same paragraph, it is stated "opening sizes and moisture conditions are such that some sheet flow can occur along the walls of the fracture in quantities that are greater than the flow in the matrix of the welded unit. Again, the conservative approach (for radionuclide travel times) for the conceptual model would be to assume that no capillary barrier exists at the matrix/fracture interface until evidence shows otherwise.

4.2 Net Infiltration of Water

The document estimates the average annual precipitation to be about 150mm/year and an average recharge rate of between 0.5 to 4.5 mm/yr. The report states that infiltration of water at Yucca Mountain probably occurs either directly into fractures within bedrock exposures or from surface runoff seeping into alluvium beneath the channels of washes. The amount of water that is not evapotranspired and that percolates downward and laterally in the unsaturated zone is very small, because of the minor amount of precipitation and the rapid evapotranspiration rates. Any surface runoff is infrequent and of short duration. Direct measurement of infiltration and recharge have not been made at Yucca Mountain.

In describing the conceptual model for Yucca Mountain, the report states that water infiltrating hydrogeologic units exposed at the land surface either is returned to the atmosphere by evapotranspiration or percolates downward beyond the effects of evapotranspiration. Units exposed include alluvium, the Tiva Canyon welded unit, the Paintbrush non-welded unit, and the Topopah Spring welded unit. A large portion of the water infiltrated into the alluvium and colluvium material is stored in the first few meters of the soil and is lost to evaporation during dry periods. Percolation of infiltrated water through the exposed fractures of the Tiva Canyon welded unit is relatively rapid because of the large fracture permeability and small effective porosity of the unit. (Infiltration mechanisms in the exposed portions of the Topopah Spring welded unit are similar to those of the Tiva Canyon welded unit). A large proportion of the infiltrated water normally is percolated sufficiently deep within the fractured tuff to be unaffected by the evaporation potential that exists.

As stated in the section "Concepts of Unsaturated Flow", the depth to which water flows in fractures during infiltration is a function of rock matrix saturation, moisture capacity, permeability, and the intensity of the infiltration, among other things. Rapid infiltration rates, small matrix permeability, and small matrix moisture capacity enhance deep fracture flow. Therefore, on the exposed portions of the Tiva Canyon and Topopah Spring welded units, the potential exists for a large portion of the infiltrated water to become net infiltration.

The report does not address the percentage of surface area at Yucca Mountain exposed as welded tuff. If the potential exists for a large proportion of the infiltrated water on these surfaces to become net infiltration, portions of the exploratory block may experience fluxes greater than presented.

4.3 Non-Conservative Flux Calculation

Several references to data and information from the unsaturated zone borehole USW UZ-1 are made through the report, yet no published report is shown in the bibliography specifically pertaining to USW UZ-1. The report states that drill cuttings from USW UZ-1, which were obtained using dry drilling methods show no significant differences in the moisture contents when compared with samples collected from other boreholes which were drilled using wet methods. The report then says that this comparison provides some confidence in the validity of the saturation data for the Calico Hills nonwelded unit. However, a discrepancy exists between boreholes USW UZ-1 and USW H-1 matrix potentials, even though a similarity exists between the water-content measurements from the two boreholes. The in-situ potentials measured in USW UZ-1 are one to two orders of magnitude smaller. This discrepancy is being evaluated by the DOE.

The in-situ potential gradient measured in USW UZ-1 and USW G-1 and the effective permeabilities obtained from core analysis were used to calculate the flux in the matrix of the Topopah Spring welded unit. The calculated downward flux ranged from $1x10^{-7}$ to $1x10^{-4}$ mm/yr, which was substantially less than previously reported values. Estimates of flux in the Paintbrush nonwelded unit range from 10 to 30 mm/yr, both in upward and downward directions when only vertical flow is considered.

Since a similarity exists between the water-content measurements from USW UZ-1 and USW H-1, and drill cutting from USW UZ-1 are similar in moisture content to drill cuttings from other wells, the conservative approach to the calculation of flux values would be to use the matrix potentials reported for borehole USW H-1. By using the in-situ potential from USW UZ-1, which is several orders of magnitude smaller than USW H-1, the flux values obtained are significantly less than those obtained using the USW H-1 data.

4.4 Drainage into Topopah Spring Welded Unit through Structural Features

During drilling of test well USW UZ-1 (Whitfield, 1985) a large volume of water was encountered in the densely welded tuff of the Topopah Spring Member at a depth of 387 meters. The bottom of the unsaturated zone at this location was estimated to be about 470 meters. Chemical analysis of the water from USW UZ-1 indicated that communication exists between test wells USW UZ-1 and USW G-1. Polymer, which was used in the drilling fluid of USW G-1 was found in the water at USW UZ-1. Test well USW G-1 is located 305 meters to the southwest of test well USW UZ-1.

The report states that limited fracture flow may occur near the upper contact of the Topopah Spring welded unit, however, movement into the matrix diminishes the extent of fracture flow in the deeper parts of this unit. The evidence contradicts this statement. The contamination of water at USW UZ-1 by drilling fluid polymer from USW G-1 indicates significant lateral flow within the deep, densely welded Topopah Spring Member. Flow from fractures in the unsaturated Topopah Spring Member of test well USW H-1 was also observed with a down-hole television cameral log.

The diversion of infiltration by the Tiva Canyon/Paintbrush contact is questionable, and when consideration is given to the possibility of subsurface fault zones becoming conduits for downward flow, there may be areas in the primary repository area that have significant downward flux. Such considerations may significantly shorten travel-times to the accessible environment.

5.0 RECOMMENDATIONS

The conceptual model provided in this report certainly seems to identify the potential flow mechanisms that may affect repository performance. Many of the mechanisms presented result in decreasing the net vertical flux into the hydrogeologic unit which has been targeted for the repository. Published data does not provide evidence supporting the existence (or absence) of these mechanisms. The data acquisition plan should be carefully and critically reviewed to insure that the data are gathered so that the existence of the important mechanisms which reduce flow into the repository horizos are verified. In general, this will required a detailed and precise water balance which may be difficult to obtain.

With respect to the conceptual model, it is recommended that the effects of resistance to air flow between matrix and fractures be evaluated. Such an evaluation would require use of a two-phase flow model. In addition, the conditions under which the vapor transport mechanisms which may occur in fractured tuff should be investigated.

6.0 REFERENCES

Whitfield, M. S., 1985. "Vacuum Drilling of Unsaturated Tuffs at a Potential Radioactive-Waste Repository, Yucca Mountain, Nevada," Proceedings of the NWWA Conference on Characterization and Monitoring of the Vadose (Unsaturated) Zone.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: USGS-WRI-84-4349

DOCUMENT: Czarnecki, J., and Waddell, R.K., 1984, Finite Element Simulation of Ground Water Flow in the Vicinity of Yucca Mountain, Nevada-California. U.S. Geological Survey, Water-Resources Investigations Report 84-4349.

REVIEWER: Williams & Associates, Inc.

DATE REVIEW COMPLETED: August 26, 1986

ABSTRACT OF REVIEW: APPROVED BY: Roy E. Williams

The report is concerned with the use of a groundwater model to better understand the groundwater flow system in the vicinity of Yucca Mountain, Nevada. Parameter estimation techniques are used to determine transmissivity values. Sensitivity analysis is used to determine the most significant flow parameters. The report uses state-of-the-art techniques for groundwater modeling and makes use of the data that are available at the present time. The authors warn against using their results out of the context of the assumptions presented in the report. Calculated groundwater travel times in the saturated zone of 85 to 17,000 years are presented. Another possible use of information in the report could be for evaluating the water resource. An extensive review of the literature concerning the Nevada Test Site is presented in the report.

BRIEF SUMMARY OF DOCUMENT:

The report describes the use of a groundwater flow model and its application to the region of Yucca Mountain at the Nevada Test Site. This model makes use of parameter estimation techniques to estimate transmissivities within the flow system and to simulate steady state groundwater flow. This model ultimately could be used for estimating travel times in the saturated flow zone as well as for evaluating the effect of future groundwater withdrawal for irrigation.

The model of the groundwater flow system includes recharge/discharge fluxes, boundary fluxes and distribution of hydrologic properties of hydrogeologic units within a three-dimensional framework. The conceptual model used is one proposed by Winograd and Thordarson (1975). The code used is that developed by Cooley (1977, 1979). The parameter estimation technique by Cooley was used to derive values for various flow parameters for zones or nodes defined throughout the modeled area. The parameter values are estimated by minimizing the weighted sum of squared residuals of simulated head. The parameter estimation techniques are not successful in estimating precise values of parameters; however, the importance of various parameters is delineated. The standard ~~area of~~ error estimated parameters reflects the ability of the model to determine these parameters. When entering the hydraulic head measurements into the parameter estimation scheme the node closest to a given measurement site is assigned the hydraulic head value at that site or an average value of the surrounding hydraulic head is applied to a central node.

Fluxes, constant head nodes and transmissivities were included as parameters for optimization at various points in the modeled region. Simulations involving constant head and transmissivity parameters, transmissivity parameters only, and one areally distributed flux parameter successfully converged. Simulations with both transmissivity and flux parameters failed to converge. The final selection of parameters involved only transmissivities.

In the final results, a standard error of 7.1 m was obtained. The standard error divided by the range in measured head values is 0.008. Although an individual residual may be small, almost 29 m in one instance, overall agreement between measured and simulated heads is good. The correlation coefficient between measured and simulated heads for final simulation was 0.997. This suggests an excellent representation of the hydrologic system by the model. The principal fluxes specified in the model are distributed areal fluxes at the Franklin Lake Playa (evapotranspiration) and at Fortymile Canyon (infiltration) and as linear distributed flux at Furnace Creek Ranch (seeps and springs). The infiltration at Fortymile Canyon was set as a parameter; however, the flux did not allow model convergence. Estimates of this flux were varied for individual runs until a minimum error variance was achieved. An extensive sensitivity analysis was carried out which resulted in the following three conclusions.

1) Scale sensitivity with respect to both discharge and transmissivity increases as distance from the point of constant head increases.

2) Absolute values of scale sensitivities with respect to transmissivity and flux decrease as transmissivity increases.

3) Scaled sensitivities with respect to both types of parameters are functions of flux.

Travel time calculations also were performed based on the possible range of aquifer thickness and porosity. Calculated travel time along various paths in the saturated zone varies from 86 to 17,000 years. The author's general conclusions are:

1) The presence of barriers in the model greatly affects the orientation of groundwater flow vectors. Few data are available regarding the shape, orientation and extent of the barrier north of Yucca Mountain.
2) The travel time estimation procedure used to determine a possible range in travel time, although not entirely accurate, provides a means of comparing travel times resulting from different values of porosity and thickness.

3) Results of this model need to be used with care, particularly with respect to the prediction of transport of radionuclides. Fluxes provided by this model may be used in a detailed transport model, but results could be misleading if the fluxes are used out of the context of the assumptions and qualifications stated in this report.

<u>SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM</u>:

Knowledge of the groundwater flow system may be needed to determine the groundwater travel time. Information on the groundwater resource also is needed to determine the possibility of development of the resource.

<u>PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT</u>:

The report has no significant deficiencies.

<u>SUGGESTED FOLLOW-UP ACTIVITIES</u>

No follow-up is needed.

REFERENCES CITED:

Cooley, R.L., 1977, A Method of Estimating Parameters and Assessing Reliability for Models of Steady State Groundwater Flow, 1--Theory and Numerical Properties. Water Resources Research, vol. 13, no. 2, p. 318-324.

Cooley, R.L., 1979, A Method of Estimating Parameters and Assessing Reliability for Models of Steady State Ground Water Flow, 2--Application of Statistical Analysis. Water Resources Research, vol. 15, no. 3, p. 603-617.

Winograd, I.J., and Thordarson, W., 1975, Hydrogeologic and Hydrochemical Framework, South-Central Great Basin, Nevada-California, with Special Reference to the Nevada Test Site. USGS Prof. Paper 712-C, p. C1-C126.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: USGS-WRI-84-4345

DOCUMENT: Conceptual Hydrologic Model of Flow in the Unsaturated Zone, Yucca Mountain, Nevada. Parviz Montazer and W.E. Wilson, U.S. Geological Survey, Water Resources Investigations Report 84-4345

REVIEWER: Williams & Associates, Inc.

DATE REVIEW COMPLETED: April 30, 1986

ABSTRACT OF REVIEW: APPROVED BY: Roy E. Williams

The report presents a conceptual model of the unsaturated zone at Yucca Mountain, which considers the various geologic formations; the product is an estimate of the flux through each layer that results from natural infiltration. The model includes so-called capillary barriers which are said to retard and divert the flow around the repository location. We note that for the purposes of the objective pursued herein capillary barriers would be valid only for the case of transient flow conditions; the moisture content of the upper material in the "barrier" would increase eventually to the point that water would move down through the lower material, thereby destroying the "barrier."

Air permeability measurements were made in various boreholes using barometric pressure variations as the driving force. The authors do not point out that this method would be in error due to the portion of the pore volume that is filled with water. The actual value measured would be the effective conductivity to air at a particular level of water saturation and not the saturated value of conductivity.

Vapor flux estimates in the conceptual model are not substantiated by data; they are questionable, as are some of the liquid flux estimates. Some of the values through various layers appear to violate continuity or conservation of mass.

The authors' model boundaries are not validated by data. The assumption of flow through structural features is not substantiated by data nor is the occurrence of a perched water table at some interfaces between hydrostratigraphic units. The validity of the assumption of lateral flow along hydrostratigraphic unit interfaces is dependent on the existence of the perched water tables.

The authors point out correctly that several aspects of their conceptual model should be investigated experimentally.

BRIEF SUMMARY OF DOCUMENT:

A summary of the conceptual model is as follows. A hypothetical model is proposed for flow through the various layers of tuff beneath Yucca Mountain. In this model flow through fractures may occur at almost all stages of saturation, but the flux magnitude in fractures is a function of the contrast between the hydraulic properties of the matrix and fractures and the magnitude of the flux through the entire profile. Downward flux is assumed to be retarded by capillary barriers that occur at the contacts between non welded and welded tuff units. These barriers are suggested to produce lateral flow. Water infiltrates into the Tiva Canyon welded tuff unit as well as into the alluvium, into the Paintbrush non welded tuff unit, and into the Topopah Spring welded tuff unit wherever these hydrostratigraphic units are exposed at land surface. Eastward lateral flow is conceptualized as occurring at the upper contact with the Paintbrush non welded tuff unit; this eastward flow is assumed to be intercepted by structural features which transmit most of the infiltrated water downward to the water table along pathways located "alongside" the repository.

Paintbrush Non Welded Tuff

Vertical flux in the Paintbrush non welded tuff unit may vary from .1 to 98 mm/yr and the lateral flux may be 100 mm/yr. The authors of the report under review believe that the ratio of vertical to lateral fluxes depends on the effectiveness of the capillary barrier at the lower contact of the unit. Downward flux is portrayed as occurring in the matrix of the Topopah Spring unit, but the probable net flux is believed to be about 1 to 2 mm/yr upward. There is little explanation of this apparent contradiction in the report.

We do not agree with many factors in this conceptual model. These issues will be pointed out in detail in the comments that follow. Throughout this report the concept of a capillary barrier is used to explain that water may not flow downward from an upper hydrostratigraphic unit to the unit immediately beneath it. The condition which would bring about this capillary barrier consists of material with fine pores occupying the upper layer with a material with large pores or fractures constituting the lower layer. A capillary barrier such as this would be effective only for a short time under a transient condition because the moisture content in the upper material would increase to the point that water would move into, and ultimately through, the larger pores or fractures of the lower layer. A capillary barrier may be effective on a short term basis in a small area such as over a tunnel or drift which has sufficient cross-sectional area in a horizontal plane in the porous matrix for the flow to pass around the drift. However in the case of an entire hydrostratigraphic unit of large areal extent the water has no alternative flow path to follow that would not increase the moisture content of the lower hydrostratigraphic unit. Flow then would occur into, and ultimately through, the large pores of the lower hydrostratigraphic unit. On the basis of this reasoning we reject the concept that the capillary barrier would prevent water from moving into the lower hydrostratigraphic unit that comprises the so-called capillary barrier.

Air permeability tests were conducted in test well UE-25A#4 using barometric pressure changes as a driving force. This test is not described in detail, but the authors should realize that air permeability is dependent on the amount of pore space that is filled with air as opposed to water. The degree of saturation (moisture content) is defined poorly in the report under review; in addition, it is doubtful that one air permeability test would produce reliable data. Insitu air permeability tests are limited by the fact that if considerable moisture exists in the material, the permeability measured with air is not the same permeability that would be measured if the material were filled completely with one fluid.

Topopah Spring Unit

Air permeability tests also were conducted on the Topopah Spring Unit using barometric pressure as a driving force. The authors point out that permeability values determined by flow of air through fractured rocks could be greater than the intrinsic permeability because of the slip flow phenomena (Klinkenburg effect). This assertion is correct, but, for the reasons just mentioned the permeability of the rock to air also could be less than the saturated hydraulic conductivity value.

Flow Through Fractured Rocks

In this section the authors develop a conceptual model of flow through the fractures. Points of contact in the fractures are hypothesized around which pendular rings of water exist under unsaturated conditions. Hypothetical curves of effective permeability to water versus matric potential then are presented. These curves are discussed in great detail, both for the fracture and the porous matrix flow. Even though these curves are completely hypothetical considerable detail is presented concerning the magnitude of the difference between the fracture flow and the matrix flow. This discussion is inappropriate because the curves are completely hypothetical and are not based on any experimental calculations or data.

In this section considerable discussion of the effect of rate of wetting on hysteresis also is presented. The authors of this report believe that the concept of hysteresis is insignificant within Yucca Mountain. Since hysteresis is dependent on changes from the wetting cycle to the drying cycle, it would occur only under unsteady flow conditions. The authors assume that the flow through the majority of Yucca Mountain is essentially steady state.

Capillary Barriers

This section begins with the statement that "Capillary barriers occur in unsaturated zones at the contact where a unit containing relatively fine pores or fractures overlies a unit containing relatively coarse pores or fractures. Such capillary barriers probably exist at Yucca Mountain and could serve to retard the rate of percolation." The validity of this statement is very questionable. The coarse material underneath the fine material would tend to retard flow early in the process of a recharge when flow is transient. Under steady state conditions of downward flow, the same flux would traverse the coarse material as the fine material. As water moves along its downward directed flow path, the moisture content will increase in the upper or finer material until water begins to move into the larger pores. After flow is established in the larger pores of the lower layer the same flux rate will be established through the coarse material as through the fine material.

Equations 1 and 2 on page 28 are incorrect. The denominator should include the radius of the tube rather than the diameter of the tube. In this discussion of various tube sizes and fracture sizes, the authors fail to mention that the critical height in the two tubes will always be attained under steady state downward flow conditions because water is being supplied to the smaller tube; the pressure will attain the value necessary to produce flow into the coarse material.

The authors describe further the effect of coarse material over fine material and point out the difference in the effective conductivity curves of the two materials. This difference is reflected in the fact that at lower moisture contents the fine-grained material will attain a higher effective conductivity than a coarse-grained material. This assertion is correct. However, the authors do not point out that the matric potential in the two materials will adjust such that the same effective conductivity develops in each of the materials even though the process occurs at different matric potentials in the two materials. The authors also discuss the effect of the curves of the two materials not intersecting. This effect is not relevant to downward flow because the two materials still will develop the same effective conductivity but at different matric potentials.

Page 31. The authors cite Palmquist and Johnson (1962) and Hillel and Talpaz (1977) to support their concept of the capillary barrier. These authors evidently show that the fine-grained material above a coarse-grained material will be substantially wetter than the coarse-grained material. We have discussed this phenomenon above (i.e., that the degree of saturation will increase until water traverses the coarse material at the same rate that it traverses the finer material).

Page 34. The authors discuss two instances in which water has been shown to move very rapidly to depths of several tens of meters through fractures within a few days after rapid snow melt. The first of these examples (Montazer, 1982) was in metamorphic rocks which have insignificant matrix conductivity; therefore all flow would occur in fractures. The second of these (Thordarson, 1965) is in Rainer Mesa in which the matrix is reported to be completely saturated.

The effect of the fairly high degree of saturation (high moisture content) on air movement in Yucca Mountain seldom has been discussed. A high degree of saturation would allow relatively little movement of air; but this factor should be evaluated by studying the air permeability of the material as affected by water saturation.

<u>Unsaturated Zone Flux</u>

The authors list many sources of information on recharge in the general area of Yucca Mountain but few data are available on recharge at Yucca Mountain itself. The estimates vary from .5 mm/yr by Czarnecki (1984) to 4.5 mm/yr by Rush (1970). Sass and Lachenbruch (1982) estimate a vertical water flux of 1 to 10 mm/yr from geothermal data. Sass and others (1980) used heat flow data and showed a negative (upward) water flux of more than 150 mm/yr in the saturated zone. The authors of the report under review state that if the method of Sass and Lachenbruch (1982) is used to calculate the upward flux of water vapor saturated air in the Topopah Spring welded tuff unit, a flux of about 1.5 mm/yr was obtained. Their calculations are not shown. It also is not clear how the method of Sass and Lachenbruch (1982) could be used for the unsaturated zone; they can assume specifically that the porous matrix is saturated. Sass and Lachenbruch state that they can say specifically that no movement of water occurs up and down the borehole outside the casing in only one of the boreholes. They also state that the drilling mud may well have been a source of heat to the rocks. The authors summary statement is that in the unsaturated zone at Yucca Mountain thermal flux is complicated by movement in both liquid and vapor phases, by heterogeneity of the hydrogeologic system, and by possible lateral flow. Both upward water vapor movement in the fractures and downward liquid flow in the matrix may occur. It is our feeling that this analysis of vapor movement is highly speculative and that very few data exist to support their assumptions.

The authors also list several other references and values for the flux; the values range from 1×10^{-7} to 30 mm/yr in both upward and downward directions. It is difficult to understand why upward flow would occur in the liquid phase; any method that suggests the occurrence of upward flow is very questionable. The authors state that data from borehole USW UZ-1 show that a large lateral component of flow must be assumed in order to explain the distribution of the matric potentials measured in the Paintbrush non welded tuff unit. The authors investigate the possibility of lateral flow further; but it is not clear whether the continuity equation is satisfied because no statement is provided concerning the ultimate disposition of flow after it moves laterally. Mathematical models of various cross-sections has not produced any indication of lateral flow.

In summary the reasoning presented in the report under review attempts to show that:

1) "From .1 to 98.6 mm/yr of vertical flux may be occurring in the Paintbrush non welded unit; but the magnitude of vertical flux depends on the effectiveness of the so-called capillary barrier at the lower contact of this unit." This statement does not make sense. Even if the capillary barrier at the bottom was effective, it would have no effect on the vertical flux through the Paintbrush non welded unit. In addition, as explained previously herein, the capillary barrier is not a valid concept in this case.

2) "The capacity to transmit flow laterally in the Paintbrush non welded tuff unit is more than 100 mm/yr or about twice the maximum estimated infiltrated water."

3) "From 10^{-7} to .2 mm/yr flux could be occurring in the matrix of the Topopah Spring welded unit. Flux in the fractures is unknown."

4) "Flux in the Calico Hills non welded unit is variable but probably is limited to .006 mm/yr in the downward direction." From the continuity equation if the downward flux in Calico Hills is only .006 mm/yr then that also would be the downward flux in all the other formations.

5) "Results of analyses of the geothermal heat flux data show that about 1 to 2 mm/yr of upward net flux occurs in the Topopah Spring welded unit possibly as a result of upward moving air saturated with water vapor; but the results are uncertain because of possible alternative interpretations of the data." This conclusion is highly speculative and the references given do not justify the 1 to 2 mm/yr upward net flux.

Flow System Boundaries

Boundaries to the flow regions are shown in figure 1. Lateral flow downdip at contacts between hydrostratigraphic units is shown even though there is no indication that such flow actually occurs. Perched water tables also are shown near the fault zones but there is no indication that these actually exist.

Page 49. The authors make the statement, "The upper contact of the unit and upward component of flux from the matrix of the Calico Hills non welded unit into the matrix of the Topopah Spring welded unit may develop because of differences in the capillary pressures." This statement is questionable because some driving force must cause upward flow. Capillary pressures will not bring about upward flow unless some phenomenon such as evaporation creates the capillary pressure difference.

In summary, the authors state (page 51) that

> "most of the infiltrated water is transmitted downward to the water table along structural features. Some matrix to matrix flow occurs from the Paintbrush non welded unit into the underlying Topopah Spring welded unit. A capillary barrier retards flow into the fractures of the Topopah Spring welded unit. Percolation rates are variable or even negative in the Topopah Spring welded unit except along completely penetrating, very conductive structural features."

This is not substantiated by data. Again quoting on page 51,

> "Therefore pulses of infiltration may cause rapid percolation down through the Tiva Canyon welded unit and into the Paintbrush non welded unit. Hysteresis effects may occur in the upper part of the Paintbrush unit and result in rejection of downward percolating water much sooner that would be predicted by drainage curves."

No evidence has been presented to the NRC that would substantiate this analysis. This report continues, "Fracture flow into the Topopah Spring welded unit is retarded by the capillary barrier that exists between the Paintbrush non welded unit and this welded unit." No evidence has been presented to the NRC that would substantiate this statement. The concept of a long term capillary barrier in this case is invalid.

> "Considering the potential for vapor transport under geothermal gradients, the net flux in parts of the Topopah Spring welded unit even may be negative (upward). Of the conservatively estimated 4.5 mm/yr net infiltration probably only a maximum of 1 mm/yr (equivalent to saturated hydraulic conductivity of the unit) is transmitted through the Topopah Spring unit. The excess net infiltration probably flows laterally into the structural features." .

Again no evidence has been presented to the NRC that would support this conclusion.

Page 52. The authors suggest the following additional work that should be done. Such investigations could include evaluations of:

1) "Flux in shallow hydrogeologic units to identify more directly the net infiltration rate." Such a study would be very valuable. Experiments should be conducted on the application of water to the ground surface to determine rates of flow into the rock and whether infiltrating water flows downward into fractures or into the matrix.

2) "Flux in the major structural features in the central block to assess the significance of such features and similar ones that might exist or develop in the central block."

