ISSUE RESOLUTION STATUS REPORT

KEY TECHNICAL ISSUE:
STRUCTURAL DEFORMATION AND SEISMICITY

Division of Waste Management
Office of Nuclear Material Safety and Safeguards
U. S. Nuclear Regulatory Commission

Revision 1

SEPTEMBER 1998

TABLE OF CONTENTS

Section

TABLE OF CONTENTS (cont'd)

Section

TABLE OF CONTENTS (cont'd)

Section

ACKNOWLEDGMENTS

This and the previous report were prepared jointly by the U.S. Nuclear Regulatory Commission and the Center for Nuclear Waste Regulatory Analyses (CNWRA) staffs. Primary authors of the reports are Philip S. Justus (NRC), John A. Stamatakos (CNWRA) [co-leads], [and in alphabetical order] Rui Chen (CNWRA), David A. Ferrill (CNWRA), Abou-Bakr K. Ibrahim (NRC), H. Lawrence McKague (CNWRA), and Darrell Sims (CNWRA). The primary authors of Appendix F are Gerry L. Stirewalt (MANDEX, Inc.), Joseph H. Bangs (CNWRA), and Alan P. Morris (University of Texas - San Antonio).

The authors thank N. King Stablein (NRC), David J. Brooks (NRC), Charles B. Connor (CNWRA), Budhi Sagar (CNWRA), Michael Miklas (CNWRA), and James R. Firth (NRC) for their early, repeated, and useful reviews. Reviews by seven technical staff at Headquarters and CNWRA helped to improve the manuscript. Editorial and document preparation assistance by Donald Moore and Annette Mandujano (CNWRA) greatly improved the quality of the document. The patience and skills of Carrie Crawford (NRC) in coordinating, editing, and producing the manuscripts are greatly appreciated.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

Data: CNWRA-generated original data contained in this report meet quality assurance (QA) requirements described in the CNWRA QA manual. Sources for other data should be consulted for determination of the level of quality of those data.

ANALYSES AND CODES: The software 3DSTRESS, Version 1.2, was used for some analyses in this report. Version 1.2 has recently been put under the CNWRA Technical Operations Procedure (TOP)-18. The TPA code, Version 3.1.1, was used for some analyses in this report. This code has not been placed under the CNWRA Technical Operations Procedure (TOP)-18.

1.0 INTRODUCTION

1.1 PURPOSE

Consistent with U.S. Nuclear Regulatory Commission (NRC) regulations on prelicensing consultations and a 1992 agreement with the U.S. Department of Energy (DOE), staff-level issue resolution can be achieved during the pre-licensing consultation period. However, such resolution at the staff level would not preclude the issue from being considered during the licensing proceedings. Issue resolution at the staff level during pre-licensing is achieved when the staff has no further questions or comments (i.e., open items) at a point in time, regarding how the DOE program is addressing an issue. There may be some cases where resolution at the staff level may be limited to documenting a common understanding regarding differences in NRC and DOE points of view. Pertinent additional information could raise new questions or comments regarding a previously resolved issue.

An important step in the staff's approach to issue resolution is to provide DOE with feedback regarding the adequacy of its program, before the viability assessment. Issue Resolution Status Reports (IRSRs) represent the primary mechanism that the staff will use to provide DOE feedback on the subissues making up the Key Technical Issues (KTIs). IRSRs comprise: (1) acceptance criteria that will be used by the staff to review the DOE license application and prelicensing submittals, as well as for indicating the basis for resolution of the subissue, and (2) the status of resolution, including where the staff currently has no comments or questions as well as where it does. Feedback is also contained in the staff's Periodic Progress Report, which summarizes the significant technical work toward resolution of all KTIs during the preceding fiscal year (FY). Finally, open meetings and technical exchanges with DOE provide opportunities to: (1) discuss issue resolution; (2) identify areas of agreement and disagreement; and (3) develop plans to resolve such disagreements.

In addition to providing feedback, the IRSRs will be guidance for the staff's review of DOE's viability assessment. The staff also plans to use the IRSRs in the future to develop the Standard Review Plan for the repository license application.

This IRSR documents the status of resolution of seismotectonic subissues determined to have significance to performance evaluations of a candidate high level radioactive waste repository at Yucca Mountain. Parts of three of the subissues are resolved at the staff level, and the bases for such resolution are provided. For parts of those three subissues unresolved at the staff level, the bases for that status are provided along with at least one mechanism for achieving resolution. Further, this report ensures that: (1) all significant seismotectonic issues are identified and adequately characterized; and (2) that their significance is sufficiently understood and fully considered and used appropriately to evaluate long-term performance and as input to an adequate repository design by DOE.

1.2 SCOPE OF KEY TECHNICAL ISSUE

The scope of the Structural Deformation and Seismicity (SDS) Key Technical Issue includes the geologic features, events, processes, and conditions in and around the candidate repository that result from tectonic activities (except Igneous Activity, subject of a separate KTI), and that may affect or do affect evaluation of long-term performance. Subissues that may affect or do affect evaluation of natural and engineered barrier systems (EBS) and performance include: (1 faulting; (2) seismicity; (3) fracturing and structural framework models; and (4) tectonics. Matters that concern SDS effects on waste containment and isolation and repository design for the pre-closure phase and on flow and transport in the post-closure are also within scope and will be included in a subsequent report.

1.3 CONTENT OF ISSUE RESOLUTION STATUS REPORT SECTIONS

This IRSR is organized to document the NRC staff's current position on resolution of the SDS KTI for the purpose of evaluating the performance of a repository at Yucca Mountain. The KTI will be considered resolved when all its ancillary subissues are resolved. Section 1, "Introduction," describes the purpose and scope of this KTI. Section 2, "Issue and Subissue Statements," states the objectives of the KTI and defines the key issue and the subissues. Section 3, "Importance of Subissues to Repository Performance," provides a perspective on the role each subissue has in the Total System Performance Assessment (TSPA). A quantitative analysis of significance of several subissue components to dose is based on sensitivity analyses using NRC's Total Performance Analysis (TPA) code. Relationship of subissues to DOE's Repository Safety Strategy (RSS) is also discussed.

Section 4; "Review Methods and Acceptance Criteria," describes the minimum quantity, quality and level of detail of information required of DOE for NRC staff to evaluate the adequacy of DOE's proposed resolution of each subissue. The section explains why the information is required, and what methods NRC staff may use to determine whether the standard for resolution has been met. The criteria will be used to evaluate DOE's pre-licensing and licensing submittals. Section 5, "Status of Subissue Resolution," explains the bases for resolution of Type I faults, effects of faulting and rockfall on waste packages, viable tectonic models and seismic hazard assessment methodology; Geologic Framework Model 3.0; and provides paths to resolution of open items. Open items will be tracked by the staff, and resolution will be documented in subsequent revisions of this IRSR.

2.0 ISSUE AND SUBISSUES STATEMENTS

The primary objective of this KTI is to effect an evaluation of all aspects of the seismotectonic features, events and processes (FEPs) of the geologic setting of Yucca Mountain that have the potential to compromise the performance of the proposed repository. The secondary objective of this KTI is to develop review procedures to technically evaluate the adequacy of DOE's characterization of key site- and regional-scale seismotectonic FEPs that may adversely affect performance.

The key technical issue to be resolved, broadly stated, is:

Structural deformation and seismicity (seismotectonic FEPs) that may significantly affect the performance of a repository at Yucca Mountain are: (1) identified and adequately characterized; (2) their significance is sufficiently understood and fully considered; and (3) relevant interpretations (e.g., abstractions and models) are used appropriately to evaluate long-term performance by DOE.

Subissues considered important to the resolution of this KTI include:

(i) Faulting - What are the viable models of faults and fault displacements at Yucca Mountain?

(ii) Seismicity - What are the viable models of seismic sources and seismic motion at Yucca Mountain?

(iii) Fracturing and Structural Framework of the Geologic Setting - What are the viable models of fractures and structural controls of flow at Yucca Mountain?

(iv) Tectonics and Crustal Conditions - What are the viable tectonic models and crustal conditions at Yucca Mountain?

This IRSR addresses:

(i) Faulting Components - Type I faults; Fault Displacement Hazard; Faulting Causing Waste Package Failure; Faulting Exhuming Waste Packages

(ii) Seismicity Components - Seismic Hazard; Ground Motion and Rockfall; Probabilistic Seismic Hazard Methodology;

(iii) Fracturing Components - Viable Fracture Models; Fracturing and Structural Framework of the Geologic Setting

(iv) Tectonics Components - Viable Tectonic Models; DOE's Preferred Tectonic Models; DOE Geologic Framework Models; Crustal Strain at Yucca Mountain

This report summarizes the data and pertinent conclusions of numerous geologic and seismologic publications that are relevant to the seismotectonics and structural framework of Yucca Mountain.

3.0 IMPORTANCE OF SUBISSUES TO REPOSITORY PERFORMANCE

The Yucca Mountain site region (Figure E-1) has been seismically, tectonically and volcanically active on the timescale of a geologic repository These seismotectonic activities could affect the stability of the repository and the geosphere part of the natural barrier system. For example, seismic and tectonic activities change the in situ stress field and generate faults and fractures (or change the properties and potential behavior of existing discontinuities) in ways that affect many aspects of flow of water, vapor, heat and magma, including fluctuations in the elevation of the water table. Changes to the system of discontinuities in and around a repository may be beneficial (e.g., dilation of a fracture zone may promote drainage around waste packages) or adverse (e.g., fault slip may focus flow quickly through a normally impermeable rock stratum) to waste containment and isolation, to repository (e.g., emplacement drift) design; and to long-term performance. Future changes attributable to seismotectonic activities could significantly influence the ability of a repository to isolate waste, or to perform in a reasonably predictable way. Therefore, continuing faulting and seismicity at Yucca Mountain and in the surrounding Yucca Mountain region could pose a potential risk to noncompliance with radiological safety, health, and environmental protection standards because of possible disruptions to surface and underground openings, including emplacement drifts and flow pathways.

3.1 RELATIONSHIP OF SUBISSUES TO THE U.S. DEPARTMENT OF ENERGY'S REPOSITORY SAFETY STRATEGY

DOE's RSS (*Repository Safety Strategy - U.S. Department of Energy's Strategy to Protect Public Health and Safety After Closure of a Yucca Mountain Repository, Revision 1*, 1998) continues to rely on multiple barriers to limit radionuclide movement. Therefore, the integrity of the natural barrier system (NBS-Geosphere) would need to be understood. The subissues of faulting, seismicity, fracturing, and tectonic models focus on the NBS-Geosphere. In addition, the subissues of faulting and seismicity focus on part of the EBS - waste containment by waste packages. A primary goal of the RSS is the near-complete containment of radionuclides within waste packages for several thousand years. Therefore, the premature breach of containment by mechanical failure modes, such as direct disruption by faulting or by seismically induced rockfall (or fall of chunks of concrete liner) onto waste packages, would need to be examined

Two (of four) key attributes identified by DOE as most important for predicting performance of the EBS and the NBS-Geosphere include: (1) limited water contacting waste packages; and (2) radionuclide concentration reduction during transport. Therefore, potential effects of changes to the system of discontinuities through which waters flow, such as fracture permeability, will need to be understood.

DOE stated that its RSS must address potential disruptions to the system that could release radionuclides directly to the accessible environment or otherwise adversely affect the characteristics of the system (U.S. DOE, 1998). DOE's strategy to address tectonic processes is based upon their likelihood and potential effects. DOE stated that it has initiated analyses through the Probabilistic Seismic Hazard Analysis (PSHA) and Probabilistic Fault Displacement Hazard Analysis (PFDHA) expert elicitation process to support assessment of the potential effects of such disruptions (U.S. DOE, 1998). It has enumerated two hypotheses to be tested: (1) (Hypothesis No. 16) - the amount of movement on faults through the repository horizon will be too small to bring waste to the surface, and too small and infrequent to significantly impact containment during the next few thousand years; and (2) (Hypothesis No. 17) - the severity of ground motion expected in the repository horizon for tens of thousands of years will only slightly increase the amount of rockfall and drift collapse (U.S. DOE, 1998, p. 15).

3.2 RELATIONSHIP AND IMPORTANCE OF SUBISSUES TO TOTAL SYSTEM PERFORMANCE

The staff is developing a strategy for evaluating the performance of a proposed repository at Yucca Mountain. As currently visualized by the staff, key elements of this strategy are defined as those elements necessary for DOE to demonstrate repository performance. These elements are illustrated in Appendix A. Acceptance criteria for abstracting each of these elements into an NRC determination of compliance are under development.

Structural deformation and seismicity, as defined by the prevailing tectonic, lithostatic, pore-fluid, and thermal stresses interacting with the fractured rocks at Yucca Mountain, are important factors in evaluating repository design and performance because they can cause premature waste package failures and alter the flow regime. SDS is also a factor regarding assumptions about the future integrity of the NBS-Geosphere. Therefore, the acceptance criteria for the resolution of SDS KTI and subissues are designed to complement the broader-level acceptance criteria for the abstraction of the key elements of the repository subsystems in the TSPA flowdown diagram (Appendix A; and Total System Performance Assessment and Integration KTI/IRSR).

As highlighted in the flowdown diagram, SDS needs to be abstracted into five of the key elements of the EBS and NBS-Geosphere subsystems: (1) Mechanical Disruption of Waste Package - seismicity-induced; (2) Fracture vs. Matrix Flow; (3) Spatial Distribution of Flow; (4) Flow Rate in Production Zones - when structurally controlled; and (5) Volcanic Disruption of Waste Packages. Also, the SDS KTI and its effects are important factors that need to be abstracted to determine the defense-in-depth contributions of the EBS and NBS-Geosphere subsystems of the Total System (highlighted in Appendix A).

3.2.1 Faulting - What Are the Viable Models of Faults and Fault Displacements at Yucca Mountain?

A paramount observation of the geological setting of Yucca Mountain is the presence of numerous faults, including many with evidence of Quaternary displacement (e.g., United States Geological Survey (USGS), 1996; Figures E-2 and E-3) The staff has determined that the potential effects of faults and faulting need to be abstracted into numerical performance assessment codes, specifically with regard to the following three key elements of the engineered and natural barrier subsystems. (1) mechanical disruption of waste packages, (2) structural control of ground water flow; and (3) structural influences on the spatial and temporal distribution of volcanism (Appendix A) This information needs to be considered because faults have the potential to directly intersect emplacement drifts and waste packages or act as loci of rock failure, especially rockfall. Faults can also act as conduits or barriers to flow of water, vapor, magma, or heat, as evidenced or suggested by the many washes and spring lines that follow surface fault traces and preferential magma conduits (Appendix C-3), such as dikes intruded along faults and alignments of the Quaternary or older volcanoes in Crater Flat and the Amargosa Desert (Connor, et al., 1997).

3.2.1.1 NRC/CNWRA Sensitivity Studies of Faulting

Of the three elements of the engineered and natural barrier subsystems listed previously, sensitivity to dose of faults and fault slip that directly rupture waste packages is currently being investigated. This investigation of waste package failure from faulting is based on performance assessment studies using the FAULTING Module computer code, Version 1.0 (Ghosh, et al., 1997), which was adapted for use within the NRC and Center for Nuclear Waste Regulatory Analyses (CNWRA) TPA code (Version 3.1.1; U.S. NRC, 1998a,b). This investigation bears on DOE's Hypothesis No. 16 (U.S. DOE, 1998). Detailed sensitivity studies to address the other elements are ongoing, and results and conclusions from those studies will be presented in later revisions of the SDS IRSR. A summary of completed preliminary work follows:

Conceptual Model

The FAULTING module was developed to assess the potential for direct disruption of waste packages from fault displacements in the proposed repository block. The module evaluates the potential for direct waste package rupture from fault displacement along planar decoupled fault zones. The resulting number and time of waste package failures are then incorporated into the TPA code, in which the effect on individual dose is calculated.

To model faulting in the repository block, the FAULTING module generates a new fault based on a set of independent fault parameters sampled from probability distribution functions (PDFs) that describe faulting characteristics. Geometric parameters are fault-zone location, orientation, strike, length, width, and displacement. These parameters are sampled from probability distributions derived from geologic observations of surface exposures of faults at Yucca Mountain, mainly the Ghost Dance and Sundance faults (Scott and Bonk, 1984; Scott, 1990; Spengler, et al., 1994). Recurrence parameters include recurrence rate, time of faulting event, and cumulative displacement rate. These parameters were based on preliminary values derived for Yucca Mountain faults (e.g., Pezzopane, 1995). Although, in nature, many of these geometric and recurrence properties may be related (e.g., longer faults seem to correlate with wider deformation zones or longer faults tend to be more active), for simplicity, they have been specified as independent parameters in the performance calculations conducted so far.

In the FAULTING module code, faults are considered as process zones or bands of deformation with finite width. Waste packages within these zones are considered damaged (failed), provided the fault slip exceeds a user-input threshold displacement value. It is assumed that in repository design, waste package emplacement in the proposed repository will be appropriately set back from those faults known to present a potential hazard (U.S. DOE, 1995). Thus, the FAULTING module essentially evaluates hazards related to faults not accounted for in the repository design such as (1) new faults, those that may form during the period of concern; (2) hidden faults, those within the repository that are presently unknown and unmapped; or (3) underestimated faults, those mapped faults not considered significant during design or construction that turn out to pose a significant risk over the lifetime of the repository. For simplicity, faults that fall into Categories 2 and 3 above will be referred to as underappreciated faults in this report.

A second important simplification of the FAULTING module is that faults are generated randomly, independent of the notion of linked faulting between intrabasin secondary faults, principal block-bounding, and basin-bounding faults (see Section 4.1.2 for description of principal and secondary faults). This conceptualization is used because its implementation is straightforward and because no adequate model of how secondary faulting related to motion on principal faults had been developed when the code was first implemented. Planned revisions to the FAULTING module will incorporate recent concepts about en echelon faulting at Yucca Mountain (Ferrill, et al., in review, b) and recent numerical modeling results (Stamatakos, et al., 1997b)

Recurrence Rate of Faulting Within the Repository Area

A critical abstraction for the methodology in the FAULTING module is what staff refer to as effective recurrence – the estimated frequency of faulting events within the boundary of the repository. Calculating the effective recurrence interval within the repository boundary is not straightforward because faults that initiate outside the boundary of the repository may still have a portion of their process zone intersect the repository itself. Thus, to estimate an effective recurrence rate, three additional values had to be determined: (1) the critical faulting region – that area that houses all faults capable of intersecting the repository; (2) the recurrence rate of faulting in the critical faulting region; and (3) the percentage of faults in the critical faulting region that also intersect the repository. Based on these three values, the effective recurrence rate for the repository can be estimated from the following five steps.

(1) The critical faulting region is developed from the range of mapped fault lengths and orientations at Yucca Mountain (Scott and Bonk, 1984; Simonds, et al., 1995a). From that data, nearly all faults have lengths of 30 km or shorter, or half lengths of 15 km or shorter. Fault orientations range between N55° W (azimuth 305°) and N25° E (azimuth 25°). Given these constraints, the size of the critical faulting region is defined as 15.2 km × 32.8 km, centered about the midpoint of the proposed repository.

(2) Paleoseismic studies (e.g., USGS, 1996) in the Yucca Mountain region (a region of approximately 15 × 15 km, with an area about 45 percent as large as the critical faulting region), document approximately 23 surface disrupting events in the last 150,000 yrs. This number leads to a recurrence interval of about 6,520 years (150,000 divided by 23)

(3) This recurrence interval (6,250 yr) is for all faulting, principal and secondary. In the absence of data about how this faulting should be partitioned between the two types of faulting, it is simply and

conservatively assumed that half of this faulting occurs on new or underappreciated faults. This assumption leads to a recurrence rate for secondary faults of 13,000 yr (6,250 yr divided by 0.50).

(4) This 13,000 yr recurrence interval is for the 15 × 15 km^2 area covered by the paleoseismic studies. Because the area of the critical faulting region is approximately 2.2 times as large as the area covered by the paleoseismic studies, the recurrence interval for the critical faulting region scales to approximately 6,000 yrs (13,000 yrs divided by 2.2). This scaling assumes that faulting activity in the critical faulting region is similar to that in the area covered by the paleoseismic studies.

(5) The stand alone version of FAULTING (Ghosh, et al., 1997) is then used to empirically estimate what percentage of faults generated in the critical faulting region would actually intersect the repository, given the 6,000-yr recurrence interval for the critical faulting region. Preliminary modeling results indicated that an average of 3 percent of all simulated faults intersect the repository, based on up to 1,000,000 realizations. Thus, the recurrence for faults within the repository itself is about 200,000 yrs. (6,000 divided by 0.03) or an annual probability (what can be referred to as absolute probability) of 5.0×10^{-6}.

Model Conservatism

Assumptions leading to overestimation of consequences of faulting:

(1) Absolute probability of faulting assumes up to 50 percent of faulting at the repository will occur on new or underappreciated faults. Most geological observations suggest that nearly all faulting will reactivate existing faults, i.e., those that are known and mapped (see, for example, Morris, et al., 1996). This conservative assumption is made to ensure that some package failures occur and to evaluate the consequences when some faults might not be avoided.

(2) Waste package failure mechanism assumes that after a minimum threshold displacement is exceeded, the entire waste package fails. Waste package failure is not linked to a common waste package failure mechanism used in other modules of the TPA code, for example, in EBSFAIL. In addition, all waste packages intersected by the fault zone are considered failed, instantaneously and completely. This conservative assumption is made, at present, because the forces that waste packages would encounter in an active fault zone are poorly understood.

(3) Fault zone widths were based on observations of surface faults. More recent analyses from the Exploratory Studies Facility (ESF) show that faults narrow considerably with depth. Faults in the ESF, including

exposures of the Ghost Dance and Sundance faults are 1 to 7 m wide (e.g., Sweetkind, et al., 1997b) compared to the 1–100+ m widths of those faults at the surface (e.g., Day, et al., 1997). This conservative assumption is made because the nature of faulting in the subsurface was not well established at the time this code was written

(4) Emplacement drifts are assumed to be randomly oriented. Current design, however, shows the emplacement drifts oriented roughly east-west, perpendicular to the dominant trend of Yucca Mountain faults. However, if the actual emplacement drifts are designed to be subparallel to the fault trend, then, a much greater number of waste packages may be affected by each faulting event than currently estimated by the TPA code. This conservative assumption is made because final design of the repository is not known.

Assumptions leading to underestimation of consequences of faulting

(1) Lack of a link between faulting seismicity, and volcanism. In nature, volcanic eruptions are always accompanied by numerous pre- and syn-eruption earthquakes (Luhr and Simkin, 1993; Fedotov and Markhinin. 1983). Similarly, all faulting events that will affect the proposed repository would be accompanied by significant seismicity. Such earthquakes would have a high-frequency component and strong ground motion component because the earthquakes would be centered very close, if not directly underneath, the proposed repository. Also, current TPA code does not account for the cumulative effects of these repetitive processes.

(2) The TPA code restricts the number of faulting events to one per realization irrespective of the recurrence interval selected.

(3) Unaccounted for co-seismic slip on a new or an underappreciated fault generated by rupture on other existing faults. A new fault or an underappreciated fault is generated by the module without considering the faults and fractures that already exist. In FAULTING, displacement on an existing fault does not affect other faults and fractures in the repository block. In nature, a slip on a fault may have the potential to cause sympathetic slips on other existing faults and fractures.

(4) Additional faulting from underground excavation is not considered. Regional earthquakes have been known to trigger faulting on so-called "mining-induced faults" (e.g., Gay and Ortlepp, 1979).

In summary, a number of critical assumptions and simplifications are inherent in the abstraction of the geological process of faulting into the numerical paradigm of the TPA code. In most cases, these assumptions and simplifications are conservative, in the sense that they overestimate the individual dose.

Results of Sensitivity Studies and Future Work

Sensitivity studies were carried out using TPA (Version 3.1.1). Details of the sensitivity studies will be discussed in Revision 2. Within the FAULTING module, the only input parameter that showed subsystem-level sensitivity was fault zone width. There was nearly a one-to-one correlation between the number of waste package failures and the width of the fault zone. In the analysis of variance, fault zone width was the only parameter to show statistically significant correlation with peak individual dose.

At the system level, studies show that the effect of faulting on repository performance was small, because of an assumed long recurrence rate, compared to other events (i.e. initial failure, excessive corrosion, rock fall from seismicity, and volcanism). Only in extreme cases, in which fault zones were wide (greater than 50 m) and the faulting event occurred early in the lifetime of the repository (prior to significant corrosion of the waste packages) were the effects of faulting on dose deemed significant.

Based on these preliminary results and consideration of the conservatisms and nonconservatisms built into the FAULTING module, and subject to the following caveats, staff does not view this subissue as one that will significantly affect repository performance.

The following caveats, if borne out by further work, could alter this conclusion:

(1) The regulatory period of performance of the proposed facility is significantly longer than 10,000 yrs. (e.g., more than 20,000 yrs.).

(2) Non-mechanical waste package failure mechanisms, such as corrosion, are mitigated and are not the dominant failure modes.

(3) The width of the fault process zones are significantly larger in the actual repository block than are currently estimated.

(4) Recurrence interval of faulting is significantly underestimated. For example, recent global positioning satellite (GPS) results (Wernicke, et al., 1998) suggest that the strain rate for the Yucca Mountain region may be underestimated by an order of magnitude. If this result is established as anomalous (in the sense that future faulting at the site is expected to be greater than that predicted by the geological record), and it can be shown to directly influence the rate of faulting, then new faults can be expected to offset emplacement drifts and waste packages in the repository during the lifetime of the facility, or, if underappreciated faults, such as potential buried faults, are shown to be active and in the critical faulting region.

(5) Significant low-angle faulting is found in the repository Recent excavation of Alcove 5 of the ESF revealed at least three subhorizontal

fault zones[1]. Subhorizontal faulting, if the faults are Type I and faulting occurs at the repository horizon level, could impact a significant number of waste packages.

(6) Scoping analyses indicate that the effects on performance of the coupling of faulting and seismicity or volcanism are greater than when each event is considered separately.

7) Significant changes are proposed for waste package strength, layout in drifts, quantity, and distribution within the repository.

Faulting Exhuming Waste Packages

Inherent in the DOE RSS is the proposition that cumulative slip on a fault through the repository could not bring waste packages to the surface (for example, see Hypothesis No. 16 of U.S. DOE, 1998). Evaluations of cumulative slip of faults at Yucca Mountain by staff show that this proposition is correct; it is highly unlikely that waste packages in the emplacement drifts will be exhumed to the surface by faulting. First, the repository block lies between two large block-bounding faults (the Solitario Canyon and Bow Ridge faults). Transport of the waste packages to the surface would require a new block bounding fault to form within the repository block and for that new fault to accommodate all the extension (accumulate all the slip) at Yucca Mountain over the lifetime of the repository. Second, even if such a fault were to form, 10^6 to 10^7 yrs. would be required to exhume the waste package, given current estimates of slip rates of 0.1 to 0.01 mm/yr (based on paleoseismic data summarized in Table 4.2.1 of USGS, 1996). Even higher rates of about 1.0 mm/yr, as proposed by Wernicke, et al. (1998) based on GPS results, would require 10^5 to 10^6 yrs. to exhume waste packages from the 300-m deep repository. Therefore, the staff does not regard the possibility of waste package exhumation a credible scenario for repository failure and considers this question resolved.

3.2.2 Seismicity - What Are the Viable Models of Seismic Sources and Seismic Motion at Yucca Mountain?

Because Yucca Mountain lies within a seismically active region of the Basin and Range province, moderate to large earthquakes (magnitude 6.0 and larger) are likely to occur over the life span of the repository (USGS, 1996). The principal effect of earthquakes in the region are vibratory ground motions at the repository site, (possibly in excess of 0.5 g), causing potential damage to facilities and structures, including waste packages and emplacement drifts. The staff have determined that the potential effects of seismicity need to be abstracted into numerical performance assessment codes, specifically with regard to the following key elements of the engineered and natural barrier subsystems: (1) mechanical disruption of waste packages either by induced rockfall, secondary faulting, or repeated vibratory ground motion; and (2) fracture dilation and redistribution of local stress field affecting flow (Appendix A). This information needs to be considered because seismicity-induced rockfall has the potential to

[1] Gray, M.B., Personal Communication to J. Stamatakos, May 6, 1998

directly rupture waste packages and, thus, allow premature release of radionuclides from the repository. DOE has hypothesized that this is of little importance (U.S. DOE, 1998, Hypothesis No. 17, "The severity of ground motion expected in the repository horizon for tens of thousands of years will only slightly increase the amount of rockfall and drift collapse"). Changes in the flow of groundwater to and from the emplacement drifts also has the potential to alter waste package stability and the release of radionuclides to the accessible environment.

3.2.2.1 NRC/CNWRA Sensitivity Studies of Seismicity

Of the elements of the engineered and natural barrier subsystems listed previously, sensitivity of individual dose to seismicity-induced rockfall was preliminarily investigated by SDS staff. This investigation of waste-package failure from seismicity is based on performance assessment studies using the SEISMO Module computer code, which was adapted for use within the TPA code, Version 3.1.1. A summary of completed work follows.

Conceptual Model

SEISMO (TPA Version 3.1.1; U.S. NRC, 1998a,b) evaluates the potential for direct failure of the waste packages from rockfall induced by vibratory ground motions. The code calculates waste package disruptions caused by rockfall induced by earthquakes. Detailed descriptions of the SEISMO code are given in the RDTME IRSR and Manteufel, et al. (1997). Preliminary results are summarized here.

The seismic hazard curves give the annual probabilities of exceedence of peak ground motions for a user-defined set of selected ground accelerations. These probabilities are then converted into return periods, which form the basis of seismic events used in each TPA realization. Based on the mass of largest rockfall blocks and the strength of the waste packages, SEISMO then computes the waste package failures. The number of waste packages affected and timing of seismic events are then passed to other modules of the TPA (Version 3.1.1) code, which calculate potential release and dose.

Inherent in the abstraction of the seismic hazard curves are assumptions about the degree of surface-to-subsurface attenuation of ground motion. In most cases, it was assumed that the level of peak ground motion at the repository horizon was half that for the surface. Recent numerical modeling by Ofoegbu and Ferrill (1998; Figure 7) suggests that for specific fault geometries (especially listric faults), the level of ground motion in the subsurface may be equal to that at the surface.

The seismic hazard curve developed for the ESF Design Study and summarized in Wong, et al (1996) was used as input to SEISMO. For bounding cases, two additional curves were generated based on upper and lower bounds of faulting activity from the paleoseismic record (Table 4.2.1 of USGS, 1996) and using attenuation functions of Abrahamson and Silva (1997) and Sadigh, et al. (1997).

For each seismic event in the catalog, SEISMO calculates the areas of the repository expected to undergo rockfall and the size of the blocks that fall on the waste packages. Waste package failure is determined from a calculation of impact stress, based on the size of the blocks. If the impact stress exceeds the ultimate material strength of the waste package, then the waste package is assumed to fail.

To estimate the size of the rockfall blocks, SEISMO uses joint spacing information, abstracted into five rock categories (Brechtel, et al., 1995). The size of the block in each rock category is based on that joint spacing (cross-sectional area) and an estimated block height, based on the yield zone. Height of the yield zone and susceptibility of rockfall in each category is determined by the level of ground shaking.

Model Conservatism

Assumptions leading to overestimation of consequences of seismicity (for SEISMO)

(1) A waste package is treated as a simply supported beam in which no energy dissipation takes place at the point of impact, owing to local inelastic deformation of the waste package material. In this treatment, the deformation of waste package is directly proportional to the magnitude of the dynamically applied force and the inertia of the waste package resisting an impact is neglected. The failure criterion used for assessing disruption of a waste package does not account for plastic deformation. Metal objects like the waste packages would probably sustain some level of plastic deformation without failure.

(2) The entire waste package is disrupted once the ultimate material strength of the waste package is reached.

(3) All waste packages under each rock condition are assumed to be disrupted at the same time if the impact stress of falling rock on waste packages owing to a particular earthquake condition exceeding the ultimate material strength of any of the waste packages.

(4) Falling rocks have infinite strength (i.e., all energy generated through dynamic impact is transferred to the waste package). The effective stress on a waste package from a falling rock is less if the rock breaks on impact.

(5) The thickness of yield zone, estimated from numerical modeling results using the UDEC computer code, is assumed to be the height of rock that will contribute to impact stress calculation. The other dimensions are controlled by joint spacing. This leads to an unrealistic number of large blocks falling on the waste packages.

(6) The emplacement drifts remain unbackfilled, or unfilled by repeated rockfalls. Backfilled or rock-filled drifts would offer protection against the effects of additional rockfall

Assumptions leading to underestimation of consequences of seismicity (for SEISMO)

(1) The absence of a link between seismicity and corrosion, seismicity and direct faulting of the repository, and seismicity and volcanic disruption of the repository.

(2) The waste packages do not lose strength as they corrode. In the SEISMO analyses, waste package strength is assumed constant throughout the period of interest. In reality, seismicity-induced rockfall could enhance corrosion which, in turn, could lead to weaker and more susceptible waste packages.

(3) In the base case runs, it was assumed that ground motions at the repository depth was 50 percent of those at the surface. Recent numerical modeling suggest that for some fault geometries, there is no surface-to-subsurface attenuation of earthquake-induced ground motions (Stamatakos, et al., 1997b).

In summary, a number of critical assumptions and simplifications are inherent in the abstraction of the geological process of seismicity into the numerical paradigm of the TPA code. For SEISMO, most of these assumptions and simplifications are conservative, in the sense that they overestimate the number of waste-package failures. In fact, from the initial sensitivity studies, it was determined that several of the abstractions may have been unduly conservative, leading to unrealistic estimates of waste-package failure. For example, if a given category of rock failed, all waste packages emplaced in that portion of the repository within the given rock category were assumed to have failed. In addition, rockfall block sizes were constrained to have the maximum height of the yield zone. Therefore, initial sensitivity results from SEISMO using TPA Version 3.1.1 are considered, in general, very conservative and overestimate effects. The sensitivity to repository performance of rockfall continues to be evaluated.

Results of Sensitivity Studies and Future Work

Results to date show that both the level of ground motion from earthquakes and the assumption used to predict the surface-to-subsurface attenuation of peak ground motion are important to performance. For example, higher ground motion accelerations led to a large increase in waste-package failures. The staff has performed preliminary studies of the effects of rockfall due to ground shaking on failure of waste package and has determined that this mechanism of potential release of radionuclides is of some significance within the limitations of the model proposed. These preliminary studies also showed that the size of the rockfall blocks is also important. Thus, abstractions of joint spacing and the height of the yield zone are additional parameters that must be continually evaluated. Steps are underway at NRC and CNWRA to address these parameters and DOE's Hypothesis No. 17 (U.S. DOE, 1998). Detailed sensitivity studies to address the other key elements of the natural barrier system (secondary faulting or local perturbations of the stress field) are ongoing.

3.2.3 Fracturing and Structural Framework of the Geologic Setting - What Are the Viable Models of Fractures at Yucca Mountain?

Observations and tests at the repository level of the ESF show that the site is highly fractured Pneumatic testing indicates that fractures are open and connected from depth to surface Chlorine-36 data indicate that some fractures conduct water to repository depths. Fracture flow is recognized by NRC and DOE as an operative process at YM. Given that fractures can conduct water, vapor, heat, and perhaps magma, it is necessary to understand the fracture systematics and characteristics. Fractures or their effects need to be abstracted into the following four key elements of the EBS and NBS subsystems: (1) mechanical disruption of waste package (seismicity, faulting, rockfall, and dike intrusion); (2) spatial and temporal distribution of flow; (3) fracture versus matrix flow; and (4) flow rate in production zones - when structurally controlled (Appendix A). This information needs to be considered because they are likely to be loci of rock failure (e.g., rockfall), and be pathways or barriers (low permeability zones) to flow of fluids and heat (different hydraulic and thermal conductivity relative to rock matrix).

Depending upon the geometric characteristics of individual fractures (e.g., size, aperture, roughness) and fracture populations (e.g., population distributions and interconnectedness), extent and type of fracture filling, and associated deformation and alteration along fracture or fault zones, fractures and faults may be either pathways or barriers with respect to flow. Similarly, the role of fractures and faults in repository stability is dependent on the fracture characteristics. Documentation of general fracture patterns and characteristics and analysis of potential future changes to fractures are important to assessment of flow- and stability-related performance parameters at Yucca Mountain.

Fault zone architecture and related permeability structures may strongly control fluid flow into and out of the repository (e.g., Caine, et al., 1996). Fault zones with grain-size reduction, and mineral precipitation (by and large strain-softening mechanisms) generally contain core gouge zones with lower permeability and porosity than the adjacent protolith (e.g., Goddaro and Evans, 1995; Caine, et al., 1996). These faults would form barriers to flow. In contrast, faults with coarse-grained breccias and wide fault damage zones containing numerous subsidiary structures that bound the fault core gouge may have greater permeability and porosity than the protolith, thereby, enhancing fluid flow (e.g., Chester and Logan, 1986). These faults would act as conduits to fluid flow. Faults commonly contain a less permeable core and a more permeable fault damage zone (Caine, et al., 1996). Such fault zones have enhanced permeability parallel to the fault, but reduced permeability perpendicular to the fault.

3.2.3.1 NRC/CNWRA Sensitivity Studies of Fracturing

Sensitivity of dose to fracture flow in the UZ is being investigated by NRC staff via the TPA total system code. The TPA code will simulate focused fracture flow onto a fraction of waste packages (resulting in a lot of wetting of fewer waste packages). Such studies will be compared to the cases where infiltration is distributed across flow-zones (resulting in some wetting of all waste packages). This sensitivity study will be documented in FY99

3.2.4 Tectonics and Crustal Conditions - What are the Viable Tectonic Models at Yucca Mountain?

Tectonic models are in and of themselves neither hazards nor enhancements, but they are prerequisites for evaluation of potential tectonic effects on the performance of the EBS and NBS-Geosphere. Tectonic models or their effects need to be abstracted into the following three key elements: (1) spatial and temporal distribution of flow, (2) flow rate in production zones - when structurally controlled; and (3) volcanic disruption of waste packages (Appendix A). This information needs to be considered because it could provide geological and geophysical limits on and alternative scenarios for tectonic hazards and risks.

3.2.4.1 NRC/CNWRA Sensitivity Studies of Tectonics

The NRC staff's on-going sensitivity studies on seismicity that affect waste packages consider the range of maximum earthquakes most likely to be generated by the strains implied by the various viable tectonic models (Sections 3.2.2.1, 4.4.2.2, and 5.4.3.4). This sensitivity study will be documented in FY99.

4.0 REVIEW METHODS AND ACCEPTANCE CRITERIA

Resolution of the structural deformation and seismicity KTI requires data on and estimates of (1) the prevailing hydrostatic, lithostatic, thermal, and seismotectonic stresses, (2) future states of such stresses and seismicity; and (3) the corresponding behavior of fractured, faulted, layered rocks in continual interactions with the variable stresses and strains and the hydrogeologic and potential igneous systems. These data enable performance of the structural framework portion of the natural barrier system - geosphere to be evaluated. Also needed for resolution of the SDS KTI are data on and estimates of: construction- and thermally-induced perturbations of the structural framework of the rocks of the repository operations area. DOE is in the process of obtaining data on and estimates of all of the relevant FEPs and tectonic conditions. Such data or estimates, followed by issue resolution, will enable performance of the natural barrier system and the engineered barrier system within it to be evaluated for any phase or period of performance.

NRC staff has determined that the seismotectonic activities that may significantly affect the future (10,000 to 100,000 years or more) performance of a repository at Yucca Mountain can be adequately identified and assessed by existing methods, models, and codes. With prudent projections of changes of processes and conditions and analyses of uncertainties attendant upon performance of engineered and natural systems, forward-modeled concepts of seismotectonic hazards and their effects can be reasonably applied to the analysis of risk.

Insights into the future structural deformation and seismicity of the Yucca Mountain region will continue to emanate from field observations and measurements (including analogous systems around the globe), seismic and geodetic monitoring, scale model experiments, and 3D conceptual geologic and geophysical modeling. The NRC staff's review of DOE's conclusions about future seismotectonic behavior of the site will be based on the staff's professional judgment regarding the completeness and acceptability of DOE's data and interpretations.

The staff will determine whether DOE has complied with the acceptance criteria described below for resolution of the structural deformation and seismicity issue and subissues. The staff will evaluate DOE's demonstration that it has identified and adequately characterized seismotectonic activities; has sufficiently understood and fully considered its significance; and appropriately used relevant interpretations (abstractions and models) to evaluate long-term performance. The staff will evaluate DOE's assumptions and projections by applying its standards of completeness, quality, consistency, and consideration of uncertainties. Application of such standards of review is expected to result in NRC evaluations (and DOE assessments) that are technically defensible and, when uncertainties are appropriately considered, would be deemed to be reasonable and prudent.

4.1 FAULTING

The general concept of faulting has been subdivided into two components: (1) Type I faults, and (2) fault displacement. Type I faults and fault displacement are generally investigated by deterministic methods. It is state-of-the-art to determine fault displacement hazards by probabilistic methods of analysis. In this report, acceptance and review criteria are developed for: (1) identification of Type I faults and the catalog of known faults that could potentially affect repository design and performance (Section 4 1 1); (2) fault displacement and the probability of direct fault rupture of waste packages (Section 4.1.2); and (3) seismicity and the estimates of peak ground motions at the site from earthquakes (Section 4.2).

Faults in and around Yucca Mountain have been identified and investigated by: (1) geologic mapping of surface exposures and underground openings (e.g., Day, et al., 1997); (2) geophysical methods, including gravity, magnetics, electro-magnetics, seismic reflection, and hypocenter mapping (e.g., Langenheim, et al., 1991; Brocher, et al., 1993, 1996, 1998, Oliver and Fox, 1993; Harmsen, 1994; Ponce and Oliver, 1995; Majer, et al., 1997; Connor, et al., 1997); and (3) borehole imaging and logging (e.g., Carr, 1992). Insights into faults and faulting in and around Yucca Mountain have been gained from: (4) 3D geologic framework models and balanced cross sections (Young, et al., 1992a; 1992b; Stirewalt and Henderson, 1995; Ferrill, et al., 1996b); (5) tectonic modeling (e.g., Schweickert and Lahren, 1997); (6) numerical analyses of dynamic processes (Ofoegbu and Ferrill, 1998); and (7) analog modeling (e.g., Rahe, et al., 1997).

4.1.1 Type I Faults

Type I faults are defined as faults or fault zones that are subject to displacement and of sufficient length and located such that they: (1) may affect repository design and/or performance of structures, systems and components important to safety, containment or waste isolation (sscis/wi); and/or (2) may provide significant input into models used in the design or in the assessment of sscis/wi (McConnell, et al., 1992). The concept of Type I faults in this IRSR (McConnell, et al., 1992) applies only to those faults that can directly affect the geologic repository design or performance by ground motion or direct fault slip during the period of performance.

The definition of Type I faults applies only to faults that are both known and mapped. Faults that are blind or buried, hypothesized in tectonic models, or whose existence is otherwise inferred from geologic, geophysical, seismological, or analog data are not considered Type I faults because useful attributes, such as their location, extent, age of last movement, or geometry, cannot be completely known. However, such faults may be considered in PSHA and performance assessment.

4.1.1.1 Acceptance Criteria

(1) Approved quality assurance and control procedures and standards were applied to collection; development; and documentation of data, methods, models, and codes.

(2) If used, expert elicitations were conducted and documented in accordance with the guidance in NUREG-1563 (Kotra, et al., 1996), or other accepted approaches

(3) Faulting component within the vicinity of Yucca Mountain was adequately determined. For example, has DOE investigated all known faults within an adequate distance (100 km) from the site to ensure that all candidate Type I faults have been investigated (USGS, 1996)?

(4) Maximum earthquake for each candidate Type I fault was adequately determined For example, has DOE used an appropriate and adequate fault length vs

magnitude relationship that tended not to underestimate the seismic hazard (USGS, 1996)?

(5) Maximum trace length of each candidate Type I fault was measured from acceptable sources. For example, has DOE relied on appropriate primary map sources and adequate interpretations of segmented faults that tended not to underestimate the seismic hazard (USGS, .996)?

(6) Peak ground motion acceleration for each Type I fault was adequately determined. For example, has DOE used appropriate and adequate attenuation models that tended not to underestimate the seismic hazard (USGS, 1996)?

(7) Shortest distance to site boundary of each Type I fault was adequately measured For example, has DOE used appropriate (the latest version of the smallest scale) primary geologic map and site-boundary sources (USGS, 1996)?

(8) Geologic age of last movement of each Type I fault was adequately determined. For example, has DOE used appropriate and adequately conservative interpretations of evidence of Quaternary Period movement (USGS, 1996)?

(9) Potential for future slip was adequately determined. For example, when low potential for future slip on a Type I fault was determined, did DOE use appropriate magnitudes and orientations of principal stresses, fault-orientations, and adequately conservative interpretation of slip-tendency (USGS, 1996)?

