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YUCCA MOUNTAIN

YUCCA MOUNTAIN PROJECT

TECHNICAL ASSESSMENT REVIEW REVIEW RECORD MEMORANDUM

GEOLOGIC AND GEOPHYSICAL EVIDENCE PERTAINING TO STRUCTURAL GEOLOGY IN THE VICINITY OF THE PROPOSED EXPLORATORY SHAFT

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UNITED STATES DEPARTMENT OF ENERGY
NEVADA OPERATIONS OFFICE/YUCCA MOUNTAIN PROJECT OFFICE

Yucca Mountain Project
Technical Assessment Review (TAR) Review Record Memorandum (RRM)

Geologic and Geophysical Evidence Pertaining to Structural Geology in the Vicinity of the Proposed Exploratory Shaft

Revision 0

TAR Notice: May 18, 1989
RRM issued: January 10, 1990

RRM Approval	Signature and Date
Richard C. Lee, Chairperson	Richard C. Lee 01/10/90
Michael W. Parsons, Secretary	Michael W. Parsons 1/10/90
David C. Dobson, Yucca Mountain Project Office Representative	David C. Dobson 1/10/90

TABLE OF CONTENTS

	Page
1 Introduction	1-1
1.1 Purpose	1-1
1.2 Scope	1-1
1.2.1 Geology Subcommittee	1-2
1.2.2 Geophysics Subcommittee	1-2
1.2.3 Engineering Subcommittee	1-2
1.3 Conduct of Technical Assessment Review	1-3
1.3.1 Controlling Procedure	1-3
1.3.2 Initiation of the TAR and TAR Plan	1-3
1.3.3 TAR Team Selection and Participants	1-3
1.3.4 TAR Package	1-4
1.3.5 Approach to Developing Comments, Conclusions, and Recommendations	1-4
1.3.6 Reference Verification	1-4
1.4 Records	1-4
1.4.1 QA-Related Records in the RRM	1-4
1.4.2 Other Records in the RRM	1-5
1.4.3 The RRM as a QA Record	1-5
2 Historical Perspective	2-1
2.1 Early Geophysical Studies in the Coyote Wash Area	2-1
2.2 Selection of Original Exploratory Shaft Location	2-1
2.3 Geological and Geophysical Work Undertaken to Address Recommendations of Bertram (1984)	2-9
2.4 Other Geologic and Geophysical Data Pertinent to Investigations of Coyote Wash	2-9
2.5 Faults Interpreted from Resistivity Data Shown in Open File Report 84-792	2-10
2.6 Decisions to Revise Shaft Locations	2-10
2.7 Conclusions and Recommendations	2-15
2.7.1 Site Selection Method Used by Bertram (1984)	2-15
2.7.2 Ability of the Project to Correlate Data	2-16
2.7.3 Documentation of Changes in Shaft Location	2-17
3 Summary of Geology Subcommittee	3-1
3.1 Methods Used in Previous Geologic Mapping of Coyote Wash Area	3-1
3.1.1 Lipman and McKay (1965) Mapping	3-1
3.1.2 Scott and Bonk Mapping	3-2
3.1.2.1 Preliminary Geologic Map of Yucca Mountain, Nye County, Nevada, with Geologic Sections, 1984, USGS Open File Report 84-494	3-2
3.1.2.2 ESF Potential Site Mapping (Dixon Letter Report, 7/16/82)	3-6
3.1.3 Barton, Page, and Morgan Mapping	3-6
3.2 Evaluation of Borehole Data	3-9
3.3 Review of Aerial Photography	3-13
3.3.1 Photo Set 1	3-13
3.3.2 Photo Set 2	3-14
3.4 Review of Field Relations	3-15
3.4.1 Background Data on the Field Review	3-15

TABLE OF CONTENTS (continued)

Page

3.4.2 Selection and Nature of Contacts 3-15
3.4.3 Surface Expression of Known Faulting 3-15
3.4.4 Evidence of Faulting in the Vicinity of the Exploratory Shafts 3-17
3.4.5 Evaluation of Fracture and Breccia Zones 3-18
3.5 Conclusions and Recommendations 3-20
3.5.1 Conclusions Concerning the Existing Mapping 3-20
3.5.2 Conclusions Concerning the Geologic Evidence For or Against a Fault in the Vicinity of the Exploratory Shaft 3-23
3.5.3 Recommendations on Future Geologic Investigations . . . 3-23
3.5.3.1 Recommendation 1 3-23
3.5.3.2 Recommendation 2 3-24

4 Summary of Geophysics Subcommittee 4-1
4.1 Introduction 4-1
4.2 Geophysical Data Applied to Exploratory Shaft Facility Location and Inferred Fault Evaluation 4-2
4.2.1 Original Surveys Interpreted by University of Utah Research Institute 4-2
4.2.1.1 Background 4-2
4.2.1.2 Data Acquisition 4-7
4.2.1.3 Data Reliability 4-9
4.2.1.4 Data Position Reliability 4-10
4.2.1.5 Topographic and Surface Effects 4-12
4.2.2 Other Surveys and Data Pertinent to Geoelectric Analysis 4-13
4.3 Geoelectric Model 4-16
4.3.1 Models of Smith and Ross (1982) for Lines A, B, and B' . 4-16
4.3.1.1 Data Parameters 4-16
4.3.1.2 Modeling Method 4-17
4.3.1.3 Characteristics of Models 4-20
4.3.2 Model Relationships to Other Geoelectric Data 4-25
4.3.2.1 Sources of Independent Data 4-25
4.3.2.2 Lithological Relationships 4-25
4.3.2.3 Structural Relationships 4-26
4.3.3 General Discussion of Misfit, Uniqueness, Resolution, and Sensitivity 4-27
4.3.3.1 Misfit 4-27
4.3.3.2 Resolution, Uniqueness, and Sensitivity 4-31
4.3.4 Other Models That May Satisfy the Data 4-34
4.3.5 Summary 4-34
4.4 Technical Issues Identified as a Result of Reviewing Interpretations of Resistivity Profiles (Open File Report 82-182) 4-39
4.4.1 Introduction 4-39
4.4.2 Technical Issues Related to Specific Discussion by Smith and Ross (1982) 4-39

TABLE OF CONTENTS (continued)

Page

4.4.3 Identification of Other Uncertainties (Including Alternative Explanations) Related to Interpreting the Resistivity Data 4-40
4.4.4 Correlation of Technical Issues with Modeling Uncertainty 4-41
4.4.5 Summary of Technical Issues 4-41
4.5 Sensitivity Analyses for Geoelectric Modeling 4-41
4.5.1 Two-Dimensional Effects 4-42
4.5.1.1 Basis Model for Sensitivity Tests 4-42
4.5.1.2 Analysis of Sensitivity to a Resistivity Anomaly 4-45
4.5.1.3 Summary of 2-D Sensitivity Studies 4-55
4.5.2 Three-Dimensional Effects 4-57
4.5.2.1 Finite Element Code, Basic 3-D Mesh, and Test Cases 4-58
4.5.2.2 Three-Dimensional Terrain Effects 4-64
4.5.2.3 Three-Dimensional Near-Surface Resistivity Structure 4-66
4.5.3 Summary of Two-Dimensional and Three-Dimensional Sensitivity Studies 4-72
4.6 Geologic Interpretation 4-73
4.6.1 Geologic Interpretation of Geophysical Data Made by Smith and Ross (1982) 4-73
4.6.2 Relationship of Smith and Ross (1982) Interpretations to Known Geology 4-74
4.6.3 Petrophysical Relationships 4-76
4.6.3.1 Resistivity Data from Various Sources 4-76
4.6.3.2 Evidence for Alteration at Coyote Wash 4-78
4.6.3.3 Electrolytic Conduction vs. Surface Effects . . 4-80
4.6.3.4 Induced Polarization Response of Near-Surface Units at Coyote Wash 4-82
4.6.3.5 Other Geophysical Properties 4-84
4.6.4 Summary Discussion of Geologic Interpretation 4-85
4.7 Conclusions and Recommendations 4-87
4.7.1 Applicability of the Smith and Ross (1982) Interpretation to the Suitability of the ESF Location 4-87
4.7.2 Recommended Geophysical Program 4-89

5 Summary of Engineering Subcommittee - Performance Evaluation 5-1
5.1 Impact of Possible Faulting and/or Zone of Higher Saturation on Shaft Performance 5-2
5.1.1 Impact of Faulting on Ground-Water Flow 5-2
5.1.1.1 Brief Description of Unsaturated Zone Flow . . 5-2
5.1.1.2 Consideration of Flow Diversion into the Exploratory Shafts 5-3
5.1.1.2.1 Water Concentration Caused by Infiltration Pulses 5-3
5.1.1.2.1.1 Summary of Effects Caused by Infiltration Pulses 5-5

TABLE OF CONTENTS (continued)

Page

5.1.1.2.2 Water Concentration Caused by Lateral Diversion 5-5
5.1.1.2.2.1 Summary of Effects Caused by Lateral Diversion 5-6
5.1.2 Impact of Faulting on Gaseous Movements in the Exploratory Shaft 5-6
5.2 Summary and Conclusions 5-7

6 Summary of Engineering Subcommittee - Construction-Related Implications 6-1
6.1 Faults and Their Effect on Shaft Construction 6-1
6.1.1 Faults 6-1
6.1.2 Worker Safety 6-13
6.1.3 Fault Movement 6-13
6.1.4 Specific Shaft Locations 6-13
6.1.5 Shaft Pillar 6-14
6.1.6 Seals 6-14
6.1.7 Shaft Sinking Through an Anomalous Zone 6-14
6.2 Conclusions and Recommendations 6-15

7 General Summary and Recommendations 7-1
7.1 General Conclusions on the Possibility of a Fault in the Vicinity of the Exploratory Shaft 7-1
7.2 Recommendations on Additional Measures to Increase Project Confidence on Anticipated Rock Properties Prior to Exploratory Shaft Construction 7-3
7.3 Recommendations on Mitigating Actions for Uncertain or Poor Rock Properties Discovered in the Course of Exploratory Shaft Excavation 7-4
7.4 Adequacy of the Implementation of the Bertram (1984) Recommendations on the Original Exploratory Shaft Location 7-5
7.5 Procedures for Geological and Geophysical Investigations as a Result of the 1987 Exploratory Shaft Relocation 7-6
7.6 Project Integration of Technical Data and Interpretations . . . 7-6

References R-1

Appendix A QMP-02-08 with ICN Number 1 . . . . . A-1

Appendix B TAR Notice and Plan B-1
B.1 TAR Notice
B.2 TAR Plan
B.3 Project Office QMP-06-03 Review Comments on Draft TAR Plan

TABLE OF CONTENTS (continued)

		Page
Appendix C	QA Related Records	C-1
	C.1 TAR Team Selection Record (N-QA-008)	
	C.2 Employer Certification of TAR Team Member Qualifications	
	C.3 QMP-02-08, ICN Number 1, and TAR Plan Training Documentation	
	C.4 Questionnaire for Documenting Independence of TAR Team Members	
Appendix D	Meeting Minutes	D-1
Appendix E	TAR Reference List (TAR Data Package List)	E-1
Appendix F	Correspondence Related to TAR	F-1
Appendix G	TAR Comment Forms	G-1
Appendix H	List of Reviewers by Name, Organization, and Discipline . .	H-1
Appendix I	Supporting Documentation for the TAR	I-1
	I.1 Computer Code Verification and Validation	
	I.2 Results of Verification and Validation Activities, and Listing of Pertinent Files	
Appendix J	TAR Team Member Concurrence Sheets	J-1

LIST OF FIGURES

Figure		Page
2-1	Inferred faults in the Coyote Wash area as interpreted by Smith and Ross (1982)	2-6
2-2	Location of faults shown by Scott and Bonk (1984) and siting area and shaft locations recommended by Bertram (1984)	2-8
2-3	Faults interpreted from resistivity data by Hoover, mapped faults shown by Lipman and McKay (1985), locations of resistivity lines	2-11
2-4	Faults interpreted from electrical resistivity data as shown on Figure 32 of USGS Open File Report 84-792 and in SCP Figure 1-40	2-12
2-5	Location of shaft siting area and shaft locations recommended by Bertram (1984) and revised shaft locations recommended by Cross (1986)	2-14
3-1	Geology of the Coyote Wash area as shown on the map of Lipman and McKay (1965)	3-3
3-2	Geology of the Coyote Wash area as shown on the map of Scott and Bonk (1984)	3-5
3-3	Geology of the Coyote Wash area as shown on the map of Scott and Bonk in Dixon (1982)	3-7
3-4	Geology of the Coyote Wash area as shown on the map of Barton et al. (1989)	3-8
3-5	Cross section through boreholes USW G-4, UE25a-6, and UE25a-7 showing the correlation of lithologic zones recorded on the core logs	3-10
3-6	Section along direction of dip calculated for the top of the quartz latite caprock zone in the Topopah Spring Member using data from boreholes USW G-4, UE25a-6, UE25a-5	3-12
3-7	Photographs of the upper lithophysal zone and rounded step zone of the Tiva Canyon Member	3-16
3-8	Photographs of breccia zones found on the south-facing slopes of Dead Yucca Ridge between the Ghost Dance fault and ES-1	3-19
3-9	Photographs of cooling joints in a pavement found on the crest of Dead Yucca Ridge near the Ghost Dance fault	3-21

LIST OF FIGURES (continued)

Figure		Page
3-10	Photograph of pocket or hole formed at the intersection of two fractures in a cleared pavement found on the crest of Dead Yucca Ridge near the Ghost Dance fault	3-22
4-1	Map showing electrical surveys conducted in the vicinity of Drill Hole and Coyote Wash	4-4
4-2	Same as Figure 4-1 except fault map taken from Lipman and McKay (1965)	4-5
4-3	Map showing location of faults inferred from dipole-dipole geoelectric data and location of dipole-dipole lines	4-6
4-4	Map showing the location of dipole-dipole lines and electrode locations in relationship to topography for the vicinity of Drill Hole Wash and Coyote Wash	4-8
4-5	Selected data from Smith and Ross (1982) for Line A plotted as dipole-dipole "soundings"	4-11
4-6	Observed apparent resistivity pseudo-sections for the west section of Lines A and B (200-ft dipoles)	4-22
4-7	Simplified representation of the resistivity models of Smith and Ross (1982) for the west sections of Lines A, B, and B′.	4-24
4-8	Dipole-dipole resistivity data for Line A	4-28
4-9	Dipole-dipole resistivity data for Line B	4-29
4-10	Dipole-dipole resistivity data for Line B′	4-30
4-11	Modification of the Smith and Ross (1982) model for Line A .	4-35
4-12	Modification of the Smith and Ross (1982) model for Line B .	4-36
4-13	Simplified geoelectric model of Smith and Ross (1982) . . .	4-43
4-14	Comparison between the 3-D terrain corrected data for Line A and the computed apparent resistivity	4-44
4-15	Basis model for 2-D sensitivity studies of Line A	4-46
4-16	Schematic of systematic perturbations to the basis model A1 for 2-D sensitivity studies	4-47
4-17(a)	Comparison between the 3-D terrain-corrected data for Line A and the computed apparent resistivity for sensitivity test model A1	4-48

LIST OF FIGURES (continued)

Figure		Page
4-17(b)	Comparison between the 3-D terrain-corrected data for Line A and the computed apparent resistivity for sensitivity test model E2	4-49
4-17(c)	Comparison between the 3-D terrain-corrected data for Line A and the computed apparent resistivity for sensitivity test model A2	4-50
4-17(d)	Comparison between the 3-D terrain-corrected data for Line A and the computed apparent resistivity for sensitivity test model D2	4-51
4-17(e)	Comparison between the 3-D terrain-corrected data for Line A and the computed apparent resistivity for sensitivity test model B2	4-52
4-17(f)	Comparison between the 3-D terrain-corrected data for Line A and the computed apparent resistivity for sensitivity test model C2	4-53
4-18	Histograms of misfit between selected sensitivity test models and 3-D terrain-corrected data, for a portion of Line A corresponding to the area of interest	4-54
4-19	Plots of misfit between selected sensitivity test models and 3-D terrain-corrected data vs. along-line position for a portion of Line A corresponding to the area of interest	4-56
4-20	Schematic of 3-D finite element mesh used in sensitivity calculations	4-59
4-21	Map showing relationship of the 3-D finite element mesh used to calculate terrain effects, to the terrain of Coyote Wash and vicinity	4-60
4-22	Comparison of a pseudosection calculated by Dey and Morrison (1979) for a representative 3-D problem	4-62
4-23	Comparison of (a) a pseudosection calculated for a 2-D terrain problem by Rijo (1977), and (b) a 3-D simulation of the same problem performed for this review	4-63
4-24	Terrain effect calculated for Line A of Smith and Ross (1982)	4-65
4-25	Strike-length sensitivity study for a shallow conducting body	4-68
4-26	Sensitivity study of the effect from a shallow off-axis surface conductor	4-69

LIST OF FIGURES (continued)

Figure		Page
4-27	Sensitivity study of the effect of a buried conductor . . .	4-71
4-28	Map view of recommended locations for additional dipole-dipole, slingram, and shallow seismic refraction survey lines	4-91
6-1	Faults/joint interaction	6-11
6-2	Vertical persistence of fault in shaft	6-12

LIST OF TABLES

Table		Page
2-1	Chronology of events for exploratory shaft site selection process	2-2
3-1	Stratigraphic column for rocks present in the Coyote Wash area	3-4
4-1	Rules of thumb for resolution of a target of thickness T below a flat earth	4-32
4-2	Causes of uncertainty in geoelectric modeling	4-33
6-1	Construction methods and recommended temporary ground support	6-2
	Sheet 1 - Good conditions	6-2
	Sheet 2 - Fair to poor conditions	6-3
	Sheet 3 - Very poor to extremely poor conditions	6-5
	Sheet 4 - Definition of fault classes	6-6
	Sheet 5 - Supplementary data	6-9

Chapter 1

INTRODUCTION

The initiation of this Technical Assessment Review (TAR) was motivated by informal questions to the U.S. Department of Energy (DOE) from the U.S. Nuclear Regulatory Commission (NRC) on geophysically inferred faults in the vicinity of the Exploratory Shaft Facility (ESF). The inferred fault in question was interpreted from dipole-dipole resistivity surveys conducted along Coyote Wash (reported in U.S. Geological Survey (USGS) Open File Report 82-182). Another interpretation of this survey is illustrated in Figure 1-40 of the DOE Yucca Mountain Project (Project) Site Characterization Plan (SCP). The questions were raised out of concern that the possible fault was not properly referenced in the exploratory shaft (ES) site location documents and may not have been fully considered in ESF Title I design.

1.1 PURPOSE

As outlined in the TAR Plan (see Appendix B.2), there are five principal purposes for this review: (1) assess the data and interpretations associated with SCP Figure 1-40 and USGS Open File Report 82-182 (Smith and Ross, 1982) related to the inferred fault in the vicinity of the ESF; (2) review other geological and geophysical data that may bear on faulting in the vicinity of the ESF; (3) make a determination on the possible interpretations of faulting in the vicinity of the ESF; (4) determine how the geological and geophysical data were considered in making the ESF location determination, and, more specifically, whether the geological and geophysical site selection recommendations of the Bertram (1984) report were adequately implemented; and (5) if it was concluded that a fault may exist in the vicinity of the ESF, evaluate the impacts on the ESF Title II design process.

1.2 SCOPE

The scope of the TAR included, but was not limited to: (1) developing a historical perspective of the development of the geological and geophysical model for Coyote Wash by reviewing Project files that pertain to this subject and compiling a chronological summary; (2) summarizing the past geological and geophysical work in that vicinity, the rationale for the work, the limitations of the data, and exploring the possible interpretations of the data; (3) developing findings on the presence of a fault near the proposed ESF, on whether the available data were adequately considered in the process of selecting the ESF location, and on whether there is an impact on Title II design if a finding is made that a fault may exist near the ESF; and (4) make recommendations for further studies or action. This rather broad technical scope was achieved by developing three subcommittees: (1) a geology subcommittee to review the geologic evidence for faulting in the Coyote Wash area, as well as the history of the site selection process; (2) a geophysics subcommittee to review USGS Open File Report 82-182 and other geophysical evidence bearing on faulting near Coyote Wash; and (3) an engineering

subcommittee to evaluate what impact any fault in the vicinity of the ESF may have on facility safety, constructability, or waste isolation performance.

1.2.1 GEOLOGY SUBCOMMITTEE

In addition to the scope described above, the geology team undertook a field reconnaissance effort to review the results of the mapping done in the vicinity of Coyote Wash. This exercise included the evaluation of exposed stratigraphic contacts along the south side of Dead Yucca Ridge, for the purposes of reviewing previous mapping conducted along that ridge, and to specifically estimate the resolution of the method for determining vertical offsets that might be present. In addition, the subcommittee reviewed the available air photos of the Coyote Wash area.

1.2.2 GEOPHYSICS SUBCOMMITTEE

Additional tasks undertaken by the geophysics subcommittee included an explicit evaluation of some of the resistivity modeling assumptions made by Smith and Ross (1982). A more generalized computer model (a three-dimensional structure versus a two-dimensional) was used to test the influence of site topography on their resistivity model and interpretation. An evaluation was made of other resistivity models that may satisfy the data equally as well, including models constrained by more recently collected geological and geophysical data. There were two computer codes used by the committee for these tasks. It was determined that QA procedures for code verification and implementation were not required because these codes were used to verify the assumptions and validity of the Smith and Ross work and to determine whether additional analyses would be needed to evaluate these geophysical data. However, procedures were followed to provide reasonable assurances of proper computer code development and operation. These procedures are described in Appendix I.

1.2.3 ENGINEERING SUBCOMMITTEE

The engineering team was initially tasked to evaluate the impact, if any, that faulting in the Coyote Wash area may have on safety, constructability, and repository waste isolation. It became apparent at the onset of the review that the possibility of relatively small offset faults could exist in the vicinity of the ESF, and in fact throughout the repository block given current information (and remain undetected), or could intersect the shaft at depth. For this reason, and for TAR schedule purposes, it was decided that the engineering subcommittee should characterize a suite of faults that could conceivably intersect the ESF, and evaluate what contingencies would be required for the safety, constructability, and performance issues that might occur. This considerably larger scope would also provide guidance to the TAR team on the nature and magnitude of geological structures that should be considered in Title II design.

1.3 CONDUCT OF TECHNICAL ASSESSMENT REVIEW

1.3.1 CONTROLLING PROCEDURE

Following Project Office direction at the onset of the TAR, the TAR was conducted under Quality Management Procedure (QMP)-02-08, Rev. 0 of August 8, 1988, subject to Interim Change Notice Number (ICN) 1 of February 7, 1989 (see Appendix B.1).

1.3.2 INITIATION OF THE TAR AND TAR PLAN

Under the QMP-02-08 responsibilities, the designated Project Office Branch Chief or designee is responsible for developing the TAR Notice and Plan, and selecting the TAR Chairperson. The TAR Chairperson is responsible for determining the technical disciplines and qualifications of personnel required for the Plan. The Project Office submitted a preliminary TAR Notice with attached Plan and schedule for Project Quality Manager (PQM) review and approval on April 19, 1989. That review was conducted under QMP-06-03 (Document Review/ Acceptance/Approval) and was completed by the Project office on May 16, 1989; that review is contained in Appendix B.3 of this Review Record Memorandum (RRM). The conclusion was reached that the optional technical adequacy review, specified in QMP-02-08, was not required by the responsible Branch Chief, D. C. Dobson. The TAR Notice and attachments (Plan) were signed by the PQM on May 18,1989. R. C. Lee was the designated TAR Chairperson.

1.3.3 TAR TEAM SELECTION AND PARTICIPANTS

The TAR Secretary was designated to be J. M. Davenport, and because of additional Project commitments, his Secretarial duties were subsequently given to M. W. Parsons during the week of July 10, 1989.

The technical disciplines required for the TAR were determined to be the geosciences (geology and geophysics) and engineering (geotechnical, mining, performance assessment). Minimum qualifications necessary for the review of these disciplines were determined to be advanced degrees in the technical area of expertise, and/or applicable work experience in similar technical areas. A listing of the TAR team members and their function on the TAR are contained in the TAR Team Selection Record (Appendix C.1). Documentation of review team members' qualifications were obtained from each of their employers, except for one team member (an independent consultant) whose qualifications were reviewed by the Project Office. The employee qualification documentation is contained in Appendix C.2. As discussed above, it was determined that the review could be best accomplished by three subcommittees. The subcommittee leaders were T. A. Grant, E. L. Hardin, and T. E. Hinkebein for geology, geophysics, and engineering, respectively. QA support was provided by F. D. Peters. Team members were selected from the Project Office; DOE Headquarters (DOE/HQ); the USGS; Sandia National

Laboratories (SNL); and Parsons, Brinckerhoff, Quade, and Douglas, Inc. (PBQ&D).

The review team members were trained on QMP-02-08, the TAR Notice, and Plan; this training was documented by the Special Training Assignment under QMP-02-09. The documentation is contained in Appendix C.3.

Documentation of review team member independence was accomplished by questionnaire. This questionnaire queried the team members' Project experience in subject areas of geological and geophysical interpretations, technical and/or policy reviews, or committees that reviewed reports that would bear on the geological structure in the vicinity of the ESF. These questionnaires are contained in Appendix C.4.

1.3.4 TAR PACKAGE

The initial TAR Package was assembled and distributed with the training materials when individuals were inducted into the TAR. Over the course of the TAR, additional material was added to the Package. Appendix E contains the list of TAR Package materials.

1.3.5 APPROACH TO DEVELOPING COMMENTS, CONCLUSIONS, AND RECOMMENDATIONS

Each of the three subcommittees developed its respective QMP-02-08 comments in a similar fashion: the subcommittee leader developed a list of recommendations that reflected the team's findings, and the subcommittee leader signed the comment forms. Each subcommittee member's general concurrence with the subcommittee leaders comments is indicated on the individual TAR team members 02-08 comments.

1.3.6 REFERENCE VERIFICATION

The TAR team was directed by the Project Office to verify all references used in the conduct of the TAR. This verification documentation is contained in the Project QA record containing the TAR Data Package.

1.4 RECORDS

1.4.1 QA-RELATED RECORDS IN THE RRM

The following QA records are contained in Appendices B and C.

- TAR Notice and attachments.
- TAR Team Selection Record.
- TAR team member's qualifications certification.

- Questionnaires documenting TAR team member independence.
- Records of team member training.

The TAR QMP-02-08 comment forms are contained in Appendix G.

1.4.2 OTHER RECORDS IN THE RRM

- TAR meeting minutes (Appendix D).
- Computer Code Verification and Validation documentation (Appendix I).
- Final TAR Package (Appendix E).

1.4.3 THE RRM AS A QA RECORD

In accordance with QMP-02-08, a QA record has been compiled (the TAR Data Package). This package is composed of the RRM, the TAR Package, and any supplements that may be required, including disposition of the TAR Comments.

Chapter 2

HISTORICAL PERSPECTIVE

This section gives a brief overview of how geological and geophysical information was used in the selection of sites for the exploratory shafts (ESs). Table 2-1 gives a chronology and summary of the events involved in the site selection process and the geophysical survey by Smith and Ross (1982). The information in this section was compiled by T. A. Grant and J. M. Davenport of the TAR team using published reports, file material, and personal communications with R. W. Spengler and G. L. Dixon of the U.S. Geological Survey (USGS).

2.1 EARLY GEOPHYSICAL STUDIES IN THE COYOTE WASH AREA

In 1978, a slingram survey of the Yucca Mountain area indicated a conductive zone underlying Drill Hole Wash (Flanigan, 1981). This zone was inferred to be a possible zone of significant faulting and fracturing based on comparison of the survey results over known faults (Smith and Ross, 1982). Because of the possibility of a significant fault in the repository block, additional studies were performed to evaluate the structure under Drill Hole Wash in 1979. The resistivity and induced polarization study of Smith and Ross (1982) was one of these studies. The Smith and Ross report inferred from resistivity contrasts that faulting may have dropped the area of Drill Hole Wash with respect to the ridges on either side (Spengler and Rosenbaum, 1980). In order to test this interpretation, a series of drillholes (UE25a-4, -5, -6, -7) was completed in 1979 and 1980 in the area of Drill Hole Wash (Spengler and Rosenbaum, 1980). The results from these drillholes showed no evidence of vertical offsets, but Spengler and Rosenbaum (1980) inferred possible strike-slip movement on the basis of paleomagnetic and foliation trends. Other studies, such as the mapping by Scott and Bonk (1984), were completed during the 1979 to 1982 period and were also used to evaluate the Drill Hole Wash area. Scott et al. (1984) reviewed all of the available data and concluded that Drill Hole Wash and other washes to the northeast were probably underlain by right-lateral strike-slip faults.

In addition to the fault/fracture zone inferred in Drill Hole Wash, Smith and Ross (1982) also inferred the presence of a minor normal fault in Coyote Wash (Figure 2-1). This inferred fault was located about 1,300 ft east of Ghost Dance fault and was inferred to be downthrown to the east.

2.2 SELECTION OF ORIGINAL EXPLORATORY SHAFT LOCATION

In March, 1982, a working group was organized by the Project to evaluate ES construction methods and to conduct a screening of potential ES sites. Procedures were developed by the working group and approved on April 28, 1982 (Bertram, 1984). At this time, the working group became the Ad Hoc Technical Overview Contractor (TOC) Committee at the request of the NNWSI Project Technical Integration Group (TIG). A draft report on the ES selection was completed by the committee on June 7, 1982.

Table 2-1. Chronology of Events for Exploratory Shaft Site Selection Process

Date	Event	Source
-/-/78	A slingram survey locates a conductive zone under Drill Hole Wash which was inferred to represent a zone of fracturing and faulting.	USGS OFR 82-182 Introduction
6/19/79	Purchase order to University of Utah Research Institute (UURI) (Smith and Ross) to provide resistivity/IP interpretation of several lines to be taken at Yucca Mtn. Purpose of the surveys was to investigate the possible zone of faulting in Drill Hole Wash.	USGS OFR 82-182 p. 2, Introduction
6/26/79	Drilling starts on boreholes UE25a-4, -5, -6, -7 in Drill Hole Wash area. One purpose of the drilling was to investigate the IP results of UURI that indicated that faulting may have dropped the area of Drill Hole Wash with respect to the ridges on either side, and that the faulting may extend to depths greater than 1,500 ft.	SCP, p. 1-222 USGS OFR 80-929, p. 2
8/6/79	Interim interpretation of resistivity data submitted to USGS by UURI.	USGS OFR 82-182, pp. 2, A-1
9/13/79	Tests of alternate resistivity models submitted to USGS by UURI.	USGS OFR 82-182, pp. 2, B-1
10/-/79	UURI submits text of report that will become USGS OFR 82-182 to USGS.	USGS OFR 82-182, Title page
10/5/80	Drilling completed on boreholes UE25a-4, -5, -6, -7.	SCP, p. 1-222
-/-/80	USGS releases Open File Report 80-929 on results of UE25a-4, -5, -6, -7. Results indicate that large vertical displacements not present, but that minor strike-slip faulting could be present in Drill Hole Wash.	USGS OFR 80-929, p. 31 Telephone call Grant to Spengler, 3/2/89
3/29/82	Working Group first established to develop procedures for evaluating construction methods and screening ESF sites.	SAND84-1003, p. 10
4/2/82	USGS releases USGS OFR 82-182 on interpretation of resistivity and IP profiles.	Telephone call Grant to Glanzman, 3/2/89

Table 2-1. Chronology of Events for Exploratory Shaft Site Selection Process (continued)

Date	Event	Source
4/21/82	Memo from Working Group chairman (Bertram) to TIG members describing proposed procedures for selecting ESF site.	Memo dated 4/21/82
4/28/82	Procedures developed by Working Group approved and Working Group becomes the Ad Hoc TOC Committee at the request of the TIG. Members of Ad Hoc TOC Committee are: S. G. Bertram (SNL), A. E. Stephenson (SNL), C. W. Myers (LANL), D. C. Nelson (LANL), T. J. Merson (LANL), J. Robison (USGS), R. Spengler (USGS), L. W. Scully (SNL), J. A. Milloy (SNL), S. Francis (LANL), J. N. Fiore (DOE).	SAND84-1003, pp. 10, ii
4/28/82-6/7/82	Ad Hoc TOC Committee prepares site selection study. Spengler (USGS geology rep. on committee) reports that a preliminary version of the Scott and Bonk map was used to define areas that were screened out due to faulting. Spengler was aware of the IP survey (OFR 82-182), but the Scott and Bonk mapping was considered more reliable because of concern that topographic effects could have significantly affected the results of the IP survey and because of the results of the UE25a boreholes. Therefore, the Scott and Bonk mapping superseded the results of OFR 82-182 in the site selection study. The faults shown in OFR 82-182 were not considered a major factor at that time because the shaft location that the committee selected was further upstream than the present sites and farther away from the faults interpreted from the IP survey. Also, one of the considerations in the site selection was to select a location where it was possible to drift over to the imbricate fault zones and the potentially fractured or faulted area in Drill Hole Wash for study.	Telephone call Grant to Spengler 3/2/89
6/1/82	Due date for Ad Hoc TOC Committee to recommend preferred ESF site(s) to the TIG.	SAND84-1003, p. 10
6/7/82	Report on "Ad Hoc Committee Determination of the Site for the NNWSI Exploratory Shaft" completed and distributed to TIG members.	NVO-326, p. 51

Table 2-1. Chronology of Events for Exploratory Shaft Site Selection Process (continued)

Date	Event	Source
6/14-15/82	TIG Meeting. Ad Hoc TOC Committee presents recommendation to TIG of Coyote Wash (Site 4) as ESF location. The TIG approved the selection of Coyote Wash, but requested that the recommendations about additional USGS geological and geophysical work that appear on page 91 of SAND84-1003 be added to the Ad Hoc TOC Committee report.	NVO-326, pp. 51-56
6/25/82	Recommendation of Coyote Wash as ESF location by TIG transmitted to DOE/NV and Project Office along with Ad Hoc TOC Committee report and recommendations for additional USGS geological and geophysical work.	NVO-326, p. 55
7/16/82	Letter from G. L. Dixon (USGS) to Vieth discussing detailed geologic mapping of five sites recommended by Ad Hoc TOC Committee.	Letter dated 7/16/82
8/2/82	Briefing for DOE/HQ on ESF location selection process and selection of Coyote Wash.	NVO-326, p. 56
8/11/82	DOE/HQ concurs with selection of Coyote Wash as location of principal borehole and ESF.	NVO-326, p. 56
8/22/82	Start drilling borehole USW G-4 at location selected by Ad Hoc TOC Committee. Purpose of hole was to study geologic and geophysical features of the ESF site.	USGS OFR 84-789, pp. 3, 7
1/12/83	Complete drilling and testing at borehole USW G-4. Concentrations of fractures with evidence of possible fault movement noted at seven intervals in core.	USGS OFR 84-789, pp. 7, 40
8/-/84	SNL releases SAND84-1003 on NNWSI Exploratory Shaft Site Recommendation.	SAND84-1003, Title page
-/-/84	USGS releases OFR 84-567. This report synthesizes the geological and geophysical evidence of structures in the northwest-trending washes. This report explicitly considers the results of OFR 82-182 in its analysis.	USGS OFR 84-567, p. 13

Table 2-1. Chronology of Events for Exploratory Shaft Site Selection Process (continued)

Date	Event	Source
8/27-28/85	NRC expresses concern over shaft locations with respect to flooding, erosion, and flow of water around the area of the shaft liners.	Action Memo, Vieth to Kale, 11/29/86
7/29/86	F&S proposes new locations out of drainage and in competent rock.	Letter, Cross to Vieth, 7/29/86
11/29/86	Project Office proposes change in shaft location to DOE/HQ to address NRC concerns.	Action Memo, Vieth to Kale, 11/29/89
2/-/87	Background paper prepared discussing changes in ES location.	
4/14-15/87	Meeting with NRC and State to discuss changes in ES location.	

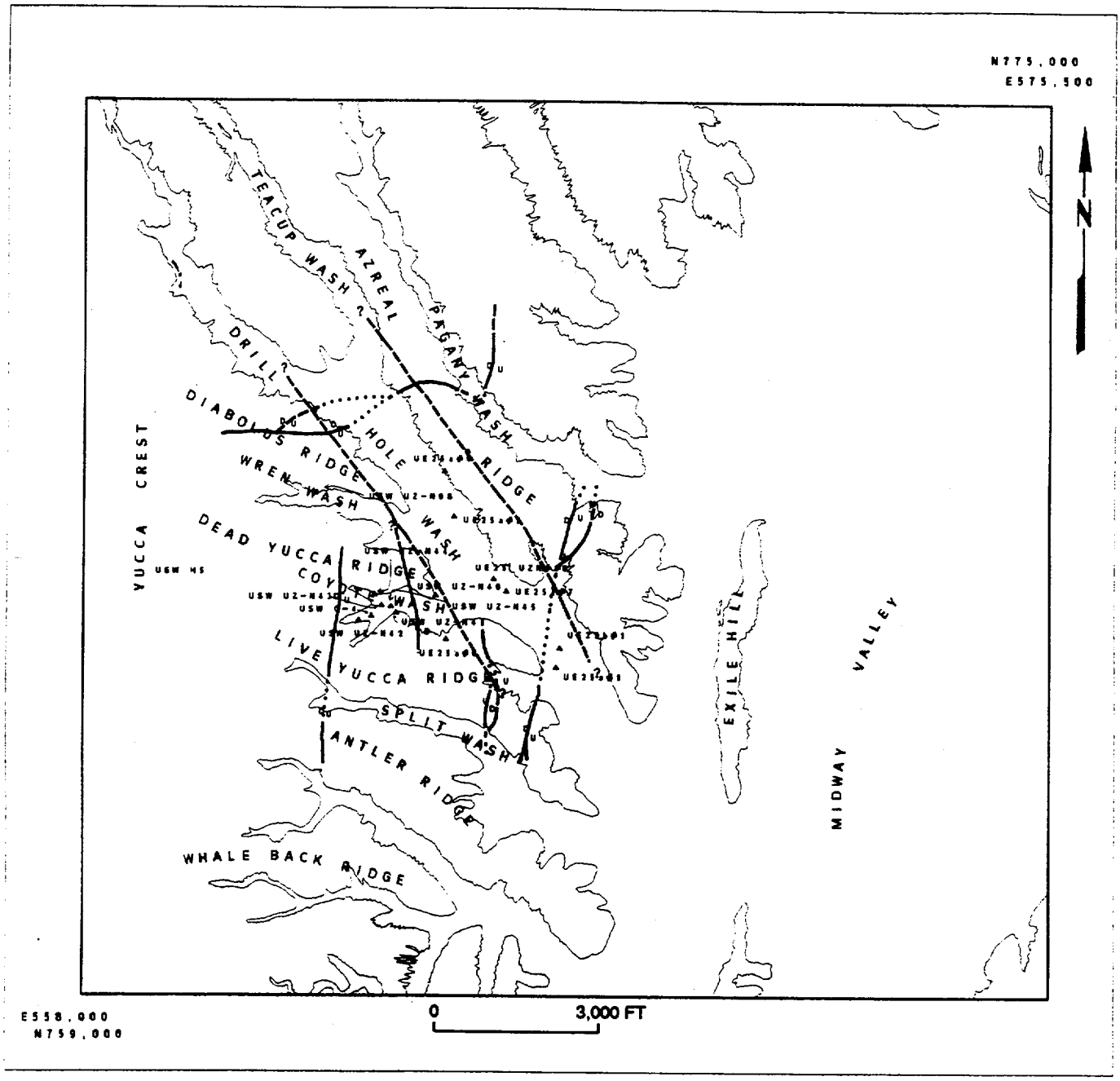


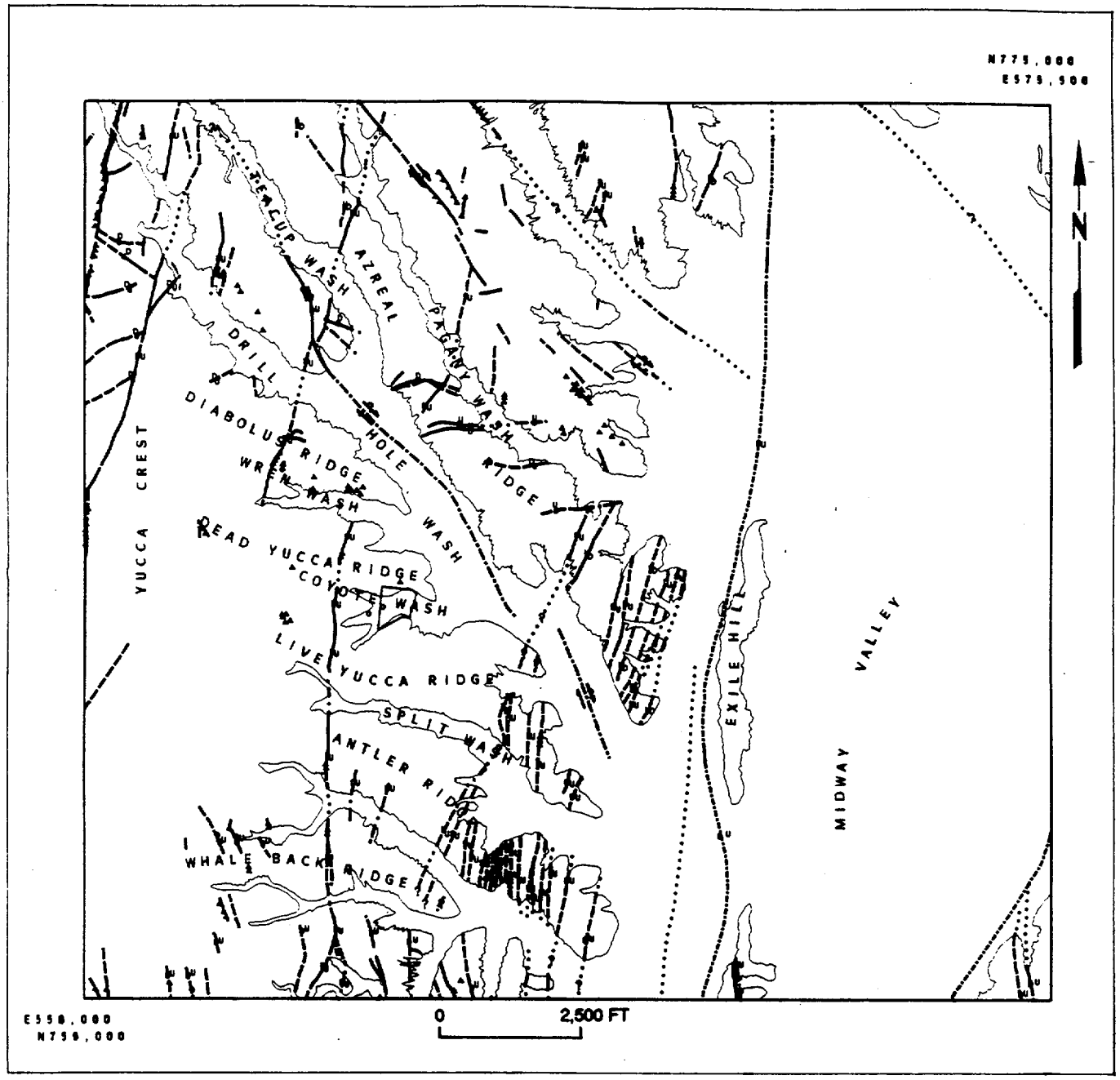
Figure 2-1. Inferred faults in the Coyote Wash area as interpreted by Smith and Ross (1982).

Because of the uncertainty at that time about structures in Drill Hole Wash, the Ad Hoc TOC Committee generated a selection criterion that established a set-back distance of 1,000 ft from Drill Hole Wash. The set-back was established to account for the possibility of bedrock fractures extending westward from Drill Hole Wash. In selecting the shaft location, it was desired that the shaft be far enough away from Drill Hole Wash (>1,000 ft) that the shaft and drifts would have a low likelihood of encountering fractures associated with the repository block bounding structure. At the same time, it was considered desirable to be within a distance (<2,000 ft) that was feasible for horizontal drilling from the ES to intersect the Drill Hole Wash structures (Stephenson, 1982). A similar criterion was generated for other "potentially adverse structures" where it was considered desirable to be within 1,000 to 2,000 ft of these structures. Sites having subsurface facilities closer than 100 ft to a potentially adverse structure were to be excluded (Stephenson, 1982).

A map identifying potentially adverse structures was prepared using a preliminary version of the Scott and Bonk (1984) map as a source (Spengler, oral communication). The only potentially adverse structure identified on this map in the Coyote Wash area was the Ghost Dance fault (Figure 2-2). One committee member was aware of the report by Smith and Ross, but was of the opinion that the Scott and Bonk mapping was more reliable because of concern that topographic effects may have affected the resistivity/IP survey and that the interpretation of Smith and Ross was not confirmed by the drilling program in Drill Hole Wash (Spengler, oral communication). Also, the main concern at the time was to identify significant throughgoing structures; apparently minor features, such as the fault inferred by Smith and Ross (1982) in Coyote Wash, were not considered in shaft selection because they had no mapped extent (Dixon, oral communication). Therefore, the faults shown in the Smith and Ross (1982) report in Coyote Wash were not considered to be potentially adverse structures.

Five preferred site areas for the exploratory shaft location were identified by the Ad Hoc TOC Committee largely on the basis of the location of potentially adverse structures and topography (Bertram, 1984). The area in Coyote Wash was evaluated as having the highest ranking of the five site areas; thus it was the unanimous recommendation of the committee that the shaft be located on the western side of the Coyote Wash area at 766000N and 563300E (Figure 2-2) (Bertram, 1984). The committee recognized the potential need for minor relocation resulting from architectural/engineering design considerations, but advised caution in making such changes because of the small size of the preferred area (Bertram, 1984). The recommendation of Coyote Wash as the preferred site was approved by the TIG, the Project Office, and DOE Headquarters (DOE/HQ) between June 14 and August 11, 1982.

Use of the term "potentially adverse" in Bertram (1984) and in this report is not the same as the use of the term in 10 CFR Part 60. In 10 CFR Part 60, the term "potentially adverse" is used solely in the context of those things or conditions that "may compromise the ability of the geologic repository to meet the performance objectives relating to isolation of the waste" (10 CFR 60.122(a)(2)). Use of this term in Bertram (1984) and in this report is more generic, because it refers to any condition which may affect the design or construction of the Exploratory Shaft Facility (ESF), including but not necessarily restricted to those aspects which would affect "waste



EXPLANATION

SITING AREA AND SHAFT LOCATION RECOMMENDED BY BERTRAM (1984)

FAULT, LOCATION INDICATED BY SURFACE MAPPING

TECTONIC BRECCIA, NOT ASSOCIATED WITH PLANAR DISCONTINUITIES

FAULT, LOCATION INDICATED BY ELECTROMAGNETIC SURVEYS

FAULT, LOCATION INDICATED BY AEROMAGNETIC SURVEYS

Figure 2-2. Location of faults shown by Scott and Bonk (1984) and siting area and shaft locations recommended by Bertram (1984).

isolation" in the repository. Thus, the use of the term "potentially adverse" in Bertram (1984) and in this report does not automatically infer that waste isolation may be compromised.

2.3 GEOLOGICAL AND GEOPHYSICAL WORK UNDERTAKEN TO ADDRESS RECOMMENDATIONS OF BERTRAM (1984)

Bertram (1984), in recommending the Coyote Wash area as the ES site, included three recommendations for additional studies prior to the start of shaft construction. These recommendations were (1) prepare detailed surface geologic maps of the five sites considered; (2) implement a geophysical evaluation (ranging from a review of existing data to the acquisition of new, site-specific data) of the possibility of subsurface structure that could compromise the constructibility or characterization utility of the ES beneath washes such as Coyote Wash; (3) if the first two recommendations could not be implemented prior to the start of drillhole USW G-4, then the objective of USW G-4 would be considered exploratory (that is, it would be necessary to determine the potential existence of structure), rather than confirmatory, and the geophysical evaluation should still be completed. These recommendations were added at the request of the TIG during its review of the Ad Hoc TOC Committee recommendations in June 1982.

The first recommendation was addressed by the transmittal of a set of geologic maps in a letter from G. L. Dixon to D. L. Vieth on July 16, 1982. No additional geophysical surveys were undertaken at this time because of time constraints imposed by the existing ES schedule (Dixon, oral communication). The USW G-4 drillhole was started on August 22, 1982, and completed on January 12, 1983 (Spengler et al., 1984).

2.4 OTHER GEOLOGIC AND GEOPHYSICAL DATA PERTINENT TO INVESTIGATIONS OF COYOTE WASH

Geologic mapping that covers the Coyote Wash area includes Lipman and McKay (1965, 1:24,000 scale), Scott and Bonk (1984, 1:12,000 scale; and in Dixon (1982, 1:12,000 scale), and Barton et al. (1989, 1:6,450 scale). Details concerning these maps are given in Section 3.1. Reports describing the results from drillholes in Coyote Wash include Spengler et al. (1984) for the USW G-4 drillhole, and Spengler and Rosenbaum (1980) for the UE25a-6 drillhole. Geophysical surveys that are specific to Coyote Wash are a slingram survey by Flanigan (1981), and the resistivity and induced polarization profiles by Smith and Ross (1982). The details of these surveys, and other more generalized geophysical coverage, are discussed in Section 4.2.

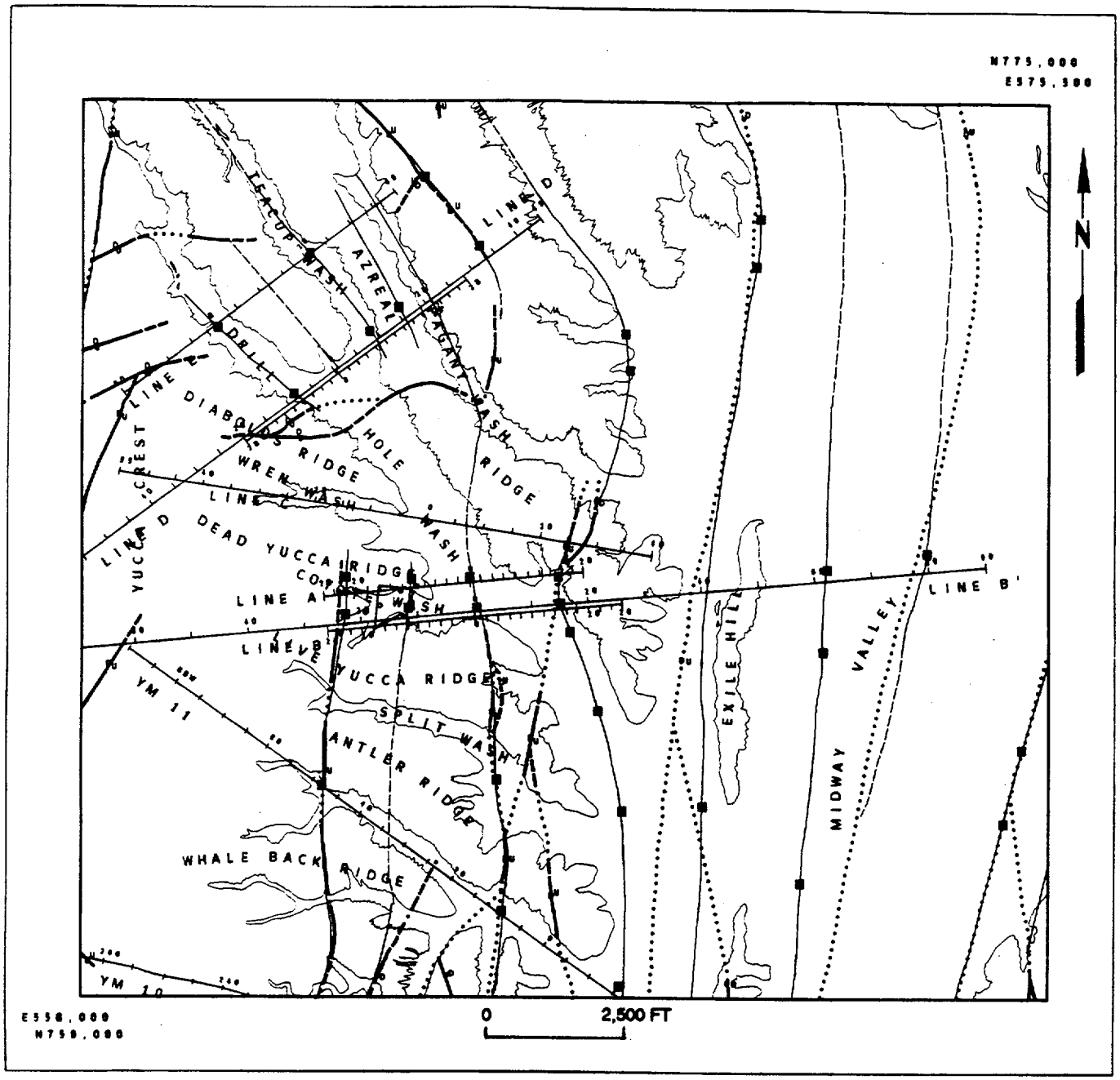
2.5 FAULTS INTERPRETED FROM RESISTIVITY DATA SHOWN IN OPEN FILE REPORT 84-792

USGS Open File Report 84-792 is a compilation and interpretation of geologic data on the Yucca Mountain region acquired before January 1, 1983. The report was used as a source in the preparation of the geologic descriptions of Yucca Mountain for the Environmental Assessment (EA) (DOE, 1986) and the Site Characterization Plan (SCP) (DOE, 1988). Figure 32 of the Open File Report shows a map of "Faults and (or) fractures at Yucca Mountain interpreted from electrical resistivity data." The text of the Open File Report does not give any additional information on the source of this interpretation. The same figure was also duplicated in the SCP as Figure 1-40. This figure shows a fault in Coyote Wash at the location where a fault was inferred by Smith and Ross (1982), but also shows the fault extending much farther to the south than Smith and Ross indicated. D. P. Klein reviewed the USGS files to determine the origin of this expanded interpretation of the fault in Coyote Wash.

The Open File Report figure is apparently based on an unpublished interpretive map of published and unpublished electrical resistivity data compiled by D. B. Hoover. This unpublished map indicates that the location of the northern end of this longer fault cutting Coyote Wash is based on the interpretation of Smith and Ross (1982). Hoover used a dashed line to connect the inferred fault in Coyote Wash with another fault inferred to cross unpublished resistivity line YM10 at a point about 7,500 ft south of Coyote Wash (Figure 2-3). The location of the inferred fault cutting line YM10 coincides with a fault mapped by Lipman and McKay (1965), which trends to the northeast of the hypothesized connection between the inferred resistivity faults and terminates near Whale Back Ridge (Figure 2-3). However, in the figure that appears in the Open File Report and the SCP, the dashed line connecting the two inferred fault segments has been replaced by a solid line (Figure 2-4). This appears to represent a drafting error in the preparation of the published figure since other dashed lines shown on the unpublished version of the map were generally deleted from the published map (D. B. Hoover, oral communication to G. Shideler).

2.6 DECISIONS TO REVISE SHAFT LOCATIONS

An "NRC-NNWSI Project Exploratory Shaft Design/Construction Meeting" was held with the NRC on August 27-28, 1985, in Silver Spring, Maryland. One of the observations by the NRC recorded in the minutes of that meeting expressed the concern that flooding events could occur in Coyote Wash that might affect repository performance if the exploratory shafts were sited at the location recommended by Bertram (1984). The specific concern about locating the shafts in the alluvial filled wash was described by D. L. Vieth (November 29, 1986, Action Memo to S. H. Kale) as "...the potential for channelling [sic] of water run-off over the ES location and the eventual erosion of alluvium fill. This would eventually lead to preferential channeling of the run-off into the top of the sealed ES, and the disturbed annulus around the sealed shaft. It is believed by the NRC staff, that a more prudent approach would be to set the shaft collar in hard rock outside the flow channels."



EXPLANATION

FAULT MAPPED BY LIPMAN AND McKAY (1965)

LOCATION OF RESISTIVITY LINE (YM 11)

FAULT INFERRED FROM RESISTIVITY DATA BY HOOVER

AREA RECOMMENDED BY BERTRAM (1984) WITH ORIGINAL SHAFT LOCATIONS (OPEN CIRCLES) AND REVISED SHAFT LOCATIONS (SOLID CIRCLES)

Figure 2-3. Faults interpreted from resistivity data by Hoover, mapped faults shown by Lipman and McKay (1965), locations of resistivity lines.

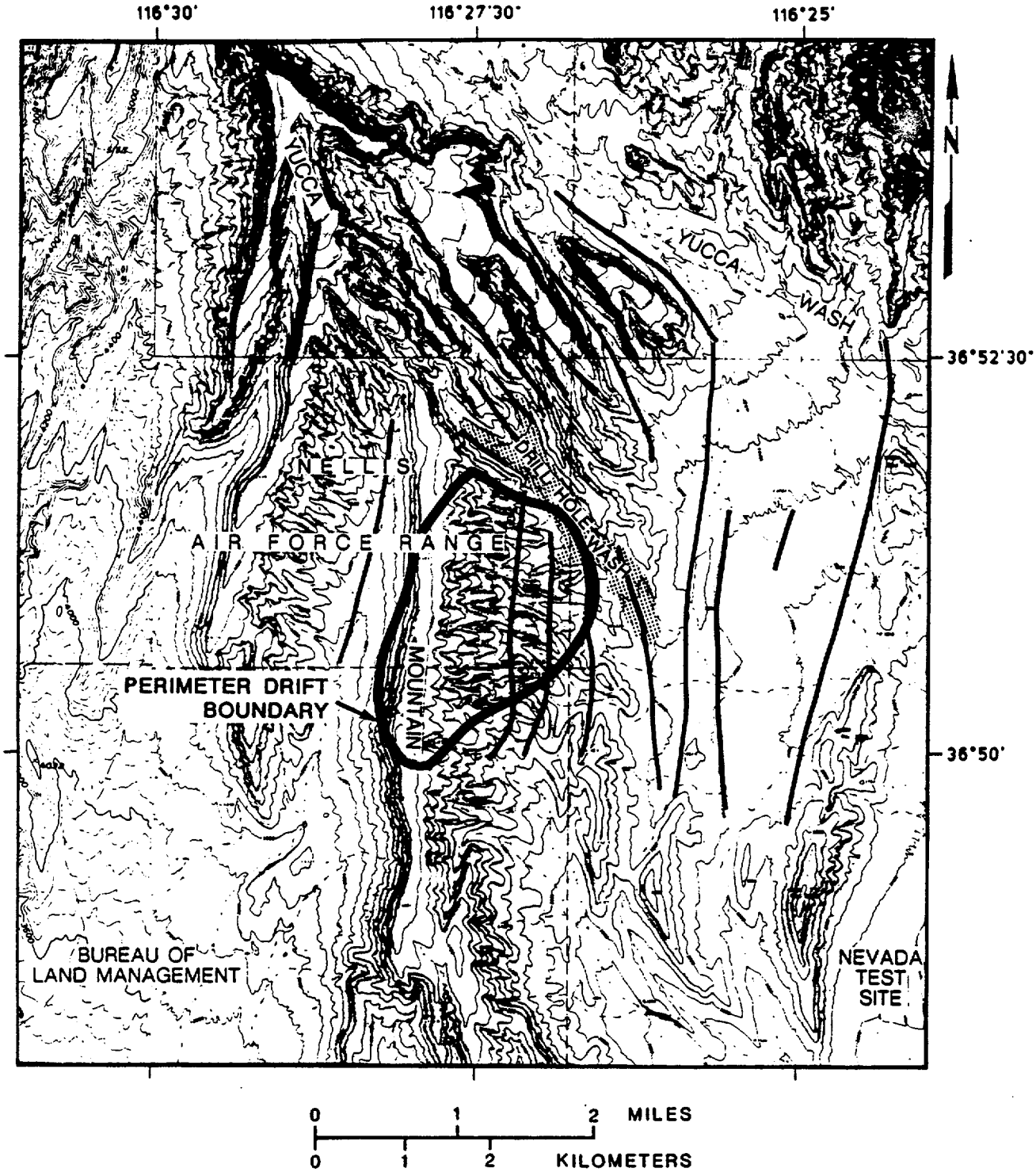


Figure 2-4. Faults interpreted from electrical resistivity data as shown on Figure 32 of U. S. Geological Survey Open File Report 84-792 and in SCP Figure 1-40.

On July 29, 1986, J. A. Cross of Fenix & Scisson, Inc. (F&S) addressed a letter to the attention of D. L. Vieth noting the necessity of defining the locations of the ES-1 and ES-2 shafts in order to make the surface pad layout and tie in the underground test area layout with the shafts. The letter went on to recommend a location for ES-1 that is very close to the current shaft location (N766275, E563530) (Figure 2-5). It also recommended that the ES-2 shaft be located on a bearing of N65E from the ES-1 location. The letter concluded with a request that DOE/Project Office approve these locations so that design work could proceed. An attachment to the letter gave the considerations that were used to select the ES-1 location. The considerations were:

1. The shaft should be within the area defined by the Bertram (1984) report (Figure 2-5).

2. The shaft should be located out of any main natural drainage channel.

3. The shaft should be collared in solid competent material.

4. The shaft should be located where it can easily be accessed.

5. The shaft should be located where a good balance between cut and fill can be achieved in preparing the surface pad.

6. There should be a potential for pad expansion if necessary.

7. The ES-1 location must be in the general proximity of the USW G-4 borehole.

The attachment then discussed how these considerations were applied to select the proposed location. Although the letter does not mention the NRC concerns about water flow in the wash, the second and third considerations appear to be aimed at responding to these concerns. Geologic considerations, such as the proximity of faults or adverse structures, were not directly included in the selection. Apparently, the group making the evaluation assumed that such considerations were addressed by remaining within the area defined by Bertram (1984).

There was an Exploratory Shaft Facilities Studies Kick-Off Meeting held in Las Vegas, Nevada, on August 20, 1986. This meeting was attended by representatives of DOE/NV, F&S, Science Applications International Corporation (SAIC), and Holmes and Narver (H&N). The minutes of the meeting, transmitted to the Project Office by S. D. Murphy on September 16, 1986, indicate that "upon receipt of approval of the letter by F&S recommending a location for ES-1 shaft location, F&S will have a Geologist [sic] look at the surface area at that location. The main emphasis will be to check for any gross geologic features which might cause a problem with collaring the shaft at that location. The geologists [sic] findings will be forwarded to the DOE." The TAR team could find no record in the Project files that this geological review was undertaken.