3) "The presence or absence of perched water tables to assess the impact on repository construction and integrity." This type of study definitely should be pursued; the present model assumes that perched water tables will form near the structural features. Perhaps drilling in fault areas should be implemented to determine whether perched water tables exist.

4) "Two-phase flux in the Topopah Spring unit to evaluate the potential for upward moving water."

5) "The assumptions made in developing the conceptual model to assess the appropriateness of the model to provide a basis for its revision." We agree that the aforementioned topics of work are important to determine the validity of any conceptual model that may be used.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

A well verified conceptual model is a prerequisite to the evaluation of the movement of water through the unsaturated zone at the repository site. Such a model probably will lead to a defensible analysis for time of travel to the accessible environment. This report is a first draft of such a model. But as it exists presently much of it is very speculative.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The concept of a long term capillary barrier is used incorrectly in the report. Such a barrier is not a valid reason for diversion of water around the repository site. Several portions of the conceptual model, such as interfaces between hydrogeologic units, should be simulated with a two dimensional model in order to investigate the effect of a sloping contact. Movement of water around backfilled drifts and movement of water into the tuff immediately below the ground surface should be evaluated also.

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Montazer, Parviz, 1982, Permeability of Unsaturated Fractured Metamorphic Rocks Near an Underground Opening. Golden, Colorado School of Mines, unpublished Ph.D. Thesis, v. 1, 311 p.

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Thordarson, William, 1965, Perched Ground Water in Zeolitized-bedded Tuff, Rainier Mesa and Vicinity, Nevada Test Site, Nevada. U.S. Geological Survey Trace Elements Investigative Report TEI-862, 90 p.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: USGS-WRI-85-4030

DOCUMENT: Whitfield, M.S., Eshom, E.P., Thordarson, William, and Schaefer, D.H., 1985, Geohydrology of Rocks Penetrated By Test Well USW H-4, Yucca Mountain, Nye County, Nevada. USGS Water Resources Investigations Report 85-4030, Denver, Colorado.

REVIEWER: Williams & Associates, Inc., James L Usunsky

DATE REVIEW COMPLETED: February 25, 1987

ABSTRACT OF REVIEW: APPROVED BY: Roy E. Williams

The report under review presents a discussion of the geohydrology of rocks penetrated by test well USW H-4. The report is a basic data interpretation report. The report presents interpretations of borehole geophysical logs with respect to the degree of induration or welding of the rocks penetrated, the intervals in which the borehole is out of gauge, and the percentage of porous rock penetrated by the borehole. In addition, the report presents interpretations of aquifer test data for a long-term aquifer test (8.9 days). The primary importance of the report under review will be in combination with companion reports dealing with the evaluation of the hydrogeologic conditions in the saturated zone beneath Yucca Mountain.

BRIEF SUMMARY OF DOCUMENT:

The report under review presents the results of geophysical logging and hydraulic testing in test well USW H-4. Test well USW H-4 is one of a series of wells designed to obtain data in the saturated zone in the vicinity of Yucca Mountain.

Test well USW H-4 is located approximately 45 km northwest of Mercury in southern Nevada. Drilling of USW H-4 began on March 22, 1982. A total depth of 1,219 m was reached on April 28,

1982. Test well USW H-4 was drilled with a drilling fluid of air foam consisting of air, detergent, and water from well J-13.

A generalized lithologic description of the units penetrated by test well USW H-4 is presented in Table 2 of the report. This table shows that all rocks penetrated by USW H-4 are of volcanic origin. These volcanic rocks consist of seven major ash flow tuffs. They are in descending order: the Tiva Canyon and Topopah Spring Members of the Paintbrush tuff, the ash flow tuffs of Calico Hills, the Prow Pass, Bullfrog, and Tram Members of the Crater Flat tuff, and the Lithic Ridge tuff. Figure 2 of the report summarizes the welding and induration characteristics of these ash flow tuffs.

Borehole geophysical logs of test well USW H-4 were recorded during two separate periods of logging. Geophysical logs were recorded and water level measurements were made after the well was drilled to a depth of 564 m. After the logging was completed, the well was cased to a depth of 561 m and cemented at its base. Drilling continued to its total depth after which the hole was logged again. According to the report, borehole geophysical logs were recorded for test well USW H-4 in order to: 1) determine a more exact depth of the major lithologic changes; 2) obtain porosity and fracture data; and 3) gauge the diameter of the open hole for selecting packer seats. Table 3 of the report lists the types of logs and the depth intervals logged.

The results of the caliper log are shown on Figure 3 of the report. Figure 3 shows the locations of "out-of-gauge" intervals within the borehole. According to the report, out-of-gauge is defined as a diameter of 100 mm greater than the diameter of the bit used to drill the hole. The percentage of borehole wall that is out of gauge in each stratigraphic unit is shown in Table 4 of the report. Table 5 of the report lists the out-of-gauge zones considered by the authors of the report to be associated with fractures.

The percentage of porous rock with depth was estimated by using density and neutron logs. Figure 4 of the report shows the vertical distribution of percentage of porous rock that is greater than the average porosity determined from density and neutron logs. The largest percentage of porous rock occurs between the depths of 0 and 800 m. According to the report, the percentage of porous rock in the lower part of the Tiva Canyon and Topopah Spring Members ranges from 15 to 46 percent. The report notes that these percentages appear to be the result of fractures and may be misleading because the hole is out of gauge. Based on Figure 4, the authors of the report make the following conclusions (according to descending stratigraphic sequence): 1) the Tiva Canyon and Topopah Spring Members contain a large percentage of porous rock, mainly due to fractures; 2) the tuffaceous beds of Calico Hills have a smaller percentage of porous rock; 3) the Prow Pass Member has a rather large percentage of porous rock throughout; 4) the Bullfrog Member has a small percentage of porous rock; and 5) the Tram and Lithic Ridge tuff have a small percentage of porous rock.

According to the report, the conceptual model of the groundwater flow system in the general Yucca Mountain area in the vicinity of test well USW H-4 is based on model concepts presented in Rush and others (1984). This conceptual model is based on the following assumptions:

1) Tuffaceous rock containing the primary-matrix porosity is nearly homogeneous and isotropic and is of great areal extent.

2) Secondary porosity is controlled by fractures.

3) Primary and secondary porosity may be decreased by precipitation of minerals.

4) Flow to the well is through the fracture network only; however, flow probably occurs between pores and fractures.

5) Distances between fractures are small in comparison with the dimensions of the groundwater system under consideration.

6) In ash flow tuffs, zones of approximately the same degree of welding have approximately the same density of fracturing, with greater fracture density in more welded tuffs. Where dense fracture spacing occurs, water moves in fractured ash flow tuffs in a similar manner as water in a granular porous medium.

In addition to the aforementioned assumptions of the conceptual model for groundwater flow in the Yucca Mountain area, the authors of the report made the following assumptions in their conceptual model of the flow system at test well USW H-4:

1) Tension fractures that are subsidiary to a major north-northeast-striking fault located 110 m to the southeast are assumed to exist at the site.

2) In addition, long homogeneous linear fractures may exist in the northwest trending wash in which test well USW H-4 is located.

3) Major fractures that conduct water probably are widely spaced in the tension fracture zone related to the fault.

4) During pump tests, porous-media solutions for the homogeneous equivalent model in the Yucca Mountain area (Rush and other, 1984) may be used only after long periods when the response to pumping indicates a psuedo radial-flow period. During this psuedo radial-flow period, radial-flow equations may be used to calculate transmissivity in the area beyond the large elliptical zone of linear flow (Raghavan and Hadinoto, 1978; Jenkins and Prentice, 1982).

The conceptual model for flow in the vicinity of test well USW H-4 is transformed to a mathematical model of a single vertical fracture. However, the authors note that several vertical or very steep fractures are penetrated by the test well. Because of this fact, the conceptual model was used only to explain the linear flow period during pumping tests in which the vertical fractures were assumed to control flow.

According to the report, several preliminary short-term, single well pumping tests were conducted in test well USW H-4. These tests were followed by a long-term, single well main pumping test (pumping test 6). All pumping tests were conducted in the depth interval from 519 to 1,219 m. The authors of the report attribute significant water level fluctuations during the pumping tests to temperature and water density changes in the water column in the well. The authors assume that the density of water in the borehole decreased as higher temperature water flowed into the well. Figure 6 of the report illustrates the water level fluctuations that occurred during pumping test 2.

Pumping test 6 was conducted at a pumping rate of 17.4 L/sec for a period of 12,818 minutes. The authors of the report suggest that water probably was pumped from several intervals (possibly multiple aquifers) of fractured tuff (Williams, 1985). Data for the pumping tests were analyzed for aquifer transmissivity and hydraulic conductivity using the Jacob straight line method and the Theis recovery method. The method developed by Raghavan and Hadinoto (1978) was used to explain the straight line segment of drawdown data versus time on a log-log plot. This straight line segment of the data is attributed by the authors of the report to a linear flow period in vertical fractures. The straight line slope (equal to 0.5 on the log-log plot shown in Figure 7 of the report) occurs from 80 to 3,000 minutes. The Jacob straight line method was used to analyze the drawdown data from 8,000 to 11,000 minutes. The authors of the report suggest that the slope of the straight line indicated by the Jacob straight line method (Δs=1.4 m) is close to the slope (0.81 m) predicted for the straight line in the psuedo radial flow period by the method of Raghavan and Hadinoto (1978).

According to the report, the Theis-recovery method was used to analyze residual drawdown data between 100 and 1,000 minutes.

These data are shown on Figure 9 of the report. Based on the authors interpretation of the data from pumping test 6, transmissivity was estimated to be approximately 200 m^2/day (based on the straight line method) and 790 m^2/day (based on the Theis-recovery method).

According to the report, a radioactive tracer test, a borehole flow test and a temperature survey were conducted during pumping test 6. The borehole flow survey began 45 hours and 40 minutes into pumping test 6. The borehole flow survey indicated that the entire length of the borehole from the water surface at 519 m to the bottom of the hole at 1,219 m produced water during the pumping tests. Figure 10 of the report presents the results of the borehole flow and temperature survey.

A water sample was collected on May 17, 1982, near the end of pumping test 6. The report notes that approximately 14,700,000 L of water were pumped from the test well prior to collecting the water sample. Lithium chloride was added to water used during drilling and in the injection tests. Based on the concentration of lithium in the water sample (4.6 mg/L), the authors of the report concluded that during sample collection the well was producing mostly formation water. However, the report notes that the water sample was "soapy" from the drilling detergent. Table 8 of the report presents the results of the chemical analysis of the water sample. These data indicate that the water is predominantly sodium bicarbonate type with a carbon-14 age date of about 17,200 years.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

The report under review discusses the geohydrology of rocks penetrated by test well USW H-4. The report is significant to the NRC Waste Management Program in that it presents interpretations of data collected during drilling and testing of the test well. The primary significance of this report will be in combination with other reports such as Whitfield and others (1984) which present additional data for test well USW H-4.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The report under review is a basic interpretation report of the data collected in test well USW H-4. The primary limitation of the report is that it is not complete. For example, geohydrologic and drill hole data for test well USW H-4 also are presented in Whitfield and others (1984); this report contains additional hydrogeologic data including a detailed lithologic log. Dividing of the detailed hydrogeologic data and interpretations into several different documents is standard practice by the USGS. This practice makes the detailed evaluation of each report more difficult because important but related data often are presented in separate reports.

An additional limitation of the report may exist in the interpretation of the aquifer test data for pumping test 6. These data were analyzed by using the Jacob straight line method and the Theis-recovery method. Values for transmissivity based on analysis of the data by these methods range from 200 m^2/day for the Jacob straight line method to 790 m^2/day for the Theis-recovery method. These estimates of transmissivity are limited primarily by the conditions of the aquifer test (i.e., a highly variable discharge rate during the first 80 minutes of the test, and the effects of varying density due to temperature changes) and the Theis assumptions rather than problems with the authors interpretation of the data. Perhaps more importantly, it should be noted that the transmissivity value of 200 m^2/day estimated by the Jacobs straight line method (Figure 8 of the report) is based on five data points.

SUGGESTED FOLLOW-UP ACTIVITIES:

Additional review of this document and companion documents may be necessary in the future during detailed site characterization.

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Jenkins, D.N., and Prentice, J.K., 1982, Theory for Aquifer Analysis in Fractured Rock Under Linear (Nonradial) Flow Conditions. Groundwater, vol. 20, no. 1, p. 12-21.

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Whitfield, M.S., Thordarson, William, and Eshom, E.P., 1984, Geohydrologic and Drill Hole Data for Test Well USW H-4, Yucca Mountain, Nye County, Nevada. USGS Open-file Report 84-449, 39 p.

Williams, R.E., 1985, Comment on "Double-Porosity Models for a Fissured Groundwater Reservoir With Fracture Skin" by Allen F. Moench. Water Resources Research, vol. 21, no. 6, p. 889-891.

WMGT DOCUMENT REVIEW SHEET

FILE NO.:

DOCUMENT: Erickson, J.R., and Waddell, R.K., 1985, Identification and Characterization of Hydrologic Properties of Fractured Tuff Using Hydraulic and Tracer Tests--Test Well USW H-4, Yucca Mountain, Nye County, Nevada: U.S.G.S. Water Resources Investigations Report 85-4066, Denver, 30 p.

REVIEWER: Williams and Associates, Inc.

DATE REVIEW COMPLETED: October, 1985

BRIEF SUMMARY OF DOCUMENT: DATE APPROVED: Rec'd w/letter of 85/11/05 #4

The primary purpose of the report is to present results and interpretations of hydrologic and tracer tests used to identify and characterize fractures contributing to ground water flow in test well USW H-4. The report under review summarizes the results of temperature surveys, and tracer tests under pumping and non-pumping conditions. A companion report by Whitfield and others (1984), entitled "Geohydrologic and Drill-Hole Data for Test Well USW H-4, Yucca Mountain, Nye County, Nevada," presents data on drilling operations, lithology, geophysical well logs, pumping tests, and water chemistry for test well USW H-4.

Fractures intersecting the wellbore of test well USW H-4 were identified with a combination of acoustic-televiewer logs and television-camera logs. According to the report under review, the strike, dip direction, and magnitude of the dip could be determined from the acoustic-televiewer log; only the strike and dip direction could be determined with the television log. Fracture location data based on the acoustic-televiewer logs and television camera logs were correlated to data provided by the temperature survey. Data from the temperature survey were used to ascertain which fracture zones produced the greatest quantity of water. Table 2 of the report under review shows the correlation of flow points, identified from temperature logs obtained during pumping, with fractures identified from the acoustic-televiewer and television-camera logs. The data suggest that northeast-trending fractures are the most significant with respect to water production in test well USW H-4.

The temperature profile and zones that produced water during pumping are shown in Figure 5 of the report. Thirty-three separate inflow points were identified from the temperature logs.

A tracejector survey (radioactive-tracer flow survey) was conducted to provide a quantitative measure of water production in the borehole. The tracejector survey was run in test well USW H-4 during the same pumping test as the temperature survey. The results of the tracejector survey are summarized in Figure 3 of the report. The results of the tracejector survey provided an estimate of the percentage of water produced from individual intervals during the pump test in well USW H-4. According to the report under review, the flow surveys indicate that less than 21 percent of the total saturated section penetrated by test well USW H-4 contributed measurable quantities of water to the wellbore.

Tracer tests were conducted under non-pumping conditions to provide information on the rates and directions of water movement in the borehole under non-stressed conditions. Table 1 of the report under review presents a summary of the tracer-spike velocities and flow rates. The tracer test results indicate that under non-pumping conditions, water is moving toward the interval 2,500 through 3,070 feet, from both above and below, with the water leaving the borehole somewhere within this interval. According to the report under review, the two zones where water was observed entering or leaving the borehole correspond to the most permeable intervals identified by injection tests of isolated intervals.

The authors of the report under review used a method developed by Snow (1969) to construct hydraulic conductivity ellipsoids for three separate conditions. The authors of the report under review note, however, that by assuming arbitrary values for fracture apertures, the orientation and eccentricity of the ellipsoid could be determined, though the values of hydraulic conductivity would have no real significance. Hydraulic conductivity ellipsoids were constructed for the following conditions:

1) The first hydraulic conductivity ellipsoid calculated was for an equal aperture case, in which all fractures were assumed to have the same aperture.

2) A second analysis was made with the assumption that the northwest-trending fractures were closed.

3) The final hydraulic conductivity ellipsoid was calculated for the case where the northwest-trending fracture apertures were set equal to twice the value of the apertures of the northeast-trending fractures.

The construction of the three hydraulic conductivity ellipsoids was primarily an academic exercise since fracture aperture data are unavailable for test well USW H-4.

The authors of the report under review attempted to estimate the effective porosity and fracture porosity for the fractured tuffs in test well USW H-4. The procedure used to estimate fracture porosity consisted of the following steps:

1. The equivalent fracture aperture was estimated by dividing the estimated transmissivity in USW H-4 by the number of producing zones as determined by the temperature log during pumping.

2. The orientations of all fractures determined from the acoustic televiewer log were used to estimate the correction factor for sampling-frequency error caused by the high-dip angle of the fractures relative to the borehole.

3. The aperture of the fractures times the corrected number of fractures divided by the length of the borehole along which production was determined was considered to be an estimate of the fracture porosity.

According to the report under review, the fracture porosity is about 0.0001 to 0.001, and the effective porosity is the same or less. The procedure used to obtain these values will yield rough estimates of the fracture porosity only.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

The report under review presents valuable data with respect to the locations of water producing fracture zones in test well USW H-4. Valuable data pertaining to the directions of flow within the borehole also are presented in the report under review. The results presented in the report under review potentially are valuable in the interpretation of aquifer test data presented in the companion report by Whitfield and others (1984). The results of data presented in the report under review and in Whitfield and others (1984) represent very valuable information with respect to ground water flow conditions in the vicinity of test well USW H-4 and in the development of the conceptual model for the saturated zone in general.

PROBLEMS, DEFICIENCIES, OR LIMITATIONS OF REPORT:

The primary deficiency of the report under review is that the report presents results only. The actual data and methods used to interpret the data are not presented in the report. The report under review constitutes a summary of test results for test well USW H-4. Much of the information presented in the report is based upon a subjective interpretation of the data. Without the actual test data it is not possible to perform an independent analysis of the testing procedures and results of the tests conducted in test well USW H-4.

<u>SUGGESTED FOLLOW-UP ACTIVITY</u>:

The well logs, original data and methods of data interpretation associated with this test hole should be referenced and made available to the NRC and public upon request. This is necessary for performing independent analyses and reviews of testing procedures and results. These data may also be significant in the development of a conceptual model for the saturated zone. Also, attempts should be made to correlate the borehole flow survey logs among all boreholes each time a new hole is drilled and tested.

<u>REFERENCES CITED</u>:

Whitfield, M.S., Thordarson, William, and Eshom, E.P., 1984, Geohydrologic and Drill-Hole Data for Test Well USW H-4 Yucca Mountain, Nye County, Nevada: USGS Open-File Report 84-449, Denver, 39 p.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: USGS-WRI-86-4359

DOCUMENT: Thordarson, William, and Howells, Lewis, 1987, Hydraulic Tests and Chemical Quality of Water at Well USW VH-1, Crater Flat, Nye County, Nevada. U.S. Geological Survey, Water-Resources Investigations Report 86-4359, 20 p.

REVIEWER: Williams & Associates, Inc., James L Osiensky

DATE REVIEW COMPLETED: May 31, 1988

ABSTRACT OF REVIEW: APPROVED BY: Roy E. Williams

The report under review presents a generalized summary of the hydraulic tests conducted in test well USW VH-1. This test well was drilled into the saturated zone to a depth of 762 meters; it is located approximately 6 kilometers west of Yucca Mountain. Caving and sloughing of the hole during drilling and testing of the well presented significant problems in the collection of valid, defensible aquifer test data. Transmissivity values for the Topopah Spring Member of the Paintbrush Tuff and the Bullfrog Member of the Crater Flat Tuff were estimated to range from 450 to 2200 meters^2 per day.

BRIEF SUMMARY OF DOCUMENT:

The report under review describes briefly the hydrogeologic information obtained from test well USW VH-1. The report describes the hydraulic properties estimated for the Tertiary volcanic rocks penetrated by the test well.

Test well USW VH-1 is located in Crater Flat, about 2.3 kilometers east of Red Cone, and about 6 kilometers west of Yucca Mountain. Significant caving and sloughing problems were encountered during drilling of this test well. The severity of caving required use of a polymer gel during drilling and coring of some intervals. The test well was drilled to a total depth of 762.3 meters. According to the report, geophysical logs were recorded at hole depths of 197 and 762 meters. Significant problems were encountered during geophysical logging of the test well. The upper 155.5 meters of the test well contains alluvium and a basalt lense (24.3 meters thick); the remaining 606.8 meters of the test well penetrate volcanic debris consisting of 14.7 meters of ash-fall tuff and 592.1 of ash-flow tuff. Table 3 of the report presents a summary of the preliminary lithologic log for the test hole.

According to the report, the first indication of water production by well USW VH-1 was during an air-lift test at a depth of 371 meters. Fourteen air-lift tests were conducted during drilling between the depths of 234.1 and 335.9 meters. The report suggests that the major producing zone occurs within the depth interval between 626 and 643 meters. Temperature measurements in the unsaturated zone below a depth of 200 meters indicate downward water flow.

No packer tests or radioactive tracer surveys were conducted in test well USW VH-1 because of the poor borehole conditions. Six drawdown and recovery tests were conducted. According to the report,

> "None of the tests was wholly satisfactory because of problems caused by 1) caving and sloughing of the hole, 2) turbulent flow losses in the well and possibly the aquifer; 3) an increase in water temperature during pumping which caused the density of water to decrease; and 4) possible other unknown factors in the well-aquifer system."

The authors used a variety of methods to analyze the aquifer test data. A transmissivity value of 450 $meters^2$ per day was estimated from the data for test #3. A transmissivity value of 1000 $meters^2$ per day was estimated from the data for test #5. Test #4 was analyzed using Van der Kamp's (1976) method; the transmissivity was estimated to be 2200 $meters^2$ per day based on the data for test #4. A method presented by Brown (1963) for estimating transmissivity from specific capacity data was used to analyze data for test #1. Transmissivity estimated by this method was 2000 $meters^2$ per day with an assumed storage coefficient of $1x10^{-4}$.

A water sample was collected from well USW VH-1 prior to the end of aquifer test #5; the chemical analysis is shown in table 5 of the report. According to the report, the uncorrected carbon-14 age of the water is 17,000 $\pm$ 170 years before present.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

The report under review presents a generalized description of hydraulic tests conducted at test well USW VH-1. Difficulties in well construction, and poor hole conditions precluded thorough and proper testing of the test well. In general the aquifer test data for test well USW VH-1 generally are of poor quality. The aquifer consists of the Topopah Spring Member of the Paintbrush Tuff and the Bullfrog Member of the Crater Flat Tuff. Transmissivity values derived from the aquifer test data range from 450 to 2200 $meters^2$ per day.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The report under review is typical of many USGS reports of this kind. This report presents a general summary of the hydraulic tests conducted in test well USW VH-1. Actual test data are not included in the report. In addition to the generalized nature of the report, hole caving and sloughing problems encountered during construction and hydraulic testing of the hole resulted in poor quality data. Because of the generally poor quality data, the results of the aquifer tests should be treated with skepticism. Additional testing using observation wells is necessary to obtain more defensible results.

REFERENCES CITED:

Brown, R.H., 1963, Estimating the Transmissivity of an Artesian Aquifer from the Specific Capacity of a Well. U.S. Geological Survey Water-Supply Paper 1536-I, p. 336-338.

van der Kamp, Garth, 1976, Determining Aquifer Transmissivity by Means of Well Response Tests--The Underdamped Case. Water Resources Research, v. 12, n. 1, p. 71-77.

3. Isotopic data suggest that winter precipitation is the primary source of recharge.

4. Little mixing occurs between fracture systems; however, similar chemical reactions yield similar water chemistries.

5. The hydraulic response of the system (discharge from the seeps) is approximately 120 days after a recharge event.

6. Increased discharge from the tunnel seeps during a nuclear test contains a component of possible relict interstitial water high in sulfate.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

The report under review presents several hypotheses and supporting data to help explain the hydrogeology of Rainier Mesa. The data and hypotheses presented in the report are specific to Rainier Mesa. However, these data may be useful in the conceptualization of conditions within Yucca Mountain under the conceptual model that envisions significant recharge.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The report under review is more or less a typical M.S. thesis. The report presents many hypotheses in an attempt to explain the observed conditions. Sufficient data do not exist to explain the hydrogeologic system of Rainier Mesa in significant detail. The primary recommendation of the report is that additional data are needed to understand the hydrogeologic system at the site. Nevertheless, the data that were collected should be studied carefully for purposes of designing future studies, either at Rainier Mesa or Yucca Mountain. The utility of these data with respect to development of conceptual models for Yucca Mountain could be significant.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: USGS-1543-1

DOCUMENT: Hodson, J.N., and Hoover, D.L., 1978, Geology and Lithologic Log for Drill Hole UE17a, Nevada Test Site. USGS-1543-1, 14 p.

REVIEWER: Williams & Associates, Inc.

DATE REVIEW COMPLETED: October 31, 1986

ABSTRACT OF REVIEW: APPROVED BY: Roy Williams/al

Drill hole UE17a is one of a series of holes drilled to evaluate the suitability of the Unit J of the Eleana Formation as a medium for nuclear waste storage. The hole was drilled to a depth of 370 m. The report presents data on the geology of the Syncline Ridge area. The report is not significant with respect to the local geology and hydrogeology in the vicinity of Yucca Mountain. However, some of the information presented in the report may be useful with respect to interpreting the regional geology and hydrogeology of the Nevada Test Site.

BRIEF SUMMARY OF DOCUMENT:

The report under review presents geologic and lithologic data for drill hole UE17a. Drill hole UE17a is located in area 17 of the Nevada Test Site. The hole was drilled to determine the thickness of alluvium and to evaluate the lithologic and stratigraphic characteristics of the underlying Paleozoic rocks. Drill hole UE17a is located within the Syncline Ridge structural block, northwest of Syncline Ridge. The hole is 370 m deep and is bottomed in a quartzite subunit of the Eleana Formation. According to the report, drill hole UE17a was drilled into the zone of saturation to define the static water level.