(10) Minimum trace length for a Type I fault to be considered in a fault displacement hazard analysis was adequately determined. For example, has DOE used appropriate historic seismic records and surface-rupture data to determine the minimum surface-faulting earthquake and back-calculate the associated trace length (USGS, 1996)?

4.1.1.2 Technical Bases for Review Methods and Acceptance Criteria

DOE will release in 1998 the PSHA report (USGS 1998). The following is based on the preliminary PSHA report. The six expert teams for seismic source and fault-displacement considered two basic types of seismic sources, which were either fault or areal sources. The local and regional fault sources, while not identified as either NRC Type I faults or USGS relevant or potentially relevant faults in the report, were used in the manner consistent with the definition of Type I faults (McConnell et al , 1992). The teams, based on their experience and the input of experts, identified and characterized both local and regional faults. The six teams identified 30 local faults and 51 regional faults (USGS, 1998, Table 4-2) that were used in the PSHA. Some of the seismic sources were formed by joining two or more individual faults together. Faults identified as seismic sources by the experts are indicated in the last column of the table in Appendix B. In that column, faults considered as seismic sources in the PSHA report (USGS, 1998, Table 4-2) by one or more of the expert groups are indicated by a Y. faults considered as seismic sources when combined with other faults are indicated by a C, and faults not considered as seismic sources are indicated by an N

Results of the analysis of McKague, et al. (1996) reveal 78 Type I faults in the Yucca Mountain region (Appendix B-1, B-2, and B-4). USGS (1996, Table 11-1) tabulated 100 faults in the Yucca Mountain region, but these were not specifically subdivided into Type I faults. Of those faults tabulated by USGS, 69 were categorized as relevant or potentially relevant (Appendices B-1 and B-2). USGS (1996) uses the terms "relevant" for faults that have documented Quaternary displacement and the earthquake generated on the fault could produce 84th percentile peak acceleration greater than or equal to 0.1 g, and "potentially relevant" for faults that are considered subject to displacement on the basis of potential structural association with seismicity. The staff assumes these faults to be equivalent to Type I faults. Type I faults and relevant or potentially relevant faults are compiled in Appendices B-1, B-2, and B-4. Both compilations relied on essentially the same data sources (Simonds, et al., 1995a; Faulds, et al., 1994; Frizzell and Schulters, 1990; Scott and Bonk, 1984; Piety, 1996; and Nakata, et al., 1982), and both studies assumed moment magnitude scales as a function of fault trace length, according to Wells and Coppersmith (1994).

Evaluation of Type I Faults

As shown in Appendix B, McKague, et al. (1996), USGS (1996), and the six DOE seismic source teams reviewed over 115 faults in terms of their capability to affect the proposed repository (e.g., Appendix E, Figure E-2 and E-3). Of these faults, 33 have been deemed incapable of affecting repository performance (Type III fault, Appendix B-3). Appendix B-1 lists 36 faults classified as Type I by McKague, et al. (1996) and as relevant or potentially relevant by Pezzopane (USGS, 1996); B-2 lists 33 faults classified as relevant or potentially relevant by Pezzopane (USGS, 1996), 29 of these faults were classified as Type I faults by McKague, et al (1996); B-4 lists 13 faults classified as Type I by McKague, et al. (1996) but not considered by Pezzopane (USGS, 1996); and B-5 lists 11 faults considered as seismic sources by the DOE experts but not considered by McKague, et al. (1996) or USGS (1996).

Of the 82 faults identified in Appendices B-1, B-2, and B-4, 25 faults were not considered by the experts as seismic sources. One expert team (AAR team) justified not including 10 local faults on the basis of "lack of geomorphic expression in bedrock indicating significant Quaternary activity". Another expert team (RYA team) considered the Rocket Wash-Beatty Wash fault not relevant for the same reason. No justification was given for not considering the remaining 14 faults. All of them are regional faults located more than 38 km from the repository and with peak accelerations less than 0.14 g, except for the Sundance, Yucca Wash, Pagany Wash, and Sever Wash faults, which were considered as relevant or potentially relevant faults by USGS (1996) but not by McKague, et al., (1996). The Hunter Mountain fault and the Towne Pass fault, when combined with the Emigrant fault, were considered seismic sources (USGS, 1998), but not Type I faults (Appendix B-3) by McKague, et al. (1996) or relevant or potentially relevant by Pezzopane (USGS, 1996)

The main differences between the NRC and USGS fault studies were interpretations of fault lengths in regions in which the mapped trace lengths are ambiguous and the choice of an appropriate attenuation function for identifying the 0.1-g criterion. A comparison of the two sets of fault data and predicted peak accelerations forms the basis for the subsequent discussion of the status of issue resolution regarding Type I faults For simplicity, USGS relevant or potentially relevant faults are presumed to be Type I faults

Peak accelerations calculated by McKague, et al (1996) and USGS (1996) differ by as much as several tenths of a g (Appendix B). Some of this difference is caused by application of different attenuation functions For some faults, this difference is greater than can be accounted for by the attenuation function difference alone In these cases, different interpretation of fault length that leads to a different estimate of the maximum earthquake is the source of the discrepancy. The discrepancy in length may result from obtaining the length from different technical sources (i.e., paper maps vs. electronic maps), or different interpretations of how discontinuous fault traces (blind, buried, or segmented) are linked.

Fault lengths are often poorly determined This results from variable scales of mapping, buried or otherwise obscured fault terminations or fault splays, obscured connections with other fault segments, and faults mapped by remote imaging. These factors contribute to variations in estimates of individual fault length, maximum capable earthquake, and peak acceleration at the Yucca Mountain site. Faults that yield peak ground motion values less than but near the 0 1 g minimum value (i.e., 0.09 g, or greater) should be carefully examined to ensure that alternative fault-length determinations would not lead to acceleration values above the 0.1 g threshold (McKague, et al., 1996).

McKague, et al. (1996; Figure 2-1) relied on the attenuation function of Campbell (1987), because it yields the largest (most conservative) accelerations of the available published attenuation functions for the western United States, especially for near-field (within 10 km) faults. USGS (1996) provided two sets of attenuation functions to determine peak horizontal acceleration. The first function derived an average acceleration value based on equal weighting of attenuation equations of Campbell (1981), Idriss (1991), Joyner and Boore (1981) and Boore, et al. (1993). The second function was the Sea96 equation based on a new formulation by Spudich, et al. (1997). The Sea96 equation yields the smallest peak accelerations for near-field earthquakes and was not used by USGS. At distances greater than approximately 30 km, all the attenuation functions yield similar peak accelerations for a given moment magnitude earthquake and source-to-site distance.

McKague, et al. (1996) relied on the median value of the attenuation function of Campbell (1987). The USGS (1996) used different attenuation functions, and based its results on the 84th percentile value.

Both McKague, et al. (1996) and USGS (1996) conclude that the faulting component of the geologic setting has a radius of 100 km around Yucca Mountain (Figures E-2, E-3). For fault displacement hazard analysis, both staff and the USGS (Seismotectonic Synthesis Report, Ch. 11) agree that the controlled area constitutes the area of concern.

Both McKague, et al. (1996) and USGS (1996) used the Wells and Coppersmith (1994) equation to estimate the maximum earthquake for each fault in the faulting component and used the 0.1 g threshold ground motion value as suggested in NUREG-1451 USGS (1996) cites the minimum surface-rupture earthquake at Mw = 5 8 based on the Fort Sage 1950 event That value is reasonable and technically defensible given the historic seismic record Both USGS (1996) and McKague, et al. (1996) use the same data sources (mainly Piety, 1995) to determine the age of last motion on potential Type I faults

DOE used less conservative ground motion attenuation functions (McKague, et al., 1996, Figure 2-1); however, this is in part compensated for by DOE's use of the more conservative 84th percentile peak acceleration. DOE has not considered in situ stress in its analysis of relevant or potentially relevant faults. In McKague, et al. (1996), the Pagany Wash, Sever Wash, and Yucca Wash faults were eliminated from the list of Type I faults based on their unfavorable orientation within the in situ stress field.

4.1.2 Fault Displacement Hazard

The objective of fault displacement analyses is to evaluate the potential hazards of an intersection of an active fault with vital components of the repository system, especially waste packages. Yucca Mountain lies within the central Basin and Range Province of the North American Cordillera [for example, see Figure 1 of Wernicke (1992), p. 554]. The region is characterized by complex interactions of strike-slip and extensional deformation, active since the onset of the Cenozoic 65 m.y. ago. The region remains tectonically active as indicated by numerous Quaternary faults (including Holocene) and volcanism and historic seismicity (including the 1992 Little Skull Mountain earthquake) (Ferrill, et al., 1996a).

For this evaluation of faulting, both principal (including sympathetic), secondary, and distributed faulting must be considered (as defined in dePolo, et al., 1991) Principal faulting refers to displacement along the main fault zone responsible for the release of seismic energy (i.e., an earthquake). At Yucca Mountain, principal faulting is assumed to occur only on primary faults, mainly block-bounding faults. In contrast, secondary faulting is defined as rupture of smaller faults that occur in response to the rupture in the vicinity of the principal fault. These two subsets of faults are not mutually exclusive. Faults capable of principal rupture themselves can undergo secondary faulting because of faulting on another primary fault. Because principal and secondary faults pose a potential risk to repository performance, both types must be considered by DOE in its analyses.

The simplest approach for the evaluations of principal faulting, and one which was used predominantly before 1998 for siting of nuclear reactors and other critical facilities, is a deterministic analysis. In that approach, capable faults (10 CFR Part 100, Appendix A) are avoided by adequate set-back distances. This approach may not be appropriate for Yucca Mountain (as noted in Coppersmith, 1996) because of the different performance requirements between a reactor and the repository and because the proposed repository is too large to reasonably expect that virtually all faults of concern can be avoided.

Probabilistic methods have also been developed to evaluate fault displacement hazards, especially for principal faults for which detailed paleoseismic data are available. These methods construct individual fault displacement hazard curves, analogous to probabilistic seismic hazard curves, for each principal fault (Youngs and Coppersmith, 1985, USGS,1998).

Few techniques exist to evaluate the probability of secondary faulting (e.g., Coppersmith and Young, 1992). Because of the complexity of fault analyses, it will be necessary for DOE to make assumptions and develop estimates of the future behavior of faults based on a variety of data and models. The staff will evaluate the DOE assumptions and projections by examining the completeness, quality, consistency, and appropriate consideration of uncertainty. Further, this evaluation will include assessment of deterministic and probabilistic analyses of principal fault displacement, as well as integration of these analyses with structural and tectonic models used to assess secondary faulting.

4.1.2.1 Acceptance Criteria

(1) Approved quality assurance and control procedures and standards were applied to collection. development. and documentation of data. methods. and codes.

(2) If used. were expert elicitations conducted and documented in accordance with the guidance in NUREG-1563 (Kotra, et al.. 1996). or other accepted approaches?

(3) The nature of faulting within the repository block (principal and secondary) was adequately evaluated from the range of possible interpretations. For example. were DOE's interpretations of trench investigations geologically consistent with the range of viable tectonic models (Section 4 4 1) and with interpretations of the crustal conditions of Yucca Mountain (Section 4 4 2)?

(4) Models of fault geometry, kinematics. and mechanical behavior were consistent with existing geological and geophysical results. stress and strain considerations. and viable tectonic (Section 4 4 1) and structural models. For example. were projections of faults to depth compatible with data from seismic reflection surveys. borehole intersections. and structural theory?

(5) Recurrence relationships for faulting were adequately derived from paleoseismic, or historical earthquake data and consistent with recurrence models used to evaluate seismicity (Section 4 2 1) For example. was a record of long recurrence intervals between large-magnitude earthquakes determined from trenching studies consistent with a finding of long recurrence of large displacements?

4.1.2.2 Technical Bases for Review Methods and Acceptance Criteria

Nature of Faulting at Yucca Mountain

Yucca Mountain consists of a thick accumulation of volcanic tuff deposited on an irregular surface of eroded and deformed Paleozoic and Precambrian basement composed of highly faulted and folded sedimentary and metasedimentary rocks. These tuffs were erupted from a series of Middle to Late Miocene (15 to 9 Ma) calderas that collectively form what has been defined as the southwestern Nevada volcanic field (see Sawyer. et al , 1994 for the most recent regional stratigraphy of the Miocene volcanic rocks in the Yucca Mountain region) Rocks of the Paintbrush Group, principally ash flows of the Topopah Spring Tuff (12 8 Ma) and Tiva Canyon Tuff (12 7 Ma) make up the main surface exposures of Yucca Mountain (Table E-2) The Paintbrush Group tuffs rest on a sequence of older tuffs, including the Prow Pass and Bullfrog Members of the Crater Flat Group (Table E-2). Younger tuffs related to the Timber Mountain Group are locally exposed at Yucca Mountain in topographic lows between large block-bounding faults This observation. along with evidence for growth faults in the Paintbrush rocks in Solitario Canyon (e.g., Carr, 1990; Day, et al., 1997), suggests that faulting and tuff deposition were synchronous at Yucca Mountain. Trenching studies of the Solitario, Paintbrush Canyon, and Bow Ridge faults show sufficient evidence for multiple faulting events in the Quaternary (see Sections 4.6 and 4.7 of USGS, 1996). Contemporaneous faulting and basaltic volcanism have been suggested by the presence of ash in Quaternary faults in the Crater Flat - Yucca Mountain area (e.g., USGS, 1996).

The majority of faults at Yucca Mountain are either north trending normal faults or northwest-trending dextral strike-slip faults. The larger faults in these two orientations bound the fault blocks that underlie the study area. These two sets of faults are interpreted to be contemporaneous, based on mutual terminations and secondary structures between them, such as pull-apart basins (Day, et al., 1997). Some northwest trending faults are dominantly normal faults, accommodating extension in relay ramps between overlapping normal faults (Ferrill, et al., in review, b). Only four reverse faults with north-south or northeast-southwest strikes have been identified, but they are potentially key features for constraining the kinematic history of the region (Day, et al., 1997), and for identifying infiltration pathways (Levy, et al., 1997). Much of the detailed fieldwork to study faults in the central block focused on the Ghost Dance and Sundance faults, which are close to the subsurface trace of the ESF (Spengler, et al., 1994; Potter, et al., 1996). These two faults may well be smaller scale analogues for the larger north- and northwest-trending faults (Day, et al., 1997).

Yucca Mountain itself consists of a sequence of north to north-northeast-trending, fault-bound ridges crossed by occasional northwest-trending, dextral-strike-slip faults. Faults dip almost uniformly to the west and separate blocks of gentle to moderate east-dipping tuff strata. From north to south, both fault displacement and stratal tilt increases indicate progressively greater extension of the Crater Flat basin southward (e.g. Scott, 1990; Stamatakos, et al., 1997b). This pattern is most profound on the west flank of Yucca Mountain, which is defined by a series of left-stepping and north-trending en echelon faults. The southward increase in fault offset is coupled with greater block rotation, both horizontal and vertical (e.g., Scott, 1990). Work by the USGS (e.g., Hudson, et al., 1994; Minor, et al., 1997) suggests that this pattern of faulting, along with rotated paleomagnetic direction in the tuffs, resulted from a discrete period of extension followed by a discrete period of dextral shear, akin to an oroclinal bending model. More recent re-analyses of these data suggests an alternative explanation. The north to south displacement gradient and rotation of fault blocks is simply a result of increased rollover deformation in the hangingwall above a listric Bare Mountain fault (Section 4.4.1.2, Ferrill, et al., 1996b; 1996c; Stamatakos and Ferrill, in press).

An en echelon pattern of faulting is best expressed along the western edge of Yucca Crest and the fault line escarpment that follows the west-dipping Solitario Canyon, Iron Ridge, and Stagecoach Road faults (see, for example, Simonds, et al., 1995a). The geometry of faults and ridges defines a scallop trend, composed of linear, north-trending fault segments connected by discrete curvilinear northwest-trending fault segments. For example, the ends of the northwest-trending curvilinear Iron Ridge fault bend to the northwest near its overlap with both the Stagecoach Road and Solitario Canyon faults. Yucca Mountain also contains numerous swarms of small northwest-trending faults that connect the large north-trending faults. One example is at West Ridge, which is cut by numerous small faults that connect segments of the Windy Wash and Fatigue Wash faults. This geometry strongly suggests that the entire Yucca Mountain fault system is an en echelon branching fault system (Ferrill, et al., in review, b). In which faulting on the large block-bounding fault triggers relatively widespread. but predictable, secondary faulting on connecting and linking faults. Linkage of the en echelon system is either by lateral propagation of curved fault tips or formation of connecting faults that breach the relay ramps (Figure 1 of Ferrill, et al., in review, b; Peacock and Sanderson, 1994, Trudgill and Cartwright, 1994). More importantly, from this interpretation of en echelon faulting, it follows that locally developed faults and fractures were produced by local variations of the stress field (Section 4.3.1), rather than dramatic swings of the regional extension direction (Throckmorton and Verbeek, 1995). The amount, orientation, and degree of faulting directly depend on the relative position of the rock within the en echelon fault system, either in relay ramps that connect overlapping en echelon fault segments or in the hangingwall or footwall blocks of the block bounding faults.

Faulting Models from Tectonic Models

As discussed in Section 4.4.1 and summarized in Appendix C, numerous tectonic models have been proposed to explain the structural evolution of Yucca Mountain. Faults at Yucca Mountain, for example, have been interpreted as the result of: (1) hangingwall deformation related to normal fault motion on a listric Bare Mountain fault (e.g., Ferrill, et al., 1996b); (2) hangingwall deformation above a regional low-angle detachment system (Scott, 1990; Hamilton, 1988); (3) deformation of the margin of a pull-apart basin (Fridrich, in press); (4) listric faulting from a transtensional nappe deforming above the Amargosa Desert strike-slip shear system (Schweickert and Lahren, 1997); and (5) domino-style block deformation related to extension of an elastic-viscous Crater Flat graben (Janssen, 1995). These tectonic models can be used to estimate future fault activity at Yucca Mountain. For example, because a regional detachment system of the kind envisioned by Scott (1990) is assumed to have been truncated by a more recent uplift of Bare Mountain, faulting at Yucca Mountain is assumed to be relatively inactive. Alternatively, very active strike-slip motion along the Amargosa Desert fault would predict relatively active faulting at Yucca Mountain.

In addition, the style (strike-slip or dip-slip) of faulting in the alternative tectonic models is important to evaluations of faulting data from the paleoseismic investigations. In trenches, typically only the vertical component of separation can be deduced from offset stratigraphic marker beds. If the style of faulting is dominantly dip-slip, then actual fault displacements, at least for the strand of the fault exposed in the trench, can be deduced from the paleoseismic data. In contrast, strike-slip separation is not readily apparent in trenches. If this style of faulting dominates, then the trenching data may grossly underestimate actual fault activity.

Deformation Mechanism and Fault Width

The deformation mechanism in the fault zone is also an important feature of the faulting at Yucca Mountain. Cataclasis is the general deformation mechanism that operates in these fault zones, and the details of the resulting cataclastic textures bear directly on SDS KTI subissues of faulting and fracturing. First, the nature of deformation in the fault zones strongly governs whether faults will narrow or widen with time. If the products of the deformation tend to produce fault zones that are more resistant to continued cataclasis (what can be considered strain distribution and strain hardening) than their protoliths, then renewed faulting will tend to break the wall rock and the fault zones will widen with time. In contrast, if the fault zone is easier to deform as faulting renews (strain localization and strain softening), then deformation in the fault zones will tend to localize within a narrow portion of the fault zone. The result will be an intensely deformed fault-zone core with no increase in fault-zone width.

Recurrence

Recurrence relationships of faulting are generally derived from paleoseismic data of faults exposed in alluvial trenches. The objective of the trenching studies is to find datable stratigraphic markers offset by the fault and, from the age and amount of offset, determine the recurrence relationship for the fault. There are numerous potential sources of uncertainty associated with interpretations of fault slip histories from trenching studies (Ferrill, et al., 1996b) including: (1) distributed faulting, in which the trench captures only a fractional component of the total slip; (2) blind faulting, in which the offset is restricted to the fault below the surface and, thus, no surface data are available for study; (3) oblique or horizontal slip in which the trench offset records only a small component of actual displacement; (4) inaccurate age estimates of the marker beds; and (5) variability of slip from event to event and along strike of the fault.

Recurrence data for faults are then used in conjunction with regional seismicity parameters such as frequency of earthquakes to develop probabilistic fault displacement hazard curves for each fault of interest. The curves are derived from two different approaches, defined as the "faulting-occurrence" and "magnitude-occurrence" models (Cornell and Toro in Hunter and Mann, 1990). The first approach uses fault-specific data, such as cumulative displacement, fault length, paleoseismic data from trenches, and historic seismicity. The second relates the frequency of the fault's slip events to the frequency of earthquakes on the seismic sources defined in the seismic source models developed for the corresponding seismic hazard analysis. DOE has used both approaches in its recent report on the probabilities of faulting and seismicity at Yucca Mountain (USGS, 1998). Detailed analyses of its approaches and results will be reviewed and presented in subsequent SDS IRSR revisions.

Evaluation of Fault Displacement Hazard

DOE will be submitting the results of the PSHA in 1998. After reviewing the PSHA, the staff will provide its comments and evaluations in Revision 2 of SDS IRSR.

4.2 SEISMICITY

Yucca Mountain lies within the central Basin and Range Province of the North American Cordillera [see, for example, Figure 1 of Wernicke (1992), p. 554]. The region is characterized by complex interactions of strike-slip and extensional deformation, active since the onset of the Cenozoic 65 m.y. ago. The region remains tectonically active, as indicated by numerous Quaternary faults (including Holocene), volcanoes, and historic seismicity (including the 1992 Little Skull Mountain earthquake).

In general, two approaches are considered acceptable by the staff to evaluate seismic hazards These approaches are based on deterministic and probabilistic methodologies. Until January 1997, deterministic methodology has been the traditional methodology for evaluations of seismic hazards for construction and operation of nuclear facilities. Siting, review and acceptance criteria for these facilities are embedded in many existing NRC documents, such as

10 CFR Part 100, Appendix A (Code of Federal Regulations, Title 10, "Energy," 1998), and Section 2.5.1 (*Basic Geologic and Seismic Information*); 2.5.2 (*Vibratory Ground Motion*); and Section 2.5.3 (*Surface Faulting*) of the NRC Standard Review Plan (SRP) outlined in NUREG-0800 (U.S. NRC, 1997a). Although the deterministic approach has worked reasonably well for the past three decades, this approach does not explicitly account for uncertainties in geological or seismological parameters. To incorporate such uncertainties, probabilistic methods have been developed to allow for proper uncertainty analyses (such as different interpretations and expert elicitations).

4.2.1 Seismic Hazard

The PSHA methodology has been identified by NRC in 10 CFR 100.23 as an appropriate approach to address uncertainties associated with ground motion and fault displacement. DOE has outlined the methodology it intends to use for a probabilistic seismic hazard analysis in #1 (U.S. DOE, 1997a). This approach has been accepted, in principle, by NRC (Bell, 1996). The methodologies recommended in the *Senior Seismic Hazard Analysis Committee Report* (SSHAC)(U.S. NRC, 1997c) also offer acceptable approaches for evaluating the probabilistic seismic hazard at Yucca Mountain.

Specific acceptance criteria are described in this chapter from four basic technical aspects of a PSHA. These aspects include: (1) seismic source characterization; (2) earthquake recurrence characteristics; (3) ground motion attenuation; and (4) hazard calculations and presentation.

4.2.1.1 Acceptance Criteria

(1) Approved quality assurance and control procedures and standards were applied to collection, development, and documentation of data, methods, and codes.

(2) If used, expert elicitations were conducted and documented in accordance with the guidance in NUREG-1563 (Kotra, et al., 1996), or other accepted approaches.

(3) Seismic sources were adequately determined to describe the potential sources of seismicity that will affect calculation of the peak and spectral ground motions for the lifetime of the repository. For example, determination of the seismic sources included: (a) adequate characterization of the geological and tectonic setting of the site and region; (b) enumeration of regional earthquakes in the available historic seismic record; (c) adequate evaluation of faults in the region (see Section 4.1.1 on Type I Faults), including correlation of earthquake activity with geologic structures or tectonic provinces; and (d) adequate estimation of the earthquakes' magnitude ranges and maximum vibratory ground motion anticipated at the site.

(4) Descriptions of seismic activity and recurrence relationships of fault and tectonic sources were adequate to determine ground motion at Yucca Mountain. For example, determination of the seismic activity and

recurrence rates included (a) adequate characterization of the seismic activity rate for each source (areal or fault). (b) adequate determination o whether the seismic activity, especially the maximum earthquakes, was temporally independent or occurs as clustered events, and (c) development of an adequate recurrence rate-magnitude model for each source

(5) Ground motion attenuation estimates were determined to adequately estimate vibratory ground motions at the site. For example, determination of the ground motion included: (a) adequate knowledge of the site characteristics (such as amplification and shear wave velocities) considering uncertainties in site-specific geotechnical properties; and (b) adequate characterization of ground motion uncertainty (e g., SSHAC U.S. NRC, 1997c).

(6) If expert elicitations were not used, hazard calculations were adequately documented, coherent, and technically defendable. For example, implementation and integration included: principles and procedures for structuring and implementing the PSHA that are technically sound and consistent with those for the highest level of PSHA studies (e.g., SSHAC; U.S. NRC,1997c).

4.2.1.2 Technical Bases for Review Methods and Acceptance Criteria

Geological and geophysical investigations to characterize the level of ground motion at Yucca Mountain from earthquakes have been ongoing for almost two decades. In addition, the Yucca Mountain project has benefited from several more decades of research and information from weapons testing activities at the Nevada Test Site. Much of the background information on faults, seismicity, faulting models, tectonics, and tectonic models is summarized in other sections of this report. In addition, DOE has recently concluded a PSHA detailed expert elicitation to determine the vibratory ground motion and probabilistic fault displacement hazard analysis for Yucca Mountain. Detailed comments on that elicitation and results from the PSHA will be presented in future versions of the IRSR. In this version of the IRSR, a brief outline of what the SDS staff considers important components of an adequate and sufficient PSHA are presented.

The list below highlights those data and interpretations considered by staff as most pertinent to the development and evaluation of seismicity at Yucca Mountain and resulting implications for repository performance. A detailed evaluation of the seismicity at Yucca Mountain will be in Revision 2.

Seismic Source Characterization

A seismic source is a portion of the earth's crust that has relatively uniform seismicity characteristics (including earthquake potential), and is distinct from that of its neighbors. Sources can be either fault or areal sources Within a seismic source, the probability of earthquake occurrence and the size of the maximum magnitude are generally considered to be invariant Characterization of the tectonic setting and identification of seismic sources are based on regional and site geological and geophysical data, historical and instrumental seismicity data, regional stress field, and geological investigations of prehistoric earthquakes (U.S. NRC, 1997b)

Aspects of seismic sources (e g Reiter, 1991) to consider in seismic hazard analysis, particularly in support of Acceptance Criteria 3 and 4 are:

- Earthquake potential of identified geological structures
- Earthquake potential of tectonic zones (i e . regions of uniform earthquake characteristics)
- Uncertainties associated with seismic source geometry (e g , fault dip, width, segmentation, depth of seismogenic crust)
- Uncertainties i.. recurrence and recurrence models with regard to individual faults, clustered fault activity, or regional recurrence models
- Appropriate alternatives that allow incorporation of uncertainties about the geology and tectonic conditions into the overall calculation of the seismic hazard.

Aspects of seismic record (e.g. Richter, 1958) to consider in seismic hazard analysis in support of Acceptance Criteria 3 and 4 include:

- Coordinates of the epice.,ter
- Focus depth
- Time of event
- Highest intensity
- Magnitude (with appropriate designation of magnitude type)
- Seismic moment
- Distance to the site
- Strong motion recordings
- Co-seismic deformation (i.e., landslides, liquefaction, or fracturing)
- Surface rupture information

Earthquake Recurrence Characteristics

Earthquake recurrence relationships show the annual frequency of all earthquakes up to the maximum earthquake for each seismic source. These relationships are derived from earthquake catalog, paleoseismicity, and geological information. Typically, magnitude-recurrence models range between end-member exponential (Gutenberg and Richter, 1954) and characteristic (Schwartz and Coppersmith, 1984) models.

Aspects of earthquake recurrence (e.g., Reiter, 1991) to consider in seismic hazard analysis, particularly in support of Acceptance Criteria 3 and 4 are:

- Activity rate (or *a* value)
- Slope of the regression (or *b* value)
- Lower bound and upper bound earthquake magnitudes
- Shape of the recurrence curve (characteristic, logarithmic, or hybrid)
- Potential for clustered activity

Ground Motion Attenuation

Ground motion attenuation models describe the relation among earthquake magnitude, distance from source to the site, and vibratory ground motion at the site. According to SSHAC (U.S. NRC, 1997c), ground motion should be characterized by two basic approaches: (1) a spectrum of the natural logarithm of the ground motion parameter determined as a function of magnitude and distance at multiple frequencies, and (2) the standard deviation (aleatory) of the natural logarithm of the ground motion parameter. The standard deviation could be a function of magnitude, distance, and frequency level, as applicable. Ground motion should be characterized for both horizontal and vertical field-free ground motion response spectra at the ground surface and repository depth.

Aspects of ground motion attenuation (e.g. Reiter, 1991) to consider in seismic hazard analysis in support of Acceptance Criteria 3 and 4 are:

- Seismic source properties (e.g., focal mechanism, depth, directivity, or magnitude saturation effects)
- Wave propagation between source and site
- Peak ground motion and the response spectrum
- Empirical or theoretical factors controlling the near-field region (typically within 10 km of the site)

- Site-response models, especially surface-to-subsurface attenuation and amplification and deamplification characteristics

Hazard Calculations and Presentation

Probabilistic seismic hazard analysis is a powerful tool for incorporating uncertainties associated with identifying and characterizing seismic sources and ground shaking. The PSHA will lead to identifying the ground motion hazard levels that will be used as the basis for development of seismic design basis input for Yucca Mountain.

Aspects of hazard calculations and presentation are:

- PSHA structure (National Research Council, 1988)
- Uncertainties, both aleatory and epistemic (SSHAC; U.S. NRC, 1997c)
- PSHA calculation and results (both total hazard with fractiles and uniform hazard spectrum) (SSHAC; U.S. NRC, 1997c)
- Deaggregation of results (Bernreuter, et al., 1998)

Evaluation of Seismic Hazard

DOE will submit the PSHA in 1998. The staff will review the PSHA and will provide its comments and evaluation in Revision 2 of this IRSR.

4.3 FRACTURING AND STRUCTURAL FRAMEWORK OF THE GEOLOGIC SETTING

Fractures and fracture zones, and faults and fault zones provide the primary discontinuities, i.e., the structural framework, along which groundwater infiltration and percolation occurs in the unsaturated zone at Yucca Mountain, and along which flow occurs in the saturated zone beneath Yucca Mountain and in the surrounding area (e.g., National Research Council, 1996). Furthermore, fractures and faults represent planes of weakness along which roof failure occurs leading to degradation of underground excavations and potentially causing damage to waste packages in the proposed repository. Consequently, it is important to constrain: (1) distribution and characteristics of existing fracture and fault populations; (2) processes of past fracture and fault formation and reactivation; (3) processes presently affecting fracture and fault properties (e.g., in situ stress field); and (4) potential future generation and reactivation of fractures and faults (e.g., by faulting and other strain release mechanisms). The following acceptance criteria ensures that an adequate geologic framework is available to the KTIs that use fracture or fault discontinuities information either implicitly or explicitly (i.e, Repository Design and Thermal-Mechanical Effects - to evaluate rockmass properties and size of rockblocks for rockfall calculations; Unsaturated and Saturated Flow Under Isothermal Conditions - to evaluate water flow through fractures; Thermal Effects on Flow - to evaluate heat flow through fractures; Igneous Activity - to evaluate magma and associated hydrothermal fluid flow through faults; Evolution of the Near Field Environment - to evaluate seepage and mineralization in fractures; Radionuclide Transport - to evaluate radionuclide retardation in fractures; and Container Life and Source Term - to evaluate fault disruption of waste packages) The staff will evaluate

DOE's submittal to ensure that assumptions, quality, consistency, and consideration of uncertainty are adequately addressed.

4.3.1 Viable Fracture Models

Fractures are surfaces along which rocks or minerals have broken and lost cohesion (Twiss and Moores, 1992). Extension fractures (Mode I fractures) are characterized by motion perpendicular to the fracture walls. Shear fractures (Mode II and III fractures) are characterized by motion parallel to the fracture surface. Mode II shear fractures are distinguished by motion perpendicular to the edge of the fracture, whereas, sliding on mode III shear fractures is parallel to the edge of the fracture. Fractures that display very small displacement normal to their surfaces and very little or no displacement parallel to their surfaces are called joints. Joints may originate in any of the above fracture modes. Fractures that have opened perpenaicular to the fracture walls and that are filled with a mineral filling are termed filled (or partially filled) fractures or veins.

Joints in the central repository block may be divided by age and genesis into three groups: (1) oldest cooling joints; (2) tectonic joints of intermediate age; and (3) youngest unloading joints (Barton and Larsen, 1985; Barton and Hsieh, 1989; Barton, et al., 1993; Sweetkind, et al., 1995a; 1995b; Throckmorton and Verbeek, 1995; Sweetkind and Williams-Stroud, 1996). A total of eight joint sets have been identified between these origins and ages, but no exposure contains all eight sets. Cooling joints are distinguishable because they: (1) locally have degassing tubular structures (Barton, et al., 1984); (2) do not cut lithophysae; (3) have a smooth planar appearance; (4) have surface areas in excess of 100 m^2; and (5) other joints abut against them because they are older. Tectonic joints are distinguishable from cooling joints because they: (1) lack tubular structures; (2) cut lithophysae; (3) are not normally as smooth; (4) are commonly smaller, and (5), in many cases, abut against cooling joints. Not all tectonic joints terminate at cooling joints, which suggests that either the cooling joints were infilled with vapor phase minerals at the time of tectonic joint propagation, or that the crossing tectonic joints originated as shear fractures. Thus, some cooling joints were not voids that blocked propagation of tectonic joints. Finally, unloading joints are: (1) subhorizontal; (2) near surface; (3) rough and curviplanar; and (4) generally terminate against cooling and tectonic joints.

Fractures, including faults, impart a permeability characteristic to the rocks that may be measured. A fault is a surface or thin tabular zone along which opposing sides have moved in a direction parallel to the surface or zone, across which, the displacement parallel to the zone is appreciably greater than the thickness of the zone, and in which, the deformation is greater than outside the zone (Twiss and Moores, 1992; Groshong, 1988). Fault zones commonly consist of a fault core within which most of the displacement is accommodated and a fault damage zone that consists of a network of subsidiary structures that bound the fault core (Caine, et al., 1996). Fault cores commonly have lower permeability than the protolith, because of grain size reduction and mineral precipitation. Fault damage zones commonly have enhanced permeability because of fracturing and faulting. Fault core and fault damage zone development is variable from fault to fault and along an individual fault (Caine, et al., 1996).

The following acceptance criteria are designed to ensure adequate characterization of existing fractures and their appropriate utilization in assessments of repository safety and performance.

4.3.1.1 Acceptance Criteria

(1) Approved quality assurance and control procedures and standards were applied to collection, development, and documentation of data, methods, models, and codes

(2) If used, expert elicitations were conducted and documented in accordance with the guidance in NUREG-1563 (Kotra, 1996), or other accepted approaches.

(3) Distribution and geometric characteristics (e.g., orientations, spacing, clustering, abutting relationships, interconnectedness, apertures, lengths) of fractures were adequately determined For example, a comprehensive unit-by-unit description of fractures that captures lateral and vertical variability of fracture development and interconnectivity throughout the Tertiary volcanic rock sequence and pre-Tertiary rock sequence at Yucca Mountain should be estimated or bounded to reasonably assess aspects of fractures and faults that affect repository performance.

(4) Origins of fractures were adequately defined. For example, DOE provided an adequate explanation of the mechanisms for fracture generation that include development of cooling joints, tectonic joints, and unloading joints that is consistent with evolution of the applicable regional and/or local stress field and detailed to the extent necessary to assess aspects of fractures and faults that affect repository performance.

(5) Subsequent modifications of fractures by dissolution, precipitation, wall rock deformation, and other fracture-filling processes (e.g., deposition of water-entrained particles) were adequately constrained. For example, characteristics of fracture-filling materials that would affect fracture absorption of surface water, role of fractures as barriers to flow, isolation of fracture water from host rock due to armoring of wall rock surfaces by fracture coatings, and dissolution along fractures that may enhance hydraulic conductivity were estimated or bounded to reasonably assess aspects of fractures and faults that affect repository performance (see ENFE, RDTME, and RT KTIs).

(6) Potential current and future tectonically and thermally controlled alteration of fracture characteristics during the repository performance period were adequately defined and accounted for in process level models For example, evaluations of structural and tectonic models for contemporary, or future changes to, fracture characteristics (e.g., increases and decreases in fracture apertures) caused by in situ stress, contemporary strain accumulation, seismic and aseismic deformation events, or differential thermal expansion and contraction were documented and propagated through flow and transport and total system models to the

extent necessary to assess aspects of fractures and faults that affect repository performance (see RDTME KTI)

4.3.1.2 Technical Basis for Review Methods and Acceptance Criteria

Fracturing at Yucca Mountain has been the subject of numerous focused investigations Revision I summarizes selected results.

Cooling joints form during thermoelastic contraction due to heat loss after deposition of the welded tuffs. During heat loss in the thick cooling units, isotherms are not arranged in a blanket-like manner parallel to the unit boundaries. Instead, some fluid circulation occurs, creating thermal plumes and sinks that would have locally affected joint intensity and orientation. Typically, igneous cooling joints form polygonal patterns in situations where the minimum and maximum horizontal stresses are near equal, and the rocks are not free to expand laterally, which is the "fixed-grip" situation (Engelder and Fischer, 1996). Yet, the cooling joints in the welded tuffs of the Paintbrush Group are orthogonal (Sweetkind and Williams-Stroud, 1996) with two joint sets subnormal to layering and one parallel to layering. This deviation from typical geometry may be controlled by lateral thickness variations, paleotopography differential compaction, tectonic stresses, and horizontal stresses that were significantly anisotropic. The setting was not "fixed-grip" but rather one of regional east-west extension during the Miocene (Zoback, et al., 1981; Scott, 1990; Wernicke, 1992; Ferrill, et al., 1996b; Morris, et al., 1996; Day, et al., 1997). Thus, cooling joints at Yucca Mountain formed in a local stress field that was probably produced by a combination of sources, including thermoelastic cooling stresses, topographic stresses, lateral thickness variations, differential compaction, remote regional stress field, and stress perturbations around active faults (Engelder, 1993).

Tectonic joint development did not necessarily postdate cessation of cooling joint formation by an extended period because the oldest tectonic joints (T1, Sweetkind and Williams-Stroud, 1995) strike north-south, are subnormal to layers and are attributed to the east-west horizontal extension during the Miocene. The next youngest joint set, northwest-trending T2 joints, would appear to require a regional stress field where minimum principal stress trended northeast-southwest. This stress-field geometry is undocumented by other geological features, and the existence of this set is not strongly supported (Sweetkind and Williams-Stroud, 1995). Later in this report, it is concluded that at one site where T2 fractures are prominently noted (Pavement P2001, Sweetkind, et al., 1995b), the fractures are faults and not joints. T3 joints strike northeast-southwest and are related to the recent regional stress field where the minimum principal stress trends northwest (Sweetkind, et al., 1995b). The youngest tectonic joints are east-west trending T4 joints, which have a problematic tectonic origin as no regional stress field has been identified to account for north-south extension. As a result, Throckmorton and Verbeek (1995) and Sweetkind and Williams-Stroud (1995) attributed fractures of this set to an unspecified surficial unloading event. However, many of the ridges and washes in the central block strike east-west (Day, et al., 1997), which is surprising if T4 fractures are the least important of the six subvertical sets of cooling and tectonic joints. This geomorphological trend, if the result of erosion-exploiting T4 joints, indicates that these joints are better developed than previously observed. Also, abundant east-west striking trending joints were a surprise discovery during boring of the ESF, where at a depth of 300 m, unloading joints are unlikely to form. Many of these fractures are interpreted as cooling joints If true, then not all east-west trending joints are later-stage T4 tectonic joints, and care should be used in identifying T4 joints in the field, based on orientation alone. A possible tectonic rather than unloading origin for some T4 fractures would be as secondary structures accommodating north-south extension in the regions between two overlapping normal faults that strike north-south (Trudgill and Cartwright, 1994; Peacock and Sanderson, 1994; Ferrill, et al., in review). As previously described, late subhorizontal joints with significant surface roughness and curviplanar form are attributed to erosional unloading (Sweetkind and Williams-Stroud, 1995).

One important morphological aspect of the joint sets was first noted during pavement studies by Barton, et al. (1993). Joints do not have uniform spacing. Instead, some joints are closely spaced in "swarms" or "clusters" with fracture spacings of about 10 cm. The clusters are separated by large distances in excess of 10m, where joint spacing is in excess of 1 m. Development of joint clusters clearly demonstrated that deformation in the rock was heterogeneously distributed in the rock during fracture formation. One type of cluster geometry is best exemplified by the joints in the hangingwall of the Ghost Dance fault (Sweetkind and Williams-Stroud, 1995). Surface mapping around the north-south striking Ghost Dance fault has identified a 50 m wide zone of highly fractured rock in the hanging wall of the fault (Sweetkind and Williams-Stroud, 1995). North-south striking joints and north northwest-south southeast striking joints are intensely developed with spacings of a few centimeters at distances up to 50 m from the main fault trace, which also strikes north-south. The deformation concentrator here appears to be partitioning of a small portion of the east-west regional extension that produced the fault into hangingwall deformation by joint formation, perhaps, in a dilational quadrant during fault displacement. The width of hanging-wall fault-damage zones is smaller in the ESF than at the surface. Fault footwalls typically show little or no increase in fracturing near faults (Sweetkind, et al., 1997a and b). Another type of cluster geometry is closely spaced cooling joints (Barton, et al., 1993). These extensive planar smooth fractures occur in sets of 6 to 12 fractures with spacings of about 25 cm and trace lengths typically in excess of 10 m. Why cooling joints would be heterogeneously distributed in space is not well understood, but may be a function of thermal gradients during cooling.

The presence of clusters may indicate that the majority of cooling joints initially contained precipitated vapor phases, because, otherwise, these large fractures should generate significant stress shadows up to meters away. These shadows would prevent nearby initiation of new joints, so joint spacings should be on the order of meters and not 10's of centimeters. The spacings at a scale of 10's of centimeters would either be achieved by filling the joints so that they do not act as voids and do not generate stress shadows after formation, or by increasing the driving stress for joint formation due to increased regional extension.

Overall fracture intensity of the PTn is lower than in the overlying and underlying welded tuffs of the Tiva Canyon Tuff and Topopah Springs Tuffs, respectively, and fractures are poorly connected within and between layers of the PTn (Sweetkind et al., 1996, 1997a and b). Extension fractures in the Ptn typically terminate at welding or lithologic breaks. Faults, which typically originate as shear fractures capable of fracturing across discontinuities, are considered to be structural pathways through the PTn. The exposures of the PTn in the ESF have lower fracture densities than those observed on the surface (Rousseau, et al., 1996).

Characterization of fracture networks at Yucca Mountain is impaired by several important sampling biases that are common to fracture analyses. If left uncorrected, these sampling biases lead to underepresentation of fracture intensity, porosity, permeability, and connectivity. First, the lengths of the longest fractures in a population are often unconstrained because the ends of the fracture are often obscured. This bias can lead to underestimation of fracture connectivity. Second, the orientation of a 1-D sampling line (e.g. borehole or detailed line survey (DLS) scanline) or 2D sampling surface (e.g. pavement, roadcut) inherently biases sampling against discontinuities parallel to the sampling line or surface, in favor of sampling discontinuities at a high angle to the sampling line or surface. Mathematical corrections (Terzaghi 1965) can partially compensate for this sampling bias. Third, because measuring every fracture from microscale to megascale is impractical or impossible for large sample areas, fracture studies usually have a size (e.g. length) cutoff. Fractures smaller than a given dimension are not counted. Consequently, small fractures are underepresented in fracture characterization. This bias is pronounced in nonwelded, lithophysal, or densely fractured units because they often contain an abundance of small fractures. Exclusion of small fractures could lead to an underestimation of hydrologic properties such as porosity, permeability, and fracture connectivity in these units. Elimination of fractures less than 1 m also may modify fracture intensity interpretations near faults such as for the Ghost Dance Fault in the ESF, where the 1 m cutoff for trace length leads to extremely different fracture intensity estimates over a wide zone (Sweetkind, et al., 1997a and b).

In addition to sampling biases, fracture characterization based on existing studies is impaired because fracture data were collected from different sources including boreholes, pavements, and the ESF, and different information was collected from each of the three sets of studies. The only observations consistent to all data sets are orientation and lithology (Sweetkind and Williams-Stroud, 1996). Thus, combining the data sets for determining statistical distributions may not be entirely justifiable.