On August 21, 1986, D. L. Vieth responded to the recommendation by Cross. This letter stated that "it is understood that while your recommended

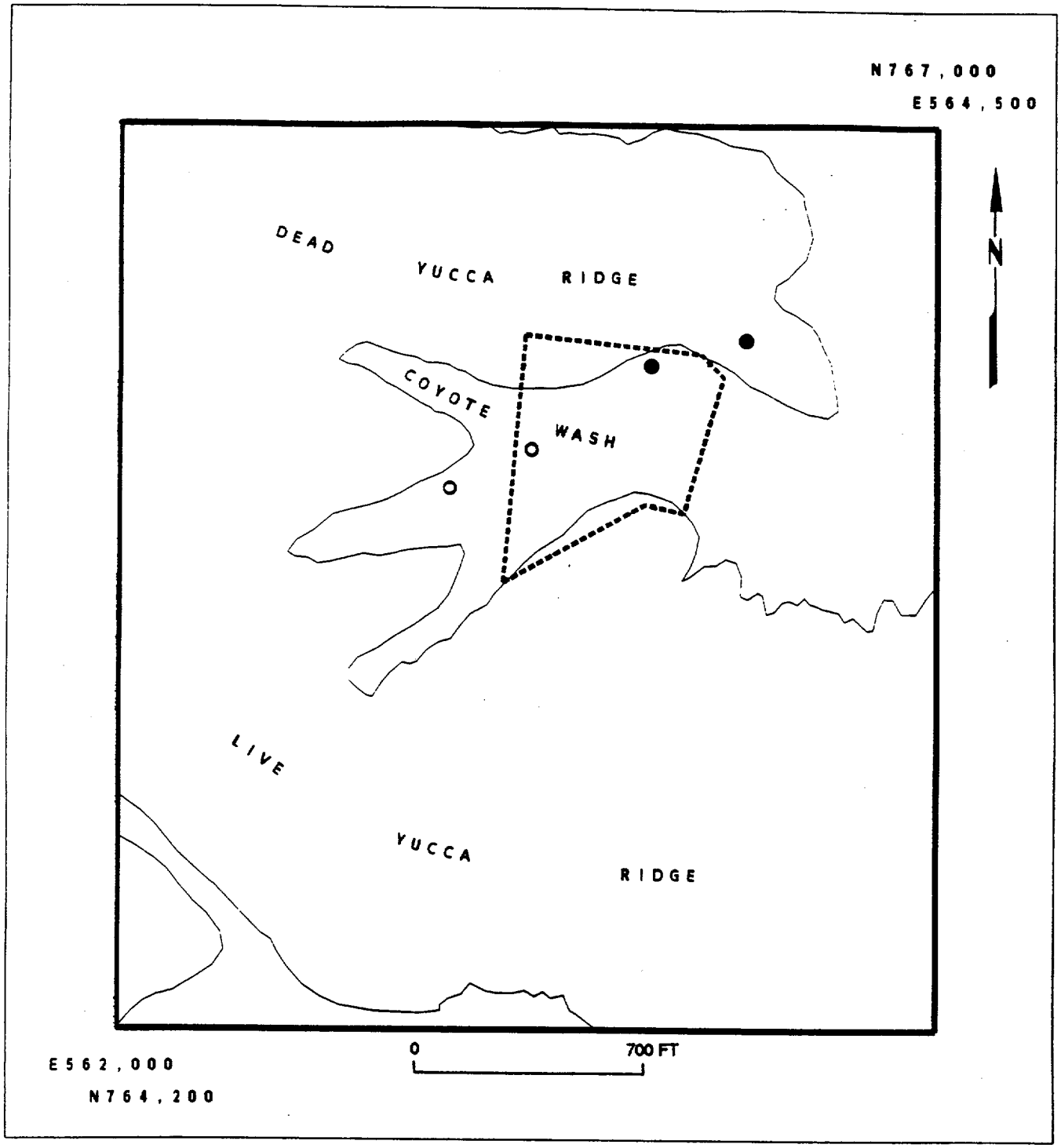


Figure 2-5. Location of shaft siting area and shaft locations (open circles) recommended by Bertram (1984) and revised shaft locations (solid circles) recommended by Cross (1986).

location is the result of the siting considerations and discussion topics listed in your letter, review and concurrence by Sandia National Laboratories and Los Alamos National Laboratory (for repository design and technical coordination with the Principal Investigators, respectively) will be required before final approval of this location can be given." The TAR team could find no evidence in the files of this review and concurrence by SNL and LANL, or of Project Office approval of the proposed location.

On November 29, 1986, the Project Office proposed to DOE/HQ a move in the location of the exploratory shafts (Action Memo, D. L. Vieth to S. H. Kale, 11/29/86). The move of the shaft location was included with a number of other recommendations on ESF design. The recommendation was to move the ES-1 location 440 feet to the northeast. This recommendation basically implemented the recommendation of Cross that was made in July 1986. The reason given for this change was to provide a specific response to comments of the NRC concerning flooding, erosion, and flow of water around the area of the shaft liners. In February 1987, a background paper was prepared entitled "Proposed Changes to the Nevada Nuclear Waste Storage Investigations (NNWSI) Project Exploratory Shaft Facility" for presentation to the NRC and the State of Nevada. Among the changes proposed in this background paper was the relocation of the shaft sites. The nature of this change and the reasons for it were the same as contained in the November 1986 Action Memo. The meeting with the NRC and State of Nevada to discuss these changes occurred on April 14-15, 1987 (Vieth, 1987).

2.7 CONCLUSIONS AND RECOMMENDATIONS

2.7.1 SITE SELECTION METHOD USED BY BERTRAM (1984)

In general, the methodology used by the Ad Hoc TOC Committee to select ES sites is reasonable and defensible. Minor shortcomings in the report involve (1) the lack of a clear distinction in the report between shaft site selection methodology (criteria in the report) and shaft site suitability criteria, and (2) absence of a clear listing of the sources of data that were or were not considered in applying the methodology.

In the application of the methodology related to potentially adverse structures, the site suitability criterion for the maximum distance from potentially adverse structures (being close enough to horizontally drill into the potentially adverse structure) is clearly defined and the source of site selection methodology (preference for being within 2,000 ft of structure) is also clear (limits on drilling technology). However, the site suitability criterion for the minimum distance from potentially adverse structures is not as clearly defined. Bertram (1984) states the concern as the "likelihood that the shaft itself and drifts from the shaft would encounter fractures associated with those (potentially adverse) structures." This presumably indicates that the concern being addressed is related to worker safety, shaft engineering or construction problems, and repository performance. The actual site suitability criterion is then the absence of something similar to "poor" ground conditions in the shaft as discussed in Section 6.1 of this memo. In the case of the Bertram (1984) study, as well as other similar site selection

studies considering an area the size of Yucca Mountain, detailed data are generally not available that would allow the direct determination of the location of areas of such poor ground. In these cases, a surrogate site selection methodology that can use existing data is usually adopted to address the concern, with the surrogate being defined using technical judgment. In this case, a preference for being greater than 1,000 ft from faults shown on a preliminary version of the map of Scott and Bonk (1984) and an exclusion zone within 100 ft of faults shown on a preliminary version of the map of Scott and Bonk (1984) was adopted. While this is an acceptable technique for completing the site selection study, it should be noted that the distance from mapped faults does not necessarily directly correlate with ground conditions. It should also be noted that, after a small site is selected, the surrogate site selection criteria no longer apply and subsequent evaluations of the site should directly address the site suitability criteria (the absence of poor ground in this case).

As noted above, Bertram (1984) states the site selection method related to potentially adverse structures as distances from those structures. In actual application, Bertram (1984) used a preliminary version of the faults mapped by Scott and Bonk (1984) as the basis for determining excluded or less preferred areas (R. W. Spengler, oral communication). It would have been better if the report had defined the term "potentially adverse structures" in terms of the physical ground conditions that were the true basis of concern (see Section 6), since it was probably not the intent of the committee to create a situation where any fault or structure of any size would automatically disqualify the site if one were found in the future. The report should then have documented the rationale for selecting the preliminary map of Scott and Bonk (1984) as the source for the location of potentially adverse structures and discussed why other sources were or were not used.

2.7.2 ABILITY OF THE PROJECT TO CORRELATE DATA

As part of this review, the TAR team members attempted to identify the location of mapped faults and inferred faults from geophysical sources for a relatively small area in the controlled area. The team found that this type of information is not easily compiled for use by Project participants. Currently such data are scattered among a large number of published and unpublished reports that in some instances may be produced by different participants. With the large number of people working on the Project and the planned volume of site characterization work, it appears probable that it will become increasingly difficult for individuals or task groups to successfully locate all of the data potentially pertinent to a specific analysis. It is recommended that the Project review its systems of data management to evaluate whether they are comprehensive and timely enough for routine use by the Project staff. One example of the use of such systems is provided by the fault inferred to exist in Coyote Wash by Smith and Ross (1982). When low resolution techniques are interpreted to indicate the presence of possible structures, the potential existence of such a structure needs to be highlighted in the system to indicate the need for more detailed follow-up studies to determine the nature of such anomalies.

2.7.3 DOCUMENTATION OF CHANGES IN SHAFT LOCATION

The file record does not appear to be complete with regard to the process of relocating the exploratory shafts. The TAR team could find no record of the review and concurrence on the new site by the national laboratories required by the Project Office, or of the geological investigation planned by F&S. Geological factors were apparently not considered during the relocation because the ES-1 location was kept in the area identified during the previous screening by Bertram (1984). However, the new ES-2 location was placed outside the area identified by Bertram (1984). The NRC was aware of this fact, and documented its approval in a letter from J. Linehan to M. Kunich, dated August 19, 1987. While such a move is acceptable given the new factors being considered in 1986, it would seem reasonable to have evaluated the new site with respect to the presence of potentially adverse structures that could affect shaft construction, worker safety, and repository performance. Such concerns would appear to be equally applicable to both shafts.

The TAR team recommends that current procedures for the creation of file packages documenting such Project decisions be reviewed to determine if the procedures have adequate requirements for the creation of file packages and that reviews of such packages exist to ensure that the packages are complete and the disposition of all required or planned actions has been documented.

Chapter 3

SUMMARY OF GEOLOGY SUBCOMMITTEE

The approach of the geology subcommittee was to review the existing geologic data in the Coyote Wash area in order to evaluate the geologic evidence for, or against, the presence of faulting in the vicinity of the exploratory shafts. This review consisted of three steps. The first step was to identify the geologic mapping and other geologic data available in the area, review the interpretation of the ES area shown on the mapping, determine the mapping methods used, and evaluate the probable level of map accuracy. The second step was an interpretation of aerial photography covering the area to evaluate the geologic interpretation shown by the existing mapping, and to look for evidence of potential faulting in the ES area (lineaments, etc.). The third step was a field review of the geologic mapping in the vicinity of the exploratory shafts to evaluate the reasonableness and accuracy of the existing mapping, and to review and evaluate the field evidence for or against the existence of faulting.

3.1 METHODS USED IN PREVIOUS GEOLOGIC MAPPING OF COYOTE WASH AREA

The following information was compiled by R. P. Snyder and G. L. Shideler of the geology subcommittee. The sources of information for this summary were published reports, material contained in the USGS files, and personal communications with USGS staff involved in the original work.

3.1.1 LIPMAN AND MCKAY (1965) MAPPING

The first geologic mapping effort in the Coyote Wash area was conducted by Peter W. Lipman and Edward J. McKay of the USGS in 1962. The mapping was done as part of the preparation of a geologic map of the Topopah Spring SW 7 1/2 Minute Quadrangle. This map was first released as Technical Letter NTS-72 in 1964. This map was subsequently published as the "Geologic Map of the Topopah Spring SW Quadrangle, Nye County, Nevada," in 1965 as USGS Map GQ-439. The quadrangle was one of several 7 1/2 minute (scale 1:24,000) geologic maps published by the USGS as part of a regional mapping program in the early and mid-1960's covering the area of the Nevada Test Site. The Paintbrush Tuff and its members, including the Tiva Canyon Member, were first described as part of this project.

The quadrangle was mapped in the field using standard USGS practices: the geological contacts, structural data, and sample locations were entered on aerial photographs in the field. The data were then transferred to a scale-stable topographic base map, using state-of-the-art (stereo-plotter, etc.) methods employed at the time.

Lipman and McKay found no surface evidence of faulting in the vicinity of the electrical resistivity contrast (near location 9W, Lines A and B of Smith and Ross, 1982) between the present ES-1 and ES-2 sites. The only fault mapped by them in the immediate Coyote Wash area was the Ghost Dance

fault located 0.25 mi west of the ES sites, and a small fault located approximately 0.25 mi southeast of the ES sites (Figure 3-1).

3.1.2 SCOTT AND BONK MAPPING

The most detailed mapping of the structure and stratigraphy in the Coyote Wash area was done by Robert B. Scott and Jerry Bonk of the USGS during the 1981-82 period, as part of the NNWSI program. Their mapping effort consisted of two separate activities that are described as follows, with details provided by R. B. Scott (personal communications, May, 1989):

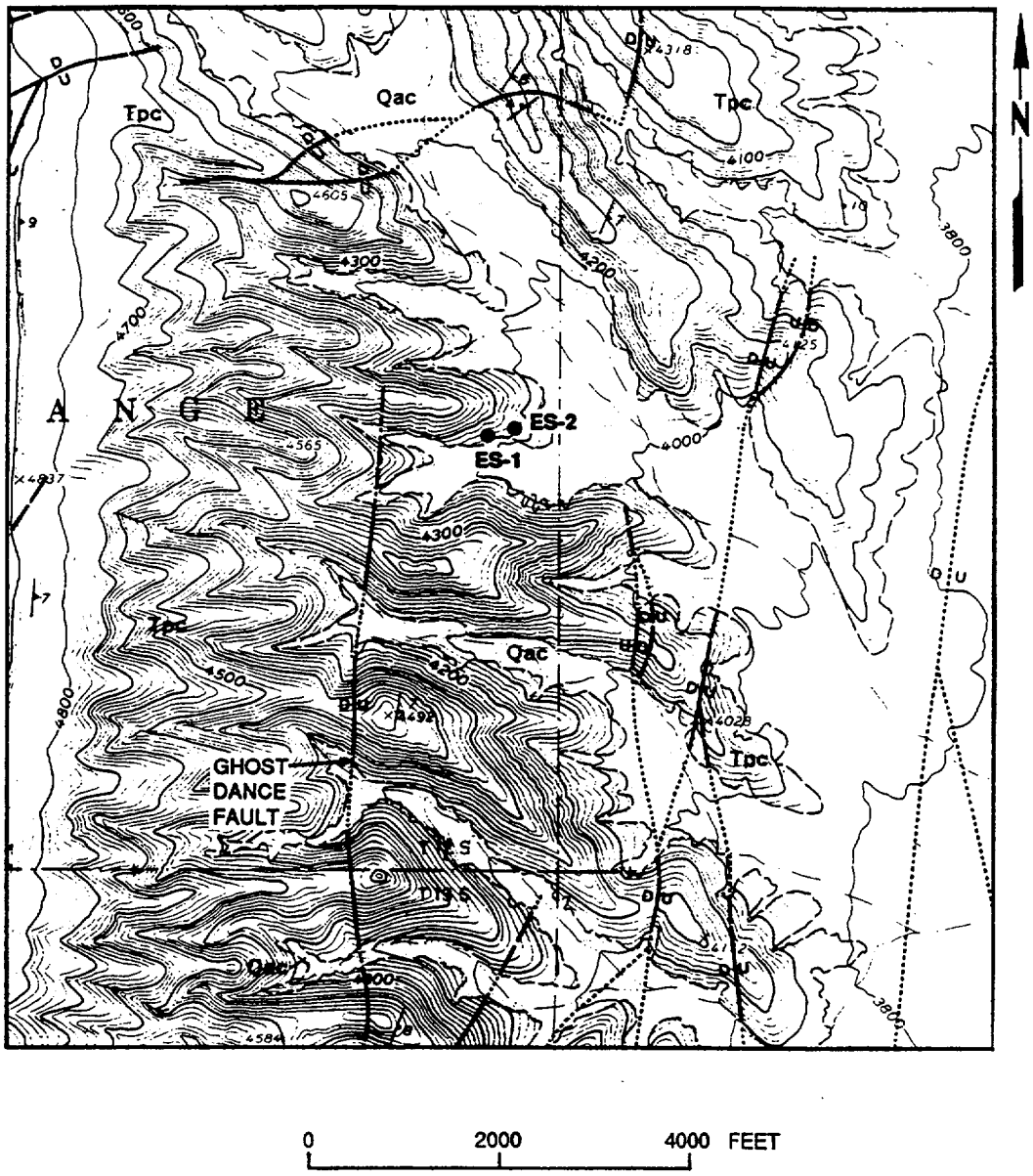
3.1.2.1 Preliminary Geologic Map of Yucca Mountain, Nye County, Nevada with Geologic Sections, 1984, USGS Open File Report 84-494

This mapping effort was conducted during the winter months of both 1981 and 1982, and encompassed all of Yucca Mountain, including Coyote Wash. The mapping was done entirely in the field. It consisted of mapping structural features (bedding or foliation strike and dip, faults, fractures, and tectonic breccias) and lithostratigraphic units down to the informal zone level (Table 3-1). Structures and geologic contacts were walked-out in the field, and the field data were plotted on 1:12,000 aerial photographs flown in 1978 by American Aerial Photograph Services. The aerial photographs, in stereo pairs, were used to systematically delineate areas of progressive mapping and to establish field locations. The field locations of structures were identified on the aerial photos by pinholes punched through the photos. Each pinhole locality was given a unique identifier number on the back of the photo, and field notations regarding the locality were recorded in a field notebook and keyed to the identifier number.

The aerial photographs containing the field data were then mounted in a PG-2 plotter and the data transferred to a scale-stable mylar topographic base map. The base map was published by the National Mapping Division of the USGS (Topopah Spring NW and SW, 1961) at a 1:24,000 scale. During the transfer process, the plotter removed any optical distortion inherent in the aerial photographs.

Regarding map accuracy, Scott and Bonk were able to locate field positions on the aerial photos to within 5 m in hilly terrain such as Coyote Wash; in flat terrain, accuracy was reduced to less than 10 m. According to Scott, faults having less than 3 m of vertical offset may not be recognizable along the gradational contact between the lower lithophysal zone (cll) and the overlying rounded step zone (crs) of the Tiva Canyon Member, which is probably the best exposed stratigraphic contact within the Coyote Wash area.

The purpose of this mapping effort was to prepare a detailed, site-specific geologic map of the Yucca Mountain repository block. During their field work, Scott and Bonk did not observe any surface evidence of faulting at the location of the electrical resistivity contrast between the ES-1 and ES-2 sites (Figure 3-2). The only structural features mapped by them in the Coyote Wash area were the Ghost Dance fault west of the ES sites



Tpc TIVA CANYON MEMBER

Qac ALLUVIUM AND COLLUVIUM

Figure 3-1. Geology of the Coyote Wash area as shown on the map of Lipman and McKay (1965).

Formation	Member/Age/Thickness	Zone
Paintbrush Tuff	Tiva Canyon Member /12.6 MY /295-459 ft	ccr — Caprock zone. Quartz-latitic Upper port of the cooling unit that caps Yucca Mountain.
		cuc — Upper cliff zone. Moderately to densely welded, devitrified, rhyolitic tuff. This zone forms the base of the cliff under the caprock, contains 5 to 10 percent lithophysae, and has an exfoliated weathered surface.
		cul — Upper lithophysal zone. Moderately welded, devitrified, rhyolitic tuff. Lithophysae are abundant (10-20 percent) and rock has exfoliated weathered surface.
		crs — Rounded step zone. Moderately welded, devitrified, rhyolitic tuff. Zone is characterized by conchoidal fractures, uniform textures, sparse or no lithophysae, and presence of ledges.
		cll — Lower lithophysal zone. Moderately to densely welded, devitrified rhyolitic portion of the cooling unit. Lithophysae are abundant (10-15 percent), small, and spherical to oblate. Weathering surface is characterized by exfoliation except for hackly fractures near base.
		ch — Hackly zone.
		cc — Columnar zone.
	Bedded Tuff /10 ft	Vitric ash-fall tuffs, reworked tuffs, and thin nonwelded ash-flow tuffs.
	Yucca Mountain Member/0.8 ft	Nonwelded to densely welded ash-flow tuff.
	Bedded Tuff /19.4 ft	Pumiceous pyroclastic-fall tuff.
	Pah Canyon Member /19.8 ft	Ash-flow tuff.
	Bedded Tuff /40.0 ft	Nonwelded, reworked tuff, and ash-fall tuff.
	Topopah Spring Member/13.2 MY /1,178.8 ft	Multiple-flow compound cooling unit of a compositionally zoned rhyolitic to quartz latitic ash-flow tuff.

Table 3-1. Stratigraphic column for rocks present in the Coyote Wash area. Modified from Scott and Bonk (1984); ages from Maldonado (1985); thickness of pre-Tiva Canyon Members from USW G-4 (Spengler et al., 1984)

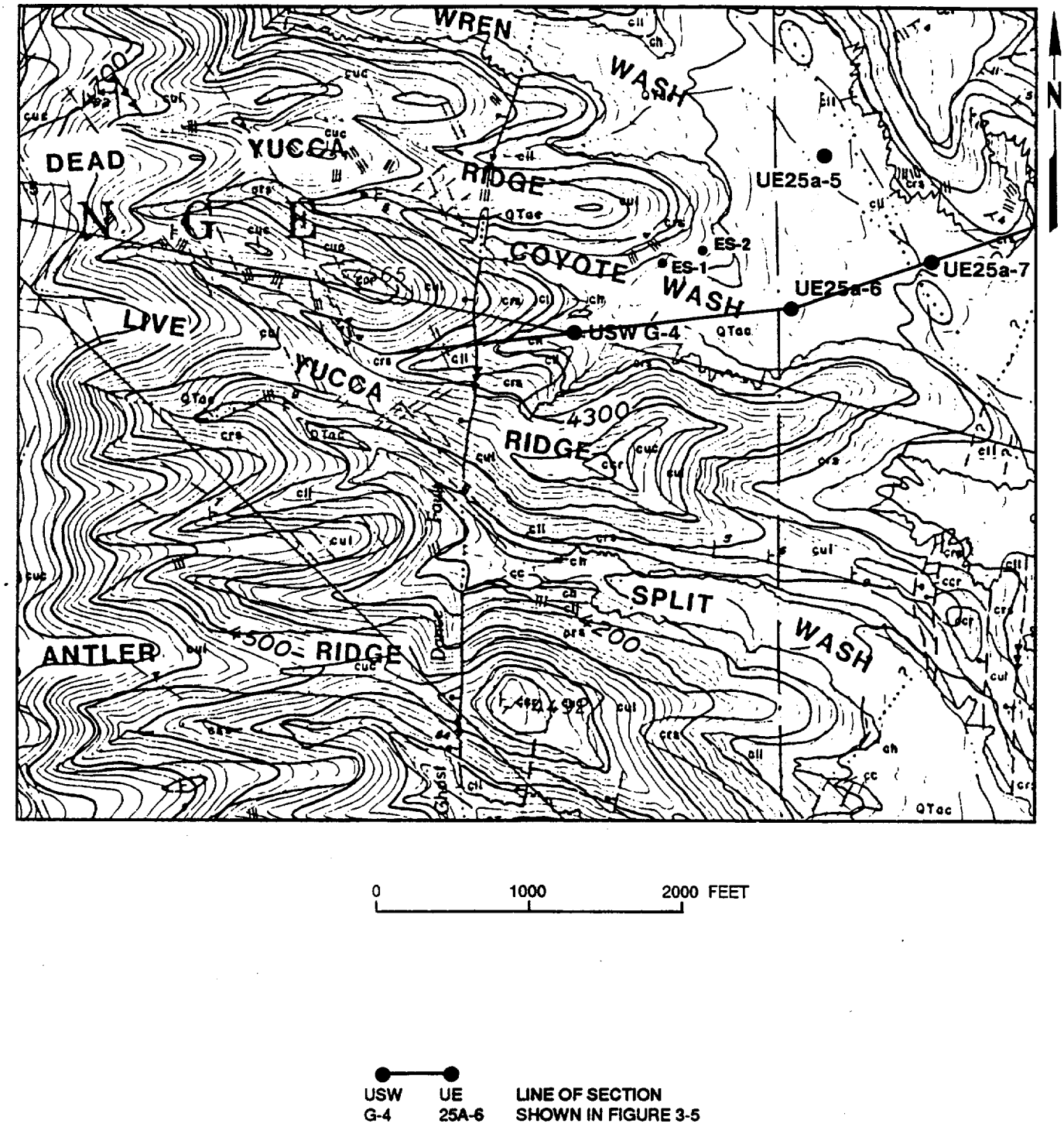


Figure 3-2. Geology of the Coyote Wash area as shown on the map of Scott and Bonk (1984). Explanation of map units shown on Table 3-1.

and a brecciated zone about 150 ft north of the ES-1 site that trends into one of two fracture sets with a N40W trend. These two northwest-trending fracture sets were observed about 100 ft upslope from ES-1 on Dead Yucca Ridge. A preliminary draft of the Scott and Bonk map was used in the original ES site selection process conducted by the Ad Hoc TOC Committee.

3.1.2.2 ESF Potential Site Mapping (Dixon Letter Report, 7/16/82)

This mapping effort was conducted by Scott and Bonk in 1982, in response to a Project Office request to provide detailed, site-specific geologic maps of the five potential ESF sites recommended by the Ad Hoc TOC Committee. The only site in Coyote Wash is Site #1 in the Letter Report (TOC Committee Site #4).

The detailed mapping of the Coyote Wash site extended from the Ghost Dance fault eastward to the approximate current location of ES-1 (Figure 3-3); consequently, it did not include the area of the electrical resistivity contrast between ES-1 and ES-2. Mapping was done entirely in the field. Zone contacts within the Tiva Canyon Member were walked-out and inspected for fault displacements, zones of brecciation, and fracture patterns. Structures were plotted on 1:12,000-scale aerial photographs, transferred to a stable topographic base map, then blown-up to a 1:2,000 scale for readability. The map accuracy is the same as the Scott and Bonk OFR 84-494 map; points are located to within 5 m in the field, with a 1:12,000-scale plotting accuracy. The mapping indicated three minor northwest-trending fault traces located several hundred feet west of the present ES-1 site. Because vertical displacements associated with these faults were too small to be detected by the offsets of zone boundaries, the existence of offset on these features was inferred from the presence of chattermarks on fracture surface. Two brecciated zones also were noted a few hundred feet west of ES-1. The only structure mapped in the vicinity of the electrical resistivity contrast was the same brecciated zone associated with a northwest-trending fracture set that was mapped near the ES-1 site on the OFR-84-494 map.

3.1.3 BARTON, PAGE, AND MORGAN MAPPING

C. C. Barton, W. R. Page, and T. L. Morgan (1989, USGS-OFR-89-92) also prepared a geologic map of the Coyote Wash area as part of a study of fractures in outcrops in the vicinity of drillhole USW G-4. This mapping effort used the 1:5,000 scale topographic map of S. S. C. Wu (1985, USGS-OFR-85-620) as a base. This map uses the same volcanic stratigraphy as Scott and Bonk (1984). Altimeters were used to plot stratigraphic contacts on the metric base map. The geologic map is very similar to the map of Scott and Bonk, except that it assigns somewhat different elevations to the contacts between zones.

This map covers the ES area and does not show any faults in the vicinity of the shafts (Figure 3-4). The contact between the lower lithophysal and rounded step zones is shown to extend across this area without offset. The only structure shown in the mapped area is the Ghost Dance fault. Vertical

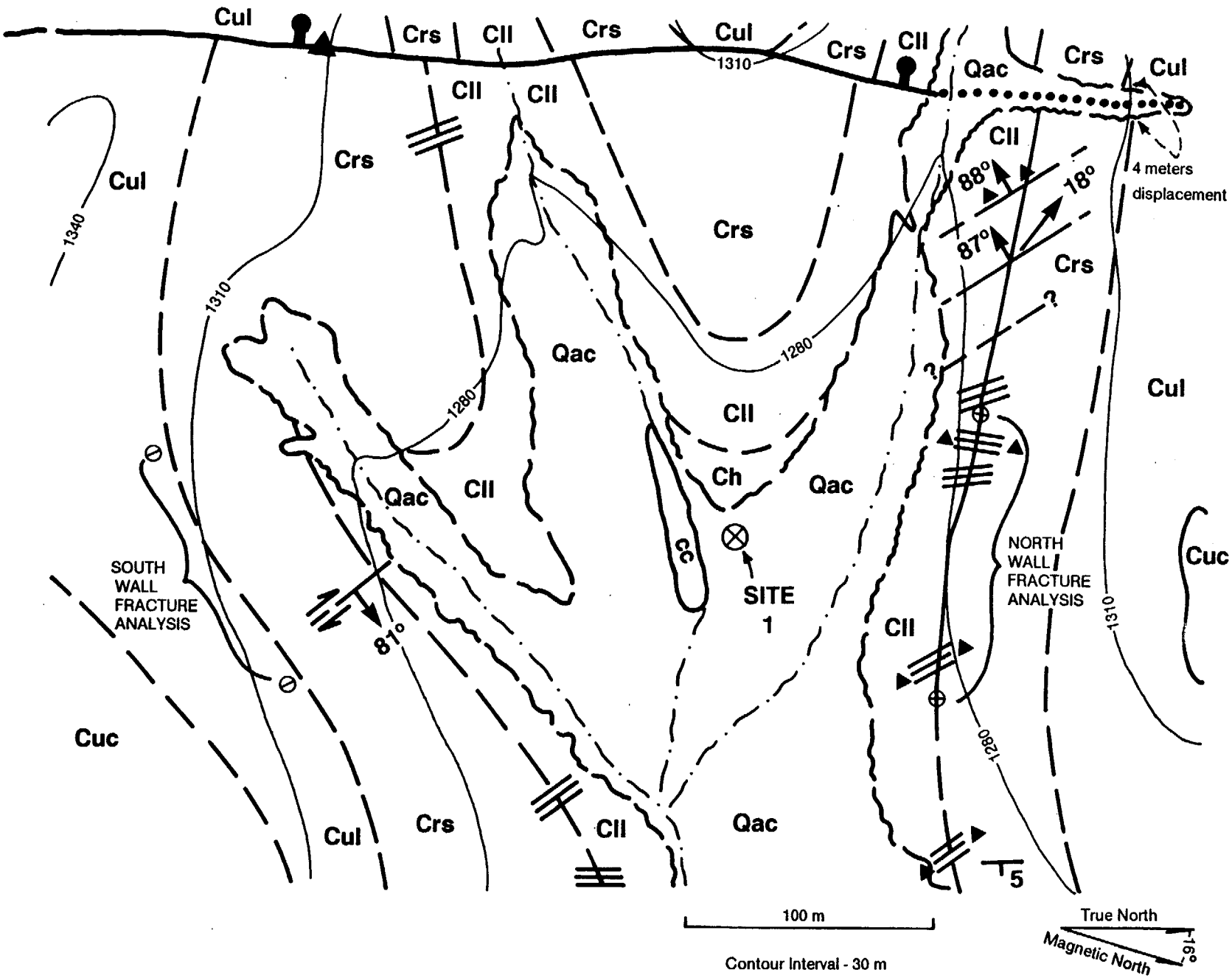


Figure 3-3. Geology of the Coyote Wash area as shown on the map of Scott and Bonk in Dixon, 1982.

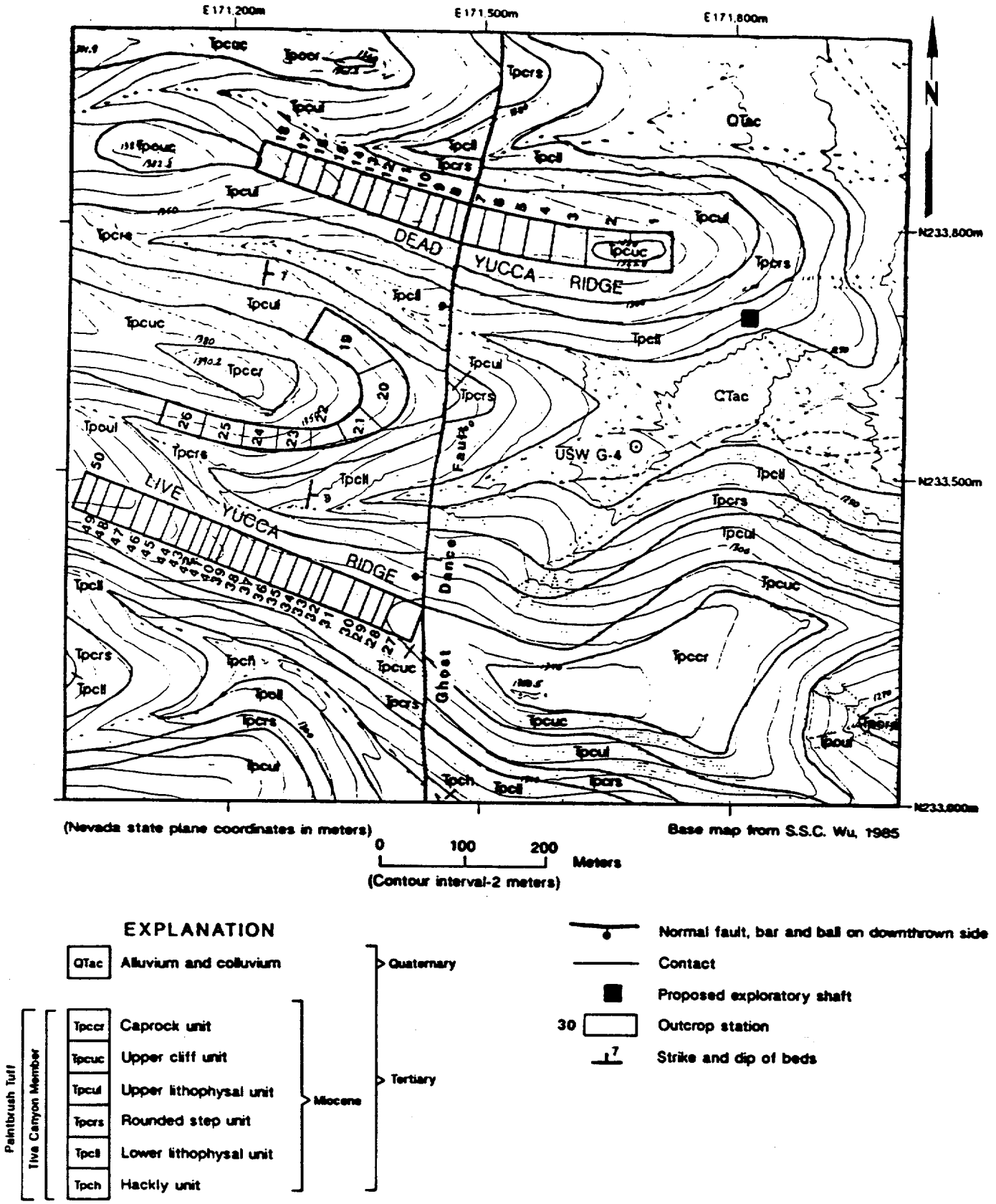


Figure 3-4. Geology of the Coyote Wash area as shown on the map of Barton and others (1989).

offset on the fault was found to decrease from 8 m on the south side of Live Yucca Ridge to 4 m on the south side of Dead Yucca Ridge.

3.2 EVALUATION OF BOREHOLE DATA

The data from the boreholes in the area are less sensitive than the mapping data in evaluating faulting because of the spacing between these borehole data points. The lithologic logs of the boreholes in the vicinity of Coyote Wash were evaluated mainly to determine if there was any evidence of pre-Tiva Canyon faulting in the area.

Figure 3-5 shows a cross section extending down Coyote Wash and across Drill Hole Wash through boreholes USW G-4, UE25a-6, and UE25a-7. Lithologic zones logged in the lower Tiva Canyon Member and upper Topopah Spring Member were correlated and plotted on the section to evaluate the possibility of changes in dip between the two units and missing, thickened, or thinned section that might be the result of faulting that predates deposition of the Tiva Canyon Member. The cross section shows a high degree of conformity in the section between the lower Tiva Canyon Member, bedded tuffs, Yucca Mountain Member, Pah Canyon Member, and the upper Topopah Spring Member. The contacts between the units are on line across the three boreholes and there is no missing or added section on the borehole logs. There is also very little change in the total thickness of the sequence between the base of the Tiva Canyon Member and the top of the Topopah Spring Member, although the Pah Canyon Member does thicken at the expense of the bedded tuffs above and below it in UE25a-7. The dip of these units is also parallel to the dip of the lithostratigraphic zones in the Tiva Canyon Member that were mapped by Scott and Bonk (1984). The contacts between the cll, crs, and cul zones also are plotted on the cross section by projecting the contacts mapped by Scott and Bonk (1984) on Live Yucca and Dead Yucca Ridges to the line of section. (The line of section is nearly parallel to dip (see below) and, even though there is a bend in the section, the low dip (4-5°) would not result in noticeable increases or decreases in apparent dip on the figure.) The subcommittee concluded that the uniformity of the section between the three boreholes, and the parallelism of the apparent dip between the various lithostratigraphic units, was not suggestive of significant pre-Tiva Canyon faulting in the Coyote Wash area.

As an additional check on the nature of subsurface structure in the region, a three-point problem was solved for the upper Topopah Spring Member using boreholes USW G-4, UE25a-6, and UE25a-5. The problem was solved using the upper contact of the quartz latite caprock zone. This is a distinctive zone that is noted on all the core logs in the area. The upper contact of the quartz latite caprock zone is found about 20 to 40 ft below the upper contact of the Topopah Spring Member. The strike and dip calculated for these three points was N6W and 4 1/2°E. This is very close to the attitude (N01W, 4.4°E) of the top of the upper vitrophyre in the Topopah Spring Member in this area, as calculated by Spengler and Rosenbaum (1980) on the basis of borehole data. In order to evaluate whether the plane defined by the three boreholes matched the attitude of this surface as defined by other boreholes in the area, the elevation of the contact in other boreholes in the area was also projected to a line parallel to the calculated dip direction (Figure

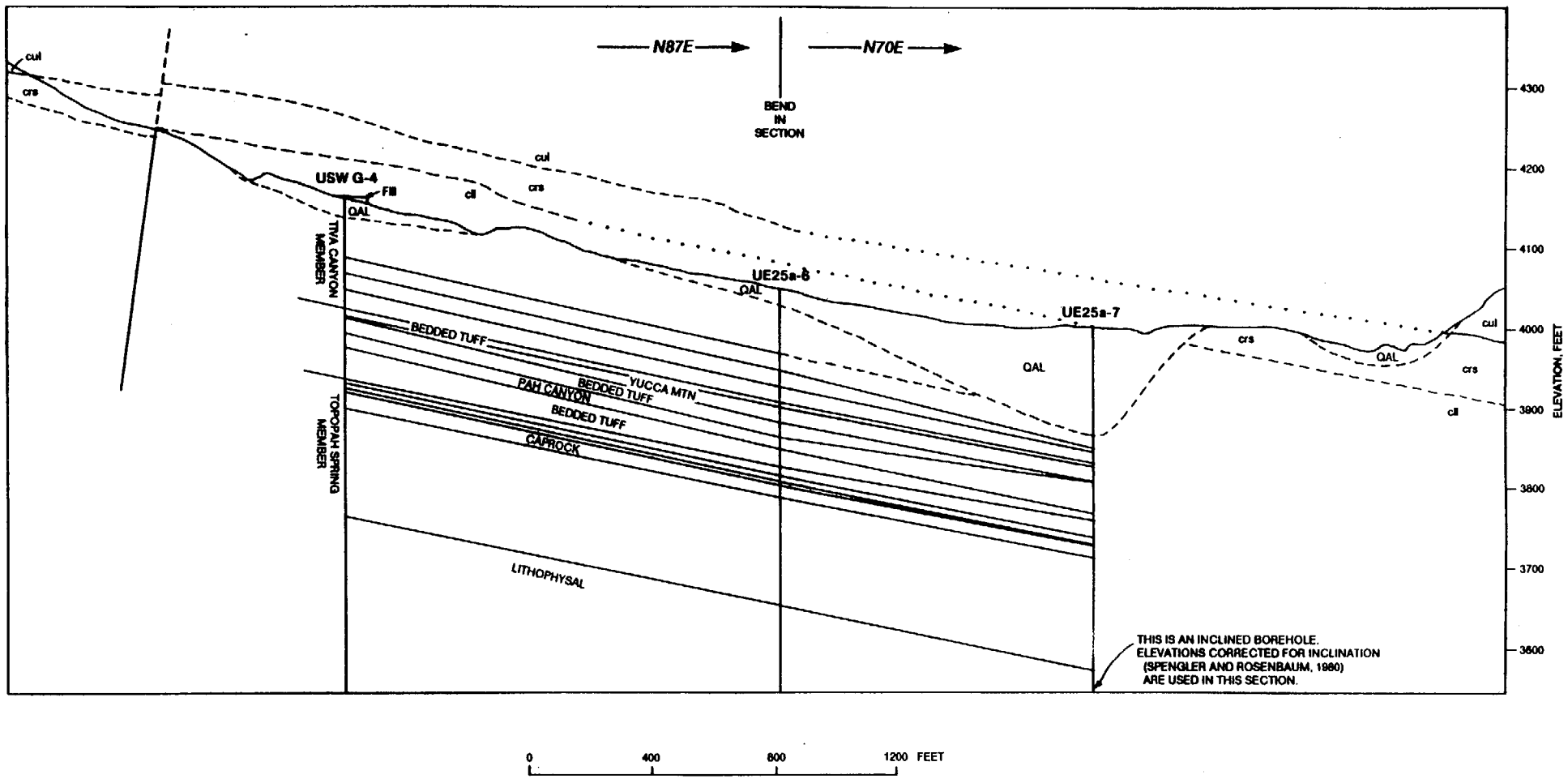


Figure 3-5. Cross section through boreholes USW G-4, UE25a-6, and UE25a-7 showing the correlation of lithologic zones recorded on the core logs (Spengler and Rosenbaum, 1980; Spengler and others, 1984). Lithologic zones in the upper Tiva Canyon Member are taken from Scott and Bonk (1984) and projected into the line of section. See Figure 3-2 for location of section.

3-6). All of these points plotted very close to the plane calculated for the original three points, indicating that the quartz latite caprock defines a planar surface across the area with no evidence of anomalous points that might be evidence of local offsets produced by faulting. Spengler and Rosenbaum (1980, pp. 20-23) got similar results from their analysis of borehole data in the area. The elevations of the top of the cul zone in the Tiva Canyon Member, as shown on the map of Scott and Bonk (1984), were also projected to the line shown on Figure 3-6 in order to determine if there are differences in dip between the Tiva Canyon and Topopah Spring Members. The line through the points representing the Tiva Canyon Member cul zone on Figure 3-6 is parallel to the line through the points defining the top of the Topopah Spring Member quartz latite caprock, and the good match between the points and the line indicate that there is little angular difference between the two members.

The results of the three-point solution can be compared with the results of foliation-trend measurements, using alignments of flattened pumice fragments in oriented core from USW G-4 (Spengler et al., 1984). The results from two welded zones in Topopah Spring Members give a scatter of data with dips ranging from 4 to 24° and strikes ranging from N37W to N10E. The average of these foliation measurements gives a strike of N15W. Similar foliation measurements from other boreholes in the area (Spengler and Rosenbaum, 1980) give average strikes of N9W (UE25a-4), N17W (UE25a-5), N23E (UE25a-6), and N6W (UE25a-7). With the exception of UE25a-6, the strikes of foliation in all of these boreholes are close to that estimated for the Topopah Spring Member on the basis of the elevation of the top of quartz latite caprock zone.

The inconsistency in the strike of foliation observed in the UE25a-6 borehole was inferred by Spengler et al. (1984) to represent possible block rotation by faults located near the borehole. However, any rotation that may be present has apparently not produced detectable variances in the elevations of lithostratigraphic zones with respect to other boreholes in the area (Figures 3-5 and 3-6). Spengler and Rosenbaum (1980) also noted the apparent absence of vertical offset between boreholes, and they inferred possible strike-slip movement in Drill Hole Wash on the basis of possible block rotations about a vertical axis as indicated by changes in paleomagnetic directions and foliation strikes between boreholes. Scott et al. (1984) reviewed additional data collected after the Spengler and Rosenbaum (1980) study and concluded that no significant block rotation was indicated by the data, although they concluded that Drill Hole Wash was underlain by minor, northwest-trending, strike-slip faults.

The average dip (10°) of foliation in borehole USW G-4 (Spengler et al., 1984) and the average dip of 8° in borehole UE25a-6 (Spengler and Rosenbaum, 1980) is greater than that indicated by the correlation of lithostratigraphic zones between boreholes in the area. This may indicate that foliation is not necessarily parallel to bedding in the welded flows. Spengler and Rosenbaum (1980) suggested the following reasons for the degree of scatter observed in the foliation measurements from a borehole: (1) errors in measurement, (2) minor slumping, and (3) non-uniform compaction of the ash-flow tuff following emplacement. Some of these factors may also serve to produce a systematically increased average dip of foliation compared to the dip of lithologic contacts.

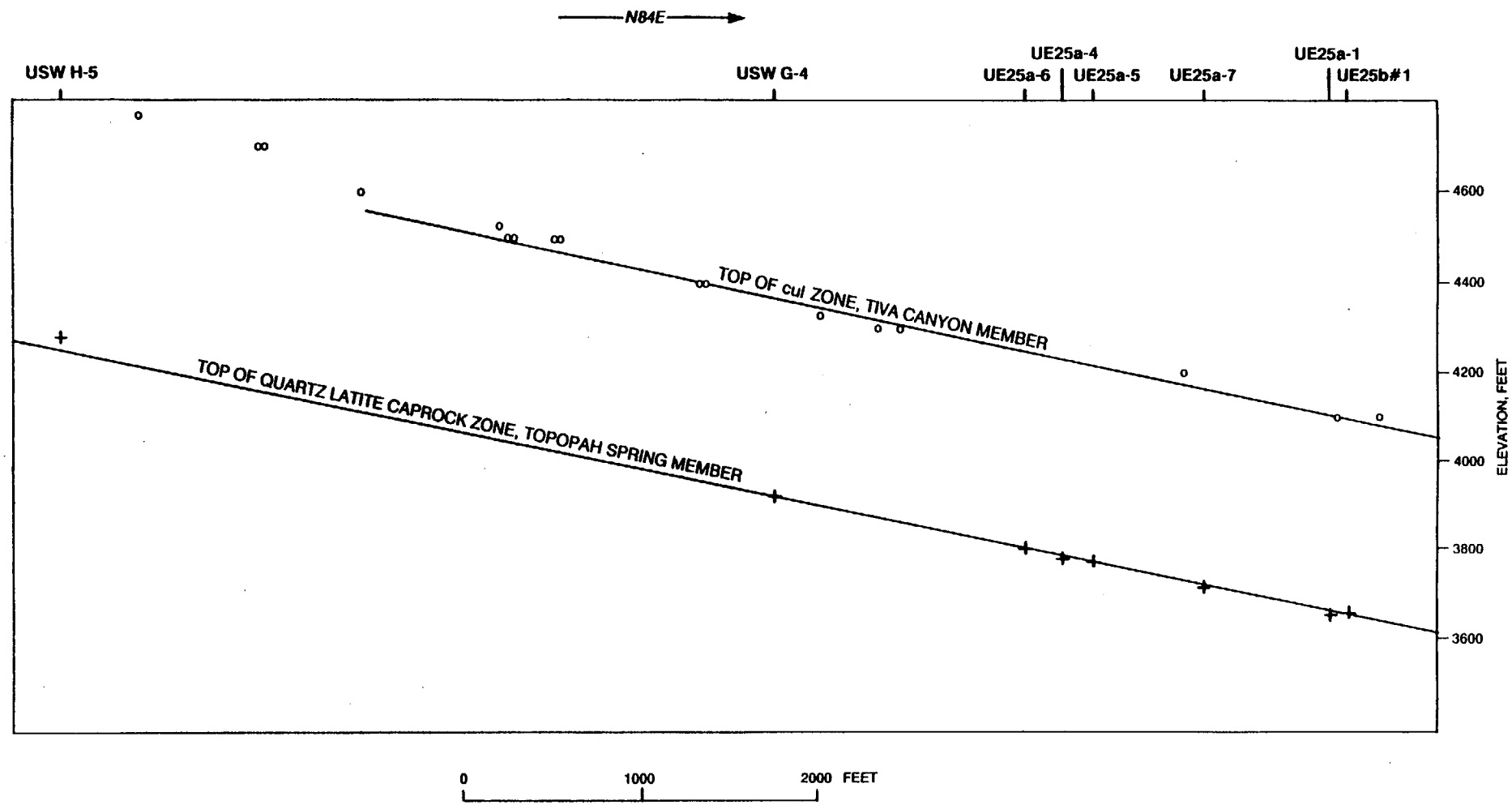


Figure 3-6. Section along direction of dip calculated for the top of the quartz latite caprock zone in the Topopah Spring Member using data from boreholes USW G-4, UE25a-6, and UE25a-5. Data on the elevation of the quartz latite caprock zone from other boreholes in the area and the elevation of the top of the cul zone in the Tiva Canyon Member from Scott and Bonk (1984) are projected to the section to determine accuracy of calculation. Borehole data from Spengler and Rosenbaum (1980), Spengler and others (1984), Lahoud and others (1984), Spengler and others (1979), and Bentley and others (1983). Location of boreholes shown on Figure 2-1.

3.3 REVIEW OF AERIAL PHOTOGRAPHY

Two sets of aerial photographs were reviewed by members of the geology subcommittee. The subcommittee members who reviewed the photographs were T. A. Grant, J. M. Davenport, D. Cummings, D. F. Fenster, G. L. Shideler, and R. P. Snyder. The purpose of this review was to evaluate the geologic interpretations shown on the mapping by Scott and Bonk (1984, and in Dixon, 1982), and also to evaluate whether there was any remote sensing evidence that might indicate the presence of a fault near the ES locations as shown on Smith and Ross (1982).

3.3.1 PHOTO SET 1

This is the same set of photographs that was used by Scott and Bonk (1984) to plot their mapping results. Specific data on the photographs reviewed are:

Mission: USGS NTS
Date: 9-29-78
Scale: 1:12,000
Frames: 769, 770, 771

This set provides black-and-white coverage of Coyote Wash and the surrounding area and is of good quality. In general, units that apparently correspond to the mapping zones used by Scott and Bonk (upper cliff, upper lithophysal, rounded step, lower lithophysal) can be distinguished on the airphotos by differences in tone, texture, vegetation, and slope. The lithologic zones are more readily distinguished on the south-facing slopes than the north-facing slopes because of the thinner accumulation of colluvium on south-facing slopes. The accuracy with which contacts can be traced varies along the hillslopes and ground checking would be needed to accurately plot contacts. The Ghost Dance fault is a reasonably well-defined lineament marked by aligned, linear minor drainages and tonal changes in the areas of bedrock exposure on Dead Yucca and Live Yucca ridges. The expression of the fault is much more pronounced to the south of Live Yucca Ridge.

Comparison of the photo-interpretation by the subcommittee members with the Scott and Bonk (1984, and in Dixon, 1982) mapping shows a close agreement on the location of contacts and the Ghost Dance fault. The minor faults shown on the ESF potential site map (in Dixon, 1982) cannot be distinguished on the air photos.

Interpretation of this photo set agrees with the interpretation of Scott and Bonk (1984) that there is no evidence of faulting in the area between the exploratory shafts. Contacts appear to cross this area without interruption and no vegetation, tonal, or geomorphic lineaments are visible. This can be contrasted with the Ghost Dance fault which is very evident on the photos even though vertical displacement is only about 4 m in this area (map in Dixon, 1982). Based on an analogy with the Ghost Dance fault, the subcommittee members estimate that faults with displacements of greater than about 4 m would be detectable on these photos, while faults with displacement of less than 3 m may or may not be.

3.3.2 PHOTO SET 2

This photo set was flown over the ES area after the Scott and Bonk mapping was completed. Specific data on the photographs reviewed are:

Mission: ES-1
Date: 7-26-83
Scale: 1:2,400
Frames: 36-41, 51-55, 64-69

The photos are black-and-white and are generally of good quality. However, some flight lines have bends in them and the westernmost of the lines appears to have been flown at a different height above the ground surface. These photos were interpreted stereoscopically and as lay-down mosaics to check for agreement with the contacts as mapped by Scott and Bonk. The photos were also checked for lineaments for comparison with the faults mapped by Scott and Bonk.

The zonal contacts used by Scott and Bonk (1984, and in Dixon, 1982) can be discerned on the photos by differences in tone, texture, and slope. The locations of the contacts between these zones agree with those shown by their mapping in the area. However, the contacts are generally not sharply defined on the photos. A strong jointing or fracture pattern is evident in the area, particularly in the upper lithophysal (cul) zone of the Tiva Canyon Member of the Paintbrush Tuff. These fractures are expressed on the photos as prominent vegetation alignments. The fractures generally trend NW and NE, but other trends were also noted. A particularly well-developed area of fracturing occurs on the south-facing slope of Dead Yucca Ridge, just west of the Ghost Dance fault and is indicated as such on the Scott and Bonk (1984) map.

The Ghost Dance fault is well defined across Dead Yucca Ridge as an aligned gully system. The fault is much less prominent across Live Yucca Ridge on this set of photos. No lineaments or evidence of offset were noted in the area of the exploratory shafts and the inferred fault in Smith and Ross (1982). One lineament (not shown as structure on the Scott and Bonk map) was noted near the western side of frame 36 by one of the interpreters. It consists of a faint, NNE-trending alignment of vegetation that crosses Drill Hole Wash and the eastern tip of Diabolus Ridge. The lineament therefore occurs in areas of both alluvium and bedrock. A fault mapped across Azreal Ridge by Scott and Bonk (1984) may connect with this feature. The cause of the lineament is unknown and no offset was observed. The lineament does not appear to extend to Dead Yucca Ridge.

The Ghost Dance fault, with about 4 m of offset in this area, is generally well-expressed in the area, but not continuously so. This indicates that a long fault with this amount of displacement should be detectable, but a shorter fault with displacement in this range may not always be detectable on this set of photos.

3.4 REVIEW OF FIELD RELATIONS

3.4.1 BACKGROUND DATA ON THE FIELD REVIEW

The field review took place on June 7 and 8, 1989. The geologic mapping of Scott and Bonk (1984, and in Dixon, 1982) was reviewed on Dead Yucca Ridge over an area that extends eastward from the Ghost Dance fault and includes the present ES locations. The geology subcommittee also reviewed the exposures on the north-facing slope of Live Yucca Ridge and the expression of the Ghost Dance fault on Live Yucca Ridge, in Split Wash, and on Whale Back Ridge.

The field review was conducted by locating, evaluating, and tracing out contacts, fracture zones, and breccia zones shown on the maps being reviewed. The geology subcommittee worked as a single group in evaluating and tracing contacts in the area of the exploratory shafts. In this area, the contacts were located and marked by stakes and flagging as the contacts were traced across the face of the slope. The criterion for evaluating the presence or absence of faulting was based on the definition of a fault, i.e., evidence of displacement of lithologic contacts.

3.4.2 SELECTION AND NATURE OF CONTACTS

Three zones in the Tiva Canyon Member, informally termed the lower lithophysal, rounded step, and upper lithophysal zones, are identified on the existing maps of the Coyote Wash area. The geology subcommittee traversed the north slope of Coyote Wash and reviewed the selection of mapping subdivisions in the Tiva Canyon Member by Scott and Bonk (1984, and in Dixon, 1982). The subcommittee located the zonal contacts used by Scott and Bonk and found that the contacts were characterized by changes in the abundance of lithophysae, fracture density, and weathering characteristics (Figure 3-7). The nature of the zonal subdivisions was described by R. P. Snyder and others to the group on June 7. The subcommittee agreed with Scott and Bonk that these subdivisions are reasonable in this section of the Tiva Canyon Member.

The subcommittee also found that these contacts could be traced across the area with an accuracy that would be suitable for the 1:12,000-scale mapping used by Scott and Bonk. However, the subcommittee also found that the contacts between these zones are gradational over a vertical range of 1 to 2 m and that the contacts need not be planar, but may undulate. These factors, as well as the variable degree of exposure on the hill slope, impose limits when very precise results are required from surface geologic mapping.

3.4.3 SURFACE EXPRESSION OF KNOWN FAULTING

The geology subcommittee and the rest of the TAR team also reviewed the expression of known faulting in the area, in order to evaluate whether distinctive characteristics were present that could be used in the detection of faulting in the area. The review consisted of examining the Ghost Dance

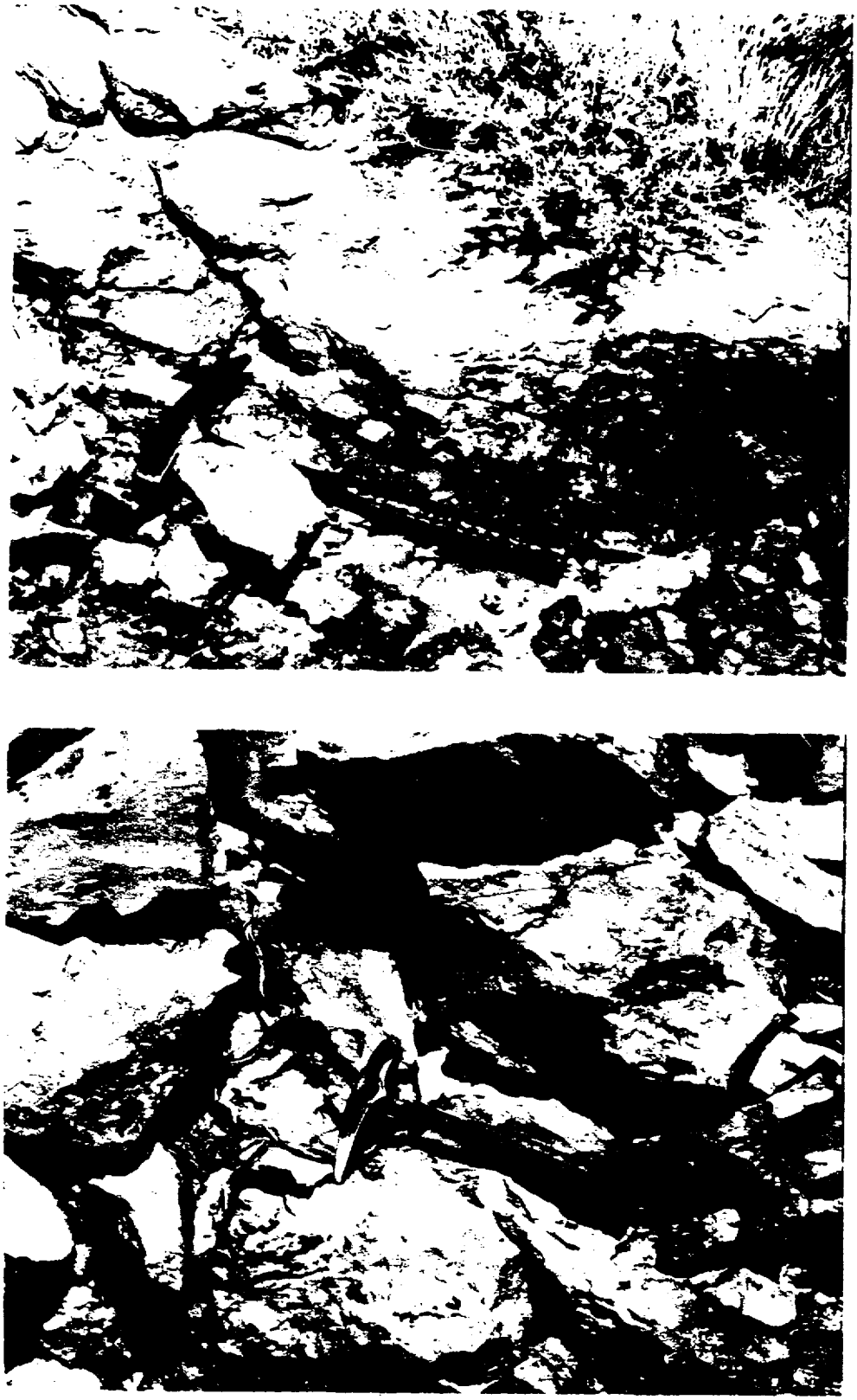


Figure 3-7. Photographs of the upper lithophysal zone (upper photo) and rounded step zone (lower photo) of the Tiva Canyon Member.

fault, the closest mapped fault to the ESF that has measurable offset, at several points along its trace.

Bedrock exposures of the fault were not present in the Coyote Wash area because the fault trace is covered by talus and alluvium. However, about a 3 to 4 m offset of the contact between the rounded step and upper lithophysal zones could be detected across an alluvial/colluvial-filled gully on the south-facing slope of Dead Yucca Ridge. Near the crest of this ridge, exposures are nearly continuous across the area where the fault would be projected, but no expression of the fault such as a breccia zone or increase in fracture density was evident.

The geology subcommittee also reviewed the area where the Ghost Dance fault crosses the south-facing slope of Live Yucca Ridge. Two long, narrow strips had been cleared of talus on this slope for earlier fracture studies. Features such as breccia zones or intensely fractured zones indicative of faulting were not evident in these cleared areas. However, these cleared strips probably had not been optimally located so as to intersect the Ghost Dance fault. A trench across the alluvium in Split Wash at the base of this slope also was visited by the TAR team; no evidence of faulting was observed in these alluvial units. However, some team members felt that the trench may not have extended far enough to the west to intersect the fault.

The final location along the Ghost Dance fault visited by the subcommittee and the TAR team was the unnamed, east-trending wash south of Whale Back Ridge. This is the area where displacement on the fault appears to be the greatest. Drillhole USW WT-2 is located at the west end of this wash with USW UZ-N48 and -N49 located adjacent to the Ghost Dance fault. Prominent breccia zones up to about 0.5 m wide were noted along the fault trace on slopes on both sides of the wash in this area. Stratigraphic offset is quite noticeable on the south-facing slope of the wash. The caprock zone is downthrown on the west and the upper vitrophyre (upper cliff zone?) is juxtaposed with the upper lithophysal zone along the crest of Whale Back Ridge. D. Dobson and D. Fenster noted that downslope creep of blocks from the caprock zone on the downthrown side of the fault may give the impression of greater apparent dip-slip displacement than has actually occurred. Evidence of faulting was not apparent on the north-facing slope of Whale Back Ridge where colluvial cover is thick.

The summary finding of the geology subcommittee was that small faults may not necessarily have distinctive or recognizable secondary features such as breccia zones or prominent fracturing that would aid in their recognition in the Coyote Wash area. The subcommittee, therefore, concluded that the tracing of contacts and the recognition of offset was the most suitable field geological method for locating faults in this area.

3.4.4 EVIDENCE OF FAULTING IN THE VICINITY OF THE EXPLORATORY SHAFTS

The geology subcommittee reviewed in detail the contacts between the lower lithophysal (cll), rounded step (crs), and upper lithophysal (cul) zones of the Tiva Canyon Member on the south-facing slope of Dead Yucca Ridge in the vicinity of the exploratory shafts. The subcommittee members that

participated in the field review of this area were T. A. Grant, J. M. Davenport, R. P. Snyder, G. L. Shideler, and D. F. Fenster. Smith and Ross (1982), on the basis of modeling of a resistivity and induced polarization survey obtained along Coyote Wash, inferred a fault trending through the area between the two shafts. However, Scott and Bonk (1984) and Barton et al. (1989) show zonal contacts extending across this area without any offset on their geologic map. The geology subcommittee first located and traced the contact between the cll and crs zones across this area to review the interpretation of Scott and Bonk (1984) and Barton et al. (1989). As the subcommittee traced the contact across the slope, they marked the contact with stakes and flagging in order to aid in locating potential offsets. The crs-cul contact was then traced in a similar manner across the area.

No evidence of faulting was found in either traverse along the two contacts. The contacts, as marked by the stakes and flagging, showed continuity with no evidence of offset. The geology subcommittee also found no evidence of fracture or breccia zones across the area of inferred faulting that might be indicative of fault movement. Because of the gradational nature of the contacts and degree of exposure, the level of confidence or accuracy in locating the contacts varied somewhat along each of the traverses. In some areas, such as along much of the crs-cul contact, and along the eastern end of the cll-crs traverse where the contact curved around the nose of the ridge, the subcommittee had a relatively high level of confidence in picking the contact; it was probably located within a vertical error of about $\pm$ 0.5 m. In other areas, the possible error in locating the contact was somewhat greater. It was the consensus of the geology subcommittee that vertical offsets greater than 2 to 3 m would have been detected along these traverses. As a result of this field review, the geology subcommittee found no reason to disagree with the mapping interpretation shown by Scott and Bonk (1984) or Barton et al. (1989) for the ES area.