According to the report, air foam mist was used as circulating medium during drilling; the report notes that sepiolite air foam inadvertently was added to the hole. Water in the hole caused the sepiolite to settle out of the drilling fluid. Drilling problems were encountered between the depths of 251.5 and 239.5 m due to caving of the hole. According to the report, high-viscosity bentonite mud was placed in the hole to stop caving and to hold the hole open for geophysical logging.

Drill hole UE17a was cased to a depth of 368.8 m with 10.8 cm-diameter steel casing. According to the report, "The drilling mud was circulated out of the hole with water." A gun perforator was used to perforate the casing in the following intervals: 227.1 to 251.5 m, 306.3 to 309.4 m, and 324.6 to 362.7 m. According to the report, drilling tools were used to push debris from the perforating operation downhole to a depth of 367.9 m. The report notes that hydrologic testing was conducted by the USGS. However, the results of this testing are not presented in the report.

Drill hole UE17a penetrates 22.3 m of alluvium of Quaternary age, 144.2 m of Tippipah Limestone of early Pennsylvanian to early Permian (?) age, and 203.6 m of Unit J of Eleana Formation of Mississippian age. Table 1 of the report presents a lithologic log of drill hole UE17a.

According to the report, an east-trending, pre-Tertiary, strike-slip fault is present between drill holes UE17a and UE16c. Lateral displacement along the fault is estimated to be at least 1 km. Vertical displacement along the fault is estimated to be at least 144.2 m because that thickness of Tippipah Limestone is missing from drill hole UE16c. Table 2 of the report lists probable faults penetrated by drill hole UE17a.

The report notes that groundwater was first detected during drilling at a depth of 176.8 m. Groundwater inflow into the hole became significant at a depth of 324.6 m; inflow remained relatively constant during the remainder of drilling. According to the report, water appeared to be coming from open_fractures.

A core index was calculated for each core sample obtained from drill hole UE17a to evaluate the rock competency. According to the report, a fracture analysis was performed on the first two cored intervals to evaluate fracture frequency. Core index information for the three cored intervals is presented on page 11 of the report.

Fracture analysis data for drill core from the Tippipah Limestone is presented in table 3 of the report. These data are presented graphically in figure 3 of the report. According to the report, 63% of the fractures penetrated in drill hole UE17a were closed and 37% were open.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

The report under review is one of a series of basic data reports on drill holes in the Syncline Ridge area. The report is significant with respect to the geology of the Syncline Ridge area; however, drill hole UE17a is located approximately 35 km northeast of the proposed repository in Yucca Mountain. Drill hole UE17a was drilled in 1976 to provide data for a preliminary investigation of the Eleana Formation as a possible repository for nuclear wastes. The report is not significant with respect to the local geology and hydrogeology in the vicinity of Yucca Mountain. However, data presented in the report may be valuable with respect to understanding the regional geology and hydrogeology of the Nevada Test Site.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The report under review contains no significant problems, deficiencies, or limitations. The report is a basic data report.

SUGGESTED FOLLOW-UP ACTIVITIES:

No follow-up activities are suggested.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: USGS-1543-1

DOCUMENT: Hodson, J.N., and Hoover, D.L., 1978, Geology and Lithologic Log for Drill Hole UE17a, Nevada Test Site. USGS-1543-1, 14 p.

REVIEWER: Williams & Associates, Inc.

DATE REVIEW COMPLETED: October 31, 1986

ABSTRACT OF REVIEW: APPROVED BY: Roy Williams/al

Drill hole UE17a is one of a series of holes drilled to evaluate the suitability of the Unit J of the Eleana Formation as a medium for nuclear waste storage. The hole was drilled to a depth of 370 m. The report presents data on the geology of the Syncline Ridge area. The report is not significant with respect to the local geology and hydrogeology in the vicinity of Yucca Mountain.. However, some of the information presented in the report may be useful with respect to interpreting the regional geology and hydrogeology of the Nevada Test Site.

BRIEF SUMMARY OF DOCUMENT:

The report under review presents geologic and lithologic data for drill hole UE17a. Drill hole UE17a is located in area 17 of the Nevada Test Site. The hole was drilled to determine the thickness of alluvium and to evaluate the lithologic and stratigraphic characteristics of the underlying Paleozoic rocks. Drill hole UE17a is located within the Syncline Ridge structural block, northwest of Syncline Ridge. The hole is 370 m deep and is bottomed in a quartzite subunit of the Eleana Formation. According to the report, drill hole UE17a was drilled into the zone of saturation to define the static water level.

According to the report, air foam mist was used as circulating medium during drilling; the report notes that sepiolite air foam inadvertently was added to the hole. Water in the hole caused the sepiolite to settle out of the drilling fluid. Drilling problems were encountered between the depths of 251.5 and 289.6 m due to caving of the hole. According to the report, high-viscosity bentonite mud was placed in the hole to stop caving and to hold the hole open for geophysical logging.

Drill hole UE17a was cased to a depth of 368.8 m with 10.8 cm-diameter steel casing. According to the report, "The drilling mud was circulated out of the hole with water." A gun perforator was used to perforate the casing in the following intervals: 227.1 to 251.5 m, 306.3 to 309.4 m, and 324.6 to 362.7 m. According to the report, drilling tools were used to push debris from the perforating operation downhole to a depth of 367.9 m. The report notes that hydrologic testing was conducted by the USGS. However, the results of this testing are not presented in the report.

Drill hole UE17a penetrates 22.3 m of alluvium of Quaternary age, 144.2 m of Tippipah Limestone of early Pennsylvanian to early Permian (?) age, and 203.6 m of Unit J of Eleana Formation of Mississippian age. Table 1 of the report presents a lithologic log of drill hole UE17a.

According to the report, an east-trending, pre-Tertiary, strike-slip fault is present between drill holes UE17a and UE16c. Lateral displacement along the fault is estimated to be at least 1 km. Vertical displacement along the fault is estimated to be at least 144.2 m because that thickness of Tippipah Limestone is missing from drill hole UE16c. Table 2 of the report lists probable faults penetrated by drill hole UE17a.

The report notes that groundwater was first detected during drilling at a depth of 176.8 m. Groundwater inflow into the hole became significant at a depth of 324.6 m; inflow remained relatively constant during the remainder of drilling.According to the report, water appeared to be coming from open fractures.

A core index was calculated for each core sample obtained from drill hole UE17a to evaluate the rock competency. According to the report, a fracture analysis was performed on the first two cored intervals to evaluate fracture frequency. Core index information for the three cored intervals is presented on page 11 of the report.

Fracture analysis data for drill core from the Tippipah Limestone is presented in table 3 of the report. These data are presented graphically in figure 3 of the report. According to the report, 63% of the fractures penetrated in drill hole UE17a were closed and 37% were open.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

The report under review is one of a series of basic data reports on drill holes in the Syncline Ridge area. The report is significant with respect to the geology of the Syncline Ridge area; however, drill hole UE17a is located approximately 35 km northeast of the proposed repository in Yucca Mountain. Drill hole UE17a was drilled in 1976 to provide data for a preliminary investigation of the Eleana Formation as a possible repository for nuclear wastes. The report is not significant with respect to the local geology and hydrogeology in the vicinity of Yucca Mountain. However, data presented in the report may be valuable with respect to understanding the regional geology and hydrogeology of the Nevada Test Site.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The report under review contains no significant problems, deficiencies, or limitations. The report is a basic data report.

SUGGESTED FOLLOW-UP ACTIVITIES:

No follow-up activities are suggested.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: USGS-1543-2

DOCUMENT: Hodson, J.N., and Hoover, D.L., 1979, Geology of the UE17e Drill Hole, Area 17, Nevada Test Site. USGS-1543-2, Denver, 33 p.

REVIEWER: Williams & Associates, Inc.

DATE REVIEW COMPLETED: October 31, 1986

ABSTRACT OF REVIEW: APPROVED BY: Roy Williams/pl

The report under review describes the geology of drill hole UE17e at the northwest corner of Syncline Ridge. Drill hole UE17e is one of a series of test holes drilled in the vicinity of Syncline Ridge to evaluate the Eleana Formation as a potential horizon for a nuclear waste repository. Data presented in the report are specific to the Syncline Ridge area and are not significant with respect to the local geology and hydrogeology of the Yucca Mountain area. However, data presented in the report may be of value with respect to understanding the regional geology and hydrogeology of the Nevada Test Site.

BRIEF SUMMARY OF DOCUMENT:

The report under review describes the geology of drill hole UE17e, located at the northwest corner of Syncline Ridge on the Nevada Test Site. The drill hole was drilled to obtain lithologic data for the quartzite and argillite subunit of Unit J of the Eleana Formation and to obtain samples for mineralogical, chemical and physical-property analyses. Drill hole UE17e is one of a series of test holes drilled to evaluate the potential suitability of the Eleana Formation as a geologic repository for nuclear wastes.

Drill hole UE17e is located in area 17 of the Nevada Test Site approximately 35 km northwest of the potential geologic repository in Yucca Mountain. The drill hole was drilled to a total depth of 914.4 m within Unit J of the Eleana Formation. Drill hole UE17e was cored from the depths of 3.05 to 914.4 m. According to the report bentonite mud was used as the circulating medium during drilling. In addition, heavy (barite) mud was used to control the zones that were squeezing during geophysical logging of the hole. According to the report, geophysical logs recorded for the drill hole include caliper, resistivity, inductives, gamma-ray neutron, 3-dimensional velocity, and temperature.

According to the report, the Eleana Formation of Devonian and Mississippian age contains 10 units from Unit A at the base to Unit J at the top. Figure 2 of the report presents the pre-Tertiary stratigraphic units of the Syncline Ridge area. Table 1 of the report presents the lithologic log for drill hole UE17e. The lithologic log shows that drill hole UE17e is bottomed in the argillite subunit of Unit J at a total depth of 914.4 m.

Drill hole UE17e is located within the Syncline Ridge structural block. Evidence of regional compressional deformation is present in the drill hole as highly variable bedding plane dips, fractures, shear plans, faults, and folded and sheared quartz-filled fractures. According to the report, the majority of fractures and shear planes penetrated by drill hole UE17e are parallel to bedding planes. Table 2 of the report lists the depths at which faults were penetrated by the drill hole. According to the report, faults were identified by visual observation of the core and with the aid of the geophysical logs.

Core index was calculated for each cored interval to evaluate the rock competency; in addition, a fracture analysis was performed on the core from 3.05 to 914.4 m. Figures 3 and 4 of the report present histograms of core indices within Unit J of the Eleana Formation.

Table 3 of the report lists the number of fractures penetrated by drill hole UE17e for specific depth intervals. According to the report, the fracture frequency is 8.4 fractures per meter above a depth of 152.7 m; the fracture frequency is 3.5 fractures per meter below a depth of 152.7 m. Information on the condition (open or closed and clean and polished) is presented in tables 4 and 5 of the report. Rosette diagrams of the fractures are presented in figures 5 through 17 of the report. Table 6 of the report lists the quartz-filled, calcite-filled, and calcite and quartz-filled fractures penetrated by the drill hole. Table 7 of the report lists the clay-filled, iron-stained, and iron and clay-filled fractures penetrated by the drill hole.

Thermal conductivities of the core at 25°C were measured by the USGS at Menlo Park, California. Table 8 of the report lists these conductivity measurements. In addition to thermal conductivities, natural state densities and porosities were measured for 30 different core samples of argillite from drill hole UE17e. These data are presented in table 9 of the report. Table 10 of the report lists the results of geomechanical measurements conducted on 15 core samples from the drill hole.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

The report under review presents data on the geology of drill hole UE17e located at the northwest corner of Syncline Ridge. Drill hole UE17e was drilled to evaluate the quartzite and argillite subunits of Unit J of the Eleana Formation as a horizon for a potential geologic repository for nuclear wastes. The report under review is not significant with respect to the local geology and hydrogeology in the vicinity of Yucca Mountain. However, some of the information presented in the report may be of value in understanding the regional geology and hydrogeology of the Nevada Test Site.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The report under review contains no significant problems, deficiencies or limitations. The report is one of a series of basic data reports describing the geology in the vicinity of Syncline Ridge. Geophysical logs for drill hole UE17e are not presented in the report.

SUGGESTED FOLLOW-UP ACTIVITIES

No follow-up activity is suggested.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: USGS-1543-2

DOCUMENT: Hodson, J.N., and Hoover, D.L., 1979, Geology of the UE17e Drill Hole, Area 17, Nevada Test Site. USGS-1543-2, Denver, 33 p.

REVIEWER: Williams & Associates, Inc.

DATE REVIEW COMPLETED: October 31, 1986

ABSTRACT OF REVIEW: APPROVED BY: Roy Williams/sl

The report under review describes the geology of drill hole UE17e at the northwest corner of Syncline Ridge. Drill hole UE17e is one of a series of test holes drilled in the vicinity of Syncline Ridge to evaluate the Eleana Formation as a potential horizon for a nuclear waste repository. Data presented in the report are specific to the Syncline Ridge area and are not significant with respect to the local geology and hydrogeology of the Yucca Mountain area. However, data presented in the report may be of value with respect to understanding the regional geology and hydrogeology of the Nevada Test Site.

BRIEF SUMMARY OF DOCUMENT:

The report under review describes the geology of drill hole UE17e, located at the northwest corner of Syncline Ridge on the Nevada Test Site. The drill hole was drilled to obtain lithologic data for the quartzite and argillite subunit of Unit J of the Eleana Formation and to obtain samples for mineralogical, chemical and physical-property analyses. Drill hole UE17e is one of a series of test holes drilled to evaluate the potential suitability of the Eleana Formation as a geologic repository for nuclear wastes.

Drill hole UE17e is located in area 17 of the Nevada Test Site approximately 35 km northwest of the potential geologic repository in Yucca Mountain. The drill hole was drilled to a total depth of 914.4 m within Unit J of the Eleana Formation. Drill hole UE17e was cored from the depths of 3.05 to 914.4 m. According to the report bentonite mud was used as the circulating medium during drilling. In addition, heavy (barite) mud was used to control the zones that were squeezing during geophysical logging of the hole. According to the report, geophysical logs recorded for the drill hole include caliper, resistivity, inductives, gamma-ray neutron, 3-dimensional velocity, and temperature.

According to the report, the Eleana Formation of Devonian and Mississippian age contains 10 units from Unit A at the base to Unit J at the top. Figure 2 of the report presents the pre-Tertiary stratigraphic units of the Syncline Ridge area. Table 1 of the report presents the lithologic log for drill hole UE17e. The lithologic log shows that drill hole UE17e is bottomed in the argillite subunit of Unit J at a total depth of 914.4 m.

Drill hole UE17e is located within the Syncline Ridge structural block. Evidence of regional compressional deformation is present in the drill hole as highly variable bedding plane dips, fractures, shear plans, faults, and folded and sheared quartz-filled fractures. According to the report, the majority of fractures and shear planes penetrated by drill hole UE17e are parallel to bedding planes. Table 2 of the report lists the depths at which faults were penetrated by the drill hole. According to the report, faults were identified by visual observation of the core and with the aid of the geophysical logs.

Core index was calculated for each cored interval to evaluate the rock competency; in addition, a fracture analysis was performed on the core from 3.05 to 914.4 m. Figures 3 and 4 of the report present histograms of core indices within Unit J of the Eleana Formation.

Table 3 of the report lists the number of fractures penetrated by drill hole UE17e for specific depth intervals. According to the report, the fracture frequency is 8.4 fractures per meter above a depth of 152.7 m; the fracture frequency is 3.5 fractures per meter below a depth of 152.7 m. Information on the condition (open or closed and clean and polished) is presented in tables 4 and 5 of the report. Rosette diagrams of the fractures are presented in figures 5 through 17 of the report. Table 6 of the report lists the quartz-filled, calcite-filled, and calcite and quartz-filled fractures penetrated by the drill hole. Table 7 of the report lists the clay-filled, iron-stained, and iron and clay-filled fractures penetrated by the drill hole.

Thermal conductivities of the core at 25°C were measured by the USGS at Menlo Park, California. Table 8 of the report lists these conductivity measurements. In addition to thermal conductivities, natural state densities and porosities were measured for 30 different core samples of argillite from drill hole UE17e. These data are presented in table 9 of the report. Table 10 of the report lists the results of geomechanical measurements conducted on 15 core samples from the drill hole.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

The report under review presents data on the geology of drill hole UE17e located at the northwest corner of Syncline Ridge. Drill hole UE17e was drilled to evaluate the quartzite and argillite subunits of Unit J of the Eleana Formation as a horizon for a potential geologic repository for nuclear wastes. The report under review is not significant with respect to the local geology and hydrogeology in the vicinity of Yucca Mountain. However, some of the information presented in the report may be of value in understanding the regional geology and hydrogeology of the Nevada Test Site.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The report under review contains no significant problems, deficiencies or limitations. The report is one of a series of basic data reports describing the geology in the vicinity of Syncline Ridge. Geophysical logs for drill hole UE17e are not presented in the report.

SUGGESTED FOLLOW-UP ACTIVITIES

No follow-up activity is suggested.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: USGS-1543-6

DOCUMENT: Maldonado, F., Muller, D.C., and Morrison, J.N., date unknown, Preliminary Geologic and Geophysical Data of the UE25A-3 Exploratory Drill Hole, Nevada Test Site, Nevada. U.S. Geological Survey, Denver, CO, USGS-1543-6,

REVIEWER: Williams & Associates, Inc., James L Osiensky

DATE REVIEW COMPLETED: September 17, 1987

ABSTRACT OF REVIEW: APPROVED BY: Roy E Williams

The report under review presents preliminary geologic and geophysical data from drill hole UE25A-3. Drill hole UE25A-3 is located in the Calico Hills area, approximately 7 miles west of Yucca Mountain. The drill hole penetrates various subunits of the Eleana Formation. Drill hole UE25A-3 was drilled to evaluate the Calico Hills area as a possible nuclear waste repository site. The report has little significance to the local hydrogeology in the vicinity of Yucca Mountain. However, the report may contain useful data with respect to understanding the regional hydrogeology in the vicinity of the Nevada Test Site.

BRIEF SUMMARY OF DOCUMENT:

The report under review presents preliminary interpretations of the geologic and geophysical data collected from drill hole UE25A-3. Drill hole UE25A-3 is located in the Calico Hills area, approximately 7 miles east of Yucca Mountain. The drill hole was drilled during the investigation of Calico Hills as a possible nuclear waste repository site. According to the report, the purpose of the drill hole was to verify the existence of an intrusive crystalline body in the subsurface and to determine the stratigraphy, structure, and nature of fractures in the cored rock.

Drill hole UE25-A was spudded on August 11, 1978. Drilling was completed at a depth of 2530.1 feet (771.2 meters) on October 10, 1978. The drill hole was cored from a depth of 100 feet (30.5 meters) to the total depth. Table 1 of the report presents a lithologic description of the rock units penetrated by the drill hole. This table indicates that the entire drill hole penetrated various subunits of the Eleana Formation. The Eleana Formation consists primarily of argillite, altered argillite, and marbles. Table 2 of the report lists the locations of brecciated zones which possibly are indicative of fault zones penetrated by the drill hole. Table 3 of the report lists faults intersected by the drill hole.

A core index was calculated for all of the core as part of the engineering geology investigation of the drill hole. Core index is a relative measure of the rock competency. In addition to the core index, a fracture analysis was performed on the core. According to the report, the fracture analysis consisted of sampling a portion of the total population of fractures because of the great number of fractures present in the core. The fracture analysis was performed on a total of 2430 fractures; this number represents approximately 30 percent of the total number of fractures. Figure 5 of the report lists fracture frequencies observed in each 30.5 meter thick sampled that was sampled. Figure 6 of the report presents the average fracture frequencies in the entire cored interval. Figure 7 presents fractures per 10 degree dip interval for the interval between 30.5 and 771.2 meters. Figure 8 of the report lists fractures per 10 degree dip interval in the argillite, altered argillite, calcareous argillite and marble intervals. Figures 9 and 10 of the report present open and closed fractures per 10 degree interval for sampled intervals 30.5 to 396.4 meters, and 396.4 to 771.2 meters, respectively. Figure 11 presents a comparison of open and closed fractures per 10 degree dip interval, in argillite, altered argillite, calcareous altered argillite, and marble intervals. Figures 12, 13 and 14 of the report present the types of fracture sealing and coating observed in the core.

Borehole geophysical logs including caliper, density, resistivity, spontaneous potential, velocity, neutron and gamma logs, plus an in hole Vibroseis geophone survey and a deviation survey were run on drill hole UE25A-3. A copy of the geophysical logs is presented as Plate 1 of the report. According to the report, at the time of logging, the mud level was at a depth of 2104 feet (641.3 meters) which limited the coverage of logs that require fluid filled boreholes. Table 6 of the report presents digitized values of the geophysical logs for the drill hole. The report under review presents a short description of each of the geophysical logs recorded in drill hole UE25A-3.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

The report, when combined with other information, may contain useful information with respect to understanding the regional hydrogeology in the vicinity of the Nevada Test Site.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The report under review consists of a basic data report. The report contains no major problems, deficiencies or limitations.

SUGGESTED FOLLOW-UP ACTIVITIES

No follow-up activities are suggested with respect to this report.

ATTACHMENT D: SUMMARY OF GEOHYDROLOGIC DATA FOR TEST WELLS UE-16D AND UE-16F

Dinwiddie, G.A., and Weir, J.E., Jr., September, 1979, Summary of Hydraulic Tests and Hydrologic Data for Holes UE16D, and UE16F, Syncline Ridge Area, Nevada Test Site. U.S. Geological Survey, Denver, Colorado, 1543-3, 25 pp.

Test hole UE-16D was drilled by Reynolds Electrical and Engineering Co. to a total depth of 914 meters. Drilling began in May 1977. Completion and testing were delayed until early August 1977, due to unstable hole conditions. The well is located south of the Jurassic Lateral Fault at 37°04'6" north latitude and 116°09'56" west longitude. The method of drilling is not specifically mentioned for the upper portion of this hole. However, intervals within the argillite squeezed into the hole requiring the use of mud and dual string, reverse-circulation drilling for the lower 220 m. The report pictorially illustrates the construction of the well, but is not precise about well completion details.

The lithologic log (based on cuttings, cores, and geophysical logs) of 16D exhibits the Tippipah limestone and the quartzite and argillite of the Eleana Formation, unit J. Geophysical logging included 15 different surveys of which only the tracejector test was discussed. Results of this survey suggest significant downward motion within the interval of 284-396 m, below ground (mid to lower Tippipah Limestone). A lack of vertical movement was observed between 235-251 m (mid Tippipah) with little or no motion in the Upper Eleana Formation (465 to 538 m).

Hydraulic testing included one pump test, 4 slug tests, and water level measurements during drilling. The pump test was performed within the interval of about 232 to 637 m below ground. The values for transmissivities in the tables and texts conflict. Slug test results from the lower part of the Tippipah Limestone for the intervals 262-313 m, 313-365 m, 398-464 m are presented. The reported transmissivities are too high to be accurately determined by this test method. Consequently, the determined values are suspect. Graphic results of the slug injection are presented without supporting data.

The results of water quality analysis and dating for samples extracted at numerous intervals reveal that water from the Eleana may have originated from the Tippipah via mixing by the nearby strike-slip fault. Water from the Tippipah is predominantly calcium-magnesium bicarbonate with a low TDS (400 mg/l).

Similar to 16D, UE25-16F was drilled by Reynolds Electrical and Engineering Company during August to September 1977 to a depth of 451 m below ground. This hole is located at the south end of the central Syncline Ridge Block at 37°02'09"N latitude and 116°09'23" W longitude. Dual string, reverse-circulation method of drilling encountered poor hole conditions within the argillitic zones of the Eleana Formation. The 16F test hole (based on cuttings, cores and geophysical logs) penetrates only unit J of the Eleana Formation, from 24 to 451 m below ground. Only schematic information is supplied on the details of well construction. Geophysical logging included 12 surveys, of which the results are not discussed.

The hydrologic testing program included one slug test performed over the interval 394 to 431 m and water-level measurements recorded during drilling. The highest reported hydraulic head potential was within the interval of 394-431 m and was reported to be 192.1 m below ground. The lowest potential was 243 m measured within the interval of 65 to 384 m below ground. Transmissivity determined by slug tests were calculated to be 0.1 m^2/d. Graphic water level data are given in the report; no supporting data was supplied.

Water quality analysis and dating reveal a dominantly sodium bicarbonate water existing in the Eleana at well 16F. Water from the Tippipah consisted of calcium-magnesium bicarbonate with a low TDS (400 mg/l). Recharge area of the Eleana at 16F is probably located further than the recharge area for 16d. Mixing of waters from Eleana and Tippipah occurs in the Eleana at test hole 16d.

GEOTRANS COVER LETTER OF 8/4/0

ATTACHMENT C: SUMMARY OF GEOHYDROLOGIC DATA FOR TEST WELL UE-17a

Weir, J.E., Jr., and Hodson, J.N., 1979, Geohydrology of UE-17a, Syncline Ridge Area, Nevada Test Site, U.S. Geological Survey, Denver, Colorado, 1543-4, 14 pp.

Test well UE-17a was one of a series of seven test wells installed to determine the thickness and lithology of the underlying strata. UE-17a was drilled to a depth of 119 m during July, 1976 and completed to 370 m during September, 1976. The test well is located west of the gap in Syncline Ridge. The circulation medium for drilling was air-foam mist with mud used at lower depths to inhibit caving. The casing (100 mm I.D.) was installed to a depth of 368m and perforated at depth intervals of 227-251, 306-309, and 325-363 m below ground.

Test hole 17a is located where the Tippipah Limestone is locally thrusted over Unit J of the Eleana Formation. This is within the Syncline Ridge-Southern Eleana structural block. The stratigraphic interval includes the Tippipah Limestone and the strongly sheared unit J of the Eleana Formation. The test hole terminates in a thick argillitic interval. Evidence of thrusting was found in the cores at 177 m below ground.