The list below highlights selected data and interpretations considered by staff as most pertinent to the development and evaluation of fracturing processes at Yucca Mountain and resulting implications for repository performance. A more detailed evaluation of the fracturing processes at Yucca Mountain will be in Revision 2.

Regional and Local Stratigraphic Elements

Stratigraphic elements to consider in fracture models particularly in support of Acceptance Criteria 3 and 4 are:

- Age of host geologic units, especially with respect to timing of fracture formation events (e.g., Sawyer, et al., 1994; Buesch, et al., 1996; Day, et al., 1997)

- Host rock types (igneous rocks, lithified sedimentary strata, and unlithified sediments) in the saturated and unsaturated zone at Yucca Mountain, including lateral and vertical lithologic variations, such as degree of welding, lythophysal development, alteration, and pumice content of tuff (Sweetkind, et al., 1997a and b) that could potentially affect fracturing.

- Host rock types in the Proterozoic and Paleozoic units of the subregional saturated zone, with particular emphasis on solubility features of Paleozoic carbonate units potentially related to karstic flow systems

Regional, Subregional, and Local Structural and Tectonic Elements

Regional and subregional structural and tectonic elements to consider in fracture models particularly in support of Acceptance Criteria 3, 4, and 6 are.

- Evolution of regional stress field (e.g., Zoback, et al., 1981, Minor, 1995. Minor, et al., 1997, Ferrill, et al., 1996b; Morris, et al., 1996)

- Contemporary stress field (e.g., Stock, et al., 1985; 1986, Stock and Healy, 1988; Zoback, 1992; Zoback, et al., 1992; Wittmeyer and Ferrill, 1994; Wittmeyer, et al., 1994; Barton, et al., 1995; Ferrill, et al., 1994. 1995a; 1996b; Morris, et al., 1996; also cf. Engelder, 1993; Wesnousky and Jones, 1994)

- Geologic maps (e.g., Swadley and Parrish, 1988; Frizzell and Shulters, 1990; Scott and Bonk, 1984; Faulds, et al., 1994; Day, et al., 1997): Scott, 1990; Piety, 1996; Simonds, et al., 1995a)

- Structural cross sections (e.g., Scott and Bonk, 1984, Scott, 1990; Young, et al., 1992a; 1992b; 1993; Ferrill, et al., 1996b; Ofoegbu and Ferrill, 1995; 1996; 1998; Day, et al., 1997)

- Structural and tectonic setting including known and interpreted regional and subregional scale structural features such as faults and folds, with emphasis on structural features (both emergent and buried) in Crater Flat (including the Bare Mountain fault), Yucca Mountain, Jackass Flat, and Amargosa Valley (Snyder and Carr, 1982; Swadley, et al., 1984; Reheis, 1988; Scott, 1990; Young, et al., 1992b; Ferrill, et al., 1995b; Menges, et al., 1995; Ferrill, et al., 1996a; 1996b; 1996c; Ferrill, et al., 1997; Stamatakos, et al., 1997b; Ofoegbu and Ferrill, 1998; Stamatakos, et al., in press)

- Geophysical data to constrain fault-related deformation (Brocher, et al, 1998, Majer, et al, 1997)

- Geodetic strain measurements (Gilmore, 1992; Savage, et al., 1994. Ferrill, et al, 1996b; Bennett, et al., 1997; Wernicke, et al, 1998)

- Long-term strain and deformation estimates, including geologically derived strain and fault displacement estimates and paleoseismic (trenching) studies (e.g., Ferrill, et al., 1996a; 1996b; 1997, Stamatakos, et al., 1997b)

- Local stress field including lithostatic, tectonic, topographic, and excavation-related stresses and fluid pressure and effects on permeability (e.g., Whittmeyer and Ferrill, 1994; Whittmeyer, et al., 1994; Barton, et al., 1995; Finkbeiner, et al., 1997)

- Fracture and fault characteristics at Yucca Mountain, resulting from surface studies such as pavement mapping, outcrop investigations, subsurface studies such as borehole analyses, ESF mapping and scanline studies (Barton and Hsieh, 1989; Carr, 1992; Stuckless, et al., 1992; Barton, et al., 1993; Carlos, et al., 1993; Lin, et al., 1993; Barton, et al., 1995; Chekuri, et al., 1995; Throckmorton and Verbeek, 1995; Sweetkind, et al., 1995a; 1995b; 1996; 1997a; 1997b; Sweetkind and Williams-Stroud, 1995; 1996; Paces, et al., 1996; Piety, 1996; Potter, et al., 1996; Anna, 1997; Anna and Wallman, 1997)

- Three-dimensional geometry of Yucca Mountain faults and fault blocks, intersection relationships of faults, and patterns of fault displacements (e.g., vertical and lateral gradients) (Scott, 1990; Stamatakos and Ferrill, in press; Ferrill, et al., in review; also Gay and Ortlepp, 1979; Allan, 1989; Higgs, et al., 1991; Peacock and Sanderson, 1991; 1994; Scholz, et al., 1993; Dawers and Anders, 1995; Willemse, et al., 1996; Zhang and Sanderson, 1996; Davies, et al., 1997; Ferrill and Morris, 1997; Willemse, 1997; Yielding, et al., 1997; Alexander and Handschy, 1998; Ferrill, et al., 1998)

- Partitioning of regional and subregional strain (Ferrill and Dunne, 1989; Dunne and Ferrill, 1995) among mechanisms such as seismic and aseismic slip on large faults (e.g., Pezzopane, 1995; Ferrill, et al., 1996a; Stamatakos, et al., 1997a; Ofoegbu and Ferrill, 1998), dilation and slip on fractures, small faults (Lienkaemper, et al., 1987), and bedding-parallel foliations and layering (Morris, et al., 1996; Ferrill and Morris, 1997; Ferrill, et al., 1998), elastic deformation, and dike intrusion (Wernicke, et al., 1998; Connor, et al., in review)

- Hydrologic features associated with structural features such as faults or fracture zones (Hill, et al., 1995; also Mozley and Goodwin, 1995)

Topographic Elements

Local topographic elements to consider in fracture models particularly in support of Acceptance Criteria 3, 5, and 6 are:

- Morphology of topographic surface (Henderson, et al, 1996)

- Geometric relationship of topographic surface with respect to layering, foliations, and structural features (important for surficial and mass-wasting processes).

- Depth

Hydrologic, Geochemical, and Pneumatic Elements

Hydrologic, geochemical, and pneumatic elements to consider in fracture models particularly in support of Acceptance Criteria 3, 5, and 6 are:

- Observations, measurements, and models of infiltration and subsurface flow processes (Montazer and Wilson, 1984; Barton, et al., 1993; Flint and Flint, 1995; Flint, et al., 1996; Stothoff, et al., 1997; also Ritzi and Andolsek, 1992; Mayer and Sharp, 1998)

- Cl36 measurements in ESF (Levy, et al., 1997)

- Air and seepage permeability measurements (Le Cain, 1997; -Wang, et al., 1997, 1998)

- Water table elevation data and their relationship to fracture systems (Czarnecki, et al., 1997)

- Saturated-zone tracer test and pump test results (Geldon, et al., 1997)

Evaluation of Viable Fracture Models

TBD in 1999.

4.4 TECTONICS AND CRUSTAL CONDITIONS

4.4.1 Viable Tectonic Models

Much of the specific technical criteria for tectonic model development and subsequent evaluation is predicated on how the models will be used in the evaluation of repository performance. Technical bases for review and acceptance criteria are primarily derived from consideration of the application of the models as tools to evaluate seismic sources, faulting probability, structural control of groundwater flow, long-term evolution of natural and engineered barriers, and related SDS subissues.

4.4.1.1 Acceptance Criteria

(1) Approved quality assurance and control procedures and standards were applied to collection, development and documentation of data, methods, models and codes.

(2) If used, expert elicitations were conducted and documented in accordance with the guidance in NUREG-1563 (Kotra, et al., 1996), or other accepted approaches.

(3) A suite of viable tectonic models for Yucca Mountain and surrounding region was developed from the numerous published tectonic models and supporting geological, geophysical and modeling data and results. The development of these models should

include: (1) a reasonable explanation of the bases for selection of viable tectonic models; (2) purposes of each model; and (3) demonstrations that each model is internally consistent with the appropriate structural style and deformation mode and compatible with the tectonic framework of the southern Cordillera and Basin and Range province.

(4) Viable tectonic models were consistent with existing geophysical, geological, seismological, and geodetic data, including reasonable explanations of how data that are inconsistent with the model are accounted for. For example, all appropriate data, (including but not restricted to: (1) geophysical: gravity magnetics, paleomagnetics, seismic refraction/reflection, teleseismic; (2) geological: structural, geothermal, geochronological; (3) seismological: historical seismicity, crustal condition, paleoseismicity; and (4) geodetic: GPS, trilateration survey, level line survey) have been adequately evaluated, and include sufficient treatment of data inconsistences.

(5) Viable tectonic models clearly depicted the tectonic, structural, and seismic elements and the uncertainties associated with the quantification of each element critical for the model's intended purpose. For example, scaling tools, including (but not restricted to) geologic maps, block diagrams, and restorable cross-sections have been adequately used; and reasonable interpretations of geologic, geometric, kinematic, and mechanical relationships to constrain the key uncertainties have been adequately evaluated.

4.4.1.2 Technical Bases for Review Methods and Acceptance Criteria

Geological and geophysical investigations to characterize the Yucca Mountain site have been ongoing for two decades. In addition, the region has been the subject of detailed geological and geophysical investigations related to: (1) weapons testing activities at the Nevada Test Site (NTS); (2) academic research in the Basin and Range; and (3) mineral and petroleum exploration. All of these efforts have provided DOE (and subcontractors) and NRC (and subcontractors) with a plethora of geological and geophysical data and interpretations.

The list below highlights those data and interpretations considered by staff as most pertinent to the development and evaluation of viable tectonic models. Additional evaluation of this subissue will be in Revision 2.

Regional and Local Stratigraphic Elements

Regional and local stratigraphic elements to consider in tectonic models are

- Archean and Proterozoic rocks (Table E-1) that make up the basement in the Yucca Mountain region (e.g., Bowring and Karlstrom, 1990).

- Neoproterozoic, Paleozoic, and Mesozoic rocks (Table E-1) that constitute the bulk of the seismogenic crust in the Yucca Mountain region (e.g., Cornwall and Kleinhample, 1961, 1964; Stewart, 1970; Cornwall, 1972; Monsen, 1983, Poole, et al., 1992, and references therein; Stevens, et al., 1991; Trexler, et al., 1996)

- Cenozoic sedimentary and igneous rocks that underlie most of the Quaternary basins (Table E-1) and make up Yucca Mountain itself (e g . Ransome, et al . 1910. Byers et al., 1976. Christiansen, et al , 1977; Vaniman and Crowe, 1981. Swadely, et al , 1984. Carr, et al., 1986a; Bradshaw and Smith, 1994. Sawyer, et al., 1994, Connor and Hill. 1995; Crowe, et al., 1995; Buesch, et al . 1996; Fleck, et al., 1996. Hill and Connor. 1996).

Regional and Local Tectonic Elements

Regional and local tectonic elements to consider in tectonic models are:

- Paleozoic and Mesozoic tectonic features including the Mississippian Antler (e.g . Nilsen and Stewart, 1980; Burchfiel and Davis, 1972; Oldow, 1984), Permian Last Chance (Snow, 1992a), Permian Sonoma (e.g., Gabrielse, et al., 1983), and Mesozoic Sevier (e.g., Armstrong, 1968; Camilleri and Chamberlain, 1997) orogenies.

- Oligocene and older (Table E-2) extensional features (e.g., Wernicke, et al., 1987; Hodges and Walker, 1992; Axen, et al., 1993) including those presently exposed along the southwestern face of BM (Ferrill, et al., in review; Stamatakos and Ferrill, 1996a).

- Neogene (Table E-2) Tectonic features including: (1) plate motions (e.g., Atwater, 1970; Dokka and Travis, 1990; Bohannon and Parsons, 1995; Dickenson, 1996); (2) Walker Lane seismotectonics (Stewart, 1988; Hardyman and Oldow, 1991; Oldow, et al., 1994); (3) Basin and Range detachment faulting (e.g., Anderson, 1971; Wright and Troxel, 1973; Stewart, 1978; Wernicke, 1981; Burchfiel, et al., 1982, 1987; Hamilton, 1987; Wernicke, et al., 1988; Maldonado, 1990), and (4) Basin and Range core complexes (e.g., Davis and Coney, 1979).

Geometric Elements

Geometric elements to consider in tectonic models are:

- Seismic reflection data (Majer, et al., 1997; Brocher, et al., 1993, 1996, 1998; Young, et al., 1992a)

- Gravity and aeromagnetic data (Snyder and Carr, 1982; Kane and Bracken, 1983; Langenheim, et al., 1991, 1993; Ponce, et al., 1992; Oliver and Fox, 1993; Langenheim and Ponce, 1995; Ponce and Oliver, 1995; Brocher, et al., 1996)

- Ground magnetic data (Brocher, et al., 1996; Connor, et al., 1997; Stamatakos, et al., 1997)

- Geologic maps (Cornwall and Kleinhample, 1961; Nakata et al., 1982; Scott and Bonk, 1984; Swadely and Parrish, 1988; Frizzel and Shulters, 1990; Maldonado, 1990, Monsen, et al., 1992; Faulds, et al., 1994; Simonds, et al., 1995a; Day, et al , 1997)

- Borehole data (e g . Carr and Parrish, 1985; Carr, et al., 1986b, 1995)

- Structural cross-sections (Scott and Bonk, 1984; Scott, 1990; Young, et al., 1992b, Ferrill, et al., 1996b; Fridrich, in press)

Kinematic Elements

Kinematic elements to consider in tectonic models are:

- Vertical-axis rotation markers from paleomagnetism (Gillett and Van Alstine, 1982; Nelson and Jones, 1987; Rosenbaum, et al., 1991; Hudson, 1992; Gillett and Geissman 1993; Holm, et al., 1993; Snow, et al., 1993; Zhang, et al., 1993; Hudson, et al., 1994, 1996; Sonder, et al., 1994; Ferrill, et al., 1995; Stamatakos and Ferrill, 1996b; Fridrich, et al., in press; Stamatakos, et al., in review) and sedimentological markers (e.g., Snow and Prave, 1994)

- Exhumation and horizontal-axis tilting from radiogenic thermochronology studies (Noble, et al., 1989; Maldonado, 1990; Noble, et al.,1991; Monsen, et al., 1992; Hoisch and Simpson, 1993; Sawyer, et al., 1994; Ferrill, et al., 1996b; Weiss, 1996; Hoisch, et al., 1997, Ferrill, et al., in review), calcite-twin deformation studies (Ferrill, et al., in review; Stamatakos and Ferrill, 1996a), conodont color alteration indices (Grow, et al., 1994), and paleomagnetic data (Stamatakos and Ferrill, 1996b; Stamatakos, et al., in review)

- Three dimensional (3D) motions from regional reconstructions based on palinspastic markers (Prave and Wright, 1986; Stewart, 1983; Snow and Wernicke, 1989; Carr, 1990; Stevens, et al., 1991; Caskey and Schweickert, 1992; Snow 1992a, 1992b; Axen, et al., 1993; Snow, 1994; Serpa and Pavlis, 1996; Schweickert and Lahren, 1997).

- Fault displacement analyses (Wesnousky and Jones, 1994; Minor, 1995; Ofoegbu and Ferrill, 1995; Ofoegbu and Ferrill, in press; Bruhn and Schultz, 1996; Ferrill, et al., 1996a; Piety, 1996; Ferrill, et al., 1997; Stamatakos, et al., 1997).

- Geodetic and GPS results (Gilmore, 1992; Savage, et al. 1994; Ferrill, et al., 1996b; Bennett, et al., in press).

- Stress analyses (Stock, et al., 1985, 1986; Zoback, 1992; Zoback, et al., 1992; Bellier and Zoback, 1995; Morris, et al., 1996) or seismic moment analysis (e.g., Smith, et al., 1989; King, et al., 1994).

Paleoseismic and Historical Seismic Elements

Paleoseismic and seismic elements to consider in tectonic models are:

- Historic seismicity in the Yucca Mountain region, including the Little Skull Mountain earthquake (e.g., Arabasz and Julander, 1986; Harmson, 1991; Rogers, et al., 1991, Smith and Arabasz, 1991; Harmsen and Bufe, 1992; Harmsen, 1993, 1994, Stover and Coffman, 1993; Meremonte, et al., 1995)

- Paleoseismic data from trenching studies along fault scarps and aerial photography analyses of surface deformation studies (Reheis, 1988, 1994, Anderson and Klinger, 1994; Menges, et al., 1995, Pezzopane, 1995; USGS, 1996), including triggered and clustered seismicity (e.g., Anderson, et al., 1994, Bodin and Gomberg, 1994).

Viable Tectonic Models

Review of the geologic literature by staff suggests that tectonic interpretations of the Yucca Mountain region can be organized into 11 tectonic models. Staff from NRC, CNWRA, DOE, USGS, and the State of Nevada met in San Antonio on May 7-8, 1996, for an Appendix 7 meeting to discuss conceptual tectonic models. In this meeting, the 11 tectonic models proposed for the Yucca Mountain region were reviewed in the context of the most recent geological and geophysical data.

From discussions in the meetings, it was clear that 5 out of the 11 tectonic models were presently supported by the existing data (Appendix C-1) Although new data may promote one of the other six models currently considered not viable (Appendix C-2), the five models listed in Appendix C-1 form the bases for issue resolution at this time. In addition, there was no general consensus on which models are truly independent and which models may function as subsets of others. In a broader sense, these five models can be considered in two general categories of deformation. The first three are dominantly related to extensional deformation and the latter are dominantly related to strike-slip deformation. Moreover, the five models are not mutually exclusive. Locally, extensional-dominated deformation (within Crater Flat, for example) can exist within a larger region of trans-tensional deformation related to a pull-apart basin. The implications of the five viable models to repository performance subissues are summarized in Appendix C-3. Unless new data or scientific arguments can be developed to allow one or more of the models to become preferred, all five models should be used to bound the impact of faulting and seismicity on repository performance. DOE's PSHA expert elicitation process appears to be heading in the direction of consideration of an appropriate range of tectonic models.

O'Leary (USGS, 1996) proposed a reclassification of the 11 tectonic models and suggested the elastic-viscous model was the "preferred model." O'Leary (USGS, 1996), organized tectonic models into three generic classes, based on what O'Leary termed "bulk mechanical behavior" (USGS, 1996, p. 8-51). These classes were simple shear, pure shear, and lateral shear. The caldera model of Carr (1982, 1984, 1988, 1990, and Carr, et al., 1986a) was considered as a fourth unique model. The synclinorium model of Robinson (1985) was not discussed in USGS (1996). By simple shear, O'Leary (USGS, 1996) actually refers to models that evoke some form of detachment faulting, that is the deep, intermediate, and shallow detachment models described in Appendices C-1 and C-2. By pure shear, O'Leary (USGS, 1996), refers to models that evoke horsts and graben fault block models like the planar fault block and domino fault block models (Stewart, 1978; Fridrich, in press). By lateral shear, O'Leary (USGS, 1996) refers to strike-slip-dominated models like the Amargosa Shear model of Schweickert and Lahren (1997).

In summary, O'Leary (USGS, 1996), presents a USGS "preferred" model of planar, steeply-dipping faults. Fault blocks are considered to deform internally, and voids between fault blocks are allowed to be filled by a ductile (fluid) middle crust. The model is based on the boundary element modeling of Janssen (1995). In the model, the seismogenic crust is treated as a quasi-elastic layer resting on a viscous middle and lower crust. According to O'Leary (USGS, 1996) the model addresses the following important geological and geophysical considerations:

- Faulting and basaltic volcanism are episodic and coupled.
- The Crater Flat domain is essentially a half-graben with Yucca Mountain faults antithetic to the master BM fault.
- The vertical-axis rotations from strike-slip faulting are a secondary phenomena, related to a discrete period of oroclinal bending.
- Faults are planar to the base of the seismogenic crust and dip between 30° and 60°. They are essentially linear cracks in which displacements are treated as stress perturbations.
- Stress conditions at the base of the crust control distribution of basaltic volcanism.
- Faulted blocks are in isostatic equilibrium.
- Elastic behavior of the crust (brittle and ductile) during an earthquake with relaxation creep in lower crust between earthquakes.
- Rollover into faults in Crater Flat, especially the Bare Mountain fault, is not a result of fault geometry but of elastic flexure of the hangingwall.

Evaluation of Viable Tectonic Models

The following addresses the USGS (1996) "preferred" model:

USGS (1996), following Fridrich, et al. (in press), further subdivides the Crater Flat domain by a subdomain boundary simply referred to as the "hinge line" (see Figure 8.6 in USGS, 1996). The hinge line is defined as both a conceptual and physical feature. It apparently follows a subtle, but sudden, decline in average elevation of Yucca Mountain blocks—lower to the southeast (Fridrich, et al., in press)—along a series of ridge terminations, aligned fault splays, Z-shaped bends in the ridge crests, and several small-magnitude aeromagnetic anomalies (USGS, 1996). Northeast of the line, fault blocks with relatively high relief are juxtaposed across steeply dipping faults with relatively small displacements. Southwest of the hinge line, fault blocks are more strongly tilted and juxtaposed across faults with shallower dips and greater displacement (Scott and Bonk, 1984; Scott, 1990; Day, et al., 1997).

Both Fridrich, et al. (in press) and USGS (1996) consider the amount of clockwise vertical-axis rotations indicated by anomalous paleomagnetic declinations in the tuffs (Rosenbaum, et al 1991; Hudson, et al., 1994) to be the most important indicator of the hinge line. Northeast of the line, clockwise vertical-axis rotations are limited to 20° or less. Southwest of the hinge line, vertical-axis rotations range between 20° and 45°. The vertical axis rotations are interpreted in terms of a discrete period of dextral, strike-slip strain following within about 1 m.y. of the major pulse of Crater Flat extension (Hudson, et al., 1996) or the result of "concentrated strain along bending beams" due to differential extension of southern Yucca Mountain (USGS, 1996). Along with spatial and temporal variations in the amount of extension on faults, the significance of the paleomagnetic data is that the main locus of deformation in the Crater Flat domain has migrated to the southwest with time. The implication is that the hinge line effectively isolates Yucca Mountain in the northeast subdomain from active deformation in the southwest subdomain, thereby, reducing the risk of future seismicity and volcanism at Yucca Mountain.

Several aspects of the hinge-line argument are inconsistent with the available geological and geophysical data. First, structural and gravity data define a diffuse eastern margin of the Crater Flat half graben well east of the ridges that comprise Yucca Mountain proper (Ferrill, et al., 1996b; Connor, et al., 1996). Within this half-graben, Yucca Mountain appears, in plan-view, as "bow-shaped," convex toward the east. Similar to many curvilinear structural features worldwide, curvature alone is not indicative of horizontal bending of a previously more linear feature (e.g., Stamatakos and Hirt, 1994), as supposed by the USGS (1996) explanation. Numerous curved structural features are primary and simply reflect the interplay between local variations of the imposed deformation and lateral variations in crustal anisotropy (e.g., Marshak, 1988; Ferrill and Groshong, 1993).

Second, the interpretation that all faults change strike northwest and southwest of the hinge line is misleading. In northern Crater Flat, the northeast-trending faults are an extension of the radial pattern of faulting in the region immediately surrounding the Miocene Timber Mountain and Rainier Mesa calderas. In southern Yucca Mountain, there are some northeast-trending faults, but many faults also have north-south strikes, contrary to the USGS interpreted fault map (compare Figure 4-1 and Figure 1; Fridrich, et al., in press).

Third, the interpretation that anomalous paleomagnetic declinations necessarily signify vertical axis rotations related to oroclinal bending is overly simplistic (e.g., Gray and Stamatakos, 1998). The rigorous test of vertical-axis rotations resulting from oroclinal bending was defined in Schwartz and Van der Voo (1984). The test plots paleomagnetic declinations as a function of the orientation of structural trends. The assumption in an oroclinal bending model is that both prebending structures (in this case, normal faults) and corresponding paleomagnetic vectors will correlate if both were passively reoriented by vertical-axis rotations. A significant correlation between declination and strike with a slope of one implies bending of an originally linear feature (e.g., Van der Voo, et al., 1997). Significant correlations between declination and strike with a slope of less than one implies bending of an originally curved feature (e.g., Eldredge, et al., 1985).

Plots of the paleomagnetic declination versus strike of structural trends in Crater Flat and at Yucca Mountain based on available data do not support a simple orocline (vertical-axis rotation) model (Figure 2b, Stamatakos and Ferrill, in press), especially when compared to regions in which oroclinal bending is well established (cf. Figure 8 in Van der Voo, et al., 1997). The analysis of Stamatakos and Ferrill (in press) shows that the distribution of magnetic declinations recorded in the Tiva Canyon Tuff (Rosenbaum, et al., 1991) at Crater Flat and Yucca Mountain is independent of structural trend

An alternative explanation of the rotated paleomagnetic directions is that they resulted from differential displacement on listric normal faults (Figure 3a, Stamatakos and Ferrill, in press) In this geometry, hangingwalls rotate about a steeply inclined axis as displacement proceeds (Figure 3b, Stamatakos and Ferrill, in press). Faults that are incorporated into the hangingwalls of other faults may also rotate. Faults that form the ultimate footwall (not incorporated into a hangingwall of another fault) or faults that form after an initial period of extension may not necessarily be rotated (Figure 4c, Stamatakos and Ferrill, in press) This situation appears to mimic that at southern Yucca Mountain [compare Stamatakos and Ferrill (in press), Figure 4c with Figures 1 and 2] In this interpretation, the increase in the amount of clockwise rotations indicated by the paleomagnetic declinations in southwestern Crater Flat result from lateral southward increases in displacement on Crater Flat faults, like the Solitario Canyon Fault (e.g., Scott, 1990). Moreover, this interpretation is entirely consistent with the observation that the greatest amount of extension is in the southern part of Crater Flat (e.g., Scott, 1990; Ferrill, et al., 1996a; Stamatakos, et al., 1997b; Fridrich, in press).

The Role of Faults In the Distribution of Dikes and Volcanoes

Studies of dike and volcano alignments in Crater Flat and Amargosa Desert are being reviewed at CNWRA and NRC and will be presented in FY99.

Planar versus Listric Fault Geometries

The first-order structure of the Crater Flat-Bare Mountain region is the pronounced rollover of the Miocene tuffs into the Bare Mountain fault (Young, et al., 1992b; Ferrill, et al., 1996b). This rollover defines the shape of the Crater Flat half-graben, in which the deepest portion of the Crater Flat basin is adjacent to the Bare Mountain fault (e.g., Snyder and Carr, 1982; Ferrill, et al., 1996b). Rollover has long been recognized as the result of hangingwall deformation above a curved or listric fault (Groshong, 1990). The exact geometry of rollover and fault shape depends on the nature of deformation in the hangingwall (Dula, 1990), on the assumption that faulting is restorable because hangingwall volume is preserved during deformation.

The alternative proposed by O'Leary (USGS, 1996) supposes that elastic flexure of the hangingwall causes the roll-over geometry. The model does not consider surface geometry as a constraint to deformation kinematics. The ductile middle crust is allowed to fill voids in the subsurface where gaps open between fault blocks. Fault blocks can deform internally if space problems at the surface exist where fault blocks of different dip overlap The potential mechanisms for internal block deformation, including increased fracturing, are not discussed According to O'Leary (in USGS, 1996), the model accounts for the observation that few, if any, historic earthquakes ruptured shallow-angle (detachment) normal faults, including the 1992 Little Skull Mountain earthquake, which appeared to have ruptured a steeply dipping fault near the base of the seismogenic crust.

Geologic Framework Model Version 3.0 (GFM3.0)

DOE's GFM3.0 is a significant update of the geologic framework model embedded in its Integrated Site Model (ISM) 2.0. GFM3.0 incorporated the Geologic Map of the Yucca Mountain Area (Day, et al., 1997), the revised lithostratigraphic nomenclature (Spengler and Buesch, 1998), and the precise stratigraphic contacts mapped in the Exploratory Studies Facility. The GFM3.0 is DOE's stratigraphic and fault framework model shared by the following users: (1) unsaturated flow and transport; (2) saturated zone flow and transport; (3) near-field environment models; (4) repository design; (5) mineralogy; and (6) performance assessment (D. Bryan, Translation and Use of GFM3.0, Handout at DOE/NRC Quarterly Technical Meeting, June 18, 1998). The SZ, Repository Design and PA groups will be relying on the stratigraphic and fault depictions for their assessments (ibid.). The staff has reviewed GFM3.0 for the purposes of evaluating its various uses by DOE and considering using it to enhance the staff's 3D-modeling capability.

The staffs at CNWRA and NRC Headquarters, in coordination, conducted tests and evaluations of GFM3.0. Briefly, the staffs addressed the following questions: (1) Are the input data necessary and sufficient to define faults and stratigraphy in the model? (2) Do modeled fault traces and surfaces and stratigraphic boundary-surfaces match the field data? (3) Were the essential data bases provided by DOE with the model? (4) Are alternative representations - or interpretations - of stratigraphy and faults warranted? (5) Is it possible to reasonably incorporate alternative interpretations of subsurface fault geometry into GFM3.0? and (6) What observations or limitations relative to representation of faults and stratigraphic horizons in GFM3.0 might require further explanations? Also, selected cross sections were assessed. Overall, the staffs found GFM3.0 adequate for the purposes of: (1) depicting faults (42 are included), fault blocks (43 are included), stratigraphic horizons (50 surfaces are included) and the topographic surface at the scale of the repository site vicinity, and (2) providing a geologic framework for displaying and assessing the parameter distributions of other site characteristics The testing and assessment procedures, results and selected observations and limitations are presented in Appendix F.

As a result of the staff's favorable review of GFM3.0 and with consideration of the time and resources needed to develop a tool similar to GFM3.0, the staff will adopt and adapt GFM3.0 and updates, as needed, for its purposes of independent evaluation and analyses of the Yucca Mountain site.

4.4.2 Crustal Conditions

Crustal conditions characterize past, current, and predicted future stress and strain states and strain rates at the Yucca Mountain site and tectonic environs. Crustal conditions are critical to tectonic model development, fault slip, seismic motion, and development and reorientation of fractures. Technical bases for acceptance and review criteria are primarily derived from consideration of the application of crustal conditions as tools to evaluate seismic sources, faulting probability, structural control of groundwater flow, long-term evolution of natural and engineered barriers, and related SDS issues.

4.4.2.1 Acceptance Criteria

TBD FY 1999.

4.4.2.2 Technical Bases for Review Methods and Acceptance Criteria

Geologic stress components applicable to resolution of the SDS KTI are lithostatic, hydrostatic thermal, and seismotectonic stress. The present and predicted future states, including occurrence, distribution, and mechanisms of strain accommodation and how these strains affect the Yucca Mountain site and tectonic environs, form the primary bases for review methods and acceptance criteria for crustal conditions.

Stress states in rock may be (1) measured directly from fluid pressure, overcoring, borehole strain meters, hydro/gas-fracturing in well bores, (2) indirectly inferred from strain measurements, faults, fractures, overburden, dike orientations, earthquake focal mechanisms, or (3) abstracted from numerical and physical analogue models. Stress states determined from local in situ strain or stress measurements yield local values that are extrapolated over large volumes and may not reflect stress states at the larger scale. For example, upward scaling of locally determined stress and strain values may be affected by topography (Jaeger and Cook, 1979; Stock, et al., 1985, Stock and Healy, 1988), changes in lithology (Engelder, 1993) or mechanical interactions between structures (Dupin, et al., 1993). As a result, regional stress fields determined from direct and indirect local strain or stress measurements require sampling in multiple and spatially distributed locations (Bellier and Zoback, 1995, Minor, 1995; Minor, et al., 1997).

Strain release in the upper crust may be local or regional in scale and induce a combination of seismic, microseismic, or aseismic responses. Seismic response results from significant displacement or rupture along discrete fault surfaces or fault zones and may result in regional or local uplift or subsidence or both, with present or subsequent effects upon groundwater levels. Displacement along faults may introduce fast communication pathways between previously discrete fluid reservoirs or conduits or create or sever conduits between fluid systems or aquifers (Allan, 1989). Microseismic response may result from microcracking, formation or growth of fractures or joints, or slip on small-scale faults. The introduction of new fractures or fracture sets may provide new fluid pathways that accelerate, retard, or redirect fluid flow (Finkbeiner, et al., 1997). Aseismic responses include positive or negative dilation of existing fractures or both, depending upon fracture orientations relative to the stress field (Engelder, 1993). Preferential fracture dilation results in anisotropic changes in porosity and permeability. In every case, introducing fractures and faults reduces, to some degree, the bulk strength of coherent rock (Hoek and Brown, 1980).

Geologic strain rates and related seismic hazard risk analyses are commonly determined by comparing the length of palinspastically restored or retro-deformed cross-sections with the present-day length along the same line of section, given the longevity of the regional deformation. One of the basic assumptions in this method, when applied to rocks deformed in the uppermost crust, is that all strain is accommodated by cross-section scale faulting.

Estimates of regional extension based upon cross-section construction and restoration are minimum estimates of strain and do not account for the nonseismogenic strains accommodated by fractures, joints, small-scale faults, and microscale deformation (Wu 1993, Dunne and Ferrill, 1995). Considering the contribution of fractures, small faults, dikes and pressure solution features, it seems improbable that the total strain of the Yucca Mountain region is accommodated by seismogenic rupture on fault surfaces.

Strain rates are inherently sensitive to errors in estimation and timing of cumulative slip on faults Estimates of slip on individual faults or fault systems as determined from neo-tectonic features, including techniques such as trenching, stream offset mapping and alluvial fan mapping, are considered minimum values (Reheis, 1988; Klinger and Anderson, 1994, Ferrill, et al., 1996a; 1997). Fault restoration models assume that deformation or slip rates are constant throughout the life of the developing structure. This assumption effectively smooths or averages crustal deformation to a constant or fixed strain rate and cannot account for the likely episodic nature of many crustal scale deformation events. An average rate will neither distinguish nor accurately model areas where quiescence is interspersed with periods of strain rates that are relatively high when compared to the averaged or smoothed strain rate. For the same reasons, Global Positioning System (GPS) and other geodetic measurements of extension rates, gathered over the span of a few years or tens of years, represent only a small fraction of the life of crustal-scale structures and may not accurately reflect longer term rates of strain. Recent GPS and geodetic results from several locations, including the Yucca Mountain site, indicate possible anomalously high rates of strain (Wernicke, et al., 1998; Martinez, et al., 1998; USGS, 1998) with varying degrees of confidence (Gilmore, 1992; Savage, et al., 1994).

Geodetic leveling surveys beginning in 1907 (Gilmore, 1992) indicate subsidence in at least southern Crater Flat, across the eastward-dipping, normal-slip Bare Mountain fault zone. East of the Bare Mountain fault, survey results indicate a 20–100 mm drop in elevation over a period of 69 years (Gilmore, 1992), corresponding to throw rates well in excess of those measured from paleoseismic data (e.g., Anderson and Klinger, 1994). Slip rates on the Bare Mountain fault zone appear to increase southward concomitant with an increase in fault dip (Monsen, et al, 1992; Stamatakos, et al., 1997a). The change in slip rate and subsequent southward-increasing subsidence of Crater Flat is supported by studies of alluvial fan deposits along the eastern flank of Bare Mountain (Ferrill, et al., 1996a). Although the level-line results of Gilmore (1992) are not reflected in later surveys along a different line (USGS, 1996), the earlier level line surveys present additional uncertainty about the nature and rate of faulting on the Bare Mountain fault.

Although the USGS (1996) reports no changes in elevation due to displacement on the Bare Mountain Fault zone, its level line survey does not cross the southern portion of the Bare Mountain Fault zone. Instead, the survey deviates northward on the east side of the Bare Mountain Fault (benchmark S16, Figure 6-1) to cross Crater Flat to the northeast. The USGS (1996) does report negative height changes in the 1980–1984 survey with respect to the 1915 survey (Gilmore, 1992) Considering the brief (4 yr) time span of the level-line surveys (USGS, 1996) and the deviation from the level line of the 1915 survey, sufficient evidence does not exist to negate the possibility of height change across the southern portion of the Bare Mountain Fault.

Large slip rates exist within 50–100 km to the west and southwest of the Yucca Mountain site GPS surveys indicate high slip rates on the Death Valley Fault and Hunter Mountain fault systems within the Death Valley Shear Zone southwest of Yucca Mountain (Bennet, et al, 1997) Rates on the Death Valley Fault alone are 3–5 mm/yr If these rates persist or increase over time, the potential exists for multiple M_w 6 5–7 5 seismic events in the next 10,000 yr (Bennet, et al, 1997) Seismic activity to the east of the Yucca Mountain site at Little Skull

Mountain resulted in measurable changes in elevation related to the 1992 Little Skull Mountain earthquake (M5.4) (Savage, et al., 1994; USGS, 1996).

Wernicke, et al. (1998) document crustal scale elongation rates across Yucca Mountain that greatly exceed those inferred from the geologic record (Ferrill, et al., 1996a; 1997). These results are important because they provide alternative estimates to significant SDS and IA performance parameters including: (1) the frequency and magnitudes of earthquakes; (2) recurrence rates of faulting; and (3) probability of volcanism. Results from Wernicke, et al., (1998) suggest contemporary strain rates of 2 mm/yr across Yucca Mountain and Crater Flat in contrast to much smaller strain rates reported by Savage, et al., (1994). The strain rate reported by Wernicke, et al (1998) is more than ten times the strain rate estimated from the geological record of faulting and volcanism. Wernicke, et al. (1998) interpreted these "anomalous" rates to suggest an order-of-magnitude increase in seismic (including faulting) and volcanic hazards over the next 10 ka.

The results from the GPS survey require a serious examination of potential impact upon the Yucca Mountain site. However, assessing an increase in hazard of proportion equal to the increase in strain rate requires a series of suppositions that, at present, are either not supported by the structural setting at Yucca Mountain or are not addressed in the current tectonic models or assessment of crustal conditions (Connor, et al., in review). Suppositions that must be evaluated before seismic and volcanic hazards and hydrogeologic effects can be considered using GPS-determined strain rates are:

(1) That high strain rates must persist on time scales (10^3–10^4 yr) of duration sufficient to affect hazard estimates compared to estimates derived from the geologic record (10^5–10^6 yr)

(2) That episodic strain accumulations must directly correlate with episodic volcanic eruptions or increased seismicity

(3) The degree to which strain is partitioned between seismic, microseismic, and aseismic responses

(4) The effects of partitioned strain upon groundwater flow.

Critical Elements to Consider in Crustal Conditions

TBD FY 1999.

Evaluation of Crustal Conditions

TBD FY 1999.

5.0 STATUS OF SUBISSUE RESOLUTION

The Structural Deformation and Seismicity issue is an open item because the ancillary subissues are still under investigation. When the four subissues are adequately addressed by DOE, the SDS KTI will be resolved.

5.1 FAULTING

The goal of the faulting analyses performed by DOE was to locate and characterize the properties of faults that may be significant to repository design and repository performance. Faults (and fractures, discussed subsequently) constitute the principal structural weaknesses of the repository block, and the preferred pathways for heat and fluids through the natural barrier and engineered systems. With respect to design, DOE sought faults that might be seismogenic or able to intersect waste packages, in order to ascertain the faulting and seismic hazards for consideration as pre- and post-closure design bases. DOE intends to place its waste packages in positions that are setback from known faults. This consideration has already greatly influenced the repository boundary and layout plan for waste packages. With regard to long-term performance, faults and recurrence of faulting are significant for their effects on waste package performance, such as by rockfall, and for possibly influencing the flow of groundwater, heat and magmatic fluids, such as by providing conductive pathways or low permeability boundaries.

5.1.1 Analysis of Subissue Resolution

Criterion by criterion analysis of issue resolution TBD FY 1999.

5.1.2 Summary of Items Resolved at the Staff Level

5.1.2.1 Type I Faults

DOE (ref. Seismotectonic Synthesis Report, USGS, 1996) uses the terms relevant and potentially relevant in describing faults. Relevant faults are defined as those having documented Quaternary displacement and the capability of the maximum magnitude earthquake on the fault to produce 84th percentile peak acceleration greater than or equal to 0.1 g. Potentially relevant faults are considered subject to displacement on the basis of potential structural association with seismicity. Therefore, the following items are resolved:

(a) Seventy-eight specific faults are considered to be Type I faults by NRC staff (McKague, et al., 1996). These faults are listed in Appendices B-1, B-2, and B-4. Appendix B-1 lists 36 faults that both DOE and NRC have defined as relevant or potentially relevant or Type I, respectively. Appendix B-2 lists 33 faults that DOE defined as relevant or potentially relevant. The staff considers 29 of these to be Type I faults.

(b) DOE's identification of 33 faults that do not need to be investigated in detail (Appendix B-3). Type III faults are faults or fault zones that either are not subject to displacement, or, if subject to displacement, are of such length or located in such manner, that they will not affect repository design and/or performance (NUREG-1451; McConnell, et al., 1992).

(c) DOE's boundaries of areas to be investigated include (1) the faulting component of the geologic setting has a radius of 100 km around the Yucca Mountain site center, and (2) the controlled area constitutes the area of regulatory concern about direct effects of fault displacement

(d) DOE's use of Wells and Coppersmith (1994) equation to estimate the maximum capable earthquake for each fault in the faulting component

(e) DOE's use of 0.1 g threshold ground motion at the site, as suggested in NUREG-1451 (McConnell, et al., 1992)

(f) DOE's use of the 84th percentile peak ground acceleration value, which is more conservative than the median value used by McKague, et al (1996), as long as it compensates for DOE's use of non-conservative attenuation model (for faults closer than about 30 km to the site)

(g) DOE's selection of the minimum surface-rupture earthquake of Mw = 5.8, based on the Fort Sage 1950 event. Staff considers that value reasonable in light of the historic record.

(h) DOE's use of Piety (1995) as the principal source of data on age of faulting events younger than about 2 million years

5.1.2.2 Faulting Causing Waste Package Failures

The following item is resolved with the caveats enumerated in Section 3 2.1 1:

Faulting is not likely to cause sufficient waste package failures that would significantly affect repository performance (this appears to coincide with DOE's position), based on sensitivity studies described, with the caveats enumerated in Section 3.2.1 1.

5.1.2.3 Faulting Exhuming Waste Packages

The following item is resolved (see discussion in Section 3.2.1.1)

Faulting through the repository horizon will not likely have single or cumulative displacements sufficient to cause exhumation of a waste package during the performance period

Based on the conclusions in Section 3 2 1 1 above, the staff accepts DOE's Hypothesis No 16, "The amount of movement of faults through the repository horizon will be too small to bring waste to the surface, and too small and infrequent to significantly impact containment during the next few thousand years" (U.S DOE, 1998, p 15)

5.1.2.4 Site Characterization Analysis (SCA) Items

Comments 36, 62, 64, and 71 on the characterization, location, and setback from significant faults are resolved (see Appendix D for resolution rationale).

5.1.3 Summary of Items Open and Path to Resolution

5.1.3.1 Faulting

Open Item. The Faulting subissue - have faults and faulting that may significantly affect the performance of a repository been identified, characterized, and understood - is an open item because the PFDHA component has not been reviewed. When PSHA and Topical Report (TR#3) are reviewed, it is expected that the subissue will be resolved.

5.1.3.2 Type I Faults

Open Item. Thirteen specific faults listed in Appendix B-4, described by DOE (Simonds, et al., 1995a) are considered Type I faults by NRC (McKague, et al., 1996), but not all of them (eight faults) have been considered to be of significance to design or performance by DOE experts. However, these eight candidate Type I faults and the mutually resolved Type I faults have been brought to the attention of DOE's expert panelists (PSHA expert elicitation) who are evaluating them. Staff expect DOE's PSHA/PFDHA report and TR #3, both due in FY98, to contain DOE's evaluation of such potential Type I faults and re-evaluation of the accepted Type I faults (Appendices B-1, B-2, and B-4). Thus, staff expects to update status of remaining Type I faults in FY99, following review of PSHA/PFDHA and TR#3 Staff have found (McKague, et al., 1996) that the differences in DOE's and NRC's classifications of particular faults are rooted in just a few parameters, which can generally be resolved. The parameters are: (1) fault trace length; (2) attenuation function; and (3) selection of median or 84th percentile for identification of 0.1 g criterion. Resolution of significance of any specific faults that remain in contention should be discussed parameter by parameter with DOE experts, to constrain points of disagreement and mutually address those points.

5.1.3.3 Fault Displacement Hazard

Status will be provided in Revision 2 of this IRSR in FY99.

5.1.3.4 Site Characterization Analysis (SCA) Items

To date, NRC staff has identified ten comments: four comments were resolved: and six remain unresolved (Numbers 48, 59, 60, 61, 63, and 69) in the general area of faulting in the SCA of DOE's Site Characterization Plan (Appendix D)

5.2 SEISMICITY

The goal of the ground motion analysis performed by DOE was to identify ground motion models for input in the PSHA. The ground motion evaluation involved collecting and interpreting data, proposing models, and examining geological and geophysical information The ground motion evaluation was performed through workshops and expert elicitation Using various information and available data, each expert developed a series of ground motion estimates for a defined suite of earthquake magnitudes and distances, fault geometries and fault styles. Each of the experts provided the aleatory and epistemic uncertainties associated with his estimates, and these estimates were discussed in several workshops.