3.4.5 EVALUATION OF FRACTURE AND BRECCIA ZONES

The Scott and Bonk mapping (1984 and in Dixon, 1982) shows fracture zones and breccia zones occurring in the area between the Ghost Dance fault and the exploratory shafts. The geology subcommittee reviewed this area and did find these areas of fractures and thin zones of breccia that were indicated by the prior mapping.

The breccia zones are thin (about 2 to 10 cm wide) and may extend for considerable distances across the hill slope. At the surface, the zones consist of angular clasts of tuff in white carbonate(?) matrix (Figure 3-8). No evidence of differential movement could be found across these breccia zones. This probably indicates that the breccia zones are not faults, but are the result of slight deformation in the brittle tuffs. At some locations, it was also noted that the breccia did not appear to be of tectonic origin, but instead may consist of deposits of angular colluvium that collected in bedrock depressions and were cemented by pedogenic carbonate-forming processes. Some of the breccia zones may also be the result of surficial processes that consist of the filling of weathered and eroded fractures with colluvium, which is cemented by pedogenic processes

Figure 3-8. Photographs of breccia zones found on the south-facing slopes of Dead Yucca Ridge between the Ghost Dance fault and ES-1.

that moved carbonate and silica down the fractures. This would be a similar process to that proposed for the carbonate fillings in Trench 14 by Taylor and Huckens (1986). This possibility could indicate that these breccia zones may have a different character at depth than at the surface. An alternate view would be that the breccias are the result of minor tectonic adjustments along fractures and that the carbonate fillings are the result of vein deposition by upward moving fluids.

Fractures and cooling joints are also common features in the area. Fractures may or may not contain a thin filling of carbonate. Cooling joints are most common in the upper lithophysal zone. The cooling joints have a smooth joint surface that is cut by a series of interconnecting channels or grooves that are thought to be the result of outgassing of the tuff into the cooling joint as the ash flow cooled (Figure 3-9). This hypothesis is based on mineralization that occurs in the grooves and an observation that some grooves appear to emanate from lithophysae. The geology subcommittee noted some evidence that fractures and joints were strata-bound within the mapped zones of the Tiva Canyon Member. This would indicate that fracture density should be expected to vary in the exploratory shafts as different zones are penetrated. It was the conclusion of the subcommittee that these breccia zones, joints, and fractures are ubiquitous in the Coyote Wash area (and probably to the entire repository area) and should be anticipated in the exploratory shafts.

While the geology subcommittee was reviewing a cleaned bedrock pavement at the crest of Dead Yucca Ridge, near the Ghost Dance fault, it was noted that relatively large and deep pockets or holes were formed where two prominent fractures intersected (Figure 3-10). This was apparently the result of fracturing of the rock in the area of the acute angle between the two fractures, followed by the weathering and removal of the fractured material during the cleaning process. It was speculated by some geology subcommittee members that, if these intersections occurred at depth along the resistivity lines, the fractured areas might be locations where increased moisture may collect, and that these moisture concentrations could produce some of the anomalies noted by the resistivity survey. It is also possible that the cooling joints with their associated outgassing grooves or channels might be areas where increased moisture might collect.

3.5 CONCLUSIONS AND RECOMMENDATIONS

3.5.1 CONCLUSIONS CONCERNING THE EXISTING MAPPING

The geology subcommittee agreed with the geologic mapping of the Coyote Wash area as presented in Lipman and McKay (1965), Scott and Bonk (1984, and in Dixon, 1982), and Barton et al. (1989). The geology subcommittee found the methods used in preparing the maps to be reasonable for the scales used in the compilation of these maps. The geologic interpretation and map accuracy also were found to be reasonable and acceptable for the mapping scale used.

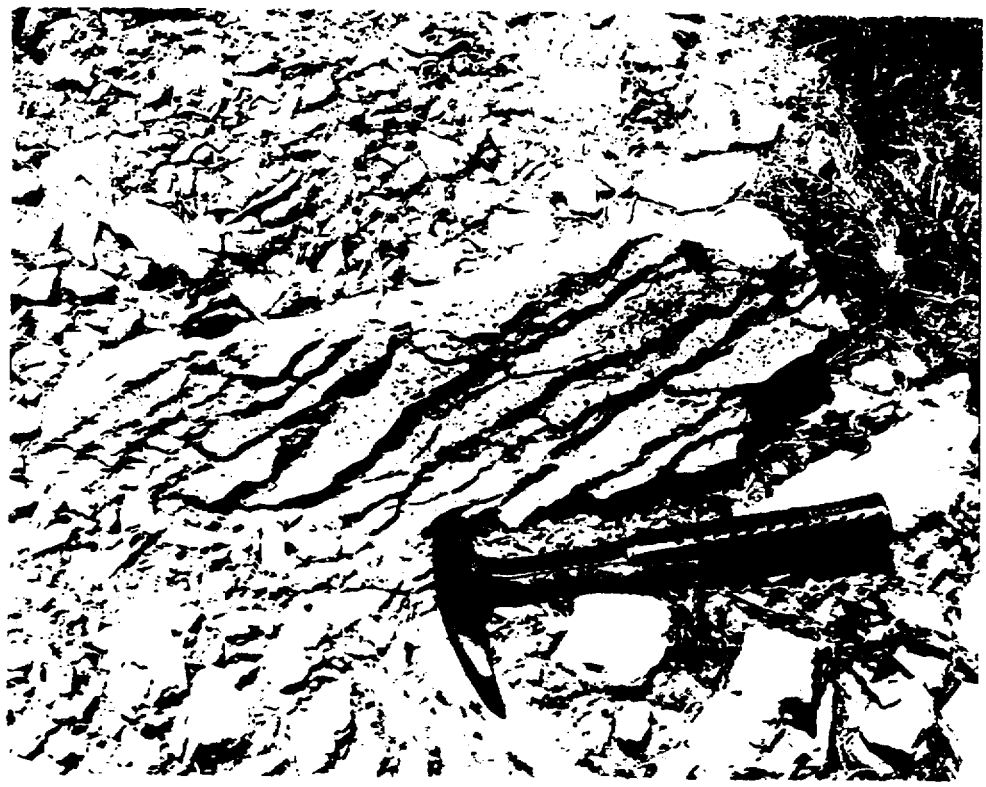


Figure 3-9. Photographs of cooling joints in a cleared pavement found on the crest of Dead Yucca Ridge near the Ghost Dance fault.

Figure 3-10. Photograph of pocket or hole formed at the intersection of two fractures in a cleared pavement found on the crest of Dead Yucca Ridge near the Ghost Dance fault.

3.5.2 CONCLUSIONS CONCERNING THE GEOLOGIC EVIDENCE FOR OR AGAINST A FAULT IN THE VICINITY OF THE EXPLORATORY SHAFT

The geology subcommittee found no evidence that would indicate the presence of a fault in the area between the two exploratory shafts, as postulated by Smith and Ross (1982). The review of the aerial photography revealed no lineaments or other evidence of faulting in this area. The lithologic logs from boreholes in the area show no evidence of lithologic contacts occurring at anomalous elevations, or missing or added section that might indicate a concealed fault below the Tiva Canyon Member. The field review of the contacts between the lower lithophysal, rounded step, and upper lithophysal zones of the Tiva Canyon Member confirmed that these contacts cross the area immediately upslope from shaft locations without any recognizable offset. No evidence of breccia or gouge zones was detected that might affect shaft construction (see Section 6.1).

The nature of the contacts and the exposures in the area between the exploratory shafts indicates that the methods employed by Scott and Bonk (1984) and the review geology subcommittee would have detected faults with displacements greater than 2 to 3 m. However, minor faults with small displacement are known to exist at other localities where conditions favor their detection (Scott and Bonk, 1984, and in Dixon, 1982). The presence of such minor faults, with offsets less than the detection limits allowed by the nature of contacts and local exposures, should be considered as possible at other localities, such as Coyote Wash. Because faulting in the area is not always accompanied by prominent secondary features, it is possible that a fault with a displacement that is less than 2 to 3 m could exist, undetected, in this area. It is also possible that faulting could exist in this area as a zone of distributed displacement along numerous small faults. However, the total offset across such a zone of distributed displacement would have to be small because an apparent increase in the dip of the contact is not evident in this area. A third possibility is that a fault is present at depth that predates, and is buried by, the Tiva Canyon Member. Figures 3-5 and 3-6 indicate that a significant pre-Tiva Canyon fault may not be present.

3.5.3 RECOMMENDATIONS ON FUTURE GEOLOGIC INVESTIGATIONS

The geology subcommittee has the following recommendations that could be implemented to detect faults in the Tiva Canyon Member with greater accuracy than that discussed above.

3.5.3.1 Recommendation 1

The first step recommended by the geology subcommittee is that the contact between the lower lithophysal and rounded step zones be cleared of talus in the area between the shafts and the resulting continuous exposure be mapped in detail. The purpose of this effort would be to detect and locate any faults characterized by breccia or gouge zones with a width of about 3 ft or greater ("moderate faults" as defined in Section 6.1). As discussed in Section 6.1, such faults may increase shaft excavation costs and delay

schedules. Section 6 recommends that such faults be avoided if they can be detected during the pre-construction site selection process.

It is recommended that a strip about 4 to 5 m wide and 160 m long be cleared along the cll-crs contact in the area of the exploratory shafts. The clearing could be accomplished by a crew using compressed air or water and pry bars. The cleaned exposure should then be photographed and mapped in detail at a suitable scale (1:20 to 1:50) to show the nature of the contact and any structural features that might offset it.

3.5.3.2 Recommendation 2

A second step in the process to acquire even more detailed information would be to map the extensive exposures that will be created by ES pad excavation. The Title I design indicates that the cuts for the pad parallel to the wash would create bedrock exposures up to 20 m high across the area where the fault postulated by Smith and Ross (1982) is located. It is recommended that the pad excavation site be cleared of talus prior to blasting operations, using the procedures stated in Recommendation 1. The site should then be examined for faults, breccias, and fracture systems prior to the development of blast-induced effects. After excavation, the exposures should be cleaned and inspected before other ES work begins. The results of the inspection should be documented as shaft pad construction proceeds by photographing and mapping the exposures in detail at a suitable scale (1:20 to 1:50) to describe the nature of any faults, fractures, joints, and breccia zones that might be present. It is also recommended that the northern limit of the pad excavation be moved slightly to the north so that the contact between the lower lithophysal and rounded step zones is exposed in the cut. The pad excavation in the vicinity of the ES-1 shaft should also be designed to expose the fractures and breccia zone shown on the Scott and Bonk (1984, and in Dixon, 1982) maps near this location.

Chapter 4

SUMMARY OF GEOPHYSICS SUBCOMMITTEE

4.1 INTRODUCTION

This chapter of the RRM was prepared according to an outline that was developed by the geophysics subcommittee early in the activities of the TAR. The committee members individually expressed their concerns with the Smith and Ross (1982) report, and then jointly developed an outline for the chapter. The concerns used as the basis for the outline are summarized as technical issues in Section 4.4.

The reasoning underlying the outline makes several major distinctions in handling the subject matter. The original field surveys, including data collection, measurement accuracy, and position accuracy are treated together. Geoelectric modeling is treated next, and geologic interpretation is treated last. Modeling and interpretation are separated principally so that apparent resistivity structure, and the attendant uncertainty, can be understood separately from the uncertainty on geologic interpretation of that structure. This does not mean that known geologic information is not used to constrain the geoelectric modeling.

The following paragraphs give brief descriptions of each section:

Section 4.2 contains a description of the original dipole-dipole field surveys, and discussion as to the accuracy of electrical measurements. The location accuracy of the surveys is discussed, along with implications for the degree of misfit that is achievable in geoelectric modeling. Other geophysical surveys, particularly geoelectric surveys run at the site are also discussed briefly, with mention of their applicability to assessing the modeling and interpretation of Smith and Ross (1982).

Section 4.3 describes and analyzes the geoelectric models generated by Smith and Ross (1982) for Lines A, B, and B′ in Coyote Wash. The analysis includes definition of an index of average misfit between computed and observed data. Misfit between the observed data and the Smith and Ross geoelectric models is computed and analyzed. A systematic process of simplification is used to reduce the complexity of the Smith and Ross models, and the misfit resulting from the simplified models is computed and analyzed. A summary of geoelectric modeling considerations is provided in Section 4.3.5.

Section 4.4 presents the technical issues, or concerns with the Smith and Ross (1982) report, that were expressed by the geophysics subcommittee members at the beginning of the TAR. These issues were then used as the basis for developing the outline of Chapter 4, and for planning the other subcommittee activities.

Section 4.5 describes an extensive series of 2-D and 3-D sensitivity analyses performed by the geophysics subcommittee to test various hypotheses about the types of geoelectric models that fit the dipole-dipole data. Limits on the resolution of geoelectric structure, using available models and

data, are explored in a systematic manner. The effects of 3-D terrain are computed, and possible ways that off-axis conductive bodies can be misrepresented using 2-D modeling are investigated. A summary of sensitivity study results is provided in Section 4.5.3.

Section 4.6 discusses the possible geologic interpretations that could be used to explain results obtained from geoelectric modeling. The geologic interpretation of Smith and Ross (1982) is described, and then closely compared to what is currently known about geologic conditions. Available information on the geoelectric properties and electrical conduction mechanisms for earth materials at the site is reviewed, and the applicable data on electrical resistivity for stratigraphic units are summarized. A list of possible alternative geologic interpretations to that of Smith and Ross (1982) is presented. A summary of geologic interpretation considerations is provided in Section 4.6.4.

Finally, Section 4.7 provides a summary statement on the applicability of the geologic interpretation of Smith and Ross (1982) to the question of a possible fault at the planned location of the exploratory shafts. The section also proposes an additional, limited program of geophysical exploration of the Coyote Wash area. The rationale and detailed description of the recommended program are given, and the relationship of the recommended geophysics to recommended geologic studies is described. Major categories of geophysical methods and surveys that were considered in generating the recommendation, but not included in the program, are discussed.

Some TAR team members have noted that Chapter 4 has redundant parts, and some explanation is appropriate. For example, Section 4.2.2 (Other Surveys and Pertinent Data) shares some material with Section 4.6.3 (Petrophysical Relationships). Also, several topics are addressed both by Section 4.3 (Geoelectric Model) and Section 4.5 (Sensitivity Analyses for Geophysical Modeling), particularly Section 4.5.1 (Two-Dimensional Effects). Although the section could conceivably be shortened by perhaps one fourth, some benefit is derived from redundancy. More of the relevant information is readily available for assimilation in particular sections. Thus the subsections of Chapter 4 can be more easily read on different occasions. A well cross-referenced and thereby less redundant report also requires extra steps in preparation.

4.2 GEOPHYSICAL DATA APPLIED TO EXPLORATORY SHAFT FACILITY LOCATION AND INFERRED FAULT EVALUATION

4.2.1 ORIGINAL SURVEYS INTERPRETED BY THE UNIVERSITY OF UTAH RESEARCH INSTITUTE

4.2.1.1 Background

The polar dipole-dipole method and the slingram electromagnetic (EM) method were selected for a geoelectric evaluation of portions of Yucca Mountain because they are economical, and suitable for use on rugged terrain

(Hoover in Smith and Ross, 1982, p. 3). The dipole-dipole method was used to a greater extent than other resistivity methods because the equipment for it is portable, the method has inherently high-resolution, and the setup is more efficient than for other widely used resistivity methods (e.g., the Schlumberger method). The slingram method is quite portable, but was used mainly for reconnaissance because it has less ground penetration. Resistivity methods were preferred over EM methods for more detailed investigation because of depth penetration. Also, 2-D modeling algorithms for resistivity methods were more generally available than for EM methods at the time of the surveys. Published interpretation for several dipole-dipole lines is the principal subject of this review.

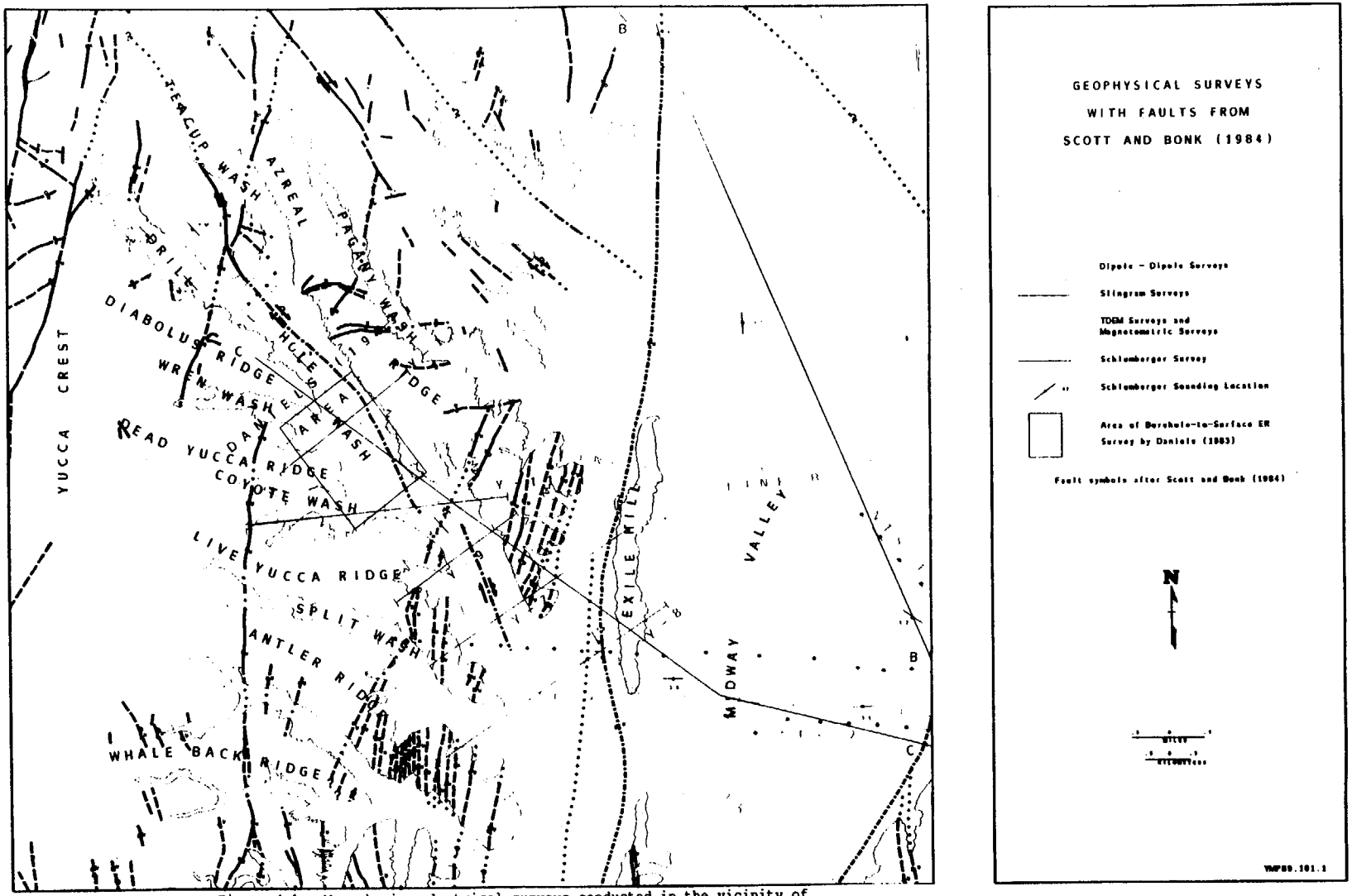
The USGS contracted with the Earth Science Laboratory, University of Utah Research Institute (UURI), in 1978 and 1979 for dipole-dipole induced polarization (IP)/resistivity interpretations of data from several survey lines at the NTS. Interpretation of data from two field campaigns resulted from these contracts.

The June 8, 1978, contract resulted in a report prepared by Ross and Lunbeck (September 1978). The areas surveyed were located in the Calico Hills and at Yucca Mountain, on the NTS. The resistivity/IP survey interpreted by Ross and Lumbeck was performed during June and July 1978 by Heinrichs Geoexploration Company of Tucson, Arizona. Five survey lines were completed, two of which were in the vicinity of Yucca Mountain (Figure 4-1, lines TR-3 and TR-4). The northwest segment of line TR-3 is along Drill Hole Wash; the southeast segment is in Midway Valley. Line TR-4 is oriented approximately east-west; the western end is in Split Wash. Neither of these lines crosses the "fault" interpreted by Smith and Ross (1982) in Coyote Wash, and neither crosses the along-strike extrapolation of the "fault," either to the south or to the north.

The June 19, 1979, purchase order resulted in a report prepared by Smith and Ross (October 1979), with interim interpretations submitted as letter reports by Smith and Ross to D. B. Hoover, USGS, on August 6, 1979, and September 13, 1979. The October 1979 report was released in 1982 as a USGS Open File Report with an introduction by D. B. Hoover. The field work for these surveys was performed by a USGS contractor, Phoenix Geophysics. Fifteen dipole-dipole lines were surveyed on Yucca Mountain, mostly on the northern and eastern portions. Most of these lines have not been interpreted, except for the seven lines in the area of Drill Hole Wash and Midway Valley that are interpreted by Smith and Ross (1982). Three of these lines are in Coyote Wash: one (Line A) is on the north side of the alluvial-filled wash and the other two (Lines B and B′) are on the south side (see Figure 4-1). Interpretations by Smith and Ross (1982) of the data collected along these three lines form the basis for the interpreted "electrical resistivity fault" in Coyote Wash near the proposed ESF location. Of the IP-resistivity lines acquired by Phoenix Geophysics, the lines that were not interpreted by Smith and Ross (1982) lie outside of the area of interest and have little bearing on the question of faulting in Coyote Wash.

The line locations and electrode positions shown on Figures 4-1 and 4-2 are based on a copy of the best location map available (Don Hoover, personal communication, June 1, 1989). The locations of dipole-dipole Lines A, B, and B′, are also shown on Figure 4-3. Also shown on Figure 4-3 are the positions

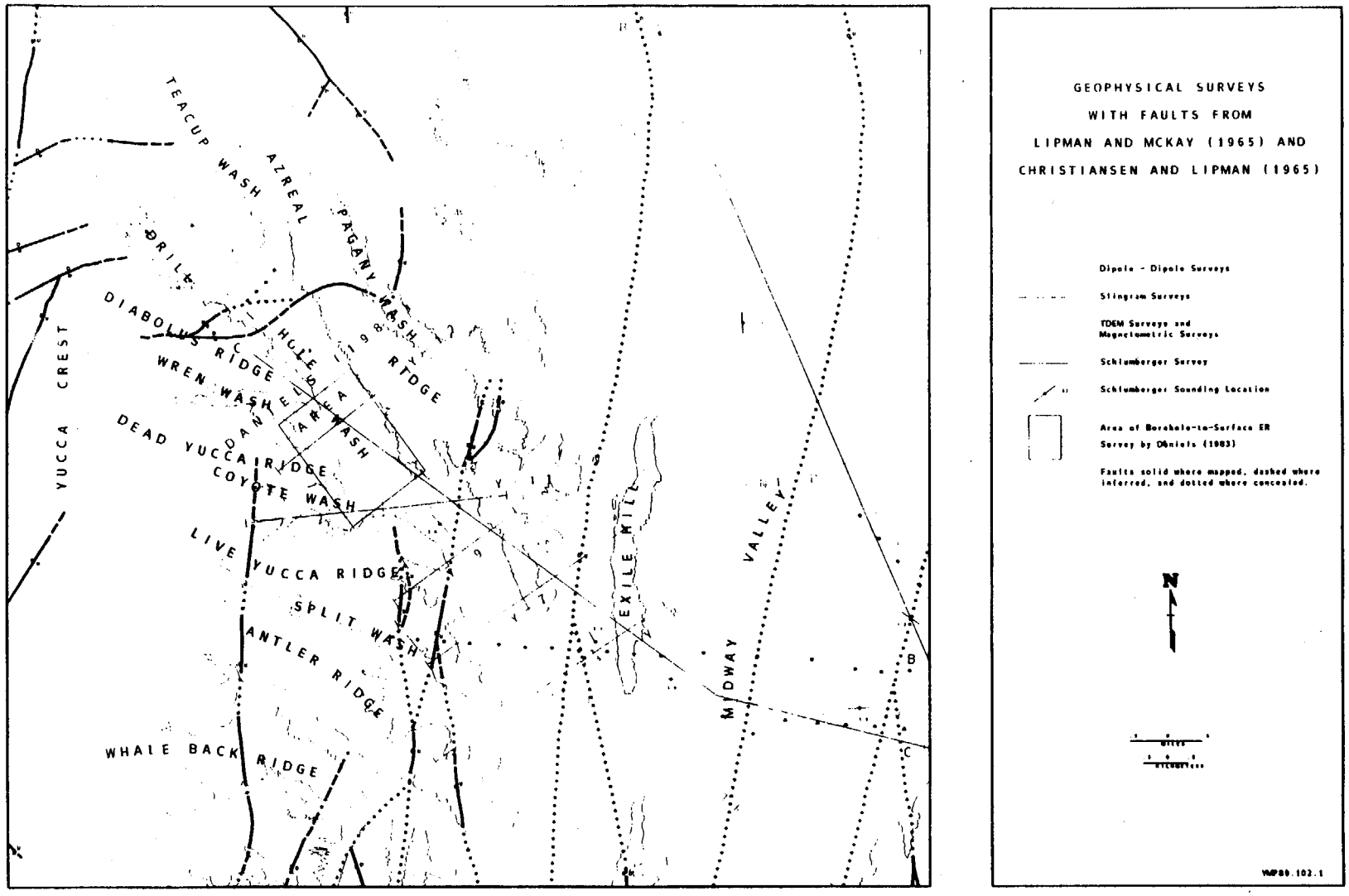
N775,000
E575,500



E558,000
N759,000

Figure 4-1. Map showing electrical surveys conducted in the vicinity of Drill Hole and Coyote Wash. Labeled surveys are described in Section 4.2 of the text. Fault map taken from Scott and Bonk (1984), and interpreted faults of Smith and Ross.

N775,000
E575,500



E558,000
N759,000

Figure 4-2. Same as Figure 4-1 except fault map taken from Lipman and McKay (1965)

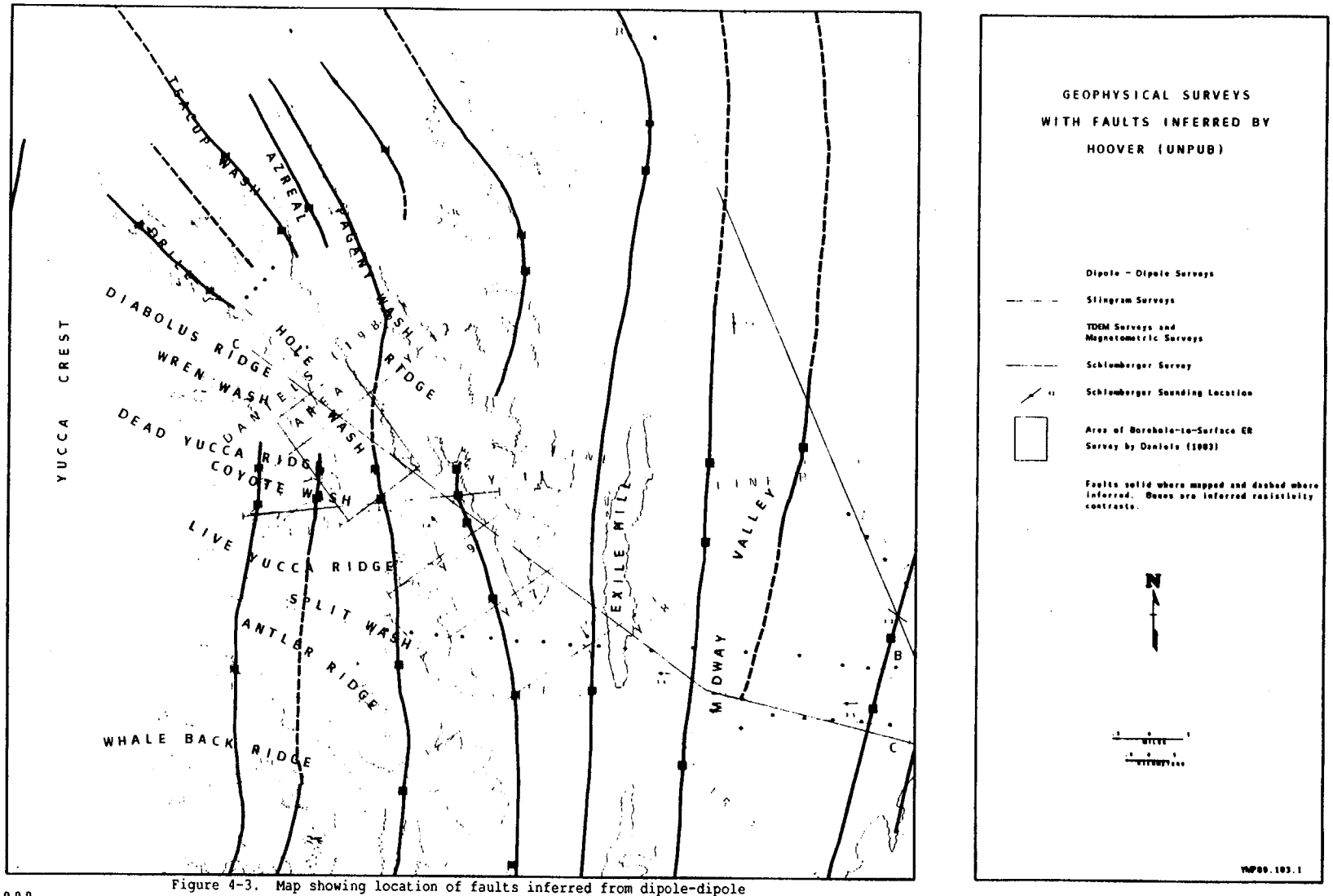


Figure 4-3. Map showing location of faults inferred from dipole-dipole geoelectric data and location of dipole-dipole lines. Boxes show where faults were interpreted from data on particular lines.

of faults inferred from the geoelectric data. This figure is based on a map (D. P. Klein, unpublished, written communication, 6-1-89) that was the basis of Figure 32 in USGS OFR 84-792 (USGS, 1984).

Smith and Ross (1982, pp. 10-13) suggest that the resistivity contrasts at the western ends of these lines are representative of the Ghost Dance fault mapped by Lipman and McKay (1965). Smith and Ross (1982, p. 11; Figure 4-2 this report) define a fault at stations 9W on both Lines A and B. They indicate (p. 11) that this "fault" is not shown on the map prepared by Lipman and McKay (1965). This "fault" at station 9W is the basis of this TAR. Line B' has a dipole spacing of 1,000 ft and is parallel to Line B; the center point of both lines is approximately at the same place. Smith and Ross (1979, 1982, p. 15; Figure 4-1 this report) define faults at Stations 4W, 1W and 0, and elsewhere.

A fault is not shown at Station 1W on Line B' (Figure 4-1) that would correspond to the inferred fault at station 9W, lines A and B. A consistency check between sense of displacement for faults inferred from Lines B and B' (Smith and Ross, 1982, Plates II and IV) is therefore not possible. Similarly, Smith and Ross (1982) did not estimate vertical offset for inferred faults, which is another possible basis for showing consistency between partially coincident lines.

Dipole-dipole lines TR3 and TR4 have been modeled using a 2-D algorithm (without including topography) by Ross and Lunbeck (1978). Data for dipole-dipole lines YM10 and YM11, also shown on Figure 4-1, are available but have not been published or modeled.

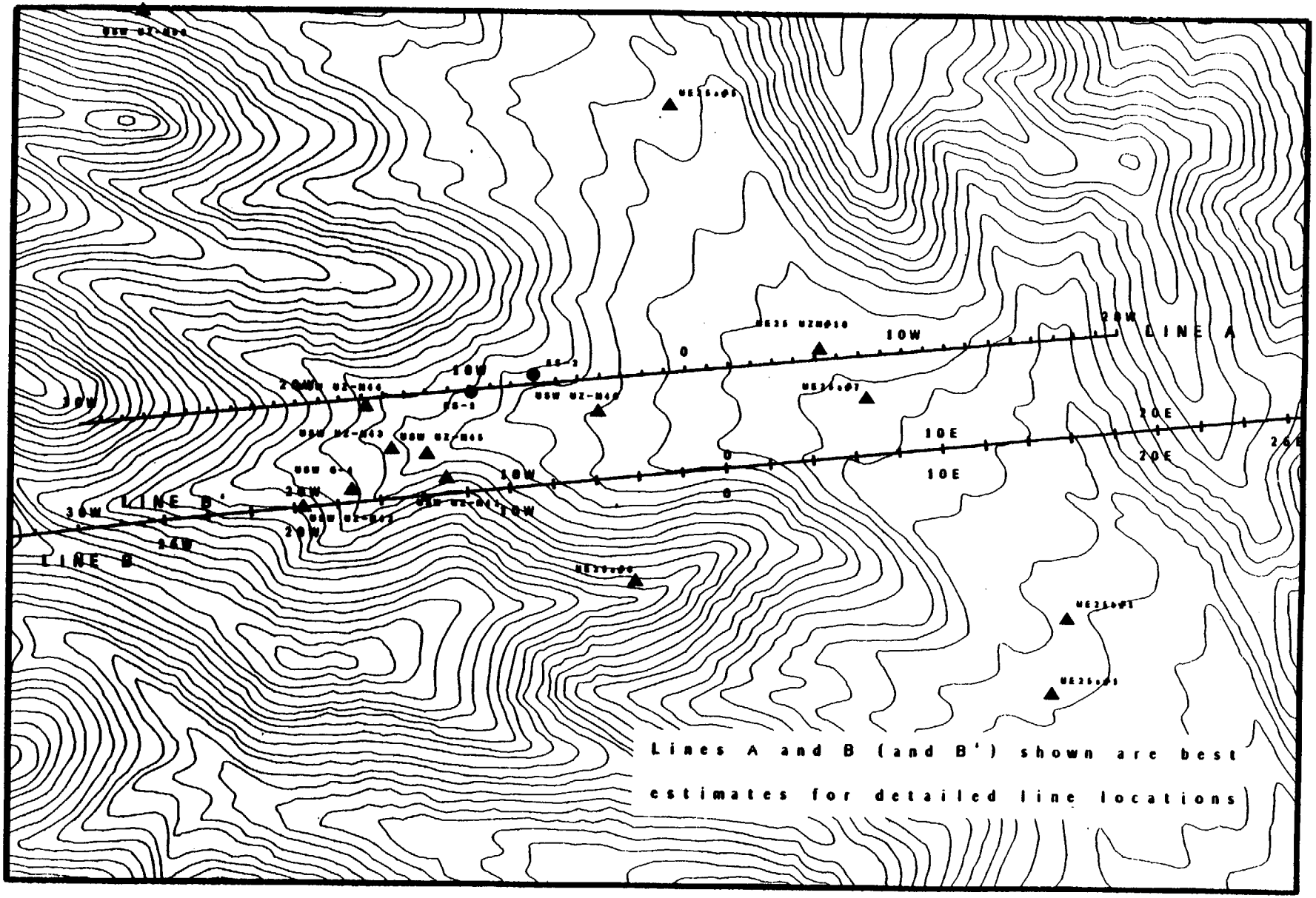
4.2.1.2 Data Acquisition

Dipole-dipole resistivity and IP data were acquired using Phoenix Geophysics instrumentation (Bell, 1980) and survey procedures described by Sumner (1976). Schlumberger resistivity soundings were acquired under the same contract (above) and are also described by Bell (1980). Schlumberger soundings locations were limited to basin areas, including the axes of major washes, where long electrode spreads could be used. Schlumberger sounding 38 (Senterfit et al., 1982; also see Figure 4-2) is adjacent to dipole-dipole lines A, B, and B', and is considered in this review as a means to constrain the geoelectric model.

Lines A and B were surveyed with 200 ft dipoles (A=200'; this is the separation between electrodes for both source and receiver dipoles), and separations between dipole centers of N=1 to 6 (400 to 1,400 ft; N refers to the number of dipole-lengths, "A," between the nearest electrodes of the source and receiver). The electrodes of Lines A and B were placed at positions 28W to 28E (Figure 4-4) spanning a total distance of 5,600 ft, part of which crosses Drill Hole Wash and traverses the flanks of Coyote Wash (note the station location units of 100 ft). Line B' used 1,000-ft dipoles with separations N=1 to 6 (2,000 to 7,000 ft). The electrodes of Line B' were placed at positions 10W to 8E (note the units of 1,000 ft). Line B' was coincident with Line B, but spanned a distance of 18,000 ft. The same origin for station location coordinates (station 0) was used for Lines B and B'. In

N7[illegible],000

E567,500



E561,500

N764,000

Figure 4-4. Map showing the location of dipole-dipole lines and electrode locations in relationship to topography for the vicinity of Drill Hole Wash and Coyote Wash.

YMP89.104.1

the following discussion, the positions of electrodes on Line B′ will be referred to by numbers 100W to 80E, corresponding to station location units of 100 ft and consistent with the units of lines A and B.

Signals were generated using a current source of about 3 amperes peak-peak. Variations from 2.5 to 3.5 amperes occurred as a result of variable grounding conditions. The signals consisted of square-waves at 0.125 and 1.25 Hz. The difference in received voltages at the two frequencies provides the IP response, whereas the apparent resistivity is based on the 0.125 Hz signal. Received signals were measured in millivolts with three significant digits; typical received voltages were in the range of 100 to 600 mV. Data records of the measured values are available at the offices of the USGS Branch of Geophysics, Denver, Colorado.

Line positions were established by fixing a starting point based on triangulation using a Brunton compass. The lines subsequently followed an azimuth, based on Brunton compass sighting. Electrode positions along each line were measured with a tape.

Basic data consists of received voltage (V), source current (I), and distance parameters of the array (N and A). The observed voltage is normalized by the source current, and reduced using an equation based on a 1-D response that converts the observed parameters into units of resistivity (ohm-m). The equation (Sumner, 1976, p. 25) is:

$$R = 3.1416\ (V/I)\ N(N+1)(N+2)A$$

where N and A have been defined above. R is referred to as "apparent resistivity," and is the equivalent uniform resistivity of a half-space earth model that would produce the observed response (V/I for given A and N). Apparent resistivity as a function of position is the "observed" data used in modeling and interpretation.

4.2.1.3 Data Reliability

Measurement errors that would affect the observations can be caused by miscalibration, transient electronic malfunctions, operational or recording errors by field personnel, interference from signal sources other than the source dipole, voltage transients caused by vibrations of the receiver wire or grounding noise, and errors in data reduction.

Collected data were reviewed in the field by on-site apparent resistivity reductions and pseudosection plots. Significant variations in the earth response could thus be identified, and if appropriate, measurements could be repeated. Also, the contract for data acquisition specified that measurements for N=6 geometry be repeated at regular intervals. Observed data (Smith and Ross, 1982, plates II and IV) show numerous repeat values with typical discrepancies on the order of 1% for apparent resistivities of 100 to 2,000 ohm-m. These plates have been checked against the contractor data, for this review, to verify that they accurately represent the original data. From repeat measurements, one may infer that expected random

uncertainty in measurements is about 5%, defined in terms of relative error (RE):

$$RE = \Sigma \left[\frac{|Ri - Rm|}{Rm}\right] \times 100\%$$

where Ri are repeat measurements and Rm is the mean value of Ri.

Further tests of data consistency were performed for this review. The data were plotted as "sounding curves" (resistivity vs. N for a given source location). Figure 4-5 is an example (the computed apparent resistivities from the Smith and Ross report are also plotted) that shows the observed data exhibit consistency and "smoother" variation with depth than the calculated values. The data have also been recontoured at intervals of 100 ohm-m and at 10 equal-logarithmic intervals per log-cycle (more than twice the detail of the contours in Smith and Ross, 1982) to look for outliers. The results confirm that the observed response is internally consistent. A few outliers are found (e.g., on dipole 8E to 10E of Line A: values of 1437, 1512, and 615). These outliers may in fact not be "errors," but may be due to shallow (< 1*A) resistivity contrasts. A final test was to plot the data in profile, where data for a given N are plotted as a function of distance along profile for all source and receiver locations. These plots also showed no major discrepancies in smoothness, or the along-line variation of data for different N.

One cannot evaluate constant bias that may affect all measurements equally except with a repeat survey. Phoenix Geophysics is a well-established company in the geophysical industry, and has likely developed instrumentation and calibration techniques so that bias can be detected and is not an important factor. However, the contract submittal report (Bell, 1980) does not document the calibration procedures or expected errors in the data.

4.2.1.4 Data Position Reliability

Mislocation of lines affects modeling and interpretation because topography and surface resistivity contrasts are probably important, and may be misplaced and thus modeled incorrectly. Triangulation using the Brunton compass is not particularly precise, but the resulting location error should be less than 200 ft. Station location errors could accumulate as survey lines are extended along an azimuth. Accordingly, it would be reasonable to assume a probable resultant uncertainty of +/- 200 ft on the survey line location.

The associated elevation uncertainty may be estimated using the Topopah Springs SW quadrangle (7.5', scale 1:24,000), and assuming that uncertainty in the placement of contours is probably about 1 contour interval. Lines A, B, and B' traverse topographic gradients of 20% to 40% in the Coyote Wash area (see Section 4.2.1.5). Thus, with misplacement of 200 ft, one can expect a mean station elevation error of about 60 ft. The effect of location

LINE A-A'

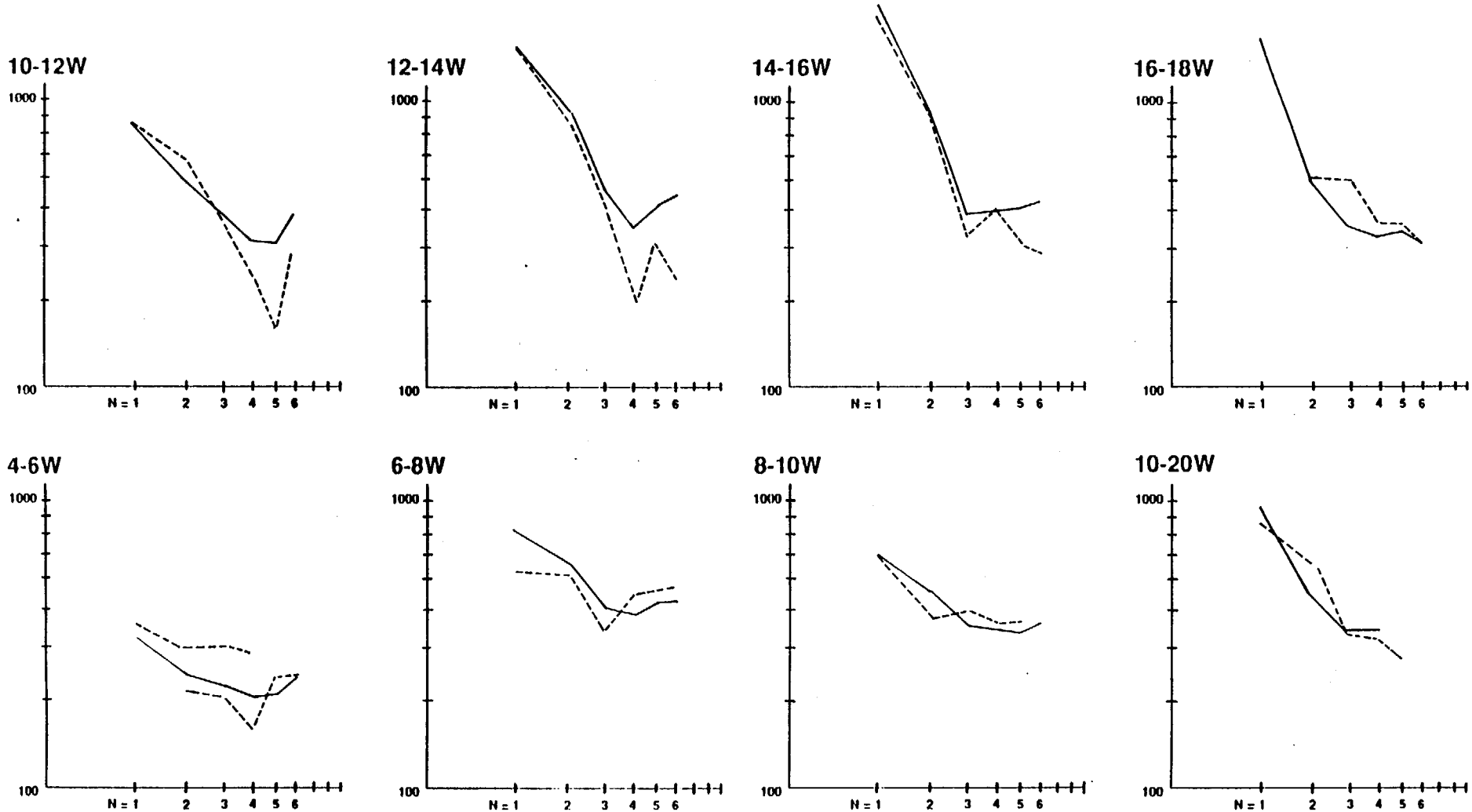


Figure 4-5. Selected data from Smith and Ross (1982) for Line A plotted as dipole-dipole "soundings" (see text). Circles show observed data; dots show the model response.

error tends to dominate the uncertainty of contour placement, so the mean elevation error is probably about 60 ft.

The modeling mesh used by Smith and Ross (1982) has a minimum vertical grid interval of 20 ft. Although individual elevation values may have errors of 60 ft, or several model elements, the error of relative differences in elevation between adjacent stations is much smaller, probably on the order of one element or less. Topographic effects are minor unless gradients of ten degrees (about 17%) or more are encountered for distances of at least 2*A (Fox et al., 1980). Thus elevation uncertainty is probably not a major source of error in modeling. The effects that could be associated with uncertainty as to the location of survey lines with respect to surface alluvium, are very likely more important as discussed in the next section.

4.2.1.5 Topographic and Surface Effects

Dipole-dipole lines A, B, and B' (Figure 4-4) were run across the strike of Drill Hole Wash and along the strike of Coyote Wash. Line A is on the north flank of Coyote Wash, and lines B and B' are along the south flank of Coyote Wash about 400 to 500 ft to the south of Line A.

Coyote Wash is a canyon with a base-width of 400-500 ft, and with side slopes of 20% to 40% gradient. The ridges to the north and south of Coyote Wash rise as much as 200 to 300 ft higher than the dipole-dipole line locations, although some parts of the lines are adjacent to much lower parts of the ridges (Figure 4-4).

Drill Hole Wash strikes about 60 degrees E of the azimuth of lines A and B. It is also a canyon, but with less steep sides than Coyote Wash. Lines A and B cross Drill Hole Wash at an acute angle, thus the 2-D topography as represented by the models shown in Smith and Ross (1982, Plates II and IV) probably accounts for the important topographic effects of this wash.

The 2-D topographic effect calculations performed by Smith and Ross (1982) and described in Section 4.3.1.2.2, account for the in-line terrain effects in Coyote Wash with reasonable accuracy. The principal uncertainties related to terrain are the effect of small-scale (< 1*A) terrain variations, the impact of location uncertainty on the relative elevation differences between stations, and the effect of 3-D terrain features. Relative elevation errors and small-scale terrain variation are of limited magnitude, especially for larger values of N, but they are irreducible in the sense that no feasible application of additional constraints or modeling detail will provide reliable and realistic reduction of the attendant misfit. 3-D effects are probably much more important for the west end of Lines A and B than for the portion of the lines in Drill Hole Wash. Calculation of the magnitude of 3-D terrain effects is the subject of Section 4.5.2 of this review.

The thickness of alluvium has not been mapped in Coyote Wash, but it is known to be about 30 ft at borehole USW G-4, and 20 ft at UE25a#6 (Spengler and Rosenbaum, 1980, Spengler et al., 1984). Additional constraint is available from "neutron holes" UZN-40 through UZN-45. The resistivity of

alluvium in Coyote Wash has not been measured directly; the information available to constrain this parameter has largely come from Drill Hole Wash as discussed in Section 4.6.3.1.

Sensitivity studies published by Beyer (1977) show that a small (< 1*A) 2-D conductive body outcropping under a dipole-dipole survey line can have a significant effect on observed data. A similar effect may occur wherever Lines A and B traverse the alluvium-bedrock contact. The geometry of the contact is 3-D, but the resistivity contrast is potentially 1:10 or greater. Thus it is important to use available information on the geometry of the alluvium-bedrock contact, to understand the geoelectric structure of Coyote Wash. The uncertainty of line locations, azimuths, and station locations along the lines (+/- 200 ft as discussed in Section 4.2.1.4) translates to uncertainty of one dipole length (+/- 1*A) in the in-line location for structure known to cross the survey line. For surface bodies that are off-axis or marginal to the survey lines, location uncertainty translates to uncertainty as to whether the lines cross the bodies. Sensitivity studies presented in Section 4.5.2 address the magnitude of the possible effect.

In summary, there is no reason to suspect that either random or systematic measurement error, or relative elevation errors between stations are significant. 2-D terrain effects are basically accounted for in the original study of Smith and Ross (1982). 3-D terrain effects are probably limited to the western portions of Lines A and B, and are comparable to the calculation 2-D effects. Location uncertainty for surface conductors known to outcrop beneath the survey line produces uncertainty as to the position of the resulting data trend. Location uncertainty for off-axis surface conductors could produce greater uncertainty as to the location and magnitude of a resulting trend. Based on these considerations and the judgement of TAR team members, there is a level of uncertainty in the observed data that cannot be modeled or interpreted realistically. This uncertainty corresponds to a misfit or "noise" level of about 15% relative error.

4.2.2 OTHER SURVEYS AND DATA PERTINENT TO GEOELECTRIC ANALYSIS

Nine electrical surveys were run in the area of Coyote Wash from 1978 to 1981. Of these, three surveys were conducted in Coyote Wash near the proposed location of the ESF: (1) an electromagnetic (slingram) survey performed in 1978, (2) the 1979 electrical resistivity survey reported by Smith and Ross (1982), and (3) an E-field ratio telluric profile. Some of the other surveys were located in Midway Valley, Calico Hills, Jackass Flats, Fortymile Canyon, south of Whale Back Ridge, and in Drill Hole Wash.

Flanigan (1981) conducted EM horizontal loop (slingram) surveys in the general vicinity of Drill Hole Wash (see Lines Y1-Y4, Y7-Y9, Y11-Y15 shown in Figure 4-1) for the purposes of determining, by EM methods, whether the northwest-trending washes to the northeast of the site area are fault controlled. Another purpose of the survey was to evaluate three EM methods (slingram, turam, and VLF) for detecting conductors that might be associated with highly fractured or faulted zones. Diagnostic tests of the VLF and slingram methods were conducted across the Paintbrush fault (survey Y1 and Y2). The survey used a transmitter-to-receiver coil separation of 800 ft.

Measurements for the slingram survey were taken at intervals of 200 ft and at five different frequencies (222, 444, 888, 1777, 3555 Hz). Flanigan (1981) reports a depth of penetration of 400 ft at 888 Hz. Flanigan did not illustrate Turam and VLF survey results; however, the author concluded that these methods were apparently not sensitive enough to detect the relatively low contrast conductances. The slingram signature observed across the mapped trace of the Paintbrush fault was interpreted as a zone (340 ohm-m) about 400 ft in width. The resistivity contrast across the fault was not estimated.

Slingram Line Y-11 (Figure 4-1) was run along the axis of Coyote Wash, and is apparently coincident with Line B of Smith and Ross (1982). The data profiles shown in Flanigan (1981) for Line Y-11 do not show a definitive anomaly (> 10%) at the location (Station 1800) where Smith and Ross (1982) interpret a fault (Lines A and B, Stations 9W). The slingram acquisition parameters were such that the structure interpreted by Smith and Ross (1982) should have produced some recognizable slingram signal (see also Section 4.3.2.3) from dipole-dipole data. There is an apparent contrast at the intersection with Drill Hole Wash, which is consistent with other slingram data (Y-7, 8, 9, and 12), and indicates a highly conductive zone estimated to be less than 100 ft in width. There was no conductive anomaly associated with the Ghost Dance fault; however, as with the dipole-dipole lines, only the end of the line crossed the fault, and thus neither survey was well-suited to investigate it. The southwest end of Line Y-12 (Flanigan, 1981, pp. 5, 19) is on Dead Yucca Ridge north of Coyote Wash. This line would cross the Smith and Ross fault if the fault was extrapolated along its strike (near Station 800, Y-12). Line Y-12 does not show any indication of a fault at this station at any of the frequencies measured. Flanigan's (1981) data elsewhere indicate anomalous conductors, at various locations including some near dipole-dipole lines from which Smith and Ross (1982) have inferred faults. Based on limited review, the two data sets seem to correspond more closely elsewhere than at Coyote Wash.

The dipole-dipole IP/resistivity lines interpreted by Ross and Lunbeck (1978) include Lines TR-3 and TR-4 of Figure 4-1. Both of these lines used 1000-ft dipole spacing, and were recorded at multiple in-line spacings of 1, 2, 3, and 4. Interpretations were made using the 2-D finite-element program initially developed by Rijo (1977), and modified by UURI (topography not included). Line TR-4 trends N84W, and several faults were interpreted based on 2- to 3-fold subsurface resistivity contrasts. One fault seen on the interpreted TR-4 line at the mouth of Split Wash is consistent with surface evidence of Lipman and McKay (1965) and Scott and Bonk (1984). There are several other inferred faults in Midway Valley west of the Paintbrush Canyon fault, that are not evident from surface mapping. Line TR-3, trending N46W approximately along the strike of Drill Hole Wash, was considered less detailed by the authors because of the "averaging" effect from running the profile at 45 degrees to the presumed strike of faulting.

Some 29 Schlumberger vertical electrical soundings (VES) were reported by Senterfit et al. (1982) for a large area east and north of Yucca Mountain, including soundings along Fortymile Wash and Drill Hole Wash. The purpose of these surveys was to attempt to determine the electrical properties of the lithologic units found in the area. Soundings were done with typical separations of 1-2 km (locations shown in Figure 4-1), and were sensitive to

structure at depths of 2,000 ft or more. Interpretation was based on 1-D modeling, with data from multiple soundings composited and contoured to form geoelectric profile sections. High contrast, low resistivity regions were interpreted as possible vertical faults. Sounding number 38 (along the east side of Drill Hole Wash) was closest to Coyote Wash.

The resistivity of alluvium in Drill Hole Wash, can be estimated from Schlumberger sounding 38 to be 70 to 150 ohm-m (for about the upper 20 ft of the sounding model). Starting at about 30 ft depth, sounding 38 indicates a rapid increase in resistivity to over 700 ohm-m. Sounding 38 is centered in Drillhole Wash about 800 ft south-southeast of Line B, and about 400 ft north-northeast of borehole UE25a-1. Alluvial thickness at drillhole UE25a-1 is logged at 30-ft depth (Spengler et al., 1979); thus the sounding model provides an accurate geoelectric description of the alluvial cover. Use of this sounding to constraint resistivity values is discussed further in Section 4.6.3.1.

A magnetometric resistivity (MMR) survey was conducted in the Fortymile Wash area in proximity to the Paintbrush Canyon fault (Fitterman, 1982) for the purpose of field-testing the method. The MMR technique uses a known current input, and the output is magnitude and orientation of the induced magnetic field. Portions of the survey lines NTS-1 and -2 are shown in Figure 4-1, and were interpreted to be consistent with previous dipole-dipole resistivity results of a conductor associated with the Paintbrush Canyon fault.

Frischknecht and Raab (1984) reported the results of time-domain electromagnetic (TDEM) sounding profile conducted January through June 1981 along an approximately EW direction running from Split Wash to the west across Midway Valley to the east, nearly overlying the dipole-dipole survey TR-4 of Ross and Lunbeck (1978) (see TDEM lines in Figure 4-1). Square transmitting and receiving loops of side dimensions 1,000 ft and 500 ft were used. The data were interpreted by using a 1-D layered earth model for each of the soundings, and the data were composited to form a geoelectric section. Lateral contrasts in resistivity vs. depth cross-sections were interpreted as faults. A slight contrast was seen in the uppermost 500 m in the vicinity of the Paintbrush Canyon fault; a much larger contrast (higher conductivity that might indicate vertical faulting downthrown to the west) was observed in Midway Valley east of Exile Hill.

There are several well-logs that are pertinent to this study: USW G-4, UE25a-4, UE25a-5, UE25a-6, and UE25a-7. Well-logs of USW G-4 were reported by Spengler et al. (1984); geologic and geophysical well-logs for holes UE25a-1, 4, 5, 6 are reported by Spengler and Rosenbaum (1980), Daniels et al. (1981), and Spengler et al. (1979). The stratigraphic and resistivity variation controls provided by these logs were used in this review and are described in detail in Chapter 3 and Section 4.6.3.

Daniels (1983) performed a borehole-to-surface DC resistivity survey to measure the spatial distribution of resistivity in a large area of Drill Hole Wash that extends into the mouth of Coyote Wash, approximately 300 ft west of UE25a-6. Current electrode sources were placed in boreholes UE25 a#1, a#4, a#5, and a#6. Dipole potential measurements were made on a 50-ft grid on the ground surface. Residual resistivity contour maps were prepared which

correct the observed patterns for plane-layered stratigraphic effects, leaving regions considered anomalous. This type of survey is insensitive to individual layers, responding to average properties between source and receiver. The region near Coyote Wash was characterized as a "high-resistivity anomaly." This anomaly was persistent, conspicuously observed from several different sources. Daniels interprets the anomaly to be a near-surface body, possibly associated with a mineralized fracture zone.

Hoover et al. (1982) reported an E-field ratio telluric survey, of two lines extending from Jackass Flat on the east, to the flank of Yucca Mountain. Electrode spacing was 500 m (1640 ft) for these lines. Line 2 extended through Coyote Wash, ending approximately at the trace of the Ghost Dance fault. The data exhibit some anomalies related to low resistivity features striking normal to the lines at the Paintbrush Canyon fault, and other places to the east of Yucca Mountain where Hoover interpreted faults, but no faults were interpreted in the region of Coyote Wash (see also Section 4.3.2.3).

4.3 GEOELECTRIC MODEL

This section reviews the modeling and interpretation reported by Smith and Ross (1982). The intent is to focus on the original work, and the geoelectric models developed for Lines A, B, and B'. These models are analyzed without resort to extensive sensitivity calculations, which are discussed in Section 4.5. A definition is developed for average misfit between observed data and computed apparent resistivities. In order to evaluate misfit for the original work of Smith and Ross, the models for Lines A, B, and B' are recomputed using a simplification scheme that reassigns a small number of different resistivity values to the many bodies in the Smith and Ross models, in an informative manner. Analysis of these lines continues with further simplification of the geoelectric models that captures most of the major features of the Smith and Ross models, but results in great simplification and better agreement with constraints based on currently available borehole data. The misfit attendant to these simplified models is compared to that for the original models. Finally, a number of steps are outlined as the recommended basis for future geoelectric modeling of data from the Coyote Wash area.

4.3.1 MODELS OF SMITH AND ROSS (1982) FOR LINES A, B, AND B'

4.3.1.1 Data Parameters

Apparent resistivity is the primary parameter of modeling (Smith and Ross, 1982); the IP percent-frequency effect (PFE) is a secondary parameter. The latter are not considered here (see Section 4.6.3.4). Smith and Ross present the data as pseudosections of apparent resistivity (and IP response) with values plotted at the intersection of diagonals (usually 45-degree diagonals) extended downward from the midpoints of the source and receiver

dipoles. This is standard presentation (Sumner, 1976) for polar dipole-dipole data.

Smith and Ross do not discuss the data acquisition or quality. Data quality has been discussed in Section 4.2.1, where it was estimated that the data could be realistically modeled to an overall average misfit of about 15% relative error.

The location of data relative to features that are not incorporated in the model, namely topography and alluvium-bedrock contacts, have been discussed in Section 4.2.1.1.5. Smith and Ross address the features of topography roughly perpendicular to the azimuth of the lines, but do not discuss topography off-axis to the lines, nor its effect on the modeled geoelectric section. Their models do not explicitly include alluvium.

4.3.1.2 Modeling Method

Algorithm

Smith and Ross (1982, pp. 3-5) used a finite-element algorithm developed by Rijo (1977) and Killpack and Hohmann (1979). The algorithm allows 2-D modeling of resistivity contrasts below an arbitrary topographic surface (2-D topography and resistivity contrasts have infinite strike-length perpendicular to the survey lines). Rijo (1977) and Fox et al. (1980) describe the mathematical aspects of the algorithm and present numerous illustrations of the effect of topography and subsurface resistivity contrasts. The algorithm has been extensively tested (Rijo, 1977) and is probably accurate to about 5%.

An alternate algorithm based on a finite difference method (Dey and Morrision, 1979; Dey, 1976) has been used by Beyer (1977) to provide a catalog of 2-D effects in the absence of topography. The two methods provide equivalent results (within 5%) for a flat earth which provides additional verification that the algorithms are adequately accurate within the limitations of the model employed.

Intrinsic limitations of the algorithm (Rijo, 1977) include the following:

1. Contrasts of finite strike-length cannot be accounted for.

2. Contrasts and topography that strike other than 90 degrees from profile cannot be accounted for.

3. Contrasts off-axis of the profile cannot be accounted for.

4. Air/topography contrasts are limited to be within the range 1,000 to 100,000 (Fox et al., 1980, p. 78).

5. Anistropic media cannot be accounted for.

Practical limitations of the algorithm (Rijo, 1977) include the following:

1. Contrasts along strike (the 2-D model) can be incorporated only within a region of 16 dipoles (the model is filled out with the end-conditions that create a horizontally layered earth at +/- 8 dipoles from center).

2. Gradational contrasts cannot be incorporated (except as approximated by closely spaced mesh intervals).

3. Model resolution is limited by mesh design, which is usually a function of tradeoffs between run-time and total model size.

   a. Horizontal mesh intervals used are typically A/4.

   b. Vertical mesh intervals are limited to fit within a total mesh-design of about 20-40 elements in the vertical direction, typically using a fine mesh (A/10) near the surface and increasing the interval with depth where the deepest interval should be 8*A or greater.

Interpretation limitations of the algorithm are related to the fact that DC resistivity data may have "equivalent" solutions, whereby contrasts, widths, and thicknesses may be modified to produce similar responses (Keller and Frischknecht, 1966, p. 158). Equivalence is well-defined for the 1-D problem, but it has not been extensively investigated for 2-D and 3-D contrasts. In present practice, multi-dimensional equivalence can only be quantified by extensive and costly "sensitivity" tests where modeled bodies are systematically modified in alternate computations, or by inversion techniques that compute variance in the derived parameters (Tripp et al., 1984).

Approach

Smith and Ross (1982) used a modeling approach consisting of iterative forward calculations (computing apparent resistivity from a hypothesized geoelectric model), altering the geoelectric model by trial and error. This interactive approach is standard practice in geophysical modeling and interpretation.

Specific details of the Smith and Ross approach were dictated by the characteristics of the modeling algorithm and the length of the profiles. There were four steps: (1) segmentation of each profile and evaluation of the topographic effect for each segment; (2) modeling of the geoelectric structure, and evaluation of the "fit" and sensitivity of the model parameters, for each segment; (3) selection of a preferred model for each segment; and (4) compositing the segments into an overall model for the profile. These steps are discussed further below.

1. Each profile was modeled in segments, which typically overlapped by eight dipoles (Smith and Ross, 1982, Appendices A, B, C). Topographic distortion for a uniform earth was investigated (Smith

and Ross, 1982, Appendix A, summary on p. A-II) and a decision was made on whether to include topography in the geoelectric model or not. If the topographic distortion was 10% or more, topography was included. Topography was included for all segments of profiles A and B', but was not included for the western and central segments of profile B (designated here by B/W, B/C). The topography effect for B/W and B/C are not documented, but topographic profiles for this line suggest that topography is not a significant factor (see Fox et al., 1980).