Hydraulic testing included to two jetting tests of which only one was considered representative. The first test was performed immediately after drilling and water-level recovery was erratic. The second test was run after the hole was cleaned and the casing perforated. The two hour jetting test produced 1.3 liters per second and recovery was measured over two hours. Graphs of water-level recovery are presented. The occurrence of ground-water and fluid level measurement changes were monitored during the drilling period. Hole instability and insufficient time for equilibration of water levels decreased the usefulness of these measurements. However, recorded changes in the return water quantity were useful for identifying areas of relatively high yield. The most significant yield occurs between the interval 326-368 m below ground within the Eleana Argillite.

One sample of water was collected at the termination of the jetting tests for quality determinations and is representative of water from unit J of the Eleana Formation. The dominant cations and anions are sodium, bicarbonate, and sulfate respectively. The concentration of total dissolved solids is 1,190 milligrams per liter.

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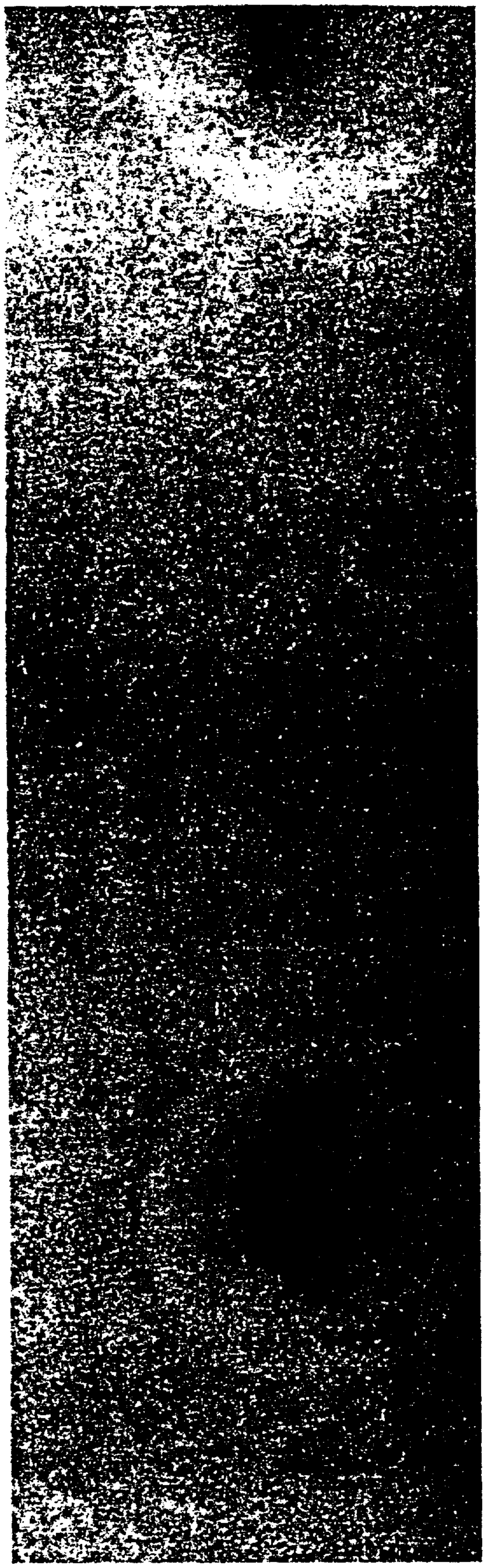

Evaluation of Past and Future Alterations in Tuff at Yucca Mountain, Nevada, Based on the Clay Mineralogy of Drill Cores USW G-1, G-2, and G-3

Los Alamos

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EVALUATION OF PAST AND FUTURE ALTERATIONS IN TUFF AT YUCCA MOUNTAIN, NEVADA, BASED ON THE CLAY MINERALOGY OF DRILL CORES USW G-1, G-2, AND G-3

by

David L. Bish

ABSTRACT

The tuffs at Yucca Mountain in south-central Nevada are being studied by the Yucca Mountain Project (YMP) to determine their suitability for a high-level radioactive waste repository. For predictive purposes, it is important to understand the alteration history of Yucca Mountain and to know how the minerals in Yucca Mountain tuffs respond to changing conditions such as elevated temperatures. The clay mineralogy of these tuffs has been examined using x-ray powder diffraction, and approximate temperatures of alteration have been determined using available clay mineral data and fluid inclusion analyses. Also, several illites from drill holes USW G-1 and G-2 have been dated using K/Ar techniques, yielding ages of about 11 Myr. The clay minerals in Yucca Mountain tuffs are predominantly interstratified illite/smectites, with minor amounts of chlorite, kaolinite, and interstratified chlorite/smectite at depth in USW G-1 and G-2. The reactions observed for these illite/smectites are similar to those observed in pelitic rocks. With depth, the illite/smectites transform from random interstratifications (R=0) through ordered intermediates (R=1) to illite in USW G-2 and to Kalkberg (R≥3) interstratifications in USW G-1. The illite/smectites in USW G-3 have not significantly transformed. It appears that the illites in deeper rocks result from hydrothermal and diagenetic reactions of earlier-formed smectites. These data demonstrate that the rocks at depth in the northern end of Yucca Mountain were significantly altered about 11 Myr ago. Both clay mineralogy and fluid inclusions suggest that the rocks at depth in USW G-2 have been subjected to postdepositional temperatures of at least 275°C, those in USW G-1 have reached 200°C, and USW G-3 rocks probably have not exceeded 100°C.

The temperature estimates from clay mineral and fluid inclusion data suggest stability limits for several minerals at Yucca Mountain. Clinoptilolite became unstable at about 100°C, mordenite was not a major phase above 130°C, and analcime transformed to albite above 175° to 200°C. It appears that cristobalite transformed to quartz at about 90° to 100°C in USW G-2 but must have reacted at considerably lower temperatures in USW G-3. Comparison of the clay mineral data with the bulk-rock mineralogy shows that the reactions seen with increasing depth are coupled. Clinoptilolite and cristobalite disappear approximately simultaneously in USW G-2 and G-3, supporting aqueous silica activity as the controlling variable in the clinoptilolite-to-analcime reaction. The reaction of clinoptilolite to analcime also coincides with the appearance of calcite, chlorite, and interstratified chlorite/smectite. Breakdown of clinoptilolite probably provided the source of Ca for calcite, Mg for chlorite, K for illite/smectites found deeper in the section, and Na for analcime and albite.

The vertical distribution of minerals across Yucca Mountain demonstrates that the alteration at depth is most profound to the north in USW G-2, and there is little evidence for elevated-temperature alteration in USW G-3. Drill cores USW G-1 and UE-25a#1 show the

effects of hydrothermal alteration, but at a greater depth and to a lesser extent than in USW G-2. The observed alteration mineralogy and the age of illites in USW G-1 and G-2 are consistent with Timber Mountain volcanism about 11 Myr ago as the source of hydrothermal alteration. The available data suggest that no significant hydrothermal alteration has occurred since Timber Mountain time.

Using the rocks in USW G-1, G-2, and G-3 as natural analogs to alteration under the thermal effects of a waste repository suggests that the bulk of the clinoptilolite- and mordenite-bearing rocks in Yucca Mountain will not react to less sorptive phases such as analcime over the required life of the repository. However, the zeolites in zeolite interval I, directly underlying the candidate repository horizon, may transform at the predicted repository temperatures. The reaction of clinoptilolite to analcime in interval I may require the transformation of all of the abundant opal-CT and glass to quartz in these unsaturated-zone rocks.

I. INTRODUCTION

The secondary minerals in the ash-flow and bedded tuffs at Yucca Mountain near the Nevada Test Site (NTS) in south-central Nevada (Fig. 1) are being studied as part of a comprehensive investigation to determine the suitability of the tuffs for an underground high-level radioactive waste repository. The study of this area, sponsored by the Yucca Mountain Project (YMP) of the U.S. Department of Energy, includes a concern with the past alteration history and future alteration of the tuffs and associated volcanic rocks at Yucca Mountain. It is particularly important to understand the secondary minerals in these rocks, including zeolites and clays, because of their high sorption capacity for many waste elements and their relatively low thermal stability. The relationship between bulk-rock sorption capacity and mineralogy has been described by Bish et al. (1984b). They showed that the sorption of many elements was related to the bulk-rock clinoptilolite, mordenite, and smectite contents and that clinoptilolite and smectite were the minerals most important to sorption. Smyth (1982) emphasized the problems involved with the low thermal stability of the clinoptilolite and mordenite in the tuffs but did not discuss clay minerals. Bish et al. (1982) discussed the thermal stability of both zeolites and smectites.

It is noteworthy that whereas the distribution of zeolites (mordenite, clinoptilolite, and analcime) in Yucca Mountain is stratified, smectites are present in small to moderate amounts (1-10%) in virtually all stratigraphic units in Yucca Mountain. This was first shown in the preliminary description of the clay mineralogy of the Bullfrog and Tram Members of the Crater Flat Tuff from drill core USW G-1 (Bish 1981). That report, which included a summary of the effects of elevated temperatures on illite/smectites, described the conditions of clay formation in USW G-1. Evidence from smectites shallower than 1067 m (3500 ft) in USW G-1 suggested that clay formation postdated zeolite crystallization, although the exact timing was unclear. Comparisons of the zeolite zonation in Yucca Mountain with data from Iijima (1975, 1980) suggested that a steeper geothermal gradient existed in the past (Smyth 1982), but other studies of the clay minerals (Bish 1981) suggested that diagenetic temperatures were never over 100°C. Based

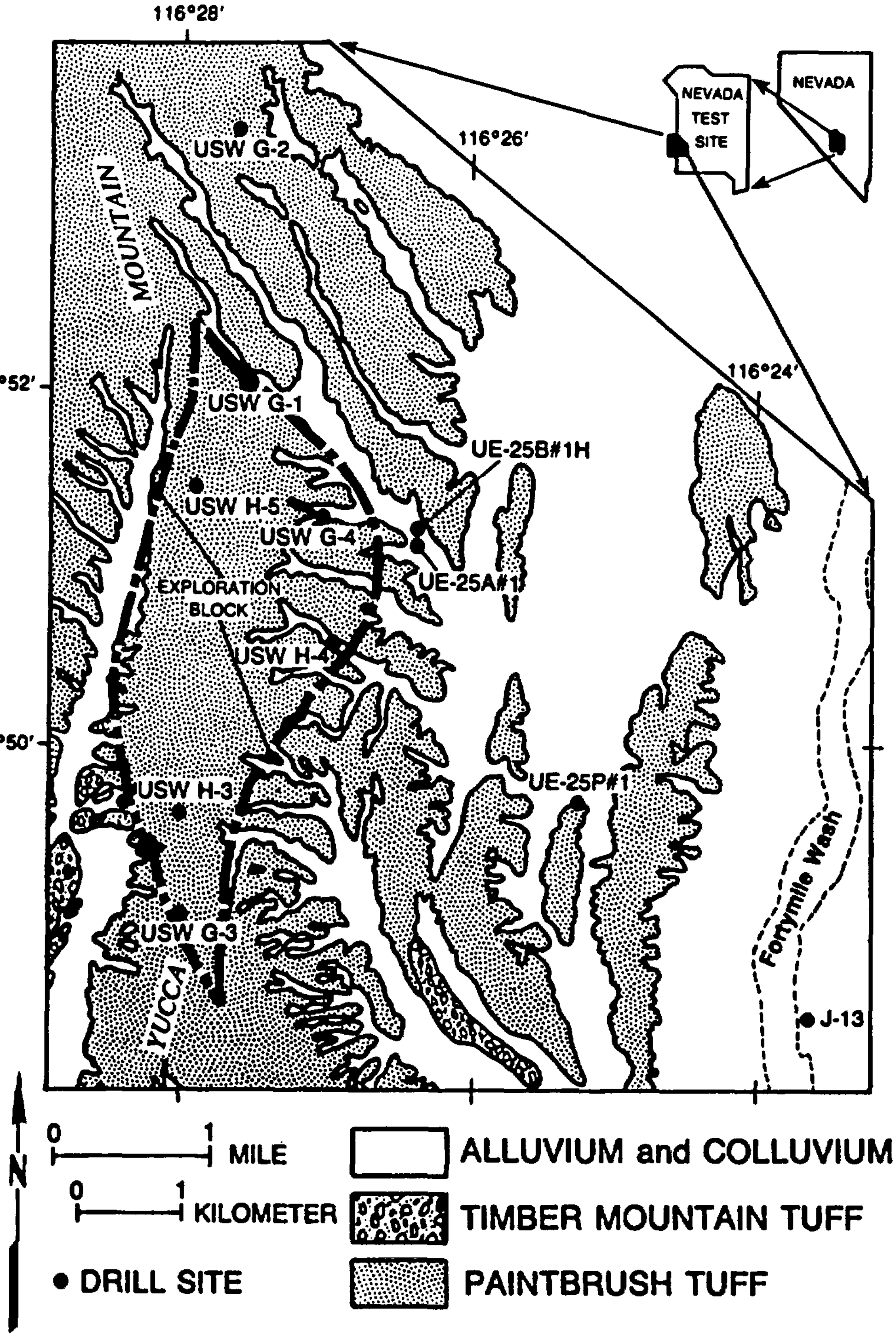


Fig. 1.
Location map of Yucca Mountain, Nevada, showing the outline of the exploration block for the Yucca Mountain Project and the locations of drill holes mentioned in the text.

on further studies of the zeolites at Yucca Mountain (Broxton et al. 1986), it now appears that higher temperatures need not be invoked to explain the zeolite distribution in Yucca Mountain; smectite and zeolite formation may have been contemporaneous.

After the preliminary work on the clay mineralogy in USW G-1, a more complete study of the clays in drill holes USW G-1, G-2, and G-3 was undertaken. This was done not only to outline the clay mineral abundances as a function of depth in these drill cores but also to obtain information on the timing, extent, and temperature of alteration in the tuffs of Yucca Mountain.

The transformation of smectite to illite with increasing temperature in pelitic rocks has been thoroughly studied and well documented (Burst 1959; Perry and Hower 1970, 1972; Hower et al. 1976; Hoffman and Hower 1979; Hower and Altaner 1983). When an abundant supply of potassium exists, 100% expandable smectites react through a series of intermediate interstratified illite/smectites to a nonexpandable illite containing additional potassium and aluminum. This reaction is influenced by several variables, including time, temperature, mineralogic assemblage, and water composition (Eberl and Hower 1976; Howard 1981; McCubbin and Patton 1981; Roberson and Lahann 1981). Because the extent of this reaction is highly temperature dependent (Eberl and Hower 1976; Hower and Altaner 1983), it is possible to obtain consistent estimates of the temperatures to which a particular illite/smectite has been subjected, given sufficient K, Al, and reaction time.

The reaction of smectite to illite in nonpelitic rocks has received considerably less attention, but it appears that the general trends with temperature noted above for pelitic rocks hold for other rocks (Steiner 1968; Inoue et al. 1978; Bish and Semarge 1982; Hower and Altaner 1983). Roberson and Lahann (1981) have shown, however, that the addition of >100 ppm Mg, Ca, or Na to K-bearing solutions significantly inhibits the reaction of smectite to illite, and Howard (1981) proposed that competing ions in interstitial waters influence the illitization reaction as much as the supply of K. Unfortunately, it is difficult to extrapolate their results to a system with a composition typical of present-day J-13 well (Fig. 1) water at Yucca Mountain (~2 ppm Mg, ~13 ppm Ca, ~5 ppm K^+, and ~50 ppm Na) (Bish et al. 1984a; Ogard and Kerrisk 1984). The composition of the paleogroundwater is not known, but the presence of authigenic K-silicates (illite and adularia) in Yucca Mountain rocks (Caporuscio et al. 1982) suggests that sufficient K and Al existed for the smectite-to-illite reaction to proceed. Given the age of the tuffs in Yucca Mountain (~12 to 16 Myr), the amount of time available for reaction, and the observed illite/smectites, there is no evidence for suppression of the smectite-to-illite reaction in tuffs due to groundwater composition effects.

Ideally, it should be possible to map out the distribution of clay minerals in Yucca Mountain, to determine the time and temperature at which the minerals formed, and to map out the extent of hydrothermal alteration in Yucca Mountain. A very important application of this time-temperature information will be predicting the effects of prolonged high temperatures on the mineral assemblages in possible repository horizons. To aid prediction of these effects, the alteration observed in deeper parts of drill holes may be used as a natural analog to repository-induced alterations. Using this natural system to provide information on reaction temperatures and products circumvents some of the problems inherent in laboratory studies, e.g., the requirement that higher than natural temperatures be used to increase recrystallization rates, with the associated problem of extrapolating high-temperature kinetics to low temperatures. The work described here deals mainly with correlations of temperatures of reactions and zeolite assemblages in the tuffs. If the zeolites in Yucca Mountain formed early and were subjected to the same temperature and pressure conditions as the smectites, the clay mineralogy should provide information on the stability ranges of the zeolites in Yucca Mountain.

This report addresses topics of concern for evaluating the long-term changes that may occur in Yucca Mountain tuffs as a result of the heat load imposed by a waste repository. By determining the temperatures of clay mineral formation, it is possible to assess the temperatures at which clinoptilolite, mordenite, and analcime transformed to other mineral assemblages in the past at Yucca Mountain. This study of natural, thermally induced transformations at Yucca Mountain provides one method for predicting the repository-induced thermal alteration of existing secondary minerals within the thermal aureole around the repository.

Additionally, this report presents the first information available for the timing of past hydrothermal alteration at depth below Yucca Mountain. This information indicates that post-emplacement hydrothermal alteration at Yucca Mountain is an old event, probably correlated with Timber Mountain igneous activity. No mineralogical evidence exists to suggest that significant hydrothermal activity has occurred more recently than 11 Myr ago.

II. EXPERIMENTAL METHODS

Many techniques are used for clay mineral identification (e.g., Jackson 1979; Brindley and Brown 1980), but specific techniques are required depending on the rock type and information desired. For this reason, the procedures used in our work will be described in detail.

We typically start with drill core samples that have been brushed or washed clean of surface contaminants. After breaking a 2- to 4-cm slice of core into pieces smaller than about 0.5 cm, the sample is loaded into a shatterbox and crushed for 5 minutes. After crushing the entire slice of core by portions in the shatterbox, the crushed powder is mixed and stored in plastic vials. The use of large amounts of sample and subsequent homogenization of powder is important because of the typical inhomogeneity of tuffs. We use an automated Siemens D-500 diffractometer in our powder x-ray diffraction analysis, and we count for 0.6 to 2.0 seconds every 0.02° 2θ, using a rotating sample holder when quantitative results are desired.

For clay mineral separations, 20-50 g of powdered sample are suspended in 500 to 700 ml of deionized water in a 1000-ml beaker. To disaggregate the sample, the beaker with suspended sample is vibrated in an ultrasonic bath for at least 1 hour or with an ultrasonic probe for 15 minutes. After disaggregation, the beaker is covered for about 4 hours to allow the coarsest material to sediment out.

The material remaining in suspension is decanted into centrifuge tubes and centrifuged at 2500 rpm for 30 minutes. We have found this speed and time sufficient to remove all quartz, feldspar, and zeolites from suspension. After centrifugation, the supernatant is decanted into other centrifuge tubes and centrifuged at a speed of 8000 rpm for 1 hour. This centrifugation sediments the fine clay fraction (<1 μm). The material at the bottom of the tubes is saved for analysis. If the supernatant is cloudy, it is centrifuged at 15 000 rpm for 45 minutes, and the sediment is removed and saved. This ultrafine fraction sediment (<0.1 μm) is ideal for making oriented mounts of clays for x-ray diffraction. A layered sediment with a clear, gel-like top layer and an opaque bottom layer is often observed after centrifuging the ultrafine fraction. When this occurs, separate oriented mounts of the two materials are prepared.

The above procedure provides clay mineral concentrates that can be used for chemical analysis and x-ray diffraction. X-ray powder diffraction of clay minerals usually involves the preparation of two types of mounts: (1) oriented thin films and (2) "random" cavity mounts. Many procedures exist for producing oriented mounts (see Brindley and Brown 1980, p. 309). We employ the method of sedimentation from an aqueous suspension under gravity onto a glass slide. Our procedure is to suspend 50-150 mg of the <1-μm or <0.1-μm clay fraction in 10 to 20 ml of deionized water contained in a small beaker. Suspension may be improved by ultrasonic vibration if necessary. This suspension is dripped from an eye dropper or pipette onto a clean, dry, level glass slide appropriately sized for the diffractometer sample holder. Only enough sample to completely cover the slide is used, and the slide is not overfilled. The suspension is allowed to dry undisturbed on the glass slide, and no more suspension is added after drying begins. Several points must be considered when making an oriented clay mount. If one is interested in ratios of basal $00l$ intensities or in absolute intensities, extra care must be taken in mount preparation. The sample area must be large enough so that the x-ray beam is fully contained within the sample at all angles of interest. If the sample is too narrow, a portion of the beam will be outside of the sample area at low angles where the beam has significant divergence, and low-angle peak intensities will be low when compared to higher-angle peaks for which the beam is completely within the sample. It is also important to consider the thickness of the oriented sample. If one is interested in accurate intensities, the sample should be effectively infinitely thick at the maximum angle of interest (see Brindley and Brown 1980, pp. 309-310; Reynolds 1980, p. 299). For typical specimens, thicknesses on the order of 30-50 μm are required at $30°2\theta_{Cu}$, and for accurate intensities at high angles, at least 20 mg of clay per cm^2 are required. These thicknesses are typically not obtained with sedimentation on a glass slide. Reynolds (1980, p. 299) also discussed the effects of sample displacement from the goniometer axis of rotation. The errors are largest at low angles and follow the relation (Parrish and Wilson 1959)

$$\Delta 2\theta = 2S \cos\theta / R$$

where $\Delta 2\theta$ is the error in radians, S is the sample displacement in cm, and R is the goniometer radius in cm. When one considers this relation, the drawbacks to thick smear mounts on glass slides are obvious.

Finally, it is useful to have a homogeneous particle size, and if the above centrifugation procedure is followed, this requirement should be met.

Oriented mounts are useful primarily because a highly oriented clay specimen yields only the 00*l* series of basal reflections with little or no evidence of *hkl* reflections (because clays have excellent 00*l* cleavage). The basal spacing yielded by patterns of oriented mounts is related to the type of layers present, and this technique is thus very useful for clay mineral identification. These are also the most commonly used mounts in the study of interstratified clay minerals; techniques employed in the investigation of these more complex clays are given below.

In contrast to oriented mounts, "random" cavity mounts are employed when one is interested in the complete diffraction pattern, including *hkl* reflections. Random powder mounts are used also to determine whether a clay is dioctahedral or trioctahedral. The 060 or 06*l* reflection located about $60°2\theta_{Cu}$ is often used for this purpose; dioctahedral minerals yield reflections with spacings between 1.48 and 1.50 Å, whereas trioctahedral minerals have d(060) values about 1.53 to 1.55 Å. Just as with oriented mounts, there are a variety of methods for producing random mounts (see Brindley and Brown 1980, pp. 310-311). One of the most common techniques used to produce a random orientation is to pack a powder into a shallow cavity in a glass, aluminum, stainless steel, or plastic holder, but the surface smoothing process inevitably produces some preferred orientation. An alternative method is filling shallow cavities from the rear. Unless one is interested in a truly random orientation, one of these methods should suffice.

Numerous treatments are employed in the identification of clay minerals. These usually can be carried out with oriented mounts, and the treatments include cation saturation, solvation with a polar organic liquid (including water at different vapor pressures), and heating. The literature on such techniques is voluminous, and only those treatments employed in this study will be discussed here. Untreated material is usually examined first, and either oriented or random mounts may be employed. A useful initial indication of the type of clay mineral one is working with may be gained from the 00*l* basal reflections. The basal spacings and intensities expected for a variety of clay minerals are listed by Brindley and Brown (1980, p. 323). Because the study described below is concerned only with smectites and illite/smectites, the other clay minerals will not be discussed. Further information on identification of nonsmectites can be obtained from Brown (1972) and Brindley and Brown (1980).

The swelling behavior of smectites is a well-known phenomenon and is discussed at length in Brown (1972), Brindley and Brown (1980), and Bish (1988). Depending upon relative humidity, layer charge, and interlayer composition, smectites have a range of basal spacings from ~10 Å to ~19 Å under room conditions. Because it is a major factor, the relative humidity should always be noted when recording an x-ray diffraction pattern of a smectite. Our standard analysis routine involves recording an x-ray pattern of an oriented clay separate under room conditions, usually 10 to 40% relative humidity, and noting whether the smectite has 0, 1, 2, or 3 layers of water in the interlayer. From this information and using data in Gillery (1959) and Suquet et al. (1975), knowledge of the interlayer composition of the smectite can be obtained. At the relative humidity in our laboratory, we normally see evidence for a potassium-rich interlayer (0 water layers) or a mixed sodium, calcium, potassium interlayer (1 to 2 water layers). After examining the oriented mount under room conditions, the mount is placed in an ethylene glycol vapor for at least 12 hours at about 50°C. Martin (1982) has shown that the minimum contact time for a Mg-montmorillonite in ethylene glycol to obtain a regular ethylene glycol-smectite complex is 4 hours. A diffraction pattern of the ethylene glycol-solvated smectite is made immediately after removing the sample from the ethylene glycol vapor. Solvation of smectites with ethylene glycol yields a stable well-ordered complex that gives an easily interpretable x-ray pattern regardless of whether or not interstratified illite is present.