5.2.1 Analysis of Subissue Resolution

Criterion by criterion analysis of subissue resolution TBD FY 1999.

5.2.2 Summary of Items Resolved at the Staff Level

5.2.2.1 Probabilistic Seismic Hazard Methodology

DOE's probabilistic approach to seismic hazard analysis (U.S. DOE, 1997) was accepted in principle by NRC staff (Bell, 1996) for the evaluation of the seismic hazard and fault displacement hazard at Yucca Mountain (see DOE's TR #1). DOE decided, and the staff accepted, that the seismic hazard component of the 'Seismicity' subissue will be addressed through the issuance of three TRs (U.S. DOE, 1997, "Methodology to Assess Fault Displacement and Vibratory Ground Motion Hazards at Yucca Mountain)."

The staff has conducted an acceptance review of TR #1 in accordance with NRC's Division of High-Level Waste Management Review Plan, dated February 1994. In a letter dated September 7, 1994, the staff provided its comments on TR #1. On January 29, 1996, DOE provided responses to the staff comments. In a letter dated July 25, 1996 (Bell, 1996), the staff informed DOE that sufficient information had been provided to close all open issues related to TR #1. Because TR #1 is limited to describing the seismological assessment methodology, and TR #2 (U.S. DOE, 1997b), which also had been accepted by the staff, addressed "Preclosure Seismic Design Methodology for Geologic Repository at Yucca Mountain," the staff decided to issue a Preliminary Evaluation Report after receiving TR #3, which will document the results of both PSHA and seismic design values needed for the design of the facilities.

5.2.2.2 Site Characterization Analysis (SCA) Items

All SCA items on seismicity are resolved NRC staff has resolved Comments 66 and 67 in the area of seismic motion. Comment 66 dealt with the 10,000-year, cumulative-slip earthquakes, and Comment 67 dealt with a magnitude 5 5 cutoff (see Appendix D for resolution rationale)

5.2.3 Summary of Items Open and Path to Resolution

5.2.3.1 Seismic Hazard

Open Item The seismicity subissue - what are the viable models of seismic sources and seismic motion at Yucca Mountain - will be addressed upon staff review of PSHA and TR #3 in FY99 Resolution of the probabilistic seismic hazard methodology component has been already documented in this IRSR (Section 5 2 2 1)

The seismic hazard analysis results reflect the interpretation of different experts of the seismic source characteristics and earthquake ground motions Several workshops were held to address the needs of the experts For example, one of the workshops was held to identify important issues related to. (1) seismic source characterization, (2) recurrence models, (3) fault segmentation, (4) multiple fault ruptures and (5) fault geometry and kinematics. A second workshop goal was to address the methods and approaches to characterize seismic sources in the Yucca Mountain region and review new data available since the first workshop Another workshop debated the tectonic models, characterization of the faulting in the repository block, and the maximum background earthquakes In another workshop, the experts discussed the issue of how to apply ground motion estimates from regions other than Yucca Mountain Following the workshops, each of the ground motion experts documented the rationale behind his ground motion estimates. These estimates were discussed in a feedback workshop where the experts were informed of the implications of their interpretations of the ground motion estimates. Because earthquake data recorded in the Basin and Range Province are not sufficient to constrain an attenuation model for Yucca Mountain, the expert has to modify the western United States attenuation relations to the Yucca Mountain site Also, there were not enough data to measure the damping (Kappa) in the shallow tuff at Yucca Mountain. In the DOE's Draft PSHA (USGS, 1998), the experts used a value of 0.0186 sec for Kappa. As of mid-August 1998, the appropriate value of Kappa had not been presented to NRC by DOE. As presented by DOE in a Video Conference on June 18, 1998, DOE indicated that it is planning additional experiments to reassess the near ground motion attenuation values, including spatial variabilities in the repository site area. Therefore, the matters of Kappa value and seismic hazard are unresolved The staff will review the final PSHA and TR #3 when they are submitted by DOE and will provide comments in IRSR, Rev 2.

5.2.3.2 Ground Motion and Rockfall

Open Item. Relationship between ground motion and the amount and characteristics of rockfall and drift collapse.

DOE's RSS (U.S. DOE 1998) Hypothesis No. 17 states that, "The severity of ground motion in the repository horizon for tens of thousands of years will only slightly increase the amount of rockfall and drift collapse." DOE's analysis regarding this issue and how it will be treated in the disruptive events scenario has not been presented to the staff. The staff is performing sensitivity analyses and examining the significance of rockfall on the canisters. Preliminary results indicate that the number of container failures depends on the assumptions made regarding the location and properties of fractures in the rock, the strength of the canister, and the magnitude of ground motion The staff will address and comment on the resolution of this issue after reviewing DOE's TSPA-VA

5.3 FRACTURING AND STRUCTURAL FRAMEWORK OF THE GEOLOGIC SETTING

Status will be provided in Revision 2 of this IRSR FY 1999.

5.3.1 Analysis of Subissue Resolution

Criterion by criterion analysis of issue resolution TBD FY 1999

5.3.2 Summary of Items Resolved at the Staff Level

TBD in FY 1999.

5.3.2.1 Site Characterization Analysis (SCA) Items

There are no SCA open items on this subissue.

5.3.3 Summary of Items Open and Path to Resolution

TBD in FY 1999.

5.4 TECTONICS AND CRUSTAL CONDITIONS

5.4.1 Analysis of Subissue Resolution

Criterion by criterion analysis of issue resolution TBD in 1999.

5.4.2 Summary of Items Resolved at the Staff Level

5.4.2.1 Viable Tectonic Models

The following items are resolved:

(a) DOE's general description of which tectonic models are currently viable and which are not viable: of eleven tectonic models proposed, five were currently supported by existing data, i.e., are viable tectonic models (Appendix C-1), and six are not viable (Appendix C-2).

(b) DOE's consideration that the Bare Mountain fault is the dominant or master dip-slip fault of the extensional half graben that characterized the CF-BM region

(c) DOE's consideration that the dominant mode of deformation is that of extension with secondary effects from strike-slip faulting.

(d) DOE's concept of structural domains—regions that have a similar structural style and distinctive lithology evident at a scale of about 1:100,000 separated by discrete boundaries usually composed of faults or shear zones

5.4.2.2 Geologic Framework Model Version 3.0 (GFM3.0)

The following item is resolved (see discussion in Section 4 4 1 2 and Appendix F)

DOE's GFM3.0 is an adequate tool for various site-scale analyses of stratigraphy, faults, fault blocks, and their relationship to typography and to the 3D distribution of parameters associated with hydrologic and rock properties. GFM3.0 is the framework for the soon-to-be-released Integrated Site Model Version 3.0 (ISM 3.0). The NRC staff have developed the capability to fully utilize GFM3.0 and will use it to conduct independent analyses and as a review tool for various DOE models that have incorporated GFM3.0. For example, the staff are prepared to review ISM 3.0 when it is issued in FY99.

5.4.3 Summary of Items Open and Path to Resolution

5.4.3.1 Tectonics and Crustal Conditions

Open Item. The entire "Tectonics and Crustal Conditions" subissue is an open item because the PFDHA and PSHA components are not resolved. When the components are resolved, it is expected that the subissue will be resolved.

5.4.3.2 DOE's "Preferred" Tectonic Model

Open Item. Staff does not consider the USGS (1996) "preferred" model to be a viable tectonic model because:

- To get rollover similar to that observed in Crater Flat (Ferrill, et al., 1996b), the USGS (1996) model requires the addition of at least three blind faults with approximately 1 to 3 km of vertical separation; one in the center of Crater Flat (referred to in the model as the Crater Flat fault) and two on the boundaries of the model (west of Bare Mountain and east of Jackass Flat). In addition, blind faults must be active late in the deformation sequence to achieve the desired rollover (compare Figure 8.28a with 8.28e in USGS, 1996). NRC finds no geological or geophysical evidence for the existence of such blind faults.

- Rollover in the USGS (1996) model requires an effective elastic thickness of the upper crust of only 2 km. Thicker crust, akin to a stiffer elastic beam, will not flex under nominal stress conditions. Seismic data, including the 1992 Little Skull Mountain earthquake (e.g., Harmsen, 1994), suggest that the seismogenic crust is at least 15 km deep near Yucca Mountain.

- Boundary conditions between the ductile middle crust and the brittle upper crust in the USGS (1996) model are not described. Such boundary conditions are critical to the boundary element model and must be delineated to support this model.

- There are several alternative explanations for the lack of historic earthquakes on shallow normal faults not considered by DOE (USGS, 1996) One possibility is that slip rates on shallow-dipping portions of listric faults are aseismic, too slow to produce earthquakes (Ofoegbu and Ferrill, 1995, 1996, 1998). A second possibility is that because shallow-dipping faults are more efficiently oriented than steep faults to accommodate horizontal extension, seismic activity on detachment faults is rare compared to the relatively brief historic seismic record (Wernicke, 1995)

- Little Skull Mountain earthquake occurred in the footwall of the Crater Flat-Yucca Mountain fault system well east of any listric faults proposed in the detachment models. Therefore, the location of this earthquake has little bearing on the presence or absence of listric faults in the Yucca Mountain-Bare Mountain region.

- Flexure of the stiff beams required to produce clockwise rotations of southern Yucca Mountain and, thereby, account for vertical-axis rotations indicated by the paleomagnetic data (e.g., Rosenbaum, et al., 1991) results in a plan-view geometry opposite to that observed in Crater Flat. In the USGS model (see Figure 8.32 in USGS, 1996), fault separation is greatest in northern Yucca Mountain, and parts of southern Yucca Mountain appear to form small thrust faults to accommodate the deformation.

- Consideration of this model alone is insufficient to bound or quantify uncertainty related to multiple barriers or repository performance.

Therefore, the "preferred" model is not a viable model for probability calculations (including PSHA and PVHA). Other viable tectonic models (Appendix C-1) used by DOE in arriving at its TSPA-VA, PVHA, and PSHA will be evaluated in the context of those assessments and analyses, which are due to be reviewed by staff after their release by DOE.

5.4.3.3 DOE Integrated Site Models

Open Item. The staff committed to meet DOE's request that NRC staff review and comment on DOE's Integrated Site Geologic Framework Model ISM 2.0 (letter from N. Stablein to S. Brocoum dated December 15, 1997). DOE specifically requested the staff to evaluate whether or not the ISM 2.0 model is suitable for its intended uses (letter from S. Brocoum to J. Greeves dated November 21, 1997). Early in the staff review of ISM 2.0, DOE indicated that it was preparing ISM 3.0. The staff refocused on ISM 3.0 and is planning to review it in FY99. Additional discussion of the change in focus from ISM 2.0 to ISM 3 0 is documented in a letter dated September 30, 1998, from M. Bell to S. Brocoum.

5.4.3.4 Crustal Strain at Yucca Mountain

Open Item. The affects of crustal strain on repository design and performance remains to be determined (review of strain data, interpretations and potential effects on seismotectonic and volcanic hazards is summarized in Section 4.4.2 2). The path to resolution includes addressing the following matters:

(1) Are the GPS data reliable?

Current plans call for parallel geodetic studies by the USGS and the Cal Tech group, working through the University of Nevada. These additional GPS studies are to include additional GPS campaigns that will re-occupy existing benchmarks, additional level-line surveys, and installation of a permanent GPS network NRC and CNWRA will monitor the acquisition and interpretation of these data.

(2) How should GPS-derived rates be used to derive or modify existing seismic and volcanic hazard estimates at YM?

Given the observations of Wernicke, et al. (1998), the interpretation of high GPS strain rates in terms of hazards is critical to issue resolution. The recent CNWRA comment on the Wernicke, et al. (1998) paper (Connor, et al., in press) focused on the interpreted GPS-determined strain rates in terms of hazard. Fundamental assumptions both stated and inferred by Wernicke, et al. (1998) were discussed in the comment by CNWRA staff (Connor, et al., in review). Staff consider evaluation of these assumptions vital if the issue is to be resolved. These assumptions are:

(a) There is a direct, observable link between high crustal strain and the amount of volcanism and/or faulting in a given region, and all the GPS-determined strain will result in either large earthquakes or new volcanoes.

(b) The episode of anomalous strain rate is long enough to affect hazard but short enough to be ambiguous in the longer-term geological record.

Current Operations Plans in both the SDS and IA KTIs call for several technical investigations designed to reach issue resolution by examining these assumptions. These tasks include:

1. Determining if there is a direct link between high strain rates and increased seismicity and volcanism. Approaches include: (1) field-based (including GPS survey) investigations in comparable geologic settings; and (2) analog and numerical modeling experiments to assess how strain may be distributed between mechanisms that contribute to the hazards (volcanoes and earthquakes) and mechanisms that do not (fractures, small faults, fault creep).

2. Field-based investigations in regions with current high strain rate to assess the episodic nature of strain on time scales of 10^4 yr.

Evaluation of the GPS strain rate (data reliability) and its effects upon seismic and volcanic hazard assessment are critical to issue resolution. Data reliability, the possible episodic nature of high crustal strain rates at YM, the duration of high strain-rate episodes, and the mechanisms of strain accommodation are vital components of resolution.

5.4.3.5 Site Characterization Analysis (SCA) Items

To date, staff has identified four comments (Numbers 8, 47, 68, and 98) in the area of tectonic models that are open items (Appendix D).

5.4.3.6 Site Characterization Analysis (SCA) - Other Geoscience

To date, NRC staff has identified two comments (Numbers 32 and 51) and one question (Number 8) in areas of geology and geophysics related to SDS KTI in the SCA of DOE's Site Characterization Plan. All are open items. (Appendix D, 'Other Geoscience') ['Other Geoscience' is an arbitrary grouping of items from the SCA that are not specific to the four subissues categories].

6.0 REFERENCES CITED

Abrahamson, N.A., W.J. Silva, *Empirical response spectral attenuation relations for shallow crustal earthquakes*, Seismological Research Letters 68, 94–127, 1997.

Alexander, L.L., J.W. Handschy, *Fluid flow in a faulted reservoir system: Fault trap analysis for the block 330 field in Eugene Island, south addition, offshore Louisiana*, American Association of Petroleum Geologists Bulletin 82(3), 387–411, 1998.

Allan, U.S., *Model for hydrocarbon migration and entrapment within faulted structures*, American Association of Petroleum Geologists Bulletin 73(7), 803–811, 1989.

Anderson, R.E., *Thin-skinned distension in Tertiary rocks of southwestern Nevada*, Geological Society of America Bulletin 82, 43–58, 1971.

Anderson, L.W., R.E. Klinger, *Preliminary evaluation of the Bare Mountain fault zone, Nye County, Nevada*, Administrative Report in Support of Yucca Mountain Site Characterization Activity 8.3.1.17.4.3, Denver, CO, Bureau of Reclamation, 1994.

Anderson, J.G., J.N. Brune, J.N. Louie, Y. Zeng, M. Savage, G. Yu, Q. Chen, D. dePolo, *Seismicity in the western Great Basin apparently triggered by the Landers, California earthquake, 28, June 1992*, Bulletin of the Seismological Society of America 84, 863–891, 1994.

Anna, L.O., *Preliminary three-dimensional discrete fracture model of the Topopah Spring Tuff in the exploratory studies facility, Yucca Mountain area, Nye County, Nevada*, U.S. Geological Survey Open-File Report, Lakewood, CO, U.S. Geological Survey, 1997.

Anna, L.O., P. Wallman, *Characterizing the fracture network at Yucca Mountain, Nevada, Part 2; Numerical simulation of flow in a three-dimensional discrete fracture network*, Fractured Reservoirs: Descriptions, Predictions, and Applications: Rocky Mountain Association of Geologists 1997 Guidebook, Hoak, T.E., P.K. Blomquist, and A. Klawitter, e's, Denver, CO, Rocky Mountain Association of Geologists, 199–208, 1997.

Arabasz, W.J., D.R. Julander, *Geometry of seismically active faults and crustal deformation within the Basin and Range Province, northeastern Nevada. Extensional tectonics of the Southwestern United States: A Perspective on Processes and Kinematics*, L. Mayer, ed. Geological Society of America Special Paper 208, Boulder, CO, Geological Society of America, 43–74, 1986.

Armstrong, R.L., *Sevier orogenic belt in Nevada and Utah*, Geological Society of America Bulletin 79, 439–458, 1968.

Atwater, T., *Implications of plate tectonics for the Cenozoic tectonic evolution of western North America*, Geological Society of America Bulletin 81, 3,513–3,536, 1970.

Axen, G.J., W.J. Taylor, J.M. Bartlet, *Space-time patterns and tectonic controls of tertiary extension and magmatism in the Great Basin of the western United States*, Geological Society of America Bulletin 105, 56–76, 1993.

Barton, C.C., E. Larsen, Fractal geometry of two-dimension fracture networks at Yucca Mountain, Fundamentals of Rock Joints: Proceedings of the International Symposium on Fundamentals of Rock Joints, O. Stephanson, ed, Sweden, Bjorkliden, 77–84, 1985.

Barton, C.C., P.A. Hsieh, *Physical and Hydrologic-Flow Properties of Fractures*, Washington, DC, American Geophysical Union, 1989.

Barton, C.C., E. Larsen, W.R. Page, T.M. Howard, *Characterizing Fractured Rock for Fluid-Flow, Geomechanical, and Paleostress Modeling: Methods and Preliminary Results from Yucca Mountain, Nevada*, U.S. Geological Survey Open-File Report 93-269, Denver, CO, U.S. Geological Survey, 1993.

Barton, C.A., M.D. Zoback, D. Moos, *Fluid flow along potentially active faults in crystalline rock*, Geology 23(8), 683–686, 1995.

Barton, C.C., T.M. Howard, E. Larsen, *Tubular structures on the faces of cooling joints—A new volcanic feature*, EOS, Transactions of the American Geophysical Union 65, 1,148, 1984.

Bell, M.J., Letter (July 25) to S. J. Brocoum, U.S. Department of Energy, Washington, D. C., U.S. Nuclear Regulatory Commission, 1996.

Bellier, O., M.L. Zoback, *Recent state of stress change in the Walker Lane Zone, western Basin and Range province, United States*, Tectonics 14, 564–593, 1995.

Bennett, R.A., J.L. Davis, P. Elósegui, B.P. Wernicke, J.K. Snow, M.J. Abolins, M.A. House, G.L. Stirewalt, D.A. Ferrill, *Global positioning system constraints on fault slip rates in the Death Valley region, California and Nevada*, Geophysical Research Letters 24, 3,037–3,076, 1997.

Bernreuter, D. L., A. C. Boissonade, C. M. Short, Investigations of technique for the development of seismic design basis using probabilistic seismic hazard analysis, NUREG/CR-6606, 1998.

Bodin G.E., J. Gomberg, *Triggered seismicity and deformation between Landers, California, and Little Skull Mountain, Nevada, earthquakes*, Bulletin of the Seismological Society of America 84, 835–843, 1994.

Bohannon, R.G, T. Parsons, *Tectonic implications of post-30 Ma Pacific and North American relative plate motions*, Geological Society of America Bulletin 107, 937–959, 1995.

Boore, D.M., W.B. Joyner, T.E. Fumal, 1993, *Estimation of Response Spectra and Peak Accelerations from Western North American Earthquakes: An Interim Report*, U.S. Geological Survey Open-File Report 93-509, Denver, CO: U.S. Geological Survey, 1993.

Bowring, S.A., K.E. Karlstrom, *Growth and stabilization of the Proterozoic lithosphere in the southwestern United States*, Geology 18, 1,203–1,206, 1993.

Bradshaw, T.K., E.I. Smith, *Polygenetic Quaternary volcanism at Crater Flat, Nevada*, Journal of Volcanology and Geothermal Research 63, 165–182, 1994.

Brechtel, C.E., M. Lin, E. Martin, D.S. Kessel, *Geotechnical characterization of the north ramp of the exploratory studies facility, volume I of II data summary*, SAND95-0488/1UC-814, Albuquerque, NM, Sandia National Laboratories, 1995

Brethauer, G.E., D.L. Healy, C.H. Miller, *Statistical Analysis of the Gravity Method of Calculating the Depth of the Pre-Cenozoic Surfaces in Yucca Flat, Nevada Test Site*, Geological Prospecting Vol. 29, 31-38, 1981

Brocher, T.M., M.D. Carr, K.F. Fox, P.E. Hart, *Seismic reflection profiling across tertiary extensional structures in the eastern Amargosa Desert, Basin and Range Quadrangle, Nevada* Geological Society of America Bulletin 105, 30–46, 1993.

Brocher, T.M., P.E. Hart, W.C. Hunter, V.E. Langenheim, *Hybrid-source seismic reflection profiling across Yucca Mountain, Nevada, regional lines 2 and 3*, U.S. Geological Survey Open-File Report 96-02, Menlo Park, CA, U.S. Geological Survey, 1996.

Brocher, T.M., W.C. Hunter, and V.E. Langenheim, *Implications of seismic reflection and potential field geophysical data on the structure frame work of Yucca Mountain-Crater Flat Region, Nevada*, Geological Society of America Bulletin 110, 947-971, 1998.

Bruhn, R.L., R.A. Schultz, *Geometry and slip distribution in normal fault systems: Implications for mechanics and fault-related hazards*, Journal of Geophysical Research 101, 3,401–3,412, 1996.

Buesch, D.C., R.W. Spengler, T.C. Moyer, J.K. Geslin, *Proposed Stratigraphic Nomenclature and Macroscopic Identification of Lithostratigraphic Units of the Paintbrush Group Exposed at Yucca Mountain, Nevada*, U.S. Geological Survey Open-File Report 94-469, Denver, CO, U.S. Geological Survey, 1996.

Burchfiel, B.C., G.A. Davis, *Structural framework and evolution of the southern part of the Cordilleran orogeny, western United States*, American Journal of Science 272, 97–118, 1972.

Burchfiel, B.C., D.S. Cowan, G.A. Davis, *Tectonic overview of the Cordilleran orogen in the western United States*, The Cordilleran Orogen, Conterminous U.S.: The Geology of North America Volume G-3, B.C. Burchfiel, P.W. Lipman, and M.L. Zoback, eds, Boulder, CO, Geological Society of America, 407–479, 1982.

Burchfiel, B.C., K.V. Hodges, L.H. Royden, *Geology of Panamint Valley-Saline Valley pull-apart system, California, Palinspastic evidence for low-angle geometry of a Neogene range-bounding fault*, Journal of Geophysical Research 93, 10,422–10,426, 1987.

Byers, F.M., Jr., W.J. Carr, P.P. Orkild, W.D. Quinlivan, K.A. Sargent, *Volcanic Suites and Related Cauldrons of the Timber Mountain-Oasis Valley Caldera Complex, Southern Nevada*, U.S. Geological Survey Professional Paper 919, Reston, VA, U.S. Geological Survey, 1976.

Caine, J.S., J.P. Evans, C.B. Forster, *Fault zone architecture and permeability structure*, Geology 24, 1,025–1,028, 1996.

Camilleri, P.A., K.R. Chamberlain, *Mesozoic tectonics and metamorphism in the Pequop Mountains and Wood Hills region, northeast Nevada: Implications for the architecture and evolution of the Sevier orogen*, Geological Society of America Bulletin 109, 74–94, 1997.

Campbell, K.W., *Near-source attenuation of peak horizontal acceleration*, Bulletin of the Seismological Society of America 71: 2,039–2,070, 1981.

Campbell, K.W., *Predicting strong ground motion in Utah*, Evaluation of Regional and Urban Earthquakes and Risk in Utah, W.W. Hays, P.L. Gori, eds. U.S. Geological Survey Professional Paper 87-585II, L1-L90, Washington, D.C.: U.S. Geological Survey, 1987.

Carlos, B.A., S.J. Chipera, D.L. Bish, S.J. Craven, *Fracture-lining manganese oxide minerals in silicic tuff, Yucca Mountain, Nevada, U.S.A.*, Chemical Geology 107, 47–69, 1993.

Carr, W.J., *Regional Structural Setting of Yucca Mountain, Southwestern Nevada, and Late Cenozoic Rates of Tectonic Activity in Part of the Southwestern Great Basin, Nevada and California*, USGS Open-File Report 84-854, Denver, CO, U.S. Geological Survey, 1984.

Carr, W.J., *Structures in continuously cored, deep drill holes at Yucca Mountain, Nevada, with notes on calcite occurrence*, SAND91-7037, Albuquerque, NM, Sandia National Laboratories, 1992.

Carr, W.J., *Styles of extension in the Nevada test site region, southern Walker Lane belt; An integrated volcano-tectonic and detachment fault model*, Geological Society of America Memoir 176, Boulder, CO, Geological Society of America, 283–303, 1990.

Carr, W.J., *Volcano-tectonic history of Crater Flat, southwestern Nevada, as suggested by new evidence from drill hole USW-VH-1*, USGS Open-File Report 82-457, Denver, CO, U.S. Geological Survey, 1982.

Carr, W.J., *Volcano-tectonic setting of Yucca Mountain and Crater Flat, southwestern Nevada in geologic and hydrologic investigations of a potential nuclear waste disposal site at Yucca Mountain, southern Nevada*, M. Carr, and J. Yount, eds, U.S. Geological Survey Bulletin 1790. Denver, CO, U.S. Geological Survey, 35–49, 1988.

Carr, W.J., L.D. Parrish, *Geology of Drill Hole USW VH-2, and Structure of Crater Flat, Southwestern, Nevada*, USGS Open-File Report 85–475, Denver, CO, U.S. Geological Survey, 1985.

Carr, W.J., F.M. Byers, Jr., P.P. Orkild, *Stratigraphy and Volcano-Tectonic Relations of Crater Flat Tuff and Some Older Volcanic Units, Nye County, Nevada*, U.S. Geological Survey Professional Paper 1323, Reston, VA, U.S. Geological Survey, 1986a.

Carr, W.C., S.M. Keller, J.A. Grow, *Lithologic and Geophysical Logs of Drill Holes Felderhoff Federal 5-1 and 25-1, Amargosa Desert, Nye County, Nevada*, U.S. Geological Survey Open-File Report 95-115, Denver, CO, U.S. Geological Survey, 1995.

Carr, W.J., S.J. Wadell, G.S. Vick, J.M. Stock, S.A. Monsen, A.G. Harris, B.W. Cork, F.M. Byers, Jr., *Geology of Drill Hole UE25p#1: A Test Hole into Pre-Tertiary Rocks Near Yucca Mountain, Southern Nevada*, USGS Open-File Report 86-175, Denver, CO, U.S. Geological Survey, 1986b.

Caskey, S.J., R.A. Schweickert, *Mesozoic deformation in the Nevada Test Site and vicinity: Implications for the structural framework of the Cordilleran fold and thrust belt and Tertiary extension north of Las Vegas Valley*, Tectonics 11, 1,314–1,331, 1992.

Chekuri, V.S., S.W. Tyler, J.W. Fordham, *The role of fracture coatings on water imbibition into unsaturated tuff from Yucca Mountain*, Nevada Agency for Nuclear Projects/Nuclear Waste Project Office NWPO-TR-024-95, Carson City, NV, Nevada Agency for Nuclear Projects, 1995.

Chester F.M., J.M. Logan, *Composite planar fabric of gouge from the Punchbowl Fault, California*, Journal of Structural Geology 9, 621–634, 1986.

Christiansen, R.L., P.W. Lipman, W.J. Carr, F.M. Byers, Jr., P.P. Orkild, K.A. Sargent, *Timber Mountain-Oasis Valley caldera complex of southern Nevada*, Geological Society of America Bulletin 88, 943–959, 1977.

Connor, C.B., B.E. Hill, *Three nonhomogeneous Poisson models for the probability of basaltic volcanism: Application to the Yucca Mountain region, Nevada*, Journal of Geophysical Research 100, 10,107–10,125, 1995.

Connor, C.B., J.A. Stamatakos, D.A. Ferrill, B.E. Hill, *Technical Comment on Anomalous Strain Rates in the Yucca Mountain Area, Nevada by Wernicke, et al.*, Science, submitted, In review.

Connor, C.B., J.A. Stamatakos, D.A. Ferrill, B.E. Hill, S.B.L. Magsino, P. La Femina, R.H. Martin, *Integrating structural models into volcanic hazard assessments: An example from Yucca Mountain, Nevada*, EOS Transactions of the American Geophysical Union, San Francisco Annual Meeting, Washington, DC, American Geophysical Union, F20, 1996.

Connor, C.B., S. Lane-Magsino, J.A. Stamatakos, R.H. Martin, P.C. La Femina, B.H. Hill, S. Lieber, *Magnetic surveys help reassess volcanic hazards at Yucca Mountain, Nevada*. EOS, Transactions of the American Geophysical Union 78, 73, 77–78, 1997.

Coppersmith, K.J., *Update on data related to fault displacement and vibratory ground motion hazard at Yucca Mountain for use in EPRI performance assessment, in Yucca Mountain total system performance assessment, Phase 3*, Prepared by Kessler, J., and R. McGuire, EPRI

TR-107191 3055-02 Final Report, Palo Alto, CA, Electric Power Research Institute, 11-1 to 11-15, 1996.

Coppersmith, K.J., R.R. Youngs, *Risk-Based Approach to High-Level Waste Repository Evaluation Plan 2*, EPRI TR-100384, 1992.

Cornwall, H.R., *Geology and mineral deposits of Nye County, Nevada*, Nevada Bureau of Mines and Geology Bulletin 77, Reno, NV, Nevada Bureau of Mines, 1972.

Cornwall, H.R., F.J. Kleinhample, *Geology of the Bare Mountain Quadrangle*, U.S. Geological Quadrangle Map GQ-157, Scale 1:62,500, Reston, VA, U.S. Geological Survey, 1961.

Cornwall, H.R., F.J. Kleinhample, *Geology of the Bullfrog quadrangle and ore deposits related to the Bullfrog Hills caldera, Nye County, Nevada and Inyo County, California*, U.S. Geological Survey Professional Paper 454-J, Reston, VA, U.S. Geological Survey, 1964.

Crowe, B., F. Perry, J. Geissman, L. McFadden, S. Wells, M. Murrell, J. Poths, G.A. Valentine, L. Bowker, K. Finnegan, *Status of volcanism for the Yucca Mountain site characterization project*, Los Alamos National Laboratory Report 12908-MS, Los Alamos, NM, Los Alamos National Laboratory, 2-18 to 2-21, 1995.

Czarnecki, J.B., C.C. Faunt, C.W. Gable, G.A. Zyvoloski, *Hydrogeology and Preliminary Three-Dimensional Finite-element Groundwater Flow Model of the Site Saturate Zone, Yucca Mountain, Nevada*, Yucca Mountain Project Milestone Report SP23NM3, Denver, CO: U.S. Geological Survey, 1997.

Davies, R.K., M Crawford, W.F. Dula, Jr., M. Cole, G. Dorn, *Outcrop interpretation of seismic-scale normal faults in southern Oregon: Description of structural styles and evaluation of subsurface interpretation methods*, The Leading Edge 16, 1,135–1,141, 1997.

Davis, G.A., P.J. Coney, *Geologic development of the metamorphic core complexes*, Geology 7, 120–124, 1979.

Dawers, N.H., M.H. Anders, *Displacement-length scaling and fault linkage*, Journal of Structural Geology 17, 607–614, 1995.

Day, W.C., C.J. Potter, D.S. Sweetkind, R.P. Dickerson, C.A. San Juan, *Bedrock geologic map of the central block area, Yucca Mountain, Nye County, Nevada*, U.S. Geological Survey Miscellaneous Investigations Series Map I-2601, Denver, CO, U.S. Geological Survey, Scale 1:6000, 1997.

dePolo, C.M., D.G. Clark, D.B. Slemmons, A.R. Ramelli, *Historical surface faulting in the Basin and Range Province, western North America, Implications for fault segmentation*, Journal of Structural Geology 13, 123–126, 1991.

Dickenson, W.R., *Kinematics of Transrotational Tectonism in the California Transverse Ranges and Its Contribution to Cumulative Slip Along the San Andreas Transform Fault System*, Geological Society of America Special Paper 305, Boulder, CO, Geological Society of America, 1996.

Dokka, R.K., C.J. Travis, *Role of the eastern California shear zone in accommodating Pacific-North American plate motion*, Geophysical Research Letters 17, 1,223–1,326, 1990

Dula, W.F., Jr., *Geometric models of listric normal faults and rollover folds*, American Association of Petroleum Geologists Bulletin 75, 1,609–1,625, 1990.

Dunne, W.M., D.A. Ferrill, *Fractal strain distribution and its implications for cross-section balancing, Discussion*, Journal of Structural Geology 17, 757–760, 1995.

Dupin, J.-M., W. Sassi, J. Angelier, *Homogeneous stress hypothesis and actual fault slip, a distinct element analysis*, Journal of Structural Geology 15, 1,033–1,043, 1993.

Earthfield Technology, Inc., *Summary Report Magnetic and Gravity Study of the Yucca Mountain Area, Nevada*, prepared for L. Berkeley Lab., November 1995.

Eldredge, S., V. Bachtadse, and R. Van der Voo, *Paleomagnetism and the orocline hypothesis*, Tectonophysics 119, 153–179, 1985.

Engelder, T., *Stress Regimes in the Lithosphere*, Princeton, NJ, Princeton University Press 1993.

Engelder, T., M.P. Fischer, *Loading configurations and driving mechanisms for joints based on the Griffith energy-balance concept*, Tectonophysics 256, 253–277, 1996.

Faulds, J.E., J.W. Bell, D.L. Feuerbach, A.R. Ramelli, *Geologic map of the Crater Flat Area, Nevada*, Nevada Bureau of Mines and Geology Map 101, Scale 1:24,000, Reno, NV, Nevada Bureau of Mines and Geology, University of Nevada, Reno, 1994.

Fedotov, S.A., Y.K. Markhinin, *The Great Tolbachik Fissure Eruption*, Cambridge, United Kingdom, Cambridge University Press, 1983.

Ferrill, D.A., A.P. Morris, *Geometric considerations of deformation above curved normal faults and salt evacuation surfaces*, The Leading Edge 16, 1,129–1,133, 1997.

Ferrill, D.A, R.H. Groshong, Jr., *Kinematic model for the curvature of the northern Subalpine Chain, France*, Journal of Structural Geology 15, 523–541, 1993.

Ferrill, D.A., W.M. Dunne., *Cover deformation above a blind duplex, an example from West Virginia, U.S.A.*, Journal of Structural Geology 11, 421–431, 1989.

Ferrill, D.A., J.A. Stamatakos, A.P. Morris, *Structural controls on progressive deformation of the Yucca Mountain (Nevada) region*, Geological Society of America Abstracts with Programs 28, A–192, 1996c.

Ferrill, D.A., J.A. Stamatakos, D. Sims, *Normal fault corrugation: Implications for growth and seismicity of active normal faults*, Journal of Structural Geology, In review, b.

Ferrill, D.A., J.A. Stamatakos, H.L. McKague, *Quaternary slip history of the Bare Mountain fault (Nevada) from the morphology and distribution of alluvial fan deposits. REPLY*, Geology 25. 190, 1997.

Ferrill, D.A., A.P. Morris, D.B. Henderson, R.H. Martin, *Tectonic Processes in the central Basin and Range region*, NRC High-Level Radioactive Waste Research at CNWRA, July-December 1994, B. Sagar, ed, San Antonio, TX, Center for Nuclear Waste Regulatory Analyses, 121–139, 1995b

Ferrill, D.A., A.P. Morris, S.M. Jones, J.A. Stamatakos, *Extensional layer-parallel shear and normal faulting*, Journal of Structural Geology 20, 355–362, 1998.

Ferrill, D.A., A. P. Morris. J.A. Stamatakos, J.A. Sims, D.W. Sims, *Crossing conjugate normal faults*, IM 20 1402-47771-950 (invited manuscript to American Association of Petroleum Geologists Book, "Recognition and Characterization of Reservoir Scale Structures"), 1998.

Ferrill, D.A., D.B. Henderson, J.A. Stamatakos, K.H. Spivey, A.P. Morris, *Tectonic processes in the central Basin and Range*, NRC High-Level Radioactive Waste Research at CNWRA, January-June, 1995, B. Sagar, ed, CNWRA 95-01S, San Antonio, TX, Center for Nuclear Waste Regulatory Analyses, 6.1-6.27, 1995a.

Ferrill, D.A. S.R. Young, G.L. Stirewalt, A.P. Morris, D.B. Henderson, *Tectonic processes in the central Basin and Range region*, NRC High-Level Radioactive Waste Research at Center for Nuclear Waste Regulatory Analyses, January–June 1994, B. Sagar, ed, CNWRA 94-015, San Antonio, TX, Center for Nuclear Waste Regulatory Analyses, 139–160, 1994.

Ferrill, D.A., G.L. Stirewalt, D.B. Henderson, J.A. Stamatakos, K.H. Spivey, B.P. Wernicke, *Faulting in the Yucca Mountain Region, Critical Review and Analyses of Tectonic Data from the Central Basin and Range*, NUREG/CR-6401, Washington, DC, U.S. Nuclear Regulatory Commission, 1996b.

Ferrill, D.A., J.A. Stamatakos, A.P Morris, R.D Donelick, A.E. Blythe, S.M. Jones K.P. Spivey, *Geometric, thermal, and temporal constraints on the tectonic evolution of Bare Mountain*, Geological Society of America Bulletin, In review, a.

Ferrill, D.A., J.A. Stamatakos, S.M. Jones, B. Rahe, H.L. McKague, R.H. Martin, A.P. Morris, *Quaternary slip history of the Bare Mountain fault (Nevada) from the morphology and distribution of alluvial fan deposits*, Geology, 24, 559-562, 1996a.

Finkbeiner, T., C.A. Barton, M. Zoback, *Relationships among in-situ stress, fractures and faults, and fluid flow, Monterey formation, Santa Maria Basin, California*, American Association of Petroleum Geologists Bulletin 81, 1,975–1,999, 1997.

Fleck, R.J., B.D. Turrin, D.A. Sawyer, R.G. Warren, D.E. Champion, M.R. Hudson, S.A. Minor, *Age and character of basaltic rocks of the Yucca Mountain region, southern Nevada*, Journal of Geophysical Research 101, 8,205–8,227, 1996

Flint, A.L., J.A. Hevesi, L.E. Flint, *Conceptual and Numerical Model of Infiltration for the Yucca Mountain Area, Nevada*, U.S. Geological Survey Water Resources Investigation Report, Milestone 3GUI623M, Denver, CO, U.S. Geological Survey, 1996.

Flint, L.E., A.L. Flint, *Shallow infiltration processes at Yucca Mountain, Nevada-Neutron logging data 1984-93*, U.S. Geological Survey Water-Resources Investigations Report 95-4035, Denver, CO, U.S. Geological Survey, 1995.

Fridrich, C.J., *Tectonic evolution of the Crater Flat Basin, Yucca Mountain region, Nevada, Cenozoic Basins of the Death Valley Region*, L. Wright, ed, Geological Society of America Special Paper, In press.

Fridrich, C.J., J.W. Whitney, M.R. Hudson, B.M. Crowe, *Late Cenozoic extension, vertical a... rotation, and volcanism in the Crater Flat basin, southwest Nevada, Cenozoic basins of the Death Valley region*, L. Wright and B. Troxel, e's, Geological Society of America Special Paper, In press.

Frizzell, V.A. Jr., J. Shulters, *Geologic Map of the Nevada Test Site, Southern Nevada*, U.S. Geological Survey Miscellaneous Investigations Series, Map I-2046, scale 1:100,000, Denver, CO, U.S. Geological Survey, 1990.

Gabrielse, H., W.S. Snyder, J.H. Stewart, *Sonoma orogeny and Permian to Triassic tectonism in western North America*, Geology 11, 484–486, 1983.

Gay, N.C., W.D. Ortlepp, *Anatomy of a mining-induced fault zone*, Geological Society of America Bulletin, Part I, 90, 47–58, 1979.

Geldon, A.L., A.M.A. Umari, M.F. Fahy, J.D. Earle, J.M. Gemmell, J. Darnell, *Results of hydraulic and conservative tracer tests in miocene tuffaceous rocks at the C-Hole complex, 1995 to 1997, Yucca Mountain, Nye County, Nevada*, 1997 Milestone Report SP23PM3, Las Vegas, NV, U.S. Geological Survey, 1997.

Ghosh, A., R.D. Manteufel, G.L. Stirewalt, *FAULTING Version 1.0 – A code for simulation of direct fault disruption*, Technical description and User's Guide, CNWRA 97-002, San Antonio, TX, Center for Nuclear Waste Regulatory Analyses, 1997.

Ghosh, A., J. A. Stamatakos, S. Hsiung, R. Chen, A. H. Chowdhury, H. L. McKague, *Key Technical Issue Sensitivity Analysis with SEISMO and FAULTO Modules within the TPA (Version 3.3.3) Code*, CNWRA Intermediate Milestone 1402-471-710, San Antonio, TX: Center for Nuclear Waste Regulatory Analyses, 1998.

Gillett, S.L., D.R. Van Alstine, *Remagnetization and tectonic rotation of Upper Precambrian and Lower Paleozoic strata from the Desert Range, southern Nevada*, Journal of Geophysical Research 87, 10,929–10,953, 1982.

Gillett, S.L., J.W. Geissman, Regional Late Paleozoic remagnetization of shallow-water carbonate rocks in the Great Basin, *The usefulness of "micro"-fold tests from late compaction fabrics, Application of Paleomagnetism to Sedimentary Geology*, Society for Sedimentary Geology (SEPM) Special Publication 49, 129–147, 1993.

Gilmore, T.D., *Geodetic leveling data used to define historical height changes between Tonopah Junction and Las Vegas, Nevada*, U.S. Geological Survey Open-File Report 92-450, Menlo Park, CA, U.S. Geological Survey, 1992.

Goddard, J.V., J.P. Evans, *Chemical changes and fluid-rock interactions in faults of crystalline thrust sheets, northwestern Wyoming, USA*, Journal of Structural Geology 17, 533–547, 1995.

Gray, M.B., Personal Communication to J. Stamatakos, 1998. (Footnote 1)

Gray, M. B., J.A. Stamatakos, *A new model for evolution of fold and thrust belt curvature from integrated structural and paleomagnetic results around the Pennsylvania Salient*, Geology 25, 1,067–1,070, 1998.

Groshong, Jr., R.H., *Low-temperature deformation mechanisms and their interpretation*, Geological Society of America Bulletin 100, 1,329–1,360, 1988.

Groshong, Jr., R.H., *Unique determinations of normal fault shape from hanging-wall bed geometry in detached half grabens*, Eclogae Geologica Helvetica 83, 455–471, 1990.

Grow, J.A., C.E. Barker, A.G. Harris, *Oil and gas exploration near Yucca Mountain, southern Nevada*, Proceedings of Fifth Annual International Conference on High-Level Radioactive Waste Management, La Grange Park, IL, American Nuclear Society International, 1,298–1,315, 1994.

Gutenberg, B., and C.F. Richter, *Seismicity of the Earth*, Princeton, NJ, Princeton University Press, 1954.

Hamilton, W.B., Crustal extension in the Basin and Range province, southwestern United States, *Continental Extensional Tectonics*, M.P. Coward, J.F. Dewey, and P.L. Hancock, e's, London, England, Geological Society Special Publications 28, 155–176, 1987.

Hamilton, W.B., Detachment faulting in the Death Valley Region, California and Nevada, *Geologic and hydrologic investigations of a potential nuclear waste disposal site at Yucca Mountain, southern Nevada*, M.D. Carr and J.C. Yount, e's, U.S. Geological Survey Bulletin 1790, 51–85, 1988.

Hardyman, R.F. J.S. Oldow, *Tertiary tectonic framework and Cenozoic history of the central Walker Lane, Nevada, Geology and Ore Deposits of the Great Basin*, G.L. Raines, R.E. Lisle, R.W. Schafer, W.H. Wilkinson, e's, Las Vegas, NV, Geological Society of Nevada Symposium Proceedings 1, 279–301, 1991.

Harmsen, S.C., *Seismicity and focal mechanisms for the southern Great Basin of Nevada and California in 1990*, USGS Open-File Report 91-367, U.S. Geological Survey, 1991

Harmsen, S.C., *Seismicity and focal mechanisms for the southern Great Basin of Nevada and California in 1991*, USGS Open-File Report 92-340, U.S. Geological Survey, 1993

Harmsen, S.C., *The Little Skull Mountain, Nevada, earthquake of 29 June 1992: Aftershock focal mechanisms and tectonic stress field implications*, Bulletin of the Seismological Society of America 84, 1,484–1,505, 1994.

Harmsen, S.C., C.G. Bufe, *Seismicity and focal mechanisms for the southern Great Basin of Nevada and California, 1987 through 1989*, USGS Open-File Report 91-572, U.S. Geological Survey, 1992.