2. Each segment was modeled interactively (trial and error) to find a model that fit the data. The "fit" was qualitatively evaluated; no "fit" criteria are documented. Resulting models with satisfactory tests were based on comparison of a "preferred" model to alternate models incorporating perturbations in resistivity and geometry. This analysis was aimed at testing specific hypothesis. The hypotheses of interest here are:

   A/W - Test 1 and 2 (pp. B-1 - B-2, Figures B2 and B3 of Smith and Ross, 1982): Low resistivity bodies (100-300 ohm-m) under 10W and 4W may be thinned or removed. The conclusion was that the hypotheses was not true.

   B/W - Test 1 (pp. B-3 - B-4, Figure B8 of Smith and Ross, 1982): Low resistivity bodies (100-300 ohm-m) under 12W and 8W may be removed. The conclusion was that the hypothesis was not true.

   Comment: There are minor discrepancies between the text and the model perturbations shown. There are no quantitative measures of changes in fit; however, the resulting model response data are presented and contoured to compare with the observed data (Smith and Ross, 1982, Plate II), or to the preferred models.

   Comment: The "sensitivity" tests are poorly designed and documented. Reasons for this are as follows: (1) the mesh was modified along with the model geometry and resistivity values, hence the perturbations are wide in scope rather than being limited to specific aspects; and (2) no quantitative measure of variations in "fit" due to model perturbations was established. Sufficient information is available to verify the conclusion, but verification entails redrawing the perturbed models to overlay the test models with the preferred models. Graphical presentations of the data are practically incomparable (the perturbed models are presented as unscaled computer input, and the results have variable contour intervals compared to the observed data, or to the preferred model being tested).

3. Based on the sensitivity tests, a final model for each segment was chosen (Smith and Ross, 1982, Appendix C). For lines A, B and B', the "final" model was the preferred model of the sensitivity tests.

4. Resulting segment models were merged into a composite model for each line. The composite models are shown in Smith and Ross (1982), Plates II (Lines A and B) and IV (Line B'). This step was interpretative; parts of each segment were selected, rejected, or modified to include in the composite (compare model A/W on p. C-1 with the model for Line A on Plate II, Smith and Ross, 1982). Criteria for selection, rejection, or modification of the composite from the final segment models are not documented. Because of practical limitations of computing large models, the actual computed data for the composite are not presented. Misfit must be evaluated for each of the segments, and assumed to represent the misfit of the total composite.

   Comment: The main parts of the model's interest to this report are associated with the low-resistivity (65-100 ohm-m) bodies under 12W on Lines A and B (see Section 4.3.1.3.2). There are no substantial modifications to these bodies on the composite as compared to the final segment models.

Calculations performed for this report indicate that the composite models have an overall misfit (average absolute difference between observed and computed) of about 20% (see Section 4.3.3.1).

4.3.1.3 Characteristics of Models

Geophysical models are generally abstractions of geologic conditions, which results from two causes: (1) modeling methods have limited ability to constrain the distribution of physical properties, particularly at the level of detail often needed for practical problems; and (2) physical properties are not always correlative to geologic conditions. Interpretation of geophysical models generally requires selection of the best constrained model features, that also have geologic significance.

This section considers these factors for geoelectric models for Coyote Wash. First, the degree of constraint (or resolution through the use of data) in the model parameters (i.e. body size, location, depth, and resistivity) is discussed under the heading of complexity. Next, the available models are generalized to bring out consistency, under the heading of major features. Possible geologic significance of these major features is discussed in Section 4.3.2.

Complexity

The model for Line B/W (Smith and Ross, 1982, p. C-4) will serve as an example; other models have similar characteristics of complexity. This model is based on 57 data points from 24W to 4W. The model extends from 28W to 0 center. There are 32 bodies whose resistivities vary over 7 values (65 to 1600 ohm-m). Thus, the model has 39 free parameters (32 bodies, 7 resistivities) derived from 57 degrees of freedom (data points). Horizontal interfaces extend to a depth of 500 ft (2.5 dipole lengths). Widths of the bodies are as small as 50 ft (minimum horizontal mesh size). Thicknesses of

the bodies vary from 60 ft (at the surface) to 100 ft (at a depth of 400 to 500 ft).

Comment: A general inversion could conceivably produce a model with 57 parameters, thus 39 parameters in this model is not open to major criticism. Neither is the size distribution of bodies, which varies roughly as a function of depth. The bodies are basically distributed so as not to be resolvable below 3 dipoles depth (600 ft), which agrees with the usual assumptions in dipole-dipole modeling.

Comment: The model contains numerous small (less than 0.5 dipole length) contrasts of about 2 or more within the upper 200 ft of bedrock. This characteristic is not geologically intuitive. If one takes the position that the best model has minimal bedrock complexity (minimal contrast) consistent with the data, then the models are ill-conceived. Ideally, modeling with a large number of free model parameters (more than about 1/3 the number of data points) would result in an approximation of gradational contrasts, which is not the case here. Small-size, large-contrast subsurface bodies can result from trying to match the model to data affected by surface contrasts such as resistivity variations associated with alluvial cover.

The effects of outcropping contrasts are illustrated by Beyer (1977, pp. II-152 and II-154). Beyer shows 2-D models of dipole-dipole psuedosections for small (0.25*A vertical and 0.5*A horizontal) conductive bodies that outcrop in an otherwise homogeneous halfspace. These models show diagonal anomalies in apparent resistivity of 25% to 50% for contrasts of 1:100 and 1:10 respectively. The anomalies persist for all N (the models shown were computed for N=1 to 15). Thus, outcropping or near-surface (< 0.25*A) contrasts can be recognized by diagonals that show anomalously high or low apparent resistivities starting at N=1. Such contrasts would be found directly below the dipole where such diagonals intersect at N=1. Figure 4-6 shows the observed data of lines A and B recontoured from Smith and Ross (1982, Plate II). Anomalous apparent resistivities occur along diagonals as described above. Highs occur on Line A and B along diagonals at 10-12W. Lows occur along diagonals at 2W to 4W on Line A, and at 16W to 18W on Line B. The highs cited occur where outcrop protrudes into Coyote Wash. The low at 16W to 18W on Line B occurs where Coyote Wash widens and intersects a side wash. The low at 4W to 2W on Line A occurs near a contact of alluvium and bedrock outcrop. These observations suggest that surficial contrasts have a major influence on the data being considered here, and may be partly responsible for the complexity in the models. Confirmation of this suggestion would require remodeling of the data to include available information on the thickness and resistivity of alluvium.

Major Features

To analyze the major features, the models of Lines A, B and B' (Smith and Ross, 1982) were recomputed. The algorithm used was that of Rijo (1977); the code includes modifications so that long profiles of up to 40 dipoles can be modeled (Halliday, 1985). It is essentially the same algorithm used by Smith and Ross (1982). Because of differences in computers and numerical

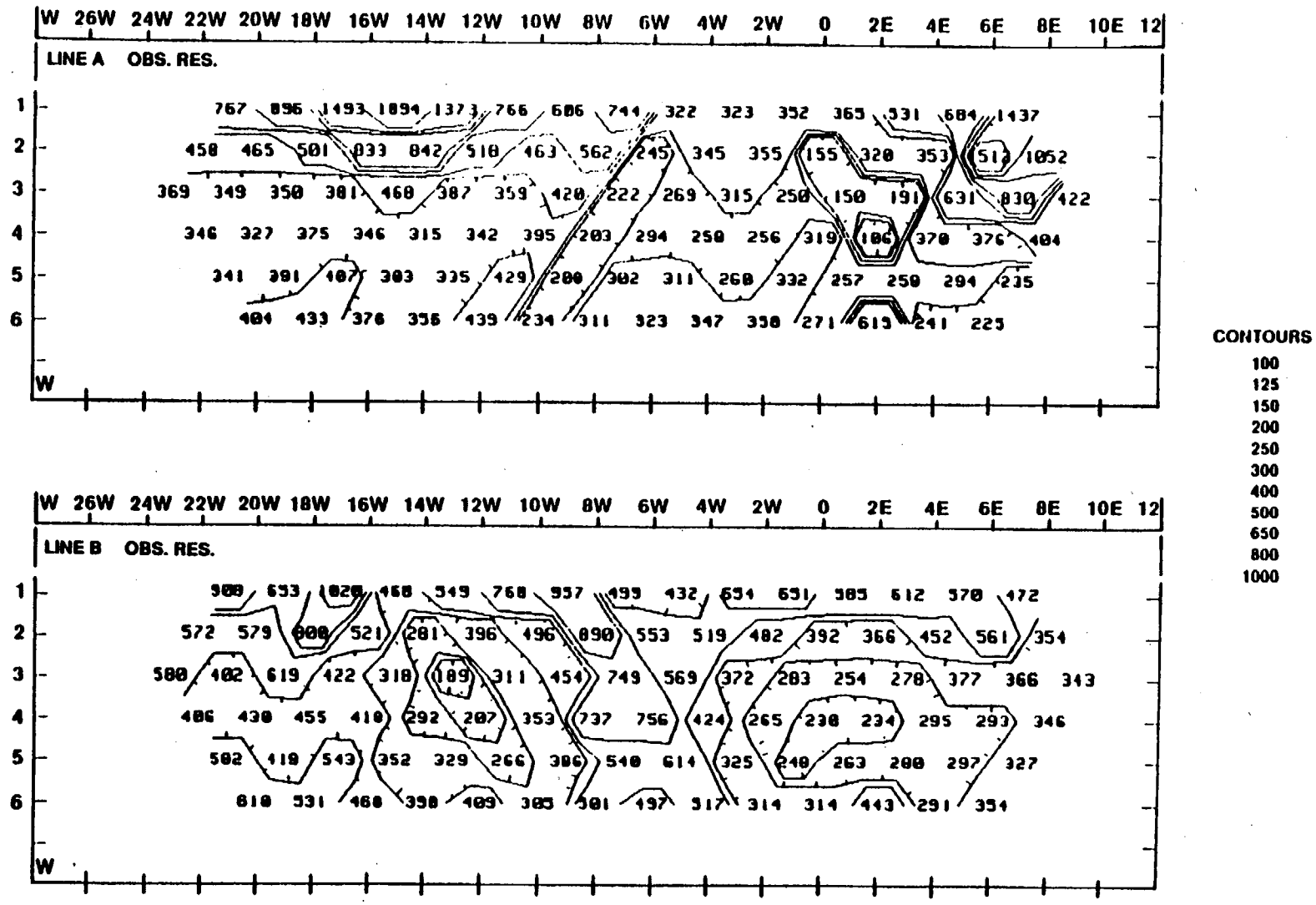


Figure 4-6. Observed apparent resistivity pseudo-sections for the west section of lines A and B (200-ft dipoles). Contours are at approximately equal logarithmic intervals of 10-per-log-cycle. The contours intervals increase in relative magnitude of about 25%. Ticks are on the side of lower resistivity.

implementation the results may differ slightly, but tests against model results given by Rijo (1977) indicated that differences should be within 5%. Greater sources of difference are that the models computed are not precisely those of Smith and Ross due to the fact that their model segments were combined into one full model for the present computations.

The basic subsurface geometry of the recomputed models is unmodified from Smith and Ross, but topography was added to Line B. The number of model resistivities is reduced by combining selected resistivities of the Smith and Ross models to fit the maximum (7) allowed by the code used. This reduction of the number of resistivities results in reducing the number of bodies as well, but the major features of the Smith and Ross models remain intact. The models computed have resistivities listed below:

Line A :	100, 200, 300, 500, 700, 1000, 1800
Line B :	70, 150, 300, 500, 700, 1000, 1800
Line B':	100, 200, 300, 400, 500, 700, 2000

Figure 4-7 summarizes the major features of the recomputed models by showing the major contrasts that occur at a depth of 1*A (200 ft) or more. The region of diagonal lines shows where resistivities are less than 300 ohm-m. Dots along the surface show the distribution of alluvial cover from Lipman and McKay (1965). Faults are from Smith and Ross (1982). The area of interest to this report is 8W to 12W on all lines.

Major features are:

1. A low resistivity layer (< 300 ohm-m) layer at about 200 ft depth on Lines A and B. Contrasts of about 1:2 to 1:10 identify this layer. It is modeled with a thickness of 200 to 500 ft west of 8W on Line A and west of 12W on Line B. Thickness of the low resistivity body is modeled to depths deeper than the depth of resolution east of 2E on Line A and east of 0 on Line B.

2. A zone of high resistivity (> 300 ohm-m) that disrupts the low-resistivity layer in the vicinity 8W to 4W on Line A and 10W to 4W on Line B.

The vertical contrasts associated with the disruption of the low resistivity layer in the vicinity of 8W to 12W on lines A and B is the definition of the "fault" that is the focus of this report. Smith and Ross (1982) put the "fault" at 9W. The contrasts range from about 1:2 to 1:10, and have a horizontal spread of about 2*A (from about 7W to about 11W; this is a reasonable uncertainty).

At depths below 1,000 ft (model B'), the "fault" of Smith and Ross (1982) is placed at 10W, and shows a contrast in the opposite sense (conductive to the east) with a maximum contrast of less than 2:1. It is not necessarily contradictory to have geoelectric contrasts change sense as different lithologies are encountered along a "fault," but contrast magnitudes of less than 2:1 are of questionable reliability.

Contrasts are occasionally modeled by Smith and Ross (1982) to depths greater than the depth of resolution (about 3*A). This implies that the data

Figure 4-7. Simplified representation of the resistivity models of Smith and Ross (1982) for the west sections of lines A, B and B'. Resistivity contrasts are shown along major interfaces. Low resistivity regions (less than 300 ohm-m) are indicated by diagonal lines.

did not sense a termination of the contrast. The extension to depths greater than 5*A (probably 3*A) has no significance.

Observed apparent resistivity data on the pseudosection of Figure 4-6 show decreasing resistivity below N=1. Anomalously low apparent resistivities are present at N > 3 in the regions of 8W to 14W and 0 to 4E on both lines A and B. These are the data characteristics that result in the main features of the models described above. Inasmuch as these regions of anomalous apparent resistivity are at N of 3 or greater, they are not associated with near-surface features or on-axis topography. However, the possibility that the lateral variations in apparent resistivity at N > 3 are associated with off-axis bodies or topography cannot be ruled out. 3-D models of buried conductive bodies under a flat earth show that the maximum anomaly for bodies off-axis occurs at greater N than for equivalent bodies on-axis (Dey and Morrison, 1979, Figure 10, p. 770).

4.3.2 MODEL RELATIONSHIPS TO OTHER GEOELECTRIC DATA

4.3.2.1 Sources of Independent Data

Independent data are not discussed by Smith and Ross (1982) as most of the additional data available come from reports post-dating their work. The major share of independent data is outside of the area of Coyote Wash; thus, it would be instructive to evaluate the total set of dipole-dipole models in light of information currently available. However, the focus here will be on data in the immediate vicinity of Coyote Wash (see also Section 4.2.2), which include:

1. Drillhole resistivity data (Spengler and Rosenbaum, 1980; Spengler et al., 1984; Daniels et al., 1981).

2. Schlumberger sounding 38 (Senterfit et al., 1982).

3. EM horizontal-loop (slingram) traverse Y11 (Flanigan, 1981).

4. Telluric (E-ratio) line 2 (Hoover et al., 1982).

4.3.2.2 Lithological Relationships

Smith and Ross present lithological correlations based on the cross-sections of Lipman and McKay (1965) (Smith and Ross, 1982, pp. 7 to 9). Currently, the drillhole log from USW G-4 is more instructive. Nonwelded tuff generally has low resistivity (typically 50 ohm-m) compared to welded tuff (greater than 300 ohm-m). A nonwelded tuff interval (corresponding approximately to the PTn unit of Ortiz et al., 1985) at 125 to 250 ft depth is the principal electrical target within the range of penetration for dipole-dipole lines in Coyote Wash, particularly Lines A and B. The PTn unit correlates well in depth (especially the upper surface), and roughly in

resistivity, with the low-resistivity layer defined by various models for Lines A and B (Figure 4-7).

The models for profiles A and B, however, suggest a lateral contrast within this layer in the vicinity of 8W to 12W on Line A, and 10W to 16W on Line B. The contrast is inferred by Smith and Ross (1982) to be related to alteration due to increased fluid mobility at a fault zone (see below).

It should be noted that the PTn nonwelded unit shows a similar electrical-log signature at drillholes UE25 a#1, a#4, a#5, a#6, and a#7 (Daniels et al., 1981) and USW G-4. Thus, the logs provide no confirmatory evidence of lateral changes corresponding to the contrast inferred from dipole-dipole data. However, the drillholes are not located over the apparent contrast. Also, the mineralogic/petrologic data discussed in Sections 4.6.3.2 and 4.6.3.3 indicate significant differences in alteration.

4.3.2.3 Structural Relationships

The contrast at 8W to 12W was interpreted as a fault by Smith and Ross (1982). Faulting as inferred would decrease the resistivity by increasing the porosity within a zone of fault deformation, thus allowing increased fluid migration within the zone, with attendant rock alteration and increased clay-mineral content. High volumetric fluid content combined with conductive alteration products would lower the resistivity.

EM data along profile (Flanigan, 1981) show no conclusive evidence of an important contrast at 8W to 12W. A sensitivity study was performed for this review to investigate the type of slingram signal that would be associated with the geoelectric model of Smith and Ross (1982). A preliminary model of a finite, buried, conductive body was computed several times to investigate the effects of resistivity contrast, burial depth, and conductive overburden. Regardless of whether the resistivity contrast was 1:3 or 1:10, or whether burial depth was 200 or 400 ft, or whether 25 ft of overburden (140 ohm-m) was present on the surface, there remained a significant slingram anomaly (10% to 20% of the in-phase primary field) in the EM response for frequencies from 222 to 1777 Hz. The observed anomaly in the vicinity of 8W to 12W was less than 5% at 222 Hz, and smaller at higher frequencies. The importance of lateral interference from other conductive bodies or topography, possibly from 3-D structure or terrain, was not explored in this review.

The telluric profile (Hoover et al., 1982, Line 2) also shows no indication of a major deep electrical contrast. Although E-ratio telluric data are highly sensitive to vertical contrasts such as associated with faulting, the electrode spacings of 500 m (1,640 ft) used in the telluric line may not have resolved a fault whose signature terminates at depth below about 300 to 500 ft. The telluric signature of the contrast modeled by Smith and Ross (1982) has not been modeled to verify this possibility.

Where geoelectric surveys are used for fault detection, the targets have generally been zones of lower resistivity caused by alteration associated with increased permeability of a fault or fracture zone. Faults or fractures zones are typically modeled as vertical, conductive, 2-D bodies of finite

thickness. Faults and fracture zones are not generally distinguishable unless there is a geoelectrically obvious fault offset. For most applications there may be no reason to discriminate between faults and fractures. The notion of minor faults (where the geoelectric signature cannot be attributed to offset) as geoelectric boundaries between regions of different properties is rather new. Much of the uncertainty regarding the structural implications of geoelectric data from Coyote Wash is related to the novelty of interpreting a fault under such circumstances.

4.3.3 GENERAL DISCUSSION OF MISFIT, UNIQUENESS, RESOLUTION, AND SENSITIVITY

A principal objective of geophysical modeling is to find a model that "fits" the data. Another objective is to evaluate uncertainty in the model produced. The latter is difficult and often ignored because of cost constraints. The uncertainty of a model is a complicated function of uncertainties in the observed data and non-uniqueness (equivalence of solutions) characteristic of many geophysical problems.

The first part of this section evaluates the fit of the models of Smith and Ross (1982) to the dipole-dipole data. The next part (Section 4.3.3.2) provides some general observations on resolving capability and associated uncertainty in dipole-dipole modeling, based largely on published 2-D and 3-D modeling studies. Related discussion of resolution and sensitivity may be found in Section 4.5.

4.3.3.1 Misfit

The criterion for finding a fit is "misfit," which is a measure of discrepancy between observed data and model response. Smith and Ross (1982) do not analyze the misfit of their models; thus it was necessary to generate models approximating those of Smith and Ross (1982), compute the responses, and compare these to the observed data quantitatively. The modeling algorithm (Halliday, 1985) used for this exercise was described in Section 4.3.1.3.2.

Figures 4-8, -9, and -10 show the results for the west parts of lines A, B, and B', respectively. Each figure shows the observed data, the computed response for the Smith and Ross models, and the relative errors (labeled % diff.). Relative error (RE) for each apparent resistivity data point (Ri) is:

$$RE = 1 - (\text{computed } Ri/\text{observed } Ri)$$

With this definition, positive and negative errors mean that the observed data indicate higher and lower resistivities than are modeled, respectively.

Apparent resistivities are contoured at roughly equal logarithmic intervals, 10 per cycle. This corresponds to about 25% relative difference between contours. The errors are contoured at 10% intervals. The summary

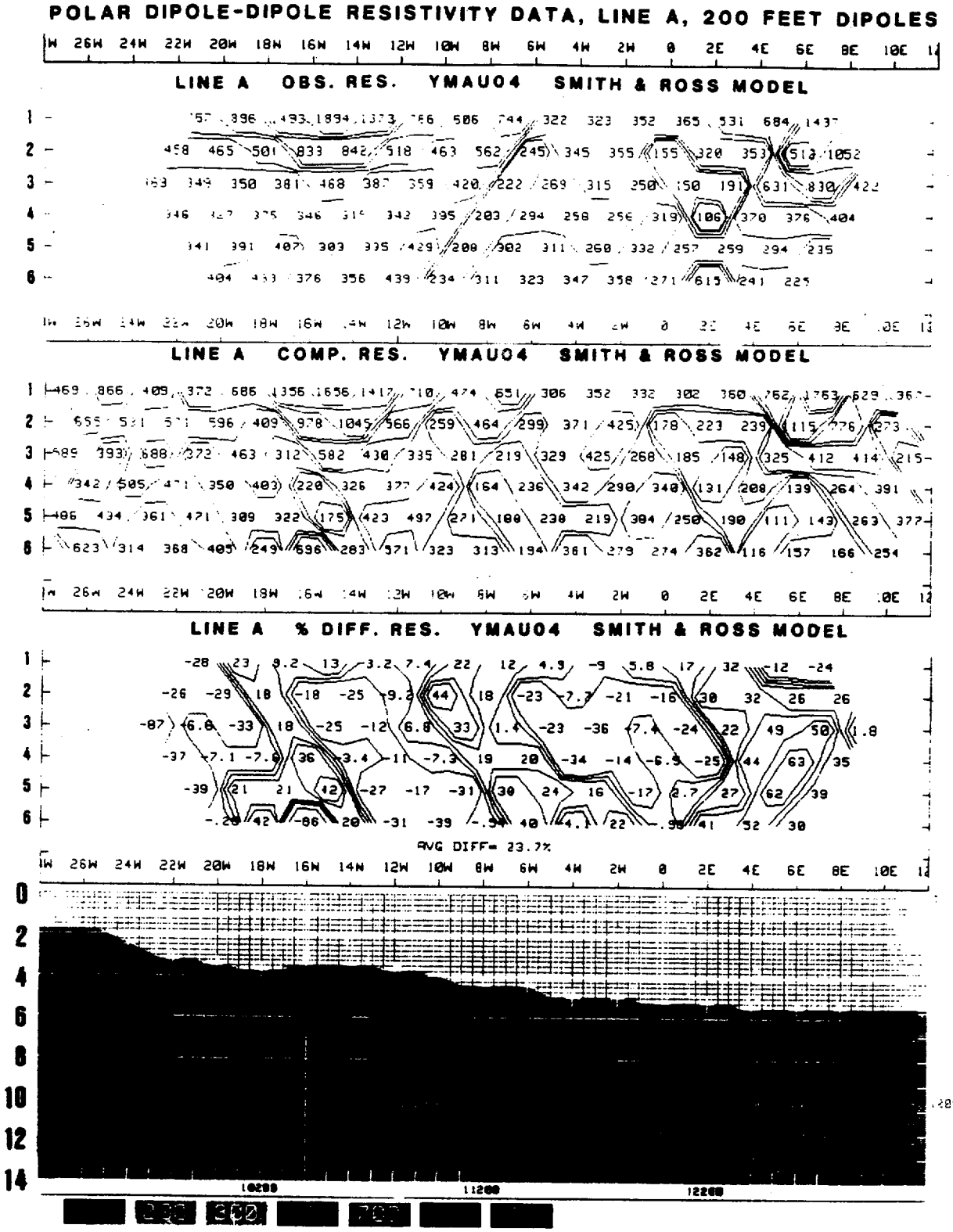
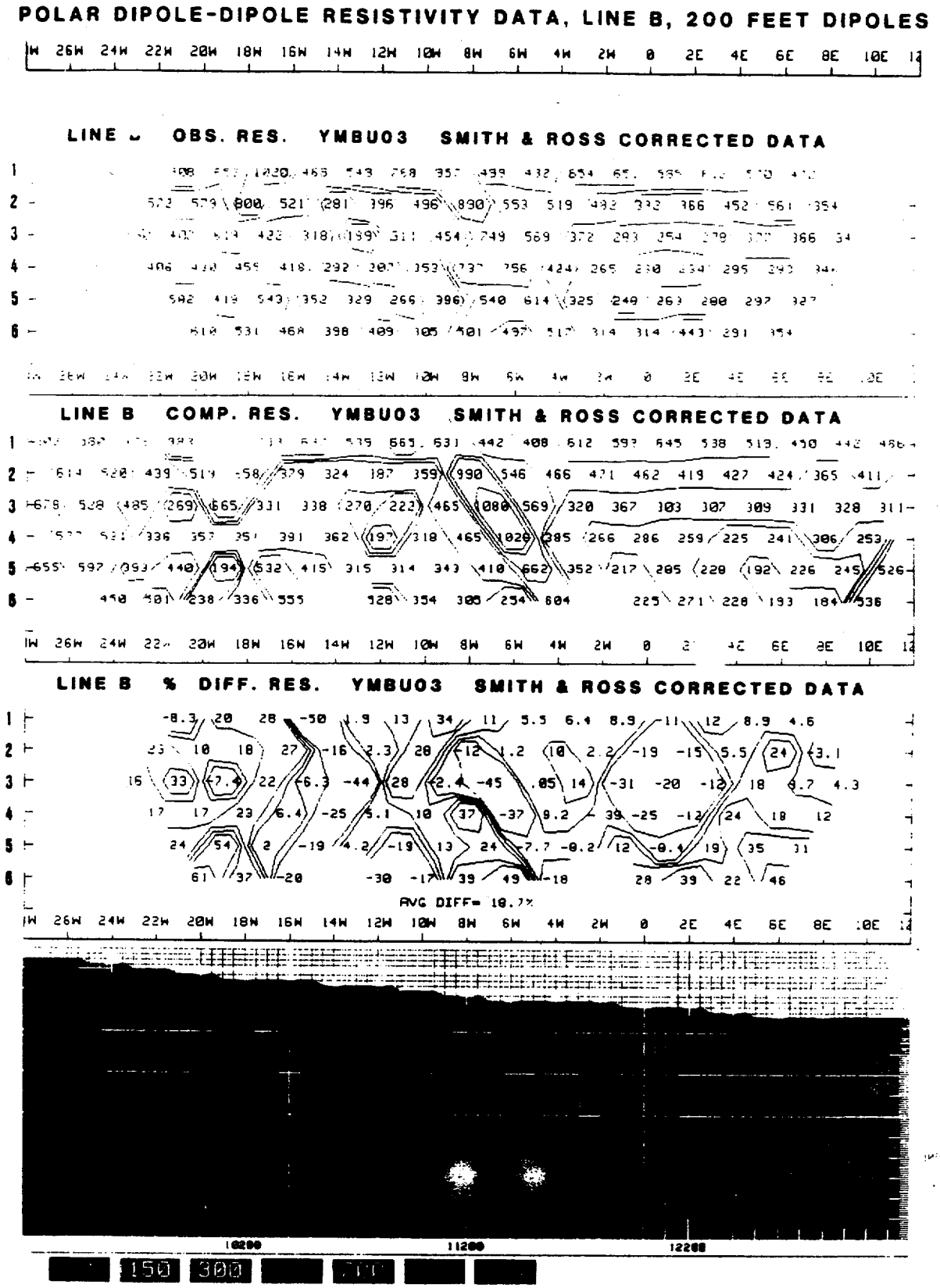
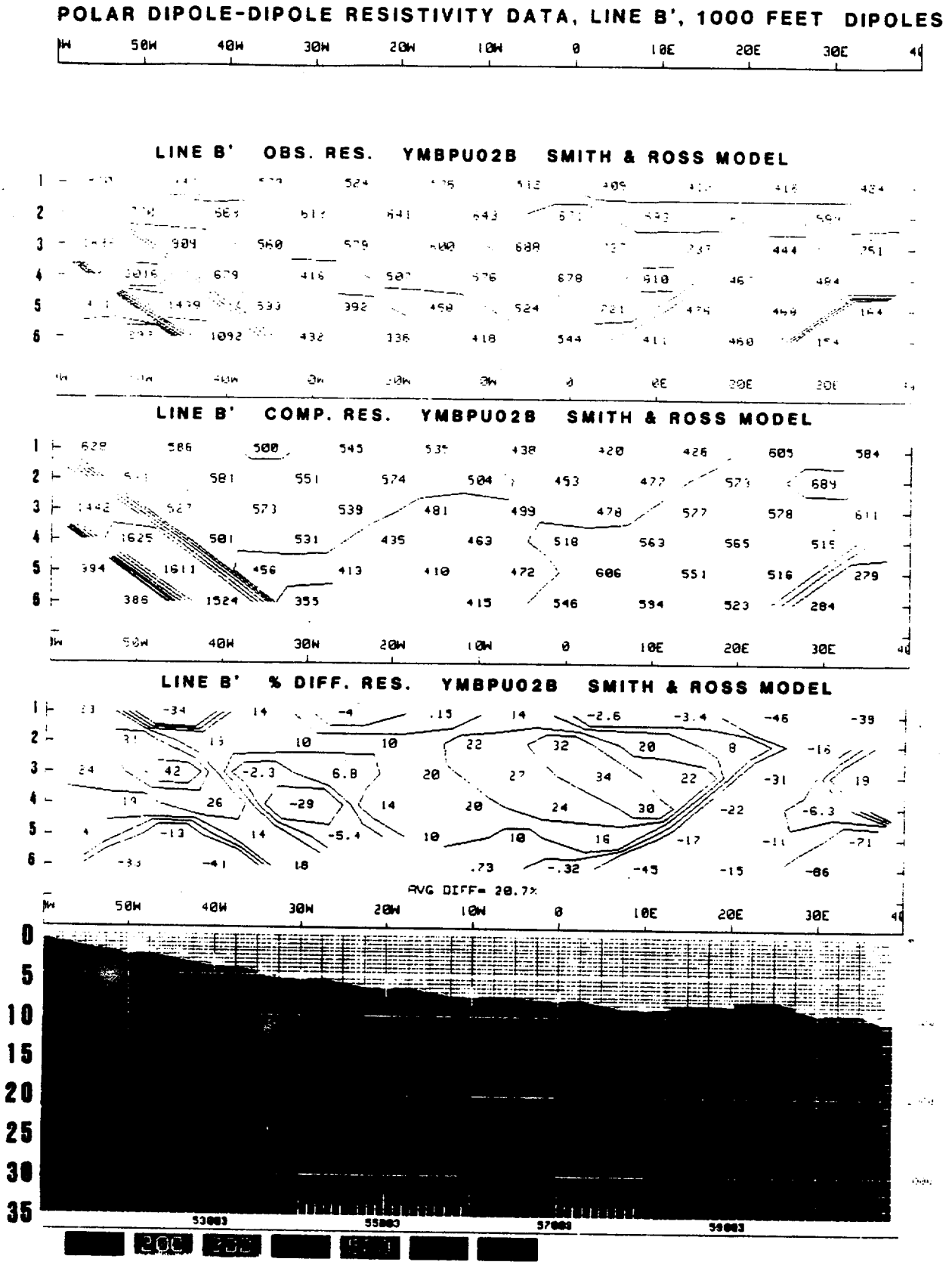


Figure 4-8. Dipole-dipole resistivity data for Line A. The computed pseudosection is the response of the 2-D model shown at the bottom; this model closely approximates that given by Smith and Ross (1982) (see text). "Ave. Diff." shown on the "% Difference" section is the mean of absolute values of the relative differences, and is used as a measure of overall "misfit."



Contour Interval: 10% (DIFF.)
: 100, 125, 150, 200, 300, 400, 500, 650. 800. 1000: COMP. & DES.

Figure 4-9. Dipole-dipole resistivity data for Line B. (See explanation on Figure 4-8.)



Contour Interval: 10% (DIFF.)
: 300, 400, 500, 650, 800, 1000, 1250, 1500, 2000
(OBS. & COMPUTED RES.)

Figure 4-10. Dipole-dipole resistivity data for Line B'. (See explanation on Figure 4-8.)

misfit quantity for each model is the mean of the absolute-value of relative error.

The models are seen to have summary misfits of about 20%, which is acceptable, though greater than the 15% judged in Sections 4.2.1.4 and 4.2.1.5 to be a practical limit. The overall configurations of the observed and computed contours also correspond, at least at the 5 interval/log cycle level, which more closely corresponds to the contour intervals given by Smith and Ross (1982, Appendix C, Plates II and IV).

However, it is important to note that at the level of 20 to 30% average misfit, for the models considered, there are major diagonal discrepancies. When the distribution of errors is strongly non-random, the goodness of model fit is strongly correlated with position, indicating a systematic deficiency in the model. The strong diagonals may be an indication that shallow (< 1*A) contrasting bodies are lacking, or are modeled incorrectly. The sensitivity of model results to shallow, outcropping bodies is discussed in Sections 4.5.1 and 4.5.2.

The portion of the data set that is sensitive to geoelectric structure in the area of interest in lower Coyote Wash is indicated by dashed lines on the misfit data of Figures 4-8 and 4-9. The misfit data for Line A in this area is acceptable with about 3/4 of the data showing misfits of less than 25%. One diagonal extending east from 12W to 14W is the principal exception. The misfit data for Line B are less acceptable with about half of the data points showing errors in excess of 25%, and showing definite correlation along at least two diagonals.

4.3.3.2 Resolution, Uniqueness, and Sensitivity

Resolution involves target detectability (sensitivity to target parameters), and parameter uncertainty if a target is detected. Parameter uncertainty involves equivalence of models for the same observed data and is generally referred to as non-uniqueness. Models of perfect and complete data (spatially comprehensive) have some inherent non-uniqueness; imperfect (noisy) and incomplete data add to this. The problem is further complicated by data that are sensitive to non-targets (such as alluvium), which increases the parameter uncertainty of the target, as well as broadening the equivalence of target parameters if the non-target parameters are imprecisely known.

For polar dipole-dipole data, Table 4-1 summarizes several rules of thumb regarding resolution for a flat earth. These rules can be inferred from the models presented by Beyer (1977) and Dey and Morrison (1979). Table 4-2 summarizes the factors that lead to uncertainty (as identified by the TAR team), and indicates the magnitude of these factors for the data under investigation.

Table 4-1. Rules of thumb for resolution of a target of thickness T below a flat earth, for the polar (or colinear) dipole-dipole resistivity method using dipole lengths A and full separation of N*A. The term "contrast" refers to low resistivity target bodies.

Depth of detection (top of a contrast)	3*A
Resolution of detection (top of a contrast).	0.5*A
(Both of the above decrease with dimensionality. Bodies with dimensions less than about .5*N*A are virtually undetectable.)	
Maximum thickness of resolution (bottom of a contrast)	0.5*T
(Decreases with depth and lower contrast)	
Best lateral resolution (edge of a contrast).	0.5*A
(Decreases with greater depth, smaller lateral extent and smaller contrast.)	
Resistivity-contrast resolution	2
(Decreases with depth and smaller lateral extent of target.)	
Absolute resistivity resolution	20%
(Depends strongly on the complexity of the situation. For a layered earth, resolution may be closer to 5%, but for 2- or 3-D targets in a layered earth the absolute resolution decreases dramatically.)	

Table 4-2. Causes of uncertainty in geoelectric modeling: estimates are given for the relative magnitude or importance of different sources of uncertainty in geoelectric modeling, which are applicable to the modeling of Smith and Ross (1982).

Data uncertainty	
Electric measurements	2nd order
Measurement locations	2nd order
Model algorithm accuracy	2nd order
Model algorithm limitations	
Finite discretization	2nd order
Dimensionality (off-axis effects)	
Topographic effects	1st order
Surficial contrasts (alluvium)	1st order
Buried contrasts	2nd order
Model size	2nd order
Equivalence of model parameterization (nonuniqueness)	1st order
Dip and strike of contacts	2nd order
Sharpness of contacts (gradational lithology)	2nd order
Anisotropic properties	2nd order

4.3.4 OTHER MODELS THAT MAY SATISFY THE DATA

Little can be said about other models that may satisfy the data without additional modeling, and speculation should be avoided. However, it is appropriate to describe the modeling approaches that should be used. Based on the analysis above, and the availability of new data since the Smith and Ross (1982) analysis, the following can be recommended:

1. Start with a lithological/structural model based on Section B-B' of Scott and Bonk (1984), resistivity and core-samples from G-4 and the UE25a#1, a#4, a#5, a#6, and a#7 series of holes, and the known distribution of outcrop. Build up a series of models to test the hypotheses:

   a. That the data fit the estimated resistivity section:

      Alluvium (based on drillhole data and drainage maps):
      thickness 0 to 150 ft: 100 ohm-m (70-150)

      Bedrock lithology:

0 to 150 ft:	500 ohm-m (300-1,000)
* 150 to 250 ft:	70 ohm-m (30-150)
250 to 1,400 ft:	500 ohm-m (300-1,000)
* below 1,400 ft:	50 ohm-m (30-300)

      * Indicates nonwelded tuffs, which are the fundamental low resistivity units in the Yucca Mountain geologic section.

   b. That the data require lateral changes in resistivity or thickness, or both, of the 70 ohm-m layer at 150 ft depth.

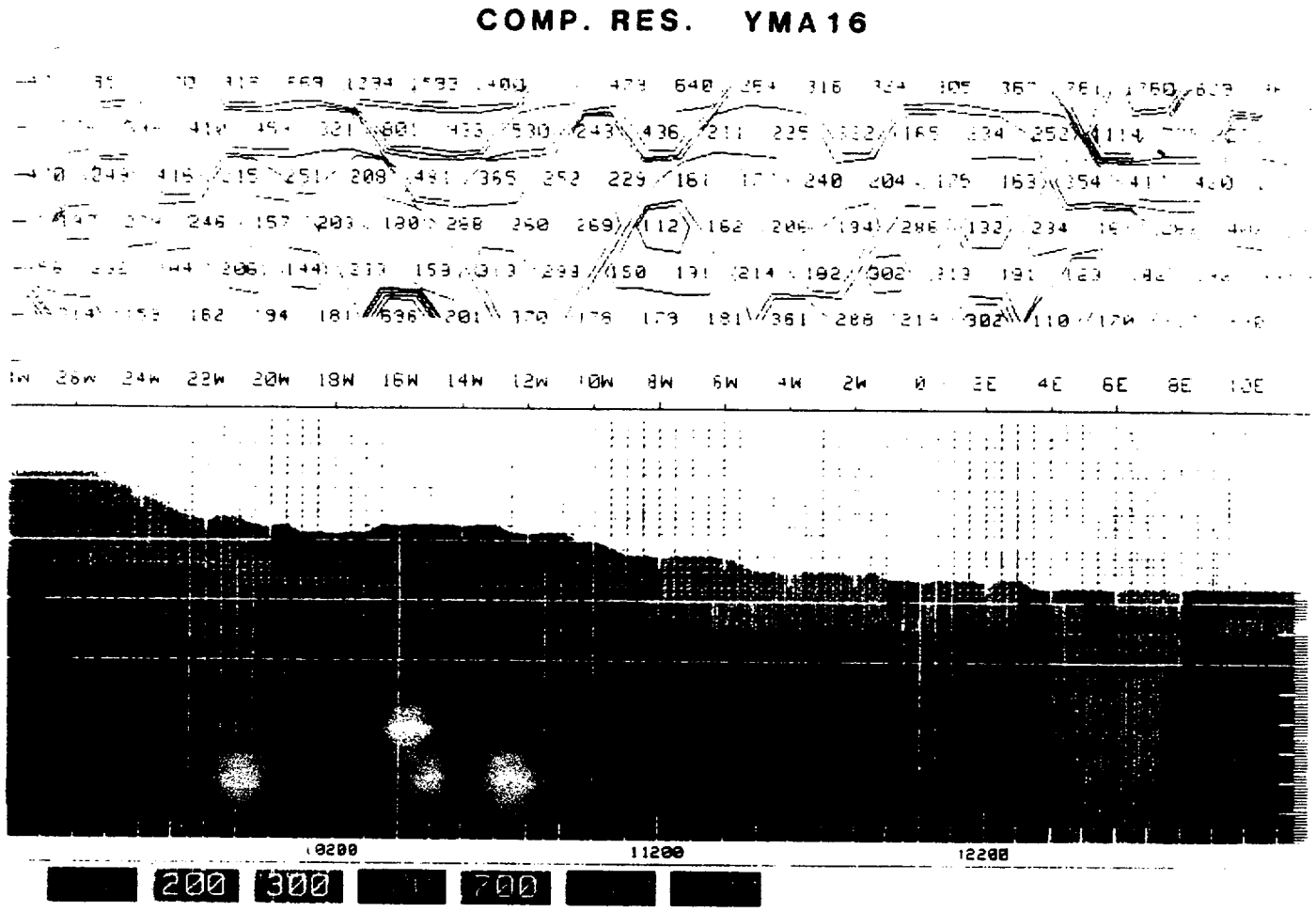
2. Initial modeling should be based on the 2-D assumption. 3-D modeling may be required to test the hypothesis that misfits that cannot be modeled with the 2-D assumption are due to off-axis contrasts in terrain features or geologic bodies.

3. If the above do not result in satisfactory models (20% misfit), then localized bodies should be added to test various hypotheses that unmapped faults or lithogical changes may be present.

Preliminary 2-D modeling using the Smith and Ross (1982) models as a basis are illustrated in Figures 4-11 and 4-12. These figures illustrate the result if the Smith and Ross models are modified to resemble the geoelectric section described above. In both cases, the misfit increased. The change in misfit is less than 10%, however, which suggests that by incorporating relatively small changes such a model might be viable.

4.3.5 SUMMARY

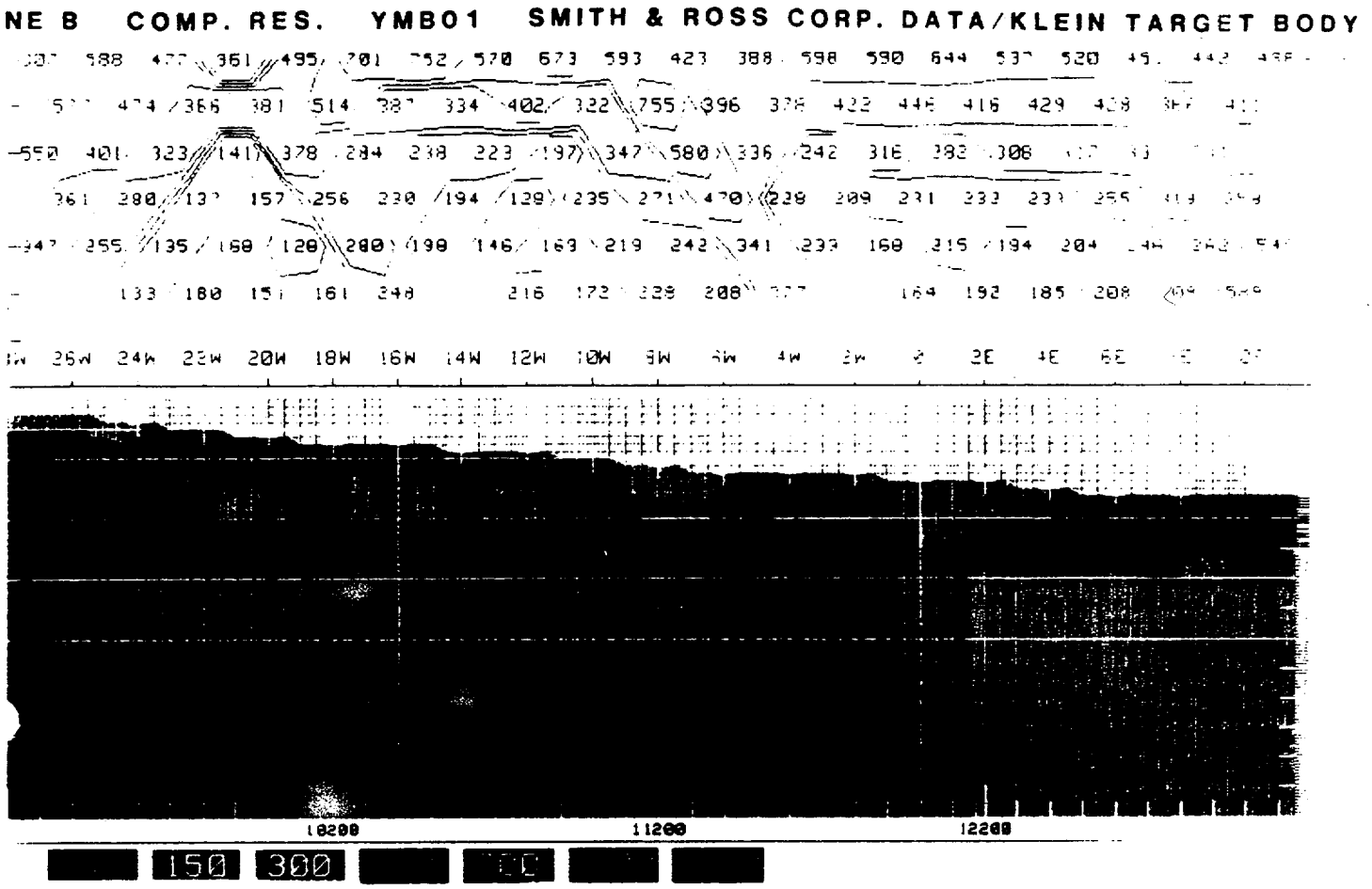
Section 4.3 has focused on the applicability of the geoelectric model used by Smith and Ross (1982) as the basis for inferring a fault across lower



LINE A

Contour Interval: 100, 125, 150, 200, 300, 400, 500. 650, 800, 1000

Figure 4-11. Modification of the Smith and Ross (1982) model for Line A (west section) where the depth interval of roughly 200 to 400 ft (red) is given a constant resistivity of 100 ohm-m, and the deeper (green) region a constant resistivity of 500 ohm-m. The remainder of the model is the same as the Smith and Ross model for Line A. The Smith and Ross model has a misfit (see text) of 23.7%; this modified model has a misfit of 27.4%. Note that the small vertical offsets in the laterally contiguous conductors are a way to reproduce dipping stratigraphy and realistic burial depth, and do not signify faults.



Log contour interval: 100, 125, 150, 200, 250, 300, 400, 500, 650, 800, 1000

Figure 4-12. Modification of the Smith and Ross (1982) model for Line B (west section) where the depth interval of roughly 250 to 450 ft (red) is given a constant resistivity of 70 ohm-m, and the deeper (green) region a constant resistivity of 500 ohm-m. The remainder of the model is the same as the Smith and Ross model for Line B. The Smith and Ross model is shown with coded resistivity symbols. The Smith and Ross model has a misfit (see text) of 18.7%; this modified model has a misfit of 30.8%. Note that the small vertical offsets in the laterally contiguous conductors are a way to reproduce dipping stratigraphy and realistic burial depth, and do not signify faults.

Coyote Wash. The conclusions and other major points brought out are as follows:

1. Measurements based on surface resistivity traverses using a standard dipole-dipole profiling method probably have about 15% uncertainty. Subjectively included in this figure are uncertainties related to electrode locations in relationship to alluvium-bedrock contacts and topography.

2. The modeling algorithm is based on the assumption that 2-D adequately approximates geoelectric structure as represented in the observed data. With this assumption and other less important constraints, the modeling algorithm is estimated to be accurate to about 5%.

   The modeling approach consisted of iterative trials, to generate a geoelectric model that "fit" the data. The resulting model was tested for sensitivity to specific perturbations in resistivity structure. One such perturbation was that which led to the inference of a fault in lower Coyote Wash.

   The algorithm and modeling approach used is standard, and accepted in the geophysical exploration industry. However, specific factors implemented in application of the approach to Coyote Wash are worthy of mention:

   a. 3-D effects were essentially neglected.

   b. Mapped alluvium-bedrock contacts were not incorporated in the model.

   c. Criteria for model "fit" were not established.

   d. Results of sensitivity tests were not convincingly documented.

   e. The range of acceptable (or equally acceptable) geoelectric models was not considered.

   These factors probably contributed to the outcome of the original work as discussed below.

3. For the models presented, the number of model parameters in relation to the number of data, and the number of "small" bodies relative to the dipole length and separation, is probably not justified. The effect of the resulting complexity is to increase the ambiguity in the relationship between the geoelectric model and the available geologic constraint information.

   A low resistivity body that led to the interpretation of the faults near the ES is one of the larger features in the Smith and Ross models; thus it is probably more justified. The parameters of this body in the geoelectric model are:

   a. Modeled resistivity varied between 70 and 150 ohm-m.

b. Width (along the east-west survey lines) was about 400 ft.

c. The top of the body occurs at about 100 to 200 ft.

d. Lateral and vertical contrasts in resistivity associated with the boundaries of the body varied from 1:2 to 1:10.

These parameters should produce a detectable ground-EM survey response, but a survey using the slingram method, which was analyzed for this review, did not detect an anomaly. Thus the data, modeling, or interpretation of one of these surveys is misleading. The existence of a buried low resistivity body is generally consistent with borehole logs, resistivity measurements on core samples, and stratigraphic information from boreholes in the vicinity of Coyote Wash. Thus the discrepancy between geoelectric models based on the dipole-dipole data, and modeling of the slingram data, is evidently caused by uncertainty as to the actual magnitude of the lateral heterogeneity of the conductive body.

4. Review of the modeling approach of Smith and Ross (1982) suggests that significant, unquantified uncertainty in their results was caused by the factors listed in item 2 above. The complexity of the Smith and Ross (1982) models, and the parameters used to describe the buried conductive body (see item 3 above), also probably resulted from these factors. Concrete verification of this, however, will require additional geophysical data collection and modeling.

5. The level of average "misfit" of the Smith and Ross (1982) models for Lines A and B is about 20%, as determined by recomputation using an equivalent 2-D algorithm. The 20% level is greater than the estimated data accuracy (see item 1 above), so it is very likely influenced by some of the factors listed in item 2 above, in conjunction with survey location uncertainty, elevation uncertainty, and small-scale earth variability as discussed in Section 4.5.1. Sensitivity tests for the TAR were inconclusive in that no models were found for Line A or B that are unequivocally simpler than those of Smith et al. (1982). Test results indicate that simpler models "fit" the data in a way that is roughly comparable, but because "fit" is difficult to define, it is not possible to assert that these models meet or exceed the "fit" achieved by Smith et al. The simplest models used in these sensitivity tests did not incorporate a resistivity structure that would be interpreted as a fault or fault zone.

4.4 TECHNICAL ISSUES IDENTIFIED AS A RESULT OF REVIEWING INTERPRETATIONS OF RESISTIVITY PROFILES (OPEN FILE REPORT 82-182)

4.4.1 INTRODUCTION

The purpose of this section is to document technical issues raised by geophysics subcommittee members, early in the TAR process, as to the data, modeling, and interpretation reported by Smith and Ross (1982). Team members identified technical issues that were then used to focus subcommittee activities on determining whether the Smith and Ross interpretation of an inferred fault at about 9W on lines A and B was the most supportable interpretation given current information. The term "technical issues" is used collectively to refer to major uncertainties, alternative geoelectric models, or alternative geologic interpretations for the observed resistivity data. These technical issues were used to formulate the outline for Chapter 4 of this review, which then provided the framework for data review, numerical sensitivity studies, and judgements produced by the subcommittee discussed respectively in Sections 4.2, 4.3, and 4.6; Section 4.5; and Section 4.7 of this report.

While the technical issues discussed below may be critical of the interpretation of Smith and Ross (1982), it should be recognized that these comments are based on additional information that has become available subsequent to the resistivity work. Had this information been available to Smith and Ross, they may have arrived at a different interpretation.

The organization of the remaining portions of this section is as follows: technical issues related to specific discussion by Smith and Ross (Section 4.4.2), identification of other uncertainties (possible alternative explanations) related to interpreting the resistivity data (Section 4.4.3), correlation of technical issues to modeling uncertainty (Section 4.4.4), and summary of issues identified (Section 4.4.5).

4.4.2 TECHNICAL ISSUES RELATED TO SPECIFIC DISCUSSION BY SMITH AND ROSS (1982)

One issue pertains to the potential effect of topography. The report states: "depending on the location and length of the dipoles, these topographic features create moderate to severe distortions in the data" (p. 2); and "non-two-dimensional topography is not fully accounted for in this study" (p. 5). 2-D topographic effects were considered in the modeling process, and appear to have been adequately treated. By comparing the line locations with the 3-D topography, however, questions are raised regarding the impact of off-axis terrain variation on the modeling and interpretation. 3-D terrain effects are a major source of interpretive uncertainty.

A second issue pertains to the correlation of resistivity lows with potential faults or fracture zones. Statements in the report are: "fracture zones, susceptible to zeolitization, have been inferred from areas of low resistivity within the Tiva Canyon tuff that extend to depth" (p. 6); and "the abrupt lateral contrasts in resistivities (Lines A, B, B′) rarely

coincide with the tuff-alluvium boundary; the alluvium itself is not the low resistivity body" (p. 10). Even the effects of thin alluvium may be significant, particularly if associated with terrain effects in an additive manner. The apparent correspondence of resistivity lows with areas of alluvium indicates that the possible existence and the effects of surface conductors should be evaluated.

A third issue discussed by the team pertains to the criteria used by Smith and Ross (1982) to infer the presence of faults. Comparison of the published interpretations for Lines B and B' suggests that there may be inconsistencies in the criteria used. Also, a fault is indicated on the geoelectric models by Smith and Ross (1982) where the Ghost Dance fault shown by Lipman and McKay (1965) intersects Lines A and B at about 22W. Whereas these lines include less data which would constrain such an inference at the ends relative to the middle, the criteria for interpretation are not clear.

4.4.3 IDENTIFICATION OF OTHER UNCERTAINTIES (INCLUDING ALTERNATIVE EXPLANATIONS) RELATED TO INTERPRETING THE RESISTIVITY DATA

This section discusses geologic and geophysical information that should be used to constrain any further modeling or interpretation of resistivity (or other geophysical data) from Coyote Wash. It is necessary to use such information in order to consider an appropriate range of possible alternative geoelectric models and geologic interpretations.

Further geophysical modeling should use available geologic, geophysical, and petrophysical data. Much additional data have become available since the resistivity data were interpreted by Smith and Ross (1982). While certain available geologic and geophysical data were recognized by the original interpreters, the models produced appear to lack such constraints. This suggests that if currently available information is used for constraint, that alternative explanations of the observed resistivity data will result. For example, one alternate interpretive explanation not considered by Smith and Ross (1982) is the possibility for lithological changes unrelated to structure. Low resistivities can be caused by increased porosity and/or increased content of minerals with high cation-exchange capacity (see Section 4.6). Thus, it is now possible to integrate extensive additional information with geophysical modeling and geologic interpretation.

Geologic mapping (Dixon, 1982; Scott and Bonk, 1984; and Section 3 of this review) has identified no surface evidence for a fault near stations 9W on lines A and B. However, the TAR team recognizes the difficulty of extrapolating surface geologic mapping to depth, particularly in volcanic terrane with complex tectonics, and where deposits are created more rapidly and irregularly than in sedimentary terrane. Faulting observed at the surface, such as the Ghost Dance fault, could be relatively recent and nonrepresentative of total slip or throw at depth. Also, mapped faults could be single strands of distributed fault zones at depth.

Team members also note that if faulting at depth is detected from surface geoelectric data, then the feature is likely a rather wide zone of combined fracturing and faulting, with high permeability to fluid, and

associated alteration. This is inconsistent with indications from surface mapping on the eastern slope of Yucca Mountain, which generally finds simple fault interfaces that in principle would not have strong geoelectric signature. The specific relationship between surface geophysical data and subsurface characteristics of faults near the ESF will be further elucidated by detailed subsurface geologic mapping. For the present, it is important that engineering considerations for the ESF should include the possibility that unmapped faults are present and that mapped faults may become more distributed at depth, forming zones of disturbance that give rise to anomalous geophysical properties over widths of 100 ft or more.

4.4.4 CORRELATION OF TECHNICAL ISSUES WITH MODELING UNCERTAINTY

The final observation made in this section pertains to the apparent complexity of the modeling presented by Smith and Ross (1982), leading to the impression that the data may have been "overinterpreted," particularly given the lack of supportive data integrated into the interpretation. This observation is consistent with the review of the modeling found in Section 4.3. Given the current available information and the technical issues outlined in Sections 4.4.2 and 4.4.3, an attempt should be made to determine if simpler models, integrated with current supportive information, could be used to explain the observed resistivity.

4.4.5 SUMMARY OF TECHNICAL ISSUES

Provided below is a list of the primary technical issues identified, which have been used to provide some of the bases for the modeling completed in Section 4.5. The significant technical issues are:

1. 3-D topographic (lateral terrain) effects.

2. Effect of patches of alluvium as potential low resistivity bodies.

3. Uncertainty in the assumption that resistivity lows are structurally disturbed zones.

4. Full integration of available geologic, geophysical, and petrophysical data to constrain the interpretation of observed resistivity.

5. Evaluation of whether simpler models using available information could be used to model the observed resistivity data.

4.5 SENSITIVITY ANALYSES FOR GEOELECTRIC MODELING

This section addresses a number of the technical issues identified in Section 4.4 by means of sensitivity tests. These are test cases that assess the effects of various changes in a basis geoelectric model on the misfit

between observed data and computed apparent resistivity. The sensitivity tests are divided into 2-D (Section 4.5.1) and 3-D (Section 4.5.2). The 2-D cases explore the sensitivity of misfit to variation of model parameters such as the magnitude of the resistivity contrast, and depth extent of the buried conductor. The 3-D cases explore the approximate magnitude of off-axis terrain effects, and off-axis conductors of different geometry both buried and on the surface. Approximate 3-D terrain corrections are calculated for the data of Line A, and the terrain-corrected data are used in the 2-D sensitivity tests. Sensitivity tests show that different types of models are discernible at different levels of misfit. In particular, the models representing a stratigraphically limited conductor, and the depth-extended conductor, are just discernible at the level of misfit achieved in sensitivity testing. A summary of sensitivity testing is presented in Section 4.5.3.

4.5.1 TWO-DIMENSIONAL EFFECTS

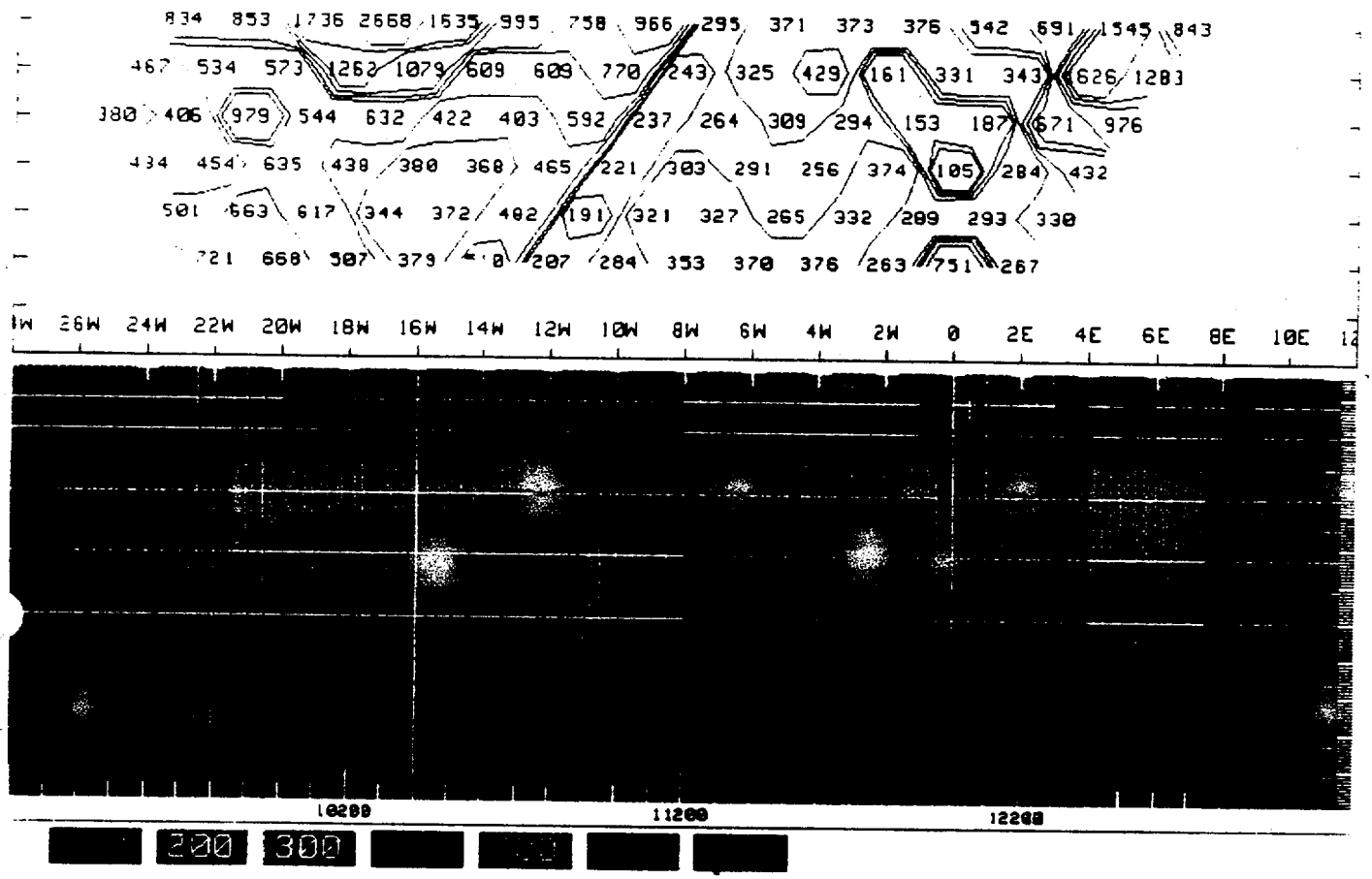
Sensitivity studies were performed using the 2-D algorithm described in section 4.3.1.3.1. The object was to obtain insight into the resolution capability of dipole-dipole data for a model configuration similar to that provided by Smith and Ross (1982). The studies consist of evaluating the changes in the dipole-dipole response as changes are incorporated into the resistivity structure of a starting model, or "basis" model. The data used were for Line A, approximately corrected for 3-D topography (see Section 4.5.2). The use of such data allowed the use of a flat earth model which eliminated one source of complications in the response of the basis model.

4.5.1.1 Basis Model for Sensitivity Tests

A basis model is an arbitrary model on which perturbations are added to test the resolution of a geophysical signal. For the present case, the basis model included "real" data (the 3-D corrected data for Line A) to provide a constant comparative data set for computing residuals (or misfit; the sum of absolute values of residuals; see Section 4.3.3.1).