To interpret the patterns of ethylene glycol-solvated illite/smectite interstratifications, we use the method of Reynolds (1980) (see also Reynolds and Hower 1970; Srodon 1980; Hower 1981). The approximate percentage of illite (or 10 Å) layers was estimated using techniques described by Reynolds (1980) and Srodon (1980), and the estimates were refined by calculating patterns using a FORTRAN version of Reynolds' (1980) program. Examples of these calculated patterns are shown in Fig. 2. The proportions of expanded and collapsed components are indicated above the individual patterns. All calculations were done with an ethylene glycol-smectite complex thickness of 16.6 Å. The small peaks on either side of the main peak at about 5.2° 2θ for the 99% smectite/1% illite and the peaks at about 27° 2θ for the Kalkberg-ordered clays are due to series termination errors and are not representative of what is observed with natural samples (see Reynolds 1980, p. 264). The random-powder Lorentz-polarization factor was used for all calculations of randomly interstratified illite/(glycol)smectite (R=0), allevardite (R=1, IS ordered), and pure illite. The single-crystal Lorentz-polarization factor was used in calculations of Kalkberg-ordered (R≥3, ISII long-range-ordered) illite/(glycol)smectite below 20° 2θ because this form of the Lorentz-polarization factor is more applicable to well-oriented samples on a powder diffractometer without an incident-beam Soller slit (Siemens D-500). These different types of ordering (Kalkberg, allevardite) are often described using the term "Reichweite," denoted R (Reynolds 1980). In an interstratified layer sequence, R denotes the most distant layer that affects the probability of occurrence of the final layer. Therefore R=0 denotes a randomly interstratified illite/smectite because a given layer has no influence on the probability of occurrence of the next layer. Nearest-neighbor ordering, or allevardite-ordered illite/smectite (Reynolds and Hower 1970), in which there is a regular, ordered alternation of layers is denoted R=1. Kalkberg-ordered illite/smectites or ISII long-range-ordered illite/smectites are R≥3. Few occurrences of R=2 interstratifications have been documented, and illite/smectites seem to go rapidly from R=1 to R=3 or R≥3. In addition, evidence exists for longer-range ordering than R=3 in Kalkberg-ordered illite/smectites, hence the term R≥3 is often used for such clays.

The calculated patterns allow several parameters to be estimated, including the percentage of 10 Å layers interstratified with smectite layers, the thickness of the ethylene glycol-smectite complex, and the degree of ordering of the interstratification. Srodon (1980) discussed the relationship between the

(a)

(b)

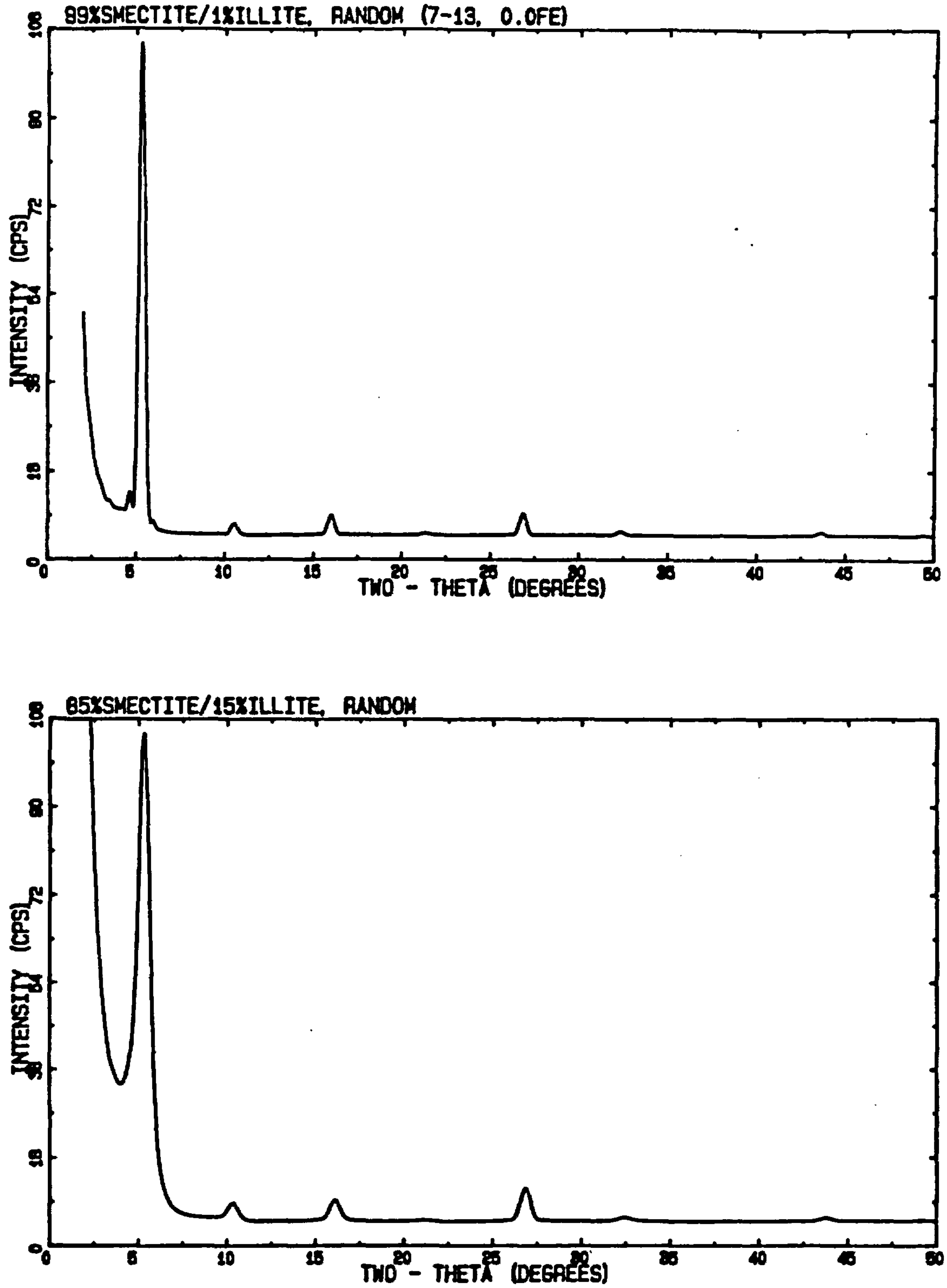
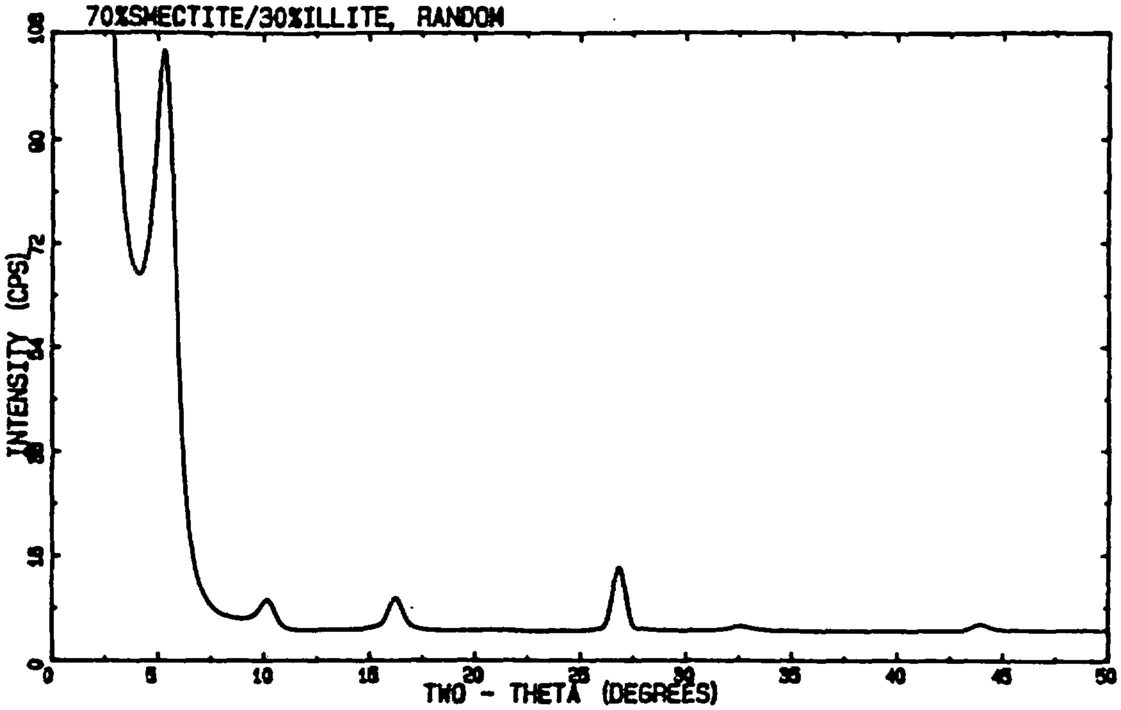


Fig. 2.
Calculated x-ray diffraction patterns (CuKα) of interstratified illite/ smectites. The number of layers in individual crystallites (N) equals 7 to 13 for a), d), e), and h), equals 4 to 10 for b) and c), and equals 9 to 15 for f) and 10 to 16 for g).

(c)


70%SMECTITE/30%ILLITE, RANDOM
INTENSITY (CPS)
TWO - THETA (DEGREES)

(d)

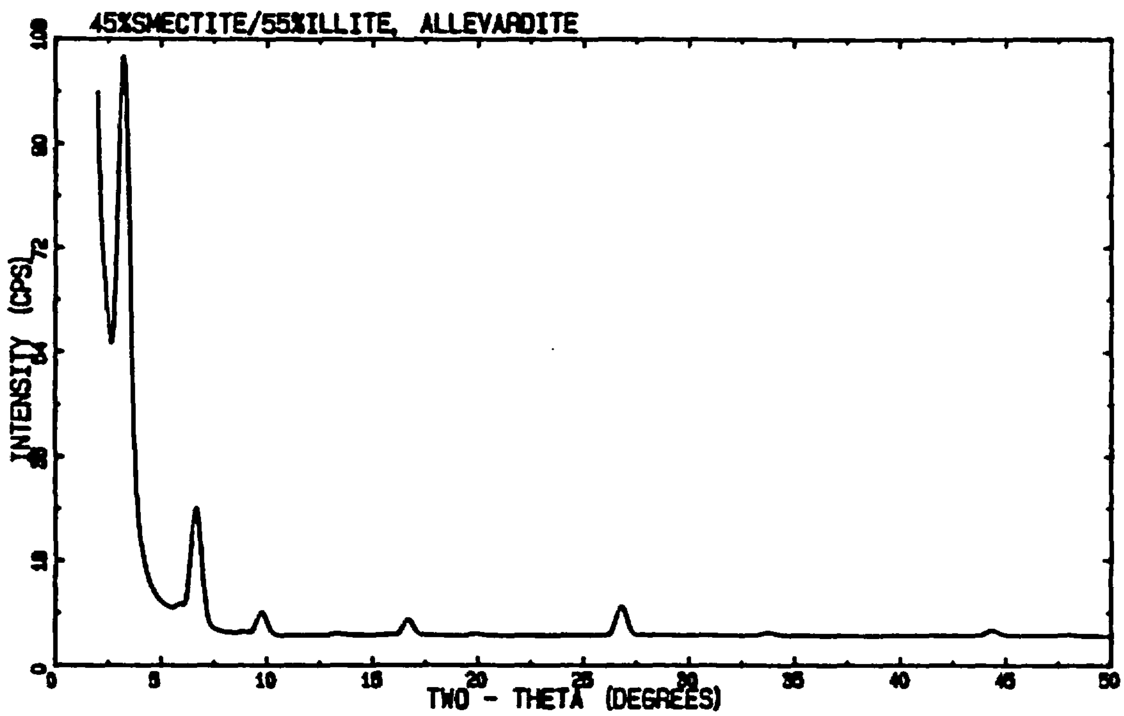
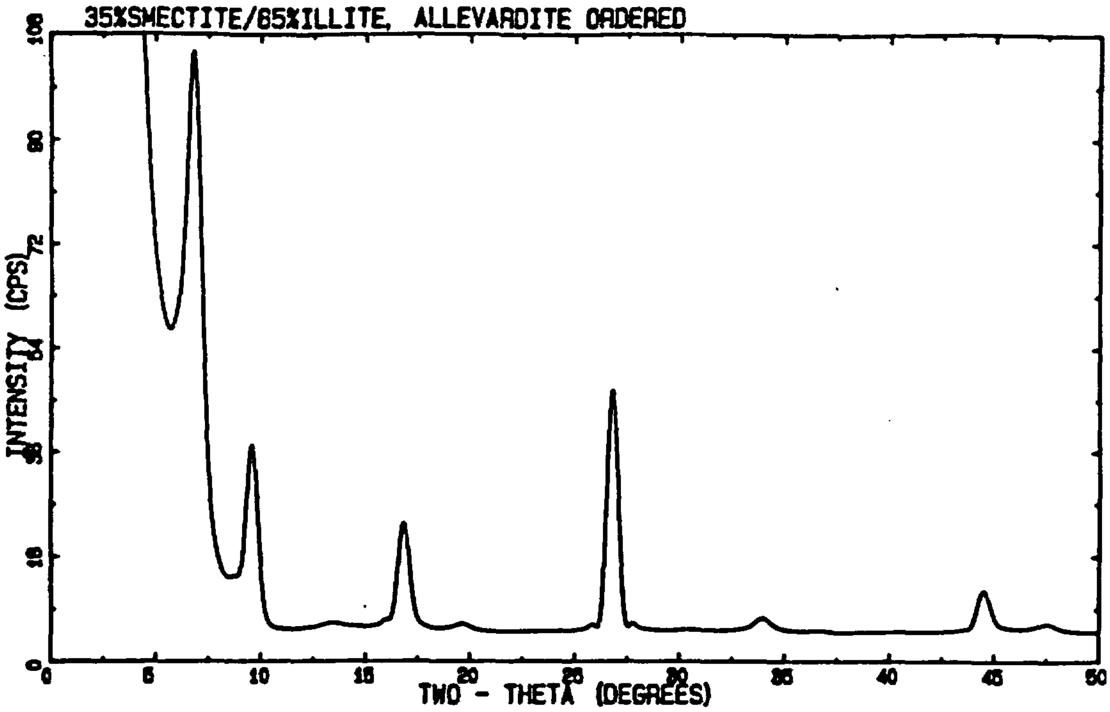

45%SMECTITE/55%ILLITE, ALLEVARDITE
INTENSITY (CPS)
TWO - THETA (DEGREES)

Fig. 2. (cont)

(e)


35%SMECTITE/65%ILLITE, ALLEVARDITE ORDERED
INTENSITY (CPS)
TWO - THETA (DEGREES)
0
18
36
54
72
90
108
0
5
10
15
20
25
30
35
40
45
50

(f)

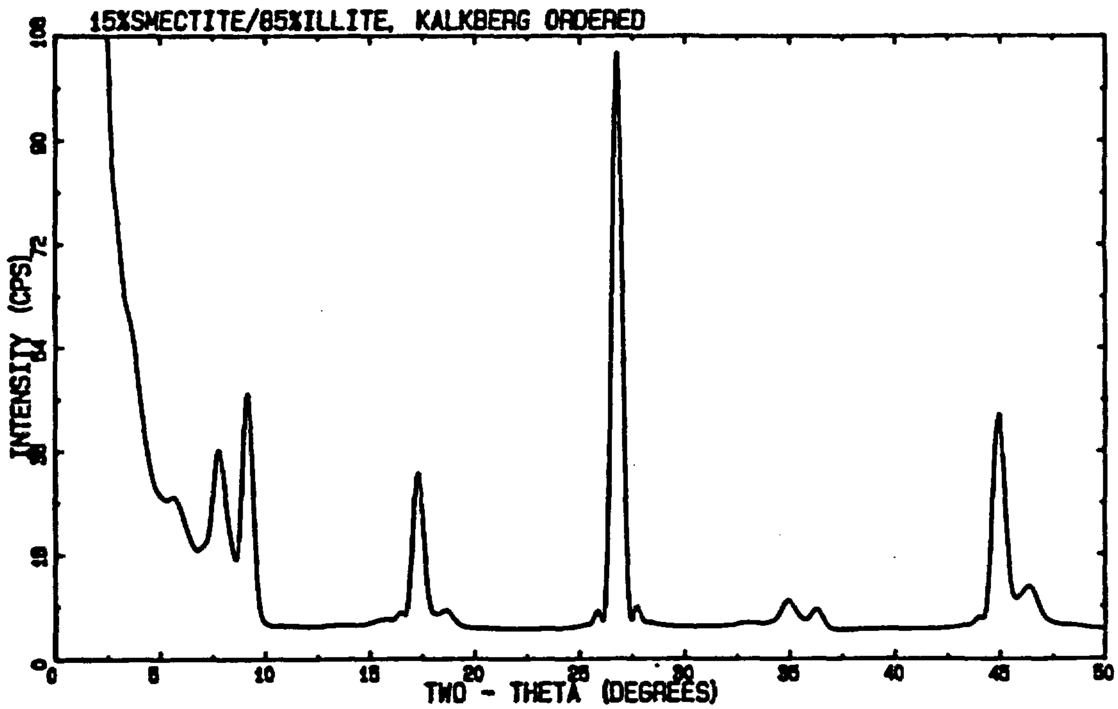
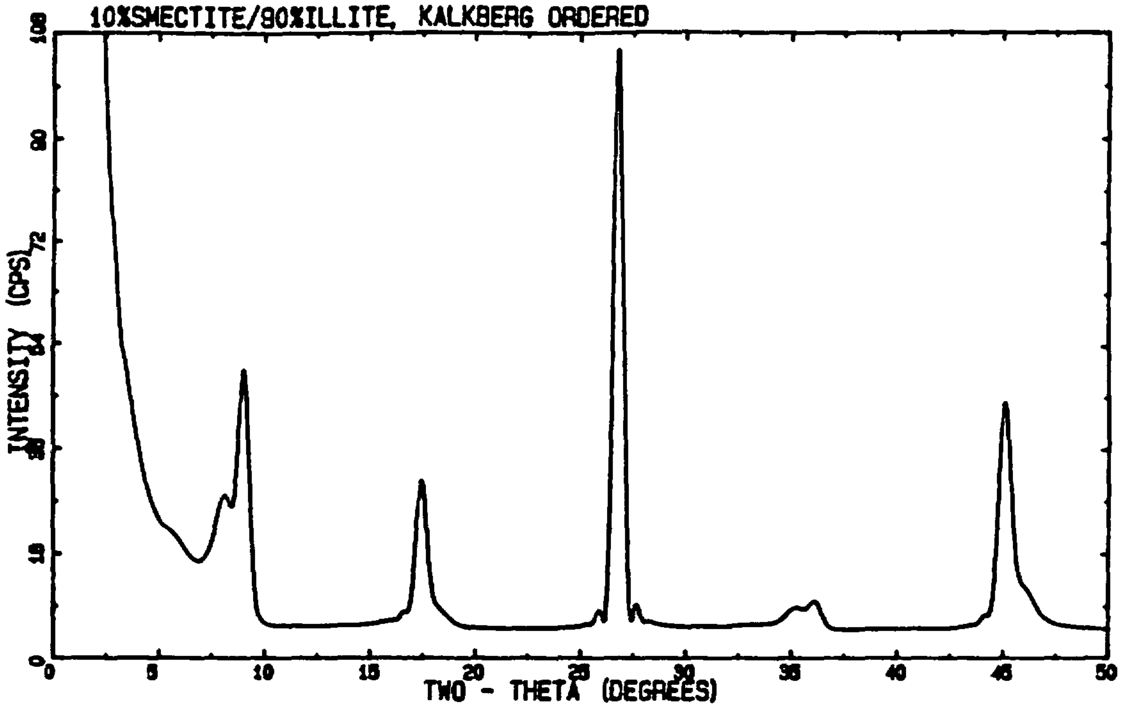

15%SMECTITE/85%ILLITE, KALKBERG ORDERED
INTENSITY (CPS)
TWO - THETA (DEGREES)
0
18
36
54
72
90
108
0
5
10
15
20
25
30
35
40
45
50

Fig. 2. (cont)

(g)


10%SMECTITE/90%ILLITE, KALKBERG ORDERED
INTENSITY (CPS)
TWO - THETA (DEGREES)

(h)

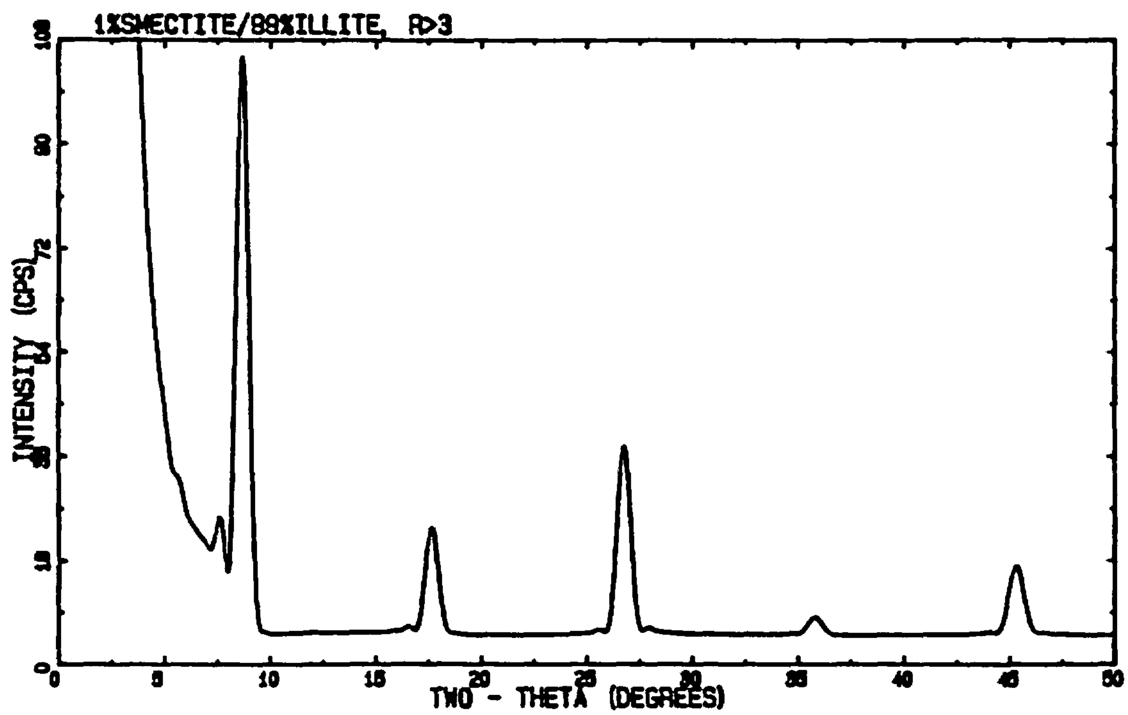

1%SMECTITE/99%ILLITE, R>3
INTENSITY (CPS)
TWO - THETA (DEGREES)

Fig. 2. (cont)

ethylene glycol-smectite complex thickness and layer charge; in general, a low ethylene glycol-smectite complex thickness is correlated with a higher layer charge and a high cation exchange capacity. Reynolds (1980) discussed interstratification at length, including methods of determining ordering and the type of interstratification.

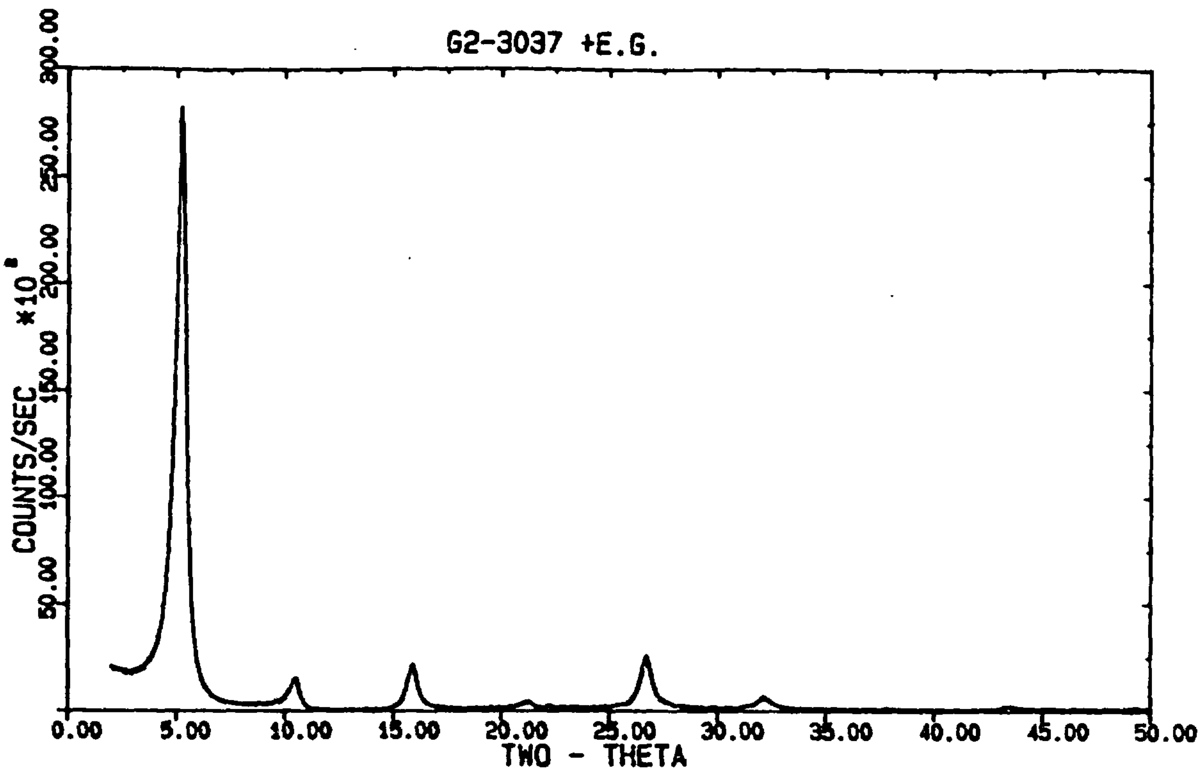
In the course of our routine examinations, we usually do not perform any other treatment on the clay. However, if other clay minerals are suspected or if the smectite appears unusual, we perform a variety of other tests including potassium saturation, lithium saturation (Greene-Kelley 1955; Bystrom-Brusewitz 1975), water solvation, and heat treatments (see Brindley and Brown 1980). Unambiguous identification of kaolinite and/or chlorite in these rocks was usually difficult because of the small amounts of the phases present. Both phases have major reflections near 12^{o}-2θ in x-ray powder patterns, and discrimination was attempted based on the presence or absence of a reflection near 6^{o} 2θ (chlorite has a reflection here) or on the basis of heating experiments. However, results were usually ambiguous due to the small concentrations, and values reported here are best estimates.