Henderson, D.B., D.A. Ferrill, and K.C. Clarke, *Mapping geological faults using image processing techniques applied to hill-shaded digital elevation models*, Proceedings of the IEEE Southwest Symposium on Image Analysis, San Antonio, TX, 1996.

Higgs, W.G., G.D. Williams, C.M. Powell, *Evidence for flexural shear folding associated with extension al faults*, Geological Society of America Bulletin 103, 710–717, 1991.

Hill, B.E., C.B. Connor, *Volcanic systems of the Basin and Range*, NRC High-Level Radioactive Waste Research at CNWRA, July–December, 1995, B. Sagar ed, CNWRA 95-02S, San Antonio, TX, Center for Nuclear Waste Regulatory Analyses, 5-1 to 5-21, 1996.

Hill, C.A., Y.V. Dublyansky, R.S. Harmon, C.M. Schluter, *Overview of calcite/opal deposits at or near the proposed high-level nuclear waste site, Yucca Mountain, Nevada, USA, Pedogenic, hypogene, or both?* Environmental Geology 26, 69–88, 1995.

Hodges, K.V., J.D. Walker, *Extension in the Cretaceous Sevier orogeny, North American Cordillera*, Geological Society of America Bulletin 104, 560–569, 1992.

Hoek, E., E.T. Brown, *Underground Excavations in Rock*, The Institution of Mining and Metallurgy, London, Hertford, England, Stephen Austin and Sons, Ltd, 1980.

Hoisch, T.D., C. Simpson, *Rise and tilt of metamorphic rocks in the lower plate of a detachment fault in the Funeral Mountains, Death Valley, California*, Journal of Geophysical Research 98, 6,805–6,827, 1993.

Hoisch, T.D., M.T. Heizler, R.E. Zartman, *Timing of detachment faulting in the Bullfrog Hills and Bare Mountain area, southwestern Nevada, Inferences from $^{40}Ar/^{39}Ar$, K-Ar, U-Pb, and fission track thermochronology*, Journal of Geophysical Research 102, 2,815–2,833, 1997.

Holm, D.K., J.W. Geissman, and B. Wernicke, *Tilt and rotation of the footwall of a major normal fault system, Paleomagnetism of the Black Mountains, Death Valley extended terrain, California*, Geological Society of America Bulletin 105, 1,373–1,387, 1993.

Hudson, M.R., *Paleomagnetic data bearing on the origin of arcuate structures in the French Peak-Massachusetts Mountains area of southern Nevada*, Geological Society of America Bulletin 104, 581–594, 1992.

Hudson, M.R., D A Sawyer, R.G Warren, *Paleomagnetism and rotation constraints for the Miocene southwestern Nevada volcanic field*, Tectonics 13, 258–277, 1994.

Hudson, M.R., S A. Minor, C.J. Fridrich, *The distribution, timing, and character of steep-axis rotations in a broad zone of dextral shear in southwestern Nevada*, Geological Society of America Abstracts with Programs 28, Denver, CO, Geological Society of America, A451, 1996

Hunter, R.L., C.J. Mann, *Techniques for determining probabilities of events and processes affecting the performance of repositories*, SAND83-1342, NUREG/CR-3354, Albuquerque, NM, Sandia National Laboratory, 1990.

Idriss, I.M., *Earthquake ground motions at soft soil sites*, 2nd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics 3, 2,265–2,272, 1991.

Jaeger, J.C., N.G.W. Cook, *Fundamentals of Rock Mechanics*, Chapman and Hall, New York, NY, 1979.

Janssen, B., *Modelisation numerique de l'extension de la croute terrestre avec des examples du basin and range, Etats-Unis*, These de doctorat, l'Universite Louis-Pasteur de Strasbourg, 1995.

Joyner, W.B., D.M. Boore, *Peak horizontal acceleration and velocity from strong motion records including records from the 1979 Imperial Valley, California, earthquake*, Bulletin of the Seismological Society of America 71, 2,011–2,038, 1981.

Kane, M.F., R.E. Bracken, *Aeromagnetic map of Yucca Mountain and Surrounding Regions, Southwest Nevada*, USGS Open-File Report 83-616, Reston, VA, U.S. Geological Survey, 1983.

King, G.C.P., R.S. Stein, J. Lin, *Static stress changes and triggering of earthquakes*, Bulletin of the Seismological Society of America 84, 935–953, 1994.

Klinger, R.E., L.W. Anderson, *Topographic profiles and their implications for late Quaternary activity on the Bare Mountain fault, Nye County, Nevada*, Geological Society of America Abstracts with Programs, A63, 1994.

Kotra, J.P., M.P. Lee, N.A. Eisenberg, A.R. DeWispelare, *Branch technical position on the use of expert elicitation in the high-level radioactive waste program*, NUREG–1563, Washington, DC, U.S. Nuclear Regulatory Commission, 1996.

Langenheim, V.E., D.A. Ponce, *Ground magnetic studies along a regional seismic-reflection profile across Bare Mountain, Crater Flat and Yucca Mountain, Nevada*, USGS Open-File Report 95-834, U.S. Geological Survey, 1995.

Langenheim, V.E., K.S. Kirchoff-Stein, H.W. Oliver, *Geophysical investigations of buried volcanic centers near Yucca Mountain, Nevada*, Proceedings of the Third International High

Level Radioactive Waste Management Conference. La Grange Park, IL. American Nuclear Society, 1,840–1,846. 1993.

Langenheim, V.E., S F. Carle, D.A Ponce, J D Phillips, *Revision of an Aeromagnetic Survey in the Lathrop Wells Area, Nevada*, USGS Open-File Report 91-46. Reston, VA, U S Geological Survey, 1991.

Le Cain, G.D., *Air-injection Testing in Vertical Boreholes in Welded and Nonwelded Tuff, Yucca Mountain, Nevada*, U.S Geological Survey, Water-Resources Investigation Report, 96-4262, 1997.

Levy, S.S., D.S. Sweetkind, D.S. Fabryka-Martin, P.R Dixon, J.L Roach, L.E Wolfsberg, D. Elmore, P. Sharma, *Investigations of structural controls and mineralogic associations of Chlorine-36 fast pathways in the ESF*, Los Alamos Milestone SP2301M4, Los Alamos, NM, Los Alamos National Labs, 1997.

Lienkaemper, J.J., S.K. Pezzopane, M.M. Clark, M.J. Rymer, *Fault fractures formed in association with the 1986 Chalfant Valley, California, earthquake sequence, Preliminary report*, Bulletin of the Seismological Society of America 77(1), 297–305, 1987.

Lin, M., M.P. Hardy, S.J. Bauer, *Fracture analysis and rock quality designation estimation for the Yucca Mountain site characterization project*, SAND92-0449, 1993.

Luhr, J.F., and T. Simkin, *Paricutin, the Volcano Born in a Mexican Cornfield*, Phoenix, AZ, Geosciences Press Inc., 1993.

Magsino, S.L., C.B. Connor, B.E. Hill, J.A. Stamatakos, P.C. La Femina, D.W. Sims, R.H. Martin, *Ground magnetic surveys in the Yucca Mountain Region, Nevada (1996–1997)*, CNWRA 98-01, San Antonio, TX, Center for Nuclear Waste Regulatory Analyses, 11–14, 1998.

Majer, E.L., M. Feighner, L. Johnson, K. Lee, T. Daley, E. Karageorgi, P. Parker, T. Smith, K. Williams, A. Romero, T. McEvilly, Milestone 0BB02, *Results of Geophysical Surveys Along North-South and South ESF Alignment* and Milestone 0BB03, *Summary Report, Interpretations of Multiple Geophysical Surveys*, Berkeley, CA, Ernest Orlando Lawrence Berkeley National Laboratory, 1997.

Maldonado, F., *Structural geology of the upper plate of the Bullfrog Hills detachment fault system, southern Nevada*, Geological Society of America Bulletin 102, 992–1,006, 1990.

Manteufel, R.D., R.G. Baca, S. Mohanty, M.S. Jarzemba, R.W. Janetzke, S.A. Stothoff, C.B. Connor, G.A. Cragnolino, A.H. Chowdhury, T J. McCartin, T.M. Ahn, *Total System Performance Assessment (TPA) Version 3.0 Code*, Module Description and User's Guide, San Antonio, TX, Center for Nuclear Waste Regulatory Analyses, 1997.

Marshak, S., *Kinematics of orocline and arc formation in thin-skinned orogens*, Tectonics 7, 73–86, 1988.

Martinez, L J , C M Meertens, R B Smith, *Rapid deformation rates along the Wasatch fault zone, Utah, from first GPS measurements with implication for earthquake hazard* Geophysi Research Letters 25, 567–570, 1998

Mayer, J R., J.M. Sharp, Jr , *Fracture control of regional groundwater flow in a carbonate aquifer in a semi-arid region*, Geological Society of America Bulletin 110(2), 269–283, 1998

McConnell, K.I , M.E. Blackford, A K Ibrahim, *Staff Technical Position on Investigations to Identify Fault Displacement Hazards and Seismic Hazards at a Geologic Repository*, NUREG–1451, Washington, DC. U.S Nuclear Regulatory Commission, 1992.

McKague, H L , *Identification of Type II Faults in the Yucca Mountain Area. Rev 2*. Letter Report, San Antonio, TX, Center for Nuclear Regulatory Analyses, 1996

McKague, H.L., J A. Stamatakos, D.A. Ferrill, *Type I Faults in the Yucca Mountain Region*. CNWRA 96-007 Rev. 1, San Antonio, TX, Center for Nuclear Waste Regulatory Analyses, 1996.

Menges, C.W., J.W. Whitney, J.A. Coe, J.R. Wesling, F.H. Swan, E M. Taylor, D J. Ponti, *Summary of paleoseismic investigations of the Paintbrush Canyon, Bow Ridge, and Stagecoach Road faults of eastern Yucca Mountain, Nye County, Nevada*. U.S. Geological Survey Open-File Report 95-738, Denver, CO, U.S. Geological Survey, 1995

Meremonte, M., J. Gomberg, E. Cranswick, *Constraints on the 29 June 1992 Little Skull Mountain, Nevada, earthquake sequence provided by robust hypocenter estimate*. Bulletin o the Seismological Society 85, 1,039–1,049, 1995.

Minor, S.A., *Superposed local and regional paleostresses: Fault-slip analysis of neogene extensional faulting near coeval caldera complexes, Yucca Flat, Nevada*, Journal of Geophysical Research 100, 12,507–12,528, 1995.

Minor, S.A., M.R. Hudson, C.J. Fridrich, *Fault-slip data, paleomagnetic data, and paleostress analyses bearing on the neogene tectonic evolution of northern Crater Flat Basin, Nevada*. U Geological Survey Open File Report 97-285, Denver, CO, U.S. Geological Survey, 1997

Monsen, S.A., *Structural Evolution and Metamorphic Petrology of the Precambrian-Cambrian Strata, Northwest Bare Mountain, Nevada*, M.S. thesis, Davis, CA, University of California at Davis, 1983.

Monsen, S.A., M.D. Carr, M.C Reheis, P.A. Orkild, *Geologic map of Bare Mountain, Nye County, Nevada*, U.S. Geological Survey Miscellaneous Investigations Series Map I-2201, Scale 1:24,000, 1992.

Montazer, P., W.E. Wilson, *Conceptual hydrologic model of flow in the unsaturated zone, Yu Mountain, Nevada*, Water Resources Investigations Report 84-4345, Lakewood, CO. U S Geological Survey, 1984.

Morris, A.P., D.A. Ferrill, D.B. Henderson, *Slip-tendency analysis and fault reactivation.* Geology 24, 275–278, 1996.

Mozley, P.S., L.B. Goodwin, *Patterns of ce ntation along a Cenozoic normal fault. A record of paleoflow orientations,* Geology 23 539–542, 1995.

Nakata, J.K., C.M. Wentworth, M.N. Machette, *Quaternary Fault Maps of the Basin and Range and Rio Grande Rift Provinces, Western United States,* U.S. Geological Survey Open-File Report 82-579, Denver, CO, U.S. Geological Survey, Scale 1:2,500,000, 1982.

National Research Council, Commission of Physical Sciences, Mathematic, and Resources, *Probabilistic seismic hazard analysis,* National Academy Press, Washington, D.C., 1988.

National Research Council, *Rock Fractures and Fluid Flow,* National Academy Press, Washington, DC, 1996.

Nelson, M.R., C.H. Jones, *Paleomagnetism and crustal rotations along a shear zone, Las Vegas range, southern Nevada,* Tectonics 6, 13–33, 1987.

Nilsen, T.J., J.H. Stewart, *The Antler Orogeny; Mid-Paleozoic tectonism in western North America,* Geology 8, 298–302, 1980.

Noble, D.C., S.I. Weiss, E.H. McKee, *Magmatic and Hydrothermal Activity, Caldera Geology, and Regional Extension in the Western Part of the Southwestern Nevada Volcanic Field,* Geology and Ore Deposits of the Great Basin, G.L. Raines, R.E. Lisle, R.W. Shafer and W.W. Wilkerson, e's. Reno, NV, Geological Society of Nevada, 913–934, 1991.

Noble D.C., S.I. Weiss, S.M. Green, *High-salinity fluid inclusions suggest that Miocene gold deposits of the Bare Mountain district, Nevada, are related to a large buried rare-metal rich magmatic system,* Geological Society of America Abstracts with Programs 21, Boulder, CO, Geological Society of America, A123, 1989

Ofoegbu, G.I., D.A. Ferrill, *Finite Element Modeling of Listric Normal Faulting,* CNWRA 95-008, San Antonio, TX, Center for Nuclear Waste Regulatory Analyses, 1995.

Ofoegbu, G.I. D.A. Ferrill, *Mechanical analyses of a Yucca Mountain fault model, Proceedings of the Topical Meeting on Methods of Seismic Hazards Evaluation, Focus '95,* La Grange Park, IL, American Nuclear Society, 115–124, 1996.

Ofoegbu, G.I., D.A. Ferrill, *Mechanical analyses of listric normal faulting with emphasis on seismicity assessment,* Tectonophysics 284, 65–77, 1998.

Oldow, J.S., *Spatial variability in the structure of the Roberts Mountain allochthon, western Nevada,* Geological Society of America Bulletin 95, 174–185, 1984.

Oldow, J.S., G. Kohler, R.A. Donelick, *Late Cenozoic extensional transfer in the Walker Lane strike-slip belt, Nevada,* Geology 22, 637–640, 1994

Oliver H W , K F Fox, *Structure of Crater Flat and Yucca Mountain, southeastern Nevada, as interpreted from gravity data*, Proceedings of the Fourth Annual International Conference, Las Vegas, Nevada, La Grange Park, IL, American Nuclear Society, 1,812–1,8· ·, 1993

Paces, J.B., L.A. Neymark, B D Marshall, J F Whelan, Z E Peterman, *Ages and origins of subsurface secondary minerals in the Exploratory Studies Facility (ESF)*, U.S. Geological Survey—Yucca Mountain Project Branch 1996 Milestone Report 3GQH450M, Denver, CO, U.S. Geological Survey, 1996.

Peacock, D.C.P , D.J. Sanderson, *Displacements, segment linkage, and relay ramps in normal fault zones*, Journal of Structural Geology 13, 721–733, 1991.

Peacock, D C.P., D.J. Sanderson, *Geometry and development of relay ramps in normal fault systems*, American Association of Petroleum Geologists Bulletin 78, 147–165, 1994.

Pezzopane, S.K., *Preliminary table of characteristics of known and suspected quaternary faults in the Yucca Mountain Region*, U.S. Geological Survey Administrative Report, Denver, CO, U.S. Geological Survey, 1995.

Piety, L.A., *Compilation of known and suspected quaternary faults within 100 km of Yucca Mountain*, Scale 1:250,000, U.S. Geological Survey Open File Report 94-112, Denver, CO, U.S. Geological Survey, 1996.

Ponce, D.A., H.W. Oliver, *Gravity investigations, Major results of geophysical investigations at Yucca Mountain and Vicinity, southern Nevada*, USGS Open-File Report 95-74, H.W Oliver, D.A. Ponce, and W.C. Hunter, e's, Menlo Park, CA, U.S Geological Survey, 1995.

Ponce, D.A., S.B. Kohrn, S. Waddell, *Gravity and magnetic data of Fortymile Wash, Nevada Test Site, Nevada*, USGS Open-File Report 92-343, Reston, VA, U.S. Geological Survey, 1992.

Poole, F.G., J.H. Stewart, A.P. Palmer, C.A. Sandberg, R.J. Madrid, R.J. Ross, Jr., L.F. Hintze, M.M. Miller, C.T. Wrucke, *Latest Precambrian to latest Devonian time; Development of a continental margin, The Cordilleran Orogen, Conterminous U.S.*, The Geology of North America Volume G-3, B.C. Burchfiel, P.W., Lipman, and M.L Zoback, e's, Boulder, CO, Geological Society of America, 407–479, 1992.

Potter, C.J., W.C. Day, D.S. Sweetkind, R.P. Dickerson, *Fault styles and strain accommodation in the Tiva Canyon Tuff, Yucca Mountain, Nevada*, EOS, Transactions, American Geophysical Union 77(17), S265, 1996.

Prave, A.R., L.A. Wright, *Isopach patterns in the Lower Cambrian Zabriskie Quartzite: How useful in tectonic reconstructions?*, Geology 14, 251–254, 1986.

Rahe, B., D.A. Ferrill, A.P. Morris *Physical analog modeling of pull-apart basin evolution*, Tectonophysics 285, 21–40, 1997.

Ransome, F.L., W.H. Emmons, G H Gary, *Geology and ore deposits of the Bullfrog District, Nevada*, U.S. Geological Survey Bulletin 407, 1910.

Reheis, M C . *Holocene faulting along the central Fish Lake Valley Fault Zone, California and Nevada*, Geological Society of America Abstracts with Programs-1994 Cordilleran Section Meeting, Boulder, CO, Geological Society of America 26. 83. 1994

Reheis, M C., Preliminary study of quaternary faulting on the east side of Bare Mountain, Nye County, Nevada, *Geologic and Hydrologic Investigations of a Potential Nuclear Waste Disposal Site at Yucca Mountain, Southern Nevada*, M D Carr, J C Yount, e's. U S Geological Bulletin 1790, 103–112, 1988

Reiter, L., *Earthquake hazard analysis, issues and insights*, Columbia University Press, New York, 1991.

Richter, C. F., *Elementary Seismology*, W. H. Freeman, San Francisco, California, 1958

Ritzi, Jr., R.W., R.H. Andolsek, *Relation between anisotropic transmissivity and azimuthal resistivity surveys in shallow, fractured, carbonate flow system*, Ground Water 30(5), 774–780, 1992

Robinson, G.D., *Structure of Pre-Cenozoic rocks in the vicinity of Yucca Mountain, Nye County, Nevada - A potential nuclear-waste disposal site*, U.S. Geological Survey Bulletin 164' Denver, CO, U.S. Geological Survey, 1985.

Rogers, A.M., S.C. Harmsen, E.J. Corbett, K. Priestly, D. dePolo, *The seismicity of Nevada and some adjacent parts of the Great Basin, Neotectonics of North America*, D.B. Slemmons, E.R. Engdalhl, M.D. Zoback, D.D. Blackwell, e's, Boulder, CO, Geological Society of America Bulletin 1, 153–184, 1991.

Rosenbaum, J.G., M.R. Hudson, R.B. Scott, *Paleomagnetic constraints on the geometry and timing of deformation at Yucca Mountain, Nevada*, Journal of Geophysical Research 96, 1,963–1,979, 1991.

Rousseau, J.P., E.M. Kwicklis, D.C. Gillis, e's, *Hydrology of the Unsaturated Zone, North Ramp Area of the Exploratory Studies Facility, Yucca Mountain, Nevada*, Water Resources Investigations Report, Denver, CO, U.S. Geological Survey Draft, 1996.

Sabetta, F., A. Pugliese, *Attenuation of peak horizontal acceleration and velocity from Italian strong-motion records*, Bulletin of Seismological Society of America 77, 1,491–1,513, 1987.

Sadigh K., C.Y. Chang, J.A. Egan, F. Makdisi, R.R. Youngs, *Attenuation relationships for shallow crustal earthquakes based on California strong motion data*, Seismological Research Letters 68, 180–189, 1997.

Savage, J.C., M. Lisowski, W.K. Gross, N.E King, J.L. Svarc, *Strain accumulation near Yucca Mountain, Nevada, 1983–1993*, Journal of Geophysical Research 99, 18,103–18,107, 1994

Sawyer, D.R., R.J. Fleck, M.A. Lanphere, R G. Warren, D.E. Broxton, M R Hudson, *Episodic caldera volcanism in the miocene southwestern Nevada volcanic field Revised stratigraphic* *framework, ⁴⁰Ar/³⁹Ar geochronology, and implications for magmatism and extension.* Geological Society of America Bulletin 106, 1,304–1,318, 1994

Scholz, C H . N H Dawers, J -Z Yu, M H Anders, *Fault growth and fault scaling laws, Preliminary results.* Journal of Geophysical Research 98, 21,951–21,961, 1993

Schwartz, D.B , K J Coppersmith, *Fault behavior and characteristic earthquakes: Examples from the Wasatch and San Andreas Faults,* Journal of Geophysical Research 89, 5,681–5,698, 1984

Schwartz, S.Y., R. Van der Voo, *Paleomagnetic study of thrust-sheet rotation during foreland impingement in the Wyoming-Idaho overthrust belt,* Journal of Geophysical Research 89, 10,077–10,086, 1984

Schweickert, R.A., M.M. Lahren, *Strike-slip fault system in Amargosa Valley and Yucca Mountain, Nevada,* Tectonophysics 272, 25–41, 1997

Scott, R.B., *Tectonic setting of the Yucca Mountain region, southwest Nevada,* Geological Society of America Memoir 176, Boulder, CO, Geological Society of America, 251–282, 1990.

Scott, R.B., J. Bonk, *Preliminary geologic map of Yucca Mountain, Nye County, Nevada with geologic sections,* scale 1:12000, USGS Open-File Report 84-494, Denver, CO, U.S. Geological Survey, 1984.

Senior Seismic Hazard Analysis Committee, *Recommendations for probabilistic seismic hazard analysis, Guidance on uncertainty and use of Experts,* NUREG/CR-6372, 1997.

Serpa, L., T.L. Pavlis, *Three-dimensional model of the late Cenozoic history of the Death Valley region, southeastern California,* Tectonics 15, 1,113–1,128, 1996.

Simonds, W.F., C.J. Fridrich, T.D. Hoisch, W.B. Hamilton, *A synthesis of detachment fault studies in the Yucca Mountain region, Methods of Seismic Hazard Evaluation,* Proceedings of the Topical Meeting on Methods of Seismic Hazards Evaluation, Focus '95, La Grange Park, IL, American Nuclear Society, Inc., 107–114, 1996.

Simonds, W.F., J.W. Whitney, K. Fox, A. Ramelli, J.C. Yount, M.D. Carr, C.D. Menges, R. Dickerson, R.B. Scott, *Map of Fault Activity of the Yucca Mountain Area, Nye County, Nevada,* scale 1:24,000, U.S. Geological Survey Miscellaneous Investigations Series Map, 1-2520, Denver, CO, U.S. Geological Survey, 1995a.

Smith, R.B., W.J. Arabasz, *Seismicity of the intermountain seismic belt, Neotectonics of North America,* D.B. Slemmons, E.R. Engdalhl, M.D. Zoback, and D.D. Blackwell, e's, Boulder, CO, Geological Society of America Bulletin 1, 185–228, 1991.

Smith, R.B., W.C. Nagy, K.A. (Smith) Julander, J.J. Viveiros, C.A. Barker, D.G. Gants, *Geophysical and tectonic framework of the eastern Basin and Range-Colorado Plateau-Rocky transition, Geophysical framework of the Continental United States,* L.C. Pakiser, and

W D. Mooney, e's, Geological Society of America Memoir 172. Boulder CO, Geological Society of America, 1989

Snow, J.K , *Large-magnitude Permian shortening and continental-margin tectonics in the southern Cordillera*, Geological Society of America Bulletin 104, 80–105, 1992a

Snow, J.K., *Mass balance of Basin and Range extension as a tool for geothermal exploration*, Geothermal Resources Council Transactions 18, 23–30, 1994.

Snow, J.K., *Paleogeographic and structural significance of an upper Mississippian facies boundary in southern Nevada and east-central California, (Discussion)*, Geological Society of America Bulletin 104, 1,067–1,071, 1992b.

Snow, J.K., A.R. Prave, *Covariance of structural and stratigraphic trends: Evidence for anticlockwise rotation within the Walker Lane Belt Death Valley region, California and Nevada*, Tectonics 13, 712–724, 1994.

Snow, J.K, B. Wernicke, *Uniqueness of geological correlations: An example from the Death Valley extended terrane*, Geological Society of America Bulletin 101, 1,351–1,362, 1989.

Snow, J.K., J.W. Geissman, B. Wernicke, *Paleomagnetic data from Paleozoic sedimentary rocks and Permo-Triassic intrusions, Death Valley area, southeast CA, Implications for Mesozoic and Cenozoic deformation*, EOS Transactions, American Geophysical Union 74, Washington, DC, American Geophysical Union, 206, 1993.

Snyder, B.B., W.J. Carr, *Preliminary results of gravity investigations at Yucca Mountain and vicinity, southern Nye County, Nevada*, U.S. Geological Survey Open-File Report 82-701, Denver, CO, U.S. Geological Survey, 1982.

Sonder, L.J., C.H. Jones, S.L. Salyards, K.M. Murphy, *Vertical axis rotations in the Las Vegas shear zone, southern Nevada: Pleomagnetic constraints on kinematics and dynamics of block rotations*, Tectonics 13, 769–788, 1994.

Spengler, R.W., C.A. Braun, L.G. Martin, and C.W. Weisenberg, *The Sundance Fault–A newly recognized shear zone at Yucca Mountain, Nevada*, United States Geological Survey Open-File Report 94-49, Denver, CO, U.S. Geological Survey, 1994.

Spuduch, P. J.B. Fletcher, M. Hellweg, J. Boatwright, C. Sullivan, W.B. Joyner, T.C. Hanks, D.M. Boore, A. McGarr, L.M. Baker, A.G. Lindh, *SEA96—A new predicative relation for earthquake ground motions in extensional tectonic regimes*, Seismological Research Letters 68, 190–198, 1997.

Stamatakos, J.A., A.M. Hirt, *Paleomagnetic considerations of the development of the Pennsylvania salient in the central Appalachians*, Tectonophysics 231, 237–255, 1994.

Stamatakos, J.A., D.A. Ferrill, *Comment on "Strike-slip fault system in Amargosa Valley and Yucca Mountain, Nevada by R.A. Schweickert and M M Lahren*, Tectonophysics, In press.

Stamatakos, J.A. D.A Ferrill, *Paleomagnetism of Ordovician Pogonip Group Carbonates in southwestern Nevada, Implications for tectonism of the Yucca Mountain region*, EOS Transactions of the American Geophysical Union, San Francisco Annual Meeting, Washington, DC, American Geophysical Union, F173, 1996.

Stamatakos, J.A., C.B. Connor, R.H. Martin, *Quaternary basin evolution and basaltic volcanism of Crater Flat, Nevada, from detailed ground magnetic surveys of the Little Cones.* Journal of Geology, v. 105, 319-330 1997a.

Stamatakos, J.A., D.A. Ferrill, K.P. Spivey, *Paleomagnetic constraints on the tectonic evolution of Bare Mountain, Nevada*, Geological Society of America Bulletin, In review.

Stamatakos, J.A., P.S. Justus, D.A. Ferrill, R. Chen, G.I. Ofoegbu, *Structural deformation and seismicity*, NRC High-Level Radioactive Waste Program Annual Progress Report, Fiscal year 1996, Sagar, B., ed, NUREG/CR-6513, No. 1, CNWRA 96-OIA, San Antonio, TX, Center for Nuclear Waste Regulatory Analyses, 1997b.

Stevens, C.H., P. Stone, P. Belasky, *Paleogeographic and structural significance of an Upper Mississippian facies boundary in southern Nevada and east-central California*, Geological Society of America Bulletin 103, 876–885, 1991.

Stewart, J.H., *Basin-Range Structure in Western North America, A Review*, Cenozoic Tectonic and Regional Geophysics of the Western Cordillera, R.B. Smith and G.P. Eaton, e's, Boulder, CO, Geological Society of America Memoir 152, 1–31, 1978.

Stewart, J.H., *Tectonic of the Walker Lane belt, western Great Basin - Mesozoic and Cenozoic deformation in a zone of shear*, Metamorphism and Crustal Evolution of the Western United States, Vol. VII, W.G. Ernst, ed, Englewood Cliffs, NJ, Prentice-Hall, Inc, 684–713, 1988.

Stewart, J.H., *Upper Precambrian and Lower Cambrian Strata in the Southern Great Basin, California and Nevada*, U.S. Geological Survey Professional Paper 620, Denver, CO, U.S. Geological Survey, 1970.

Stirewalt, G.L., D.B. Henderson, *A three-dimensional geological framework model for Yucca Mountain, Nevada, with hydrologic application, Report to accompany 1995 model transfer to the U.S. Nuclear Regulatory Commission*, CNWRA 94-023, San Antonio, TX, Center for Nuclear Waste Regulatory Analyses, 1995.

Stock, J.M., J.H. Healy, *Stress field at Yucca Mountain, Nevada, Geologic and Hydrologic Investigations of a Potential Nuclear Waste Disposal Site at Yucca Mountain, Southern Nevada*, M.D. Carr and J.C. Yount, e's, U.S. Geological Survey Bulletin 1790, 87–94, 1988.

Stock, J.M., J.H. Healy, J. Soitek, L. Mastin, *Report on televiewer and stress measurements in holes USW G-3 and UE-25pl, Yucca Mountain, Nye County, Nevada*, U.S. Geological Survey Open-File Report 86-369, Washington DC, U.S. Geological Survey, 1986.

Stock, J.M., J.H. Healy, S.H. Hickman, M.D. Zoback, *Hydraulic fracturing stress measurements at Yucca Mountain, Nevada and relationship to regional stress fields*, Journal of Geophysical Research 90, 8,691–8,706, 1985.

Stothoff, S.A., D. Or, D.P. Groeneveld, S.B. Jones, *The effect of vegetation on infiltration in shallow soils underlain by fissured bedrock*, San Antonio, TX, Center for Nuclear Waste Regulatory Analyses, 1997.

Stover, C.W., J.L. Coffman, *Seismicity of the United States, 1568-1989 (revised)*, U.S. Geological Survey Professional Paper 1527, Menlo Park, CA, U.S. Geological Survey, 1993

Stuckless, J.S., Z.E. Peterman, R.M. Forester, J.F. Whelan, D.T. Vaniman, B.D. Marshall, E.M. Taylor, *Characterization of fault-filling deposits in the vicinity of Yucca Mountain, Nevada*. Waste Management 1992 Conference Proceedings, Tucson, AZ, March 1-5 1992, Tucson, AZ, Waste Management, 929–935, 1992.

Suppe, J., *Geometry and kinematics of fault-bend folding*, American Journal of Science, vol. 283, 684-721, 1983.

Swadely, W.C., L.D. Parrish, *Surficial geologic map of the Bare Mountain Quadrangle, Nevada*, U.S. Geological Survey Miscellaneous Investigations Series Map I-1826, Denver, CO, U.S. Geological Survey, 1988.

Swadely, W.C., D.L. Hoover, J.N. Rosholt, *Preliminary report on Late Cenozoic faulting and stratigraphy in the vicinity of Yucca Mountain, Nye County, Nevada*, U.S. Geological Survey Open File report 84-788, Denver, CO, U.S. Geological Survey, 1984.

Sweetkind, D.S., S.C. Williams-Stroud, *Characteristics of fracture at Yucca Mountain, Nevada*, Synthesis Report, U.S. Geological Survey, 1995.

Sweetkind, D.S., S.C. Williams-Stroud, *Controls on the genesis of fracture networks, Paintbrush Group, Yucca Mountain, Nevada*, EOS, Transactions, American Geophysical Union 76, F597, 1995.

Sweetkind, D.S., C.J. Potter, E.R. Verbeek, *Interaction between faults and the fracture network at Yucca Mountain, Nevada*, EOS, Transactions, American Geophysical Union 77(17), S266, 1996.

Sweetkind, D.S., D.L. Barr, D.K. Polacsek, L.O. Anna, *Administrative report: Integrated fracture data in support of process models, Yucca Mountain, Nevada*, 1997 Milestone Report SPG32M3, Denver, CO, U.S. Geological Survey, 1997b.

Sweetkind, D.S., E.R. Verbeek, J.K. Geslin, T.C. Moyer, *Fracture character of the Paintbrush Tuff Nonwelded Hydrologic Unit, Yucca Mountain, Nevada*, U.S. Geological Survey Administrative Report to the U.S. Department of Energy, Denver, CO, U.S. Geological Survey, 1995a.

Sweetkind, D S . L.O. Anna, S C Williams-Stroud. J A Coe. *Characterizing the fracture network at Yucca Mountain, Nevada, Part 1, Integration of field data for numerical simulations. Fractured Reservoirs*, Characterization and Modeling Guidebook-1997. Hoak, T E . P.K Blomquist, A. Klawitter, e's, Denver, CO, Rocky Mountain Association of Geologists, 185–196, 1997a

Sweetkind, D S., E.R. Verbeek, F.R Singer, F M. Byers, Jr., L.G. Martin, Surface fracture network at pavement P2001, Fran Ridge, Near Yucca Mountain, Nye County, Nevada, *Administrative Report*, Denver, CO, U.S. Geological Survey, 1995b.

Terzaghi, R., *Sources of Error* in Joint Surveys, Geotechnique, v. 15, p. 287, 1965.

Throckmorton, C.K., E.R. Verbeek, *Joint networks in the TIVA Canyon and Topopah Spring Tuffs of the Paintbrush Group, southwestern Nevada*, U.S. Geological Survey Open-File Report 95-2, Denver, CO, U.S. Geological Survey, 1995

Trexler, J.H., Jr., J.C. Cole, P.H. Cashman, *Middle Devonian-Mississippian stratigraphy on and near the Nevada test site, Implications for hydrocarbon potential*, American Association of Petroleum Geologists 80, 1736–1762, 1996.

Trudgill, B., J. Cartwright, *Relay-ramp forms and normal-fault linkages, Canyonlands National Park, Utah*, Geological Society of America Bulletin 106, 1,143–1,157, 1994.

Twiss, R.J., E.M. Moores, Structural Geology, New York, NY, W.H. Freeman and Company, 1992.

U.S. Department of Energy, *Controlled Design Assumptions Document, Rev.2*, B000 000 00-01717-4600-00032, December 19, 1995.

U.S. Department of Energy, *Methodology to Assess Fault Displacement and Vibratory ground motion Hazards at Yucca Mountain*, YM/TR-002-NP, Revision 1, August 1997a.

U.S. Department of Energy, *Preclosure Seismic Design Methodology for Geologic Repository at Yucca Mountain*, Topical/Report YM/TR-003-NP, Revision 2, August 1997b.

U.S. Department of Energy, *Repository safety strategy, U.S. Department of Energy's strategy to protect public health and safety after closure of a Yucca Mountain repository, Revision 1*, YMP/96-01, Rev. 1, Washington, DC, U.S. Department of Energy, 1998.

U.S. Geological Survey, *Probabilistic seismic hazard analyses for fault displacement and vibratory ground motion at Yucca Mountain, Nevada, Final Report*, I.G. Wong and C. Stepp Report Coordinators, SP32IM3, WBS Number 1.2.3.2.8.3.6, Oakland, CA, U.S. Department of Energy, 1998. [PRELIMINARY]

U.S. Geological Survey, *Seismotectonic framework and characterization of faulting at Yucca Mountain, Nevada*, Denver, CO, J.W. Whitney, Report Coordinator, U.S. Geological Survey, 1996.

U.S Nuclear Regulatory Commission, *Design response spectra for seismic design of nuclear power plants*, Regulatory Guide 1.60, Washington, DC, U S Nuclear Regulatory Commission, 1973

U.S. Nuclear Regulatory Commission, *Identification and characterization of seismic sources and determination of safe shutdown earthquake ground motion*, Regulatory Guide 1.165, Washington, DC, U S. Nuclear Regulatory Commission, 1997b.

U.S. Nuclear Regulatory Commission, *NRC Sensitivity and Uncertainty Analyses for a Proposed HLW Repository at Yucca Mountain, Nevada, Using TPA 3.1: Conceptual Models and Data*, NUREG-1668, Volume 1, 1998a.

U.S. Nuclear Regulatory Commission, *NRC Sensitivity and Uncertainty Analyses for a Proposed HLW Repository at Yucca Mountain, Nevada, Using TPA 3.1: Results and Conclusions*, NUREG-1668, Volume 2, 1998b.

U.S. Nuclear Regulatory Commission, *Senior Seismic Hazard Analysis Committee, Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts*, NUREG/CR-6372, Washington, DC, 1997c.

U.S. Nuclear Regulatory Commission, *Staff Analysis of Public Comment on Proposed Rule 10 CFR Part 60: Disposal of High-Level Radioactive Wastes in Geologic Repositories*, NUREG-0804, Washington, DC, U.S. Nuclear Regulatory Commission, 1983.

U.S. Nuclear Regulatory Commission, *Standard review plan for the review of safety analysis reports for nuclear power plants*, NUREG-0800, Washington, DC, U.S. Nuclear Regulatory Commission, 1997a.

Young, S.R., G.L. Stirewalt, A.P. Morris, *Geometric Models of Faulting at Yucca Mountain*, CNWRA 92-008.

Van der Voo, R., J.A. Stamatakos, J.M. Parés, *Kinematic constraints on thrust-belt curvature from syndeformational magnetizations in the Lagos del Valle Syncline in the Cantabrian Arc, Spain*, Journal of Geophysical Research 102, 10,105–10,119, 1997.

Vaniman, D.T. B.M. Crowe, *Geology and Petrology of Basalts of Crater Flat, Applications to Volcanic Risk Assessment for the Nevada Nuclear Waste Storage Investigations*, Los Alamos National Laboratory Report LA-8845-MS, Los Alamos, NM, Los Alamos National Laboratory, 1981.

Wang, J.S.Y., P.J. Cook, R.C. Trautz, R. Salve, A. L. James, S. Finsterle, T. K. Tolunaga, R. Solbau, J. Clyde, *Field Testing and Observation of Flow Paths in Niches, Phase I Status Report of the Drift Seepage Test and Niche Moisture Study*, Yucca Mountain Project Milestone SPC314M4, Lawrence Berkeley National Laboratory, Berkeley, CA., 1997

Wang, J.S.Y., R. C. Trautz, P. J. Cook, S. Finsterle, A. L. James, J. Birkholzer, C F Ahlers, *Testing and Modeling of Seepage into Drift Input of Exploratory Study Facility Seepage Test*

Results to Unsaturated Zone Models, Yucca Mountain Project Milestone SP33PLM4, Lawrence Berkeley National Laboratory, CA, 1998.

Weiss, S I., *Hydrothermal activity, epithermal mineralization and regional extension in the southwestern Nevada volcanic field*, Ph.D. dissertation, Reno, Nevada, University of Nevada at Reno, 1996.

Wells, D.L., K.J. Coppersmith, *New empirical relationships among magnitude ture length, rupture width, rupture area, and surface displacement*, Bulletin of the Seismolo al Society of America 84, 974–1,002, 1994.

Wernicke, B.P., *Cenozoic extensional tectonics of the western Cordillera, The Cordilleran Orogen, Conterminous U.S.*, The Geology of North America, B.C. Burchfiel, P.W., Lipman, and M.L. Zoback, e's, Boulder, CO, Geological Society of America, G-3, 553–581, 1992.

Wernicke, B.P., *Low-angle normal faults and seismicity. A review*, Journal of Geophysical Research 100, 20,159–20,174, 1995.

Wernicke, B.P., *Low-angle normal faults in the Basin and Range province, Nappe tectonics in an extending orogen*, Nature 291, 645–648, 1981.

Wernicke, B.P., G.A. Axen, J.K. Snow, *Basin and Range extensional tectonics at the latitude of Las Vegas, Nevada*, Geological Society of America Bulletin 100, 1,738–1,757, 1988.

Wernicke, B., J.L. Davis, R.A. Bennett, P. Elósegui, M.J.A. Bolins, R.J. Brady, M.A. House, N.A. Niemi, J.K. Snow, *Anomalous strain accumulation in the Yucca Mountain Area, Nevada*, Science 279, 2,096–2,100, 1998.

Wernicke, B.P., R.L. Christiansen, P.C. England, L.J. Sonder, *Tectonomagmatic evolution of Cenozoic extension in the North American Cordillera Continental Extensional Tectonics*, M.P. Coward, J.F. Dewey, and P.L. Hancock, e's, London, England, Geological Society Special Publications 28, 203–221, 1987

Wesnousky, S.G., C.H. Jones, *Oblique slip, slip partitioning, spatial and temporal changes in the regional stress field, and the relative strength of active faults in the Basin and Range, western United States*, Geology 22, 1,031–1,034, 1994.

Willemse, E.J.M., *Segmented normal faults: Correspondence between three-dimensional mechanical models and field data*, Journal of Geophysical Research 102, 675–692, 1997.

Willemse, E.J.M., D.D. Pollard, A. Aydin, *Three-dimensional analyses of slip distributions on normal fault arrays with consequences for fault scaling*, Journal of Structural Geology 18, 295–309, 1996.

Wittmeyer, G.W , D.A. Ferrill, *Effect of contemporary regional stress on the anisotropy of transmissivity in fractured rock aquifers*, EOS, Transactions, American Geophysical Union 75(44), 258, 1994.

Wittmeyer, G.W., W.M. Murphy, D.A. Ferrill, *Regional hydrologic processes of the Death Valley Region, NRC High-Level Radioactive Waste Research at CNWRA. January-June 1994*, B Sagar, ed, San Antonio, TX, Center for Nuclear Waste Regulatory Analyses, 189–212, 1994

Wong, I.G., S.K. Pezzopane, C.M. Menges, R.K. Green, R.C. Qwittmeyer, *Probabilistic seismic hazard analysis of the exploratory studies facility at Yucca Mountain, Nevada*, Proceedings of the Topical Meeting on Methods of Seismic Hazard Evaluations, Focus 95, La Grange Park, IL, American Nuclear Society, 51–63, 1996.

Wright, L.A., B.W. Troxel, *Shallow-fault interpretations of Basin and Range structure, southwestern Great Basin*, Gravity and Tectonics, K.A. de Jong and R. Scholten, e's, New York, NY, John Wiley and Sons, 97-407, 1973.

Wu, S., *Fractal strain distribution and its implications for cross-section balancing*, Journal of Structural Geology 15, 1,497–1,507, 1993.

Yielding, G., B. Freeman, D.T. Needham, *Quantitative fault seal prediction*, American Association of Petroleum Geologists Bulletin 81(6), 897–917, 1997.

Young, S.R., A.P. Morris, G.L. Stirewalt, *Geometric analysis of alternative models of faulting at Yucca Mountain, Nevada*, International High-Level Radioactive Waste Management Conference Proceedings, La Grange Park, IL, American Nuclear Society, 1,818–1,825, 1993.

Young, S.R., A.P Morris, G.L Stirewalt, *Preliminary Structural Interpretation of Reflection Seismic Line AV-1*, CNWRA 92-024, San Antonio, TX, Center for Nuclear Waste Regulatory Analyses, 1992a.

Young, S.R., G.L. Stirewalt, A.P. Morris, *Geometric models of faulting at Yucca Mountain*, CNWRA. 92-008, San Antonio, TX, Center for Nuclear Waste Regulatory Analyses, 1992b.

Youngs, R.R., K.J. Coppersmith, *Implications of fault slip rates and earthquake recurrence models to probabilistic seismic hazard estimates*, Bulletin of the Seismological Society of America 75, 939–964, 1985.

Zhang, X., D.J. Sanderson, *Numerical modeling of the effects of fault slip on fluid flow around extensional faults*, Journal of Structural Geology 18(1), 109–119, 1996.