For comparison to the models in the sensitivity studies, a flat earth model analogy to the Smith and Ross (1982) model for Line A was run. The resistivity structure of Line A as shown by Smith and Ross was modified to be consistent with a flat earth (Figure 4-13), for comparison to the 3-D terrain-corrected data. Computations for comparison of alternative models are limited to the area of interest, which is centered on the anomaly at 8W to 12W. All sensitivity computations were limited to this region. The resulting average misfit of the Smith and Ross flat earth model to the 3-D terrain-corrected data was 35.3% (Figure 4-14), as compared to 23.7% for the 2-D topographic model of Figure 4-8.

The Smith and Ross (1982) flat earth model described above is inappropriate as a basis model for sensitivity studies for two reasons: (1) overly complicated subsurface resistivity distribution, and (2) the misfit is too large. Therefore a series of exploratory models were tested to



Contour Interval: 100, 125, 200, 250, 300, 400, 500, 650, 800, 1000

Figure 4-13. Simplified geoelectric model of Smith and Ross (1982). The original model has been transformed to a flat-earth model for Line A. The 3-D terrain corrected data are shown in the dipole-dipole pseudosection above (see Section 4.5.2). Note that the small vertical offsets in the laterally contiguous conductors are a way to reproduce dipping stratigraphy and realistic burial depth, and do not signify faults.

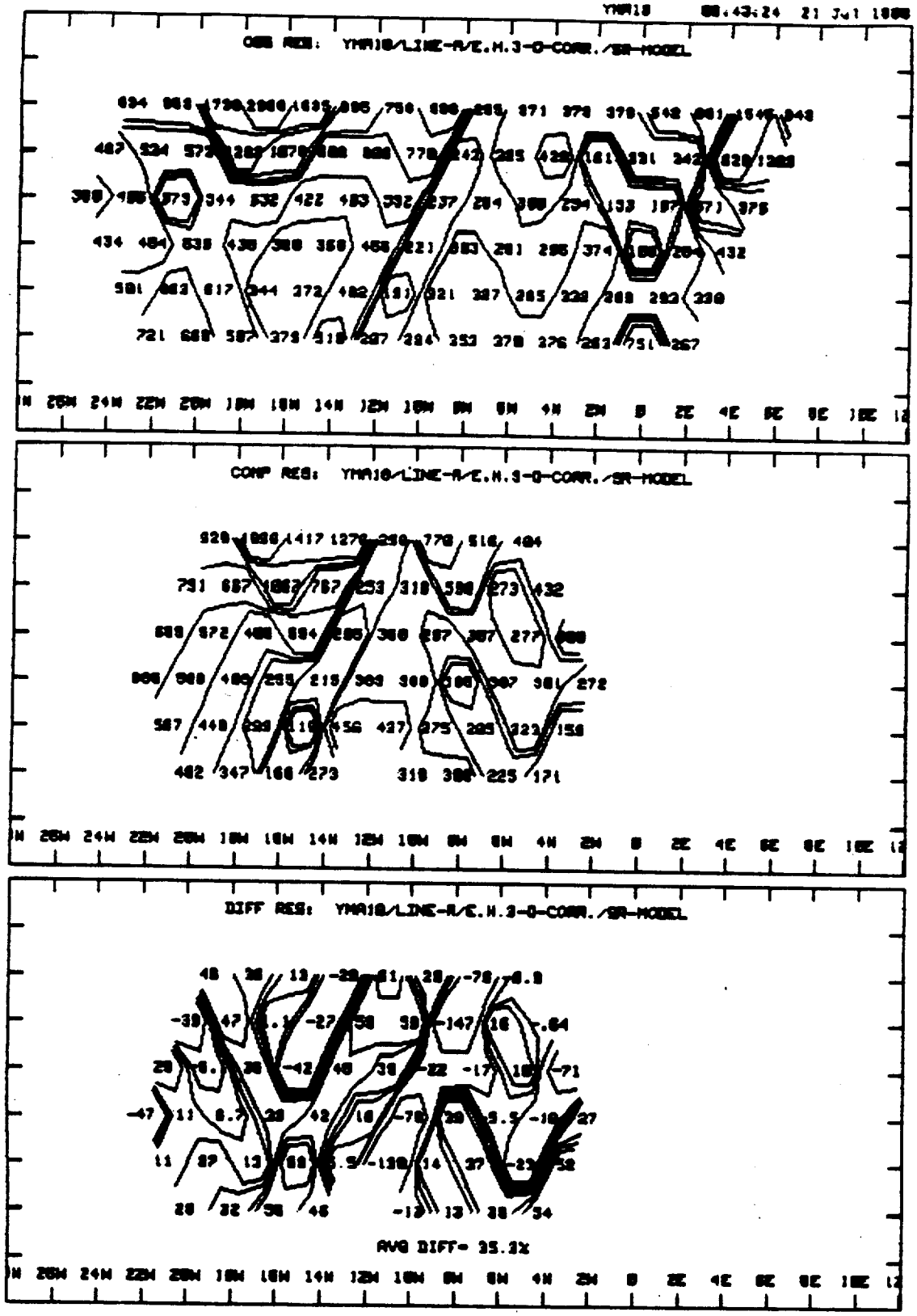


Figure 4-14. Comparison between the 3-D terrain corrected data for Line A (top), and the computed apparent resistivity for the simplified flat-earth model for Line A, based on the Smith and Ross model (middle). The misfit presented at the bottom is expressed as a percentage of the 3-D terrain corrected ("observed") values.

develop a basis model that was simpler and showed less misfit. The criteria for the basis model were (1) to honor the resistivity logs from boreholes USW G-4 and UE25 a#6, (2) to keep the model geometry as simple as possible (minimum contrasts), and (3) to have a misfit that was reasonable for the dipole-dipole field data. It was not known in advance how well these criteria could be followed, therefore no quantitative measure of these criteria were established a priori.

The basis model decided upon is shown in Figure 4-15. This model is designated "A1." Model A1 is reasonably simple, has a misfit of 21.3%, and honors the borehole logs in having a buried low resistivity layer (150-ft thick, at a depth of about 125 to 150 ft) that simulates a layer of nonwelded tuff known to have low resistivities in the borehole logs (see Section 4.3.2.2). The low resistivity layer is fundamentally a 1-D feature in model A1. Lateral variations in the layer for model A1 have a contrast of 2 and are spread out across a distance of 200 to 400 ft, whereas the upper and lower contacts of the layer have contrasts of 4 to 30 in the area of interest. The increasing depth of this layer to the west simulates the elevation relationships inferred from the simplest interpretation of drillhole logs.

4.5.1.2 Analysis of Sensitivity to a Resistivity Anomaly

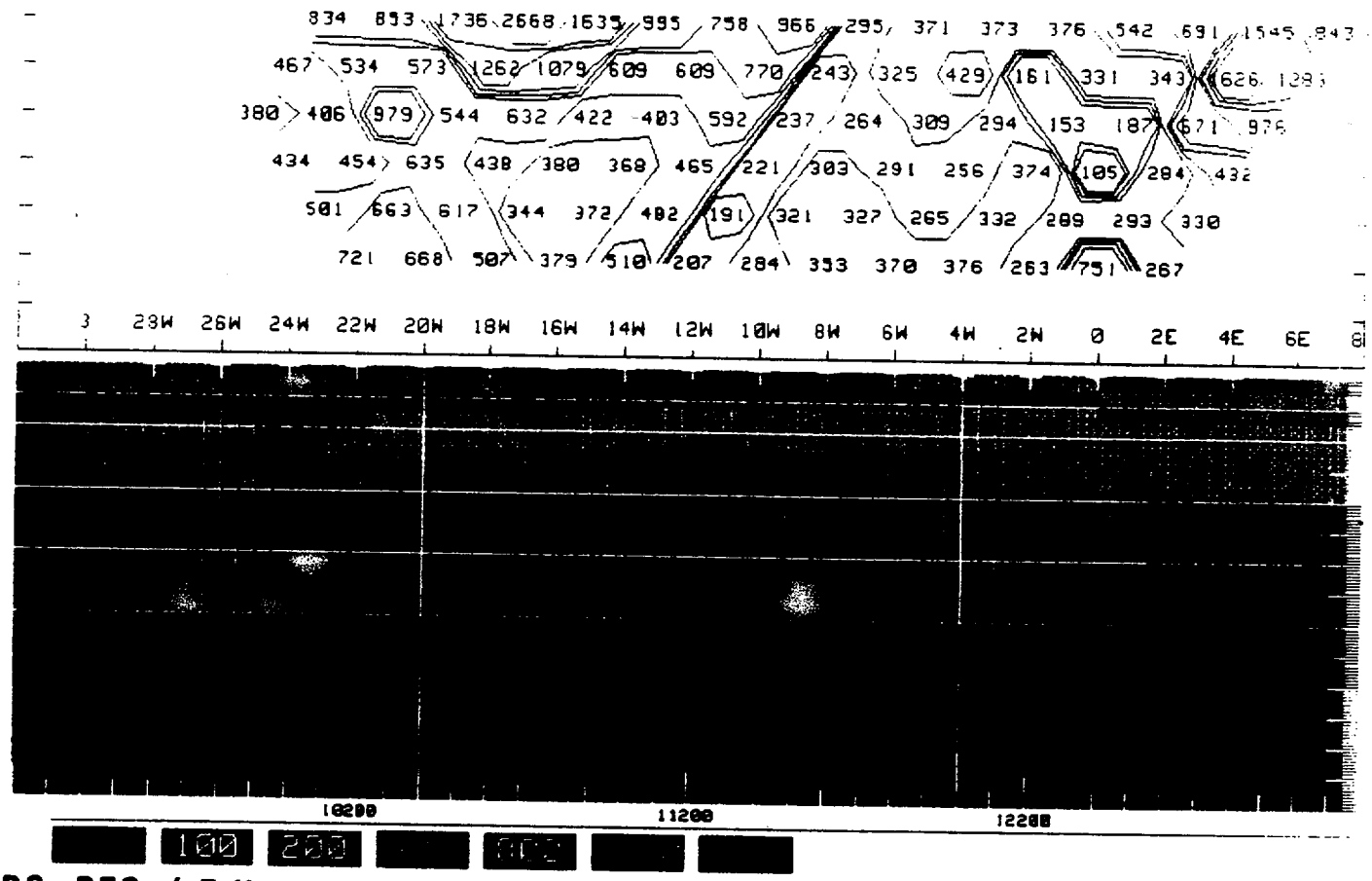
The question to be evaluated is the sensitivity of "noisy" dipole-dipole resistivity data to a 2-D anomaly such as postulated in the Smith and Ross (1982) model in the region of 10W to 12W. The tests consist of adding a low resistivity region of variable width and depth extent to the basis model A1.

The resistivity structure variations tested are shown in Figure 4-16. Models A1, A2, B2, C2, D2, and E2 are representative of the possibilities for this particular configuration. The results of the tests are shown in Figures 4-17(a) through (f), ordered from least to most conductive (Models A1, E2, A2, D2, B2, and C2), respectively.

The average misfit values are shown in Figure 4-16 beside their respective models. These values are useful in modeling, but they have limited utility for sensitivity evaluation because they are an average of possibly skewed distributions of misfit across the dipole-dipole response. Certain source dipoles and certain source-receiver separations will be more strongly affected by a given model change than other regions.

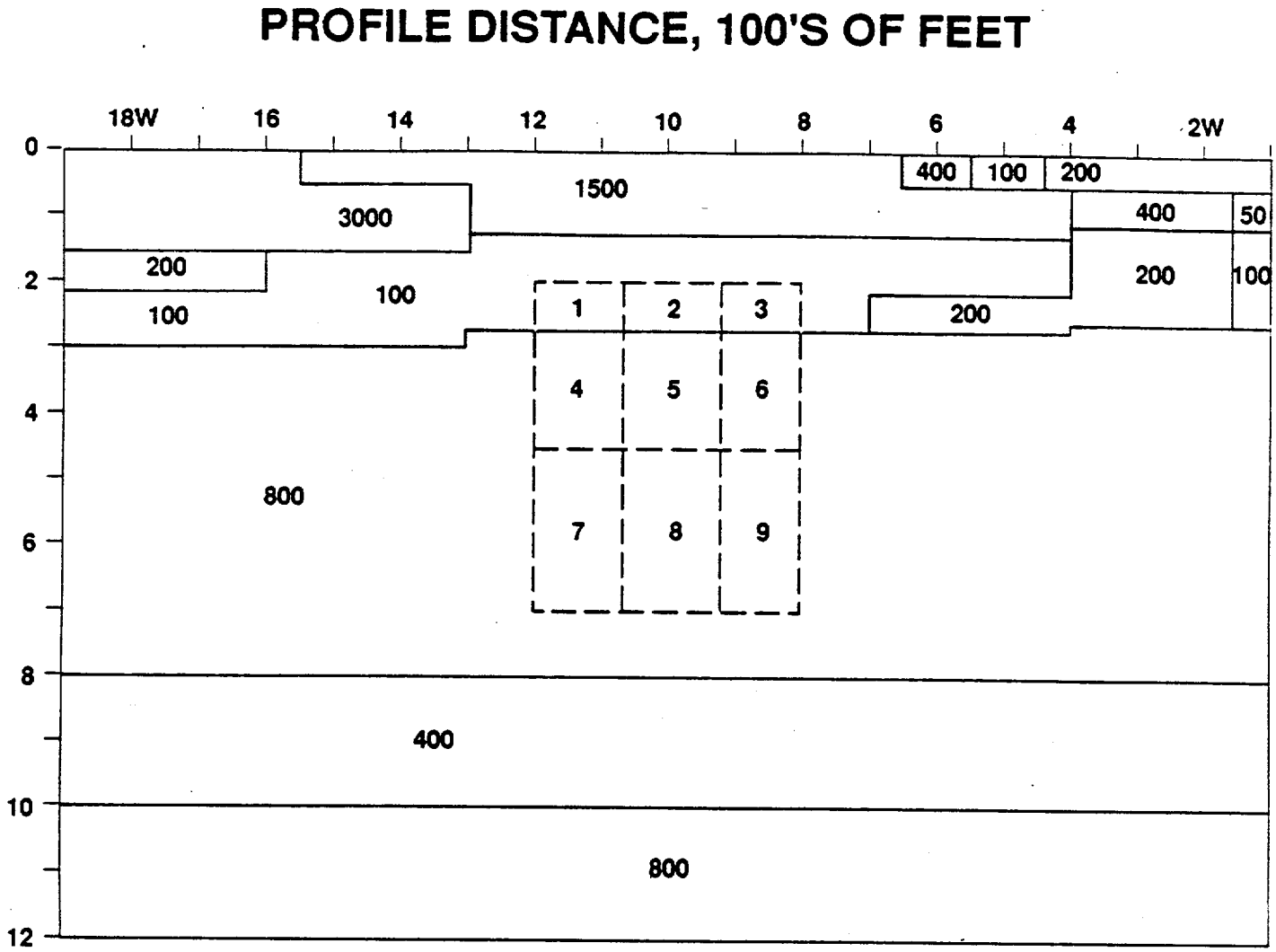
Figure 4-18 shows histograms of the residuals for the different test models and for various groupings of N. This illustrates the nature of variation of the residuals with respect to source-receiver location and model parameterization. Different representations are shown: (1) Figure 4-18(a) shows histograms of the total residuals, and (2) Figure 4-18(b) shows histograms of the difference in residuals (test model minus basis model).

The total residuals shown in Figure 4-18(a) range from less than 10% to more than 50%. If one assumes the data used is accurate to the 15% level, none of the models are optimum in the sense of having the distribution of residuals clustered in the 0 to 20% bins. However, the aim here is not to



OBS. RES. (E.H. 3-D CORR.)
Contour interval: 100, 125, 200, 250, 300, 400, 500, 650, 800, 1000

Figure 4-15. Basis model for 2-D sensitivity studies of Line A. This is a simple model (termed "A1") that produces average misfit of 21.3% with the 3-D terrain-corrected data. Note that the small vertical offsets in the laterally contiguous conductors are a way to reproduce dipping stratigraphy and realistic burial depth, and do not signify faults.



BODY RESISTIVES

MODEL	1	2	3	4	5	6	7	8	9	
A1	100	100	100	800	800	800	800	800	800	21.3%
A2	50	50	800	800	800	800	800	800	800	23.9%
B2	50	50	50	100	100	100	800	800	800	27.6%
C2	50	50	50	100	100	100	200	200	200	28.7%
D2	100	50	100	800	100	800	800	200	800	23.9%
E2	100	50	100	800	100	800	800	800	800	23.2%

Figure 4-16. Schematic of systematic perturbations to the basis model A1, for 2-D sensitivity studies. Resistivity of the labeled bodies in the schematic cross section were varied according to the table below.

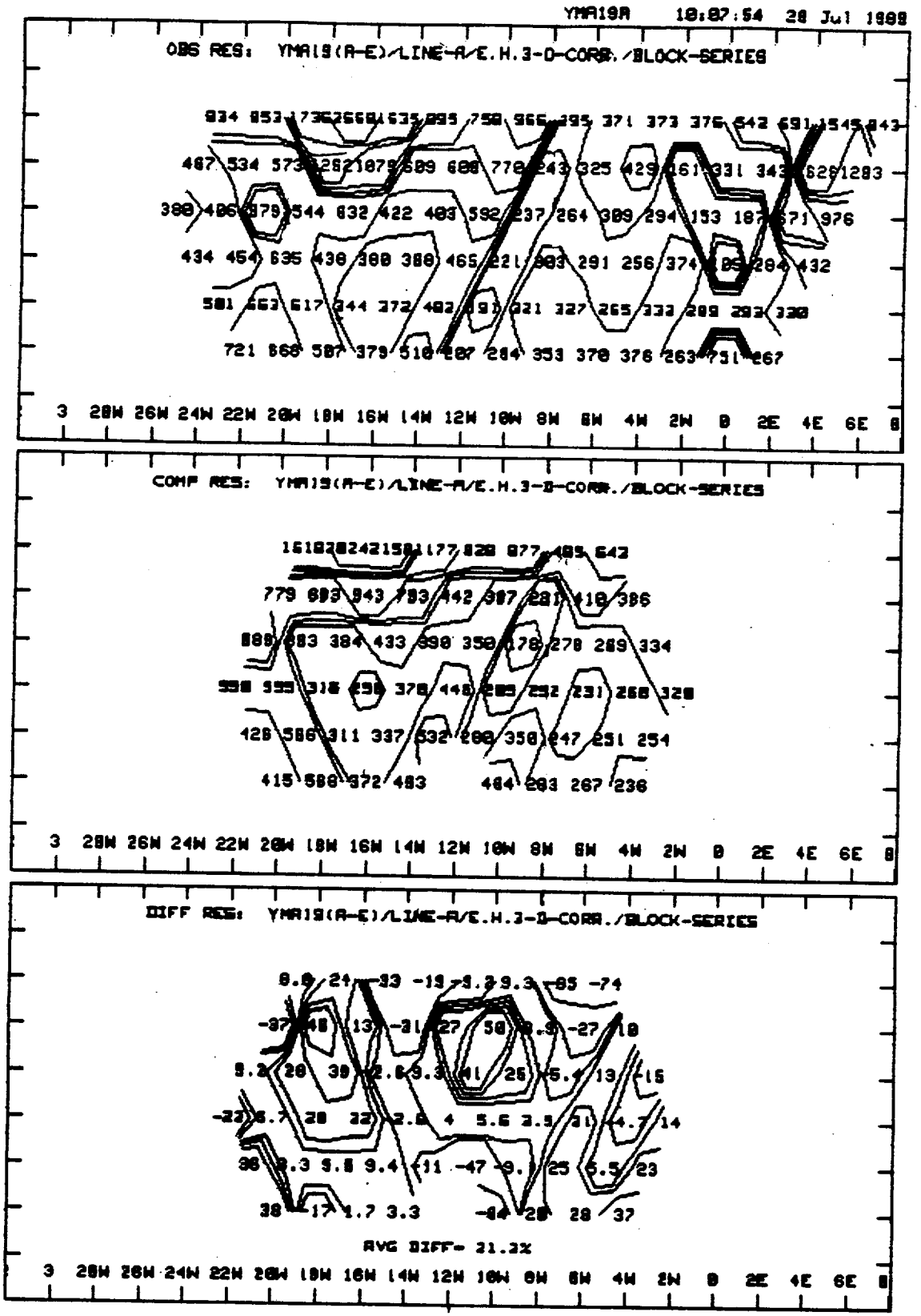


Figure 4-17(a). Comparison between the 3-D terrain corrected data for Line A (top), and the computed apparent resistivity for the sensitivity test model A1, for Line A (middle). The misfit presented at the bottom is expressed as a percentage of the 3-D terrain corrected ("observed") values.

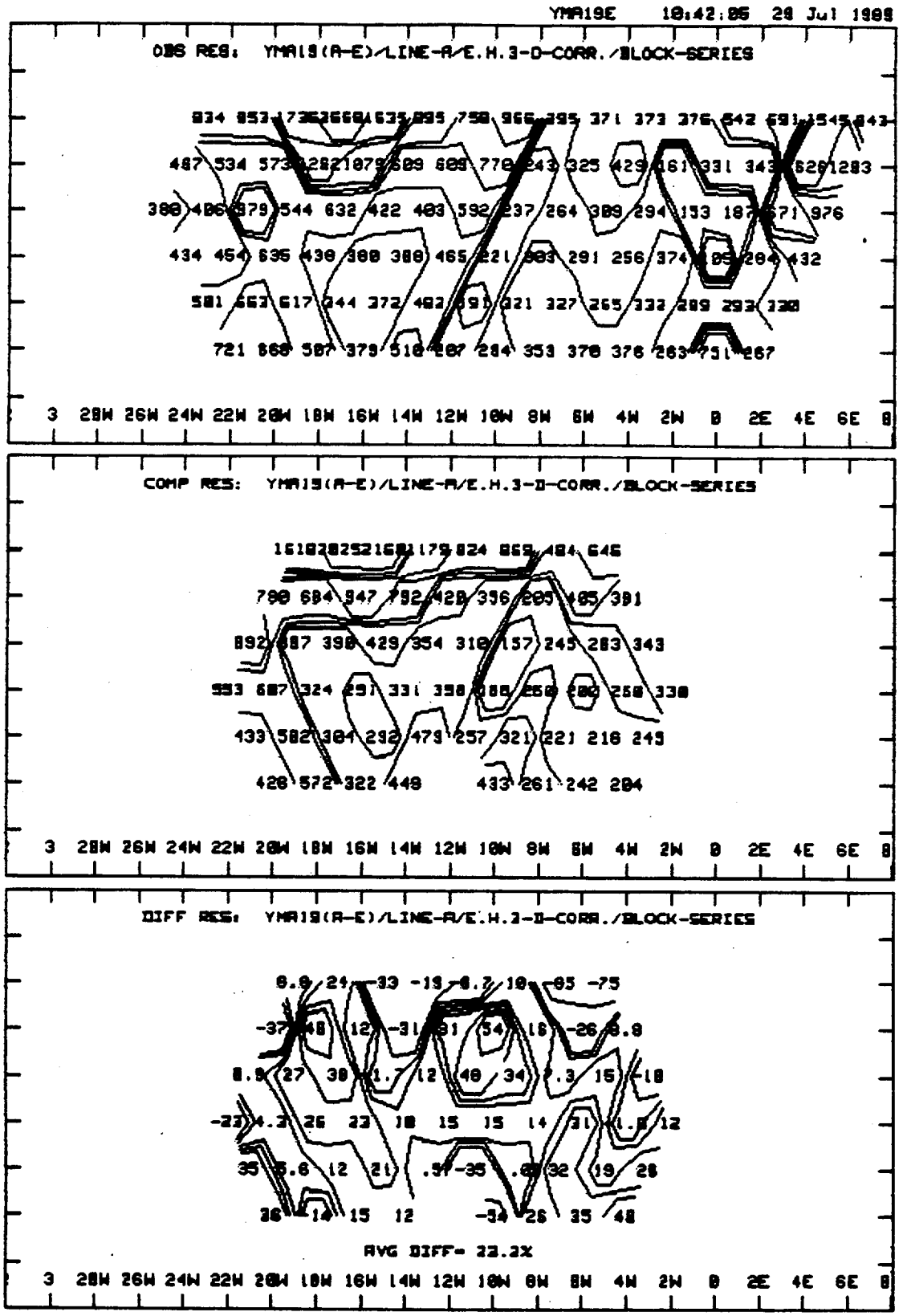


Figure 4-17(b). Comparison between the 3-D terrain corrected data for Line A (top), and the computed apparent resistivity for the sensitivity test model E2, for Line A (middle). The misfit presented at the bottom is expressed as a percentage of the 3-D terrain corrected ("observed") values.

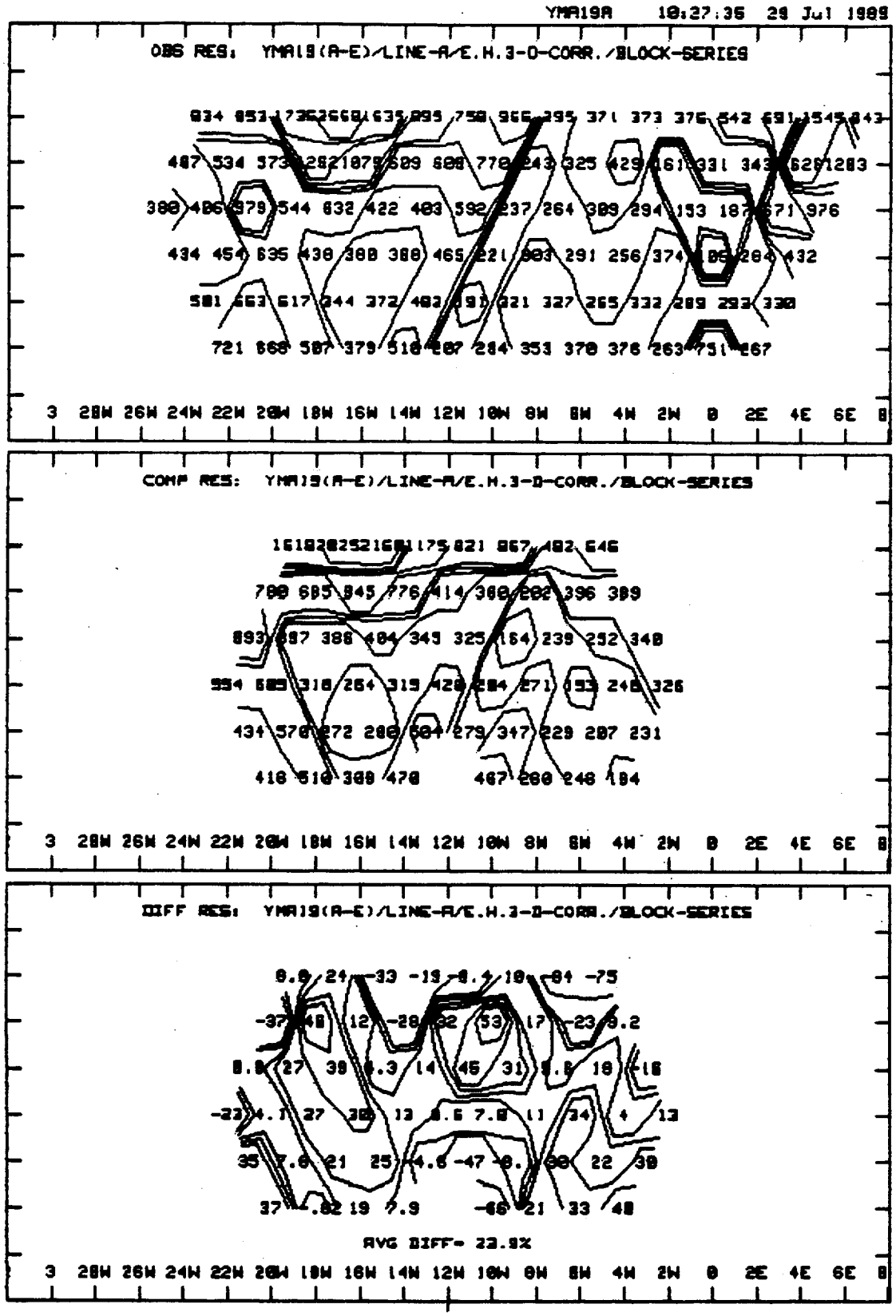


Figure 4-17(c). Comparison between the 3-D terrain corrected data for Line A (top), and the computed apparent resistivity for the sensitivity test model A2, for Line A (middle). The misfit presented at the bottom is expressed as a percentage of the 3-D terrain corrected ("observed") values.

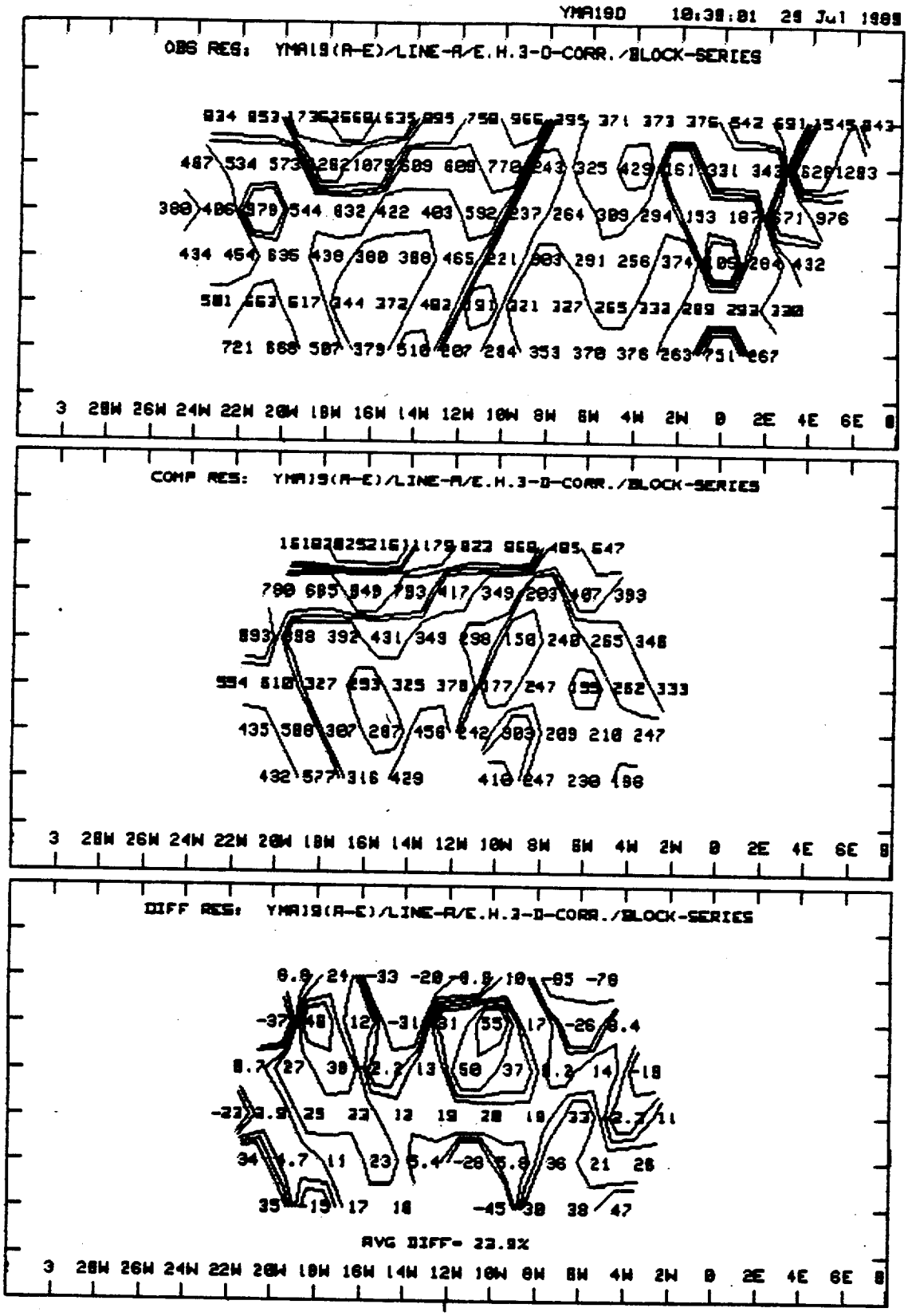


Figure 4-17(d). Comparison between the 3-D terrain corrected data for Line A (top), and the computed apparent resistivity for the sensitivity test model D2, for Line A (middle). The misfit presented at the bottom is expressed as a percentage of the 3-D terrain corrected ("observed") values.

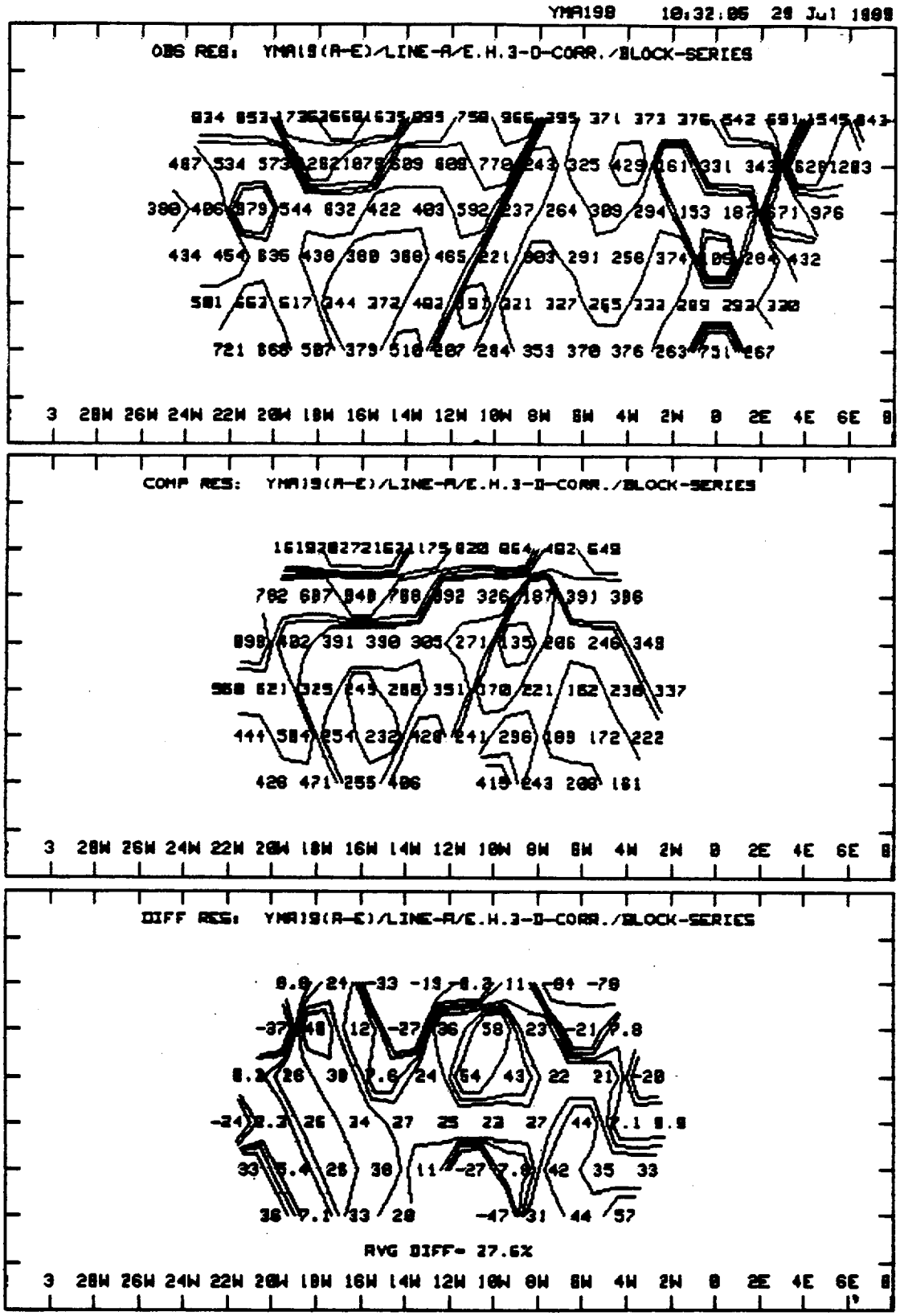


Figure 4-17(e). Comparison between the 3-D terrain corrected data for Line A (top), and the computed apparent resistivity for the sensitivity test model B2, for Line A (middle). The misfit presented at the bottom is expressed as a percentage of the 3-D terrain corrected ("observed") values.

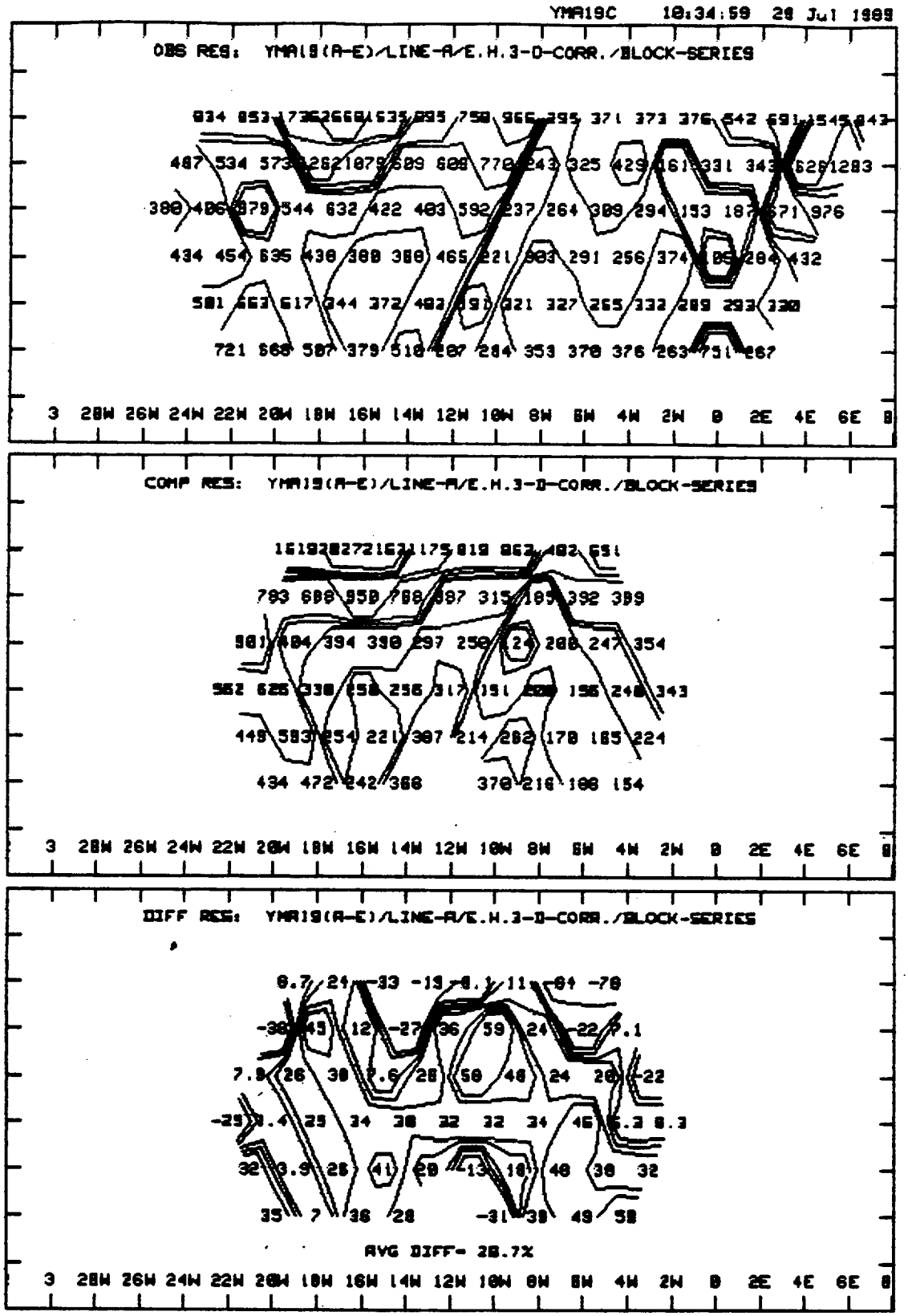
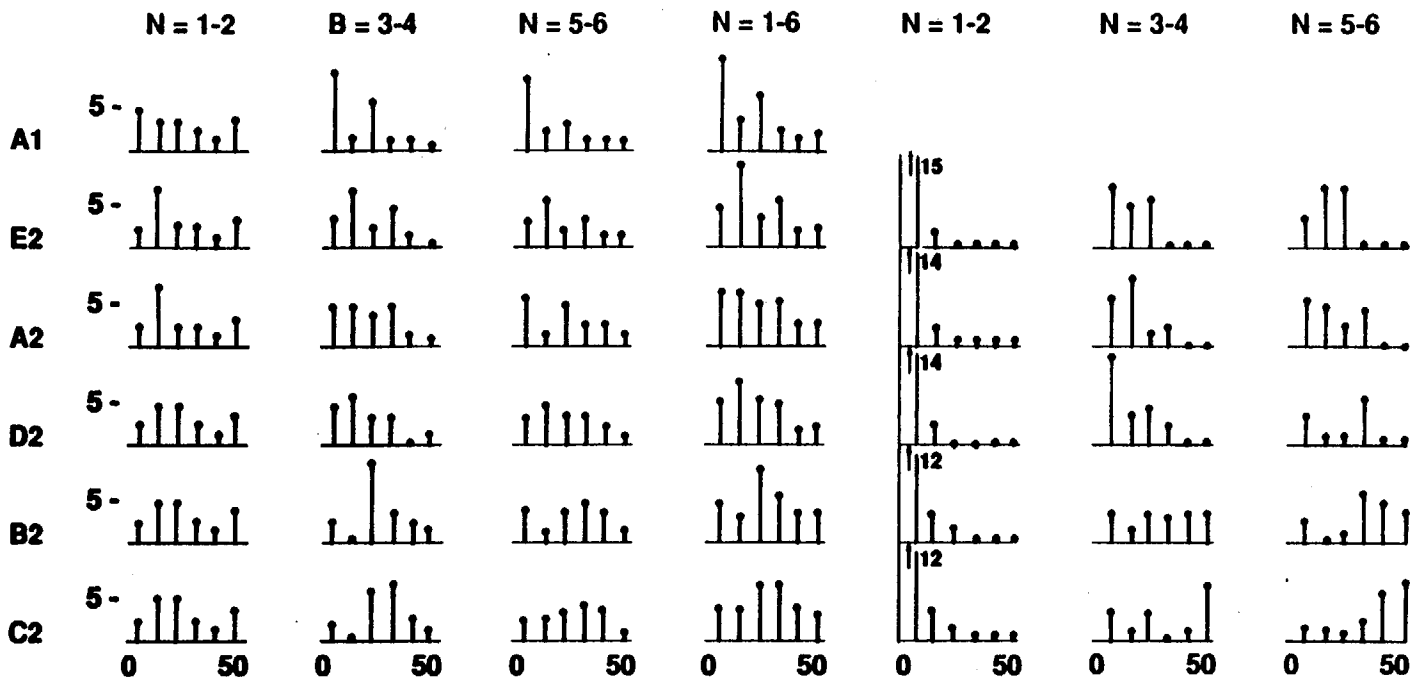


Figure 4-17(f). Comparison between the 3-D terrain corrected data for Line A (top), and the computed apparent resistivity for the sensitivity test model C2, for Line A (middle). The misfit presented at the bottom is expressed as a percentage of the 3-D terrain corrected ("observed") values.



A. DISTRIBUTION OF $|\epsilon|$ HISTOGRAM INTERVALS

= 0 - 9.9%
10 - 19.9%
20 - 29.9%
30 - 39.9%
40 - 49.9%
> 50%

B. DISTRIBUTION OF $|\Delta\epsilon|$ HISTOGRAM INTERVALS

= 0 - 4.9%
5 - 9.9%
10 - 14.9%
15 - 19.9%
20- 24.9%
> 25%

Figure 4-18. Histograms of misfit between selected sensitivity test models, and the 3-D terrain-corrected data, for a portion of Line A corresponding to the area of interest. Each tabulation represents the number of apparent resistivity values in that model, which differed from the data values by the indicated amounts. (a) Relation of misfit to dipole separation parameter N. (b) Relation of the difference between the misfit of several models and that of model A1, to dipole separation parameter N.

establish an optimum model, but to evaluate the sensitivity of the data to changes in the model. To this end, the important relationship in Figure 4-18(a) is the shift in the median of the residual with respect to various values of N, and with respect to the different models. The histograms of difference residuals of Figure 4-18(b) are more clear in this regard, because the inherent misfit of the basis model, which tends to obscure the statistical variations, is removed by using difference residuals.

The data can be looked at in more detail by plotting the difference residuals along profile. Figure 4-19 compares the difference residuals for the various test models. The difference residuals (relative to A1) for the set of test models are plotted against horizontal distance, for each value of dipole separation parameter N, to show profiles of misfit. The important aspect of this figure is where the difference residuals exceed the noise level in the data. The shaded regions of Figure 4-19 show where the difference residuals exceed an arbitrary level of 8%.

The data above suggest that the models tested fall into three groups that are distinguishable from each other at noise levels of about 15%:

I.	Model A1	(uniform buried conductive layer models)
II.	Models E2, A2	(stratigraphically-limited conductor models)
III.	Models D2, B2, C2	(depth-extended conductor models)

Different models within the groups above are distinguishable only at noise levels of 10% or less (Figures 4-18(b) and 4-19). The inferred level of noise in the data of interest in Coyote Wash is about 15% (Section 4.2.1.3). At noise levels of 20%, groups I and II are not resolvable from one another. However, this combined group (I and II) is still apparently resolvable from group III.

A corollary to the above statements is that the ultimate resolution is limited by the maximum of (1) the inherent noise level of the data, and (2) the level of misfit reached in the model development. The latter is a function of model misfit due to various causes, including computing time and cost, and provides the (higher) practical limit of resolution.

4.5.1.3 Summary of 2-D Sensitivity Studies

The set of models analyzed above explored the sensitivity of dipole-dipole modeling and interpretation to a set of variations in 2-D resistivity structure that were considered appropriate for purposes of the TAR. For observed data with a noise level (15%) appropriate to that used in the Coyote Wash survey, stratigraphically limited anomalies should be resolvable from depth extended anomalies, and both should be resolvable from uniform layer models. However, at such a noise level, the width of the anomaly in either anomalous case, is more uncertain (within about 100 ft). The tests did not explore relationships related to the magnitude of the resistivity contrast, but it is anticipated that an anomalous contrast of at least 3 is required for reliable detection and resolution, and that absolute resistivities are not distinguishable to better than a factor of 2 (Section 4.3.3, Table 4-1).

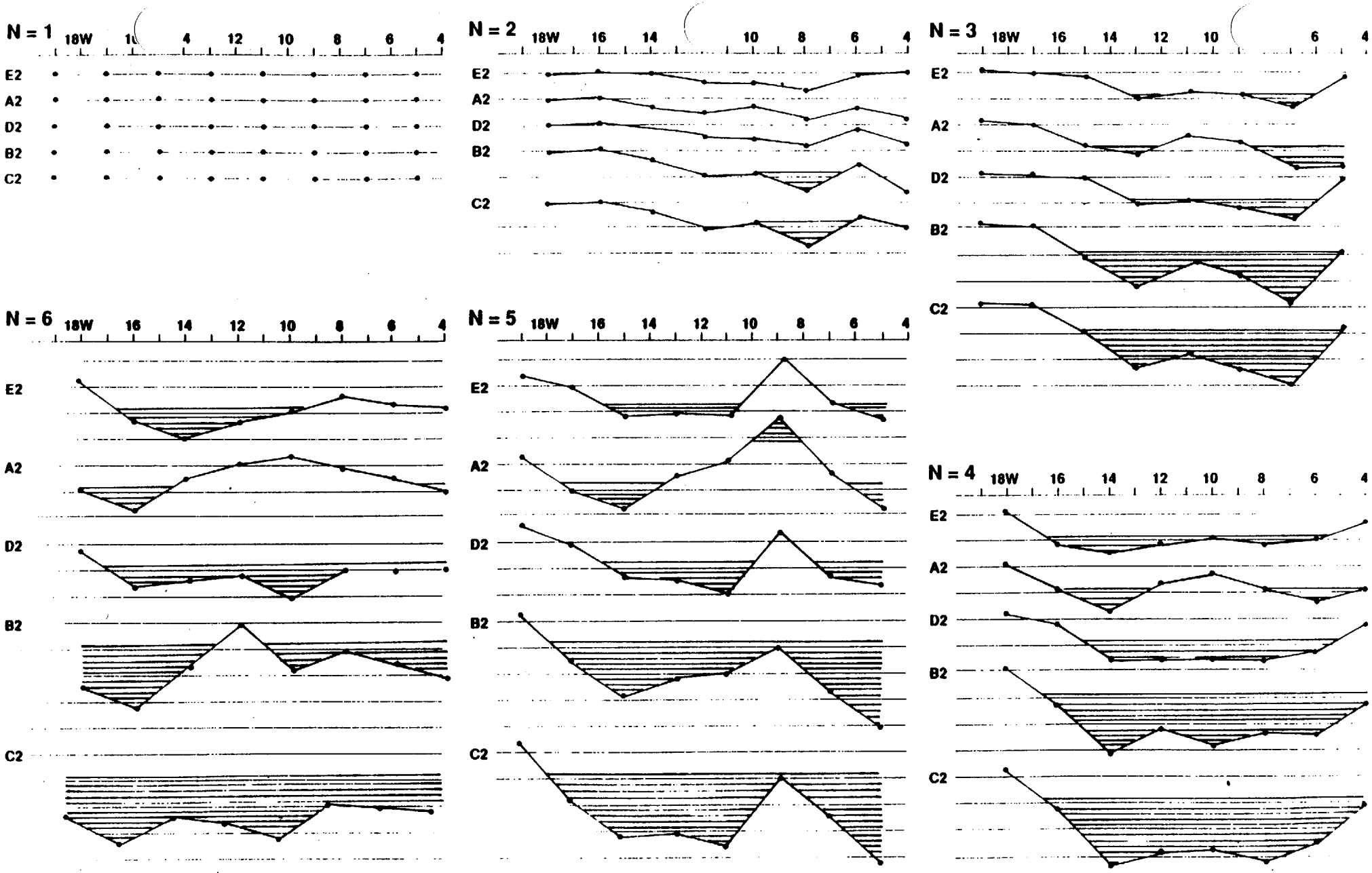


Figure 4-19. Plots of misfit between selected sensitivity test models and the 3-D terrain-corrected data, vs along-line position for a portion of Line A corresponding to the area of interest. Regions of misfit greater than 8% are shaded (an arbitrary threshold chosen for graphical impact). The curves are grouped by the value of the dipole separation parameter N, and each curve is plotted to the same linear scale.

Because "real" terrain-corrected data from Line A were used to evaluate model misfit in the sensitivity studies, it is especially important that the best fitting model among those tested was the simplest model (with no strong lateral contrast at station 9W). This reinforces the conclusion of Section 4.3.4, that modeling and interpretation of these data could be improved using currently available geologic and geophysical information for constraint.

The sensitivity tests described above were limited to the 2-D case, to a specific "basis" model, and to a limited set of resistivity structural variations. The results do not resolve ambiguities caused by equivalence of solutions or off-axis effects. Equivalence of solutions arises specifically in resolving the magnitude of the contrast vs. the dimensions of the anomaly. The nature of the starting model also plays a part in equivalence of solutions, as does the location of the anomaly relative to the axis of the profile (see Section 4.5.2 below). Such problems can only be resolved by (1) having sufficient data to model the problem in three dimensions, and (2) having alternate data with complimentary but different sensitivity to the target parameters.

4.5.2 THREE-DIMENSIONAL EFFECTS

Smith and Ross (1982) interpreted a fault at a location near the mouth of Coyote Wash where 3-D physiographic and structural changes are evident: the thickness of alluvium diminishes to zero, and the ridges forming Coyote Wash terminate in Drill Hole Wash. Smith and Ross (1982) considered only 2-D terrain variation in the direction of the dipole-dipole survey lines. Three-dimensional effects were acknowledged by the interpreters but not incorporated in the published interpretation.

The review team elected to investigate the sensitivity of the Smith and Ross (1982) interpretation to 3-D effects as one of several technical issues identified with the original work (see Section 4.4). Two topics involving 3-D effects were explored: (1) terrain effects, and (2) variation in near-surface geoelectric structure involving off-axis conductors. Based on combined 3-D and 2-D sensitivity studies, the 3-D terrain effect was found to be significant, but apparently does not account for the geoelectric anomaly under the Coyote Wash. Modeling of hypothetical near-surface 3-D structure also showed that off-axis conductors could be significant, but insufficient data are available to explicitly model the effect for Coyote Wash. Studies related to both of the topics are addressed separately in the following paragraphs.

Induced polarization (IP) effect was also considered by Smith and Ross (1982). However, as discussed in Section 4.6, IP data were not considered in 2-D or 3-D sensitivity studies because the apparent magnitude of IP effect was low, and the magnitude of variations was limited to roughly 50 to 100%.

4.5.2.1 Finite Element Code, Basic 3-D Mesh, and Test Cases

For modeling of DC resistivity, a finite element code was adopted that had originally been produced for steady-state, saturated ground-water flow problems (Istok, in press). The code is named GW1, and is described further in Appendix I and supporting references. This section describes the basic 3-D mesh used and the results from a number of 2-D and 3-D test cases to determine appropriate element sizes and types, and to compare results with 2-D and 3-D analytical solutions. In addition, several 3-D problems were run for comparison with studies published in the literature.

Basic Mesh

The principal purpose of 3-D modeling was to evaluate the magnitude of effects from 3-D terrain and off-axis geoelectric structure, and not to exactly model any of the lines traversing Coyote Wash. Consequently, generalizations were made to simplify the calculations, and Line A was chosen as the basis for the model used to compute 3-D terrain effect. The choice of Line is appropriate because Smith and Ross (1982) did not calculate 2-D terrain effect for the western end of Line B. The in-line (2-D) terrain effect for Line B was negligible according to Smith and Ross (1982).

A plane of symmetry was introduced along one side of the mesh which represented Coyote Wash, and source nodes were placed on the symmetry plane (Figure 4-20). If the symmetry plane were made to correspond with Line A or B of Smith and Ross (1982), then because these lines traverse steep slopes, the effective cross section of the modeled canyon would be very steep-sided and narrow at the bottom. Accordingly, the symmetry plane was placed about 100 ft toward the centerline of Coyote Wash from Line A (Figure 4-21). The magnitude of calculated terrain effect should therefore be reduced because the new line is further from the steep slope, but this is offset somewhat because the width of the resulting (numerically modeled) canyon is about half the actual width of Coyote Wash. Although the sensitivity of the calculations to the symmetry approximation could be tested by generating several 3-D meshes, the initial mesh was judged to be adequate for 3-D sensitivity testing.

A basic 3-D mesh was developed for the test cases, and used for all sensitivity studies. It was designed so that topography could be added and other tests could be run without changing the numbering or connectivity. The basic mesh consists of 13,200 linear parallelepiped elements, defined by 15,756 nodes. The numbers of elements along the x, y, and z directions in the rectilinear mesh are 12, 101, and 13, respectively. (The dipole-dipole line is parallel to the y-axis.) Element properties and nodal coordinates were altered for various sensitivity studies. For comparison to analytical solutions, a simulated quarter-space configuration was used with uniform model resistivity. For comparison to published cases, the quarter-space configuration was used with variable element projection. For the terrain effect sensitivity study, a uniform resistivity value was used, and the model coordinates were adjusted as discussed below.

Various studies were done in 2-D and 3-D to establish appropriate element types, element dimensions, and model size (distance to model boundary). The resulting basic mesh resembles that used by Smith and Ross

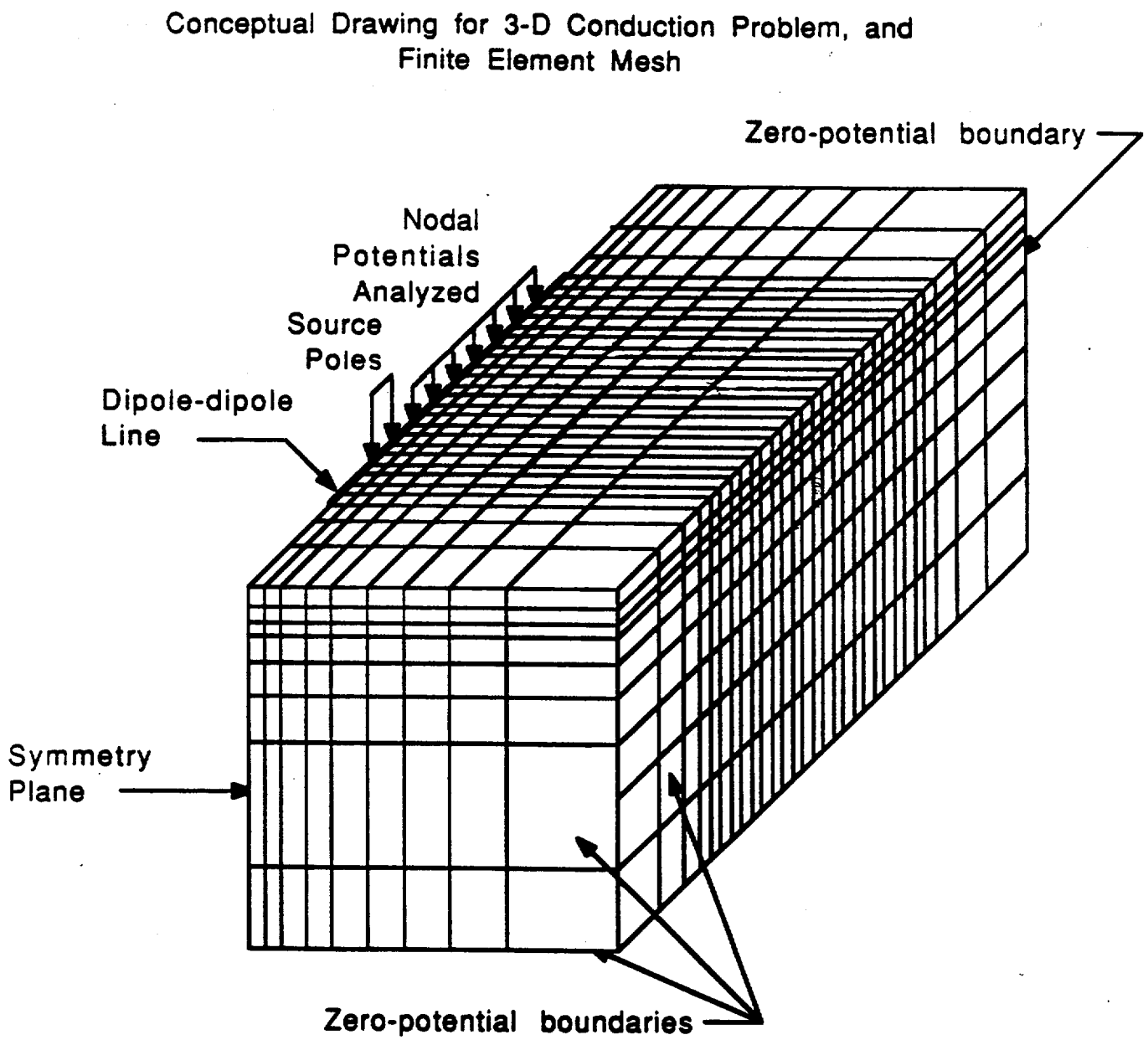
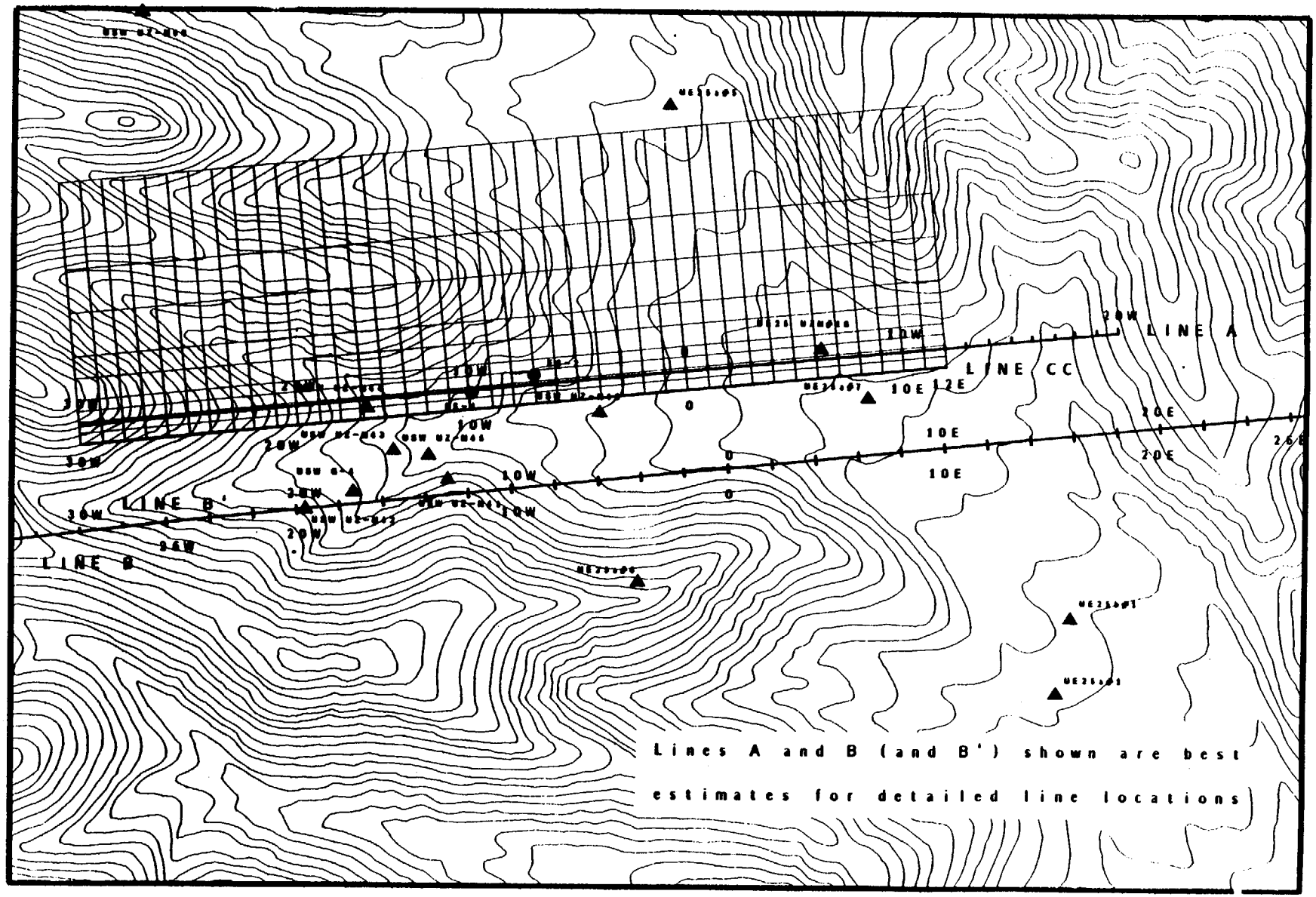


Figure 4-20. Schematic of 3-D finite element mesh used in sensitivity calculations.

N7 ,000

E567,500



E561,500

N764,000

Figure 4-21. Map showing relationship of the 3-D finite element mesh used to calculate terrain effects, to the terrain of Coyote Wash and vicinity.