In addition to examining the clay mineralogy by x-ray diffraction, fluid inclusions were examined in calcite, fluorite, and quartz in USW G-2 and G-3, using techniques described by Roedder (1984) in order to obtain additional information on the temperatures associated with the formation and alteration of the minerals in Yucca Mountain tuffs. In general only calcite and fluorite contained secondary inclusions that might provide information on secondary alteration conditions, and inclusions large enough to study were very rare. Primary inclusions in phases such as quartz were not usually examined since they yield very high initial depositional temperatures.

III. RESULTS AND DISCUSSION

Examples of the x-ray powder diffraction patterns of the clays from USW G-1 and G-2 are shown in Fig. 3 and can be compared with the calculated patterns in Fig. 2. The results for the clays from USW G-1, G-2, and G-3 are presented in Tables I, II, and III; data for the clays from the upper portion of G-1 are in Bish (1981). These data include percent illite layers, type of interstratification, the ethylene glycol-smectite complex thickness, and the basal spacing at 20±10% relative humidity. In USW G-1, the clays shallower than 1448 m (4750 ft) in depth are randomly interstratified illite/smectites (R=0) with greater than 80% expandable layers. Below 1448 m (4750 ft), ordered illite-rich interstratifications occur, with Kalkberg-interstratified illite/smectites (R≥3) and chlorite occurring below 1718-m (5637-ft) depth. The clays from USW G-2 are randomly interstratified illite/smectites (R=0) with <10% illite layers shallower than 1053 m (3454 ft). Kaolinite appears and there is an abrupt increase in interstratified illite in the illite/smectites below about 1106 m (3627 ft), with minor R=1 ordering appearing at 1097 m (3600 ft), well-ordered R=1 interstratifications occurring at 1128 m (3700 ft), and long-range ordered Kalkberg-type interstratifications (R≥3) occurring between 1158-m (3800-ft) and 1524-m (5000-ft) depth. Discrete illite predominates below 1524 m (5000 ft), with lesser amounts of chlorite, randomly interstratified chlorite/smectite, and 100%

(a)



(b)

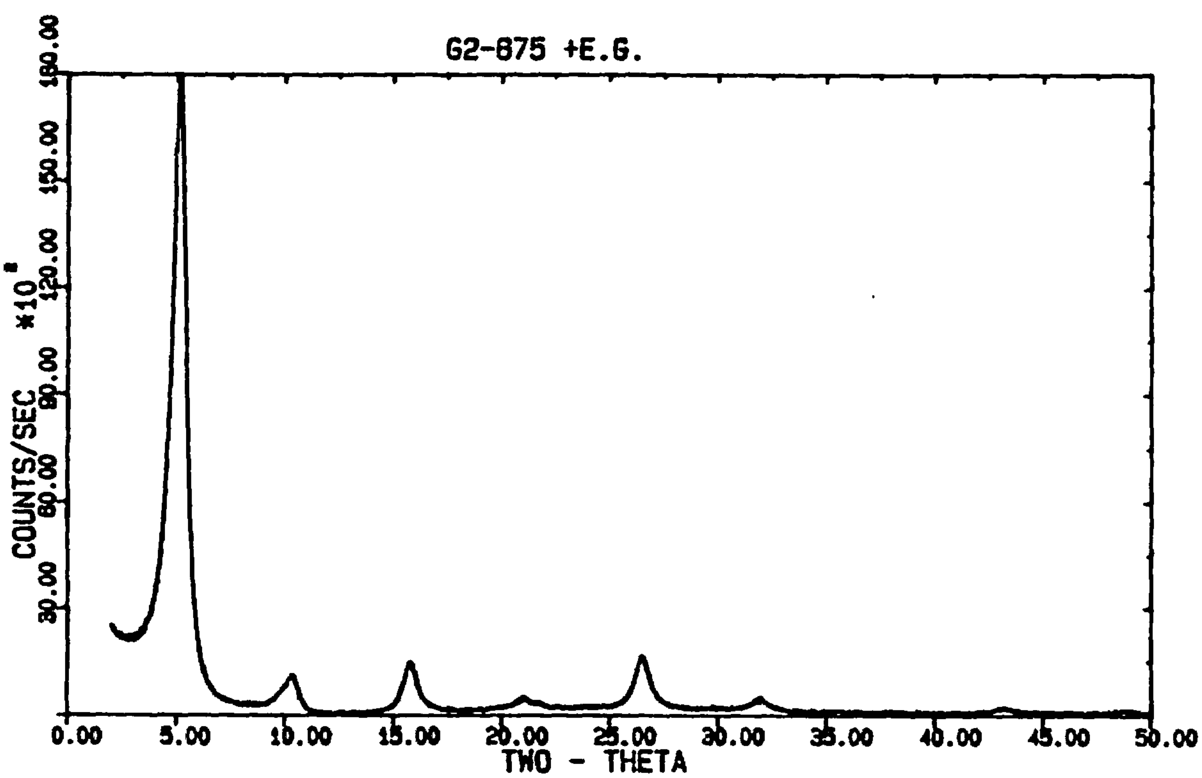
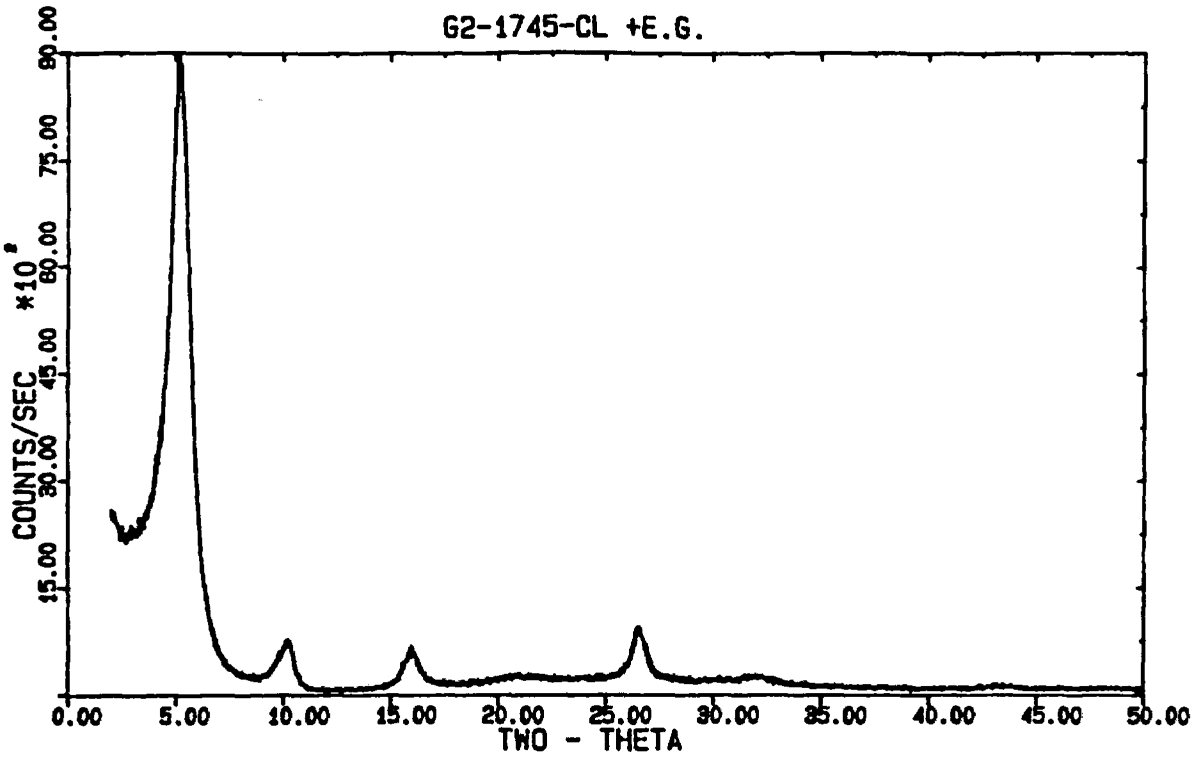


Fig. 3.
Measured x-ray diffraction patterns (CuKα) of ethylene-glycol saturated illite/smectites from USW G-1 and G-2. Depth in feet is indicated in each sample title, e.g., G2-3037 is a sample from USW G-2 at 3037-ft (925.7-m) depth.

(c)


G2-1745-CL +E.G.
COUNTS/SEC *10²
90.00
75.00
60.00
45.00
30.00
15.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
TWO - THETA

(d)

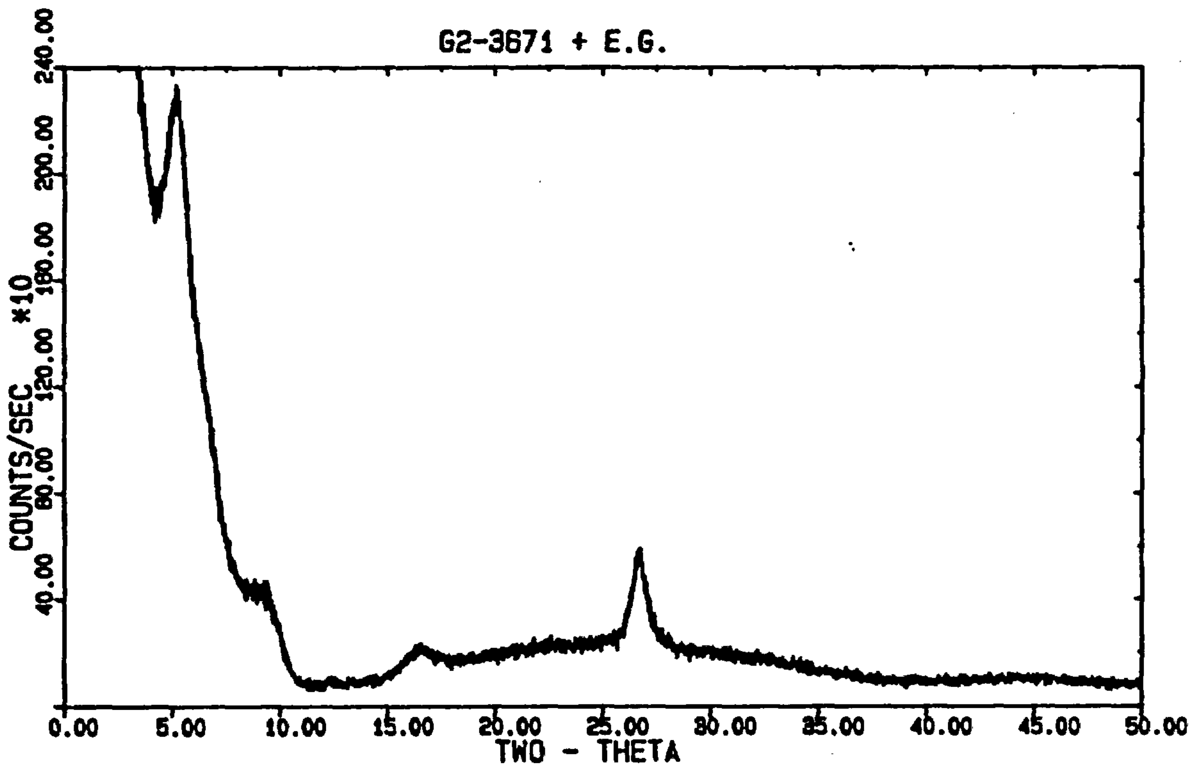
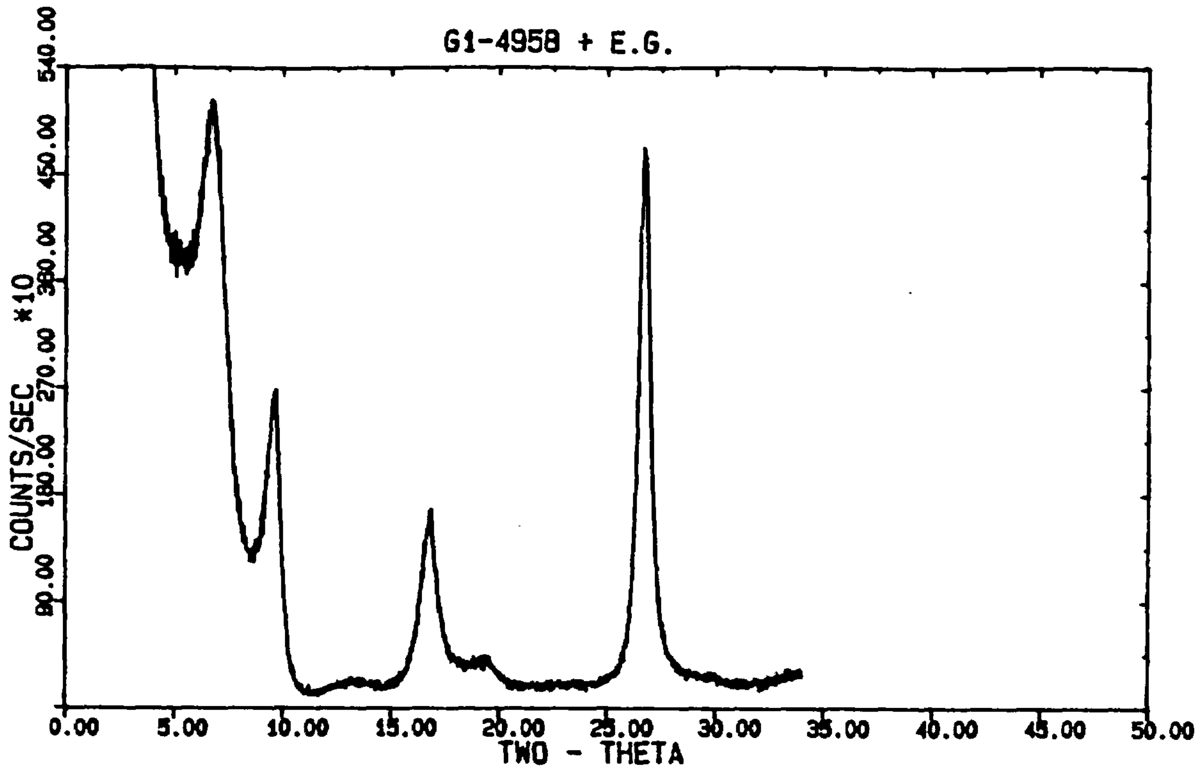

G2-3671 + E.G.
COUNTS/SEC *10
240.00
200.00
160.00
120.00
80.00
40.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
TWO - THETA

Fig. 3. (cont)

(e)


G1-4958 + E.G.
COUNTS/SEC *10
90.00
180.00
270.00
360.00
450.00
540.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
TWO - THETA

(f)

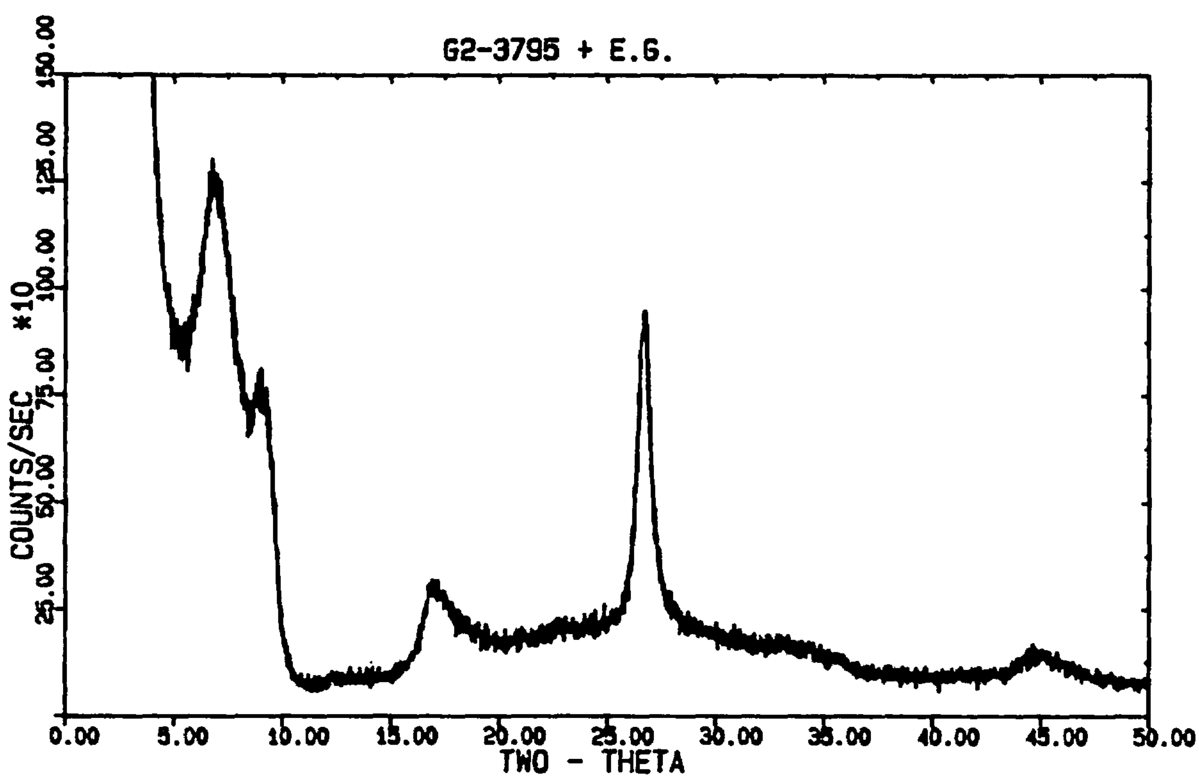
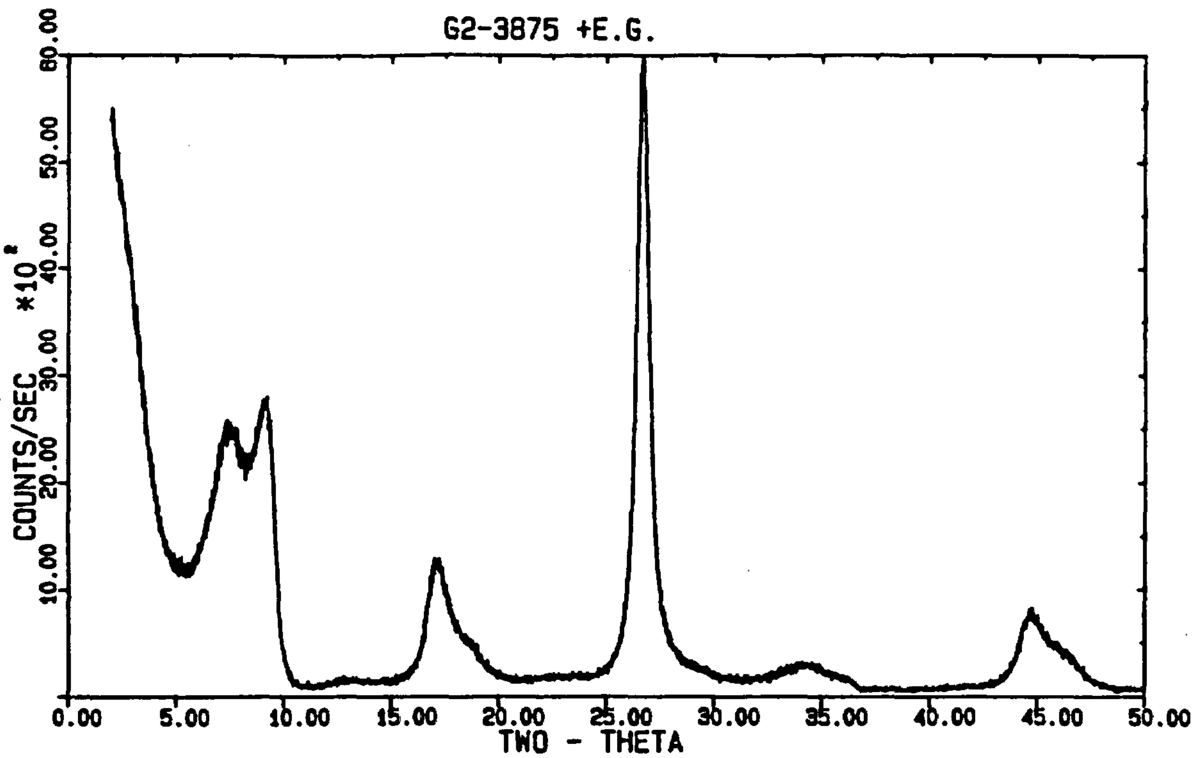

G2-3795 + E.G.
COUNTS/SEC *10
25.00
50.00
75.00
100.00
125.00
150.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
TWO - THETA

Fig. 3. (cont)

(g)


G2-3875 +E.G.
COUNTS/SEC *10²
10.00
20.00
30.00
40.00
50.00
60.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
TWO - THETA

(h)

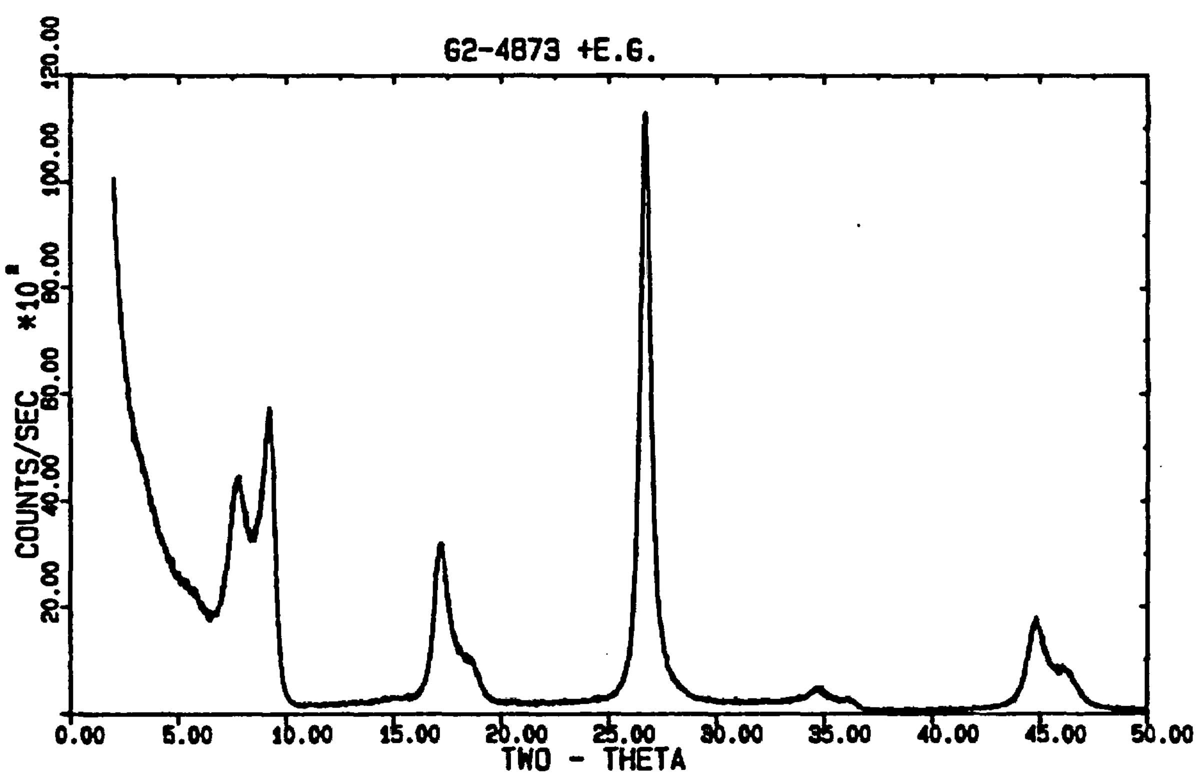

G2-4873 +E.G.
COUNTS/SEC *10²
20.00
40.00
60.00
80.00
100.00
120.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
TWO - THETA

Fig. 3. (cont)

(i)

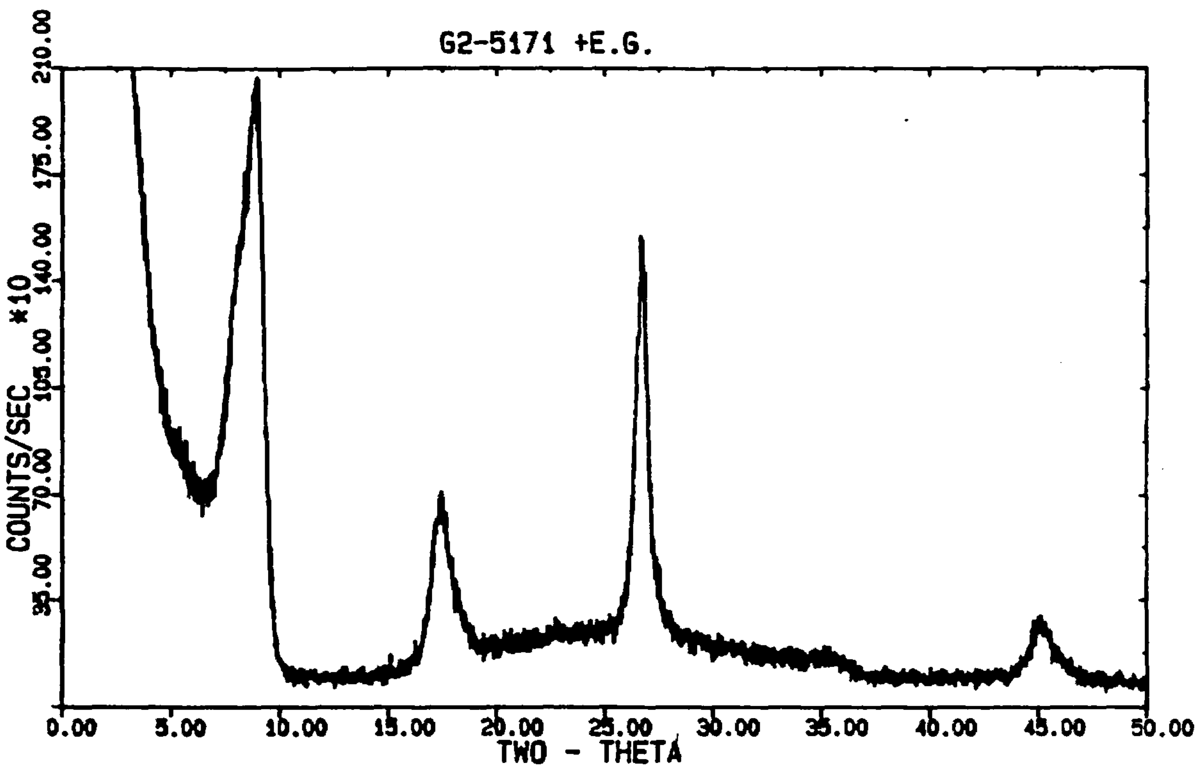

G2-5171 +E.G.
COUNTS/SEC *10
210.00
175.00
140.00
105.00
70.00
35.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
TWO - THETA

Fig. 3 (cont)

TABLE I

X-RAY DIFFRACTION RESULTS FOR CLAY MINERALS FROM USW G-1
20±10% RELATIVE HUMIDITY

Sample No.	% Illite Layers	Type of Inter-stratification	EG-Smectite Thickness (Å)	(001) at Room Temperature (Å)
G1-1286	10	Random	16.85	13.1Å
3621 dark	20	"	16.9	12.2
3621 clear	15	"	16.9	11.8
3810 dark	20	"	16.9	12.2
3810 clear	20	"	16.85	11.9
3940 dark	20	"	16.7	11.9
3940 clear	25	"	16.8	12.1
4246 dark	20	"	16.75	13.7
4400	25	"	16.6	14.1
4556	20	"	16.65	14.3
4750	50-60	"	16.6	13.7, 11.3
4958	60	Allevardite	16.65	11.4
4998	30	Random	16.7	12.7
5339 dark	30	"	16.75	14.0
5339 clear	30	"	16.75	13.6
5534	40	"	16.75	11.9
5637	85-90	Kalkberg	16.5	10.5+Chl[a]
5898	80-90	"	16.55	11.0
5980	85-90	"	16.6	10.9+Chl[a]

[a]Chl = Chlorite.