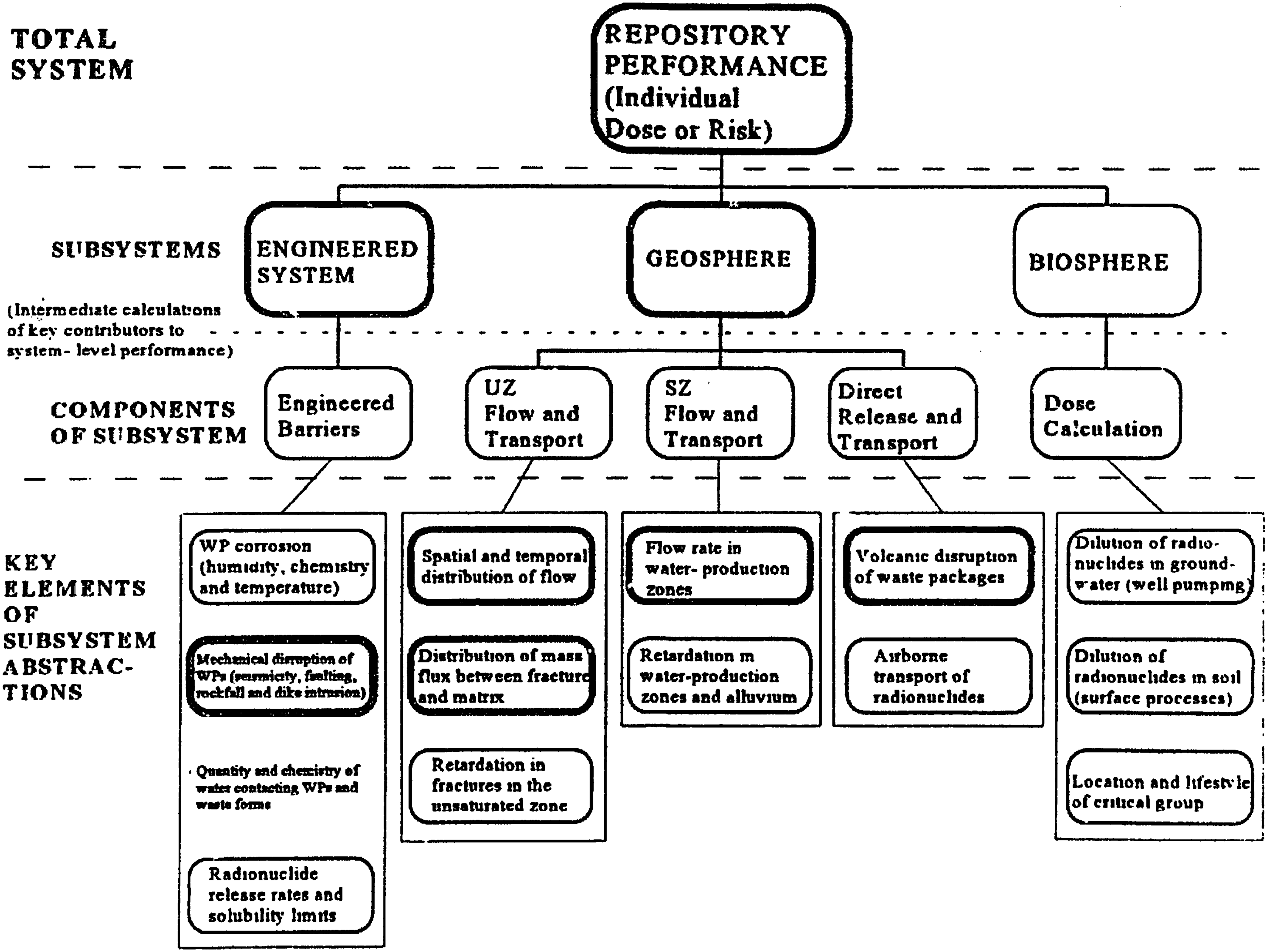
Zhang, Y., S.L. Gillett, R.E. Karlin, R.A. Schweickert, *Paleomagnetism of the Miocene dikes in Bare Mountain, southwestern Nevada, Implications for regional tectonics*, Geological Society of America Cordilleran and Rocky Mountain Section Meetings Abstracts with Programs 23(5), Boulder, CO, Geological Society of America, A169, 1993.

Zoback, M.L., and 36 project participants, *World stress map maximum horizontal stress orientations*, Journal of Geophysical Research 97, 11,703–11,728, 1992.

Zoback, M.L., R.E Anderson, G.A. Thompson, *Cainozoic evolution of the state of stress and style of tectonism of the Basin and Range province of the western United States*, Philosophical Transactions of the Royal Society of London, London, England, Royal Society of London, A300, 407–434, 1981.

APPENDIX A

FLOW-DOWN DIAGRAM REVISED


TOTAL SYSTEM
REPOSITORY PERFORMANCE (Individual Dose or Risk)
SUBSYSTEMS
(Intermediate calculations of key contributors to system-level performance)
ENGINEERED SYSTEM
GEOSPHERE
BIOSPHERE
COMPONENTS OF SUBSYSTEM
Engineered Barriers
UZ Flow and Transport
SZ Flow and Transport
Direct Release and Transport
Dose Calculation
KEY ELEMENTS OF SUBSYSTEM ABSTRACTIONS
WP corrosion (humidity, chemistry and temperature)
Mechanical disruption of WPs (seismicity, faulting, rockfall and dike intrusion)
Quantity and chemistry of water contacting WPs and waste forms
Radionuclide release rates and solubility limits
Spatial and temporal distribution of flow
Distribution of mass flux between fracture and matrix
Retardation in fractures in the unsaturated zone
Flow rate in water-production zones
Retardation in water-production zones and alluvium
Volcanic disruption of waste packages
Airborne transport of radionuclides
Dilution of radionuclides in ground-water (well pumping)
Dilution of radionuclides in soil (surface processes)
Location and lifestyle of critical group

APPENDIX B

CLASSIFICATION OF QUATERNARY FAULTS WITHIN 100 KM of YUCCA MOUNTAIN (REVISED 05/18/98)

(B-1) Faults classified as Type I by McKague, et al. (1996) and as relevant or potentially relevant by Pezzopane, in USGS (1996)

	U.S. DEPARTMENT OF ENERGY (DOE)					NUCLEAR REGULATORY COMMISSION					
				Peak Acceleration (g)							Considered as Seismic Source in USGS (1998)*
Name of Fault	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Median	84th	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	
Amargosa River	15	6.4	38	0.09	0 15	15	6.4	40	0.1		Y
Amargosa River—Pahrump	130	7.5	38	0.18	0.28	130	7.5	40	0.20	Pahrump fault in McKague, et al., 1996	Y
Ash Meadows	60	7 1	34	0.16	0.26	60	7.1	34	0.2		Y
Bare Mountain	16	6.5	14	0.27	0.44	21	6.6	15	0.31		Y
Black Cone	7	6.1	8.5	0.35	0.58	7	6.1	6	0.45	Formerly Simonds Number 10 (McKague, et al., 1996, Appendix A). BC on Figure E-3	Y
Belted Range	54	7.1	55	0.09	0.15	54	7.1	55	0.10		Y

	U.S. DEPARTMENT OF ENERGY (DOE)					NUCLEAR REGULATORY COMMISSION					
				Peak Acceleration (g)							
Name of Fault	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Median	84th	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	Considered as Seismic Source in USGS (1998)*
Boomerang Point	5	5.9	2.5	0.48	0.79	5	5.9	2	0.56	In USGS (1998) (Appendix E), AAR team evaluated this fault. Based on lack of geomorphic expression in bedrock indicating significant Quaternary activity and estimated Mw, this fault was not considered as a seismic source Fault is indicated as BP on Figure E-3.	N
Bow Ridge	10	6 2	2.5	0.52	0.85	8	6 1	2 3	0.61		Y
Cane Spring	27	6 7	29	0.17	0.27	14	6.4	29	0.13		Y
Carpetbag	30	6.8	43	0.10	[illegible]	30	6 8	43	0 11		Y

*Y—considered as a seismic source in USGS (1998); C—considered as a seismic source when combined with other faults, N—not considered as a seismic source

	U.S. DEPARTMENT OF ENERGY (DOE)					NUCLEAR REGULATORY COMMISSION					
				Peak Acceleration (g)							
Name of Fault	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Median	84th	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	Considered as Seismic Source in USGS (1998)*
Crater Flat	18	6.5	6	0.48	0.79	12	6.3	10	0.36	The Crater Flat fault is considered the Crater Flat Fault System in DOE (1998) It is composed of the Northern Crater Flat Fault (NCF), Central Crater Flat Fault (CCF), and the Southern Crater Flat Fault (SCF) In McKague, et al (1996), (Figure 1-2), Faults 11 and 12 are now considered part of the Crater Flat Fault System and have been renamed accordingly Simonds 11 is now labeled in NCF-11, and Simonds 12 on now labeled NCF-12 in Figure E-3	C

Name of Fault	U.S. DEPARTMENT OF ENERGY (DOE) Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g) Median	84th	NUCLEAR REGULATORY COMMISSION Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	Considered as Seismic Source in USGS (1998)*
Death Valley	100	7.4	55	0.12	0.19	61	7.2	50	0.12		C
Eleana Range	13	6.4	37	0.09	0.16	13	6.4	37	0.1		Y
Fatigue Wash	17	6.5	3.5	0.56	0.92	33	6.8	2	0.79		Y
Furnace Creek	145	7.6	50	0.14	0.23	123	7.5	49	0.15		Y
Ghost Dance—Abandoned Wash	5	5.9	0	0.48	0.79	9	6.2	0.4	0.69	Listed as Ghost Dance in McKague, et al. (1996)	Y
Iron Ridge	9	6.2	2.5	0.52	0.85	9	6.2	3	0.59	Fault is indicated as IR in Figure E-3	Y
Kawich Range	84	7.3	57	0.11	0.17	84	7.3	57	0.11		Y
Keane Wonder	25	6.7	43	0.10	0.16	33	6.8	42	0.12		Y
Midway Valley	8	6.1	3	0.50	0.83	8	6.1	3	0.58	Fault is indicated as MVF in Figure E-3.	Y
Mine Mountain	27	6.7	19	0.23	0.38	6	6.0	24	0.12		Y
Oasis Valley	20	6.6	24	0.17	0.28	16	6.5	24	0.18		Y

*Y—considered as a seismic source in USGS (1998); C—considered as a seismic source when combined with other faults; N—not considered as a seismic source

	U.S. DEPARTMENT OF ENERGY (DOE)					NUCLEAR REGULATORY COMMISSION					
Name of Fault	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g) Median	Peak Acceleration (g) 84th	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	Considered as Seismic Source in USGS (1998)*
Paintbrush Canyon	24	6.7	4	0.60	0.97	24	6.7	4	0.66	Fault is indicated as PBC in Figure E-3.	Y, C
Plutonium Valley—North Halfpint Range	26	6 7	46	0.09	0.14	26	6.7	46	0.10		N
Rock Valley	65	7.2	27	0.22	0.35	43	7.0	25	0.23		Y
Rocket Wash—Beatty Wash	17	6 5	19	0.23	0.39	17	6.5	19	0.23	Not considered relevant by RYA Team possibly because of lack of significant Quarternary displacement (DOE, 1998, Appendices, p RYA-13)	N
Sarcobatus Flat	51	7 1	52	0.10	0.17	51	7.1	52	0.10		Y
Solitario Canyon	20	6.6	1	0.58	0.94	19	6.6	1	0.76	Fault is indicated as SC in Figure E-3	Y

*Y—considered as a seismic source in USGS (1998); C—considered as a seismic source when combined with other faults, N—not considered as a seismic source

	U.S. DEPARTMENT OF ENERGY (DOE)					NUCLEAR REGULATORY COMMISSION					
				Peak Acceleration (g)							
Name of Fault	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Median	84th	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	Considered as Seismic Source in USGS (1998)*
Stagecoach Road	9	6.2	10	0.36	0.60	8	6.1	11	0.30	Fault is indicated as SCR in Figure E-3.	Y, C
Tolicha Peak	22	6.6	42	0.10	0.16	22	6.6	42	0.10		C
Wahmonie	15	6.4	22	0.18	0.30	15	6.4	22	0.19		Y
West Specter Range	9	6.2	33	0.10	0.16	N/A	N/A	N/A	N/A		Y
West Spring Mountain	60	7.1	53	0.10	0.16	60	7.1	53	0.11		Y
Windy Wash	25	6.7	4.5	0.56	0.91	28	6.8	4	0.69	Fault is indicated as WW in Figure E-3.	Y
Yucca	32	6.8	40	0.11	0.18	31	6.8	43	0.10		Y
Yucca Lake	17	6.5	36	0.10	0.17	17	6.5	36	0.11		Y

*Y—considered as a seismic source in USGS (1998); C—considered as a seismic source when combined with other faults; N—not considered as a seismic source

(B-2) Faults classified as relevant or potentially relevant by Pezzopane in USGS (1998); only 29 of these faults are defined as Type I by McKague, et al. (1996).

	U.S. DEPARTMENT OF ENERGY (DOE)					NUCLEAR REGULATORY COMMISSION					
				Peak Acceleration (g)							
Name of Fault	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Median	84th	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	Considered as Seismic Source in USGS (1998)*
Abandoned Wash										See Ghost Dance—Abandoned Wash fault	Y
Area Three	12	6.3	44	0.07	0.12	N/A	N/A	N/A	N/A		N
Bullfrog Hills	7	6.1	38	0.07	0.12	N/A	N/A	N/A	N/A		N
Buried Hills	26	6.7	53	0.08	0.13	N/A	N/A	N/A	N/A		Y
Checkpoint Pass	7	6.1	44	0.06	0.11	N/A	N/A	N/A	N/A		N
Cockeyed Ridge—Papoose Lake	21	6.6	53	0.07	0.12	N/A	N/A	N/A	N/A		N
Crossgrain Valley	9	6.2	48	0.06	0.10	N/A	N/A	N/A	N/A		N
Death Valley—Furnace Creek	205	7.8	50	0.16	0.26	N/A	N/A	N/A	N/A		Y
Death Valley—Furnace Creek—Fish Lake Valley	288	7.9	50	0.17	0.27	N/A	N/A	N/A	N/A		Y

*Y—considered as a seismic source in USGS (1998); C—considered as a seismic source when combined with other faults; N—not considered as a seismic source

Name of Fault	U.S. DEPARTMENT OF ENERGY (DOE) Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g) Median	84th	NUCLEAR REGULATORY COMMISSION Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	Considered as Seismic Source in USGS (1998)*
Drill Hole Wash	4	5.8	1.5	0.46	0.74	N/A	N/A	N/A	N/A	Not considered Type I fault by McKague, et al (1996) because of orientation in modern *in situ* stress field.	N
Dune Wash	3	5.6	2	0.44	0.74	N/A	N/A	N/A	N/A		C
East Pintwater Range	58	7.1	61	0.06	0.10	N/A	N/A	N/A	N/A		Y
Emigrant Valley North	28	6.8	60	0.07	0.11	N/A	N/A	N/A	N/A		Y
Ghost Dance	3	5.6	0	0.44	0.74	N/A	N/A	N/A	N/A	See Ghost Dance—Abandoned Wash Fault	Y
Grapevine	20	6.6	58	0.06	0.10	N/A	N/A	N/A	N/A		Y
Grapevine Mountains	31	6.8	67	0.06	0.10	N/A	N/A	N/A	N/A		Y
Hunter Mountain—Panamint Valley	185	7.7	95	0.07	0.12	N/A	N/A	N/A	N/A		Y

*Y—considered as a seismic source in USGS (1998); C—considered as a seismic source when combined with other faults; N—not considered as a seismic source

Name of Fault	U.S. DEPARTMENT OF ENERGY (DOE) Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g) Median	84th	NUCLEAR REGULATORY COMMISSION Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	Considered as Seismic Source in USGS (1998)*
Indian Springs Valley	28	6.8	67	0.06	0.10	N/A	N/A	N/A	N/A		N
Kawich Valley	43	7.0	61	0.08	0.13	N/A	N/A	N/A	N/A		N
Mercury Ridge	10	6.2	48	0.06	0.10	N/A	N/A	N/A	N/A		N
Oak Spring Butte	21	6.6	57	0.06	0.11	N/A	N/A	N/A	N/A		Y
Pagany Wash	4	5.8	2.5	0.46	0.77	N/A	N/A	N/A	N/A	Not considered Type I fault by McKague, et al. (1996) because of orientation in modern *in situ* stress field.	N
Pahrump	70	7.2	70	0.08	0.12	N/A	N/A	N/A	N/A	See Amargosa River—Pahrump	Y
Pahute Mesa	9	6.2	48	0.06	0.10	N/A	N/A	N/A	N/A		Y

*Y--considered as a seismic source in USGS (1998); C—considered as a seismic source when combined with other faults; N—not considered as a seismic source

	U.S. DEPARTMENT OF ENERGY (DOE)					NUCLEAR REGULATORY COMMISSION					
				Peak Acceleration (g)							
Name of Fault	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Median	84th	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	Considered as Seismic Source in USGS (1998)*
Paintbrush Canyon—Stagecoach Road	33	6.8	4	0.62	1.00	N/A	N/A	N/A	N/A	The DOE represents combined Paintbrush Canyon—Stagecoach Road Fault System.	Y
Panamint Valley	100	7.4	95	0.06	0.10	N/A	N/A	N/A	N/A		Y
Sever Wash	4	5.8	3	0.46	0.77	N/A	N/A	N/A	N/A	Not considered Type I fault by McKague, et al. (1996) because of orientation in modern *in situ* stress field	N
South Ridge	19	6.6	50	0.08	0.12	N/A	N/A	N/A	N/A		N
Spotted Range	30	6.8	59	0.07	0.12	N/A	N/A	N/A	N/A		Y
Sundance	1	5.1	0	0.38	0.66	N/A	N/A	N/A	N/A		N
West Pintwater Range	60	7.1	76	0.07	0.11	N/A	N/A	N/A	N/A		Y
West Specter Range	9	6.2	33	0.10	0.16	N/A	N/A	N/A	N/A		Y

*Y—considered as a seismic source in USGS (1998); C—considered as a seismic source [illegible]

	U.S. DEPARTMENT OF ENERGY (DOE)					NUCLEAR REGULATORY COMMISSION					
				Peak Acceleration (g)							
Name of Fault	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Median	84th	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	Considered as Seismic Source in USGS (1998)*
Yucca Wash	9	6.2	5	0.47	0.78	N/A	N/A	N/A	N/A	Not considered Type I fault by McKague, et al. (1996) because of orientation in modern *in situ* stress field.	N

*Y—considered as a seismic source in USGS (1998); C—considered as a seismic source when combined with other faults; N—not considered as a seismic source

(B-3) Faults classified as irrelevant or potentially irrelevant by Pezzopane in USGS (1998) and as Type III faults by McKague, et al. (1996).

	U.S. DEPARTMENT OF ENERGY (DOE)					NUCLEAR REGULATORY COMMISSION					
				Peak Acceleration (g)							
Name of Fault	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Median	84th	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	Considered as Seismic Source in USGS (1998)*
Bonnie Claire	27	6.7	74	0.05	0.08	N/A	N/A	N/A	N/A		N
Boundary	7	6.1	51	0.05	0.09	N/A	N/A	N/A	N/A		N
Cactus Flat	50	7.1	84	0.06	0.09	N/A	N/A	N/A	N/A		N
Cactus Flat—Mellan	35	6.9	80	0.05	0.09	N/A	N/A	N/A	N/A		N
Cactus Range—Wellington Hills	29	6.8	87	0.05	0.07	N/A	N/A	N/A	N/A		N
Cactus Springs	14	6.4	59	0.05	0.09	N/A	N/A	N/A	N/A		N
Chalk Mountain	20	6.6	87	0.04	0.07	N/A	N/A	N/A	N/A		N
Chert Ridge	14	6.4	65	0.05	0.08	N/A	N/A	N/A	N/A		N
Chicago Valley	20	6.6	90	0.04	0.06	N/A	N/A	N/A	N/A		N
Emigrant Valley South	20	6.6	66	0.06	0.09	N/A	N/A	N/A	N/A		N
Fallout Hills	8	6.1	70	0.04	0.06	N/A	N/A	N/A	N/A		N
Fish Lake Valley	83	7.3	135	0.04	0.06	N/A	N/A	N/A	N/A		N
Garlock	251	7.9	150	0.05	0.08	N/A	N/A	N/A	N/A		N

*Y—considered as a seismic source in USGS (1998); C—considered as a seismic source when combined with other faults; N—not considered as a seismic source

	U.S. DEPARTMENT OF ENERGY (DOE)					NUCLEAR REGULATORY COMMISSION					
				Peak Acceleration (g)							
Name of Fault	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Median	84th	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	Considered as Seismic Source in USGS (1998)*
Gold Flat	16	6.5	60	0.06	0.09	N/A	N/A	N/A	N/A		N
Groom Range Central	31	6.8	82	0.05	0.08	N/A	N/A	N/A	N/A		N
Groom Range East	20	6.6	85	0.04	0.07	N/A	N/A	N/A	N/A		N
Hunter Mountain	85	7.3	95	0.06	0.09	N/A	N/A	N/A	N/A	Considered a seismic source when combined with Emigrant fault	C
Jumbled Hills	27	6.7	77	0.05	0.06	N/A	N/A	N/A	N/A		N
La Madre	33	6.8	82	0.05	0.08	N/A	N/A	N/A	N/A		N
North Desert Range	24	6.7	81	0.05	0.07	N/A	N/A	N/A	N/A		N
Owens Valley	110	7.4	126	0.04	0.07	N/A	N/A	N/A	N/A		N
Pahranagat	91	7.4	106	0.05	0.09	N/A	N/A	N/A	N/A		N
Penoyer	56	7.1	97	0.05	0.08	N/A	N/A	N/A	N/A		N
Racetrack Valley	22	6.6	97	0.03	0.06	N/A	N/A	N/A	N/A		N

*Y—considered as a seismic source in USGS (1998); C—considered as a seismic source when combined with other faults; N—not considered as a seismic source

Name of Fault	U.S. DEPARTMENT OF ENERGY (DOE) Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g) Median	84th	NUCLEAR REGULATORY COMMISSION Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	Considered as Seismic Source in USGS (1996)*
Ranger Mountains	5	5.9	49	0.05	0.08	N/A	N/A	N/A	N/A		N
San Andreas	420	8 1	291	0.03	0.05	N/A	N/A	N/A	N/A		N
Stonewall Mountain	22	6 6	92	0.04	0.06	N/A	N/A	N/A	N/A		N
Stumble	33	6.8	74	0.05	0 09	N/A	N/A	N/A	N/A		N
Three Lakes Valley	27	6 7	84	0.04	0.07	N/A	N/A	N/A	N/A		N
Tikaboo	33	6.8	92	0.04	0.07	N/A	N/A	N/A	N/A		N
Tin Mountain	29	6.8	90	0 04	0.07	N/A	N/A	N/A	N/A		N
Towne Pass	38	6 9	76	0.06	0.09	N/A	N/A	N/A	N/A	Considered a seismic source when combined with Emigrant Fault.	C
White Mountains and Cedar Mountain	115	7 5	185	0 03	0 05	N/A	N/A	N/A	N/A		N

(B-4) Faults classified as Type I by McKague, et al. (1996) but not considered by Pezzapane in USGS (1996).

	U.S. DEPARTMENT OF ENERGY (DOE)					NUCLEAR REGULATORY COMMISSION					
Name of Fault	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g) Median	Peak Acceleration (g) 84th	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	Considered as Seismic Source in USGS (1998)*
Simonds Number 1	N/A	N/A	N/A	N/A	N/A	3	5.6	7	0.32	In DOE (1998) (Appendix E), AAR team evaluated these faults. Based on lack of geomorphic expression in bedrock indicating significant Quaternary activity and estimated Mw, these faults were not considered seismic sources. See Figure E-3	N
Simonds Number 2	N/A	N/A	N/A	N/A	N/A	7	6.1	6	0.44		N
Simonds Number 3	N/A	N/A	N/A	N/A	N/A	5	5.9	5	0.44		N
Simonds Number 4	N/A	N/A	N/A	N/A	N/A	5	5.9	5	0.45		N
Simonds Number 5	N/A	N/A	N/A	N/A	N/A	5	5.9	6	0.42		N

*Y—considered as a seismic source in USGS (1998); C—considered as a seismic source when combined with other faults, N—not

	U.S. DEPARTMENT OF ENERGY (DOE)					NUCLEAR REGULATORY COMMISSION					
				Peak Acceleration (g)							
Name of Fault	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Median	84th	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	Considered as Seismic Source in USGS (1998)*
Northern Crater Flat (NCF 12)	N/A	N/A	N/A	N/A	N/A	8	16.1	6	0.47	Formerly Simonds 12 [See McKague, et al. (1996), Appendix A]. Fault indicated as NCF-12 in Figure E-3	C
West Dune Number 1 (WD 1)	N/A	N/A	N/A	N/A	N/A	8	6.1	2	0.64	Formerly Simonds 14 [McKague, et al. (1996), Appendix A]. Fault indicated as WD-1 in Figure E-3	Y
West Dune Number 2 (WD 2)	N/A	N/A	N/A	N/A	N/A	4	5.8	4	0.47	Formerly Simonds 15 [McKague, et al., (1996)]. Appendix A] Fault indicated as WD-2 in Figure E-3	Y

*Y—considered as a seismic source in USGS (1998); C—considered as a seismic source when combined with other faults; N—not considered as a seismic source

	U.S. DEPARTMENT OF ENERGY (DOE)					NUCLEAR REGULATORY COMMISSION					
				Peak Acceleration (g)							
Name of Fault	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Median	84th	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	Considered as Seismic Source in USGS (1998)*
Simonds Number 15	N/A	N/A	N/A	N/A	N/A	4	5.8	4	0.47	In DOE (1998) (Appendix E), AAR team evaluated these faults Based on lack of geomorphic expression in bedrock indicating significant Quaternary activity and estimated Mw, these faults were not considered seismic sources. See Figure E-3	N
Simonds Number 16*	N/A	N/A	N/A	N/A	N/A	4	5.8	7	0.34		N
Simonds Number 17	N/A	N/A	N/A	N/A	N/A	3	5.6	13	0.19		N

*Y – considered as a seismic source in USGS (1998); C – considered as a seismic source when combined with ...

	U.S. DEPARTMENT OF ENERGY (DOE)					NUCLEAR REGULATORY COMMISSION					
Name of Fault	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g) Median	Peak Acceleration (g) 84th	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	Considered as Seismic Source in USGS (1998)*
South Crater Flat (SCF)	N/A	N/A	N/A	N/A	N/A	8	6.1	8	0.39	In DOE, 1998 (Appendix E) AAR team identifies this as the South Crater Flat fault. Formerly Fault 14, McKague, et al., 1996, (Appendix A).	C
South Windy Wash (SWW)	N/A	N/A	N/A	N/A	N/A	10	6.2	8	0.40	Formerly Simonds 17 [McKague, et al. (1996); Appendix A). Fault indicated as SWW in Figure E-3	Y

*Y—considered as a seismic source in USGS (1998); C—considered as a seismic source when combined with other faults; N—not considered as a seismic source

(B-5) Faults used as seismic sources by seismic source experts (DOE, 1998). Fault length listed is maximum value from DOE, 1998.

	U.S. DEPARTMENT OF ENERGY (DOE)					NUCLEAR REGULATORY COMMISSION					
				Peak Acceleration (g)							
Name of Fault	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Median	84th	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	Considered as Seismic Source in USGS (1998)*
Ash Hill	90	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Location shown on DOE, 1998; Figure 4-67	Y
H 95 (Carrara)	27	6.5-7.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Location shown on DOE, 1998; Figure 4-67	Y
East Busted Butte		N/A	N/A	N/A	N/A	N/A	N/A	N/A		Location shown on DOE, 1998; Figure 4-18	Y
East Death Valley	75	7.2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	May be same as DV shown in DOE, 1998; Figure 4-31	Y
East Lathrop Cone	9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Location shown on DOE, 1998, Figure 4-18	Y

*Y—considered as a seismic source in USGS (1998); C—considered as a seismic source when combined with other faults; N—not considered as a seismic source

	U.S. DEPARTMENT OF ENERGY (DOE)					NUCLEAR REGULATORY COMMISSION					
				Peak Acceleration (g)							
Name of Fault	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Median	84th	Fault Length (km)	Maximum Magnitude	Distance to Fault (km)	Peak Acceleration (g)	Comments	Considered as Seismic Source in USGS (1998)*
East Spector Range	15	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Location shown on DOE, 1998; Figure 4-31	Y
Emigrant/ Towne Pass	47	7.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Location shown on DOE, 1998; Figure 4-31	C
Peace Camp	31	6.5-7 1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Location shown on DOE, 1996; Figure 4-41	C
South Silent Canyon	17	N/A								Location shown on DOE, 1998; Figure 4-67	Y
Tolicha Pass										May be same as Tolich Peak fault	Y
Yucca Butte	49	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Location shown on DOE, 1998, Figure 4-67	Y

*Y—considered as a seismic source in USGS (1998); C—considered as a seismic source when combined with other faults; N—not considered as a seismic source

APPEND

CLASSIFICATION OF TECTONIC MODELS AT YUCCA MOUNTAIN VICINITY

Appendix C-1. Summary of Viable Tectonic Models

Model Name	References	Comments
Half Graben with Moderate Depth Detachment	Young, et al. (1992b) Ferrill, et al. (1996b)	Supported by CNWRA balanced cross sections (e.g.,Young, et al., 1992b). Also consistent with pull-apart model (Stamatakos and Ferrill, 1996a). Supported by regional observations (e.g., Wright and Troxel, 1973; Burchfiel, et al., 1987). Seismic data (e.g., Brocher, et al., 1996) neither support nor refute the models because validity of seismic data below 6 km depth is questionable (cf. Brocher, et al., 1996; Majer, et al., 1997).
Half Graben with Deep Depth Detachment	Young, et al. (1992b) Ferrill, et al. (1996b)	Supported by CNWRA balanced cross sections (e.g.,Young, et al., 1992b). Also consistent with pull-apart model (Stamatakos and Ferrill, 1996a). Supported by regional observations (e.g., Wright and Troxel, 1973; Burchfiel, et al., 1987). Seismic data (e.g., Brocher, et al., 1996) neither support nor refute the model because validity of seismic data below 6 km depth is questionable (cf. Brocher, et al., 1996; Majer, et al., 1997).
Crater Flat Pull-Apart Basin	Fridrich, (in press)	Supported by regional seismo-tectonic framework (e.g., Oldow, et al., 1994). Fault geometries at depth unspecified. Requires existence of additional blind seismic sources (McKague, et al., 1996). Requires blind strike-slip fault south of CF (Stamatakos and Ferrill, 1996a).
Elastic-Viscous Graben	Janssen (1995)	Consistent with pull-apart basin interpretation. Assumes mobile ductile middle crust and nternally deformable upper crustal blocks. Requires very thin effective elastic crust (thickness of only 2 km) and blind large-displacement faults in CF and external to the model (See Section 4.3).
Amargosa Desert Fault	Schweickert and Lahren (1997)	Explains selected geometric features (e.g., State Line fault and CF basaltic cone alignment) but requires unrecognized shallow detachments within calderas north of CF (e.g., Hardyman and Oldow, 1991). Inconsistent with thermochronologicdata (e.g., Ferrill, et al., 1996b).

Appendix C-2. Summary of Tectonic Models Considered Not Viable

Model Name	References	Comments
Collapsed Caldera	Carr (1982, 1988) Carr and Parrish (1985)	Inconsistent with geometric and kinematic data. Geophysical data (Brocher, et al., 1996; Rosenbaum, et al., 1991) and structural data (e.g., Scott, 1990; Young, et al., 1992b; Ferrill, et al., 1996b) show CF as a fault bound half graben. Thermochronological data show CF and BM fault probably existed prior to Miocene volcanism (e.g., Ferrill, et al., 1996b).
Kawich-Greenwater Rift	Carr (1984)	Inconsistent with kinematic data. Rifting assumes contemporaneous faulting and volcanism, but BM fission track data indicate significant uplift (faulting) prior to Miocene volcanism (e.g., Ferrill, et al., 1996b).
Yucca Synclinorium	Robinson (1985)	Inconsistent with nearly all geological and geophysical studies.
Planar-Domino Faults	Stewart (1978)	Inconsistent with known geometry and kinematics of faults (e.g., Fridrich, in press; Ferrill, et al., 1996b). Domino faulting layering requires all fault blocks to have similar dips and faulting to be coeval.
Regional Detachment	Wernicke (1992) Snow (1994)	Inconsistent with existing kinematic and geometric data. No evidence for shallow detachment east of BM (e.g., Simonds, et al., 1995b; Ferrill, et al., 1996b). Paleomagnetic data (e.g., Stamatakos and Ferrill, 1996b) show no large-scale vertical-axis rotation of BM as indicated in model of Snow (1994).
Shallow Detachment	Scott (1990) Hamilton (1988)	Inconsistent with geometric and kinematic data. Balanced cross sections require a minimum detachment depth of 6 km (e.g., Young, et al., 1992b; Ferrill, et al., 1996b). No detachment visible on seismic data (Brocher, et al., 1996). Thermochronology data (e.g., Ferrill, et al., in review) indicate BM exhume prior to Bullfrog Hills-Fluorspar Canyon detachment faulting (Ferrill et al., 1996b).

Appendix C-3. Summary of Effects on Performance of Viable Tectonic Models

Model Name	Comments
Half Graben with Moderate Detachment	Has least adverse effect on repository performance. Connectivity between the BM fault and the CF-YM detachment fault can lead to compensatory slip on the CF-YM faults in response to slip on the BM fault. However, the response behavior depends on the details of the strain accommodation mechanism in the BM fault hanging wall (e.g., flexural shear and outer arc extension versus oblique simple shear or vertical simple shear). Since the CF-YM faults extend to a lesser depth in this model, the potential rupture area (the area with high slip tendency) and earthquake magnitudes are smaller than those for a deep detachment (Ofoegbu and Ferrill, 1995; McKague, et al., 1996). Moreover, faults with dips coalescing into a moderate detachment are less likely to serve as magma pathways.
Half Graben with Deep Detachment	Possibility of the CF-YM domain producing large magnitude earthquakes in the future. The CF-YM faults extend to considerable depth (~15 km), hence they have large potential rupture areas with high slip tendency and can produce large-magnitude earthquakes (McKague, et al., 1996). In addition, slip on the BM may trigger slip on one or more CF-YM faults because of the supposed link at depth. Faults that maintain steep dips to the base of the seismogenic crust are also good candidates for capturing igneous dikes, thus serving as preferred magma pathways.
Crater Flat Pull-Apart Basin	Mix of strike-slip and dip-slip faulting could increase seismic hazard because the current PSHA (Wong, et al., 1995) considers only dip-slip motion on most CF-YM faults. More importantly, the hypothesized regional strike-slip system is a major seismic source that could dominate the PSHA. Such a source is not considered in the existing PSHA (Wong, et al., 1995). The pull-apart model has CF-YM faults maintaining steep dips to depth, so the structures are favorable for dike capture.
Elastic-Viscous Graben	Possibility for large rupture areas and attendant earthquakes associated with planar faults extending as deep as 15 km Faults could also serve as easily exploitable magma pathways. In contrast to the detachment models, slip on the CF-YM faults is not directly linked to movement on the BM. The planar model also predicts a significant west-dipping blind fault with 3 km of offset beneath CF (in order to contain deformation within CF)
Amargosa Shear or Amargosa Desert Fault	Raises the possibility of the most significant adverse effect on repository performance. As with the pull-apart models, the Amargosa shear requires a major strike-slip fault capable of generating earthquakes with maximum magnitudes up to $M_w = 8.0$, which would greatly affect PSHA. Furthermore, such a fault could have a major impact on rock hydrologic properties between CF and Amargosa Valley. The link with igneous activity suggests that a strike-slip event may be able to trigger another phase of basaltic activity in CF.

APPENDIX

SITE CHARACTERIZATION ANALYSIS COMMENTS REVISED

Site Characterization Analysis Open Items Reconsidered

Based on several meetings, workshops, field trips, and visits to the ESF, the staff considers that most of the SCA open-items are being considered by DOE. The staff believes that the recently-collected data and the results of the several workshops that will be discussed in FY98 and FY99 reports will form suitable bases on which to reconsider SCA open items.

Items are organized by Comment and Question, numerically, according to subissues in this IRSR, and 'Subissue: Other Geoscience.'

Numbers in parentheses refer to pages in NUREG-1347, *NRC Staff Site Characterization Analysis of the DOE's Site Characterization Plan, Yucca Mountain*, NV, 1989

- **FAULTING SUBISSUE**

Comment 36	Resolved
Comment 48	Open
Comment 59	Open
Comment 60	Open
Comment 61	Open
Comment 62	Resolved
Comment 63	Open
Comment 64	Resolved
Comment 69	Open
Comment 71	Resolved

- **SEISMICITY SUBISSUE**

Comment 66	Resolved
Comment 67	Resolved

- **FRACTURING SUBISSUE**

None

- **TECTONICS SUBISSUE**

Comment 8	Open
Comment 47	Open
Comment 68	Open
Comment 98	Open

- **OTHER GEOSCIENCES SUBISSUES**

Comment 32	Open
Comment 51	Open
Question 8	Open

COMMENT 8 **Alternative Tectonic Models**

"Alternative tectonic models for the site do not appear to be fully integrated into the site characterization plan and as a result alternatives are apparently not considered in the preliminary performance allocations and the design of the Engineered Barrier System (EBS). The site characterization program appears to be directed toward providing data that confirm the preferred tectonic model rather than determining what the '"preferred model"' should be." (p. 4-14)

RECOMMENDATIONS

* "Alternative tectonic models should be thoroughly integrated into preliminary performance allocations and the design of the EBS." Consideration should be given to prioritizing investigations giving high priority to those investigations associated with tectonic features, events, or processes that could lead to the determination of whether the site has unacceptable adverse conditions, or to a substantial change in the site characterization program." (p 4-16)

DISPOSITION

Open. DOE is fully considering alternative tectonic models. Seismotectonic scenarios reports, TSPA VA, PFDHA, and PSHA expert elicitation results will be reported in FY98 and FY99. Resolution is pending review of the DOE reports.

****

COMMENT 32 **Geophysical Data Integration**

"The program for geophysical integration as presented in the SCP is insufficiently described. The correlation between the different geophysical investigations is not presented and, in addition, the approach that will be used to integrate the geophysical activities and how these different activities will complement each other does not appear to be discussed in the SCP." (p. 4-35)

RECOMMENDATIONS

* "Integrate and evaluate existing geologic and geophysical data and provide overlays of the existing coverage and evaluations.

* Based on this integration, provide a coherent geophysical program to be implemented in the Yucca Mountain area that would provide sufficient characterization of the site." (p. 4-35)

DISPOSITION

Open. DOE has completed reports on its geophysical surveys (seismic reflection, gravity, and magnetic data). The results were utilized in several workshops held during 1996 and 1997. DOE submitted results of gravity and magnetic surveys of Yucca Mountain area (Earthfield

Technology, 1995). CNWRA recently collected gravity and magnetic data and plan to integrate the results from the different geophysical methods. The resolution of this issue is pending the outcome of staff reviews of the DOE reports and of the CNWRA results.

****

COMMENT 36 **Faults in Perimeter Drift**

"The technical rationale for this investigation states that the perimeter drift defines an area of a significantly lower concentration of faults than has been mapped in surrounding areas. However, based on other parts of the SCP, this concept may not be accurate. Further, there is no apparent indication that studies in the SCP address the potential impact on system performance of the presence within the perimeter drift (i.e., in emplacement areas) of a significant number of faults, some of which may be favorably oriented for failure under the present stress regime."
(4-38)

RECOMMENDATIONS

* "Rectify the apparent contradiction as to whether a zone of imbricate faulting is present within the perimeter drift.

* If the imbricate fault zone is present within the perimeter drift, an assessment should be made to demonstrate that the requirements of 10 CFR 60.133(h) will be met." (p. 4-38)

DISPOSITION

Resolved. DOE's ESF reports, Repository Safety Strategy, Total System Performance Assessment-Viability Assessment Plan, the plan to conduct perimeter drifting, and proposed enhanced drifting and drilling alleviate this concern. Also DOE is planning to move the perimeter drift to a location west of Ghost Dance fault, leaving the imbricate fault zone outside the perimeter. No staff questions at this time.

****

COMMENT 47 **Integrate Tectonics Into PA**

"The approach to incorporating data derived in the postclosure tectonics program into an assessment of whether performance issues related to the waste package and engineered barrier system (EBS) requirements (10 CFR 60.113(a)) will be met is confusing and may result in an inaccurate assessment of performance." (p. 4.44)

RECOMMENDATION

* "Consideration should be given to establishing a direct path for the integration of data collected in the Postclosure Tectonics program into issues 1.4 (Will waste package meet the

performance objective) and 1.5 (Will the waste package and repository engineered barrier system meet the performance objective)." (p. 4-44)

DISPOSITION

Open. DOE's Repository Safety Strategy, Seismotectonic Scenarios Report, and TSPA-VA will consider effects of seismotectonics on performance. Resolution is pending SDS and CLST review of the DOE reports.

****

COMMENT 48 **Fault Slip Rate**

"The use of fault slip rates to determine the level of hazard posed to repository facilities by faults does not appear to be a conservative approach and may result in overly optimistic predictions about the effects of faulting on system performance." (p. 4-45)

RECOMMENDATIONS

* "Demonstrate that the use of slip rates for determining hazard does not provide overly optimistic predictions of the effects of faulting on repository performance.

* Consider alternative methods (e.g., maximum event offset) or a combination of methods (e.g., maximum event offset and slip rates) to assess the level of hazard to the surface facilities and EBS posed by faulting." (p. 4-45)

DISPOSITION

Open. The results of DOE's consideration of slip rates will be presented in PSHA AND TR #3. Resolution is pending reviews of the DOE reports.

****

COMMENT 51 **Correlate Deep & Shallow Geophysical Surveys**

"Geophysical survey programs as indicated in the SCP may not be sufficient to identify and characterize both the deep crustal and shallow geologic features and their interrelationship." (p. 4-47)

RECOMMENDATIONS

* "Provide a geophysical investigation program plan that is comprehensive, integrated and sufficient to identify and understand the interrelationships of the deep crustal structure and shallow geologic structural features, and to assure that no significant structural features have gone undetected.

• Consider including a gridded program of exploratory surveys and measurements that would allow for cross-line correlations and more complete spatial definition of anomalies at the site and specifically at the locations of the exploratory shafts." (p. 4-47)

DISPOSITION

Open. DOE collected more seismic reflection, gravity, and magnetic data since the issuance of the SCP (e.g., Earthfield Technology, 1995). CNWRA also collected gravity and magnetic data in the vicinity of Yucca Mountain. Staff expects that these data will be sufficient to characterize the shallow and deep structures and their interrelationship. The resolution of this issue is pending the outcome of the review of DOE's and CNWRA's reports due in FY98 and FY99.

****

COMMENT 59 **Sequencing Fault Investigations**

"The information presented for the program of investigations for faulting does not allow the NRC staff to determine what investigations will actually be conducted. In addition, the sequencing of many geophysical and geologic activities related to faulting may lead to data collection activities that are inadequate to support assessments of performance and design bases." (p. 4-53)

RECOMMENDATION

• "Consideration should be given to re-examining the sequence of all activities dependent on input from other activities." (p. 4-53)

DISPOSITION

Open. DOE's geological and geophysical site characterization activities that bear on fault characterization are largely completed. DOE collected several seismic reflection, gravity, and magnetic data. These sets of data were utilized in PSHA, PFDHA, and PVHA. CNWRA also collected several gravity and magnetic data to enhance the identification of buried volcanic cones and blind faults. Resolution is pending reviews of the DOE reports.

****

COMMENT 60 **Fault Parameters**

"The NRC staff does not consider that the basis and rationale for the design and performance parameters. characterization parameters, and goals proposed in the SCP for fault displacement, in particular for fault investigations for facilities important to safety (FITS), have been justified. The staff is concerned, as these values appear to be used to limit the exploration program prior to having sufficient data to evaluate the site." (p. 4-53)

RECOMMENDATION

• "DOE needs to strengthen its justification for the design and performance parameters, characterization parameters, and goals for preclosure fault displacement as related to FITS, or revise these values. The justification should include a discussion of the interrelationship of the characterization parameters, performance and design parameters, and goals with the design criteria and the performance objectives of 10 CFR Part 60." (p. 4-54)

DISPOSITION

Open. DOE had held several workshops on PSHA and PFDHA to address this particular issue. DOE will present the results in upcoming reports. Resolution is pending reviews of the upcoming reports.

****

COMMENT 61 **Location of New Faults**

"The program of investigations for faulting appears to assume that any future faulting will follow old faulting patterns. The NRC staff considers that this in not a reasonably conservative assumption, and does not consider that this assumption is technically justified." (p. 4-55)

RECOMMENDATION

* "DOE needs to review its assumptions used to plan the exploration program for FITS to assure unconservative assumptions, such as future faulting only occurring at the exact locations of past faulting, do not bias the program." (p. 4-55)

DISPOSITION

Open. DOE recently presented its tectonic models and fault characterization for Yucca Mountain in several workshops. Resolution is pending reviews of the DOE reports.

****

COMMENT 62 **Fault Standoff**

The information presented for the program of investigations for study of faulting at the surface facilities does not allow the NRC staff to determine how DOE is proposing to use standoff distances in designing the program of investigations and in performing the resultant design and analysis." (p. 4-56)

RECOMMENDATION

* "DOE needs to demonstrate that:

(i) the program of investigations for faulting at not near FITS will adequately evaluate all faults that have a potential of movement; and/or

(ii) that the evaluation of the effects of faulting, taking into account the degree of resolution of the investigation, will not underestimate the effects; and

(iii) the effect of faulting will not compromise the ability of the FITS to meet the performance objectives." (p. 4-56)

DISPOSITION

Resolved. DOE is planning to avoid areas where concentration of active faults are located and relocate the repository perimeter west of the Ghost Dance fault. DOE plans to design for faults that it can not avoid (U.S. DOE, 1995, key 023). No staff questions at this time.