YMP89.105.1

(1982). The in-line dimension of each element used in both implementations was 50 ft. Both approaches used 25-ft thick elements near the surface. Element size increased laterally away from the survey line, and with depth, in geometric increments. The model boundary was set back a comparable distance from the region of interest in both implementations.

Comparison to Analytical Solutions

In general, the test case results agreed with the analytical solutions, except that the magnitude of potentials calculated for 3-D cases was affected by the proximity and geometry of the model boundaries. However, calculated differences in potential were very close (generally < 1% different; see Appendix I) to the analytical values. The boundary effect problem has been encountered by others and is described in the literature (Holcombe and Jiracek, 1984). Additional information on comparison to 2-D and 3-D analytical solutions is provided in Appendix I.

Comparison to Published Numerical Calculations

Several test cases were run to compare results calculated using GW1 with published results using other codes. The purpose for comparison was to determine if the GW1 code, using variations on the basic mesh, would generate terrain effects of appropriate magnitude. Anomaly magnitude is defined for this review as the maximum deviation of apparent resistivity from the nominal uniform model resistivity, background resistivity, or large-scale average resistivity. Test cases included two 3-D cases from a finite strike-length study by Dey and Morrison (1979), a 3-D implementation of a 2-D case from Beyer (1977), and a 3-D implementation of a 2-D model from Rijo (1977).

Two 3-D cases from Dey and Morrison (1979) were run with the GW1 model and found to agree closely with the published results. The two cases were both buried conductors under a flat earth, symmetric about the survey line, and with different strike-length. Comparison of the pseudosections for one of these cases (Dey and Morrison, 1979, Figure 5d) shows that both the magnitude and the localization of the apparent resistivity effect are similar for the two implementations (Figure 4-22). Further information and graphical presentation of test cases in support of 3-D sensitivity studies is presented in Appendix I.

Another test case was a 3-D simulation of a 2-D case from Beyer (1977), consisting of a shallow outcropping conductor (with infinite strike-length). The length was modeled by extending the body to the boundaries of the mesh. The GW1 calculations agreed with the published case (Beyer, 1977, p. 11-154) to about 1% (see Appendix I).

Rijo (1977) used a 2-D model to calculate the effect of simplified terrain on dipole-dipole resistivity response. One of the cases used (Rijo, 1977, Chapter 3, Figure 2) involved a dipole-dipole profile across a valley of infinite strike-length. This case was simulated in 3-D using the GW1 code, creating a valley by adjusting nodal coordinates. A comparison of the calculated 3-D and 2-D pseudosections (Figure 4-23) shows that the 3-D simulation produced larger anomalies in apparent resistivity associated with the terrain. The localization of the effect is the same, but the magnitudes are different. Both models used linear elements of comparable size, and both

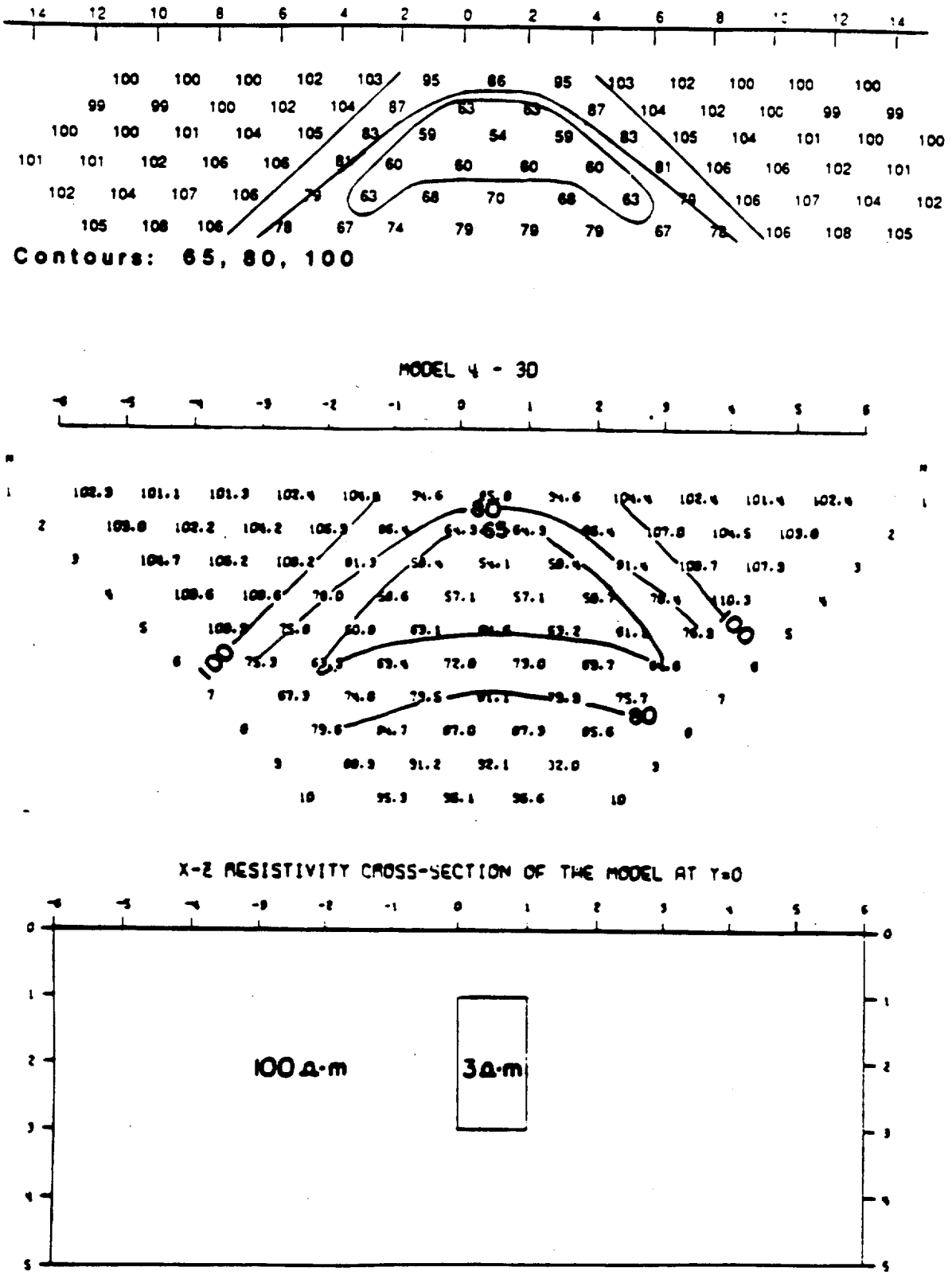
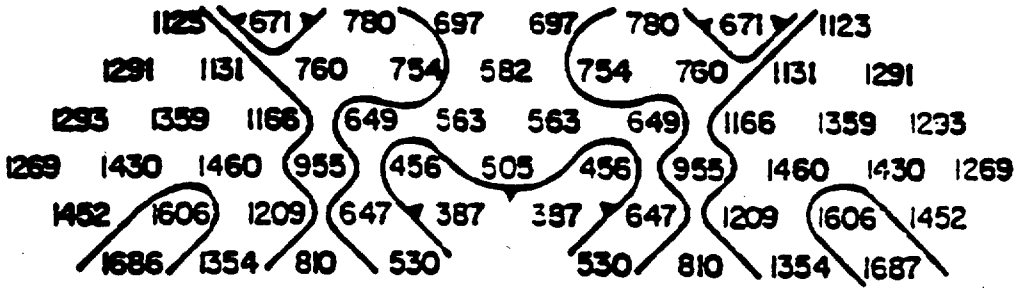
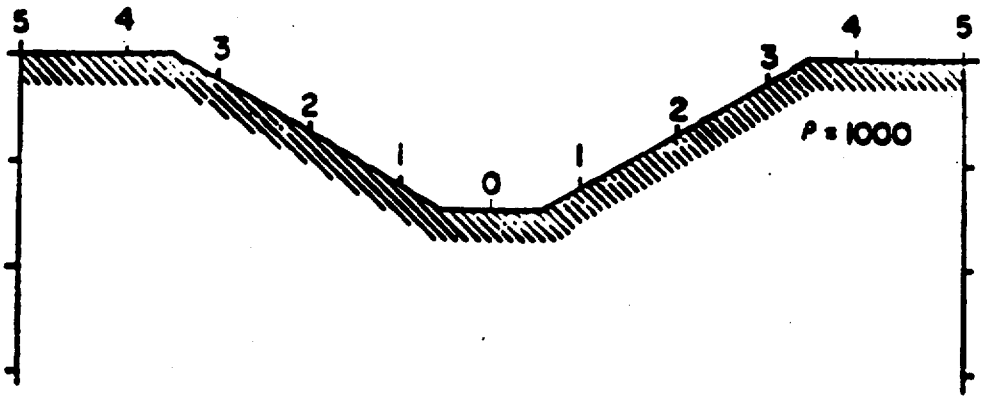
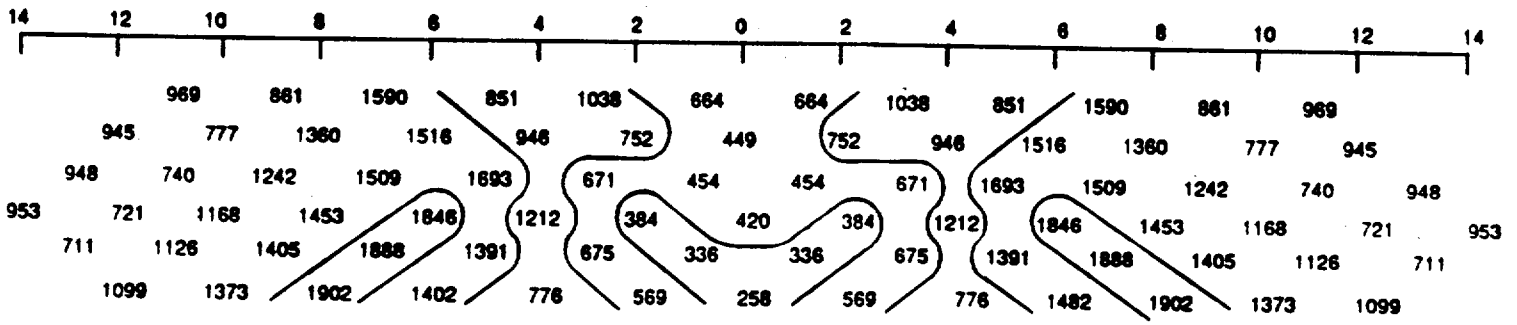


Figure 4-22. Comparison of: (a) a pseudosection calculated by Dey and Morrison (1979) for a representative 3-D problem, and (b) a calculation for the same problem performed for this review.







Contours: 500, 700, 1300, 1700

Figure 4-23. Comparison of: (a) a pseudosection calculated for a 2-D terrain problem by Rijo (1977), and (b) a 3-D simulation of the same problem performed for this review.

modeled the topographic surface explicitly. The principal differences in setting up the problem are:

1. For the upper air-earth boundary, the GW1 implementation adjusts nodal coordinates to match the terrain (Holcombe and Jiracek, 1984), whereas Rijo (1977) used triangular elements for surface definition and included air-filled elements to preserve a rectilinear nodal array.

2. The Rijo (1977) solution method solved the finite element problem in the wavenumber domain, and computed the spatial response by integrating the transform over seven wavenumber values, whereas the GW1 algorithm simulates conduction in the spatial domain.

Both of these factors may be applicable to explaining the discrepancy.

Another aspect of the Rijo (1977) formulation is that a relatively low value for air resistivity (e.g., 100,000 ohm-m) is generally needed to control the contrast between nominal earth and air resistivities, apparently to ensure numerical stability. Air has resistivity of one Giga-ohm or more, thus the effect of using a smaller value may explain at least part of the discrepancy between 2-D and 3-D results, because the GW1 code uses a no-flux boundary condition. However, the sensitivity of 2-D model results to the air-earth resistivity contrast was not tested for this review.

In summary, test cases show that calculated apparent resistivities for dipole-dipole survey geometry agree to within a fraction of a percent with the 2-D and 3-D analytical solutions considered. Model results for published 3-D cases and 3-D simulation of published 2-D cases agreed with the published results to a few percent or better, with the exception of a Rijo (1977) terrain model. The importance of this discrepancy was not emphasized in this review, because both codes produced good agreement with other published results.

4.5.2.2 Three-Dimensional Terrain Effects

Topographic elevation values for nodes on the surface of the basic 3-D mesh were picked from a contour map, for every node in the direction transverse to the dipole-dipole line and every second node (100-ft increment) in the direction of the line. Mesh geometry was transformed in the manner described by Holcombe and Jiracek (1984), so as to maintain appropriate size and shape for every element.

Terrain corrections were calculated for an idealized line located about 100 ft south of Line A. The calculated 3-D terrain effect for Coyote Wash ("topo1" model) is shown in Figure 4-24. The figure shows the calculated apparent resistivity for a uniform earth model with topography, as a pseudosection with each value normalized by the nominal uniform resistivity value. The maximum magnitude of the terrain correction is just over 40%, which is roughly double the maximum magnitude of the 2-D effect for Line A calculated by Smith and Ross (1982).

The observed apparent resistivity data from Line A were corrected for 3-D terrain by dividing the calculated terrain corrections into the resistivity values (Figure 4-24). The result is used as an approximately terrain-corrected pseudosection for Line A, in the 2-D sensitivity analysis of Section 4.5.1. (Note that Figure 4-24 represents both off-axis 3-D effects and 2-D effects.) This type of correction has been previously used and discussed by Fox et al. (1980) in the 2-D case, and by Holcome and Jiracek (1984) in the 3-D case.

The terrain-corrected apparent resistivity for Line A shows that the 3-D terrain effect very likely does not explain the low-resistivity anomaly between about 9W and 15W on lines A and B. The magnitude of the terrain effect is appreciable, but it occurs several hundred feet to the west of the anomaly near the mouth of the canyon.

4.5.2.3 Three-Dimensional Near-Surface Resistivity Structure

As discussed in Section 4.5.1, shallow conducting bodies at the surface can have an important effect on dipole-dipole interpretation. Outcropping or very shallow 2-D bodies were shown to produce diagonals in the dipole-dipole pseudosection, which are of significant magnitude and extend to all depths (e.g., the test case of Beyer, 1977, p. 11-154 presented in Appendix I). Much of the "signal" present in dipole-dipole Lines A and B may be caused by such features. The effects of off-axis structure, either buried or surface, can also be significant as shown in the literature (Dey and Morrison 1979; Holcombe and Jiracek, 1984). The importance of 3-D outcropping surface structure and buried off-axis 3-D structure are investigated in this section.

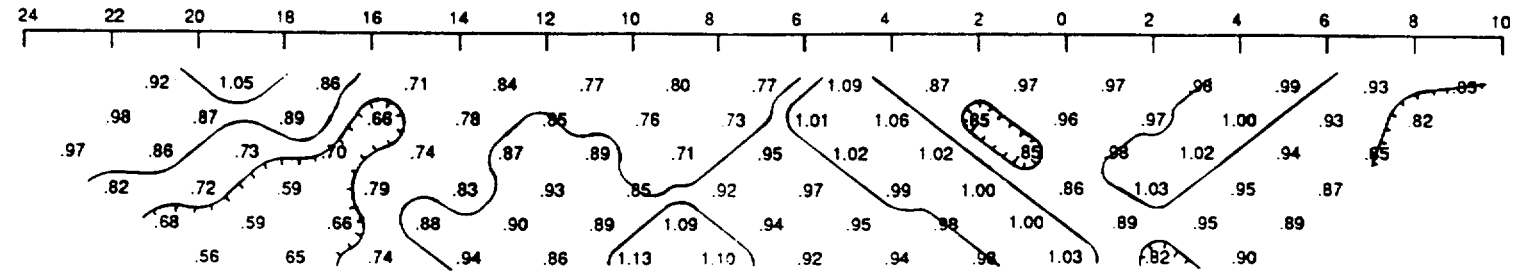
Three aspects of DC resistivity interpretation will be evaluated in this section with respect to the implications for analysis of Lines A and B:

1. Conductors outcropping under the survey line may have a significant effect on dipole-dipole data.

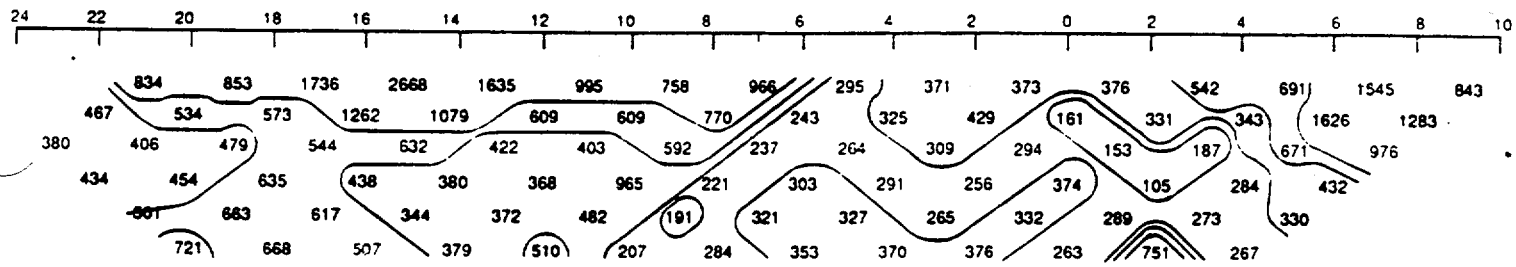
2. Off-axis conductors more than 1 or 2 dipoles away (depending on resistivity contrast) are relatively unimportant.

3. Off-axis, finite conductors cannot be distinguished from more deeply buried, infinite conductors in a 2-D interpretation.

Each of these aspects is potentially important for understanding DC resistivity survey results. The 3-D sensitivity studies will address questions that involve structure to one side of the survey line, which is the relationship of survey Lines A and B to alluvium and other resistivity structure that may be associated with Coyote Wash. However, the basic 3-D mesh described in Section 4.5.2.1 permits only symmetric resistivity structure. The sensitivity study models are therefore symmetric, and the calculated effects are larger than one-sided effects. The principal purpose of these studies is evaluate approximate effect magnitude, so for discussion purposes the calculated magnitudes are halved.



Contours: 0.70, 0.85, 0.98



Contours: 200, 300, 500, 700

Figure 4-24. Terrain effect calculated for Line A of Smith and Ross (1982) using the symmetry approximation discussed in Section 4.5.2, presented as: (a) correction factors computed by normalizing the computed apparent resistivity by the nominal uniform resistivity value, and (b) actual data from Line A divided by the correction factors in the manner of Fox et al. (1980).

Conductors Outcropping Under the Survey Line

This test is intended to compare finite strike-length conductors at the surface with similar conductors of infinite strike-length. The alluvium-filled portion of lower Coyote Wash (east of USW G-4) is about 400 ft (or two dipole lengths) wide at the narrowest part. The alluvial thickness is about 35 ft at G-4 (after pad construction) and it may increase down the canyon. Accordingly, sensitivity studies were run with a 50- by 200-ft (cross section) surface conductor with a 1:10 resistivity contrast, symmetric about the survey line with strike-lengths of 200 and 600 ft. These were then compared to the solution for the same type of body with infinite strike length, that was a test case discussed above (see Beyer 1977, p. 11-154.)

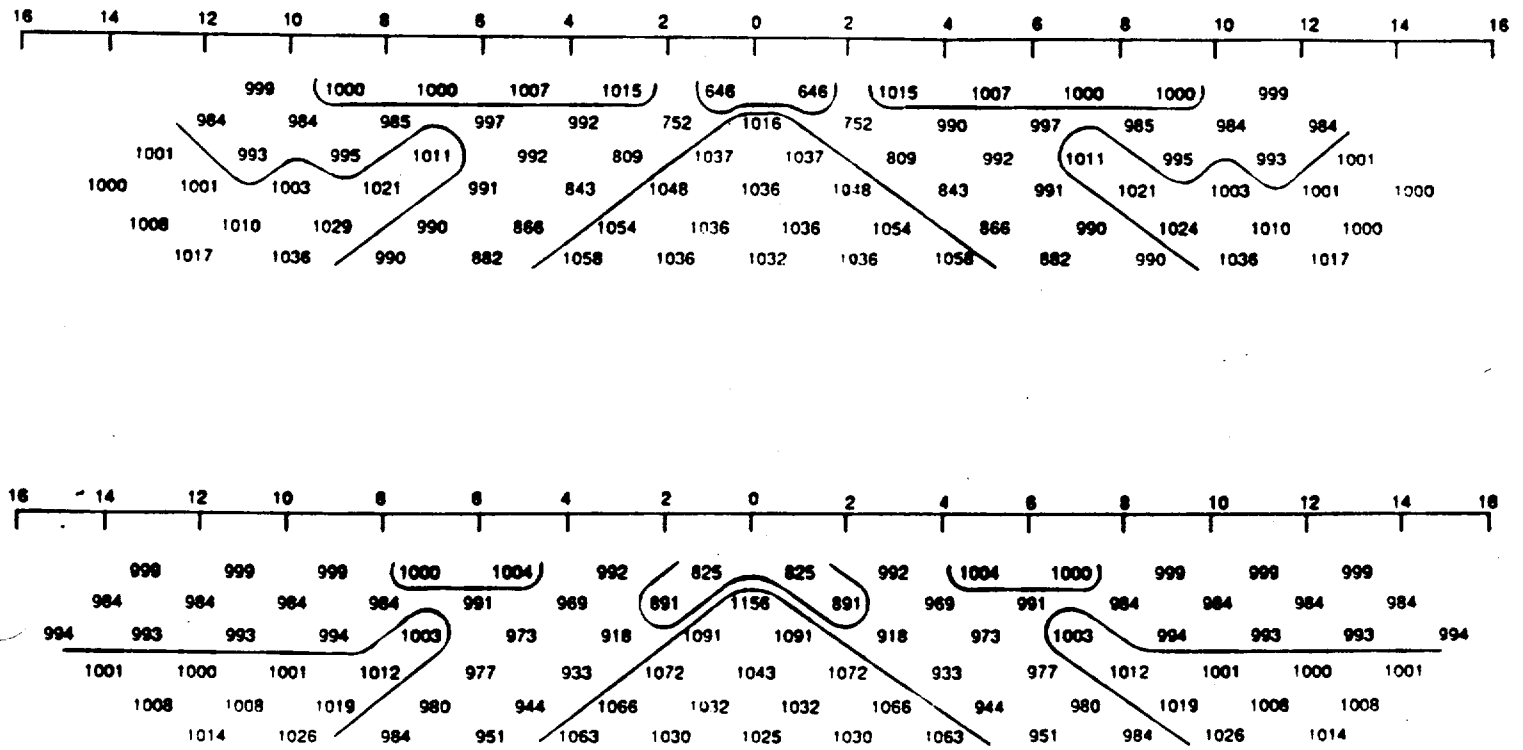
The results summarized in Figure 4-25 show that the 600-ft body produces substantially all of the response of the infinite body, and the 200-ft body produces about half. From the width of Coyote Wash, the effect of a strip of alluvium extending from the survey line to the oposite side of the canyon would be about half the infinite strike-length effect. Depending on the alluvial geometry and resistivity contrast, this could produce an apparent resistivity anomaly of 20% or more (relative to that of the underlying strata). Thus finite strike-length does not appear to preclude the possibility that conductive alluvium produces significant "signal" in the dipole-dipole data from Coyote Wash.

Off-Axis Conductors With Complex Geometry

Lines A and B traverse "fingers" of alluvium that connect with the deeper alluvium of the central channel. Such structure could increase the importance of the thicker portion of the alluvium by providing current paths from the survey line to the area of higher conductance.

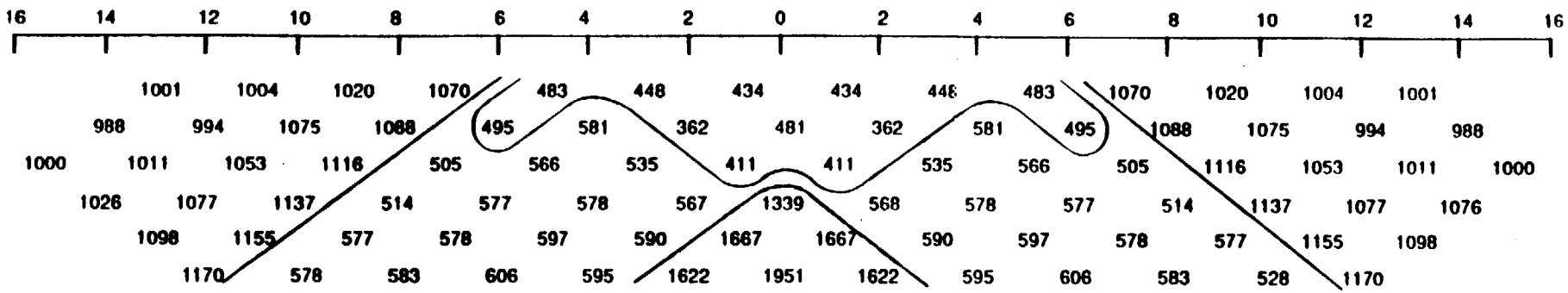
This concept is tested using an "E" shaped body. The limbs of the "E" intersect the survey line on the surface, and the spine of the "E" represents a conductive body along Coyote Wash. Three cases were run, varying the thickness of the conductive body along Coyote Wash, and varying the distance to this body from the survey line (the length of the limbs of the "E"). The magnitude of the effect (halved to account for symmetry) is about 25% for the highest conductance model (Figure 4-26). The geometry of this model consists of a thick (100-ft) body along Coyote Wash (spine of the "E"), with dimensions of 200 ft by 500 ft. This body is "connected" to the survey line by shallow strips 100 ft wide and 200 ft long (limbs of the "E"). When the thickness of the conductive body along the wash is decreased from 100 to 25 ft, the maximum magnitude of the effect decreases to about 20%. A similar effect results from increasing the length of the limbs of the highest conductance model from 200 to 400 ft.

These results show that an off-axis conductive body connected by surface conductors to the survey line can produce an effect that is about twice that of the surface conductors alone, if the off-axis body is within about 1 or 2 dipole lengths of the survey line (i.e., if the limbs of the "E" are not too long). The distance from the centerline of Coyote Wash to either Line A or B is roughly one dipole length, thus the thicker alluvium in the central part of the wash could accentuate the effect where alluvium is traversed by



Contours: 900, 1000

Figure 4-25. Strike-length sensitivity study for a shallow conducting body outcropping under the dipole-dipole survey line.



Contours: 500, 1000

Figure 4-26. Sensitivity study of the effect from a shallow surface conductor connecting the survey line with an off-axis conductive body. The dimensions of the off-axis surface body are 200 ft. wide by 900 ft. long (profile direction) by 100 ft. high. This body is connected to the survey line at 4W, 0, and 4E by shallow surface bodies with dimensions 200 ft. wide by 100 ft. long (profile direction) by 25 ft. high. The resistivity contrast of these connecting bodies is 1:20 (1000 ohm-m background).

the survey line. This result supports the explicit incorporation of surface conductors, in the geoelectric models used in this review for sensitivity studies, even though the alluvium may be thin near the edges of the wash where it is traversed by the survey lines.

Off-Axis, Buried Conductor

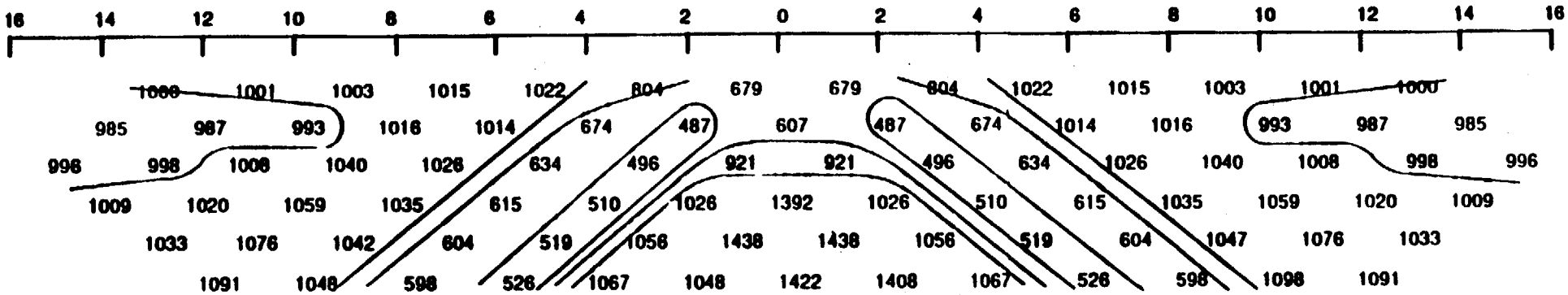
The relationship of similar response from off-axis separation in 3-D interpretation, and apparent depth of burial in 2-D interpretation, was addressed by Dey and Morrison (1979). The effect was not recalculated for this review. Rather, the magnitude of the apparent resistivity anomaly from an off-axis buried conductor was calculated using geometry and resistivity values that are approximately representative of the PTn unit beneath Coyote Wash (as sample by borehole USW G-4; see Section 4.6.3). In this case a 100-ft thick body, with dimensions of 200 by 500 ft, is situated 100 ft away from and parallel to the survey line (Figure 4-27). The magnitude of the apparent resistivity effect (halved to account for symmetry) is about 25%. For comparison, the magnitude of the diagonal feature of the pseudosection for Line A is 25% or more depending on the background resistivity value used.

From the cases studied by Dey and Morrison (1979, Figures 9 and 10), the signature of an off-axis body is comparable in magnitude to that of a body buried more deeply directly beneath the survey line. For example, the anomaly produced directly over the standard heterogeneity model (buried at 1 dipole length) was almost an order of magnitude greater than that produced by a line passing just one dipole length to the side of the standard model. This corresponds to the magnitude computed for a line passing over the standard heterogeneity buried at about 4 dipole lengths. There is also a tradeoff between the resistivity contrast, volume, and depth of burial. Thus the same magnitude could be associated with a larger body, with less contrast, at shallower depth.

The result of this sensitivity test case is that the magnitude of the anomaly computed for an off-axis body with characteristics that could be representative of conditions beneath Coyote Wash (see Section 4.6.4) is comparable to the observed anomaly. Also, the results indicate that off-axis resistivity structure could produce indications that the conductive body detected by Lines A and B extends to greater depth than is suggested by borehole and stratigraphic data. However, it is important to note from the test case (Figure 4-27) that apparent resistivity is increased immediately adjacent to the body, for $N > 3$. This effect is not readily apparent in the observed data for either Line A or B.

Summary of Sensitivity Studies of 3-D Near-Surface Structure

The 3-D studies show that resistivity structure associated with Coyote Wash, including conductive alluvium and localized conductance directly beneath the wash, could significantly affect Lines A and B. Perhaps the most important result is that the effect of shallow outcropping conductors is only mildly dependent on finite strike-length. Tests also show that the effect of shallow conductors connecting the survey line with high-conductance off-axis bodies is comparable in magnitude to the effect of shallow outcropping conductors, and provides yet another possible explanation for the diagonal structure observed in Line A. Sensitivity studies also indicate that the



Contours: 600, 800, 1000

Figure 4-27. Sensitivity study of the effect of a buried conductor, situated 0.5 dipole lengths deep and 0.5 lengths away from the survey line. The dimensions of the conductor are 200 ft. wide by 500 ft. long (profile direction) by 100 ft. high by 100 ft. burial depth. The body lies adjacent to the survey line between stations 2.5 E and 2.5 W. The resistivity contrast is 1:20 (1000 ohm-m background).

conducting body which apparently includes the PTn unit, may be situated off-axis and not persist at depth. The overall impact of these studies is to show that the existing data do not discriminate among the resistivity structures that could be associated with most of the possible geologic interpretations of a resistivity anomaly in Coyote Wash. In other words, the possible 3-D effects are such that the existing data can be explained by different scenarios, which do not necessarily include a fault at or near the exploratory shaft locations. Also, the 3-D studies indicate that the existing data are consistent with generalized geophysical models derived from known stratigraphic relationships and borehole data, plus plausible concepts of hydrologic and authigenic processes.

4.5.3 SUMMARY OF TWO-DIMENSIONAL AND THREE-DIMENSIONAL SENSITIVITY STUDIES

This section addresses two main topics:

1. The sensitivity of the dipole-dipole data acquired at Coyote Wash to a low resistivity body of infinite strike-length (2-D). Such a body provided the basis for interpreting a fault in the vicinity of the ES.

2. The sensitivity of dipole-dipole data to finite strike-length (3-D) bodies that may produce error in 2-D modeling.

The conclusions of the sensitivity studies are:

1. Dipole-dipole data of the type acquired at Coyote Wash should detect and resolve a 2-D low resistivity body with contrast of 2:1 or greater at depths of about 150 to 500 ft. Resolution, however, is strongly dependent on data uncertainty and the level of misfit achieved in modeling.

2. A low resistivity body with a 2:1 contrast located within a low resistivity stratigraphic unit is barely resolveable at the 15% misfit or "noise" level, and then only if its width (along profile) is greater than 200 ft. A contrast of 4:1 or greater would probably be unambiguously detected, but the width of such a body would not be resolvable to better than 100 ft.

3. A low resistivity body with contrast of greater than 4:1 and width of 200 ft or more extending to a depth of 400 ft below a low resistivity layer can be unambiguously detected, but the resolution of width is no better than 200 ft. A 200-ft wide body would not be distinguishable from a 400-ft body. The depth extent would probably also be unresolvable to better than 50%.

4. A stratigraphically limited body can be resolved from a depth-extended body within data uncertainty of 15%, if the modeling is carried to a comparable level of misfit.

5. Topography similar to that adjoining Lines A, B, and B′ in Coyote Wash causes 3-D terrain effects of about 40% maximum magnitude.

This is roughly twice the effect caused by 2-D representations of the along-profile topographic variation. The effect of neglecting 3-D topography is comparable to doubling the uncertainty in 2-D modeling of either Line A or B, which degrades the resolution discussed above.

6. The maximum effect of shallow outcropping conductors beneath the survey line, with 10:1 contrast and strike-length approximating the width of Coyote Wash, is rougly 50% of the effect of a similar conductor with infinite strike-length (2-D). Nevertheless, shallow outcropping conductors possibly corresponding to surface alluvium cannot be neglected in 2-D or 3-D modeling.

7. The effect of finite strike-length shallow outcropping conductors (possibly corresponding to alluvium) is enhanced if a narrow, thin surface conductor connects to an off-axis, high-conductance body such as may be the case for the central part of Coyote Wash. The effect is comparable to reducing the resistivity of the narrow, thin surface bodies traversed by the survey line. Enhancement was calculated to be roughly 25% of the effect without the off-axis conductor, but nevertheless emphasizes the importance of alluvium-bedrock contacts even for relatively short half-strike-lengths of 200 ft.

8. The effect of a buried conductive body off-axis to the survey lines is to produce an anomaly equivalent to that from a deeper body directly under the line. This result was elucidated by Dey and Morrison (1979), and was tested for a specific 3-D case involving an off-axis conductor that was elongated, parallel to the survey line, and in the depth range of the buried conductor identified from borehole data from USW G-4. The test was motivated by a hypothesis that the depth-extended body modeled by Smith and Ross (1982) may result from enhancement of the conductance of this layer, directly below the wash and off-axis to Lines A and B. The test confirmed that the off-axis resistivity distribution would produce an anomaly that if modeled in 2-D, might be interpreted to extend deeper than the actual situation. This exemplifies a case where 3-D effects may be modeled with a 2-D algorithm to produce an erroneous depth-extended body.

4.6 GEOLOGIC INTERPRETATION

4.6.1 GEOLOGIC INTERPRETATION OF GEOPHYSICAL DATA MADE BY SMITH AND ROSS (1982)

Smith and Ross (1982) provide the following general conclusions regarding the seven dipole-dipole lines which they modeled and interpreted (p. 6):

> "The Tiva Canyon tuff is moderately to highly resistive. Lateral variations in its resistivity may indicate either faults or

differential welding. Fractured zones, susceptible to zeolitization, have been inferred from areas of low resistivity within the Tiva Canyon tuff that extend to depth. The tuffs underlying the Tiva Canyon tuff display bimodal resistivity values: high below the ridges, low below the wash. This indicates that zeolitization and/or clay alteration takes place within structurally disturbed zones, i.e., mainly below the wash."

The moderate to high resistivity of the Tiva Canyon tuff is not uniform along lines A, B, and B'; low values of resistivity are used in the modeling by Smith and Ross (1982) to obtain a match to the observed data. They state (p. 20) that "the abrupt lateral contrasts in resistivities rarely coincide with the tuff-alluvium boundary; the alluvium itself is not the low resistivity body." They used Line A to provide an explanation of the lowered resistivity values by stating that the numerous vertical and horizontal contrasts between adjacent resistive bodies in their model suggests "a broad zone of faulting, fracturing, or brecciation" (p. 10) and speculated that the Drill Hole Wash "may have developed along a heterogeneous, structurally deformed zone" (p. 10).

Along Line A, in the area of stations 20W and 22W, Smith and Ross (1982) modeled a resistivity contrast. This area is near the Ghost Dance fault, which was mapped by Lipman and McKay (1965). Smith and Ross (1982, p. 11) indicated that another fault cuts Line A near station 9W. This inferred fault is the subject of this TAR and their statement of the existence of a fault is based solely on the modeled resistivity contrasts.

Along Line B they indicated (p. 11) that large contrasts in resistivity occur near stations 24W and 9W. Lipman and McKay (1965) show a fault near stations 24W (Ghost Dance Fault) but not near 9W. (Smith and Ross, 1982, p. 11) further state that "the complex distribution and range of resistivities, and the inferred displacements on the faults suggest a structurally disturbed horst block on the east flank of Yucca Mountain." However, Smith and Ross (1982, p. 16) also propose an alternate interpretation that this "horst block" may actually be a spur of a NNW-trending fractured zone characterized by low resistivity bodies, which represent areas where zeolitization or clay alteration has occurred within the Tiva Canyon tuff.

Line B' is reported by Smith and Ross (1982, p. 15) to be generally consistent with Line B in the area where the two lines overlap.

4.6.2 RELATIONSHIP OF SMITH AND ROSS (1982) INTERPRETATIONS TO KNOWN GEOLOGY

Some of the computer models for dipole-dipole surveys have resistivity contrasts that correspond to known faults (e.g., Ghost Dance Fault). The model profiles also show resistivity contrasts that do not correspond to known (mapped) faults. This becomes apparent if all the available dipole-dipole lines are considered in conjunction with a recent geologic map (Scott and Bonk, 1984).

The resistivity contrast at station 9W (Lines A and B) is inferred to be a fault. However, the geologic mapping of Lipman and McKay (1965), Scott and Bonk (1984), and Barton et al. (1989) does not show a fault on either Dead Yucca Ridge (north side of Coyote Wash) or Live Yucca Ridge (south side of Coyote Wash). Geologic field checking of these maps by TAR team members also did not find any surface evidence of a fault in the area of Station 9W on either ridge.

A slingram (electromagnetic) survey (Flanigan, 1981, Line Y-11) was run very close to Line B of Smith and Ross (1982), and the survey crossed the area of the resistivity structure inferred to be a fault. However, as discussed in Section 4.3 of this report, the slingram survey did not detect a contrast that could be expected from the resistivity structure modeled by Smith and Ross (1982).

Smith and Ross (1982, p. 6) state that abrupt lateral variation in apparent resistivity of the Tiva Canyon represents fracturing, faulting, or lithologic variation possibly related to structural deformation. Sensitivity studies for this review have shown that outcropping surface conductors and stratigraphic variation can also explain certain trends in the observed data, in a manner that is consistent with currently available geologic information (Sections 4.5.1 and 4.5.2; see for example Figure 4-15).

The statement that alluvium is not a low resistivity body Smith and Ross (1982, p. 20) is inconsistent with Schlumberger sounding #38 of Senterfit et al. (1982), and certain other information discussed in Section 4.6.3.1. This does not mean that the Tiva Canyon Member has uniform resistivity; available data from different types of surveys (reviewed in Section 4.6.3.1) show that twofold or greater lateral variation is plausible.

The statement that resistivity in the units underlying the Tiva Canyon Member is apparently low beneath washes, and high beneath ridges (Smith and Ross, 1982, p. 6), is generally consistent with the mineralogical data available from the upper portion of several boreholes in the immediate vicinity of the Yucca Mountain site. However, there are gaps in the available data on alteration and electrical properties in boreholes throughout the site area, and there are possible conflicts in the data (see Section 4.6.3.2). The referenced statement by Smith and Ross is reasonable for comparing conditions at Yucca crest (in the immediate site area) with the major washes on the eastern slope of Yucca Mountain. However, data from boreholes and surface geoelectric surveys are too sparse to support a similar comparison between conditions beneath tributary washes and minor, intervening ridges on the eastern slope.

In summary, Smith and Ross (1982) inferred the presence of a fault at station 9W totally on the basis of a resistivity contrast on Lines A and B. However, there is currently no corroborative geologic or geophysical evidence to substantiate this interpretation. As discussed throughout Chapter 4 of this report, Smith and Ross (1982) did not incorporate information on stratigraphy and geoelectric properties, which is now available. The fact that detailed mapping of the area provided no surface evidence of faulting indicates that, if the Smith and Ross (1982) interpretation is correct, their inferred fault would be a subsurface feature, possibly of pre-Tiva Canyon age. However, it should be emphasized that the resistivity contrast observed

at 9W could also be interpreted as the result of causative factors other than faulting, as discussed in the following section.

4.6.3 PETROPHYSICAL RELATIONSHIPS

Resistivity for welded tuff with low moisture content that has not been altered extensively, is generally greater than about 500 ohm-m, and dipole-dipole Lines A and B are apparently dominated by one or more bodies with resistivity as low as 50 ohm-m. The nonwelded PTn unit (unit designation by Ortiz et al., 1985), and possibly the surface alluvium, are apparently good conductors. Resistivity structure in the welded tuff units associated with variations in porosity, welding, devitrification, and composition, are not evident and may be masked by variation in more conductive zones within the depth interval of interest. Data are available which suggest that low resistivity is caused by the presence of clay or zeolites, products of the alteration of vitric tuff. This section will discuss mineralogic/petrologic data from the Coyote Wash area, and electrical conduction mechanisms, to support a position that low resistivity is strongly associated with alteration, although other conduction effects cannot be ruled out based on available data. An important result of this distinction is that a low resistivity body may be associated with alteration that is not the result of present hydrologic conditions.

The apparent IP effect observed from dipole-dipole survey at Coyote Wash is small, on the order of 1 to 2 PFE. The magnitude of variations in IP response along the profiles is also small, about 0.5 to 1.0 PFE at maximum. This section will review data from IP wireline logs, and from tests on cores taken from the unsaturated zone. The magnitude of the IP effect observed from the dipole-dipole survey at Coyote Wash is smaller than that from either logs or core testing. Possible reasons for these differences are explored. Uncertainty as to the mechanisms and variability of IP response are used to justify reliance on resistivity in assessing the signficance of electrical data from Coyote Wash.

This section also briefly reviews available data on other geophysical properties of tuff units at the Coyote Wash locale, including density, magnetic susceptibility, and seismic velocity. The extent to which these properties correlate with electrical resistivity, and could be used for detection and delineation of a buried fault, is part of the basis for further geophysical exploration recommended by the TAR team.

4.6.3.1 Resistivity Data from Various Sources

The following types of resistivity data are available for the Coyote Wash location:

1. Schlumberger sounding #38 in Drill Hole Wash, reported in Senterfit et al. (1982).

2. Wireline induction and normal resistivity logs obtained variously from boreholes USW G-4, UE25 a#6, and a#7 reported in Spengler and Chornack (1984), and Daniels et al. (1981).

3. Measurements on core samples obtained from USW G-4 and UE25 a#1 by Anderson (1981; 1984).

Note that some of the geophysical surveys discussed in Section 4.2 (i.e., slingram lines, E-ratio survey lines, dipole-dipole lines, and borehole-to-surface resistivity surveys) do not resolve resistivity vs. depth, and/or do not apply to resistivity structure at Coyote Wash in a manner that can provide useful constraints on modeling of the dipole-dipole data.

The different types of resistivity measurements are in reasonable agreement as to resistivity in the stratigraphic section of interest. Areas of non-uniform coverage or reliability of this data set are as follows:

1. The induction log is considered unreliable by Nelson et al. (in press) for unsaturated intervals with resistivity greater than 200 ohm-m.

2. Induction, normal, and IP logs were obtained from the unsaturated zone by "mudding up" the interval to maintain a fluid column, thus introducing large amounts of fluid to the formation.

3. The frequency of resistivity measurements ranged from near-DC for Schlumberger soundings, to 20 kHz for induction logging.

4. Electrical logs were not obtained from the alluvium because it had been cased off.

5. Of the eight core samples from the upper 600 ft of USW G-4 that were tested by Anderson (1984), only one sampled the PTn unit (measurements on three samples from the PTn in UE25 a#1 are reported in Anderson, 1981), and the alluvium was not tested.

The resistivity of alluvium was measured by Schlumberger soundings reported by Senterfit et al. (1982). The closest sounding to Coyote Wash was #38, which indicates a surface layer with 70 to 100 ohm-m resistivity, and modeled thickness of roughly 17 ft (a transition to higher resistivity occurs from about 13 to 23 ft apparent depth). The resistivity range for the surface layer is comparable in magnitude to some of the apparent resistivity measurements from the borehole-to-surface (mise a la masse) type survey reported by Daniels (1983), particularly those situated on alluvium farthest from the source boreholes. In this survey, a source electrode was place in each of several boreholes (a#1, a#4, a#5, and a#6) in Drill Hole Wash, and a roving orthogonal pair of potential dipoles was deployed on the surface. At large distances from the source, apparent resistivity values were typically 50 to 100 ohm-m.

Resistivity of the Tiva Canyon Member is in the range 700 to 1,000 ohm-m or higher. Five core samples produced values in the range 1000 to 1,200 ohm-m (Anderson, 1981; 1984). Wireline resistivity logs for UE25 a#6

and a#7 (16" short normal) show values of about 700 to 1000 ohm-m, with a low resistivity break near the bottom of the unit, corresponding to a lithologic transition from densely welded to underlying moderately and partially welded material. The induction log from USW G-4 indicates 500 to 700 ohm-m resistivity in the Tiva Canyon Member down to about 100 feet, decreasing gradually to about 50 ohm-m through the transition zone. Schlumberger sounding #38 indicates resistivity of 1,000 to 1,200 ohm-m from 17 ft (5 m) down to 130 ft (40 m). Finally, apparent resistivity data are available from a suite of shallow EM soundings obtained from various locations on the exposed Tiva Canyon Member caprock in the site area (Ogard and Vaniman, 1985). The data were acquired with short-spacing horizontal and vertical loop-loop equipment (Geonics EM-34), with penetration of roughly 10 to 20 m or more depending on loop orientation and spacing. Ridgetop soundings produced resistivity values of 400 to 1,000 ohm-m, whereas extensive measurements at the easternmost "toe" of Dead Yucca Ridge (Scott and Bonk, 1984) produced values of 250 to 350 ohm-m.

The nonwelded PTn unit (including the Yucca Mountain and Pah Canyon members, plus interlain bedded tuff) exhibits bulk resistivity of about 35 to 70 ohm-m. The limited core test data indicate resistivity of about 50 ohm-m. Induction and shallow focused logs from USW G-4 indicate variability with depth, in the range from 20 to 100 ohm-m. Schlumberger sounding #38 indicates a resistivity of 150 to 200 ohm-m corresponding to the PTn interval in nearby borehole UE25 a#1.

Dipole-dipole Lines A and B are insensitive to geoelectric structure below about three dipole lengths, or 600 ft. (Based on the characteristics of the method, plus the apparent existence of a shallow, low resistivity layer.) This is at least 500 ft above the bottom of the Topopah Spring Member. Core test data for this unit give a range of 300 to about 1,000 ohm-m, with somewhat lower values in roughly the upper half of the unit. This is very similar to Schlumberger sounding #38, from a depth of about 400 feet to 1,300 ft or more. Nelson et al. (in press) recommend against the use of induction logs from resistive units like the Topopah Spring Member, but values reported by Spengler and Chornack (1984), and Daniels et al. (1981) are in general agreement with the other data. Each of the types of measurements, with the possible exception of sounding #38, indicates a very resistive (>2,000 ohm-m) interval at or near the top of the Topopah Spring (e.g., from about 240 to 270 ft in UE25 a#6). This probably corresponds to the quartz-latite caprock layer or closely associated strata.

4.6.3.2 Evidence for Alteration at Coyote Wash

Anderson (1981, 1984) reports core tests using samples from Yucca Mountain boreholes, including UE25a#1 and USW G-4. Although sampling of the stratigraphic section is rather sparse, the results show that electrical resistivity is rather insensitive to changes in saturation (using Denver tap water). Also, welded tuff samples from altered zones such as the highly lithophysal portion of the Topopah Spring Member, and from welded units below the water table, appear to be somewhat less resistive. Bish and Chipera (1988) note that smectite has been observed in every core sample from Yucca Mountain (often in small concentration) that has been examined using x-ray

diffraction. The observed distribution of alteration minerals, and the nature of resistivity measurements suggest that conduction is significantly affected by alteration minerals. Such mineralization is probably authigenic, and may originate from syndepositional processes, or from secondary processes that are associated with elevated temperature and/or the availability of moisture.

The proportion of clay minerals present in core and cuttings samples from Yucca Mountain has been investigated using x-ray diffraction (XRD), as part of a mineralogic survey reported by Bish and Vaniman (1985) and Bish and Chipera (1988). The compiled XRD data are rather sparse, and do not originate from the same depths as the petrophysical core samples tested by Anderson (1981; 1984). Nonetheless, the mineralogical data exhibit stratigraphic dependence corresponding to alteration of available glass, and the resistivity logs and core test data exhibit very similar stratigraphic dependence. Thus the association of low resistivity with alteration is based on correlation, and tends to support statements by Smith and Ross (1982) concerning alteration.

XRD analyses show that clay alteration is abundant at certain stratigraphic horizons in boreholes throughout the site area. One of these horizons is at the top of the vitric nonwelded base of the Tiva Canyon Member, and may be an important low resistivity layer. The source of this apparently contiguous altered layer may be moisture evolved from the Tiva Canyon Member ash flow shortly after eruption and deposition.

Smectite is also abundant at other horizons but only in certain boreholes, indicating that alteration may have been produced by more than one process. Comparison of corehole USW G-4 in Coyote Wash with USW GU-3 on Yucca Crest, shows the extent of alteration in the PTn nonwelded interval to be advanced in G-4, which is located in a low-lying wash area. Specimens from G-4 contain as much as 30 to 40 weight percent smectite, or two to four times as much as samples from the same interval in GU-3. Alteration in G-4 also involves more of the stratigraphic section (the lower Tiva Canyon Member and the upper Topopah Spring Member). A similar comparison may be made between G-4 and borehole UE25 a#1, which is situated in Drill Hole Wash about 2,000 ft downstream from Coyote Wash. Smectite abundance in this stratigraphic interval in borehole a#1 is generally only a fraction of that observed in G-4. Although borehole a#1 is located in Drill Hole Wash, the infiltration conditions may differ from G-4, possibly because G-4 is closer to the eastern slope of Yucca Mountain, and nearly surrounded by high-gradient rock slopes. The distribution of smectite suggested by these data is consistent with the hypothesis of alteration resulting from moisture influx beneath certain wash areas, determined by the alluvial configuration and characteristics of surface runoff.

There is another trend in the abundance of alteration minerals which may contradict the association of alteration with low-lying wash locations. Several boreholes from which XRD data are available, particularly USW H-4 and WT-2, are situated in areas similar to Coyote Wash. A few samples are from the nonwelded beds, and appear not to be as extensively altered as the same unit in G-4. Also, alteration is pervasive throughout much of the section explored in corehole USW G-2 to the north (Bish, 1987). A north-south trend in alteration of the upper part of the Paintbrush Tuff would be similar to

the trend in zeolitization of the lower part, near the water table. The available distribution of borehole data is too sparse for further analysis and comparison of apparent trends.

In summary, the available data exhibit strong differences in smectite abundance at various locations. The cause is not clear, and may be associated with past or present hydrologic factors, or some other trend-forming mechanism. It is possible that the present distribution of alteration minerals is the result of more than one process acting over geologic time. For the boreholes investigated in this review, smectite abundance appears to be well-correlated with low resistivity.

4.6.3.3 Electrolytic Conduction vs. Surface Effects

Background Discussion

Common lithic materials are generally poor conductors, and bulk conduction is predominantly electrolytic, involving minerals and fluid that occupy interstitial pore space. Where significant flux of ions occurs through fluid-filled pores, small changes in salinity of the pore fluid can cause changes in resistivity. This mechanism is customarily modeled by a well-known empirical correlation between bulk resistivity, porosity, saturation, and fluid resistivity (Archie's Law, see Keller and Frischknecht, 1966, p. 21).

In a mineralogically controlled and pore structure dependent conduction mechanism, localized changes in the concentration of ions in the pore fluid (and therefore fluid resistivity) can result from interaction of the pore fluid with clay minerals. Cations can be released into the pore fluid by ionization of clay structures, depending on the cation exchange capacity of the minerals, the cations present, the concentration of various cations in the fluid, and the abundance of water. Once released into the surrounding pore fluid, the cations become available for electrolytic conduction. The effect can be significantly changed by flushing cations from the system, or by replacing cation species with others of different exchange capacity or ionic mobility. A similar conduction mechanism requires that the charged surfaces of mineral grains (such as most clay minerals) attract water molecules, forming relatively ordered layers in the surrounding fluid. These layers become preferred conduction paths under certain conditions of temperature and electric flux density.

In the framework of Archie's Law, the net effect of these mechanisms is understood to lower the apparent pore fluid resistivity, which in turn lowers the bulk resistivity. This is a standard approach to wireline electric log interpretation, and could probably be used as a simple model to predict substantial reduction of resistivity for altered intervals in the geologic section at Coyote Wash. Such computation would estimate resistivity from porosity, saturation, mineral abundance and cation exchange properties, and ion mobility estimates (Keller and Frischknecht, 1966).

A different, "true" surface conduction mechanism is related to cation mobility from site to site on the surface of clay grains. This depends on

the nature of the clay and the mobility of particular species of cations, in addition to the temperature, flux density, and other conditions. The contribution of this effect to conductance is readily changed by exchanging cations. Where it occurs, this mechanism could dominate conductance under certain conditions of saturation, pore fluid composition, or other variables.

Possible evidence indicating that cation exchange is important for understanding electrical conduction in the tuff section, is provided by the observation that nonwelded tuff samples tended to degrade when resaturated with Denver tap water (Anderson, written communication, 8-3-89; 1981; 1984). Possible causes for this include swelling and osmotic shock (D. Chesnut, personal communication, 8-3-89). Water-poor smectite clay grains could swell on application of pore water. Alternatively, the composition of tap water may have differed enough from the pore water that cation substitution occurred, with consequent changes in the hydrophyllic activity, and thus mechanical stability of clay grains. The latter mechanism could also produce significant changes in bulk resistivity, as the relative contributions of surface and electrolytic conduction were perturbed by substitution of cations with different exchange capacity or ionic mobility.

Conduction in porous rocks is often considered to have power-law dependence on saturation (e.g., Serra, 1984). According to Archie's formula, roughly 50% to 100% increase in resistivity could be expected at 0.75 saturation. However, this dependence does not account for all observed behavior. The effect of partial saturation on bulk resistivity is different for electrolytic conduction and surface effects. Removal of water from large pores has relatively little effect on conduction paths on the surface of or proximal to mineral grains. True surface conduction is probably unaffected by the drainage of a substantial portion of interstices. Also, there is evidence that the population of cations desorbed from clay grains is independent of saturation (Waxman and Thomas, 1974). In other words, as the water fraction decreases, there is an increase in ionic concentration and conductance from surface effects. Thus in the presence of surface effects the bulk resistivity is relatively insensitive to saturation at high saturation levels.

As water saturation falls below a critical level, the film of moisture covering mineral grains is depleted, resulting in large increases in bulk resistivity. The critical saturation level is higher (e.g., 0.7 to 0.8) for fine-grain rocks than for rocks with large pores (Keller and Frischknecht, 1966). Rough estimates of average bulk saturation are available for various hydrogeologic units at Yucca Mountain (DOE, 1988; Montazer and Wilson, 1984). Saturation is estimated to be about 0.6 to 0.7 for the nonwelded PTn unit, and 0.4 to 0.65 for the Tiva Canyon and Topopah Spring welded units. Thus it is more likely that saturation of the nonwelded unit exceeds the critical level, which would mean the resistivity of this material is less sensitive to local increase of saturation.

In summary, from basic petrophysical relationships and correlation of available data, the chief cause of low resistivity in the PTn and associated nonwelded intervals is probably clay and zeolite minerals. The importance of ionic processes to the electrical behavior of the nonwelded material is evidenced by degradation observed in response to changes in saturation and possibly pore water chemistry. The conduction mechanisms associated with

clay ionization and surface effects are rather insensitive to saturation changes at high saturation levels. These relationships indicate that perched water or surface infiltration transients are not necessary, and may not be sufficient to explain the observed apparent resistivity in the PTn interval below Coyote Wash.

Welded intervals generally contain less clay, and are probably more sensitive to changes in saturation (relative to the in situ saturation level). Clay minerals are present in varying concentrations in every sample of rock subjected to mineralogical analysis. Surface conduction may be possible, at least along hydrologic conduits where alteration minerals are present, in response to saturation increase relative to observed in situ saturation levels. Thus based on the limited data, it seems more likely that a saturation anomaly would be required, if the resistivity anomaly below Coyote Wash were interpreted to significantly involve welded intervals such as the Topopah Spring Member.

4.6.3.4 Induced Polarization Response of Near-Surface Units at Coyote Wash

The section will briefly compare IP measurements on core samples, from wireline logging, and from dipole-dipole surveys. IP logs from the saturated and unsaturated zones will be compared, and core data will be compared directly with IP logs for borehole UE25 a#1. Discrepancy between the IP effect magnitude observed by the three methods is discussed, with the conclusion that the dipole-dipole response probably does not signify anomalous geoelectric structure, by contrast with anomalies produced from typical targets for exploration by this method. However, little else can be determined from the available data.

IP effect has been measured on core samples from boreholes UE25 a#1, USW G-3/GU-3, and G-4 by Anderson (1981; 1984). These were time-domain measurements on samples resaturated with tap water, yielding values which are in a range typical of clay-bearing rocks. The IP tests were part of a series that included physical properties, sonic, and resistivity measurements. The properties for each core sample tested are plotted and tabulated in the referenced reports. As pointed out by Anderson (1984), there are high and low IP values among the data, but they generally do not delimit samples with greatest or smallest clay or zeolite content. The reason may be enhancement of IP in low porosity rock where conduction is restricted to paths through or proximal to polarizable minerals.

IP wireline logs have been obtained from six boreholes at Yucca Mountain (UE25 a#1, a#4, a#5, a#6, a#7, and USW G-3) using standard tools manufactured by Mt. Sopris (Nelson et al., in press). IP logs from the a-series boreholes were examined for this review (Hagstrum et al., 1980; Daniels et al., 1981). Several of these boreholes are located in the vicinity of Coyote Wash, particularly a#6 and a#7. The IP tools produced time-domain measurements, and are not calibrated in a manner permitting close comparison of logs to core data or surface geoelectric surveys.

Borehole UE25 a#1 was logged for IP in the saturated zone only, in a different stratigraphic sequence from that near the surface in Coyote Wash.

The other a-series boreholes did not penetrate the water table. However, the log from a#1 is of interest because the IP magnitudes are uniformly much smaller than those in the other a-series boreholes. IP magnitudes from the saturated zone in a#1 are similar to the core test data of Anderson (1981; 1984). The major difference contributing factor is formation saturation; hence Daniels et al. (1981) concluded that "abnormally" high IP values in the unsaturated zone were caused by partial saturation effects near the wellbore. The IP logs for a#4, a#5, a#6, and a#7 exhibit some variation of IP response with depth. Extending the conclusions of Daniels et al. (1981), however, it is likely that the relative magnitude of IP, and differences between logs in adjacent boreholes, are related to variations in formation invasion and are not closely representative of in situ geoelectric conditions.

Comparison of the IP log in the saturated zone in borehole UE25 a#1 with IP measurements on core samples from the same boreholes shows approximate agreement in magnitude and amplitude of variation. The two types of measurements respond similarly to stratigraphic features. Moreover, the range of magnitude from the IP log and core test data in a#1 compares closely with that observed in the dipole-dipole surveys at Coyote Wash.

For the unsaturated zone in Coyote Wash, the relative amplitude of variation is roughly two-fold for each type of data from the upper 600 ft of the section (the probable resolving limit for dipole-dipole Lines A and B; see Section 4.5.1). However, as discussed above there are large differences in magnitude among the different types of IP measurements. The IP logs produced an effect that is about ten times larger, and core test values are 2 to 3 times larger, than the dipole-dipole survey data. If the discrepancy is caused by fluid used during drilling, then it is interesting to note that the effects of such fluid on core test data and the IP log are comparable. Other factors complicate this straightforward explanation. Core testing and wireline logs were acquired by time-domain methods, and indicate more polarization than the frequency-domain dipole-dipole data. Caution should be observed in comparing logs, core data, and field surveys because the volume of support differs substantially. Theoretical conversions suggesting a direct relationship between chargeability and frequency effect (e.g., Telford et al., 1976) have not been applied in this review because (1) time-domain methods may not capture representative limiting rate-behavior of IP, and (2) the basic conduction processes for clay-bearing tuff from Yucca Mountain have not been defined. Also, the IP effect is known to be sensitive to frequency and electric flux density, which differ among the various methods (Keller and Frischknecht, 1966).

In summary, the dipole-dipole IP data from Coyote Wash are comparable in magnitude of variation with IP logs and samples from the saturated zone in borehole UE25 a#1. However, the log and core test data indicate much greater IP response magnitude in the unsaturated zone at Coyote Wash. Previous investigators (Daniels et al., 1981) have attributed this to the effect of drilling fluid. The relative amplitude of variation for all three methods in Coyote Wash is about two-fold, however. In view of the possible causes of IP, and the basic differences between the types of measurements, the data from Coyote Wash do not indicate an IP anomaly that is more important than the resistivity data, for inferring subsurface structure. The approach followed in Section 4.5 which focuses on resistivity, is therefore justified.

4.6.3.5 Other Geophysical Properties

Variation of other properties in conjunction with apparent trends in electrical resistivity is important with respect to possible recommendations of this review. There are two types of investigations that could make use of contrasts in other geophysical properties: (1) further study of the region of the geoelectric anomaly, and (2) exploring for a fault.

Other Properties for Further Study of Geoelectric Structure

For further study of the region of the geoelectric anomaly, there are no currently known trends in other geophysical properties that could be reliably associated with saturation, alteration, or other known possible causes for low resistivity at Coyote Wash. Core samples from the highly altered portion of borehole USW G-4 (Anderson, 1984) appear to have typical bulk density and sonic velocity for the units from which they originated (the samples were rather sparse). Changes in magnetic susceptibility may be associated with alteration. Although a relatively high magnetic susceptibility unit within the PTn interval has been identified (Daniels et al., 1981), there is insufficient data even to speculate about the association of this feature with possible alteration and geoelectric structure.