TABLE II
X-RAY DIFFRACTION RESULTS FOR CLAY MINERALS FROM USW G-2 CORE
20±10% RELATIVE HUMIDITY

Sample No.	% Illite Layers	Type of Inter-stratification	EG-Smectite Thickness (Å)	(001) at Room Temperature (Å)
G2-338	<5	Random	16.70	14.0
501	<5	"	16.70	14.4
675	~5	"	16.75	13.4
743	<5	"	16.70	12.4
921	<5	"	16.65	13.2
1032	<5	"	16.65	13.0
1382	<5	"	16.70	12.6
1634	~5	"	16.70	10.2
1745 clear	10	"	16.75	11.9
2667	10	"	-	10.3
3037	<5	"	16.60	13.5
3250	~5	"	16.55	10.2
3454 clear	10	"	16.55	12.3
3454 dark	15	"	16.60	10.1
3492	15	"	16.8	10.2
3512	20	"	16.65	10.1
3578	~5	"	16.65	10.2
3627	40-50	Minor ordering	16.55	10.1
3671	60	" "	16.60	10.2
3720 clear	~70	Allevardite	16.70	10.5
3720 dark	70	"	16.70	10.2
3724	~80	"	16.65	10.1
3750	80	"	16.60	10.1
3795	80	"	16.60	10.1
3833	80	Allevardite, some long-range order	16.60	10.1
3875	90	Kalkberg	16.60	10.1
3933	90	"	16.60	10.0
4005	70	Minor ordering	16.60	10.1
4090 clear	20	Random	16.60	13.0, 10.1
4090 dark	20	"	16.60	10.1, 13.4

TABLE II (cont)

Sample No.	% Illite Layers	Type of Inter-stratification	EG-Smectite Thickness (Å)	(001) at Room Temperature (Å)
4167	Illite + randomly interstratified chlorite/smectite			10.2
4467	85	Kalkberg	16.55	10.2
4873	90	"	16.60	10.1
4885	90	Kalkberg + smectite	16.60	10.1
4949 clear	<5	Random	16.65	12.6
4949 dark	<5	"	16.60	10.5, 12.6
5171	>95	Illite		10.3
5369	Illite + discrete smectite/ 20% Illite		16.6	10.16
5538	Illite + chlorite		10.1	
5657	Illite + chlorite		10.3	
5696	Illite + chlorite + smectite		16.65	10.5
5820	Randomly interstratified chlorite-smectite, 60-80% chlorite, minor ordering			
5931	>95	Illite	-	10.3

TABLE III

X-RAY DIFFRACTION DATA FOR CLAY MINERALS FROM USW G-3 CORE 20±10% RELATIVE HUMIDITY

Sample No.	% Illite Layers	Type of Inter-stratification	EG-Smectite Thickness (Å)	(001) at Room Temperature (Å)
G3-315.7	10-20	Random	16.7	13.5
332.5	10-20	"	16.75	13.9
414.3	10-20	"	16.8	13.0
1344.8	(poorly ordered, no higher orders of (001)		13.9	
1394.6	10-20	"	16.7	-[a]
1438.2	10-20	"	16.7	12.5
1493.7	10-20	"	16.7	-
2189.0	10-20	"	16.7	12.9
3170.5	10-20	"	16.7	12.5
3228.0	5-15	"	16.75	13.7
3264.4 clear	5-15	"	16.8	12.0
3264.4 dark	5-15	"	16.8	12.1
3310.9 clear	5-15	"	16.75	-
3310.9 dark	0-10	"	16.75	12.3
3315.1 super[b]	10-20	"	16.7	11.9
3315.1 clear	0-5	"	16.7	12.4
3315.1 dark	5-15	"	16.8	-
3799.0 clear	5-15	"	16.95	10.0
3799.0 dark	5-15	"	17.0	10.0
3847.5 clear	5-15	"	17.0	9.7
3847.5 dark	5-15	"	17.0	9.8
4288.9 clear	10-20	"	16.65	13.0
4288.9 dark	5-15	"	16.7	-
4439.0 clear	5-15	"	16.7	12.1
4439.0 dark	5-15	"	16.75	13.8
4706.9	10-20	"	16.65	14.2
4857.5 clear	15-25	"	16.80	12.0
4857.5 dark	5-15	"	16.70	13.8
4964.3 clear	15-25	"	16.7	14.1
4964.3 dark	15-25	"	16.65	13.0

[a]Not measured.

[b]Super = supernatant.

expandable smectite. Incomplete collapse of heat-treated smectites from USW G-1 and G-2 suggests that many of the smectites in the deeper portions of these drill holes are partially chloritized. G-3 clays are all randomly interstratified illite/smectites (R=0) with fewer than 25% illite layers. No consistent trends are obvious in the ethylene glycol-smectite complex thickness in these cores, although there is a tendency for the complex thickness to decrease in the deeper samples. This is consistent with an increase in smectite layer charge with depth.

The (001) spacings at room temperature and 20% relative humidity suggest (Gillery 1959; Suquet et al. 1975) that the illite/smectites in G-1, G-2, and G-3 are predominantly Na-Ca saturated, but the G-2 clays become more K rich below 457-m (1500-ft) depth. These conclusions from x-ray data are in agreement with limited microprobe data for clays from these cores (Caporuscio et al. 1982; Vaniman et al. 1984). These data show that the illite/smectites abruptly increase in K content below 975 m (3200 ft) in USW G-2, and illite/smectites shallower that 975 m (3200 ft) have Ca≥Na»K. Below 1067 m (3500 ft), the interlayer cation is predominantly K. Data for USW G-3 clays show subequal Ca and Na with variable K, but K tends to increase with depth below about 1372 m (4500 ft).

The transformations in clay mineralogy with depth can yield information concerning the temperatures to which the rocks have been subjected by employing the data of Hower and Altaner (1983). Figure 4a is a summary diagram of the relationship between temperature and the extent of the smectite-to-illite reaction, incorporating data from pelitic rocks as well as active geothermal areas (Steiner 1968; Eslinger and Savin 1973; Hoffman and Hower 1979; McDowell and Elders 1980). Figure 4b shows an example of the relationship between expandability and temperature for a Gulf Coast well at lower temperatures (Perry and Hower 1970). Application of Fig. 4 to the clay mineral data for G-1, G-2, and G-3 cores yields the schematic paleotemperature profiles shown in Fig. 5. The present-day measured geothermal gradients (Sass et al. 1983) are shown on Fig. 5 for comparison. The schematic profiles in Fig. 5 are considerably steeper than the present-day gradients; it is thus apparent from these clay mineral data that a significant thermal event has occurred in the northern end of Yucca Mountain but has not appreciably affected the rocks in USW G-3 at the southern end of Yucca Mountain. The schematic paleotemperatures in Fig. 5 assume long enough reaction times that kinetic effects are not limiting. Hower and Altaner (1983) and Thompson and Jennings (1985) concluded that the reactions below 150°C involving randomly interstratified illite/ smectites (R=0) and allevardite (R=1) are kinetically controlled; in a prograde sequence, allevardite (R=1) is formed at 90 to 100°C over long reaction times (>10^7 years) but at 130° to 150°C over short reaction times (<10^6 years). Apparently these clay mineral reactions are not kinetically limited at temperatures over 130° to 150°C.

It is unclear why the apparent thermal gradient is so steep in USW G-2 and why the percent illite in the illite/smectites rises so abruptly at about 1067-m (3500-ft) depth. The static water level at the time of alteration may have been deep, but 1067 m (3500 ft) is probably an unrealistic depth for the static water level, particularly during times of increased rainfall. This abrupt change near 1067 m is probably related to

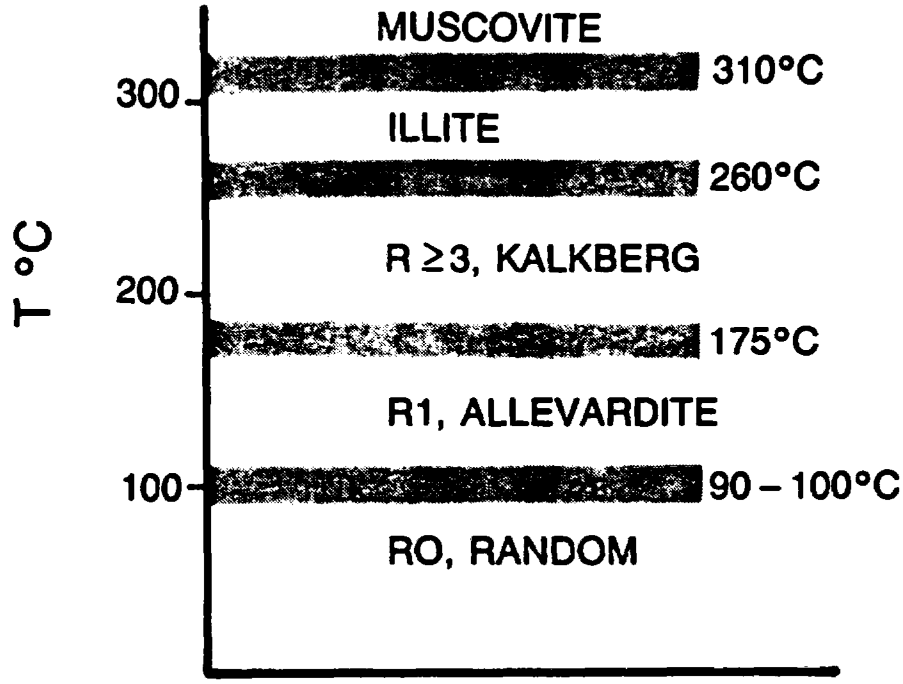


Fig. 4a.
Relationship between temperature and extent of smectite-to-illite reaction (Hower and Altaner 1983).

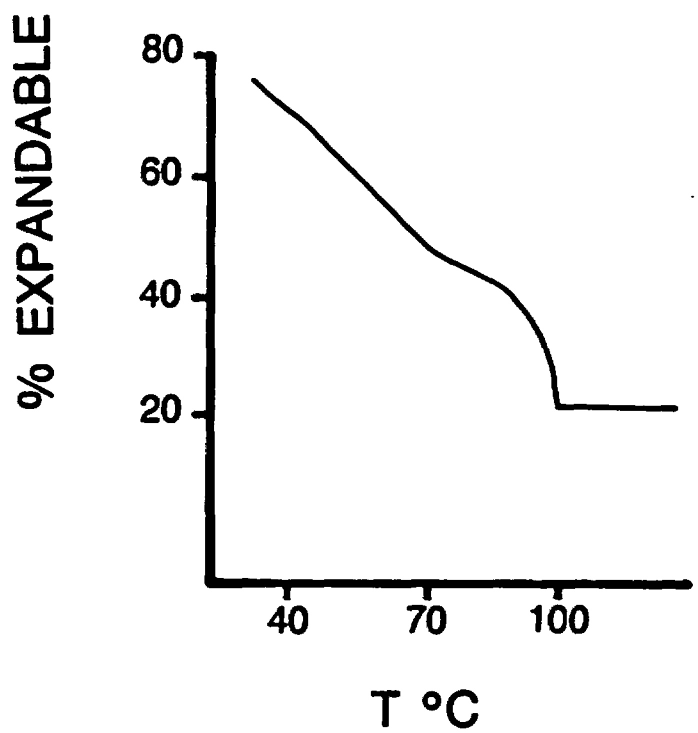


Fig. 4b.
Relationship between expandability and temperature for illite/smectites from a Gulf Coast well (Perry and Hower 1970).

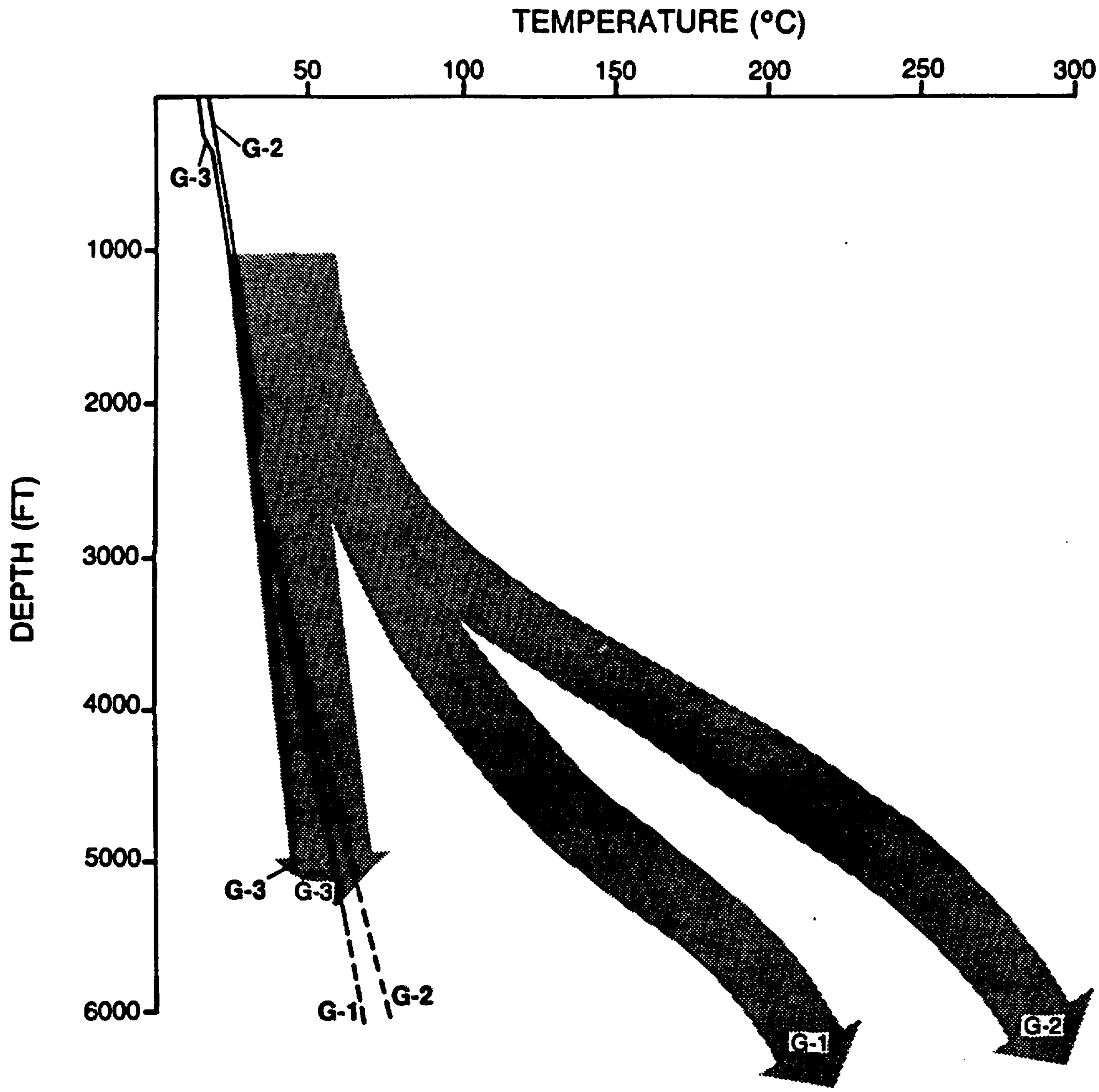


Fig. 5.
Schematic paleotemperatures for USW G-1, G-2, and G-3 estimated from clay mineral reactions and fluid inclusion data (broad, arrowed lines) with the present-day measured temperature profiles from Sass et al. (1983) (solid narrow lines).

a change from a zone that was meteorically cooled (convective) to a conductive zone. The paleogeothermal gradient presented in Fig. 5 for USW G-2 is very similar to present-day thermal gradient curves found in geothermal areas. For example, Swanberg and Combs (1986) presented the temperature-depth plot for a drill hole in Newberry Volcano, Oregon. Their plot revealed virtually constant temperature to a depth of about 1000 m (3280 ft), at which point the temperature increased abruptly by at least 30°C and took on a conductive character. They postulated that the observed change at about 1000 m is due to a transition from younger porous rocks to older, more silicic rocks unaffected by the regional groundwater flow. The remarkable similarity between the gradients in Fig. 5 and many of those measured today suggests that similar conditions may have existed at Yucca Mountain 11 Myr ago. It is likely that the rain curtain extended to approximately 1000-m depth in USW G-2, and the hydrothermal fluids responsible for rock alteration did not appreciably interact with shallower rocks.

Potentially valuable data concerning other mineral reactions in tuffs can be obtained by examining the changes in bulk mineralogy with depth and correlating these changes with the clay mineral reactions and the paleotemperatures estimated from the clay minerals. The bulk mineralogy determined by x-ray powder diffraction of drill holes USW G-1, G-2, and G-3 has been presented by Bish et al. (1981), Caporuscio et al. (1982), and Vaniman et al. (1984), respectively. Noteworthy variations in mineralogy include the gradation from unaltered volcanic glass to clinoptilolite and mordenite to analcime and finally to authigenic albite with depth. The sequence was first emphasized for these tuffs by Smyth (1982), who related these mineralogic changes to those documented by Iijima (1975, 1980). Smyth correlated the temperatures at which some of these reactions occurred (clinoptilolite-analcime, analcime-albite) to the Na-ion concentration of the waters. In contrast, Kerrisk (1983) conducted reaction-path calculations of mineral formation in tuffs near Yucca Mountain and concluded that the aqueous silica activity was the controlling variable in the mineral evolution. He was unable to reproduce the observed mineral assemblages by varying the Na-ion concentration. Duffy (1984) also concluded that the aqueous silica concentration was the variable controlling the stability of clinoptilolite and mordenite in Yucca Mountain. He used thermodynamic calculations to show that clinoptilolite is not stable with respect to albite or analcime at any temperature when the chemical potential of silica is controlled by quartz. Thus the stability of clinoptilolite may depend on whether the silica activity is controlled by cristobalite or quartz. The time interval over which clinoptilolite would remain stable would be determined by the rate of reaction of cristobalite to quartz. Other mineralogic variations with depth include the disappearance of tridymite, opal-CT, and cristobalite and the appearance of calcite and chlorite. In addition, pyrite, barite, and fluorite have been identified below 1067 m (3500 ft) in USW G-2; these three phases may be suggestive of hydrothermal alteration rather than diagenetic alteration through the action of groundwater.

Results of analysis of the few fluid inclusions found in secondary minerals from G-2 and G-3 yield temperatures below and above, respectively, those determined by the clay minerals. Inclusions in calcite from G-2 yielded homogenization temperatures of 94° to 115°C in G2-5379 [G2-5379 refers to a sample from USW G-2 at 1640-m (5379-ft) depth], 147°C in G2-5762, and 202° to 239°C in G2-5820. Freezing temperatures ranged from -0.1° to -0.6°C, reflecting low salinities in the inclusions. Homogenization temperatures in calcite from G-3 were 101° to 227°C in GU3-103, 125° to 170°C in GU3-429, and 97°C in G3-4803. Lack of mineralogical data to support elevated alteration temperatures suggests that the higher temperature inclusions in the upper part of USW G-3 probably formed during the initial deposition or cooling of the tuffs. Alternatively, the relatively high homogenization temperatures in the shallow GU3 calcites may be a result of re-equilibration or variable initial vapor-to-liquid ratios (Goldstein 1986).

A. Zeolite Stabilities

Figures 6, 7, and 8 show comparisons of the clay mineralogy with the bulk mineralogy for USW G-1, G-2, and G-3 cores, respectively. From these figures, Fig. 4, and Tables I, II, and III, approximate upper temperature limits at which zeolites have broken down in Yucca Mountain can be obtained. The clays in USW G-2 reflect higher temperatures than those from G-1 or G-3. It is clear from G-1 and G-2 that clinoptilolite was not part of the stable mineral assemblage at the depth/temperature at which ordered illite/smectite interstratifications occur. The temperature range for the onset of ordering is 90 to 100°C for reaction times in excess of 10^7 years. For shorter reaction times ($<10^6$ yr), temperatures of 130 to 150°C are required for the formation of allevardite (R=1) (Hower and Altaner 1983). Mordenite disappears in G-2 below 1091-m (3578-ft) depth; the illite/smectite at 1106 m (3627 ft) is the shallowest to exhibit measurable ordering, suggesting that the mordenite upper stability limit is 100 to 130°C. Analcime is rare below 1097 m (3600 ft) and virtually absent below 1372 m (4500 ft). The disappearance with depth of analcime as a major phase near the first appearance of Kalkberg-type interstratifications (R≥3) in G-2 implies an upper stability limit for analcime of 175 to 200°C, in agreement with limited experimental data (Liou 1971). The zeolite mineralogy in USW G-3 shows the trends obvious in USW G-1 and G-2, but the clay mineralogy suggests that temperatures have not been significantly elevated in G-3. It may be that an additional factor, perhaps water chemistry, was the controlling factor in zeolite reactions in USW G-3 in the absence of significantly elevated temperatures.

B. Chlorite Occurrence

Chlorite and randomly interstratified chlorite/smectite both occur with illite/smectite and illite in the deeper portions of USW G-1 and G-2. In addition, some of the deeper smectites in these two drill holes appear to be partially chloritized and show hindered collapse upon heating. These occurrences are similar to those documented in silicic volcanic rocks at Wairakei, New Zealand (Steiner 1968), and in silicic volcanic rocks in Japan (Inoue et al. 1978; Inoue 1985). Iijima (1978) also documented the occurrence of chlorite in the analcime and authigenic albite zones in altered silicic volcanic rocks. The presence of randomly interstratified chlorite/smectite in the deeper portions of drill hole USW G-2 suggests that this phase may be intermediate between shallower smectites and the deeper chlorites, as proposed by Inoue (1985) for his field area. In contrast to the smectite-to-illite reaction, which requires an adequate supply of K and Al, the reaction of smectite to chlorite requires additional Mg and/or Fe. Steiner (1968)

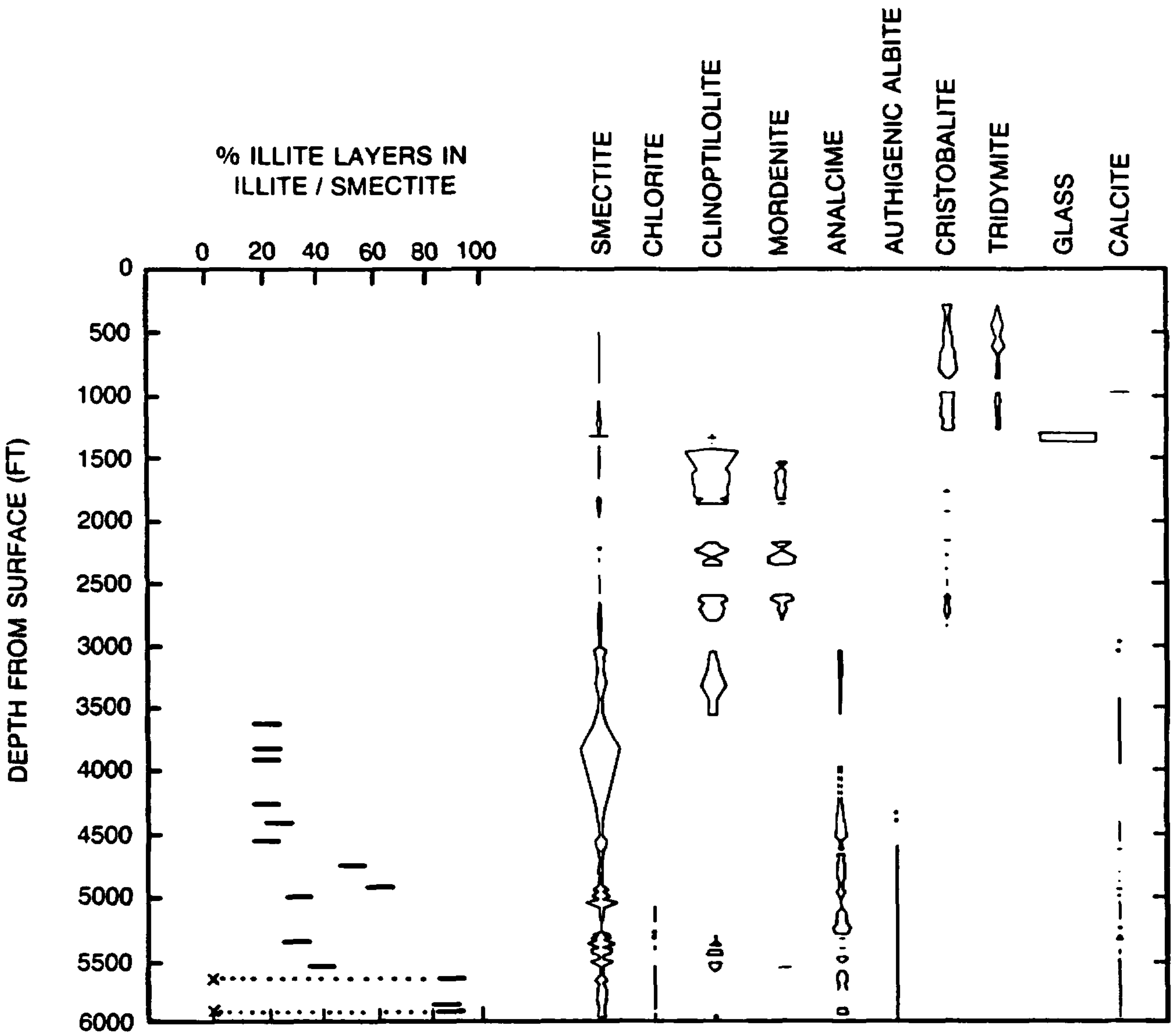


Fig. 6.
Mineral and glass abundances compared with clay mineralogy in drill core USW G-1 determined by x-ray diffraction. Occurrences of authigenic albite were determined by optical examination and are not quantitative. Dotted horizontal lines connecting clay minerals indicate that the phases are coexisting.