****

COMMENT 63 **Integrating Fault Data**

"The information presented for the program of investigations for study of faulting at the surface facilities does not appear to have integrated pre-existing information and makes assumptions about pre-existing information and on-going investigations which the NRC cannot evaluate because the NRC has not seen the background information." (p. 4-56)

RECOMMENDATION

• "Prior to the NRC staff's being able to evaluate the program of site investigations, DOE needs to complete at least the planning step of integration of the site program. This should include not only a separate integration of drilling or a separate integration of geophysics, but a complete integration of the planned program of investigations. This integration should show how ongoing activities and pre-existing information has been incorporated into the program and should demonstrate what assumptions are being made on the qualification of pre-existing data." (p. 4-57)

DISPOSITION

Open. The adequacy of DOE's fault characterization program is expected to be evaluated by reviews of DOE reports scheduled for FY98 and FY99.

****

COMMENT 64 **Significant Faults**

"The characterization parameters for the identification and characterization of "significant Quaternary faults" in the area of the repository block do not appear to fulfill the requirements in 10 CFR 60, such as investigating and evaluating the effects of potentially adverse natural conditions." (p. 4-57)

RECOMMENDATION

* "The site characterization program and performance allocation process should be designed to assure that any fault that could have an adverse impact on waste isolation will be characterized." (p. 4-58)

DISPOSITION

Resolved. Staff have resolved the disposition of potentially significant Quaternary faults (Section 5.1.1.1).

****

COMMENT 66 **10,000-Year Earthquake**

"Since the 10,000-year cumulative slip earthquake (10-kyr CSE) methodology assumes that average cumulative slip over 10,000 years is released in a single event, it appears that recurrence is implied to be fixed at 10,000 years. It is questionable whether such a methodology can properly characterize fault activity and the related seismic activity in the site region." (p. 4-58)

RECOMMENDATION

* "Recurrence-rate estimates should be given special emphasis. In particular, differences between the true maximum magnitude and the 10-kyr CSE, based on evaluations of the recurrence interval associated with the maximum earthquake determined from magnitude-frequency relationships, should be thoroughly explained. The planned site characterization activities, which are designed to provide all types of information that are material to the characterization of seismic hazard, should be conducted in a manner that will allow for a clear comparison of the 10-kyr CSE methodology with other alternative methodologies." (p. 4-59)

DISPOSITION

Resolved. DOE is not using the 10-Kyr CSE concept. DOE's current methodology presented in TR#1 (DOE, 1997; *YMP/TR-002-NP: Methodology to Assess Fault Displacement and Vibratory Ground Motion Hazards at YM*, August, 1997) is acceptable. No staff questions at this time.

****

COMMENT 67 **Magnitude 5.5 Cutoff**

"The data compiled according to Activity 8.3.1.17.4.1.2, i.e., having a magnitude cutoff of 5.5, may not be sufficient to support an evaluation of the effects of local site geology on surface and subsurface motions."

RECOMMENDATION

* "The distinction between those parameters that are to be compiled for all recorded seismic events and those that are to be compiled for events greater than magnitude 5.5 should be dropped. If it is reasonable and practical, information for any of the 19 categories of parameters listed in Activity 8.3.1.17.4.1.2 should be compiled for earthquakes in the Yucca Mountain vicinity, without regard to their size." (P. 4-60)

DISPOSITION

Resolved. In a letter dated August 15, 1991 (D.E. Shelor to J. Lichen), DOE provided clarification as follows: smaller-magnitude earthquakes than 5.5 that may have an impact on the site will be considered in seismic analysis. This comment was closed by letter from R. Ballard to J. Holonich dated October 2, 1991.

****

COMMENT 68 Detachment Fault Model

"Other aspects of detachment faulting, in addition to those described in Section 8.3.1.17.4.5 regarding key questions to be answered on earthquake sources, do not appear to be treated as similarly potentially significant." (p. 4-60)

RECOMMENDATIONS

* "The significance of detachment faulting as a key element in assessing the potential for faulting at the site needs to be readdressed giving consideration to other key concerns related to detachment faulting.

* Consideration should be given to having the results of Study 8.3.1.17.4.5 input directly into postclosure tectonics performance issues." (p. 4-61)

DISPOSITION

Open. DOE has considered detachments faults (U.S.Geological Society, 1996). Fault models were discussed in several PSHA workshops. Resolution is pending review of DOE reports.

****

COMMENT 69 NW-Trending Faults

"The SCP does not appear to integrate and synthesize data resulting from the planned activities characterizing northwest-trending faults." (p. 4-61)

RECOMMENDATION

* "Consideration should be given to specifically outlining a program of study to integrate and synthesize all activities that will collect data o^ ^orthwest-trending faults." (p. 4-61)

DISPOSITION

Open. DOE provided a report on the integration of the different activities to characterize the N-W trending faults (USGS, 1996). The results of this integration will be presented in DOE reports in FY98 and FY99. Resolution is pending the outcome of staff reviews.

****

COMMENT 71 Significant Fault

"The tentative goal, design parameter, and expected value relating faulting (e.g., "significant Quaternary fault") and performance allocation for System Element 1.1.2 are not sufficient for adequately characterizing the hazard posed by faulting in the repository." (p. 4-61)

RECOMMENDATIONS

* "Consideration should be given to using alternative fault models as a conceptual basis for assessing the preclosure hazard to the repository."

* Demonstrate that from a scientific perspective, the program of drifting in the northern part of the repository combined with the systematic drilling program and feature sampling program will provide the information necessary to ensure that conditions and processes encountered are representative of conditions and processes throughout the site and that potentially adverse conditions will be adequately investigated." (p. 4-62)

DISPOSITION

Resolved. The staff considers Type I faults to be significant faults. The staff now considers that DOE has adequately identified significant faults at Yucca Mountain and will continue to do so.

****

COMMENT 98 Alternative Conceptual Models

"Weighting alternative conceptual models according to the judgment that they are likely to be correct and using such "probabilities" to weight consequences in the construction of the CCDF is not a conservative estimate of repository performance, nor is it an advisable approach for demonstrating compliance." (p. 4-78)

RECOMMENDATIONS

* "The SCP should recognize that the approach of incorporating alternative conceptual model likelihoods into the computation of the CCDF of cumulative releases of radionuclides may not provide information about repository performance in an acceptable format because uncertainties are not delineated distinctly.

* "Plan to incorporate consideration of unresolved alternative conceptual models into the CCDF in a conservative fashion by choosing the alternative that gives the poorest performance (greatest releases of radionuclides) or by some combination of the two alternatives that ensures no underestimates of releases and develop the site characterization program accordingly." (p. 4-79)

DISPOSITION

Open. Based on expert elicitation, DOE will provide alternative models to be considered in the performance assessment. Different weights will be assigned to these models based on their credibility. The range in uncertainty in these models will be addressed in an upcoming DOE report. Resolution is pending the review of this report.

****

QUESTION 8 **Variability of Model Input**

"What measure of predictability will accompany the computer models, maps, and other illustrations? How will uncertainties be explicitly transmitted to the model users?" (p. 4-105)

RECOMMENDATION

"SCP updates should describe how local variability in the data will be presented in the block model." (p. 4-106)

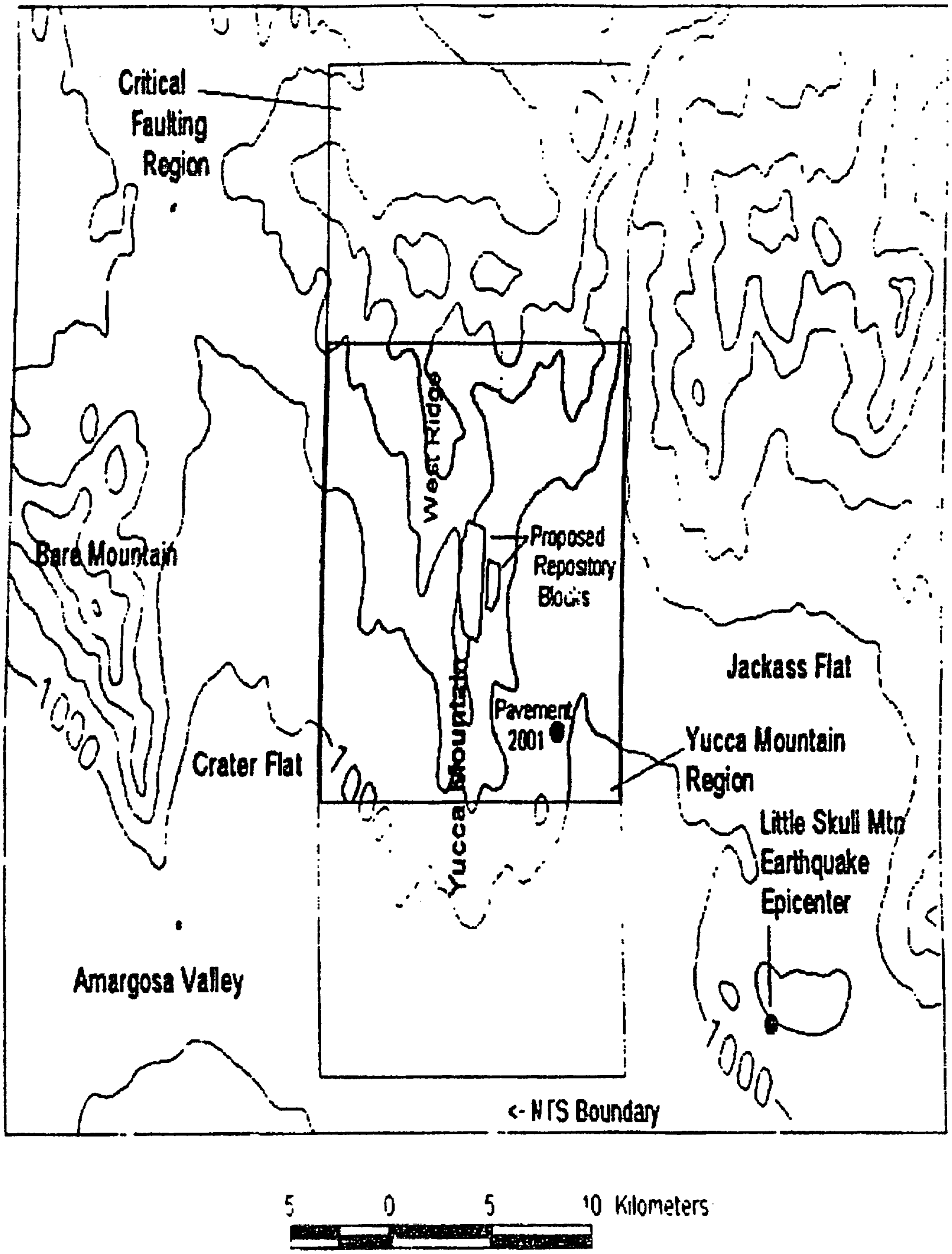
DISPOSITION

Open. DOE's ISM 2.0 and related process models will address uncertainty in data and interpretations. DOE requested NRC feedback on the adequacy of ISM 2.0 for its intended purposes. Appendix 7 interactions were held in July and September, 1997, to provide preliminary staff feedback and to brief staff on the operation of the ISM 2.0 code. DOE revised its request by submitting geologic framework model (GFM3.0) for staff review. A technical exchange on GFM3.0 was held in May 1997 by DOE to brief the staff on operation of GFM3.0 code. Resolution is pending staff's review of GPM 3.0.

APPENDIX E

FIGURES AND TABLES

Figure E-1. Regional map showing the topography and the location of geographic features near Yucca Mountain referenced in the text. The contour interval is 200m. Also shown are the Critical Faulting Region and the Yucca Mountain Region (shaded) where the paleoseismic investigations were conducted.



Critical Faulting Region
West Ridge
Proposed Repository Blocks
Bare Mountain
Jackass Flat
Pavement 2001
Yucca Mountain Region
1000
Crater Flat
Yucca Mountain
Little Skull Mtn Earthquake Epicenter
Amargosa Valley
<- NTS Boundary
5 0 5 10 Kilometers

Figure E-1

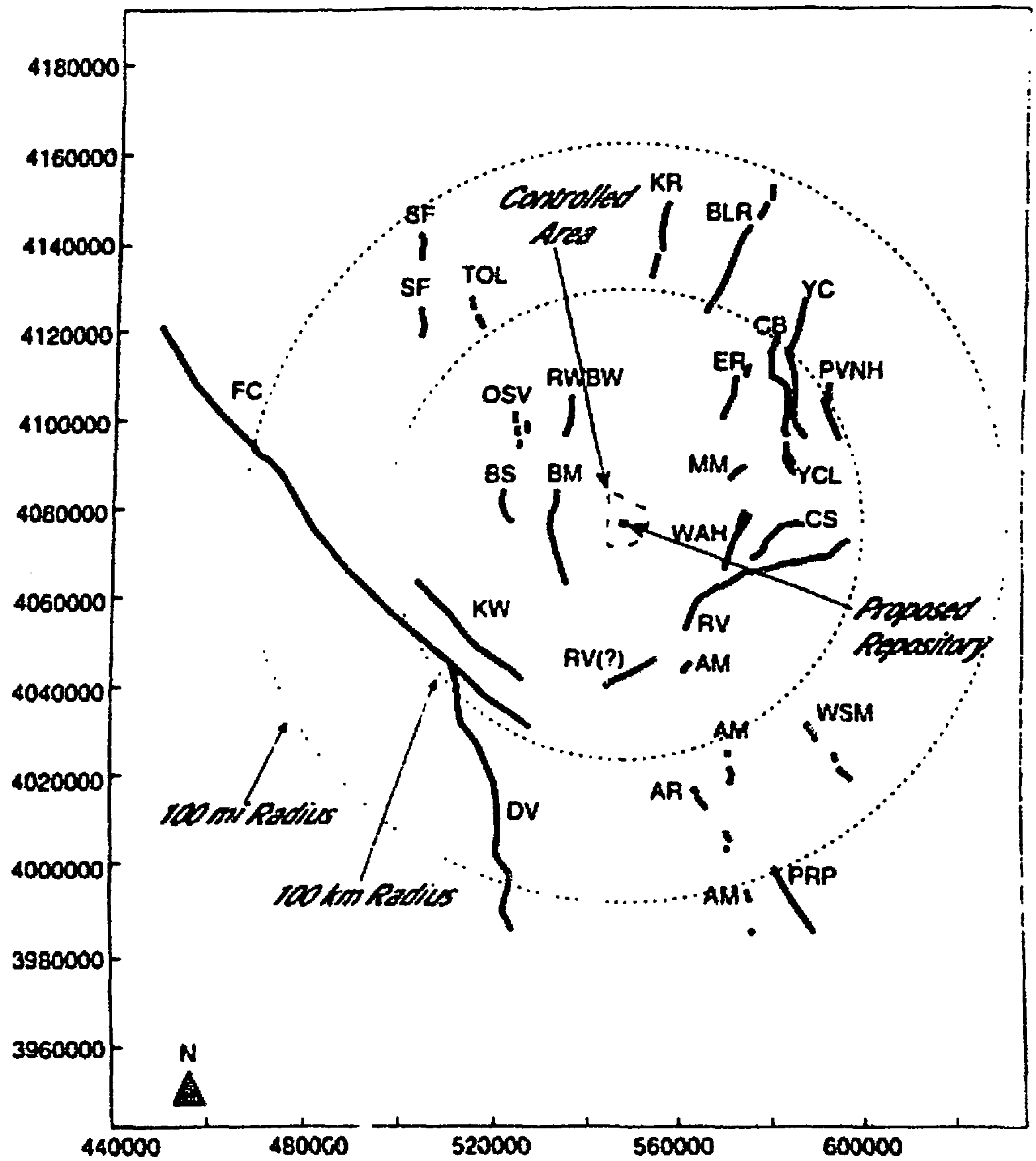

4180000
4160000
4140000
4120000
4100000
4080000
4060000
4040000
4020000
4000000
3980000
3960000
440000
480000
520000
560000
600000
Controlled Area
Proposed Repository
100 mi Radius
100 km Radius
N
SF
SF
TOL
KR
BLR
YC
CB
PVNH
ER
FC
OSV
RWBW
BS
BM
MM
YCL
WAH
CS
KW
RV
RV(?)
AM
WSM
AM
AR
DV
AM
PRP

Figure E-2

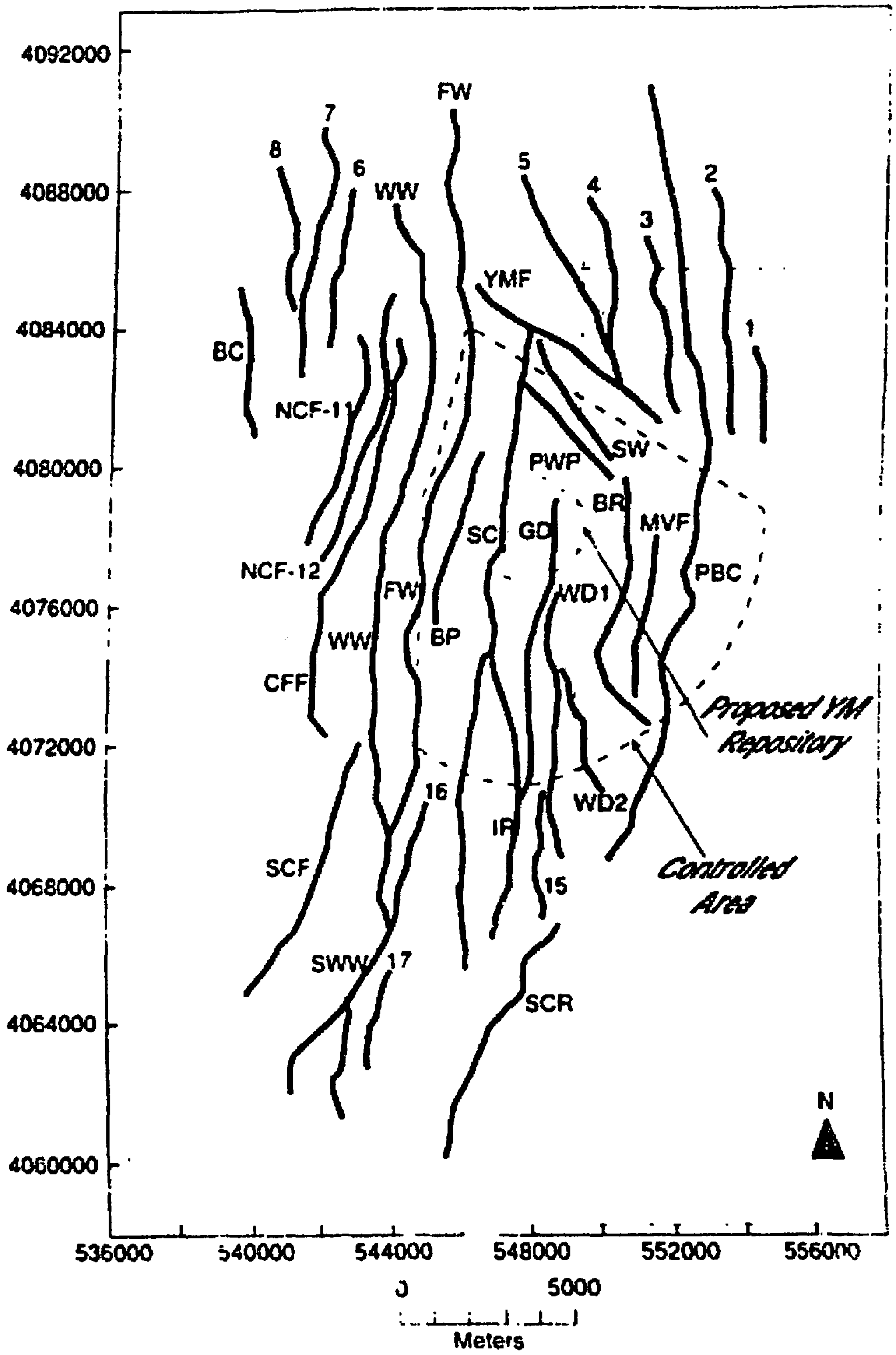

4092000
4088000
4084000
4080000
4076000
4072000
4068000
4064000
4060000
536000
540000
544000
548000
552000
556000
FW
7
8
6
WW
5
4
3
2
1
YMF
BC
NCF-11
SW
PWP
BR
MVF
SC
GD
NCF-12
PBC
FW
WD1
WW
BP
CFF
Proposed YM Repository
16
WD2
IR
SCF
15
Controlled Area
SWW
17
SCR
N
5000
Meters

Figure E-3

Figure E-2. Regional map showing locations of faults beyond 10 km radius of Yucca Mountain but within 100 km radius of Yucca Mountain. Locations of faults are from Nakata, et al. (1982); Sawyer al. (1995); and Piety, (1996). Fault names are as follows: AM - Ash Meadows; AR - Amargosa Rive BLR - Belted Range; BM - Bare Mountain; BS - Beatty Scarp; CB - Carpetbag; CS - Cane Springs; D' Death Valley; ER - Eleana Range; FC - Furnace Creek; KR - Kawich Range; KW - Keane Wonder; MI Mine Mountain; OSV - Oasis Valley; PRP - Pahrump; PVNH - Plutonium Valley-North Halfpint Range RV - Rock Valley; SF - Sarcobatus Flat; TOL - Tolicha Peak; WAH - Wahmonie; WSM - West Spring Mountain ; YC - Yucca; and YCL - Yucca Lake fault. Map coordinates are Universal Transverse Mercator (UTM), Zone 11.

NOTE: The following Type I faults do not appear on either Figures E-2 or E-3 because their locatio were not available in electronic format; they will be included in Revision 2: Fish Lake Valley; Drill H Wash; Dune Wash; East Pintwater Range; Emigrant Valley North; Grapevine; Grapevine Mountain; Hunter-Panamint Valley; South Ridge; Spotted Range; Sundance; West Pintwater; West Specter Range; and Yucca Wash.

Figure E-3. Locations of faults at or near Yucca Mountain from Simonds, et al. (1995) and Frizzell a Schulters (1990). Fault names are as follows: BC - Bonnie Claire; BP - Boomerang Point; BR - Bow Ridge; CFF - Crater Flat; FW - Fatigue Wash; GD - Ghost Dance; IR Iron Ridge; MVF - Midway Valley; NCF - Northern Crater Flat; PCB - Paintbrush Canyon; PWF - Paga Wash; SC - Solitario Canyon; SCF - Southern Crater Flat; SCR - Stagecoach Road; SW - Sever Wash SWW - Southern Windy Wash; WD - West Dune; WW - Windy Wash; and YWF - Yucca Wash. Numbe faults are the unnamed faults and refer to those described in Table E-2 and McKague, et al. (1996). Map coordinates are Universal Transverse Mercator (UTM), Zone 11.

Table E-1. Geologic time scale (after Geologic Society of America, 1983)

Era	Period	Epoch	Age (Ma)
Cenozoic	Quaternary	Holocene	0.01
		Pleistocene	1.6*
	Tertiary		
	Neogene	Pliocene	5.3
		Miocene	23.7
	Paleogene	Oligocene	36.6
		Eocene	57.8
		Paleocene	66.4
Mesozoic	Cretaceous		144
	Jurassic		208
	Triassic		245
Paleozoic	Permian		286
	Pennsylvanian		320
	Mississippian		360
	Devonian		408
	Silurian		438
	Ordovician		505
	Cambrian		570
Precambrian			
Proterozoic			2500
Archean			3800?

*2 Ma is considered start of Quaternary for regulatory purposes.

Table E-2. Yucca Mountain Area Stratigraphy (After Sawyer, et al.,1994)

Group	Formation	Age (Ma)
	Alluvium	
Timber Mountain Group	Rainier Mesa Tuff	11.6+/- 0.03
Paintbrush Group	Tiva Canyon Tuff	12.7+/- 0.03
	Yucca Mountain Tuff	
	Pah Canyon Tuff	
	Topopah Spring Tuff	12.8+/- 0.03
	Calico Hills Formation	12.9+/- 0.04
Crater Flat Group	Prow Pass Tuff	
	Bullfrog Tuff	13.25+/- 0.04
Older Tuffs		
Paleozoic and older rocks		

D McKague Misc [illegible]

APPENDIX F

TESTS AND EVALUATIONS OF DOE'S GEOLOGIC FRAMEWORK MOD VERSION 3.0

APPENDIX F

REVIEW OF U.S. DEPARTMENT OF ENERGY'S GEOLOGIC FRAMEWORK MODEL, VERSION 3.0 (GMF3.0)

[Constructed using EarthVision software, Version 4.0, by R. Clayton, M&O, Las Vegas, Nevada]

The need to review GFM3.0, and a summary of events that led to the review, can be found in a letter from M. Bell to S. Brocoum dated September 30, 1998, subject: "Review of U.S. DOE's GFM3.0 - A Step in the Review of DOE's ISM." The staff had committed to review DOE's ISM2.0 by the end of FY98, at DOE's request. DOE notified the staff, early in its review, that ISM3.0 was under development and would be issued at the end of the first quarter of FY99. The staff were also informed that ISM3.0 was to be based on GFM3.0 which was to be issued in the second quarter of FY98. Therefore, NRC refocussed its 3D model review resources from ISM2.0, and targeted GFM3.0 to be reviewed as a necessary first step toward the goal of a review of ISM3.0. This appendix provides a discussion and results of the GFM3.0 review.

OBJECTIVES OF THIS REVIEW

(1) To test and evaluate GFM3.0 for DOE's purposes of representing site stratigraphy and faults as a framework for its Integrated Site Model, Version 3.0;

(2) To evaluate GFM3.0 as a necessary step toward the evaluation of adequacy of DOE's ISM3.0; and

(3) To consider replacing NRC's EarthVision geologic site model with an adapted version of GFM3.0 as NRC's 3D-model of the site, for independent NRC analyses.

STRUCTURE OF THE REVIEW AND CREDITS

The review, tests, and evaluations of GFM3.0 were conducted cooperatively by staff from the Center for Nuclear Waste Regulatory Analyses (CNWRA), located in San Antonio, Texas, and from MANDEX, Inc., located at NRC Headquarters, under the direction of NRC staff. The review was organized as follows:

(1) Introduction and Summary of CNWRA and MANDEX Results

(2) Part I - Analysis of Stratigraphic Horizons in GFM3.0

  (i) Tests and Evaluation of Stratigraphy and Topography

(3) Part II - Analysis of Faults in GFM3.0

  (i) Tests and Evaluation of Faults and Fault Blocks

  (ii) Evaluation of Selected Geologic Cross Sections

SUMMARY OF QUESTIONS USED TO FOCUS THE ANALYSIS OF GFM3.0

The questions are enumerated here to introduce the scope of the analyses in Parts I and II

- Are the data used for defining subsurface horizons (Pt.I, question (Q) 1) and faults at the surface and in the subsurface (Pt.II, Q 1) in GFM3.0 deemed appropriate and sufficient for these purposes?
- Do the model horizon surfaces (Pt.I, Q 2) and fault traces and fault surfaces (Pt.II, Q 2) as modeled in GFM3.0 fit the input data?
- Were all essential data for constructing GFM3.0 provided in the data files that accompanied the model (Pts. I and II, Q 3)?
- Are alternative interpretations of data warranted (Pts. I and II, Q 4)?
- Is it possible to incorporate reasonable alternative interpretations of subsurface fault geometry into GFM3.0, specifically the interpretation that certain faults are non-planar and merge with or terminate against major structures at depths of less than -8000 feet above the base of GFM3.0 (Pt.II, Q 5)?
- What observations were made relative to representation of horizons (not a separate question in Part I) and faults (Pt.II, Q 6) in GFM3.0 that may require further explanation or clarification?

SUMMARY OF OBSERVATIONS OF GFM3.0

Parts I and II describe both the merits and observations of GFM3.0. Some observations that may require explanation or clarification prior to completion of the staff review of ISM3.0 in FY99 are as follows:

(1) Stratigraphy and the Paleozoic surface are not well constrained at depth or at the edges of the model;

(2) Topographic elevations over about 85% of the model area have elevation differences of less than 5 meters (comparing two sources of elevation data). Such differences are not detrimental because topography was not used to control subsurface stratigraphy;

(3) All stratigraphic borehole controls assume no deviation of boreholes from the vertical;

(4) Mismatches between true and modeled elevations of subsurface horizons typically are less than 25 feet, although a few are greater than 50 feet. Possible explanations for these mismatches include new realizations of fault dips at depth, presence of unmapped faults, or results of sparse data;

(5) A structure in Antler Wash shown on the USGS central block geologic map may need to be added to the model to help explain the hydrogeologic tracer data from C-wells;

(6) The imbricate fault zone is presently modeled as a single fault. This representation may need to be changed if it is necessary to understand or explain phenomena in that zone.

(7) Warping or folding of horizons in the hangingwall of faults is unexplained by the presence of planar faults;

(8) Boomerang Point fault shows an apparent reversal of slip sense which may need to be explained;

(9) Dune Wash fault is shown truncated against the Ghost Dance fault in one cross section, but not in sections to the north or south, and the surface traces of the two faults do not appear to intersect This observation may need to be explained;

(10) Many faults are shown with increasing displacements with depth, suggesting that they are growth faults. This may need to be explained and compared with other DOE models of fault development. However, poorly constrain. I stratigraphic horizon data in the northern and southern edges of the model may be an important factor;

(11) Complex fault interactions have been modeled at depth in some zones - a positive feature of the model. Some of the structural relationships shown, such as one fault 'beheading' another, has implications for understanding past, and perhaps future, faulting and may need to be explained in more detail.

SUMMARY OF RESULTS

The objectives of this review of GFM3.0, stated above, were met as follows, respectively:

(1) The staff considers GFM3.0 to be adequate for representing the stratigraphy, faults, fault blocks, geologic cross sections, and topography of Yucca Mountain at the site scale;

(2) The staff considers GFM3.0 to be an adequate stratigraphic, fault and fault block framework for DOE's ISM3.0, to the extent of the staff's understanding of the scope of ISM3.0 (e.g., D. Bryan, Translation and Use of GFM3.0, Handout at DOE/NRC Quarterly Technical Meeting, June 18, 1998).

(3) The staff considers an adapted version of GFM3.0 adequate for NRC's needs in conducting 3-D analyses of the Yucca Mountain site, including reviews of subsequent ISMs.

The staff have made certain observations of the model that may require explanation or clarification, particu'arly to enable the staff to fully evaluate ISM3.0 The illustrated evaluations of stratigraphy (50 surfaces, including alluvium), faults (42 surfaces), fault blocks (43 included), topography and geologic cross sections detailed in Parts I and II of this appendix, in the following two parts, are the source for observations made during this review. The observations notwithstanding, GFM3.0 was considered adequate for its intended uses Note that the following analyses were not performed for this review: (1) a critique of the quality assurance or quality control of data; and (2) a critique of the planar fault model used by DOE.

PART I - ANALYSIS OF STRATIGRAPHIC HORIZONS IN GFM3.0

1. Are the raw data appropriate and sufficient for defining subsurface horizons?

Horizons in GFM3.0 were derived from several data sources, including the EG&G digital topographic model (personal communication with R. Clayton, July 1998), the geologic map of Day and others (1997), well log horizon picks, and geophysical gravity data. These data were combined in an EarthVision geologic model that presents an interpretation of the stratigraphic units in the vicinity of the proposed repository. The relatively small number of wells and limited geophysical data sets available to the modelers necessitates an increased level of reliance on the surface geologic map to establish shallow horizon relationships that are then confirmed at depth by geophysical well logs. The deeper model horizons, i.e., Tund and Paleozoic, are not well-sampled with boreholes and were, in part, interpreted from gravity measurements. Thus, any utilization of GFM3.0 horizon data in other modeling and/or design work should be undertaken with an understanding of the accuracy of the input data and the extent to which GFM3.0 honors these data.

This analysis of GFM3.0 assumes the well log horizon picks used in building the model have been qualified by an appropriate quality process. Thus, the question addressed in this analysis is whether there are sufficient data on which to build the subsurface horizons, and whether they have been honored. Figure 1 contains an image taken from GFM3.0 showing the location of the boreholes incorporated in the model. There is a higher density of wells in the center of the model than at the model edges. Thus, the stratigraphic units at the model boundaries are the result of data extrapolation calculations by the EarthVision software application used to create GFM3.0.

2. Do model horizon surfaces fit the data?

Prior to validating the horizon ties with the borehole picks, CNWRA performed a brief comparison of the DOE and CNWRA topography models. DOE has utilized a topography model produced by EG&G with a 100-foot grid node spacing. The CNWRA uses USGS 7.5 minute digital elevation models with a 30-meter grid node spacing. After making the appropriate coordinate system conversions, the CNWRA topography model was subtracted from the DOE model, yielding a difference plot shown in Figure 2. Approximately 85 percent of the elevation differences are less than 5 meters. These differences are not considered to be significant to GFM3.0 because the topography model is used to truncate stratigraphic units at the model surface. The topography was not used to control or influence the subsurface stratigraphy.

A subsurface horizon tie analysis was performed by CNWRA to measure the agreement between borehole horizon picks and modeled horizon depths. The tie analysis compares the depth at which the borehole actually intersected a horizon and the modeled depth for that same coordinate. Borehole deviation logs were not available to CNWRA at the time this analysis was performed. All comparisons assume undeviated wells. The data processing sequence used to generate the tie analysis was:

A. Extract individual horizon surfaces using the EarthVision, Geologic Structure Builder, Horizon Export utility.
B. Compute the borehole-horizon intersection coordinate for each well penetrating the horizon. Repeat this process for several horizons in the stratigraphic column

GFM with Well Locations

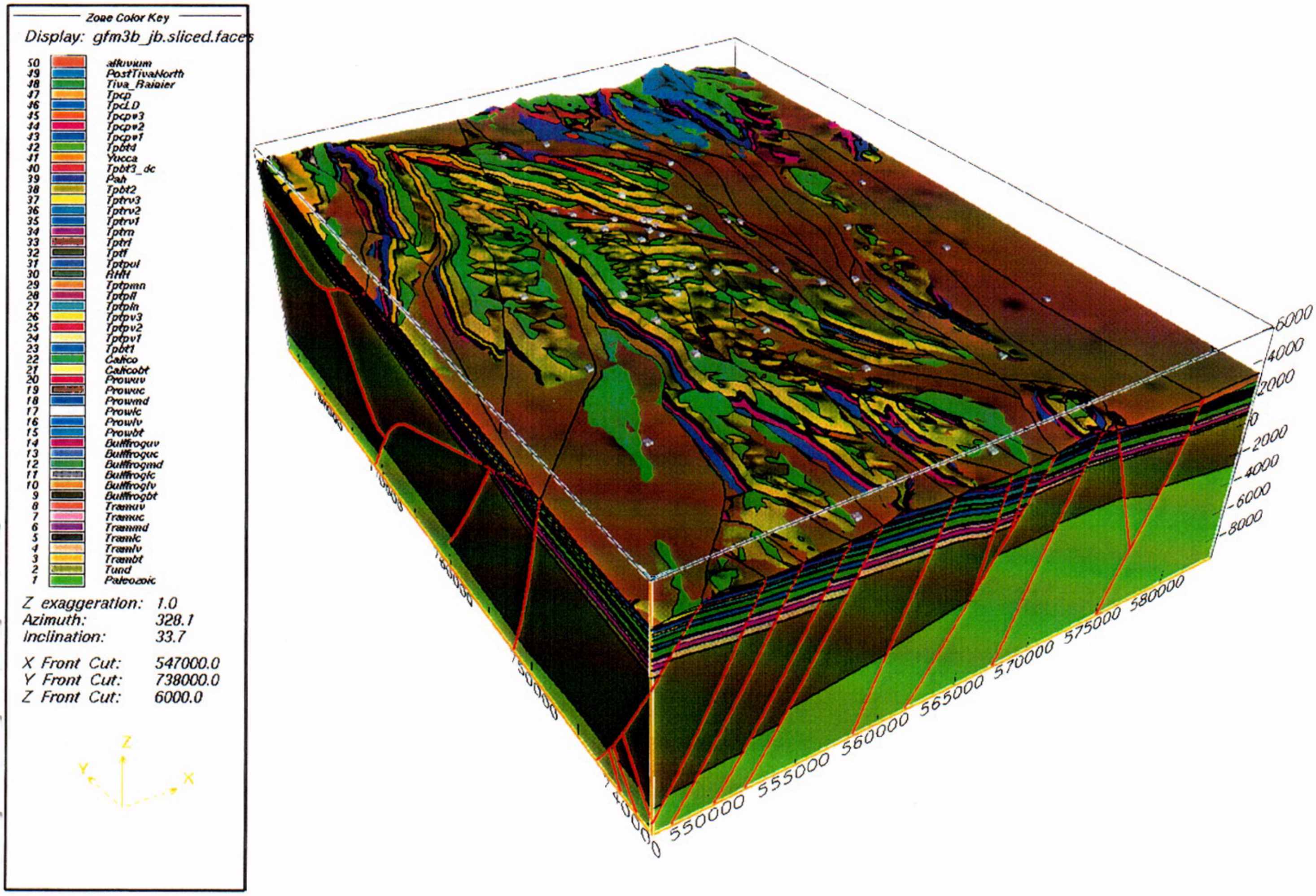


Figure 1 - Example view of GFM 3.0 with input borehole locations shown as gray cubes

C01

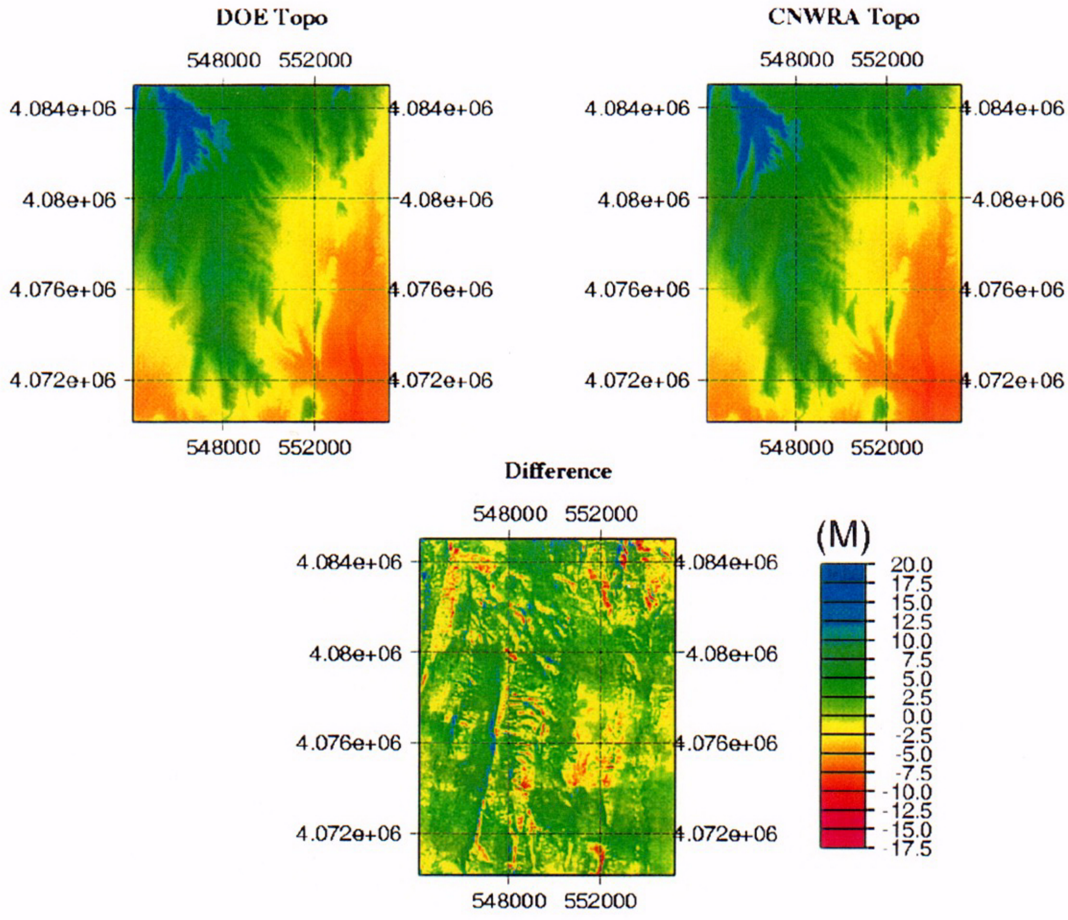


Figure 2 - Comparison of the DOE and CNWRA digital elevation models

C02

C. Compare the extracted horizon elevations with the elevations picked from the well logs

Table 1 contains the original well picks provided by DOE for the ten horizons used in this analysis. Table 2 contains the modeled horizon elevations, and Table 3 contains the difference between the well log picks and modeled elevations.

The results in Table 3 show discrepancies between the true and modeled elevations that are typically less than 25 feet. A few discrepancies greater than 50 feet warranted further investigation to determine if the discrepancies are the result of insufficient data control, inaccurate input data, or side effects from non-vertical faulting.

In computing the subsurface horizon models, EarthVision employs numerical algorithms that attempt to fit a surface to the control points established by the well log horizon picks and fault structures. The quality, number, and spatial distribution of data points all effect the accuracy with which the model surface fits the input data. In areas of poor data control, the software algorithms tend to produce smooth surfaces that follow general trends established by the sparse control points. Likewise, the software attempts to honor the majority of densely spaced data points, but outliers may have been disregarded by EarthVision if they fell outside the software parameter ranges specified by the DOE modelers. One approach to analyzing these discrepancies is to plot the model-well discrepancies on a three-dimensional representation of the horizon surface (Figure 3). This type of plot allows the viewer to examine the relationships between model-well miss-ties, well density and spatial distribution, and faulting.

Figure 3 contains a 3-D view of the upper vitrified Tram unit with the model-well discrepancies plotted as color-filled contours. The legend on the left side of the plot defines the miss-tie range as plus/minus 100 feet. The gray boxes above the model surface represent the locations of the well log data that were used as control points for computing the horizon elevations. The red circular region in the vicinity of the C#2 well represents a model-well mismatch of -53 feet. This means the EarthVision software computed the elevation of the horizon to be 53 feet higher than the geologist picked the horizon location on the C#2 well logs. Only 14 well control points were available for the computation of this Tram unit, and Figure 3 illustrates that the C#2 well is not surrounded by wells having smaller model-well miss-ties. Thus, one cannot confidently say that the C#2 well log pick is bad and has been disregarded by the EarthVision software as an outlier. A case could be made that: (1) the -53 foot C#2 discrepancy is the result of insufficient data to constrain the EarthVision software; or (2) that the fault structure in the GFM3.0 model has resulted in the C#2 well being located on the wrong side of a fault. Figure 3 shows the C#2 well in very close proximity to the Midway fault, which may possibly be explained by an incorrect assumption that: (1) the C#2 well is not deviated; or (2) that the subsurface control on the Midway fault is incorrect.

Figure 4 shows discrepancies of +117 and -56 feet where the WT-7 and WT#14 wells intersect the Calico horizon near the SolWest and Paintbrush faults, respectively. Figure 5 also shows +59 and -88 foot discrepancies for the WT-7 and WT#14 wells intersecting the Tptpll unit Again, it may be possible to ascribe the discrepancies to incorrect borehole placement or inaccurate subsurface fault control. However, the -117 foot discrepancy for the WT#6 well in Figure 5 is not as easily explained because a fault surface is not present in the vicinity of the borehole. This disagreement may possibly be explained as a data outlier, poorly constrained software calculations, or the presence of an unmapped fault.