Other Properties for Fault Detection

Several geophysical properties are potentially useful for fault detection and delineation, including bulk density, magnetic properties, and seismic properties. Density information available for interpretation of geophysical data from the Coyote Wash area consist of measurements on cores from borehole USW G-4 (Anderson, 1984), gamma-gamma density logs from boreholes UE25 a#6 and a#7 (Daniels et al., 1981), and density logs from G-4 (Spengler and Chornack, 1984). The accuracy of gravity surveys is limited chiefly by surveying requirements and terrain corrections. With an advanced terrain model and electronic surveying techniques, corrected gravity stations can likely achieve accuracy of 0.07 mgal at Yucca Mountain. This is sufficient to detect (with 3:1 S/N ratio) a high-angle fault with roughly 40 m of vertical offset, provided that terrain effect is minimal, adequate station spacing is maintained, and profiles are oriented perpendicular to strike (see DOE, in review; also Nettleton, 1976, Figure 7-4).

Magnetic intensity, or possibly component field measurement, could in principle also be used to detect faults at Yucca Mountain. The practical limit for detecting vertical offset by magnetic methods is dependent on many factors such as terrain effect, and the geometry of detector, target structure, and other magnetized bodies. A problem with detailed ground magnetic data interpretation is that the Tiva Canyon Member expressed in the terrain was deposited during a magnetic reversal epoch and exhibits strong remanence (Q ratio of 2 or greater). The use of ground magnetic traverses and aeromagnetic surveys for fault detection is the focus of planned testing and evaluation in site characterization.

Several general types of seismic surveys are applicable to fault detection at Coyote Wash: shallow refraction, shallow reflection, and seismic imaging. Shallow refraction has been demonstrated in alluvium, where paleo-soil horizons act as mappable refractors with somewhat systematic

variation in velocity (Rodriguez and Yount, in USGS, 1988). Refracted arrival velocities are typically low, in the range 1 to 2 km/s. Shallow refraction has also been demonstrated as a means for mapping the depth to bedrock in alluvial washes, and for detecting fracture or fault zones (DOE, in review). Work in this latter area has been limited, but preliminary indications suggest that faults and fracture zones produce detectable anomalies in shear wave transmissivity for surveys conducted on bedrock or shallow alluvium (DOE, in review). The Mini-Sosie method of shallow seismic reflection has been deployed in alluvium and alluvium-bedrock settings in the Yucca Mountain area with some success (Harding, in USGS, 1988). The core test data of Anderson (1984) indicate possibly useful impedance contrasts in the tuff section. Sonic logs have not been obtained from any of the boreholes in Coyote Wash because of difficulty with maintaining a fluid column in the unsaturated zone. However, prevalent fracturing and gradational velocity contrasts may adversely affect the quality of reflection data. No seismic surveys have thus far observed reflections from the tuff section at Yucca Mountain (McGovern, 1983).

4.6.4 SUMMARY DISCUSSION OF GEOLOGIC INTERPRETATION

The geologic interpretation of Smith and Ross (1979; 1982) consisted chiefly of inferred faults or fracture zones, and the concept of a "horst block" on the eastern slope of Yucca Mountain. In addition, Smith and Ross found that alluvium was unimportant to understanding the geoelectric structure, and that apparent lateral contrast in the Tiva Canyon Member was probably associated with alteration in faults or fracture zones.

A review of geophysical and geologic information from the site has produced abundant information on stratigraphy and electrical properties that is relevant to interpretation of geoelectric data from Coyote Wash. As pointed out elsewhere in Sections 4.3, 4.5, and 4.6, Smith and Ross (1982) did not consider: the possible significance of surface conductors, or constraints based on stratigraphy. Also, they did not attempt to compute 3-D terrain effects. This is not intended as unqualified criticism of the original work, but can be attributed to the availability of reliable constraining data, and of computional tools for 3-D problems.

The association by Smith and Ross (1982) of low resistivity with mineralogic alteration either in the Tiva Canyon or underlying tuff is a plausible explanation for low apparent resistivity as discussed in Section 4.6.3. The statement by Smith and Ross (1982, p. 6) that the tuffs underlying the Tiva Canyon Member exhibit low resistivity beneath washes and high resistivity beneath ridges appears to be true for comparing the crest of Yucca Mountain with low-lying areas, but is unsubstantiated for more localized comparisons between features such as the channel and ridges comprising Coyote Wash.

Sensitivity studies and reviews performed for the TAR show that the apparent resistivity contrast at the mouth of Coyote Wash (9W on Lines A and B) could be associated with causes other than faulting. Firstly, sensitivity tests indicate that if the geoelectric model is constrained by stratigraphy and other borehole information that is now available, and the distribution

and properties of alluvium are taken into account, then the contrast is attenuated relative to that modeled by Smith and Ross, with rougly comparable "misfit" to the data (Sections 4.3.4 and 4.5.1; see for example Figure 4-15). In other words, as geophysical modeling proceeds iteratively to improve the level of misfit, the development of model features (e.g., lateral resistivity contrast) depends to some extent on the constraints used, which generally includes the starting model.

Slingram line Y-11 (Flanigan, 1981; discussed in Section 4.3.2.3) did not exhibit an anomaly that could be associated with a lateral contrast in resistivity at the mouth of Coyote Wash, and is therefore in conflict with the geophysical model of Smith and Ross (1982). The location of slingram line Y-11 was approximately coincident with dipole-dipole Line B. Slingram sensitivity calculations performed for this review (Section 4.3.2.3) confirm that (for 2-D structure) an interpretable anomaly could be expected from a lateral contrast as small as 3:1.

The faulting hypothesis (i.e., fault or highly fractured fault zone) would be a plausible geologic interpretation for a sharp resistivity contrast in the east-west direction at the mouth of Coyote Wash. (Sharpness of the actual contrast is not readily resolvable from the available data, as discussed in Section 4.5.1.2.) Note that stratigraphic offset is not necessary for geophysical detection of a fault, because resistivity changes could be related to drainage of surface infiltration, or laterally diverted subsurface moisture downward through a transmissive zone. Alteration processes that occur where moisture is plentiful would be more evident on the up-gradient side of such a structure.

If the contrast is gradational, minor, or nonexistent as suggested by slingram line Y-11, and by the sensitivity studies of Section 4.5.1, then mechanisms other than faulting may be responsible. The topographic surface and the configuration of alluvium in Coyote Wash is such that runoff from the upper slopes probably slows in the lower part, where infiltration could be concentrated. Also, moisture moving through the alluvium could infiltrate more vigorously into the bedrock near a gradient change or change in alluvial transmissivity.

Infiltration could travel through the fractures of the Tiva Canyon Member, depending on saturation conditions. Such infiltration could occur beneath the alluvium of Coyote Wash as suggested above, or more pervasively in fractures open to moisture sources such as snowmelt. The distance to be travelled through the Tiva Canyon unit is on the order of 20 or 30 m downward to the top of the nonwelded PTn unit (stratigraphic designations from Ortiz et al., 1985). Once moisture reached the PTn, the relatively high hydraulic conductivity would readily permit dispersion downward and outward to encompass a large area of this unit. Operating over a long period of time, the mechanism could lead to extensive alteration in the PTn and along hydraulic conduits where water contacted vitric material. The relation to hydrologic processes would help to explain some of the observed large-scale variation in alteration of the PTn unit as discussed in Section 4.6.3.

The hydrologic concept discussed above does not preclude the existence of a fault, nor the possible contribution of a fault to the apparent geoelectrical contrast in Coyote Wash. The extent of percolation may be

limited by the amount of runoff available, or it may be truncated by a fault that drains moisture downward.

One major hydrologic aspect of the concept described above is that because the PTn does not outcrop on the eastern slope of Yucca Mountain, and because lateral diversion of ground water is possible in this unit (DOE, 1988, Section 3.9.3), the conceptual mechanism described above may involve even larger amounts of water than can infiltrate through the confines of Coyote Wash. (Although the Ghost Dance fault intervenes between most of Yucca Mountain and the lower part of Coyote Wash.)

The TAR team has identified other possible causes for the apparent geoelectric contrast in Coyote Wash. They are not exclusive, and could conceivably occur in combination:

1. Lateral variation in composition or fabric of the PTn unit, or possibly the Tiva Canyon or upper Topopah Spring members. Such a feature could cause an electrical contrast directly, or produce ground-water impoundment and associated effects.

2. Increased percolation and associated alteration could result from changes in fracture density, or from a fracture zone not directly associated with a fault. Such a zone need not strike N-S at the mouth of Coyote Wash, but could run E-W along the wash.

3. Resistivity contrast from alteration that is a remnant of previous (perhaps Miocene) hydrothermal activity.

4. The apparent contrast in the buried conductor does not exist, but is produced by insufficiency of the modeling approach to account accurately enough for surface conductors and terrain effects. In this sense, the abundance of clay alteration observed in borehole USW G-4 could be associated with lateral facies change occurring at a scale much larger than Coyote Wash.

Possible alternative hypotheses are presented as a reasonably complete list, as a basis for understanding the expected utility of the recommended geophysics program. Each alternative will be addressed by the recommended program (Section 4.7.2), to the extent that it is associated with the presence or absence of a lateral contrast in the resistivity of a buried conductor corresponding approximately to the PTn unit of Ortiz et al. (1985).

4.7 CONCLUSIONS AND RECOMMENDATIONS

4.7.1 APPLICABILITY OF THE SMITH AND ROSS (1982) INTERPRETATION TO THE SUITABILITY OF THE ESF LOCATION

To the extent that low resistivity is associated with alteration, the available geoelectric data provide information on the lateral extent of alteration as observed in borehole USW G-4. The data are consistent with a statement by Smith and Ross (1982, p. 6) that resistivity of units below the

Tiva Canyon Member (i.e., PTn unit and below) is low beneath washes and high beneath ridges. Thus the dipole-dipole data, and the Smith and Ross (1982) interpretation show that the altered lithology observed in USW G-4 will likely be encountered in the exploratory shafts. The relative importance of this expectation with respect to shaft constructability has been considered in this review (Section 6).

The Smith and Ross (1982) interpretation also has general application as a reconnaissance indication of a buried geoelectric contrast. The depth to the upper surface of the buried conductor in the Smith and Ross models for Lines A and B, is similar to the known depth to the top of the PTn unit. This continuity of this feature in their models is also comparable to possible stratigraphic constraint based on known geologic information. Inferrences drawn by Smith and Ross as to the importance of alteration and proximity to topographic features are applicable to the site as discussed in Section 4.6. This does not mean that a significant lateral contrast actually exists, but the Smith and Ross (1982) interpretation permits presentation of the dipole-dipole data in a way that can be readily considered for further study and interpretation.

Further application of the published Smith and Ross (1982) interpretation to ESF siting, beyond the applications described above, is unwarranted at this time. Sensitivity studies and data review performed by the TAR team show that the published geophysical model and interpretation are no more plausible than alternative ones. The manner of interpretation (particularly Lines A and B) resulted in geophysical models that are very complex. The published models are not constrained by currently available information such as alluvium-bedrock contacts, borehole data on thickness of alluvium and underlying strata, geophysical logs, and other measurements of electrical properties. This is generally because such information was unavailable at the time. If the geophysical model is constrained by such information, sensitivity studies show that simpler, more geologically reasonable geophysical models can result. Thus it would be wrong to overemphasize negative implications of the faulting inferred by Smith and Ross (1982), without further collection and analysis of geophysical (and geologic) data.

By way of qualifying the conclusions of this part of the TAR, it is important to reiterate that the capability to resolve and discriminate between similar geophysical models is limited by the level of irreducible misfit or "noise" associated with each alternative. As discussed in Sections 4.2.1 and 4.5.1, such misfit originates from experimental error, survey location uncertainty, unconstrained model geometry, and the inability of modeling to account for small scale variability. The smallest misfit level that can be expected for Lines A and B is estimated to be about 15%. None of the geophysical models considered, including those of Smith and Ross (1982), fit the data set to this level. Rather, the alternative models tend to cluster around a higher misfit level, so that discriminating between important alternatives is barely feasible. Two important aspects of candidate models for the apparent anomaly in lower Coyote Wash are affected:

1. Depth extent of the buried, conductive body in lower Coyote Wash. Section 4.5.1 states that stratigraphically limited (PTn unit) and

depth-extended (involving the Topopah Spring) models are theoretically discernible at 20% "noise" level.

2. Existence and sharpness of a lateral contrast in the buried, conductive body in Coyote Wash. Section 4.5.1 states that lateral constrasts in the body are discernible at 15%, but not at 20% "noise" level.

The recommendations of the geophysics subcommittee (Section 4.7.2) include measures designed to reduce the "noise" level, thereby permitting advancement in geophysical modeling, and reducing uncertainty as to the depth extent and lateral continuity of a buried low resistivity body in lower Coyote Wash.

4.7.2 RECOMMENDED GEOPHYSICAL PROGRAM

Detection and delineation of a fault that occurs at the surface in the Tiva Canyon bedrock can be readily accomplished using geological mapping methods as recommended elsewhere in this report. Geological methods will provide higher confidence than geophysics for this purpose.

Detection of a buried fault in pre-Tiva Canyon strata can be approached using borings or surface geophysics. While borings provide relatively unambiguous data on depth to stratigraphic contacts, the number of possible borings is limited. Geophysics is thus appropriate to improve confidence in the use of borings, by providing additional basis for decisions as to the number and location. Additional data collection is needed to support this use of geophysics, because of limitations on the model misfit level attainable with the existing data (see Sections 4.5.1 and 4.5.2).

Two basic approaches can be taken for using geophysics to explore for a buried fault: (1) direct fault detection and delineation, or (2) investigate geoelectric structure, to support inferences as to faulting. Direct detection would mean identifying the response of a fractured zone, or breccia along a fault plane. Such features would probably not be detected by potential field methods, or even by geoelectric methods. The effects of terrain, alluvium, and possibly the Drill Hole Wash structure would likely interfere with the capability of the DC resistivity methods to detect such a structure. If a fault or fault zone behaved as a conductive vertical sheet, it might be detected by EM methods deployed along a profile perpendicular to strike. However, the prospect of detecting a buried fault through layers of variably fractured or altered tuff is considered unlikely by the TAR team members. Surface seismic methods tested at Yucca Mountain and vicinity have provided negligible information on shallow bedrock structure (McGovern, 1983), and have not resolved unit contacts at the site, much less lateral heterogeneities of limited extent. TAR team members consider it important to recommend geophysical methods that are likely to produce results that are timely and unequivocal; therefore, the recommended program addresses delineation of geoelectric structure and not direct fault detection/delineation.

Objectives

The following are significant uncertainties in current understanding of the geoelectric structure in the lower part of Coyote Wash, which may be important to the investigation of a buried fault:

1. The existence, sharpness, and location of a significant lateral contrast in resistivity of a buried conductive body in this area.

2. The depth extent of such a body, particularly whether it is limited stratigraphically.

3. The north-south extent of such a body with respect to the surface or near-surface features of Coyote Wash.

4. Information on the variability of depth-to-bedrock and alluvium resistivity, needed to reduce geophysical model uncertainty so that similar models covering items 1 through 3 above can be better discriminated.

If a significant lateral contrast is not found, the likelihood of a buried fault is reduced. If the conductive body does not extend significantly below the base of the PTn unit (Ortiz et al., 1985), or if the base of the conductor has uniform depth, then the likelihood of a buried fault is reduced. If the north-south extent of the buried conductor is limited, then its cause can be more closely associated with hydrologic processes at the surface, and the likelihood of a buried fault is reduced depending on other findings (such as whether there is a sharp lateral contrast). These interpretive criteria are not exclusive or exhaustive, but if they are met there will be substantial doubt as to the existence of a buried fault. For example, lack of confirmation of a significant lateral contrast would not eliminate the buried fault hypothesis, but would reduce its importance and would tend to obviate further use of geoelectric methods to evaluate the hypothesis. Interpretation similar to the sensitivity studies performed for this review will be necessary to evaluate these possibilities using new data in conjunction with existing data. The depth-to-bedrock and alluvium resistivity information is needed to improve accuracy and confidence in the resulting geophysical model.

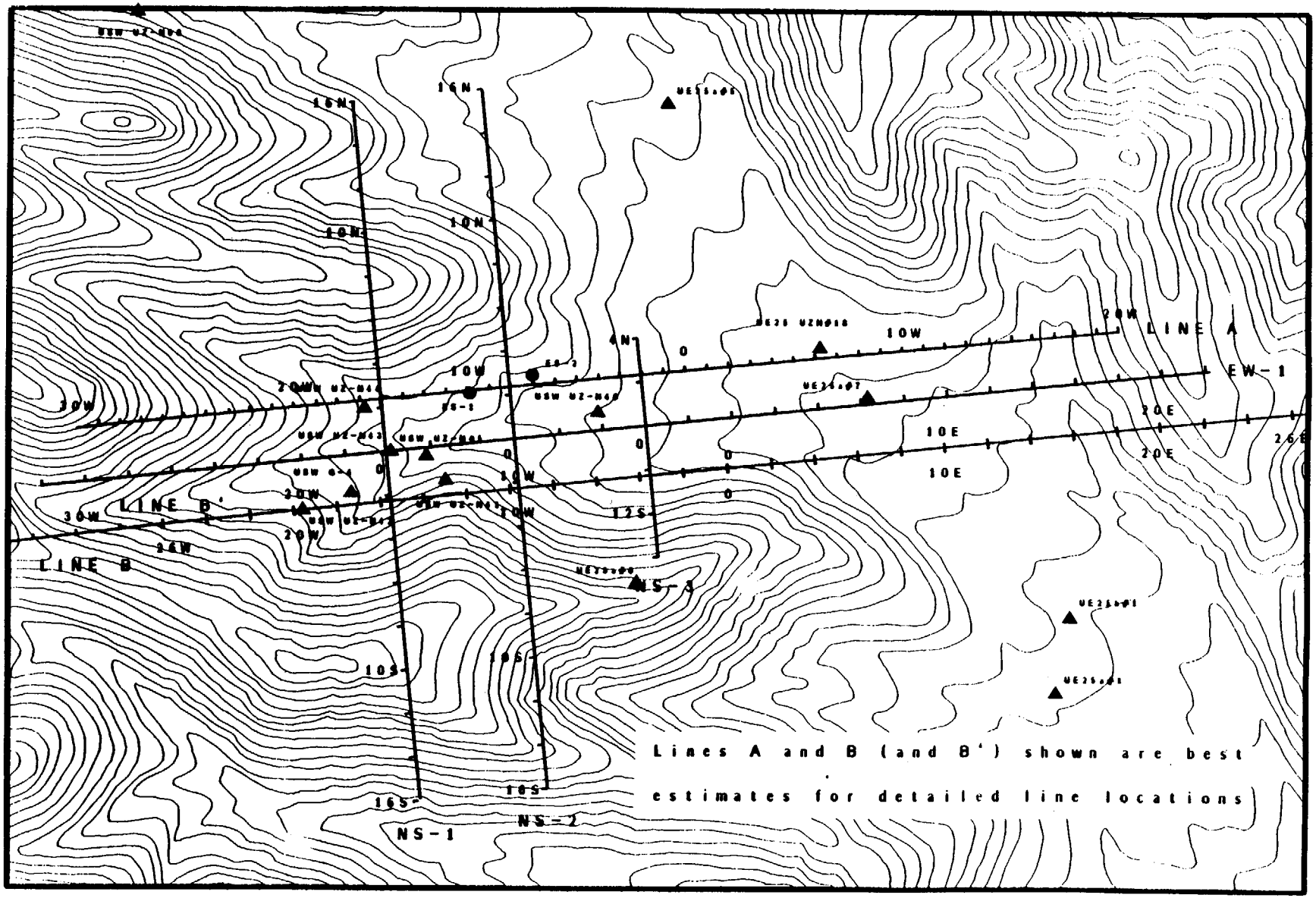
Recommendation

In consideration of the ease with which limited additional geophysical data can be collected, and the improvement and impact that this could have on modeling and interpretation, it is recommended that a specific field program and supporting interpretation be carried out immediately. The following program is recommended to address the uncertainties defined above:

1. Survey and stake geophysical lines shown in Figure 4-28. These consist of one E-W line down the middle of Coyote Wash and parallel to Lines A and B (designated line EW-1), plus three crossing lines which would intersect Line A approximately at stations 14W, 8W, and 2W (lines designated NS-1, NS-2, and NS-3, respectively). These lines will be proximal to boreholes USW G-4, UE25 a#6, USW UZN-43 and UZN-45. Place stakes every 200 ft along each of the geoelectric

N7 ,000

E567,500



E561,500

N764,000

Figure 4-28. Map view of recommended locations for additional dipole-dipole, slingram, and shallow seismic refraction survey lines.

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and seismic refraction lines as indicated. It is anticipated that savings could be realized by surveying these lines together, prior to geophysical activities.

2. Perform depth-to-bedrock and alluvium sounding surveys as follows:

   a. Conduct low-energy shallow seismic refraction surveys over portions of lines EW-1, NS-1, NS-2, and NS-3, which are on alluvium. These surveys will probably involve a sledgehammer source, and should use geophones lowered to the bottom of neutron holes UZN-43 and UZN-45, if possible.

   b. Conduct approximately 10 to 20 shallow Schlumberger soundings, to augment the refraction data. Some of the soundings should be located near the existing borings, to constrain the apparent resistivity stratification. Others should be located where there may be significant velocity-depth ambiguity, or where first arrivals are poor in quality. All of the soundings should be located and oriented with respect to structural conditions, to permit reasonable use of 1-D interpretation. The alluvium probably does not have uniform resistivity, and soundings should be located where conditions can be expected to differ (e.g., where alluvium is deepest).

   The combination of seismic and geoelectric sounding methods will produce corroborative data and increase confidence in depth-to-bedrock and resistivity estimates.

3. Perform dipole-dipole resistivity and slingram surveys over lines EW-1, NS-1, and NS-2 (Figure 4-28). Survey parameters should be selected for detecting lateral contrast in the depth range 100 to 300 ft. Based on studies performed for this TAR, suggested parameters are (a) dipole-dipole lines with A=100 ft, N=6; and (b) slingram lines with coil separation of 600 ft and measurement every 100 ft. These methods are selected for comparison to past surveys, and for cross-comparison. The slingram method is a simple and effective means for contrast detection.

4. Perform detailed interpretation of dipole-dipole and slingram data collected from the above activities, plus Lines A and B (Smith and Ross, 1982) and slingram line Y-11 (Flanigan, 1981). A 3-D starting model should be used which explicitly includes terrain, alluvium, and the PTn unit (Ortiz et al., 1985).

5. Based on assessment of the results obtained above, additional resistivity or electromagnetic methods can be deployed for contrast detection and delineation. Candidate methods are telluric-ratio profiling, and audio-magnetotellurics (AMT). The telluric method has superior resolution for contrasts perpendicular to the survey line because of closely spaced observations, but produces little specific information on resistivity values for contrasting bodies. AMT provides resistivity information in the form of a tensor quantity that can be compared with the structural setting. Both of these methods exhibit significant terrain effect.

Other Geophysical Techniques Considered

Principal alternatives are seismic reflection and refraction, other electromagnetic methods such as central loop time-domain EM, radiometric methods, and the potential field methods. Each of these would respond differently to a particular target, and would be recommended together for a comprehensive study if practical considerations (e.g., timeliness) permitted. However, the sensitivity and resolution of these methods is not well-suited to direct detection of a buried fault in complex terrain, in the presence of alluvium with variable thickness and properties, and other possible variability associated with the apparent geoelectric structure. The following methods were considered but not recommended for the indicated reasons:

1. Mini-Sosie method. This seismic reflection method (Barbier, 1983) has been used with some success in the vicinity of Yucca Mountain to image alluvium interbedding that has been offset by faults (DOE, in review). The method has not yet been used to image bedrock contacts, and has not shown capability to penetrate a low velocity layer such as the PTn (Vp of less than 1 km/sec), which would probably be necessary to detect a buried fault.

2. High-resolution seismic reflection. Large-scale profiling with truck-vibrator or explosive sources has not been successful at Yucca Mountain. Statics are a problem, especially for the bandwidth needed to detect a small, shallow target such as a fault offset or altered fault zone. Modification of survey geometry, source, and acquisition parameters to address the problem would probably result in a method similar to Mini-Sosie.

3. Time-domain electromagnetic (TDEM) method. This method is insensitive to terrain, but has limited lateral resolution and is relatively difficult to set up.

4. Micro-gravity. Lateral facies changes, saturation changes, differences in fracturing, or fault breccia would be expected to have no useful gravity signature. Scoping calculations (DOE, in review) have shown that the minimum offset on a vertical fault that could be resolved by gravity is about 40 m.

5. Ground magnetics. This technique could be of some use for reconnaissance, but interpretation is complicated by terrain, magnetic reversal of the Tiva Canyon, and strong, spatially variable remanence in the welded tuff (Q>>1; DOE, in review).

6. Radiometrics. This is an untried method with unknown potential for fault detection at Yucca Mountain. Deployment of such a survey would be quick and inexpensive, but falls in the category of feasibility testing that is inconsistent with the goal of producing timely and unequivocal results.

Rationale for New Line Locations

One possible recommendation that was rejected by the TAR team was to repeat the original dipole-dipole surveys of Lines A and B. The argument for this option was that if the repeat lines showed no evidence for the lateral contrast inferred as a fault by Smith and Ross (1982), then the original data set could be regarded as affected by some transient hydrologic phenomenon, rather than a fault.

The original line locations are uncertain as discussed in Section 4.2.1, which translates to uncertainty as to the distance from each line to the topographic features, and whether particular stations were located on or off the alluvium. These effects can produce significant variation in the observed data, as implied by the sensitivity test results of Section 4.5. Thus the new data would not be likely to agree with the original data, to an extent that is significant with respect to modeling uncertainty.

For purposes of understanding the geoelectric anomaly at Coyote Wash, a line up the center of the wash would be less sensitive to 3-D terrain effects and uncertain alluvium-bedrock contact geometry, and is thus favored over the location of Line A or B of Smith and Ross (1982). Moreover, as discussed above, further geophysical work in this area should also investigate the north-south lateral extent of the conductive body observed in lower Coyote Wash. This can only be accomplished using north-south oriented geoelectric survey lines.

If Lines A and B were repeated, the likely variation between new and old data would create a need to explain the differences. It would not be possible to address this problem by geophysical modeling, because of the uncertainty which attends the original data. Differences might be attributed to transient effects, neglecting the repeatability concerns, although no such transient effects may have actually occurred. Improvement in data coverage and quality would be less than what is likely to result from running new lines, in the judgement of the geophysics subcommittee members. For these reasons, crossed lines are recommended, which tie with existing boreholes in a reasonable manner. Based on evaluation of geophysical data from the recommended program (items 1 through 4 in the list above), additional lines could be recommended including repeat survey of Lines A and B of Smith and Ross (1982).

Summary

In summary, the presence of a fault in lower Coyote Wash will be addressed by both geological and geophysical activities. The geologic approach can provide high confidence as to the existence of a fault at the surface. For investigation of a possible buried fault, a limited program of geophysics can be effectively employed in a timely manner, in addition to a drilling program. The objective of the recommended program is to reduce uncertainties caused by basic limitations of the currently available data. The resulting information will significantly increase understanding of the geoelectrical structure of Coyote Wash, making possible more definitive statements about the possibility of a buried fault. The TAR team recommends that the program, or possibly a close variant that addresses the same uncertainties, be carried out immediately.

Chapter 5

SUMMARY OF ENGINEERING SUBCOMMITTEE - PERFORMANCE EVALUATION

The siting guideline specified by Bertram (1984) relative to faulting was that "ES sites that would have subsurface facilities (excluding horizontal boreholes) closer than 100 feet to a potentially adverse structure would be excluded." Specifically, this guideline was applied to a preliminary version of the Scott and Bonk (1984) map of Yucca Mountain to construct an exclusion zone with boundaries that were 100 ft from a potentially adverse structure. The rationale for a 100-ft setback was not given in Bertram (1984); however, conversations with S. G. Bertram-Howery, L. W. Scully, and T. J. Merson reveal that the setback was selected based on expert judgement. The first three items listed below contributed to this judgement, while the fourth provides the rationale for the maximum setback:

1. Construction of the ES would be easier if potentially adverse structures were avoided.

2. Safety during construction would be improved by avoiding a potentially adverse structure.

3. The Ad Hoc TOC Committee did not want to have faults serve as preferred pathways for vertical flow into the shaft.

4. The ES should not be located more than a specified distance from potentially adverse structures, since it was desirable to be able to investigate these structures at depth. The specified maximum distance was selected as the maximum distance that could be investigated by horizontal drilling (2,000 ft).

We have no dispute with the logic; however, a potentially adverse structure has not been defined. We will address this further in Section 6.1. More generally, the Ad Hoc TOC Committee looked upon the site selection process as a method for selecting and evaluating several sites at Yucca Mountain in order to recommend a preferred site for further study. In total, this process appears to be a wise application of engineering logic to arrive at the selection of a site which appears to be appropriate from the point of view of the scientific, engineering, environmental, and non-technical categories detailed by Bertram. A later study reported in the Design Acceptability Analysis (DAA) (DOE, 1989), Appendix J, pp. 4-6, further concludes that the performance of all sites is not significantly different "because all the locations are expected to have conditions that would allow regulatory requirements to be met by wide margins."

Since Bertram (1984) and DOE (1989) do not specifically consider the possibility of faulting very near the ES, this chapter and Chapter 6 will consider the implications of faulting on both the shaft construction and shaft performance.

5.1 IMPACT OF POSSIBLE FAULTING AND/OR ZONE OF HIGHER SATURATION ON SHAFT PERFORMANCE

The effects of a possible fault, or a zone of increased saturation located near the exploratory shafts, on the performance of those shafts is considered in the following sections. Flow of both water and gas is considered.

5.1.1 IMPACT OF FAULTING ON GROUND-WATER FLOW

The general understanding of the impact of faulting on ground-water flow in the unsaturated zone is that a fault may act as either a pathway or a barrier to moisture flow at any location depending on the amount of water entering the system as net infiltration (DOE, 1988, p. 3-193).

5.1.1.1 Brief Description of Unsaturated Zone Flow

This brief description of unsaturated zone flow is presented to focus attention on the more important aspects of faulting which may occur near the exploratory shafts. A more comprehensive description of unsaturated zone flow at Yucca Mountain is presented in Chapter 3 of the SCP (DOE, 1988). As is the case for saturated zone flow, water flows down the potential gradient; however, the potential gradient above the water table is negative as water is constrained to exist in small openings by capillary forces, which effectively dry out larger openings (fractures, faults, and mined openings). Further, pore spaces are filled in progression from smaller to larger sizes. Since the hydraulic conductivity depends approximately on the square of the pore diameter of those pores that contain water, the hydraulic conductivity of the unsaturated rock is thus dependent on the saturation state of the rock. Consequently, the larger the flux rate through the rock, the larger will be the pore size that actually conducts water. Similarly, the flux rate through an unsaturated rock is dependent on the saturation.

For the unsaturated flow conditions at Yucca Mountain, the pore size that divides water-filled pores from dry pores may be determined from a consideration of the equation of Young and Laplace (cf. Adamson, 1976), i.e.,

$$r = -\frac{2\sigma}{\psi \rho g} \qquad (5\text{-}1)$$

where r = capillary radius,
σ = surface tension of water,
ρ = density of water,
g = gravitational acceleration,
and ψ = moisture potential.

In Equation 5-1, the moisture potential has been used to define the pressure of water in a capillary. From Equation 5-1, the pore radius that separates

wet from dry pores is a function of the moisture potential of the rock. At Yucca Mountain, the moisture potentials in the unsaturated zone range from -10m to -1,000m (cf. Rulon et al., 1986). From Equation 5-1, it is found that -10m corresponds to a capillary radius of 1.5 μ and -1,000m corresponds to a capillary radius of 0.01 μ. Hence, the maximum pore size in which water is normally expected to be found is approximately 1.5 μ in radius (3 μ in diameter). Since fracture apertures in the unsaturated zone at Yucca Mountain range from 66 to 89 μ (Sinnock et al., 1984), these fractures are not expected to contain water, but rather to act as flow barriers, with water passing the fracture only at discrete contact points. In faulted zones where fracture frequencies are expected to be greater, water movement is expected to be greatly impeded.

5.1.1.2 Consideration of Flow Diversion into the Exploratory Shafts

Free water flowing into or out of a shaft must necessarily result from conditions which cause local saturation of the rock. DOE (1989), Appendix J, pp. 2-8, describes two possible methods by which water may be concentrated locally to cause water to flow into the shaft: (1) concentrations by infiltration pulses and (2) concentration by lateral diversion. Although a number of numerical models have been proposed to address the flow of water, these models are based on assumptions and data which will require field verification. Further, the hydraulic properties are unknown for any fault near the exploratory shafts, so that predictions of performance, based on calculations using these models, would contain many uncertainties which will not be resolved until site characterization allows the collection of appropriate hydrologic data.

5.1.1.2.1 Water concentration caused by infiltration pulses

Water flowing through faults and associated fractures into the exploratory shafts is one way in which ground water might contact waste packages and cause some negative impacts on repository performance. Water is assumed to be conducted through near-surface fractures or faults downward toward the shaft. As water moves through fractures in the unsaturated matrix, the rock imbibes water from the fracture until the fracture dries out. In this way, water movement through fractures is limited both in distance and in time. In order to have possible adverse performance impacts, a large quantity of water would have to enter the shafts, completely fill the ESF, and then spill over controlled drainage slopes into the repository.

Several studies have considered the migration of water through near-surface fractures and faults. Fernandez et al. (1987) considered ground-water movement in faults in Drill Hole Wash and in the Ghost Dance fault. Fault conductivities were assumed to be equivalent to fracture conductivities, based on studies of faulting in Drill Hole Wash (Scott et al., 1984). Hence, fault conductivities were assumed to range between 10^{-2} cm/s and 10^{-5} cm/s, (Scott et al., 1983, p. 299). For the anticipated conditions defined by Fernandez et al. (1987), the water supply was defined by four yearly thunderstorms that had greater than 1.3 cm of precipitation in

1 hour. The maximum amount of water entering the repository, assuming no matrix imbibition, was calculated to be 62 m^3/year. Since this inflow was much less than the total allowed to meet performance objectives (i.e., 10^3 to 10^5 m^3/yr) (Fernandez et al., 1987), no adverse performance impacts were expected.

Martinez (1988) used a model of flow through a fracture that allowed water to be imbibed by the matrix. The model determined the total distance of moisture penetration for 30 minutes of infiltration. For a fracture having an aperture of 25 μ (hydraulic conductivity of 1 x 10^{-4} cm/s based on 22 fractures/m), moisture penetrations in the Topopah Spring and Tiva Canyon were 40 and 80 cm, respectively. In a larger fracture with an aperture of 100 μ (hydraulic conductivity of 1.6 x 10^{-3} cm/s), the model indicates penetrations in the Topopah Spring and Tiva Canyon of 4.9 and 9.8 m, respectively.

Using an analytical method similar to that of Martinez, Fernandez et al. (1989) considered flow through all fractures (density of 22 fractures/m) that are predicted to intercept the exploratory shafts. Two types of probable maximum floods (PMFs) were considered to provide the water source term: a 6-hour duration thunderstorm PMF and a 14-hour duration general storm PMF. The fracture aperture was assumed to be 89m (hydraulic conductivity of 1.3 x 10^{-3} cm/s) and the total volume of water entering both shafts was calculated as a function of initial matrix saturation and porosity. For the expected case of 67% initial saturation and 11% porosity, Fernandez et al. (1989) report 3.5 m^3 of water entering the shaft for the thunderstorm PMF and 12.2 m^3 of water entering the shafts for the general storm PMF. For the worst case assumption of 90% initial saturation and 7% initial porosity, 13.3 m^3 of water would enter the shaft for the thunderstorm PMF and 47.4 m^3 of water for the general storm PMF. The assumption of 90% initial saturation may be considered to represent the higher saturation interpretation of the resistivity anomaly. This water would enter the top portion of the shaft and would be expected to migrate through the matrix below the zone of local saturation.

The calculated quantities of water were compared to the estimated storage and drainage capacity of the ESF by Fernandez et al. (1989). The storage capacity of the ESF was determined to be 630 m^3 and the drainage capacity was determined to be 11,300 m^3/year. Because the storage and drainage capacity were considerably larger than projected inflows, and because water entering the ESF was precluded from entering the repository by controlled drainage slopes in the ESF, Fernandez et al. (1989) concluded that no adverse repository performance impacts were expected.

Peters (1988) considered the injection of 10 m of water in 2.2 days into a fault zone using a one-dimensional code which assumed equilibrium between the matrix and fracture. The one-dimensional code has a limitation in that it does not allow for seepage of water out of the fault zone into the highly conductive Paintbrush Tuff (PTn) non-welded unit. Consequently, the calculations are assumed to provide an upper bound. The saturated conductivities of the Tiva Canyon and the Paintbrush Tuff were assumed to be 3.8 x 10^{-1} cm/s and 6.1 cm/s, respectively. The initial pressure head distribution was specified by a constant flux of 0.1 mm/yr through Yucca Mountain. The results of these calculations show that the slug of water did

not penetrate the Paintbrush Tuff before the water was exhausted. The flux pulse resulting from this inspection did not reach the water table until almost 10,000 years had passed. Further, the Topopah Spring unit below the PTn never reached saturation so that ground-water travel times were only minimally affected.

In a study similar to that of Peters, Wang and Narasimhan (1986) considered adding pulses of water to the top of a vertical column representing welded and nonwelded tuff units at Yucca Mountain. For average infiltration rates of 0.1 mm/yr to 0.5 mm/yr, pulses of 0.2 years duration were applied every 1, 5, 50, 500, and 5,000 years. The pulse intensity was chosen to allow the average infiltration rate to be either 0.1 or 0.5 mm/yr. As water moves down into the PTn, the rock becomes saturated. Most effects of the transient infiltration pulses are damped during the first few thousand years. The underlying unsaturated Topopah Spring welded unit responded to the pulses by showing only small changes in saturation and hydraulic potential from steady-state values.

5.1.1.2.1.1 Summary of effects caused by infiltration pulses

Surface water from precipitation events and surface hydrologic channeling has been modeled using simulated faulted/fractured rock with a wide range of rock hydrologic properties. In all cases studied, the faulted/fractured region does not conduct water for large distances that might be considered to cause deteriorated performance. Rather, the unsaturated matrix absorbs excess water from fractures so that the zone of saturation is limited to tens of feet from the ground surface. Consequently, the small quantity of water that enters one of the shafts as a result of intersections with faults or fractures is several orders of magnitude less than the drainage capacity of the ESF.

5.1.1.2.2 Water concentration caused by lateral diversion

The bedded tuff at Yucca Mountain is tilted at 5-7 degrees eastward (Scott and Bonk, 1984). The lateral component of the gravity gradient may divert water laterally to a fault zone where water concentration may occur.

Lateral diversion of water to a fault zone caused by the upward tilt of the bedded tuff units and resultant lateral component of the gravity gradient has been studied by several authors. Wang and Narasimhan (1988) considered two-dimensional flow in a sequence of bedded tuff units which modeled Yucca Mountain. A fault was assumed to form a seepage face at the eastern edge of the tuff units. These authors examined conditions of net infiltration corresponding to 0.1 and 0.5 mm/yr. At 0.5 mm/yr, virtually all units in the simulation become saturated, and the lateral tilting mechanism perturbs the system so that a fraction of the flow is concentrated at the fault zone and rapidly flows down the fault zone. Wang and Narasimhan project flow velocities in the fault of approximately 5mm/yr, which would correspond to a negligible shaft inflow of $0.01 m^3/yr$. At 0.1 mm/yr, moderately higher saturations are observed near the eastern fault boundary, but these changes are not large enough to induce significant changes in pressure and potential distributions to drive flows into the fault zone. Under these conditions,

Wang and Narasimhan conclude that the lateral tipping mechanism is a second order effect and does not significantly change the downward gravity-driven flow patterns.

Prindle and Hopkins (1989) also modeled down-dip flows for Yucca Mountain. The fault zone in their model was considered to be a highly fractured porous medium whose right boundary was a no flow boundary. The results are in qualitative agreement with those of Wang and Narasimhan (1988). Matrix flow in an essentially vertical path was observed for flux rates through the mountain of 0.2 mm/yr or less. At larger flux rates, fracture flow was initiated near the right-hand fault boundary.

Rulon et al. (1986) modeled the fault as a highly transmissive zone, postulated to be very conductive at low water saturations. This particular combination of fault properties allowed a substantial portion of vertical flux to be diverted laterally to the fault at very low fluxes of 0.015 mm/yr. Lateral diversion at such low fluxes do not agree with the results of Wang and Narasimhan (1988) or with those of Prindle and Hopkins (1989). The flows calculated by Rulon et al. (1986) occur at very negative heads (less than -40 m) and at very low liquid saturations. Consequently, if such a fault were to intersect the seepage face at a shaft wall, no flow would be expected to occur in the shaft.

5.1.1.2.2.1 Summary of effects caused by lateral diversion

Lateral diversion of water in the dipping bedded units of Yucca Mountain has been projected to occur when the flux rate exceeds some minimum value. This minimum value depends strongly on the hydrologic properties of the bedded units as well as those of the faulted zone. However, at the low flux rates projected for Yucca Mountain (approximately 0.1 mm/year based on comparisons to ambient saturation data), modeling efforts to date indicate that either (1) no flow will occur in faulted regions, or (2) flow that does occur will have very negative potentials which will not cross the seepage face at the shaft wall. At higher flux rates (0.5mm/yr), negligible amounts of water enter the shaft; however, the volume of water is much less than the drainage capacity of the ESF so that no performance impacts are expected.

5.1.2 IMPACT OF FAULTING ON GASEOUS MOVEMENTS IN THE EXPLORATORY SHAFT

A consideration of the performance implications of gaseous movement in the exploratory shafts on repository performance has been given by Fernandez et al. (1987; 1989). The authors conclude that acceptable gaseous releases from the shafts can be obtained by backfilling the shafts with crushed tuff whose hydraulic conductivity is 10^{-2} cm/sec.

If a fault were to intersect the shaft, the shaft performance is expected to be unchanged because the air conductivity of the shaft fill will be unchanged. Since gas movement in the shaft is dependent on the air conductivity, area and driving force for air movement, these properties would have to change along the flow path to effect any change. Unless there is significant movement along the fault zone to cause channeling in a significant portion of the backfill, changes in backfill properties are

unlikely. Further, gaseous movement along any fault will occur whether or not a shaft is present.

5.2 SUMMARY AND CONCLUSIONS

The performance implications of a fault zone or zone of increased saturation located near the exploratory shafts have been considered. Under normal conditions, unsaturated zone hydrology is expected to apply to the subsurface tuffs located above the water table at Yucca Mountain. For the unsaturated conditions expected at Yucca Mountain, faults and fractures are expected to be barriers to fluid flow, not conduits. Two general conditions were considered by which local saturation might allow flow into the shafts: (1) water concentration by infiltration pulses and (2) water concentration by lateral diversion. Significant water inflow into the exploratory shafts is not expected by either of these local saturation mechanisms as judged from performance calculations done by several authors. Specific features of the performance calculations which support these conclusions are:

1. Water movement through fractured and faulted rock is limited in distance and time because adjacent unsaturated rock imbibes water from them and eventually desaturates the fracture or fault.

2. Water movement away from a zone of local saturation is limited because most of the subsurface tuff is unsaturated. Conditions of local saturation were shown to be limited to regions within and above the PTn for two cases: (1) a 10-m head of water injected into a fault zone, and (2) pulses of water lasting 0.2 years injected at rates up to 25,000 times greater than the projected average flux in the mountain.

3. Water entering the shafts is judged to be insignificant if it is less than the storage (630 m^3) and drainage capacity (11,300 m^3/yr) of the ESF.

4. Water entering as a result of a PMF through a fracture network that connects the surface to the exploratory shafts is expected to be about 12 m^3. This amount is less than the drainage and storage capacity of the ESF.

5. For conditions where near local saturation prevails, water entering as a result of a PMF through a fracture network that connects the surface to the exploratory shafts is expected to be about 47 m^3. This amount is also less than the drainage and storage capacity of the ESF.

6. At anticipated flux rates of 0.1 mm/year, a disagreement between some authors exists that underground lateral diversion of water is an important mechanism. The difference between the findings of the various studies appears to be related to the hydraulic properties attributed to the fault and the assumed boundary conditions imposed. However, in all studies the calculated hydraulic potential was

strongly negative so that fluid would not flow into a shaft from an intersecting fault.

7. At higher flux rates of 0.5 mm/year, all two-dimensional underground flow studies found that the lateral diversion of water was an important mechanism. Fluid velocities in the faulted region were used to project rates of water entering a shaft which might intersect the fault. Negligible amounts (0.01 m^3/year) of water would be expected to enter the shaft.

Enhanced gaseous movement caused by a fault intersecting the shaft is not considered to be a concern because the shaft backfill properties are primarily responsible for retarding migration of gases. In order to cause reduced performance, these backfill properties would have to be altered over a significant portion of the shaft length to increase gaseous releases.

Chapter 6

SUMMARY OF ENGINEERING SUBCOMMITTEE - CONSTRUCTION-RELATED IMPLICATIONS

Anticipated impacts of faults on shaft construction are largely related to decreases in ground stability caused by the extent of the fault zone and its interaction with the joint structure of the rock and with water, if present.

6.1 FAULTS AND THEIR EFFECT ON SHAFT CONSTRUCTION

Table 6-1 lists fault types and characteristics, and also shows the combined effect of faults and ground water on excavation methods, the temporary ground support system, concrete lining arrangements, and station construction. Typical rock mass conditions that correspond to progressively worsening fault situations are also described in the table. Sketches supplement the table to show the interaction between faults and the joint structure, and the vertical persistence of faults in a shaft. A definition of a "potentially adverse structure" is included.

6.1.1 FAULTS

Minor faults may be regarded as equivalent to joints and fractures in the way that they affect opening stability. A kinematically unstable block could be formed if such a fault intersects both the opening and other discontinuities at an unfavorable angle. Such blocks require pinning with carefully sized and located rockbolts. Unexpected minor faults may often be encountered during shaft sinking with little or no appreciable disruption to sinking activities.

Moderate and major faults generally have a greater impact on sinking. Fault surfaces may be slickensided and coated with low-friction alteration minerals, and gouge and breccia fillings may be very weak. Additional support will be required in major fault zones, with more closely spaced and/or longer rockbolts for structural support, using wire mesh and mats to protect the sinker against raveling conditions. As conditions progressively worsen, the sinking cycle will be shortened, and the liner is placed in shorter lifts closer to the shaft floor. In some instances, squeezing conditions can be present in a fault zone, particularly those with clay gouge infilling. If the fault contains water under pressure, intersection of a fault zone can cause inflows of water and possibly debris into the shaft. As in competent zones, careful blasting practice should be employed to prevent damage to the rock.

In summary, minor faults are routine occurrences during shaft sinking that can be handled with no significant disruption of the sinking cycle. It is possible that a moderate or major fault may be encountered underground that has no trace on the surface. In such circumstances, support requirements will increase and the sinking cycle will be disrupted with probable cost and schedule impact. Any increased difficulties should not affect the feasibility of construction or the utility of the shaft.

Table 6-1. Construction Methods and Recommended Temporary Ground Support
Sheet 1
Good Conditions

FAULT TYPE	NO FAULT	MINOR (FLAT)	MINOR (Steep)
Ground Class[a] NGI Description* Added Category+	A Very Good*	B Good*	B/C Fairly Good+
General ground conditions relative to Yucca Mountain	Massive, welded tuff, little or no jointing	Densely welded tuff with one to three joint sets; joints are tight with no alteration	Densely welded tuff with one to three joint sets; joints as for B
Fault characteristics	No fault	Single minor[b] fault-flat (60° from vertical) minimum thickness, no gouge	Single fault steep (25° to 30° from vertical). Minor shearing, 2-3 in. broken ground
Ground water from trapped water or perched water table	Dry or slightly damp	Dry or slightly damp	Very light seepage. (Not a nuisance)
Excavation method	Burn cut, controlled blasting (8-ft pull)	Burn cut, controlled blasting (8-ft pull)	Burn cut,controlled blasting (8-ft pull)
Ground support system recommended for conceptual design	Spot rockbolting as needed	As for A but with extra bolts	Rockbolts at 5 ft centers, in diamond pattern; welded wire mesh installed as needed
Concreting arrangements	20-ft concrete lift Kerb/blast ring set 40 ft above floor	20-ft concrete lift; Kerb/blast ring set 40 ft above shaft floor	20-ft concrete lift; Kerb/blast ring set 20 ft above shaft floor
Station construction procedure	Normal excavation and support	Normal excavation and support	Normal excavation. Additional temporary support

[a] Based on Table 3-13 of SCP-CDR, also see Table 6-1, Sheet 5, Note 1 and Note 3, for additional explanation on ground classification.
[b] The terms "minor," "moderate," and "major" have been assigned specific definitions. See Sheet 4.

Table 6-1. Construction Methods and Recommended Temporary Ground Support
Sheet 2
Fair to Poor Conditions

FAULT TYPE	MODERATE	MAJOR	MAJOR (Shearing)
Ground Class NGI Description* Added Category+	C Fair*	C/D Fairly Poor+	D Poor*
General ground condition relative to Yucca Mountain	Densely welded tuff with multiple or random joint sets; little or no joint alteration	Densely welded tuff with multiple or random joint sets; some joint alteration	Heavily jointed, welded tuff; typical of conditions at transition within flow units.
Fault characteristics	Single, steep, moderate[a] fault. About 3 ft broken ground	Single steep major[a] fault, over 6 ft width of broken ground. Gouge present. No soft material	Single steep major fault, over 6 ft width of broken sheared ground. Gouge present and some breccia filling.
Ground water from trapped water or perched water table	Light seepage. (Slight nuisance)	Seepage. (Water goes out with muck. No bailing.) (Nuisance.)	Sudden released flow for several minutes, then seepage. Initial bailing, then water out with muck. Interference with sinking.
Excavation method	Burn cut shorter round (say, 6 ft)	Burn cut shorter round (say, 6 ft)	Benching
Ground support system recommended for conceptual design	Rockbolts at 5 ft centers, diamond pattern. Extra row or half row at critical intersections. Wire mesh installed routinely.	Rockbolts at 3 ft centers, diamond pattern. Wire mesh installed routinely with mats	Suspended flat steel rings with hangers. Double mesh and mats behind rings.
Concreting arrangements	20-ft concrete lift. Kerb/blast ring set 10 ft above shaft floor	10-ft concrete lift. Kerb/blast ring set 10 ft above shaft floor	10-ft concrete lift. Kerb/blast ring set 10 ft above shaft floor

Table 6-1. Construction Methods and Recommended Temporary Ground Support
Sheet 2 (continued)
Fair to Poor Conditions

FAULT TYPE	MODERATE	MAJOR	MAJOR (Shearing)
Ground Class NGI Description* Added Category+	C Fair*	C/D Fairly Poor+	D Poor*
Station construction procedure	Excavate in stages securing transition above station brow with long bolts and shot-crete lining. Provide hitch to facilitate excavation lift below.	As for C, but with additional rock-bolting	As for C/D, but with reinforced concrete brow and transition

[a] The terms "minor," "moderate," and "major" have been assigned specific definitions. See Sheet 4.

Table 6-1. Construction Methods and Recommended Temporary Ground Support
Sheet 3
Very Poor To Exceptionally Poor Conditions
(Not Representative of Conditions at the Yucca Mountain Site)

FAULT TYPE	MAJOR (Crushing)	MAJOR (Multiple)	MAJOR (Collapsing)
Ground Class NGI Description* Added Category+	E Very Poor*	E1 Extremely Poor+	E2 Exceptionally Poor+
General ground condition	Fault zone;crushed tuff in a matrix of low-strength gouge; heavy alteration	As E, but badly broken, typically associated with heavy multiple faults and crushing	As E1 but continuously collapsing material
Fault characteristics	Major fault	Multiple faults	Multiple faults
Ground water from trapped water or perched water table	Continuous flow of water (say 50 GPM max for several hours or days). Needs pumps. Changes method of work	As for E	As for E
Excavation Method	Benching, softer material removed by hand tools and Cryderman. Remainder by blasting	Hand tools and Cryderman. Minimal blasting	Hand tools and Cryderman. No blasting
Ground support system recommended for conceptual design	Suspended flat steel rings with hangers. Double mesh and mats behind ring.	Steel rings as for E, with driven spiling	Custom-designed to suit circumstances
Concreting arrangements	10-ft concrete lift set on blasted muckpile	5-ft concrete lift set on broken muck	5-ft concrete lift set on broken muck
Station construction procedure	All reinforced concrete station, driven with pilot heading,excavated and concreted in short lifts. Relocate if possible	Station should not be constructed in this ground	Station should not be constructed in this ground.

Table 6-1. Construction Methods and Recommended Temporary Ground Support
Sheet 4 (continued)
Definition of Fault Classes

A fault is defined as "[a] fracture or fracture zone upon which there has been displacement of the sides relative to one another parallel to the fracture. The displacement may be a few inches or many miles" (AGI, 1962). Faults may transect a large part of the repository (e.g., Ghost Dance) or they may be limited local features. They may be nearly tight, or they may be many feet wide. Faults may contain weak materials such as fault gouge and fault breccia. The wall rock may be slickensided and altered, and the adjacent ground mass may be disturbed by subsidiary shear and tension features, drag folds, etc. The fault and associated shear and tension features may constitute a zone of increased permeability.

For engineering purposes, the following classification of faults is proposed:

- Minor faults, less than several inches in thickness, some evidence of shear movement, but wall rock relatively intact, no or minor amounts of gouge or other fillings, little or no alteration, difficult to distinguish from other joints and other fractures, limited persistence (may occur only in one shaft or drift in mine or repository).

- Moderate faults, around 3 ft in thickness: slickensides and other evidence of shear displacement; gouge, breccia, and other fillings, possible alteration.

- Major faults, about 6 ft or greater in thickness; evidence of considerable displacement, subsidiary tension cracks, drag folds, and other damage to wall rock, gouge, breccia and other fillings; continuous (trace may be several miles or more in length), probably transects several shafts/drifts in mine or repository.

Note that the amount of displacement or "throw" of the fault is not a major factor in this classification. The thickness and properties of the disturbed zone are considered more important from a geoengineering viewpoint; faults with limited displacement can have a thick broken zone if the wall is weak, while faults with considerable displacement in competent rock might be minor features from an engineering viewpoint.

Selective judgement must be applied in using the "thickness" factors of "around 3 ft" and "about 6 ft or greater." For instance, the description (SCP, p. 1-128) of the Ghost Dance fault (which is over 1,000 ft to the west of the exploratory shafts) includes the statement "breccia zones are as much as 20 m wide." This would automatically place it in ground category C/D (fairly poor) or D (poor). PBQ&D is of the opinion, however, that the Ghost Dance Fault, though persistent, does not present a major obstacle to shaft sinking with suitable temporary ground support measures. A more appropriate classification for it may be between C (fair) and C/D (fairly poor).

Notwithstanding this observation, one would not deliberately site any shaft in a location where it had to cross through such a fault.

Potentially Adverse Structure

In the NNWSI Exploratory Shaft Site and Construction Method Recommendation Report (Bertram, 1984), part of the criteria for identification for preferred ES sites (p. 56) was "ES sites that would have subsurface facilities (excluding horizontal boreholes) closer than 100 ft to a potentially adverse structure would be excluded."

No definition was given for this excluding condition, but the 100-ft setback has been applied to the Ghost Dance fault (Fig. 4, p. 65), so a fault of this persistence and thickness may be regarded as a potentially adverse structure.

It is appropriate to provide a better definition of such a structure. The fault classification given above and the ground classes and fault descriptions in Table 6-1, Sheets 1-3, provide a starting point and a realistic demarcation line.

It is proposed that those conditions shown on Table 6-1, Sheet 1 (minor faults), do not constitute potentially adverse structures. The conditions shown on Table 6-1, Sheet 2, beginning with Column C in which a moderate fault is listed, requiring some changes to the blasting pattern and temporary support pattern, will constitute a potentially adverse structure and thus would be sufficient reason to choose a new site for either of the exploratory shafts if the structure is revealed prior to commencement of shaft sinking by:

1. Thorough reexamination of the surface at the proposed ESF site after ground clearance to assist in identification of features.

2. Construction activities for site leveling and clearance to provide a pad for rigs to drill the multipurpose boreholes (MPBHs) adjacent to each shaft.

3. Coring or logging during drilling of the MPBHs.

4. Excavation to provide a level area for construction of the exploratory shafts.

It should be noted that moderate faults are considered as affecting schedule and cost only (delays to sinking). As they can be negotiated satisfactorily with some changes to the excavation, ground support, and concrete lining cycles, such faults do not affect worker safety when correct precautionary measures are implemented. For this reason, should a moderate fault, or ground conditions as described in Column C, be found unexpectedly

Table 6-1. Construction Methods and Recommended Temporary Ground Support
Sheet 4 (continued)
Definition of Fault Classes

during sinking, it would not be considered a potentially adverse structure, requiring a 100-ft setback.

The major fault, described in Column D of Table 6-1, Sheet 2, would be considered as a potentially adverse structure if found during sinking of the shafts. In the unlikely event of meeting such a fault, the difficult conditions would need to be weighed against the additional man-hours of exposure and the delays implicit in siting the shafts in a new location and starting sinking over again.

Table 6-1. Construction Methods and Recommended Temporary Ground Support
Sheet 5
Supplementary Data

The following notes provide additional background and supplementary data to support the information in Table 6-1, Sheets 1-3:

1. The SCP-CDR (Section 8.3.6.3 - page 8-81) discussed the need for further work in rock mass classification methods. This has been expanded by work done at PBQ&D in describing the appropriate responses to ground conditions that may adversely affect excavation, and ground support activities in tunnels and shafts. Table 1, Sheets 1, 2, and 3 have been developed from that work, which used the NGI rock-mass classification system developed by Barton et al. (1989), described by Barton (1988) applied to tuff units at Yucca Mountain. Two more categories have been added to reflect ground classes between good and fair (fairly good), and fair and poor (fairly poor).

2. The effect of a fault, or series of faults, met with during shaft sinking will be influenced by the direction and frequency of the principal joint sets. Figure 6-1 is attached showing examples of the interaction.

   This figure shows the shaft floor and a length of shaft above the floor intersected by a fault plane dipping to the east. Two major joint sets are assumed and their orientation is shown as N34°E and N12°W.

   The intersection angles of the joints, and the fault plane create blocks of rock that are potentially unstable. Typical locations are marked by heavy arrows at the upper left and lower right corners of Figure 6-1. An unstable block created by the intersection of the joints themselves, independent of the fault plane, is typically shown in the bottom left corner.

   Additional information has been shown on the figure to show typical concreting arrangements and the shaft sinking stage. It should be noted that the concrete lining in normal conditions is installed 40 to 60 ft above the shaft floor. In faulted conditions, the lining is installed closer to the shaft floor as indicated in broken lines on the figure. A rotating pattern of probe holes kept at least 20 ft in advance of the shaft floor is recommended.

   Figure 6-2 illustrates how the vertical persistence of a fault within the shaft area varies dependent on the angle of inclination of the fault from the vertical and the thickness of the fault. It is significant that a near-vertical fault (which would not be easy to detect by a vertical borehole, but which could easily be avoided by relocating the shaft a short distance from its original planned position) at 2 1/2 degrees from vertical could persist throughout 50% of the total shaft depth.

Table 6-1. Construction Methods and Recommended Temporary Ground Support
Sheet 5 (continued)
Supplementary Data

3. Sinking rates of progress and worker job environment conditions will be adversely affected by the presence of water. The tables show a progression of gradually worsening conditions in which ground classifications ranging from very good to exceptionally poor are combined with increasing water problems and more severe and complex degrees of faulting. In practice, any combination, in any order of severity or lack of severity, may be possible. It should be noted, however, that the conditions described in Sheet 3 are not representative of conditions at Yucca Mountain. Sheet 3 has been added for the sole purpose of showing that a correctly selected shaft-sinking method and the right equipment will usually cope with the most adverse conditions, no matter how extreme.

4. Ground conditions should be known reliably before sinking commences, and it is recommended that a borehole be drilled from the surface, maintained by directional drilling, if needed to keep it within the excavation perimeter of the proposed shaft. If site characterization testing requirements preclude a shaft center borehole, then the planned MPBH (if drilled close enough) will be an acceptable alternative source of information. The information derived from this borehole may affect the sinking contractor's selection of method and equipment, and will provide valuable information for planning concreting lengths and in designing the temporary support system. It will also provide precise data for setting the station elevation and the type of station lining. If faults or ground water are proven by the shaft center borehole or MPBH, remedial or preventive measures may be implemented before the shaft penetrates the problem area. In addition to the center hole or MPBH, a pattern of advance probe holes should be kept at least 20 ft below the shaft floor to warn of any anomalous situation.

5. A study should be made to consider the site characterization implications of drilling a shaft center hole and maintaining it within the excavation perimeter. The alternative of using the MPBH to obtain the information requirements described in (4) above, and how close it can be drilled to the shaft, avoiding the shaft collar and related surface structures, should be addressed by the study.

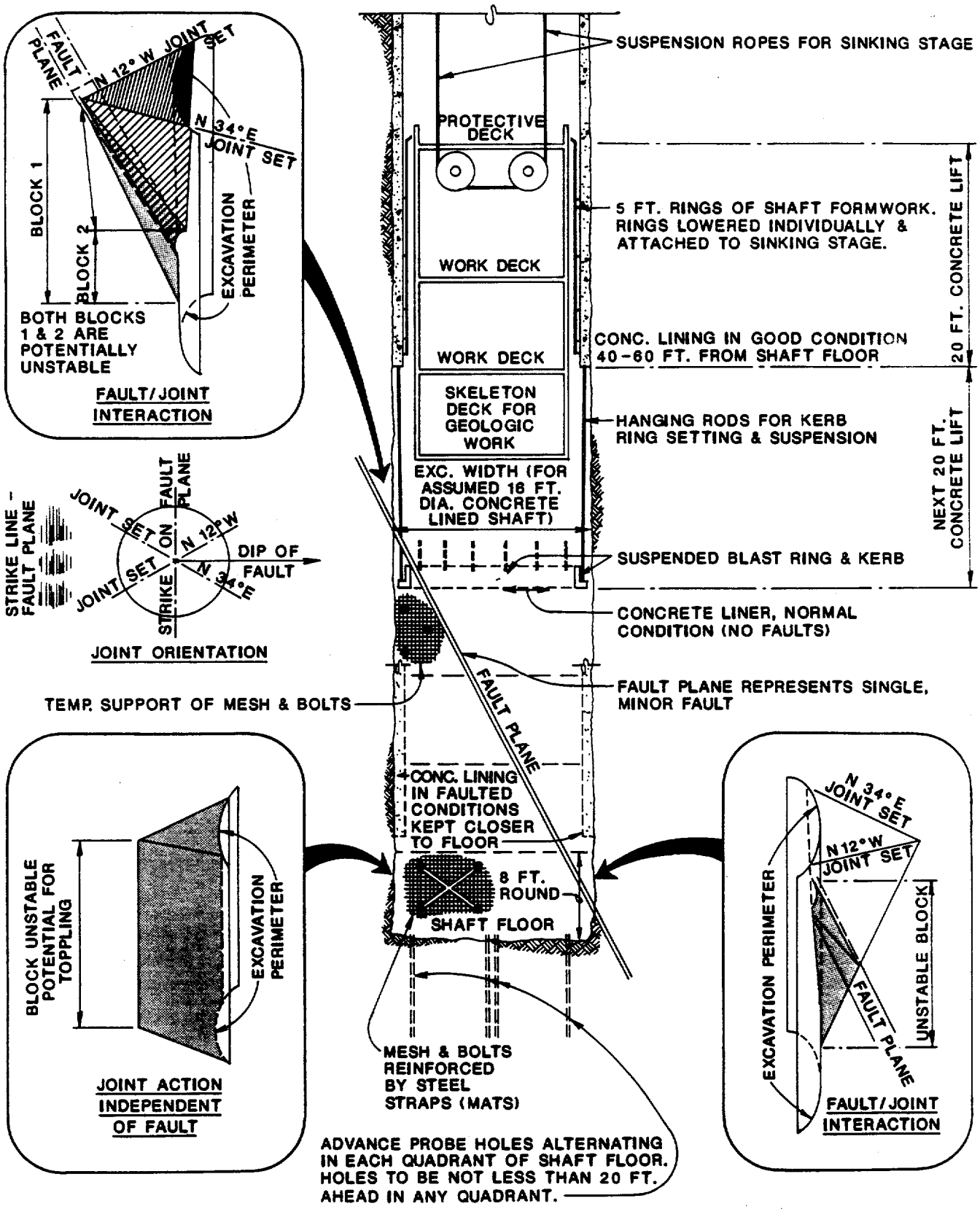


Figure 6-1. Faults/joint interaction.