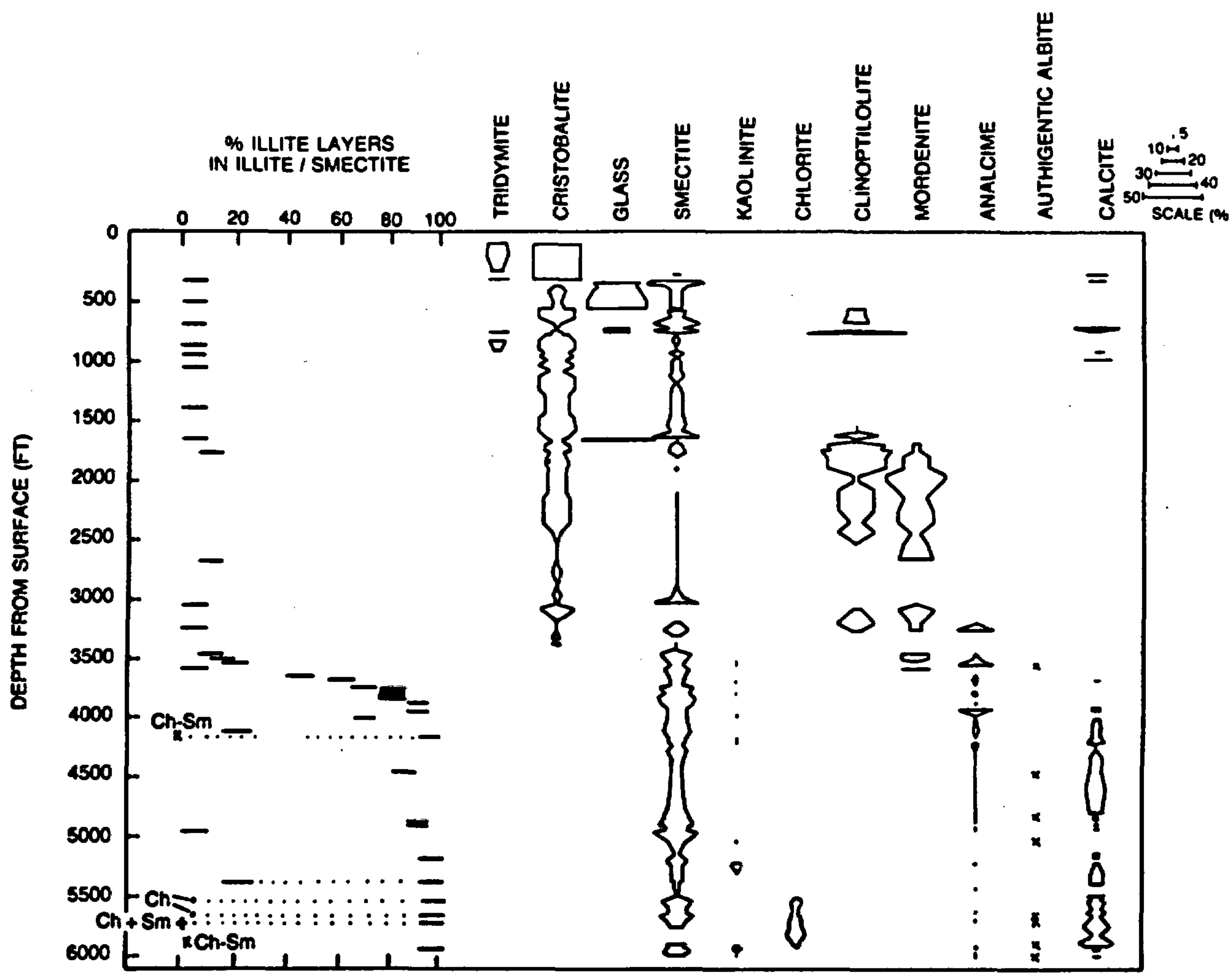


Fig. 7.
Mineral and glass abundances compared with clay mineralogy in drill core USW G-2 determined by x-ray diffraction. Occurrences of authigenic albite were determined by optical examination and are not quantitative. Dotted horizontal lines connecting clay minerals indicate that the phases are coexisting. An "X" signifies the occurrence of randomly interstratified chlorite/smectite, a "+" signifies the occurrence of chlorite + smectite, and a "*" denotes the presence of chlorite.

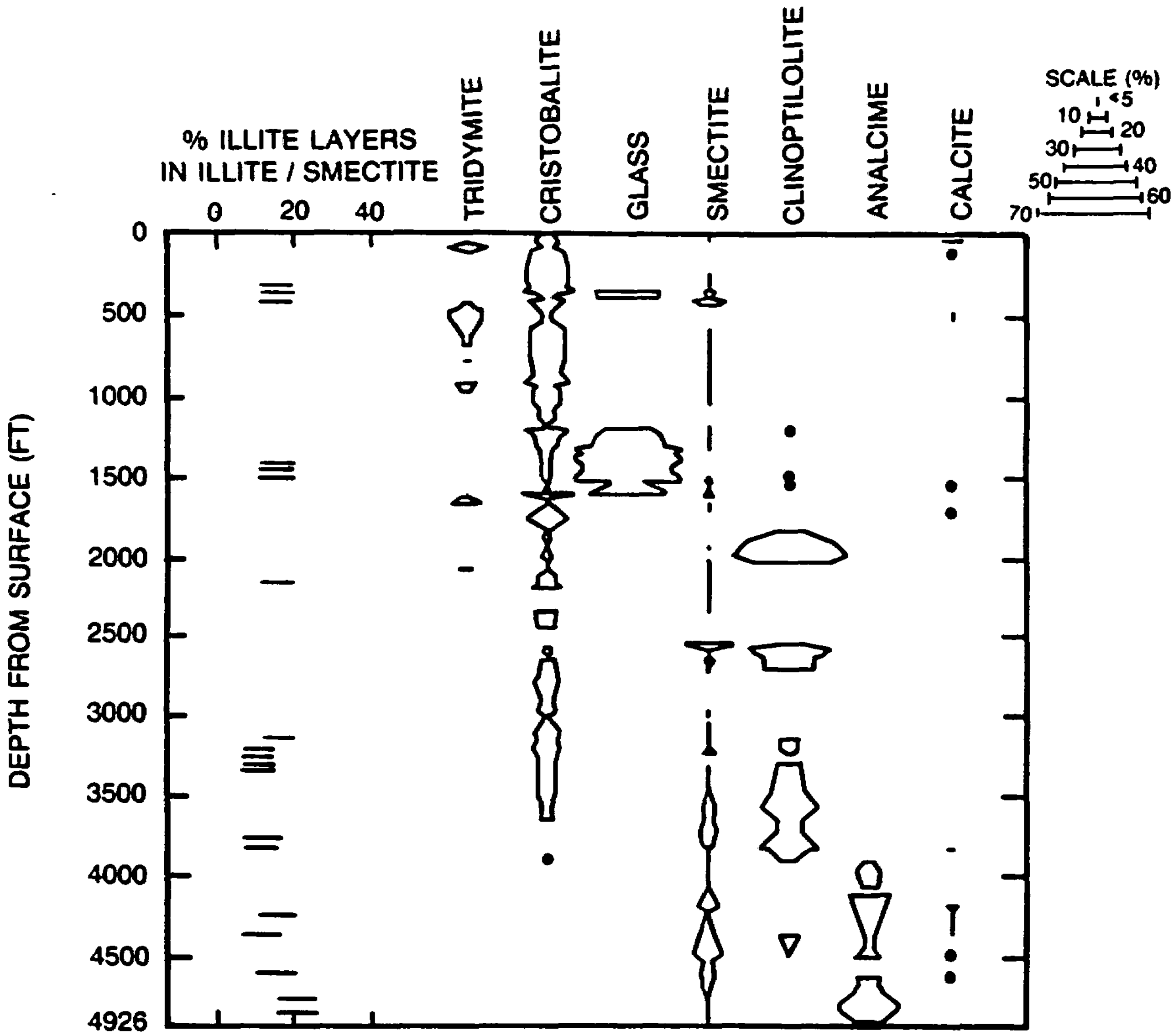


Fig. 8.
Mineral and glass abundances compared with clay mineralogy in drill core USW G-3 determined by x-ray diffraction. Authigenic albite was not found in this drill core. Depths below 914 m (3000 ft) in this figure are corrected for drill-hole deviation such that the total depth is shown as 1501 m (4926 ft) rather than 1533 m (5031 ft).

suggested that the source of Mg and Fe in the silicic volcanics at Wairakei was the glassy groundmass and the alteration of magnetite to pyrite and/or epidote. However, it is likely that the source of Mg and Fe in Yucca Mountain tuffs was the clinoptilolite and mordenite that reacted to form analcime and albite. As noted by Broxton et al. (1986), the clinoptilolites in Yucca Mountain tuffs contain significant Mg whereas analcime and authigenic albite contain little or no Mg or Fe. In addition, chlorite and/or chlorite/smectite do not coexist with clinoptilolite at Yucca Mountain.

C. Silica Phases

Several transformations among silica phases in Yucca Mountain are obvious in Figs. 6, 7, and 8. Among these transformations are the disappearance of glass, opal-CT, tridymite, and cristobalite with depth. The disappearance of volcanic glass and opal with depth in tuffs is well documented (Iijima 1978), as is the instability of tridymite and cristobalite in altering volcanic rocks (Ernst and Calvert 1969; Kano 1983). As noted above, Kerrisk (1983) and Duffy (1984) concluded that decreasing aqueous silica activity, from the shallow rocks containing tridymite, cristobalite, opal, and glass, to the deeper rocks containing quartz, was the most important factor in mineral evolution in volcanic rocks at the Nevada Test Site. The x-ray diffraction data for USW G-1, G-2, and G-3 shown in Figs. 6, 7, and 8 reveal a consistent trend in mineralogy with depth. It is noteworthy that the disappearance of clinoptilolite and mordenite as major phases coincides quite closely with the disappearance of cristobalite as a major phase, supporting the conclusions of Kerrisk (1983). The deepest occurrence of cristobalite in USW G-2 core corresponds to a temperature obtained from the clay minerals of about 100°C. If temperature is the controlling variable in the transformation of cristobalite to quartz (Ernst and Calvert 1969; Kano and Taguchi 1982), then this reaction may have provided an indirect temperature control on the clinoptilolite-to-analcime reaction. The disappearance of cristobalite as a major phase would have resulted in a lower aqueous silica activity, thus perhaps destabilizing clinoptilolite.

D. Alteration Timing

Yucca Mountain is in an area that has been volcanically active in the past, and it is bordered by numerous ancient caldera complexes (Byers et al. 1976) (Fig. 9). The Timber Mountain caldera complex is adjacent to Yucca Mountain to the north, and it or an associated cauldron segment are likely sources of the hydrothermal alteration that is apparent in drill core G-2 and less so in G-1. We have obtained preliminary K/Ar dates from illite/smectites in G-1 and G-2;* sample G1-5637 yielded an age of 10.9±0.6 Myr, and G2-3875 and G2-5171 both gave ages of 11.0±0.6 Myr. These ages are statistically equivalent to the age of the Timber Mountain tuff, 11.3±0.3 Myr (Marvin et al. 1970). The internal concordance of the three illite ages at different depths in wells USW G-1 and G-2, the increasing intensity of alteration in well G-2 closer to Timber Mountain, and the agreement of the ages with the age of Timber Mountain activity all

*Information provided by J. Aronson, Case Western Reserve University (1986).

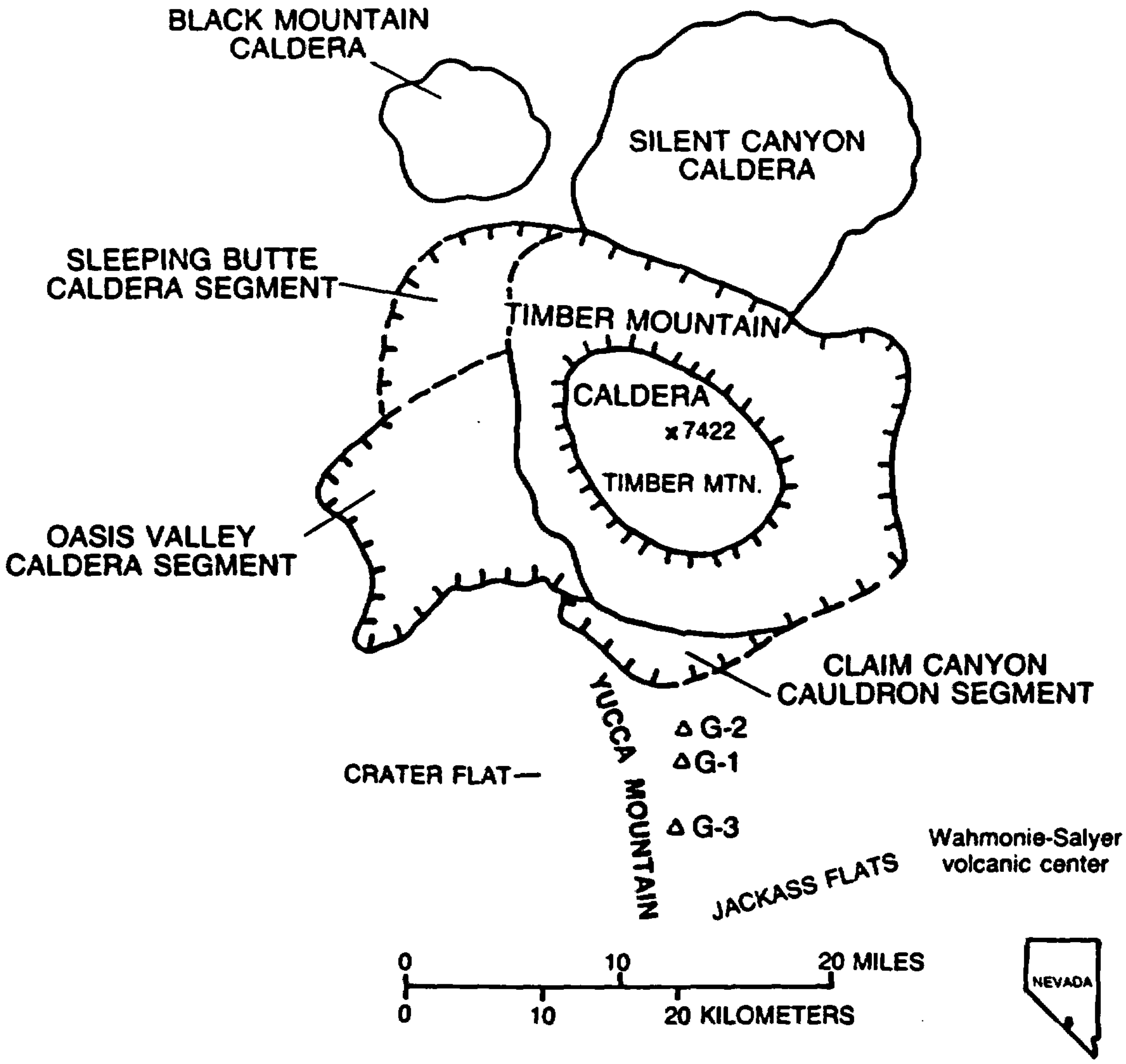


Fig. 9.
Southwestern Nevada volcanic field, Nye County, Nevada, showing the location of the Timber Mountain caldera and other volcanic centers with respect to Yucca Mountain from Byers et al. (1976). Heavy lines with hatchure marks to the inside represent the approximate outer limit of the Timber Mountain-Oasis Valley caldera complex, including the Sleeping Butte and Claim Canyon segments (dashed where indefinite). Heavy lines with hatchure marks to the outside represent the periphery of the Timber Mountain resurgent dome. Drill cores USW G-1, G-2, and G-3 are shown.

argue that hydrothermal effects of the Timber Mountain activity are responsible for the illitization at depth in these two wells. Alternatively, the illitization could have taken place earlier when this area was equally volcanically active, for example during Paintbrush or Crater Flat volcanism. If this were the case, the 11-Myr ages would then represent resetting of the older illite K/Ar system due to reheating during Timber Mountain activity. The blocking temperature below which illites quantitatively retain argon is not well established. K/Ar results on deep Gulf Coast wells indicate this blocking temperature is at least 160°C, and consistent results from other areas suggest it may be as high as 200° to 225°C.* In any case, the illite ages argue that the alteration either formed or was strongly affected by Timber Mountain activity 11 Myr ago, and the rocks have not been significantly reheated since.

However, evidence exists for continued low-temperature formation of minerals in USW G-1 and G-2. This is demonstrated by illite/smectites with a low percentage of collapsed (illite) layers occurring deeper than higher temperature-ordered illite/smectites in both G-1 and G-2 (e.g., G1-4998, G1-5339, G2-4090, and G2-4949). In addition, one sample examined (G2-5369) contained both discrete illite and randomly interstratified illite/smectite with about 80% expandable layers. It therefore appears that clay formation has continued since the waning of the Timber Mountain hydrothermal alteration event. An alternate but unlikely interpretation is that the low-illite illite/smectites could have been subjected to elevated temperatures, but the reaction to illite did not proceed due to a low K or Al supply. The occurrence of coexisting discrete illite and randomly interstratified illite/smectite does not support this alternate interpretation.

E. Applications to Predicting Repository-Induced Alteration

The effects of repository-induced heating on the properties of tuffs have been studied for some time because of the importance of predicting the long-term behavior of Yucca Mountain tuffs in a repository environment. These studies include research in the dehydration behavior of minerals in tuffs (Bish 1984, 1988) and on the hydrothermal stability of tuffs (Blacic et al. 1986; Duffy 1983a, 1983b). In a paper on the thermal constraints on radioactive waste isolation in zeolitic tuffs, Smyth (1982) concluded that the reaction of clinoptilolite to analcime would begin at about 105°C based on data summarized by Iijima (1975), thereby significantly reducing the cation sorptive capacity of the rocks. Smyth advised constraining the maximum temperature in zeolitized tuff to 85°C to prevent reaction. Smyth's conclusions were based on field observations. Laboratory research on the long-term effects of heating Yucca Mountain tuffs to relatively low temperatures (<250°C) has been hampered by the slow reaction kinetics at these temperatures, and laboratory experiments either have not reproduced the assemblages observed in Yucca Mountain (Duffy 1983a, 1983b) or only do so at higher temperatures that speed reactions (Knauss and Beiriger 1984).

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*Information provided by J. Aronson, Case Western Reserve University (1986).

A potentially effective way of circumventing the problems of slow kinetics in laboratory experiments is to use the alteration assemblages observed in Yucca Mountain, particularly in drill holes USW G-1 and G-2, as natural analogs to repository-induced thermal alterations. Because the temperatures at which reactions occur are affected by water composition (including the activity of water), this approach assumes that future water compositions will be approximately the same as those present during the alteration in Yucca Mountain 11 Myr ago. This may be a reasonable assumption, but conditions have probably changed significantly in the past 11 Myr. Present-day waters are likely much more dilute than those present during and shortly after zeolitization and clay mineral alteration. In addition, waters surrounding the repository environment may vary significantly in composition, particularly if they are concentrated by evaporation. However, for the alterations seen at Yucca Mountain, the clay mineralogy data suggest an upper temperature limit of 90° to 100°C for clinoptilolite, 100° to 130°C for mordenite, and 175° to 200°C for analcime. Coupling these data with models of the thermal profiles around a repository in tuff as a function of time (Johnstone et al. 1984) and mineral distribution data from Bish and Vaniman (1985) demonstrates that reaction of clinoptilolite to analcime should not occur in the thick, zeolitized tuff of Calico Hills underlying the candidate repository horizon. However, zeolite interval I, the first zeolite-bearing horizon below the candidate repository horizon (Bish et al. 1984a), may be significantly heated by the repository thermal pulse, and reactions among the zeolites and smectites may occur in this zone. The calculations of Johnstone et al. (1984) show that this interval will approach 90°C after about 1000 years. If the cristobalite and opal-CT in this interval react to form quartz and the aqueous silica concentration decreases, the clinoptilolite may then transform to analcime. However, there is a large amount of glass/opal-CT in interval I (Bish and Vaniman 1985) and this interval is in the unsaturated zone. Therefore, it is questionable whether the aqueous silica concentration will be controlled by quartz in the lifetime of a repository.

IV. SUMMARY AND CONCLUSIONS

These mineralogical data demonstrate that the rocks at depth in the northern end of Yucca Mountain have been significantly altered early in their history. The clay mineral reactions are similar to what has been observed in pelitic rocks, with close to 100% expandable randomly interstratified illite/smectites (R=0) transforming through ordered intermediates (R=1, R≥3) to illite with depth (increasing temperature) in USW G-2 and to Kalkberg (R≥3) interstratifications in USW G-1. The illite/smectites in USW G-3 have not significantly transformed with depth. It appears that sufficient K and Al existed in these rocks for the smectite-to-illite transformation to proceed.

It is obvious that the reactions seen with increasing depth are coupled and are not only dependent on the solution chemistry but on the chemistry of the altering phases. The contention of Kerrisk (1983) that the aqueous silica activity is the variable controlling the reaction of clinoptilolite to analcime is supported by data from USW G-2 and G-3 showing the approximately simultaneous disappearance of cristobalite and clinoptilolite. Clinoptilolite appears to have transformed to analcime at about 100°C in USW G-1 and G-2. However, analcime occurs in USW G-3 although mineralogic data suggest that temperatures did not reach 100°C. Thus there are indications that water chemistry may have exerted as great or greater an influence than temperature on the reaction of clinoptilolite to analcime in Yucca Mountain, in agreement with field observations elsewhere (Iijima 1975). The kinetics of the cristobalite-to-quartz reaction may have influenced the clinoptilolite-to-analcime reaction by controlling the aqueous silica concentration.

The reaction of clinoptilolite to analcime in USW G-2 also coincides with the appearance of significant amounts of calcite and minor amounts of chlorite and interstratified chlorite/smectite. The increase in calcite with depth is opposite to what is observed in pelitic rocks, probably reflecting the differences in mineral assemblages (Hower et al. 1976). It is likely that the breakdown of clinoptilolite provided the source of Mg for chlorite formation and the source of Ca for calcite formation, although the formation of one or both of these minerals may have been associated with the hydrothermal fluids circulating at the time of alteration. The clinoptilolite probably also provided the source for the K in the deeper illite/smectites, and the analcime and albite incorporated the Na from the clinoptilolite. The interstratified chlorite/smectites appear to be intermediate between shallower smectites and deeper chlorites, similar to what was observed by Inoue (1985).

Based on estimates from clay mineralogy and fluid inclusions, the rocks at depth in USW G-2 appear to have been subjected to temperatures of at least 275°C, those in G-1 have reached about 200°C, and the deepest G-3 rocks [about 305 m (1000 ft) shallower than G-1 and G-2] probably have not exceeded 100°C. These data can be used to apply limits to the temperature stability of several of the minerals in Yucca Mountain tuffs. Clinoptilolite became unstable at about 100°C, mordenite was not a major phase above 130°C, and analcime transformed to albite above 175° to 200°C. It also appears that cristobalite transformed to quartz at about 90° to 100°C in USW G-2 but must have reacted at considerably lower temperatures in USW G-3.

The vertical distribution of minerals across Yucca Mountain demonstrates that deep alteration is most profound to the north in USW G-2. USW G-1 core shows the effects of hydrothermal alteration, but at a greater depth and to a lesser extent than in USW G-2, and there is little evidence for significant elevated-temperature alteration in USW G-3. The mineralogy and clay chemistry from UE-25a#1, farther to the southeast along Drill Hole Wash, suggest that this drill core was also subjected to hydrothermal alteration (Caporuscio et al. 1982). Data suggest that the shallower Paintbrush Tuff Members (12-13 Myr) have not been significantly altered in any of the drill holes examined. The alteration mineralogy distribution and the age of illites in USW G-1 and G-2 (about 11 Myr) are consistent with Timber Mountain volcanism as the source of hydrothermal alteration. The widespread distribution of volcanic centers in the area suggests that alteration may have occurred before Timber Mountain volcanism (Paintbrush volcanism), perhaps culminating with Timber Mountain volcanism at about 11 Myr. It is noteworthy that the mineralogical data suggest that no hydrothermal alteration has occurred since the Timber Mountain event about 11 Myr ago.

Use of the rocks in USW G-1, G-2, and G-3 as natural analogs to alteration in a repository environment suggests that the bulk of the clinoptilolite- and mordenite-bearing rocks in Yucca Mountain will not react to less sorptive phases such as analcime and albite over the required life of the repository. However, zeolite interval I directly underlying the potential repository (Bish et al. 1984a) may transform at the temperatures predicted by thermal models (Johnstone et al. 1984). The reaction of clinoptilolite to analcime may require the transformation of the opal-CT and glass in this interval to quartz to lower the aqueous silica activity, a questionable scenario over the lifetime of a repository considering the abundance of opal-CT and glass and the unsaturated nature of the rocks at this depth.

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