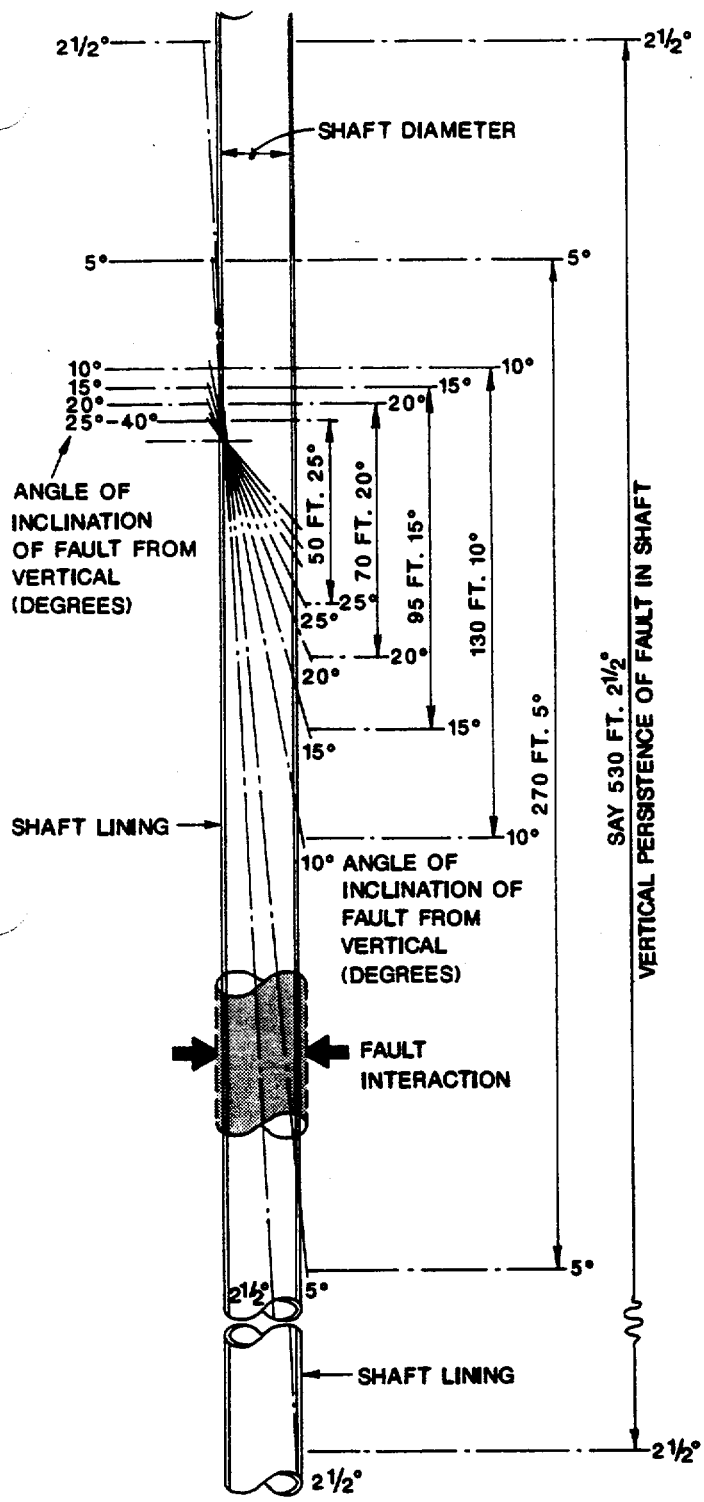
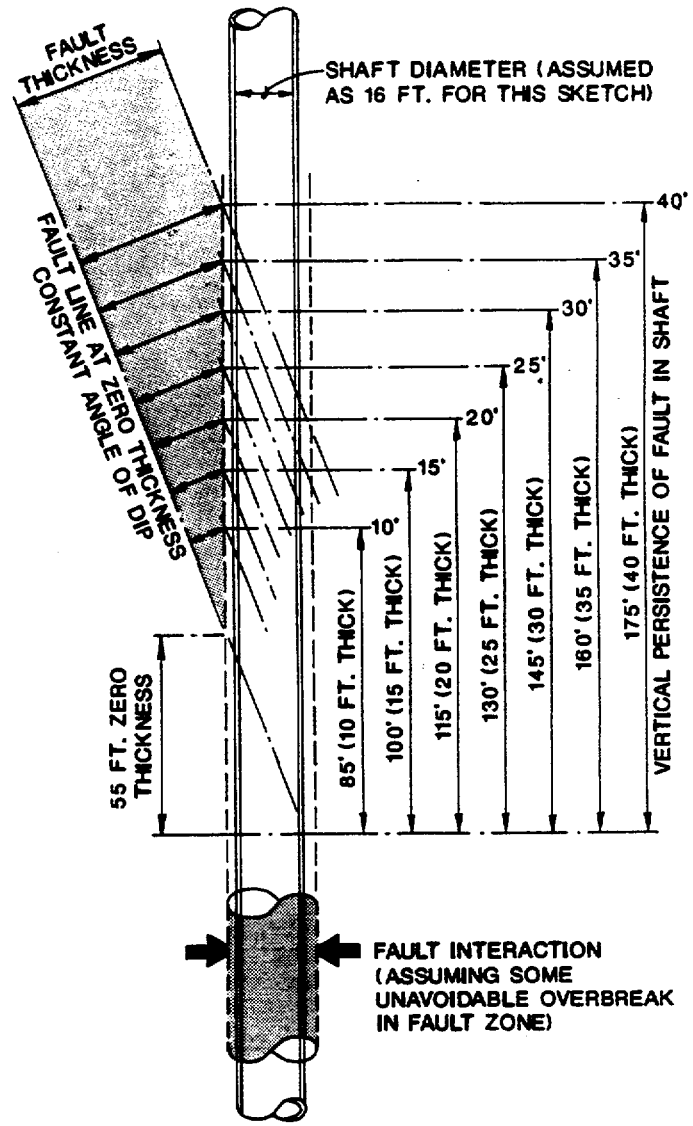


Figure A

Angle of Inclination of Fault Varies



NOTE: ALL DIMENSIONS ARE INDICATIVE ONLY, HAVING BEEN ROUNDED TO PROVIDE SYMMETRY OF PRESENTATION (NO SCALE).
MG 7/7/89

Figure B

Fault Thickness Varies

Figure 6-2. Vertical persistence of fault in shaft.

6.1.2 WORKER SAFETY

Worker safety is addressed in Table 6-1, which shows how temporary ground support is applied in incremental stages to prevent deterioration of the shaft wall and to ensure that broken ground is caught and does not fall to the shaft bottom. As ground conditions grow worse, the amount of shaft wall exposed at any time is reduced by bringing the bottom of the permanent lining closer to the shaft floor, and by shortening the concreting lifts. Worker safety is of paramount importance, and the measures described reduce exposure to potentially hazardous and uncontrolled incidents to a minimum.

6.1.3 FAULT MOVEMENT

If a fault is encountered that shows evidence of a potential for further movement during the operating life of the shaft, certain preventive actions may be applied.

Such measures could take the following forms:

- Increased width of excavation, to give additional lining thickness.
- Addition of reinforcement to the lining.
- Over-excavation of the suspect area, and (after temporary support installation) spraying it with several inches of polyurethane foam, or other compressive material before placing the concrete lining.

In the unlikely event that a slip occurs, there is no guarantee that the shaft will not require repair. There is no reason, however, why this could not be done, provided the necessary hoisting equipment is planned into the permanent shaft arrangements.

It is difficult to envision the type of evidence that could be revealed in the short time a shaft wall is exposed before concreting that would lead an observer to believe a fault is prone to current or future movement. Such evidence would typically be manifested through surface evidence of fault movements. Caution must be exercised to ensure that removal of additional ground does not become routine, rather than exceptional, whenever a fault is intersected.

6.1.4 SPECIFIC SHAFT LOCATIONS

The effect of faults on specific shaft locations (e.g., brow/station breakout construction, and loading pocket excavation) will cause more interference to construction than it does during the normal sinking cycle. Generally, the greater the height of the opening, the more the impact and interference. Where ground conditions only permit excavation of the upper part of the station, temporary support using steel rings may be required, and it may be necessary to concrete the crown of the station first to provide a protective canopy above the workers, before the lower levels of the station

and/or loading pockets are excavated. Differing degrees of interference are addressed in Table 6-1.

In the extreme case, shaft stations would not be constructed in severely faulted ground.

6.1.5 SHAFT PILLAR

It is standard mining practice to leave a pillar around a mine shaft to protect the shaft surface facilities, shaft, and stations from the effects of differential subsidence induced by mining. Generally, shafts are located outside of ore bodies, and the size of the protective pillar is reduced accordingly. In other cases, such as in coal mining, where the shafts are located in the mined commodity, the pillar is larger, its size being dictated by the depth below surface and the planned percentage of coal to be extracted. It should be noted that the extraction ratio in the ESF and that planned for the repository are much lower than in active mines. The primary purpose of the ESF shaft pillar is to provide enough standoff from the waste emplacement areas to protect the shaft from temperatures and induced thermal stresses caused by the waste. For this purpose, a fault would have no influence on the shaft pillar size.

6.1.6 SEALS

It is planned to construct an anchor to bedrock plug, and to place seals in the upper part of the exploratory shafts near the PTn/TSwl boundary. Shaft settlement plugs and shaft station plugs will be installed at the main test level. (See SNL, 1989: ESF - Repository Interface Details.)

If a fault were encountered in the shaft at locations planned for seal installation, the first step would be to inspect the exposed fault plane to determine whether the seal location should be moved to avoid the fault. If it were decided to leave the seal at the fault location, then the shaft lining at that location, and whatever temporary support was needed, would be installed in a way that would not inhibit seal installation at a later date. The location of the fault intercept would be recorded and marked on the lining as an aid to re-entry.

At that later date, the lining would be removed, and the normal excavation for the seal would be extended vertically and horizontally into the fault plane to allow as much of the fault infilling material to be removed as would be needed to ensure that adequate sealing could be achieved.

6.1.7 SHAFT SINKING THROUGH AN ANOMALOUS ZONE

The information from USW G-4 has been reported on by Spengler and Chornack (1984), physical and mechanical properties of the rock are recorded in the Reference Information Base (Yucca Mountain Project, 1989), and these

and other sources have been used in the design of the shaft lining and in developing construction methods for the exploratory shafts.

USW G-4 logging indicated there is 42% porosity in the PTn member and photographs of the core indicated that there are many joints throughout the full shaft depth. Nevertheless, calculations demonstrate that a 12-in. concrete lining is more than adequate to provide structural support, and on the basis of evidence previously examined, there is no reason to suppose that there will be abnormal problems during sinking.

Current modeling, in the form of sensitivity studies undertaken as part of this TAR, interpreting the Smith and Ross (1982) information, may indicate the presence of a conducting layer with upper surface at a depth of about 130 ft. The layer appears to coincide with the PTn stratigraphic unit. Possibilities suggested to explain this feature include perched water, percolation of runoff from Coyote Wash, the presence of products of alteration, porosity variation, changes in fracture density, or from a fracture zone or fault.

If the products of alteration consist of a high percentage of clay (say 40%), its presence could certainly cause problems during drilling, and will probably interfere with the loading and muck-dumping process if the clay is sticky. If the clay is partially free, i.e., in joints and larger cavities, then the degree of interference will be that much greater, and modifications may have to be made to the sinking equipment, e.g., self-cleaning mucking machines and muck chutes. In either case, schedule delays and additional costs may be anticipated.

Other postulated reasons for the feature (i.e., perched water, percolation, porosity variations, fracture density changes, fracture zone, or a minor fault) would have a nuisance effect on shaft sinking which could be controlled by the measures outlined in Table 6-1.

6.2 CONCLUSIONS AND RECOMMENDATIONS

The effect of a fault, or series of faults, encountered in a shaft as it is being sunk, will be influenced by the direction and frequency of the principal joint sets and by ground water.

Minor faults as defined will cause little or no appreciable disruption to sinking activities. Moderate faults as described require additional temporary support measures, will increase cost and cause some schedule delay. Major faults of the type described in Sheet 3 of Table 6-1 are not expected during shaft construction and are not representative of conditions at Yucca Mountain.

"A potentially adverse structure" (Bertram, 1984) as it applies to shaft sinking is defined in Sheet 2 of Table 6-1 as a single, steep, moderate fault. If such a fault were revealed before shaft sinking, it would be reason to choose a new site for the exploratory shafts. However, if such a fault were to remain undetected, only discovered during sinking, then the difficult conditions encountered would need to be weighed against the

additional man-hours of exposure, and the delays in siting the shafts in a new location and starting sinking all over again.

Ground conditions and water (if present) should be known reliably before sinking commences. It is recommended that a borehole be drilled from the surface at each shaft location to provide confirmation on the sinking method to be adopted, the equipment to be used, concreting lengths, temporary ground support system, and station elevation. A shaft center hole is preferred, but the MPBH (if close enough) will serve this purpose. A separate study should address the alternatives of a shaft center hole or an MPBH.

In addition to the shaft center hole or MPBH, a pattern of probe holes should be kept at least 20 ft below the shaft floor to warn of any unexpected anomalous conditions to allow remedial measures to be taken, as described in Section 6.1.7.

If faults are encountered at locations where seals or stations are to be installed, then, depending on the degree of severity of conditions met with at that time, each situation should be examined and dealt with by changes to the method or sequence of work, or by altering the system of temporary support as discussed in Section 6.1 and as set out in more detail in Table 6-1.

Chapter 7

GENERAL SUMMARY AND RECOMMENDATIONS

The purpose of this chapter is to provide a perspective on the conclusions made by the TAR team subcommittees and, in addition, provide a narrative platform for more general comments produced by the team.

7.1 GENERAL CONCLUSIONS ON THE POSSIBILITY OF A FAULT IN THE VICINITY OF THE EXPLORATORY SHAFT

The combined geophysical, geological and engineering considerations analyzed for this review do not support a finding for the presence of a fault that would affect the proposed ES constructability. This assessment is necessarily qualified because of the inherent limitations on uniqueness and resolution that electrical geophysical methods are subject to, the limitations of extrapolating geologic data to the subsurface, and the uncertainty in assumptions of engineering analyses.

Based on the analyses of three independent mapping exercises, there is no evidence of significant faulting in the Tiva Canyon Member of the Paintbrush Tuff in the vicinity of the proposed ESF locations. Two of these mapping efforts were specifically directed toward site evidence for faulting and fracturing along the south slope of Dead Yucca Ridge. Because mapping resolution was limited by degree of exposure and the gradational nature of contacts between units of the Tiva Canyon Member, there remains the possibility that relatively small faults (up to about 3 m of vertical offset) could remain undetected.

Analysis of geologic cross sections and projections of the upper contact of the Topopah Spring Member compiled from available borehole geologic logs and surface geologic data also do not show evidence of vertical offsets of the Tiva Canyon or underlying units in the Coyote Wash area. Again, however, there is a possibility that small vertical offsets (less than about 4 meters (Spengler and Rosenbaum, 1980)) or lateral offsets might not be apparent from the existing data.

The geophysical assessments of the Coyote Wash and Drill Hole Wash region are based solely on geoelectric data, as other types of corroborating geophysical data are not presently available. Our analysis (see Chapter 4) of the data collection, modeling and interpretation reported by Smith and Ross (1982) leads to the conclusion that the interpretation, based on the dipole-dipole data, of a buried zone of low resistivity in the bedrock below Coyote Wash cannot be rejected. However, our modeling shows that the available data are insufficient to determine the existence of a lateral contrast in the conductive layer because of uncertainty related to near-surface geoelectric structure and topography.

The inferred buried conductor discussed in Chapter 4 is generally consistent with the Smith and Ross model, and approximately coincides with the stratigraphic position of the Paintbrush Tuff nonwelded unit, the top of which is at a depth of approximately 50 meters in Coyote Wash. However, the

Slingram EM survey conducted by Flanigan, in Coyote Wash along lines that were approximately coincident with the dipole-dipole surveys, shows no characteristic "signature" that would indicate a significant lateral resistivity contrast, as modeled by Smith and Ross.

In summary, our analysis of the geophysical data cannot preclude the existence of a lateral contrast in the resistivity of the Paintbrush Tuff nonwelded unit, or the Topopah Springs Member, beneath Coyote Wash. If such a contrast exists, the geologic interpretation would be ambiguous based on available information. Many of the interpretations considered in this review suggest the presence of mineralogic or lithologic alteration, which is a likely explanation for low apparent resistivity observed. Thus although the interpretation of a fault from geoelectric data cannot be precluded, the data can also be explained by the presence of a fracture zone without offset, or by lithologic variation. Either of these interpretations could involve the occurrence of enhanced clay content that might affect geomechanical properties, but geoelectric surveys cannot quantify the magnitude or importance for engineering considerations.

The probability for existence of geologic features involving lateral contrast in electrical resistivity, such as those discussed above, is diminished by the observation that the nearly coincident Slingram data are not consistent with the presence of a lateral contrast. However, based solely on the available geophysical data, the committee cannot confidently discriminate among the various geologic interpretations, nor can the committee preclude the possibility of a fault structure (described by up to several meters of offset in the pre-Tiva Canyon rock or 3 ft. or more thickness of highly fractured, brecciated, or gouge filled material) at depth. Because of the geologic data, the committee believes the presence of such a fault is very unlikely, but it is not feasible to quantitatively estimate the probability that a fault is present.

Based on the analyses presented in Chapters 5 and 6 of this report, the committee believes that the existence of any small to moderate size faults permitted by the uncertainty in interpretation of the combined geologic and geophysical data would be unlikely to affect the constructability or performance of the proposed shafts. Faults of sufficient magnitude to have a significant effect on constructability or performance can be confidently excluded on the basis of the geologic data.

The team considers it possible that the exploratory shafts will encounter minor faults, fractures, and breccia zones during excavation. The occurrence of these conditions should be anticipated in shaft design. Such conditions are considered to be common throughout the Yucca Mountain area and should not adversely affect shaft construction, nor should they be a factor in the selection of shaft location, because they are equally probable throughout the site.

Nevertheless, a significant fault encountered in the course of constructing the ES could result in additional costs and programmatic delays. Therefore, in order to ensure conservatism with respect to shaft siting, the TAR team has provided several recommendations for additional geotechnical work to address remaining uncertainties, including the possibility of a buried, pre-Tiva Canyon fault, that could be completed without affecting the

schedule for shaft construction. This additional work is described below, and would be completed prior to and during ES construction, to specifically address the very unlikely possibility that a significant buried fault exists at depth near the shaft site. The work recommended consists of standard geologic and geophysical techniques.

7.2 RECOMMENDATIONS ON ADDITIONAL MEASURES TO INCREASE PROJECT CONFIDENCE ON ANTICIPATED ROCK PROPERTIES PRIOR TO EXPLORATORY SHAFT CONSTRUCTION

Currently planned Project activities will provide significant additional information on the possibility of faulting near the shafts. First, the drilling of two multipurpose boreholes (MPBHs) 50-60 ft. southeast of each shaft will provide stratigraphic control that will further resolve the question of whether significant normal offsets are present between the shaft locations. These holes, when combined with USW G-4, UE25a-6, and UE25a-7, and surface geology, will permit the construction of cross-sections (and 3-point solutions) that resolve contact geometries within a few meters. Again, however, the possibility of a buried steep fault, potentially with strike-slip offset, may remain. The core from the MPBHs will also provide important geomechanical information from the shaft area. Secondly, the currently planned mapping of excavations created for the surface facilities at the ESF, which will be completed as part of the work described in SCP Study 8.3.1.4.2.2, should completely resolve (with virtually no uncertainty) whether faults exist at the surface. Finally, the current shaft construction plans allow for the drilling of pilot holes from the bottom of the shaft in advance of shaft sinking that could provide information on rock mechanical properties as shaft construction proceeds.

In addition to these plans, the team recommends that several other measures could be taken prior to and during ES pad construction to increase confidence that rock properties are reliably known and that unexpected faulting or hydrologic conditions will not be encountered in the course of ES construction. These measures include (1) the conduct and interpretation of new shallow seismic refraction and shallow geoelectrical soundings to better define the geometry and electrical properties of the Coyote Wash alluvium (supporting more detailed geoelectric modeling), (2) the conduct and interpretation of new dipole-dipole and Slingram electrical surveys in Coyote Wash to better define the extent and contrast of the possible anomalous electrical feature located near the proposed ESF, (3) the clearing of talus along the contact between the lower lithophysal and rounded step zones of the exposed Tiva Canyon along Dead Yucca Ridge for detailed mapping, and (4) the drilling and logging to ES depth of two centerline boreholes at the locations of ES-1 and -2. None of the recommended activities are intended to be on the critical path for shaft construction. If circumstances indicated that any of the activities had become critical path, the team would recommend that the need for the activity should be re-evaluated.

The additional geophysical surveys would provide only indirect evidence pertaining to faulting in the pre-Tiva Canyon (e.g., a buried fault), but the team believes that because of the economy and timeliness of these surveys, they represent a cost-effective supplement to the planned geological and

drilling investigations. The team envisions three phases to the recommended additional investigations:

1. The conduct and interpretation of the proposed geophysical surveys. These surveys could confirm or refute the Smith and Ross (1982) apparent resistivity data, and possibly delineate the extent of any resistivity contrast that may be present. If a contrast is present, the combination of geoelectric soundings and shallow seismic data will substantially increase confidence in the interpretation of conditions at depth.

2. Clearing and mapping of the Tiva Canyon units exposed along the south slope of Dead Yucca Ridge would be conducted following the geophysics program, and should conclusively demonstrate the presence or absence of a significant fracture zone (greater than several feet in width) at the surface. This phase would be conducted prior to the start of the ESF pad construction, but could occur prior to or during the exploratory drilling program.

3. Drilling and logging of the center-line ES boreholes. These data would provide direct evidence of the material properties for mining purposes, and provide additional stratigraphic control prior to ES pad construction. If the centerline boreholes are drilled, they would probably obviate the need for the currently planned pilot holes. In addition, the existence of these boreholes could necessitate a revisitation of the scientific testing currently planned for the MPBHs. Although centerline holes would clearly provide better information (for ESF construction) on geomechanical properties than the MPBH holes, without proper sealing their existence could compromise the quality of the hydrologic information designed to be obtained from the MPBH. Therefore, an evaluation would be required to develop an optimum test strategy for the revised drilling sequence and configuration.

7.3 RECOMMENDATIONS ON MITIGATING ACTIONS FOR UNCERTAIN OR POOR ROCK PROPERTIES DISCOVERED IN THE COURSE OF EXPLORATORY SHAFT EXCAVATION

Ground conditions should be known reliably before shaft sinking commences, and the shaft center boreholes recommended in Section 7.2 and described in Table 6-1, Sheet 5 (item #4), should eliminate uncertainty in this respect. However, a near vertical minor or even moderate fault could conceivably remain undetected until encountered during sinking. Such a fault could result in schedule delays resulting from changes to the excavation method, or could increase the amount of temporary support and the need to keep the concrete lining closer to the shaft floor, as described in Table 6-1 (or Section 6.1.7). Worker safety is of paramount importance, and the measures described in Table 6-1 reduce to a minimum worker exposure to potentially hazardous situations and protect against the consequences of uncontrolled incidents.

7.4 ADEQUACY OF THE IMPLEMENTATION OF THE BERTRAM (1984) RECOMMENDATIONS ON THE ORIGINAL EXPLORATORY SHAFT LOCATION

The Bertram (1984) criteria for preferred ES areas included set-back distances from potentially adverse structures. The TAR committee has found that the Bertram report did not include a clear definition of "potentially adverse geologic structure." The inferred resistivity fault of Smith and Ross (1982) was not documented in the Bertram report. However, the team found that the Ad Hoc TOC Committee, which performed the ES site selection work, was aware of the Smith and Ross interpreted fault and dismissed the fault because (1) the fault had no mapped extent at the surface, (2) there was concern that topographic effects may not have been properly accounted for by Smith and Ross, and (3) the drilling program in Drill Hole Wash had not substantiated the Smith and Ross interpretation. Thus, the TOC Committee did not consider the fault interpreted by Smith and Ross on the basis of a resistivity contrast as a potentially adverse structure.

The Bertram (1984) site selection recommendations on the preferred area in Coyote Wash included recommendations for additional geological and geophysical studies to be performed for the purposes of delineating any subsurface structure that could compromise ES constructability, performance, or safety. The team found that the geologic component of this task was satisfied by the additional maps provided in Dixon (1982). However, there were no additional geophysical reviews or surveys conducted. Nevertheless, because USW G-4 was drilled in the presumed ESF location, prior to the conduct of any geophysical surveys, the Bertram recommendations were satisfied by treating the G-4 objectives as exploratory rather than confirmatory. The geophysics evaluation performed by this TAR committee (including recommendations) satisfies the Bertram (1984) site selection evaluation recommendations.

The basis of the "electrical fault" in the vicinity of the ES, reported in Figure 32 of USGS-OFR-84-792, and reproduced in Figure 1-40 of the SCP, was not fully documented. The origin of the fault was apparently a dashed interpolation (by D. B. Hoover) of two inferred and widely spaced fault segments: the Smith and Ross inferred fault in Coyote Wash to the north and a fault inferred from an unpublished electrical survey located approximately 7,500 ft. to the south of Coyote Wash. While other "dashed" faults from this map were omitted in USGS-OFR-84-792, this line was included and drafted as a solid line. The committee has found no compelling geological or geophysical basis for including this inferred fault on the maps described.

Although the performance implications of a fault zone or zone of increased saturation located near the exploratory shafts are not explicitly considered by Bertram (1984), these effects have been reviewed in Chapter 5 of this report. Based upon studies performed subsequent to the Bertram analysis, our current understanding of the hydrology of Yucca Mountain indicates that only minor quantities of water would migrate through a hypothetical fault and into the shaft. These quantities of water are projected to be significantly less than the drainage and storage capacity of the ESF, so that no significant repository performance impacts would be expected. For the unsaturated conditions expected for normal conditions at Yucca Mountain, faults and fractures are expected to be barriers to fluid flow and not conduits. Two general conditions were considered for this

review, by which local saturation might allow flow into the shafts: (1) water concentration by infiltration pulses and (2) water concentration by lateral diversion. Significant water inflow into the exploratory shafts would not be expected from either of these local saturation mechanisms as judged from performance calculations done by several authors. Further, enhanced gaseous movement caused by a hypothetical fault intersecting the shaft is not considered to be a concern because the shaft backfill air conductivity is primarily responsible for retarding migration of gases. In order to reduce performance of the repository, this conductivity would have to be increased over a significant portion of the shaft length to increase gaseous releases. This increase would not be expected to occur as a result of possible faulting through the ES.

7.5 PROCEDURES FOR GEOLOGICAL AND GEOPHYSICAL INVESTIGATIONS AS A RESULT OF THE 1987 EXPLORATORY SHAFT RELOCATION

The geological and geophysical investigations supporting the 1987 relocation of the ES by the Project Office are not well documented, although the record of communication and concurrence with the NRC regarding the move is well documented. Because the relocation was in the same general area evaluated in the Bertram (1984) report, the team believes that a systematic re-evaluation of the geological data was not required. However, the committee also notes that it would have been appropriate for the Project to document its review of the initial Bertram recommendations and the follow-on studies to judge their applicability to the new location. There is no evidence that a separate review for potentially adverse geologic conditions in the vicinity of revised shaft locations was conducted. A review and compilation of the available geology and geophysics at that time might have indicated a need for additional mapping beyond the area reported in Dixon (1982).

7.6 PROJECT INTEGRATION OF TECHNICAL DATA AND INTERPRETATIONS

Improvements in the management of Project technical data appear to be in order at both the Project participant and at the Project Office level. It was evident that managers and staff outside of the USGS did not have ready access to compilations of all relevant technical data and interpretations for the ES area (e.g., mapped and interpreted faults and fault segments, mapped fractures and breccia zones, geophysical survey locations, stratigraphic fence diagrams). Although there are a variety of useful technical data bases available to the Project, the extent of existing and anticipated geotechnical data indicates that the Project should continue efforts to develop a data base that is compatible with a Geographic Information System. A system capable of interactive viewing of arbitrary data "layers" at desired scales and projections, would improve program management and technical data integration.

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CODE OF FEDERAL REGULATIONS

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Appendix A

QMP-02-08 with ICN Number 1

CONTROLLED COPY 209

INTERIM CHANGE NOTICE

N-QA-023
10/88

ICN Number:	Effective Date:	Page 1 of 5
1	February 7, 1989	

Applies to QMP:

Number 02-08 Rev. 0 Title Technical Assessment Review

REQUIRED CHANGES:

QMP SECTION	CHANGE TO

1. Change "Nevada Nuclear Waste Storage Investigations (NNWSI)" to "Yucca Mountain Project (YMP)" and "Waste Management Project Office (WMPO)" to "Yucca Mountain Project Office (Project Office)" throughout the QMP.

2. Change last sentence of Section 2.0 to read: "This procedure can be used in meeting the requirements for technical assessment reviews as defined in Section 4.2.5.2 of the Systems Engineering Management Plan (SEMP), and for those specific technical reviews described in U.S. Department of Energy (DOE) Order 4700.1, Project Management System, Chapter III, Part G, Attachment III-1, 2.a., Technical Reviews, which fall within the scope of a Project Office Technical Assessment Review (see Section 3.1)."

3. Change Section 3.2, second sentence to: "The Technical Assessment Review Notice or attachments thereto (e.g., a plan) shall provide the following:

   1. ...,
   2. ...,
   3. ...."

4. Add: "4.1.3 Based upon the scope, complexity, or special nature of the planned Technical Assessment Review, the responsible Branch Chief or designee shall determine if the Technical Assessment Review Notice with attachments, including changes, is to be reviewed by a qualified individual for technical adequacy prior to issuance and, as appropriate, designate an individual as the reviewer for technical adequacy."

5. Add: "4.5 PROJECT QUALITY MANAGER (PQM)

   The PQM is responsible for the review and approval of the quality related aspects of the information required in Section 3.2, Item 1, as delineated in the Technical Assessment Review Notice or attachments, and changes thereto."

APPROVALS

Project Manager, T&MSS	Project Quality Manager	Project Manager for CARL GERTZ
Carl Gertz	James Blaylock	
Date	Date	

REQUIRED CHANGES:

QMP SECTION	CHANGE TO

6. Add: "4.6 REVIEWER (TECHNICAL ADEQUACY)

   The reviewer (technical adequacy) is the individual designated by the responsible Branch Chief or designee to perform the review of the Technical Assessment Review Notice and attachments, including changes, in order to verify that the areas and items identified to be assessed and the planned depth of the assessment are correct, adequate, applicable, and complete vis-a-vis the technical requirements imposed on the specific Technical Assessment Review."

7. Identify the paragraph under 5.1 as "5.1.1." Delete the second sentence.

8. Add:

   "5.1.2 Prior to issuance, the Technical Assessment Review Notice with attachments shall be provided to the PQM by the responsible Branch Chief or designee for review and approval in accordance with QMP-06-03, Document Review/Acceptance/Approval. The PQM shall review the quality related aspects of the Technical Assessment Review Notice and attachments to ensure the requirements of Section 3.2, Item 1, have been addressed, i.e., the purpose and scope of the planned review are within the definition of a Technical Assessment Review (see Section 3.1); the items and areas identified to be assessed and the planned depth of the assessment satisfy the requirement or request, as appropriate, for conducting the Technical Assessment Review; and the Technical Assessment Review Notice with attachments, as appropriate, includes the correct, adequate, complete, and applicable quality assurance requirements delineated in the Project Office QA Program Plan (WMPO/88-1) and this procedure.

   5.1.3 As determined appropriate by the responsible Branch Chief or designee based upon the scope, complexity, or special nature of the planned Technical Assessment Review, a review of the technical adequacy of the Technical Assessment Review Notice may be warranted. In such cases the Technical Assessment Review Notice with attachments shall be provided by the responsible Branch Chief or designee in accordance with QMP-06-03 to a qualified individual who shall review these documents to verify that the areas and items to be assessed and the planned depth of the assessment are correct, adequate, applicable, and complete vis-a-vis the technical requirements imposed on the specific Technical Assessment Review.

REQUIRED CHANGES:

QMP SECTION	CHANGE TO

5.1.4 The PQM and other reviewers, as appropriate, shall document the results of their reviews on Document Review Sheets (DRSs) and, if needed, DRS Continuation Sheet(s) (see QMP-06-03), Document Review/Acceptance/Approval). Reviewers shall provide their DRSs to the responsible Branch Chief or designee for resolution of comments, if applicable, and for inclusion in the Review Record Memorandum. Upon the documented resolution of comments regarding the technical adequacy, as appropriate, and when satisfied with the quality related aspects of the Technical Assessment Review Notice and attachments, the PQM shall indicate approval by signing/dating page 1 of the Technical Assessment Review Notice.

5.1.5 Following approval of the Technical Assessment Review Notice and attachments by the PQM, the responsible Branch Chief or designee shall transmit a copy of the original issue of the Technical Assessment Review Notice (identified as Revision 0) with attachments to the PQM; Manager, Compliance Department; designated reviewers; and other appropriate personnel in accordance with QMP-06-02, Document Control. Revisions to the Technical Assessment Review Notice or attachments (see Section 5.1.6) shall be distributed to the same individuals and organizations as the original in accordance with QMP-06-02."

5.1.6 Changes to the Technical Assessment Review Notice and/or attachments that revise the information required in Section 3.2, Item 1 shall be subject to the same review and approval controls as the original documents. Minor changes to the Technical Assessment Review Notice or attachments that do not revise the information required in Section 3.2, Item 1 shall be issued directly by the Branch Chief or designee without subjecting the revised Technical Assessment Review Notice to the reviews required in Sections 5.1.2 and 5.1.3. The responsible Branch Chief, or designee, shall indicate "Not Applicable" in the space provided in Figure 1 for the PQM's approval. Page 1 of the Technical Assessment Review Notice shall reflect its current revision indicator, beginning with Revision 0 for the original version issued and 1, 2, etc., for subsequent revisions. A change to a Technical Assessment Review Notice attachment only shall be considered a change to the Technical Assessment Review Notice, and the revision indicator of the Technical Assessment Review Notice shall be revised accordingly and distributed with the revised attachment. All revisions to a Technical Assessment Review Notice shall be distributed to the same individuals and organizations as the original."

9. Change 3.5, No. 2 to "Technical Assessment Review Notice with attachments and associated DRSs (PQM's as a minimum)."

ICN Number:	Applies to QMP:	Effective Date:	Page 4 of 5
1	02-08	February 7, 1989	

REQUIRED CHANGES:

QMP SECTION	CHANGE TO

10. Add: "WMPO/88-1, Project Office QA Program Plan," "QMP-06-02, Document Control," and "QMP-06-03, Document Review/Acceptance/Approval" to Section 6.0. Change title of QMP-17-01 to "Record Source and Record User Responsibilities" in Sections 6.0 and 8.0. Identify all references as "latest revision."

11. Change Figure 1, "Technical Assessment Review Notice," to provide designated spaces for the recording of the Technical Assessment Review Notice revision indicator and PQM's approval.

ICN Number:	Applies to QMP:	Effective Date:	Page 5 of 5
1	02-08	February 7, 1989	

REQUIRED CHANGES:

QMP SECTION | CHANGE TO

TECHNICAL ASSESSMENT REVIEW NOTICE N-QA-010 1/89

Revision _____

To _____ Date _____

Technical Area to be Reviewed _____

WBS No.: _____

Review Date _____ Location _____ Time _____

Technical Assessment Review Chairperson _____

Based on a review of the qualification documentation, this Technical Assessment Review Chairperson is qualified to execute the responsibilities of QMP-02-08 with respect to the scope and purpose of this Technical Assessment Review.

Scope of Technical Assessment Review:

Purpose of Technical Assessment Review:

Signed _____

Reviewed and Approved:

_____ Project Quality Manager _____ Date

Attachments:

Figure 1. Technical Assessment Review Notice

CONTROLLED COPY

Title	No. QMP-02-08 Rev. 0
TECHNICAL ASSESSMENT REVIEW	Effective Date 08-Aug-1988
	Page 1 of 12

1.0 PURPOSE AND SCOPE

This procedure defines the method to be used and responsibilities for performing Technical Assessment Reviews for the Nevada Nuclear Waste Storage Investigations (NNWSI) Project. The requirements of this procedure may be supplemented with further documented guidance that defines the logistics and methodologies to be used in a review.

2.0 APPLICABILITY

This procedure applies to Technical Assessment Reviews conducted by the Waste Management Project Office (WMPO) for the NNWSI Project. A Technical Assessment Review is one of a set of review methods defined for the NNWSI Project in Section 4.2.5 of the Systems Engineering Management Plan (SEMP). This procedure can be used in meeting the requirements for technical reviews defined in the SEMP and in U.S. Department of Energy (DOE) Order 4700.1, Attachment III-1, Page III-47, Section 2.

3.0 DEFINITIONS

3.1 TECHNICAL ASSESSMENT REVIEW

The Technical Assessment Review is a documented evaluation of technical status, technical progress, or technical merit, in combination or separately. It is performed by qualified individuals other than those who performed the technical work being reviewed, but who may be from the same organization. Technical Assessment Review is a management method that may be used to accomplish such items as the following:

1. Assessing requirements.
2. Determining the degree to which technical work meets requirements.
3. Identifying technical issues in a timely fashion, including interfaces with site and design efforts.
4. Assessing the technical status or technical progress of activities.
5. Providing a basis to accept technical services rendered.

APPROVED BY

Project Manager, T&MSS	WMPO Project Quality Manager	WMPO Project Manager
M Laquette	Wendell B. Marvel for S. Blaylock	for
Date 3 August 1988	Date 08/03/88	Date 8/4/88

6. Defining and directing necessary changes in accordance with WMPO procedures.

3.2 TECHNICAL ASSESSMENT REVIEW NOTICE

The Technical Assessment Review Notice (Figure 1) is issued by the responsible WMPO Branch Chief, or designee, announcing the Technical Assessment Review. The notice provides the following:

1. Technical Assessment Review scope and purpose, identifying areas and items to be assessed, including an indication of the required depth. This may be accomplished in a variety of ways, including the use of questionnaires, checklists, a list of design requirements, or through other suitable means.

2. Date, time, location, and other logistical information for the Technical Assessment Review meeting.

3. Name of the Technical Assessment Review Team Chairperson.

3.3 TECHNICAL ASSESSMENT REVIEW TEAM SELECTION RECORD

3.3.1 The Technical Assessment Review Team Selection Record (Figure 2) is completed, signed, and dated by the Technical Assessment Review Team Chairperson. It identifies the functions involved in the review, and the names of qualified individuals selected to be on the Technical Assessment Review Team. The review team members are assigned the responsibility for reviewing and providing comments, as applicable, for those functions. The review team members must be other than those who performed the technical work, but they may be from the same organization.

3.3.2 The Technical Assessment Review Team Selection Record includes the documentation of the qualifications of the review team members assigned for the various review functions.

3.4 TECHNICAL ASSESSMENT REVIEW PACKAGE

The Technical Assessment Review Package is a collection of documents (e.g., reports, schedules, plans, and drawings) that provides the information to be assessed by the review team members to achieve the established scope and purpose.

3.5 REVIEW RECORD MEMORANDUM

The Review Record Memorandum is a documented summary of the Technical Assessment Review prepared by the Secretary, which includes the following:

1. Scope of the review.
2. Technical Assessment Review Notice.
3. Technical Assessment Review Meeting minutes.
4. Technical Assessment Review Team Selection Record.
5. Technical Assessment Review Comment Records identifying comments and resolutions.
6. List of meeting attendees and, when specified, their Technical Assessment Review responsibilities.
7. Correspondence relating to the Technical Assessment Review.
8. Information presented during the Technical Assessment Review meeting and other information provided to the review team members that was not contained in the original Technical Assessment Review Package or in subsequent additions or modifications to the package.
9. Conclusions and recommendations.

3.6 TECHNICAL ASSESSMENT REVIEW COMMENT RECORD

The Technical Assessment Review Comment Record is a form used to document Technical Assessment Review comments and their resolution (Figures 3 and 4).

3.7 TECHNICAL ASSESSMENT REVIEW DATA PACKAGE

The Technical Assessment Review Package is a set of Quality Assurance (QA) records consisting of the Technical Assessment Review Package and the Review Record Memorandum, including any supplements as described in Section 5.5.6.

4.0 RESPONSIBILITIES

4.1 RESPONSIBLE WMPO BRANCH CHIEF OR DESIGNEE

4.1.1 The responsible WMPO Branch Chief or designee shall plan, schedule, and announce the Technical Assessment Review, designate the Technical Assessment Review Chairperson, and distribute the Review Record Memorandum.

4.1.2 If the responsible WMPO Branch Chief determines that a Project Participant is to be the designee, the responsible WMPO Branch Chief shall document that decision and the designated organization shall prepare and issue the Technical Assessment Review Notice.

4.2 TECHNICAL ASSESSMENT REVIEW CHAIRPERSON

The Technical Assessment Review Chairperson is responsible for the following:

1. Designating the Secretary for the Technical Assessment Review.
2. Determining the technical disciplines to be used to accomplish the scope and purpose of the review.
3. Establishing minimum qualifications (e.g., education. experience, and independence) needed by review team members to fulfill technical disciplines to accomplish the scope and purpose of the review.
4. Obtaining suitable documentation of review team members' qualifications for the various technical disciplines.
5. Ensuring that the documentation of the review team members' qualifications meets the needs of the review.
6. Determining the number of reviewers for the Technical Assessment Review Team.
7. Obtaining information for the review from the appropriate Technical Project Officer (TPO) and others, as appropriate.
8. Coordinating the Technical Assessment Review Team, the meeting, and the review process.
9. Issuing the Review Record Memorandum to the responsible WMPO Branch Chief for distribution.
10. Compiling a data package of the Technical Assessment Review.

4.3 SECRETARY

The Secretary documents the Technical Assessment Review Team activities. Specifically, the Secretary records the meeting minutes, collects comments and resolutions, and prepares the Review Record Memorandum (per Section 3.5).

4.4 TECHNICAL ASSESSMENT REVIEW TEAM MEMBERS

It is the responsibility of the review team members to review and provide comments in their technical area, as designated by the Chairperson, and to participate in the evaluation of proposed resolutions.

5.0 PROCEDURE

5.1 INITIATION OF THE TECHNICAL ASSESSMENT REVIEW

The responsible WMPO Branch Chief or designee plans, scopes, and schedules the Technical Assessment Review and designates the Technical Assessment Review Chairperson. The responsible WMPO Branch Chief or designee also issues the Technical Assessment Review Notice to Quality Assurance, Regulatory Compliance, and others, as appropriate.

5.2 TEAM SELECTION

5.2.1 The Technical Assessment Review Chairperson performs the following:

1. Designating the Secretary for the Technical Assessment Review.

2. Determining the technical disciplines to be used to accomplish the scope and purpose of the review.

3. Establishing minimum qualifications (e.g., education, experience, and independence) needed by review team members to fulfill the technical disciplines to accomplish the scope and purpose of the review.

4. Obtaining suitable documentation of review team members' qualifications for the various technical disciplines, as described in Section 5.2.2

5. Ensuring that the documentation of the review team members' qualifications meets the needs of the review, and signing and dating the Technical Assessment Review Team Selection Record(s).

6. Determining the number of reviewers for the Technical Assessment Review Team.

7. Ensuring that assigned Review Team Members are trained to this procedure and other applicable documents.

5.2.2 The Technical Assessment Review Chairperson requests the following information for each of the review team members: name of the person and a statement that the review team member meets the education, experience, and independence qualifications established for the review. This information is to be provided by the employer of the review team member.

5.2.3 If a review team member's employer is an agency outside of the NNWSI Project, the chairperson is responsible for notifying the agency that the documentation verifying the education, experience, and independence of the review team member must be obtained and retained by that agency. This documentation shall be made available for surveillance and audit by the U.S. Nuclear Regulatory Commission or the DOE. In addition, the agency shall be required to notify the WMPO prior to destruction of this verification documentation.

5.3 TECHNICAL ASSESSMENT REVIEW PACKAGE

The Technical Assessment Review Chairperson obtains the information for the review from the appropriate TPO and others, as appropriate.

5.4 TECHNICAL ASSESSMENT REVIEW

5.4.1 The review team members review the material and document their comments on Technical Assessment Review Comment Records. If a review team member has no comment, this is documented on a Technical Assessment Review Comment Record.

5.4.2 The Secretary records meeting minutes, collects comments and resolutions, and prepares the Review Record Memorandum (per Section 3.5). The Technical Assessment Review Chairperson reviews, signs, and dates the Review Record Memorandum.

5.5 RESOLUTION OF TECHNICAL ASSESSMENT REVIEW COMMENTS

5.5.1 The Technical Assessment Review Chairperson obtains resolutions for the Technical Assessment Review comments from the appropriate TPO.

5.5.2 The Technical Assessment Review Chairperson coordinates the team's evaluation of the resolutions obtained in Section 5.5.1. After deciding the appropriateness of the resolutions, such acknowledgment is documented to the appropriate TPO.

5.5.3 Any unresolved comments are referred by the Chairperson to the appropriate TPO for resolution. (The appropriate TPO is the one who has responsibility for the subject of the unresolved comment.)

5.5.4 The Chairperson, upon submittal of a review comment resolution by the appropriate TPO, shall ensure that the resolution is provided to the review team member and the responsible WMPO Branch Chief.

5.5.5 The review team member who had the unresolved comment shall evaluate the provided comment resolution, and either:

1. Sign and date the review comment resolution (according to the Chairperson's instruction) to indicate agreement, and return it to the Chairperson.

2. If a disagreement exists, attempt to achieve an agreement, (via the Chairperson) with the appropriate TPO. If agreement cannot be reached, provide the documented basis for the disagreement to the Chairperson and request assistance from successively higher levels of management.

5.5.6 The Chairperson may complete the Review Record Memorandum with a documented unresolved comment; however, supplements must be provided to the memorandum as the appeals process is pursued, such that a complete record of the comment is retained as a QA record.

5.6 REVIEW RECORD MEMORANDUM

The Technical Assessment Review Chairperson issues the Review Record Memorandum to the responsible WMPO Branch Chief for distribution to the TPO(s) and others, as appropriate.

5.7 CLOSURE OF RESOLUTION

The responsible WMPO Branch Chief or designee shall ensure that the appropriate TPO satisfies and closes out the commitments made in resolutions to the Technical Assessment Review comments.

5.8 TECHNICAL ASSESSMENT REVIEW DOCUMENTATION

The Technical Assessment Review Chairperson shall (1) compile a data package relative to the Technical Assessment Review that consists of the Technical Assessment Review Package and the Review Record Memorandum (including any supplements as described in Section 5.5.6) and (2) provide for disposition of the data package in accordance with Section 8.0.

6.0 REFERENCES

The latest revisions of the following apply:

NNWSI/88-3, NNWSI Project Systems Engineering Management Plan

DOE Order 4700.1, Project Management System

QMP-17-01, QA Records

7.0 FIGURES

At a minimum, the information needs on the forms shown on the following figures shall be satisfied. This may be accomplished by the use of the form itself or a suitable alternate.

Figure 1, Technical Assessment Review Notice

Figure 2, Technical Assessment Review Team Selection Record

Figure 3, Technical Assessment Review Comment Record

Figure 4, Technical Assessment Review Comment Record Continuation Sheet

8.0 QA RECORDS

The following are QA records and are maintained in accordance with QMP-17-01, QA Records.

1. Technical Assessment Review Package.

2. Review Record Memorandum (including any supplements as described in Section 5.5.6).

TECHNICAL ASSESSMENT REVIEW NOTICE

N-QA-010
7/88

To _____ Date _____

Technical Area to be Reviewed _____

_____

WBS No.: _____

Review Date _____ Location _____ Time _____

Technical Assessment Review Chairperson _____

Based on review of the qualification documentation, this Technical Assessment Review Chairperson is qualified to execute the responsibilities of QMP-02-08 with respect to the scope and purpose of this Review.

Scope of Technical Assessment Review:

Purpose of Technical Assessment Review:

Signed _____

Attachments:

Figure 1. Technical Assessment Review Notice.

TECHNICAL ASSESSMENT REVIEW TEAM SELECTION RECORD

N-QA-008
7/88

Technical Assessment Review Subject _____

FUNCTION	REPRESENTATIVE
Secretary	

Based on review of the qualification documentation, these representatives cover the functions for this Review and are acceptable as team members to accomplish the scope and purpose of this review.

Signed _____

Attachment:

Qualification Documentation

Figure 2. Technical Assessment Review Team Selection Record.

TECHNICAL ASSESSMENT REVIEW COMMENT RECORD

N-QA-006
7/88

Sheet ____ of ____

Technical Assessment Review Subject _____

Reviewer _____ Organization _____ Date _____

Comments Resolved By _____ Organization _____ Date _____

REVIEWER'S COMMENTS			RESOLUTION		REVIEWER'S DISPOSITION	
Item Number	Reference Doml. No.	Comments	Accept	Reject	Reason	Accept	Reject

Figure 3. Technical Assessment Review Comment Record.

TECHNICAL ASSESSMENT REVIEW COMMENT RECORD
CONTINUATION SHEET

N-QA-006
7/88

Sheet _____ of _____

Technical Assessment Review Subject _____

REVIEWER'S COMMENTS			RESOLUTION			REVIEWER'S DISPOSITION	
Item Number	Reference Doml No.	Comments	Accept	Reject	Reason	Accept	Reject

Figure 4. Technical Assessment Review Comment Record Continuation Sheet.

Appendix B

TAR Notice and Plan

B.1 TAR Notice

Attachment 2

TECHNICAL ASSESSMENT REVIEW NOTICE

N-QA-010
1/89

Revision 0

To Yucca Mountain Project Manager Date May 18, 1989

Technical Area to be Reviewed Technical Assessment Review Notice: Geologic & Geophysical Evidence Pertaining to Structural Geology in the Vicinity of the Proposed Exploratory Shaft

WBS No.: 1.2.3.2.1 (see attachment 1)

Review Date June 7 1989 Location Las Vegas Time see attachment 1

Technical Assessment Review Chairperson Richard C. Lee

Based on a review of the qualification documentation, this Technical Assessment Review Chairperson is qualified to execute the responsibilities of QMP-02-08 with respect to the scope and purpose of this Technical Assessment Review.

Scope of Technical Assessment Review: See Attachment 1

Purpose of Technical Assessment Review: See Attachment 1

Signed Richard C. Lee

Reviewed and Approved:

James B. Taylor 5/18/89

Project Quality Manager Date

Attachments:

Background, Purpose and Scope of Technical Assessment Review

B.2 TAR Plan

BACKGROUND, PURPOSE AND SCOPE OF TECHNICAL ASSESSMENT REVIEW: GEOLOGIC AND GEOPHYSICAL EVIDENCE PERTAINING TO THE STRUCTURAL GEOLOGY IN THE VICINITY OF THE PROPOSED EXPLORATORY SHAFT LOCATION

Background: U. S. Geological Survey Open File Report 82-182 (OFR 82-182) shows an interpretation of geophysical resistivity data that indicates a fault may be present near the proposed exploratory shaft site. The NRC has reviewed OFR 82-182 and may request a summary of the actions DOE has taken to address the fault shown by that report. In addition, the NRC may request a summary of the DOE actions that were taken to address the recommendations in Bertram (1984) for additional detailed geological and geophysical work in the vicinity of the exploratory shaft site. The work proposed in the Bertram report was completed; there is a letter report from Dixon to Vieth (1982) on geological mapping and open file reports summarize additional drilling and geophysical work completed in response to the recommendations.

The NRC staff have also expressed interest in an inferred fault near the exploratory shafts shown on SCP Figure 1-40. This figure is based on faults interpreted from geophysical data shown on a map in U. S. Geological Survey Open File Report 84-792. The OFR report does not give any detail on the data on which the map is based, although OFR 82-182 is referenced. R. Stein (DOE/HQ) requested in March, 1989, that DOE be prepared to talk to NRC on this topic by the end of April, 1989. Although a date for discussion with the NRC has not been firmly established, it is envisioned that this TAR will serve as the basis for such an interaction.

Purpose: The purpose of the TAR is to: (1) review the data and interpretations on which OFR 82-182 is based; (2) review the results of other geologic and geophysical investigations that relate to the possibility of faulting in the vicinity of the exploratory shafts; and (3) after reviewing the data, the TAR Team will determine the interpretations allowed by the evidence on the presence or absence of faulting in the vicinity of the exploratory shafts.

The TAR team will also review the existing documentation to determine: (1) how the geologic and geophysical data were considered in making the decision on the location of exploratory shafts; and (2) whether the recommendations of the Bertram (1984) report were adequately implemented.

Scope of Technical Assessment Review: The following tasks will be accomplished by the Technical Assessment Review Team. The findings of the team will be documented in narrative form in the Review Record Memorandum.

1. Review the data collection and processing techniques, and subsequent interpretations, which form the basis for the proposed existence of the small fault shown near the location of the exploratory shafts in U. S. Geological Survey Open File Report 82-182. The TAR team will establish and document criteria for the technical reviews. They will then summarize the original objective and purpose of the work, the limitations of the data, and they will evaluate the interpretations (including alternatives) supported by the data. If appropriate, sources for review criteria will be identified.

2. The TAR Team will determine what other geologic and geophysical data are available that may bear on the presence or absence of a fault near the location of the exploratory shafts. The TAR team will review any such data discovered and determine the original purpose of the work, the implications of the data with respect to the presence or absence of faulting in the vicinity of the exploratory shafts, and the limitations of the data.

3. At the discretion of the TAR chairperson, the reviews described in 1 and 2, above, may also include a detailed field review of the geologic mapping in the vicinity of the exploratory shafts, or field reviews of the geophysical work by members of the TAR team, or qualified designees. Prior to conducting any proposed field reviews, the TAR team shall establish and document criteria for the review.

4. After completing Items 1, 2 and 3, the TAR team will determine whether the possible fault shown in U. S. Geological Survey Open File Report 82-182 was adequately considered during the selection of the exploratory shaft location. The team will develop criteria for the determination, and then evaluate the impacts on the exploratory shaft and ESF Title II design process if it was concluded that a fault did exist.

5. The TAR Team should consider, and make recommendations on, future work that should be undertaken as a result of the findings of the technical assessment.

6. Following completion of the tasks described above, the TAR Team will compile a report which summarizes the results of the assessment, and specifically addresses at least the following topics:

   A. Historical perspective: summarize the sequence of events that occurred relevant to this topic, and the documents that exist in YMP files regarding the geological and geophysical work.

   B. Geophysical perspective: summarize the past work, the rationale for conducting the studies, the interpretations (and alternatives) that are consistent with the data, and the limitations of the data.

   C. Geological perspective: summarize the rationale for, and the results of, the past studies, the interpretations (and alternatives) that are consistent with the data, and the limitations of the data.

   D. Results of field checks (optional): summarize any work accomplished, and what results are indicated.

E. Summary and recommendations, to include, at a minimum: (A) assessment of the data relevant to the possible presence of a fault near the proposed ESF, (B) evaluation of whether the available data were adequately considered during the process of selecting the proposed shaft locations; (C) perspective on the possible impact on Title II design if the presence of a fault was demonstrated; and (D) recommendations for further action.

Logistical Information for the Technical Assessment Review

The first meeting of the Technical Assessment Review Team will be convened by the Review Chairman in May, 1989, in Las Vegas. The current schedule is shown below. Members of the team will be named by the Review Chairman, who will establish and document criteria for their selection. Team members will be notified of further details as they become available.

ESF Resistivity Fault TAR Schedule

Week	Goal
May 22, 1989	TAR Chairman makes contact with each team member; Initiate TAR and distribute Plan; Define and qualify team; distribute TAR Package.
May 26	Team members have telephone conferences with team leaders; reading assignments are completed; strategies are defined.
May 30	Preparation for field trip to Coyote Wash area; continuation of work.
June 7	Field trip to Coyote Wash taking one full day in field; one to four days of additional verification work as required by Geology team leader.
June 12	Any re-interpretation of geologic data completed.
June 19	Any re-interpretation of resistivity data completed.
June 26	TAR team caucus; complete preliminary draft of RRM.
July 10	Final RRM completed.
July 17	Transmit TAR Data Package to Document Control.

REFERENCES

Bertram, S.G., 1984, NNWSI Exploratory Shaft Site and Construction Method Recommendation Report, SAND 84-1003, Sandia National Laboratories, Albuquerque, NM.

Letter from G. Dixon to D.L. Vieth, July 16, 1982, discussing detailed geologic mapping of 5 sites recommended by Ad Hoc TOC Committee.

Smith, C. and H.P. Ross, 1982, Interpretation of Resistivity and Induced Polarization Profiles with Severe Topographic Effects, Yucca Mountain Area, Nevada Test Site, Nevada, USGS OFR 82-182, Open File Report, U.S. Geological Survey.

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

B.3 Project Office QMP-06-03 Review Comments on Draft TAR Plan

DOCUMENT REVIEW SHEET

N-QA-041
12/88

Page 1 of 1

Document Originator YMP

Document No. --- Rev. No. --- Date ---

Document Title Geologic & Geophysical Evidence Pertaining to Structure Geology of ESF Loc

Name of Reviewer M. J. Mitchell

Comment Required By (Date) 5/12/89

Dispute Correspondence

Signature of Reviewer Michael J. Mitchell Date 12 May 89

TYPE OF REVIEW REQUIRED

☐ Management* ☒ Quality Assurance

☐ Technical** ☐ Regulatory*

*Regulatory & Management Reviewers Indicate Preference for a
1) Peer Review: ☐ Yes ☐ No
2) Technical Review: ☐ Yes ☐ No

**Technical Reviewers Indicate Preference for a Peer Review: ☐ Yes ☐ No

REVIEWER'S COMMENTS			RESOLUTION			REVIEWER'S DISPOSITION FOR MAJOR COMMENTS	
COMMENT NO. & TYPE	PAGE NO.	COMMENTS	ACCEPT	REJECT	REASONING	ACCEPT	REJECT
		This document has been checked against QMP 02-08 & 02-08 LCN #1 items for TAR Review Notices.					
Major	Cover & Logistic	Please correct data, time and place of meeting as needed unless meeting took place as scheduled.	MJM		accept - schedule included see revise attach 1	MJM 16 May 89	
Edit	Gen	Please paginate document and attach 1.	MJM		accept - see revised attach 1	MJM 16 May 89	
Edit	Gen	Items checked were found present. The format of attachmnt 1 does not follow the required form re-format text.		MJM	QMP 02-08 contains content requirements for TAR notice which have been met (as noted at left). However no format is prescribed by the procedure All required information is provided in an acceptable format	MJM 16 May 89 Changes shown on draft	

DOCUMENT REVIEW SHEET

N-QA-041
12/87

Document Originator David C. Dobson

Document No. _____ Rev. No. 0 Date April 19, 1989

Document Title Technical Assessment Review Notice: Geologic and Geophysical Evidence Pertaining to Structural Geology in the Vicinity of the Proposed Exploratory Shaft.

Name of Reviewer Nancy A. Voltura

Comments Required By (Date) May 1, 1989

Dispute Correspondence N/A

Signature of Reviewer Nancy Voltura Date 5/16/89

TYPE OF REVIEW REQUIRED

☐ Management* ☒ Quality Assurance

☐ Technical** ☐ Regulatory*

*Regulatory & Management Reviewers Indicate Preference for a
1) Peer Review: ☐ Yes ☐ No
2) Technical Review: ☐ Yes ☐ No

**Technical Reviewers Indicate Preference for a Peer Review: ☐ Yes ☐ No

REVIEWER'S COMMENTS			RESOLUTION			REVIEWER'S DISPOSITION FOR MAJOR COMMENTS	
COMMENT NO. & TYPE	PAGE NO.	COMMENTS	ACCEPT	REJECT	REASONING	ACCEPT	REJECT
1. major	Att.1 p.2of3	Add page number, revision number to Attachment 1	X		accept - see revised attach. 1	NV 5/17/89	
2. editorial	p.2of3 P.1	Add title of TAR to Attachment 1	X		accept - see revised attach. 1	NV 5/17/89	
3. editorial	p.2of3 P.1	Clarify meaning of sentences regarding work recommended and completed in Bertron (1984) and Dixon letter (1982). Also,	X		accept - see revised attach. 1	NV 5/17/89	
4. editorial	p.2of3 P.1	List specific references cited in Notice	X		accept - see revised attach. 1	NV 5/17/89	
5. editorial	p.2of3 P.2	Clarify last sentence of "purpose" section	X		accept - see revised attach. 1	NV 5/17/89	

DOCUMENT REVIEW CONTINUATION SHEET

N-QA-041
12/87

Document Title: Technical Assessment Review Notice: Geologic & Geophysical Evidence Pertaining to Structural Geology in the Vicinity of the Proposed Exploratory Shaft

Name of Reviewer: Nancy A. Voltura

REVIEWER'S COMMENTS			RESOLUTION			REVIEWER'S DISPOSITION FOR MAJOR COMMENTS	
COMMENT NO & TYPE	PAGE NO.	COMMENTS	ACCEPT	REJECT	REASONING	ACCEPT	REJECT
6. major	p.2of3	List criteria for TAR	X		The TARN has been modified to require the TAR team to develop criteria. It would be inappropriate for the TAR notice (written by Branch Chief) to contain them. See revised attachment 1.	NV 5/17/89	
7. major	p.2of3 Last P	It would appear that AP5.9Q (Qualification of Data) may have an important impact on this TAR		X	The purpose of the TAR is not to qualify the data, but to assess. There is presently no reason to believe that we will need the data in the license application, but, if it is needed, qualification can be undertaken at that time.	NV 5/17/89	
8. minor	p .3of3	Clarify how detailed field review would be done	X		TAR notice was expanded to clarify that TAR team will establish & document criteria for conducting field review.	NV 5/17/89	
9. major	p 3of3 #4	List criteria for evaluation of impacts on shaft and design	X		TAR notice expanded to clarify that TAR team will establish & document criteria for evaluating impact on shaft and design.	NV 5/17/89	

DOCUMENT REVIEW CONTINUATION SHEET

N-QA-041
12/87

Document Title: Technical Assessment Review Notice: Geologic & Geophysical Evidence Pertaining to Structural Geology in the Vicinity of the Proposed Exploratory Shaft

Name of Reviewer: Nancy A. Voltura

REVIEWER'S COMMENTS			RESOLUTION			REVIEWER'S DISPOSITION FOR MAJOR COMMENTS	
COMMENT NO & TYPE	PAGE NO.	COMMENTS	ACCEPT	REJECT	REASONING	ACCEPT	REJECT
10. Editorial	P.3of3 #6	Clarify how documentation will be presented	X		Section was revised to clarify organization of final report	NV 5/17/89	
11. Major	p.3of3 last P	What are criteria for qualification of TAR team member	X		TAR Notice was expanded to clarify that Review Chairman will establish and document criteria for selection of TAR team members	NV 5/17/89	