Table 1 - DOE Well Log Horizon Picks (ft)

#wellid	Tpcpv3	Tpbt4	Tpp	Tptpul	Tptpll	Tptpv3	Tac	Tcpm	Tctuv	Tund
a#4	119	151	197							
a#5	128	149	180	475						
a#6	125	144	186	422						
b#1				440	765	1283	1385	1992	2883	3960
c#2				457	725	1205	1335	1773	2725	
G-1			135	457	815	1287	1426	1920	2639	3558
G-2	225	235	494	977	1280	1634	1757	2705	3574	3982
G-3	348	373	392	548	830	1187	1413	1663	2637	3876
G-4	118	141	168	420	774	1317	1409	1880	2756	
H-1				538	897	1410	1505	1969	2730	3661
H-3	370	400	417	540	848	1194	1400	1640	2477	3637
H-4	174	193	216	376	703	1185	1317	1746	2664	3819
H-5	404	438	471	741	1088	1582	1705	2085	2742	3422
H-6				435	795	1213	1356	1602	2258	2878
J#13	587	629	650	801	1003	1300	1482	1848	2358	3220
NRG#1										
NRG#2	276									
NRG#4	318	338	375	700						
NRG#5	140	163	215	565	902					
NRG-6	135	159	175	466	810					
NRG-7A	70	102	172	518	878	1415	1498			
ONC#1	578	597	621	810			1274			
p#1				248	640	1090	1270	1535	2262	2863
SD-7	305	326	343	490	803	1182	1406	1765	2598	
SD-9	57	92	156	473	846	1358	1480	1939		
SD-12	240	264	278	470	787	1278	1412	1787		
UZ-1			105	470	830					
UZ#4	71	99	174							
UZ#5	89	118	186							
UZ-6	383	433	450	610	917	1333	1460	1750		
UZ-7A	164	198	215		607					
UZ-14							1420	1850		
UZ#16	141	161	189	371	669	1108	1197	1571		
WT-1	395	431	446	593	888	1299	1384			
WT-2	193	227	247	421	727	1179	1319	1706		
WT#3					11	189	358	660		
WT#4	261	281	324	660	785	1091	1156			
WT#6					250	303	383			
WT-7	344	370	391	[illegible]	959	1287	1438			
WT-10	863	887	924	[illegible]						
WT#11	239	271	287	430	782	1058	1208			
WT#12	297	319	339	478	760	1151	1276			
WT#13	416	440	460	630	868					
WT#14				275	534	1024	1210			
WT#15	332	349	372	641	919					
WT#16	368	386	462	830	830	1013	1068			
WT#17	188	197	217	336	515	874	998	1318		
WT#18	314	340	497	900	1170	1501	1620			

Table 2 - GFM3.0 Horizon Picks Computed With EarthVision (ft)

#wellid	Tpcpv3	Tpbt4	Tpp	Tptpul	Tptpll	Tptpv3	Tac	Tcpm	Tcruv	Tund
a#4	125.7	153.2	199.7	548.2	889	1326	1399.2	1954	2879.3	3889.8
a#5	121.1	143	173.7	466.2	804.4	1297.4	1375.1	1943.3	2869.7	3906.4
a#6	124.4	144	184.1	421.6	765.8	1301.2	1393.7	1929.2	2845.1	3905.4
b#1	227.2	212.7	248.8	491.6	816.4	1332.7	1435.1	2042.4	2903.2	3980.9
c#2	280.1	299.7	322.2	492.8	762.1	1193.9	1324.1	1760.5	2778.3	3410.9
G-1	36.8	38.7	120.1	473.1	832.4	1309.9	1446.9	1940.8	2671	3593.9
G-2	213.3	223	482.6	963	1263.6	1621	1743.1	2690.1	3552.1	3957.4
G-3	350.7	375.1	394.2	550.3	832.9	1187.3	1412.7	1663	2636	3874.9
G-4	106.9	130.3	157.5	412.5	766.3	1310.6	1403.8	1872.8	2748.4	3755.6
H-1	39.1	71.9	169.7	520.9	879	1381	1486.7	1954.8	2716.3	3646.7
H-3	371.3	400.5	417.4	540.7	847.6	1200.1	1408.4	1649.2	2486.5	3649.6
H-4	171.2	190.2	213	373.3	700.6	1178.7	1309.8	1738.2	2650.3	3804.5
H-5	434.7	468.3	502.6	772.6	1120.7	1574.6	1697.4	2075.3	2753.7	3447.9
H-6	241.7	263.5	320.9	486.1	846	1219.8	1362.3	1608.4	2264.4	2886.5
J#13	633.6	675.5	696.4	846.7	1049.3	1296.5	1478.8	1844.4	2352.3	3213.2
NRG#1	264	280.4	310.4	573.6	796.3	1170.6	1286.3	1975.8	2833.6	3757
NRG#2	238.7	252.3	277.8	547.5	764.4	1126.6	1228.1	1927.9	2830.9	3796.9
NRG#4	329.8	349.4	386	708.2	952.3	1341.7	1419.6	2083.1	3082.7	4108.6
NRG#5	135.2	161.8	213.1	[illegible]	[illegible]	1329	1401.7	1963	2891.7	3900.7
NRG-6	127.6	151.2	167.4	460.8	805.1	1323.6	1403.9	1931.1	2848.6	3877.3
NRG-7A	60.5	92.9	165.9	510.7	871.3	1411.1	1497.5	1980.3	2804.4	3766
ONC#1	568.2	587.4	610.9	769.9	970.8	1111.7	1246.8	1722.7	2769.9	3620.3
p#1	111.1	127.6	146.9	271.9	667.1	1112.6	1293.4	1554.4	2272.3	2870.9
SD-7	324.7	345.4	362.4	508.3	820.9	1195	1414	1774.5	2595.3	3582.1
SD-9	76.7	110.1	169.3	485.6	854.7	1366.1	1482.8	1943.6	2764.6	3701.3
SD-12	265.1	289.9	304.8	493.4	808.6	1290.3	1423.2	1801.4	2535	3523
UZ-1	24.7	32.9	103.8	465.9	825.9	1298	1420.5	1858.3	2520.6	3382.6
UZ#4	57.7	85.6	160.7	552.9	794.4	1118.3	1189.4	1834.9	2795.4	3776.7
UZ#5	93.4	121.8	188.2	576	816.8	1131.2	1201.9	1849.1	2821.3	3809
UZ-6	386.1	435.3	452.8	612.7	919.9	1346.5	1474.3	1764	2482	3472.7
UZ-7A	107.1	139.9	157.9	331.1	623	1073.4	1212.4	1603.8	2374.7	3479.3
UZ-14	7.2	16.2	85.8	450.5	810.4	1288.6	1407.6	1837.9	2492	3341.5
UZ#16	151.1	170.9	198.9	381.7	678.6	1072.1	1204	1584.9	2558.6	3647.7
WT-1	395.8	431.7	446.7	592.7	887.5	1298.9	1382.4	1720.3	2658.7	3541.4
WT-2	210.4	243.1	262.2	441.8	747.4	1187.9	1318.2	1676.6	2408.6	3420.1
WT#3	13.7	13.7	13.7	13.7	13.7	142.8	311.7	613.6	1244	2035.2
WT#4	285.5	296.3	324.3	628.3	692.6	1040.6	1106.1	1850.4	2856.3	3806
WT#6	250.5	250.5	250.5	338.8	367.2	316.4	397	1462.4	[illegible]	2627.2
WT-7	359.1	384.7	406.3	562.2	900.4	1216.1	1320.6	1540.4	2362.7	3425.3
WT-10	884.9	908.9	945.7	1070.7	1469.4	1760	1900.6	2137.8	2985.1	4132.3
WT#11	211.4	243.1	259.3	401.5	753.2	1024.9	1155.8	1361.9	1526.6	2596.6
WT#12	331.7	353.8	373.7	513.1	794.3	1181.3	1305.6	1521.7	2256.6	3123.2
WT#13	413.3	437.1	457	627	866	1234.6	1432.1	1828.8	2369.1	2949.1
WT#14	110.9	128.1	151.8	362.3	621.9	1079.7	1266.2	1769.8	2471.6	3054.1
WT#15	348.8	365.8	388.4	656.5	937.6	1312.9	1437	2262.5	2612.8	3079.2
WT#16	341.5	359.6	438	821.3	821.1	1001.1	1056.8	1890.9	2543.1	3178.5
WT#17	189.3	198.2	218.1	336.8	535.8	875.1	999	1318.8	2227.6	3138.4
WT#18	326.7	352.7	506.5	899.8	1166.8	1503	1617.9	2245	3080	3976

Table 3 - Model-Well Miss-Ties Computed By Subtracting The Model Horizon Elevations In Table 2 From Well Log Horizon Picks In Table 1 (ft)

#wellid	Tpcpv3	Tpbt4	Tpp	Tptpul	Tptpll	Tpqv3	Tuc	Tcpm	Tctuv	Tund
a#4	-7	-3	-3							
a#5	7	6	6	9						
a#6	0	0	2	0						
b#1			-52		-51	-50	-50	-50	-21	-21
c#2			-36		-37	11	11	13	-53	
G-1		15		-17	-18	-23	-21	-21	-32	-36
G-2	12	12	12	14	16	13	14	15	22	25
G-3	-3	-3	-3	-2	-3	-1	0	0	1	1
G-4	11	11	11	8	8	6	6	7	7	
H-1			17		18	29	[illegible]	14	13	15
H-3	-2	-1	0	-1	1	-6		-9	-10	-13
H-4	3	3	3	3	2	6	[illegible]	8	14	14
H-5	-31	-31	-32	-32	-33	7	8	10	-12	-26
H-6			-51		-51	-7	-6	-6	-6	-9
J#13	-47	-47	-46	-46	-46	4	3	4	6	7
NRG#1										
NRG#2	38									
NRG#4	-12	-11	-11	-8						
NRG#5	5	1	2	-2	-2					
NRG-6	8	7	8	5	5					
NRG-7A	9	9	6	8	6	4	1			
ONC#1	10	10	10	40		27				
p#1			-24		-27	-23	-23	-19	-10	-8
SD-7	-20	-20	-19	-18	-18	-13	-8	-10	3	
SD-9	-20	-19	-14	-13	-9	-8	-3	-5		
SD-12	-26	-26	-27	-23	-22	-12	-12	-14		
UZ-1		1		4	4					
UZ#4	14	13	13							
UZ#5	-4	-4	-2							
UZ-6	-3	-3	-3	-3	3	-14	-14	-14		
UZ-7A	57	58	57	-16						
UZ-14						13		12		
UZ#16	-10	-10	-10	-11	-10	35	-7	-14		
WT-1	-1	-1	-1	0	1	2	2			
WT-2	-17	-16	-15	-21	-20	-9	1	29		
WT#3				-3		46	46	46		
WT#4	-25	-15	0	32	92	50	50			
WT#6				-117		-13	-14			
WT-7	-15	15	-15	-16	59	71	117			
WT-10	-22	-22	-22	-22						
WT#11	28	28	28	28	29	[illegible]	52			
WT#12	-35	-35	-35	35	-34	[illegible]	-30			
WT#13	3	3	3	3	2					
WT#14			-87		-88	-56	56			
WT#15	-17	-17	-16	16	-19					
WT#16	27	26	24	9	9	12	11			
WT#17	-1	-1	-1	1	-1	-1	-1	-1		
WT#18	-13	-13	-10	0	3	2	2			

Tramuv 2–D Grid

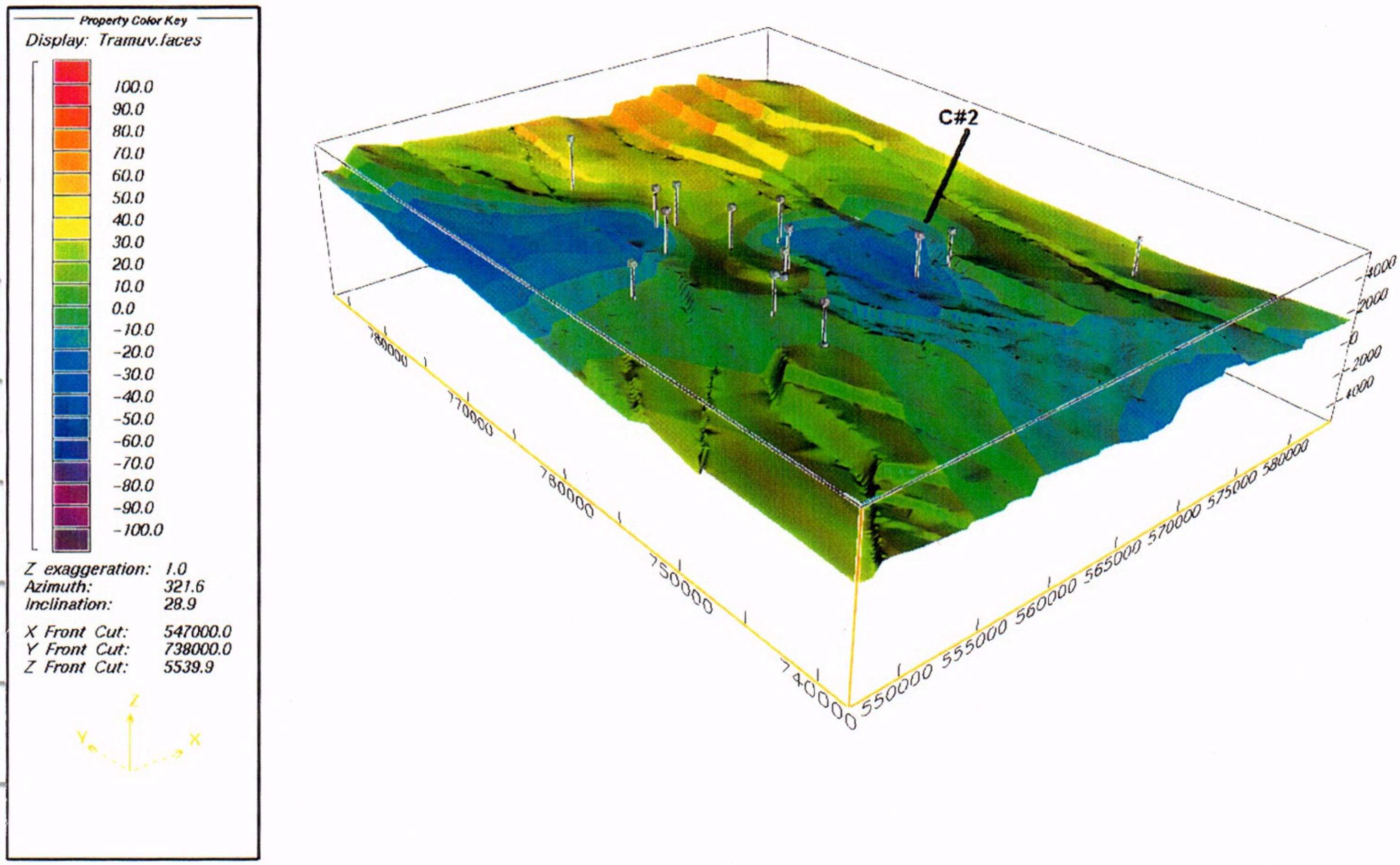


Figure 3 - Tramuv model-well miss-tie analysis plot illustrating the difference between the computed horizon and the picked well-log elevations using color coded contours

C03

Calico 2–D Grid

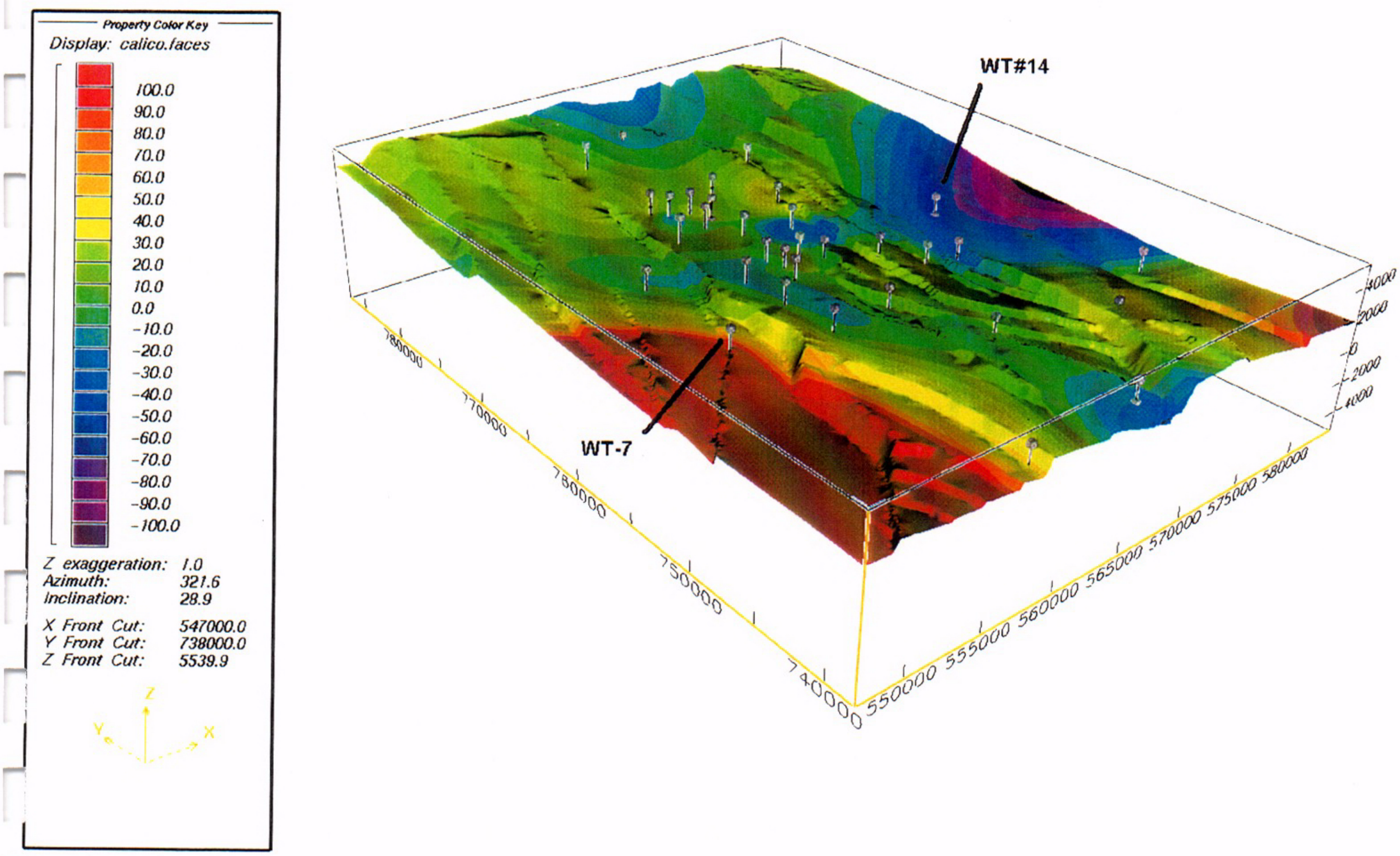


Figure 4 - Calico model-well miss-tie analysis plot illustrating the difference between the computed horizon and the picked well-log elevations using color coded contours

C04

Tptpll 2–D Grid

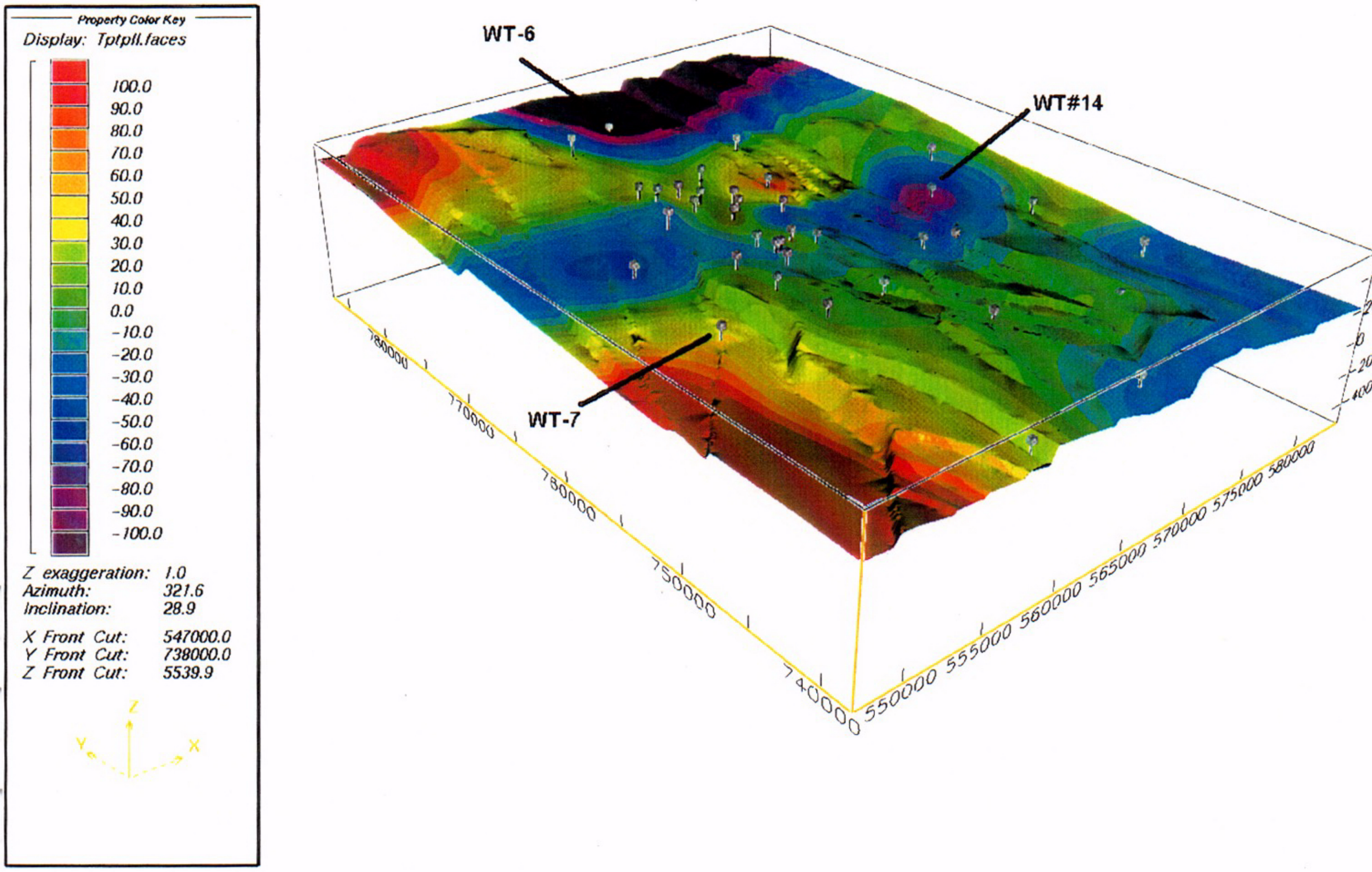


Figure 5 - Tptpll model-well miss-tie analysis plot illustrating the difference between the computed horizon and the picked well-log elevations using color coded contours

C05

3. Were all essential data provided in the data files?

The original release of GFM3.0 omitted a small number of files used by the EarthVision Geologic Structure Builder to create 3-D model files and export individual 2-D horizons. Subsequently, DOE provided these files, as well as the DOE topography model and well log horizon picks. All essential data required to manipulate and analyze GFM3.0 are available.

4. Are alternative interpretations of data warranted?

Construction of GFM3.0 was undertaken using a reference horizon-isochore approach to modeling the subsurface horizon relationships. Alternative approaches to developing GFM3.0, through the use of balanced cross-sections, are possible, but not warranted due to the relatively consistent and small discrepancies between the modeled horizons and the well log horizon picks.

In summary, as new data from wells and the ESF become available, GFM3.0 may be updated as required by the additional data. The integration of deviation data is recommended if the deviation logs identify lateral deviations of more than 10 feet. Some refinement of the fault surfaces may be warranted if model-well discrepancies persist once the deviation data has been analyzed and/or incorporated in GFM3.0.

At this time, there are no major stratigraphic discrepancies that would preclude NRC or DOE from using GFM3.0.

PART II - ANALYSIS OF FAULTS IN GFM3.0

(1) Are the data used to define faults at the surface and in the subsurface in GFM3.0 deemed appropriate and sufficient for this purpose?

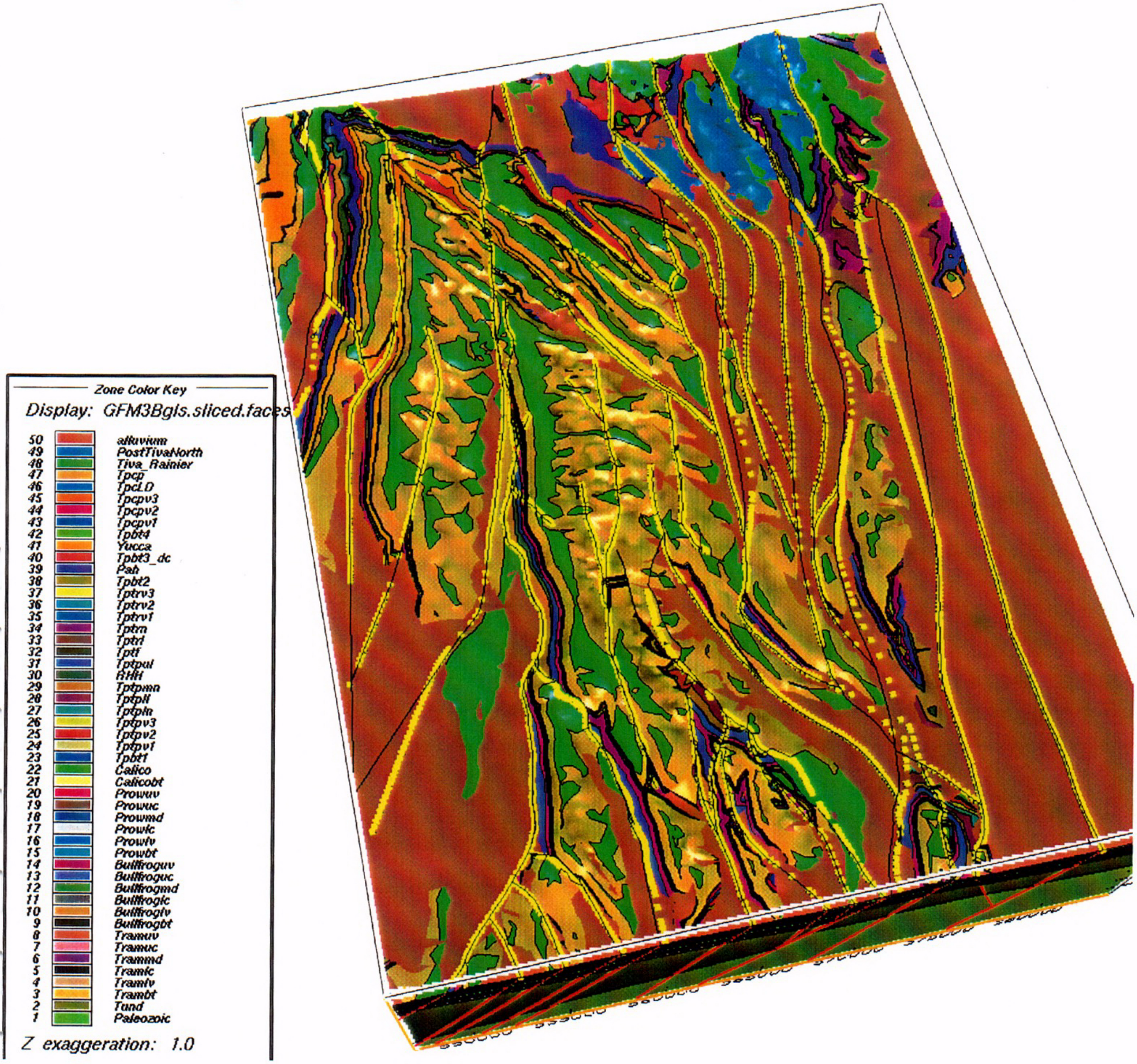
Surface data - Fault trace information derived from the geologic map of Day, et al. (1997) was used to define locations of faults at the surface in GFM3.0. Use of these data resulted in realistic representation of variations in strike of mapped faults and reasonable representation of strike of inferred faults beneath alluvium. Figure 1 illustrates the fault trace data from the original GFM3.0 database that were derived from the geologic map of Day, et al. (1997), compared with locations of surface fault trace lines actually contained in GFM3.0.

Subsurface data - Since borehole control points generally do not exist for defining dips of faults in the subsurface at Yucca Mountain (YM), dip lines generated from surface measurements of fault dips were used in conjunction with surface fault trace information to construct 2-dimensional (2D) grid (.2grd) files for modeling fault surfaces at depth. The approach amounts to projecting surface dip measurements on faults to depth for specifying fault dips in the subsurface. Lacking borehole control data directly suggesting that faults were non-planar within the depth range covered by GFM3.0, this approach was used to represent major west-dipping, north-northeast striking, normal faults as essentially planar features extending to the base of GFM3.0 (i.e., 6000 feet below sea level). A planar fault model is one possible interpretation suggested for subsurface geometry of west-dipping, north-northeast striking faults at YM (Brocher, et al, 1998). This subsurface fault geometry for YM proper is derived from the regional tectonic model for planar faulting at depth. A regional alternative tectonic model related to development of faults which are curved (i.e., listric) at depth at YM (Young, et al, 1992) is not considered in GFM3.0. Point 6(d) discusses observations specifically related to this alternative tectonic model, however.

Northwest-trending, strike-slip faults are planar and essentially vertical in GFM3.0. Certain minor west-dipping faults that are planar in the model intersect major structures and are truncated at the line of intersection rather than extending to depth. East-dipping, planar faults also intersect west-dipping, normal faults and are truncated at the line of that intersection above the base of GFM3.0. Fault Splay S off the east side of the Solitario Canyon fault is modeled in GFM3.0 as genuinely non-planar with a geometry and line of intersection with the Solitario Canyon fault similar to that of modified fault surface Ironw3 generated for this review of GFM3.0 (See Questions 4 and 5 below).

In summary, the data used in GFM3.0 to define fault surfaces from ground level to depth were appropriate and sufficient for constructing faults in the model. Fault traces and dip lines were used to construct fault surfaces as 2D grid (.2grd) files because borehole information does not exist for defining dips of faults in the subsurface. Fault surfaces are commonly planar in GFM3.0 and clipped with polygon (.ply) files as appropriate for limiting extent of a fault based on length of its surface trace. Fault trace data (as a .dat file) and polygon files (as .ply files) were provided in the GFM3.0 digital database along with all 2D grid (.2grd) files constructed for fault surfaces. Dip line files were not provided but are available from DOE should it be desired to examine these data. It was not necessary to peruse the dip line data files for this review of GFM3.0 since the fault surface dips modeled at depth reflect surface field measurements projected to depth.

Figure 1. Fault trace data points (yellow) from the original GFM3.0 database compared with fault trace lines (black) contained in GFM3.0



C06

(2) Do fault traces and fault surfaces as modeled in GFM3 0 fit the input data?

Fault traces and fault surfaces included in GFM3.0 fit the field-based input data closely Faults contained in GFM3.0, generated as polygon-clipped 2D grids as described above under Question 1, generally match well with mapped fault traces (Figure 1) and known near-surface dip angles of faults. Because borehole data do not exist for construction of refined 2D grids for the fault surfaces, fault traces and dip lines were used to generate fault surfaces in the model with the result that major west-dipping normal faults are represented as planar structures extending to the base of the model at -8000 feet. (However, see observations 6(f) and 6(h) below.)

(3) Were all data essential for constructing GFM3.0 included in the data files that accompanied the model?

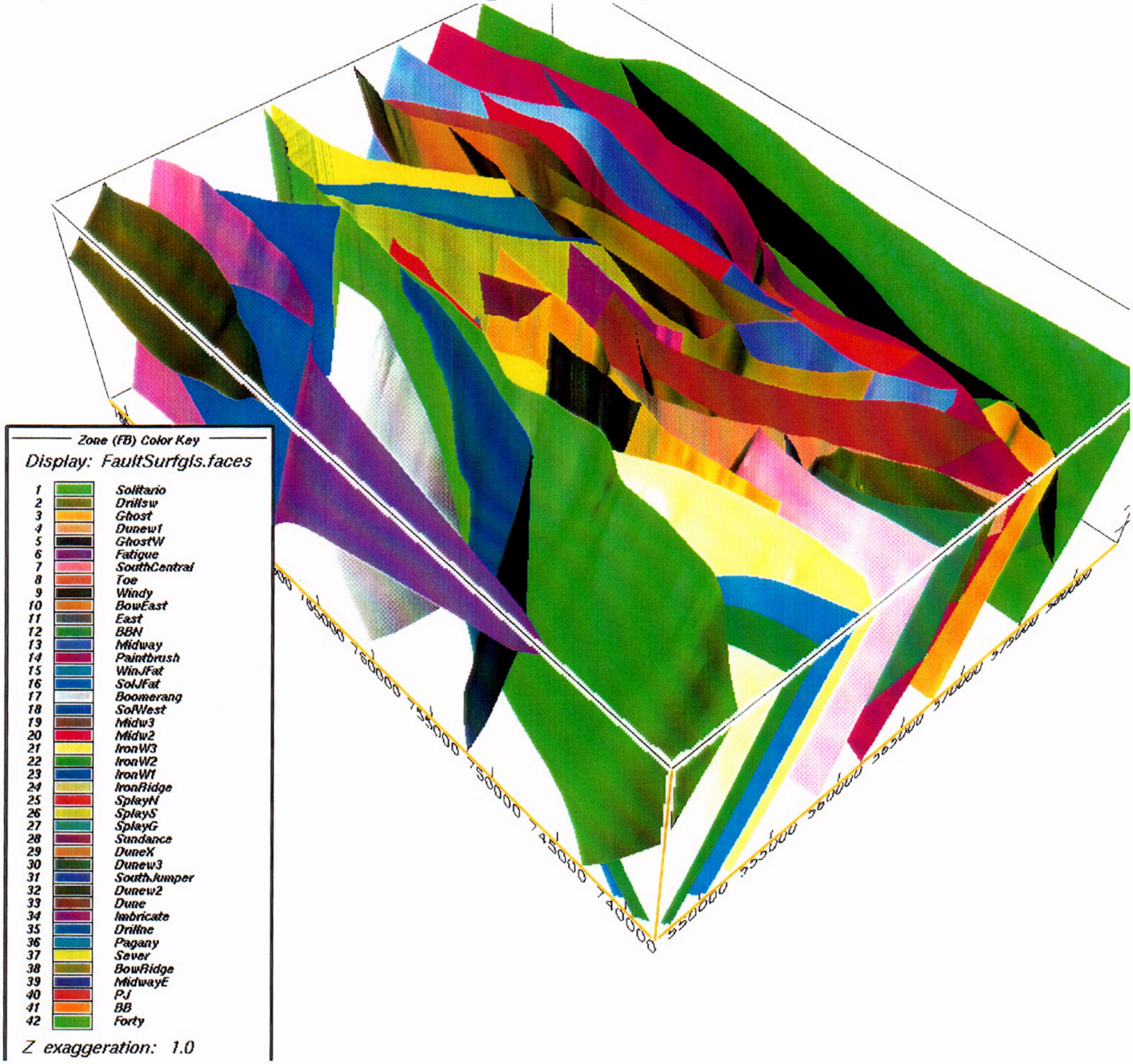
All data essential for calculating 3D structure models (i.e., models illustrating fault surfaces, fault blocks, zone surfaces, and zone blocks), using Geologic Structure Builder (GSB), are available to NRC staff. The data were either included in the database originally or provided immediately by R. Clayton upon request when determined to be missing. Consequently, the master sequence (.seq) file developed by R. Clayton and provided with the original database was successfully used after minor editorial modifications to reconstruct .faces files for fault surfaces and fault blocks, as well as zone surfaces and zone blocks in the Computerized Risk Assessment and Data Analysis Laboratory (CRADAL) at NRC Headquarters. This .seq file contained information that defined 42 faults, 43 fault blocks, and 50 stratigraphic horizons (including alluvium) for GFM3.0. The editorial changes to the original master sequence (.seq) file included renaming certain files and rearranging locations of others to be able to access those essential for construction of .faces files for fault surfaces and fault blocks. The complete set of data files may be accessed by NRC users, since these files occur in the GFM3.0 database in the CRADAL.

In summary, all data essential for constructing GFM3.0 were either included in the data files which originally accompanied the model or provided immediately by R. Clayton once determined to be missing. To determine that all data essential for constructing GFM3.0 were lodged in the database, recalculation of .faces files was undertaken for fault surfaces and blocks and zone surfaces and blocks using a master sequence (.seq) file that was only slightly modified from the original. Figures 2 through 4 illustrate reconstructed .faces files for fault surfaces and fault and zone blocks and also show the 42 faults, 43 fault blocks, and 50 stratigraphic horizons included in GFM3.0

(4) Are there alternative interpretations of the fault data suggesting that different representations of subsurface fault geometry may be reasonable to incorporate into GFM3.0?

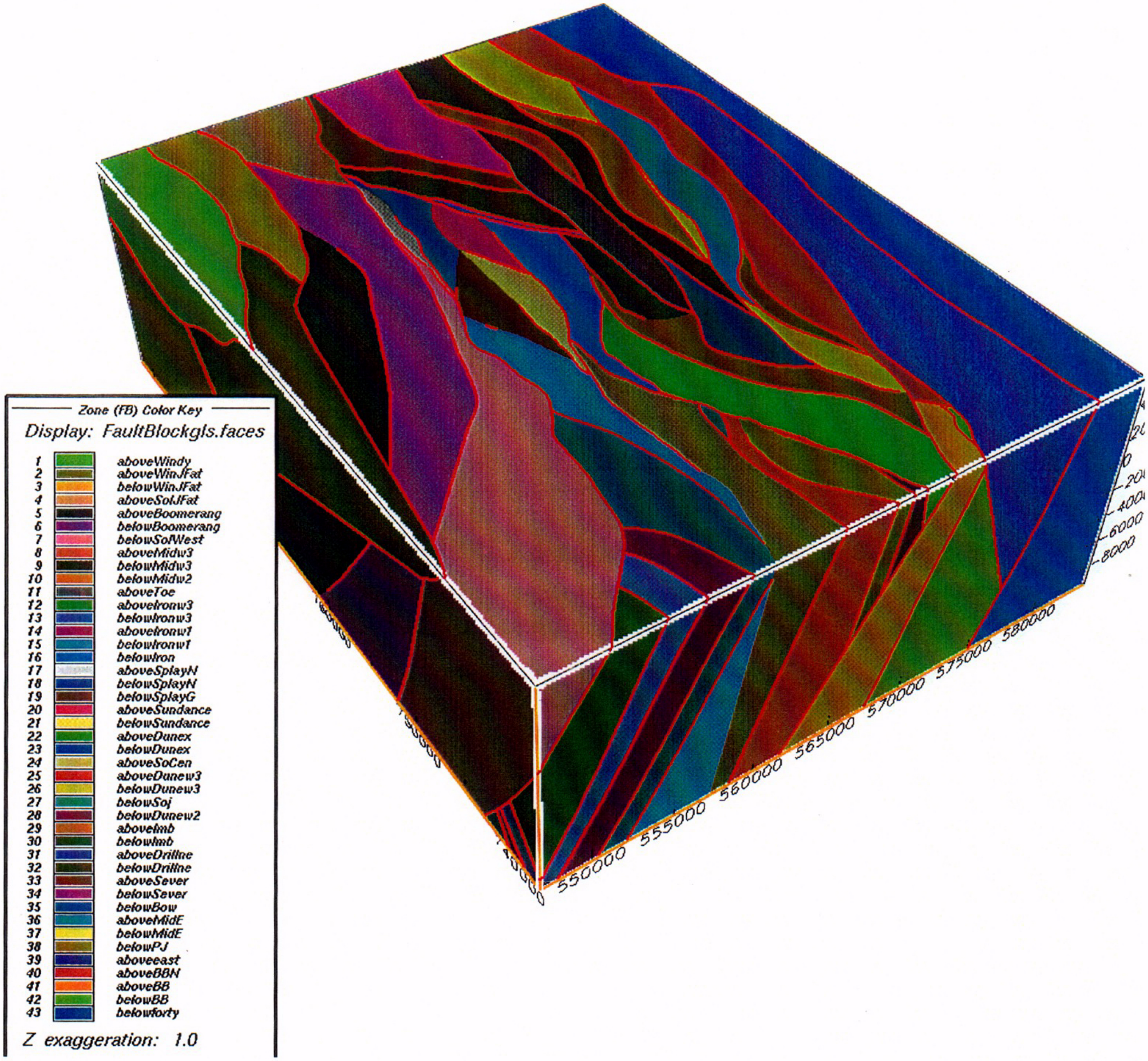
The subsurface fault geometry represented in GFM3 0 exercises the interpretation that west-dipping, north-northeast trending faults are planar to depth. An alternative interpretation for subsurface fault geometry based upon concepts developed at CNWRA (Ferrill et al. in review b) involves some structures developing as oblique faults in a relay ramp or as a connecting fault system, such that they merge with or terminate against major faults within the depth range of GFM3 0 (i e., at some depth above -8000 feet) For example, faults Ironw1, Ironw2, and

Figure 2. Recalculated .faces file for fault surfaces showing that data in the GFM3.0 database are complete and permit construction of this file



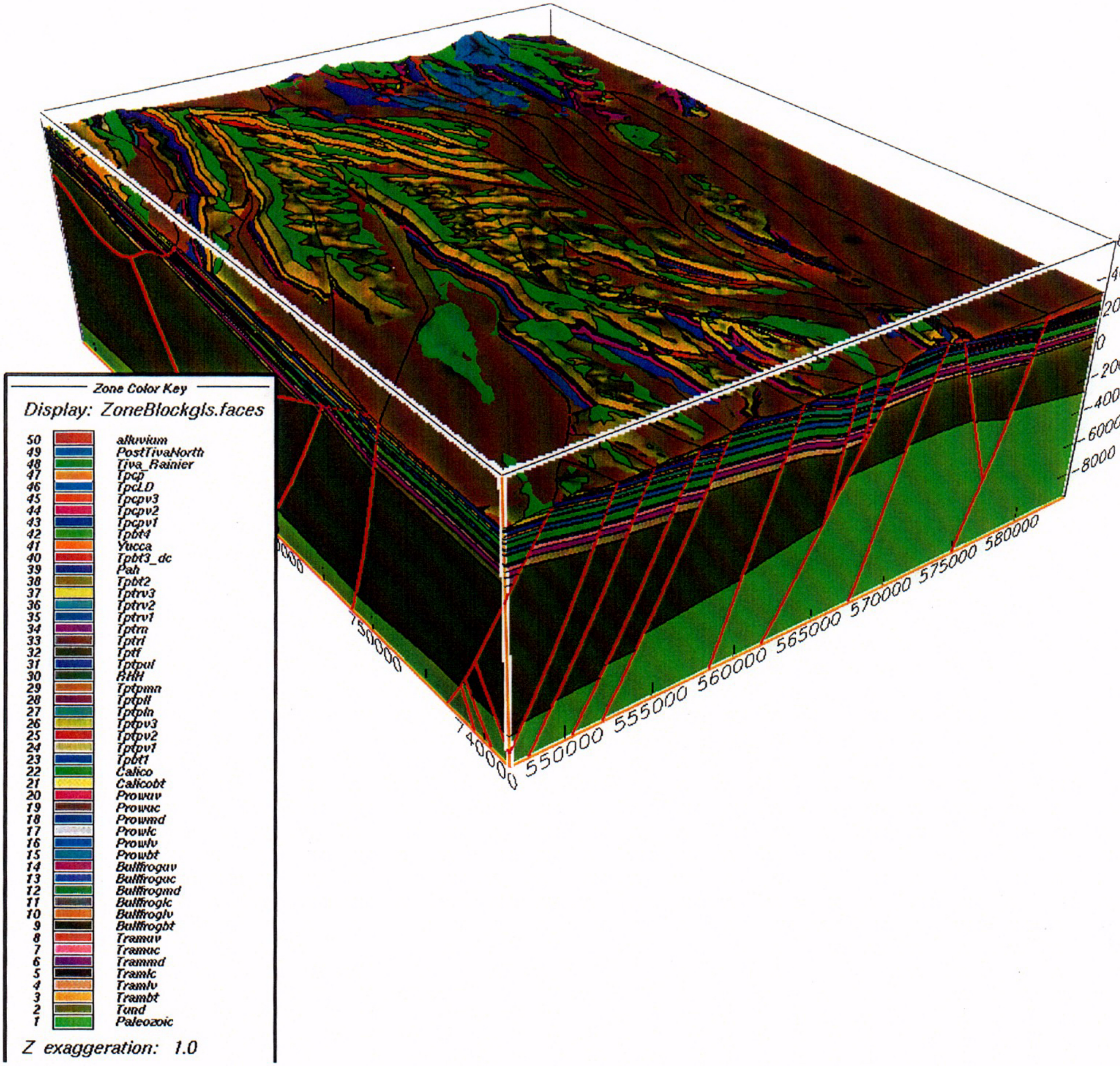
C07

Figure 3. Recalculated .faces file for fault blocks showing that data in the GFM3.0 database are complete and permit construction of this file



C08

Figure 4. Recalculated .faces file for zone blocks showing that data in the GFM3.0 database are complete and permit construction of this file



C09

Ironw3, between the Iron Ridge and Solitario Canyon faults at Yucca Mountain, are included in GFM3.0 as planar structural features. These faults are alternatively interpreted by CNWRA staff as oblique faults in a relay ramp that merge with the Solitario Canyon fault at depth rather than extending to the base of GFM3.0 as planar features (Ferrill, et al, in review, b)

In summary, all major and most minor faults included in GFM3.0 are represented as essentially planar structural features extending to the base of the model at -8000 feet. Fault Splay S off the Solitario Canyon fault is included as a truly non-planar feature that intersects the Solitario Canyon fault well above the base of GFM3.0. The interpretation that certain other faults may also be non-planar features at depth is a reasonable alternative model for subsurface fault geometry that was not considered in GFM3.0.

(5) Is it possible to incorporate reasonable alternative interpretations of subsurface fault geometry into GFM3.0, specifically the interpretation that certain faults are non-planar and merge with or terminate against major structures at depths of less than -8000 feet above the base of GFM3.0?

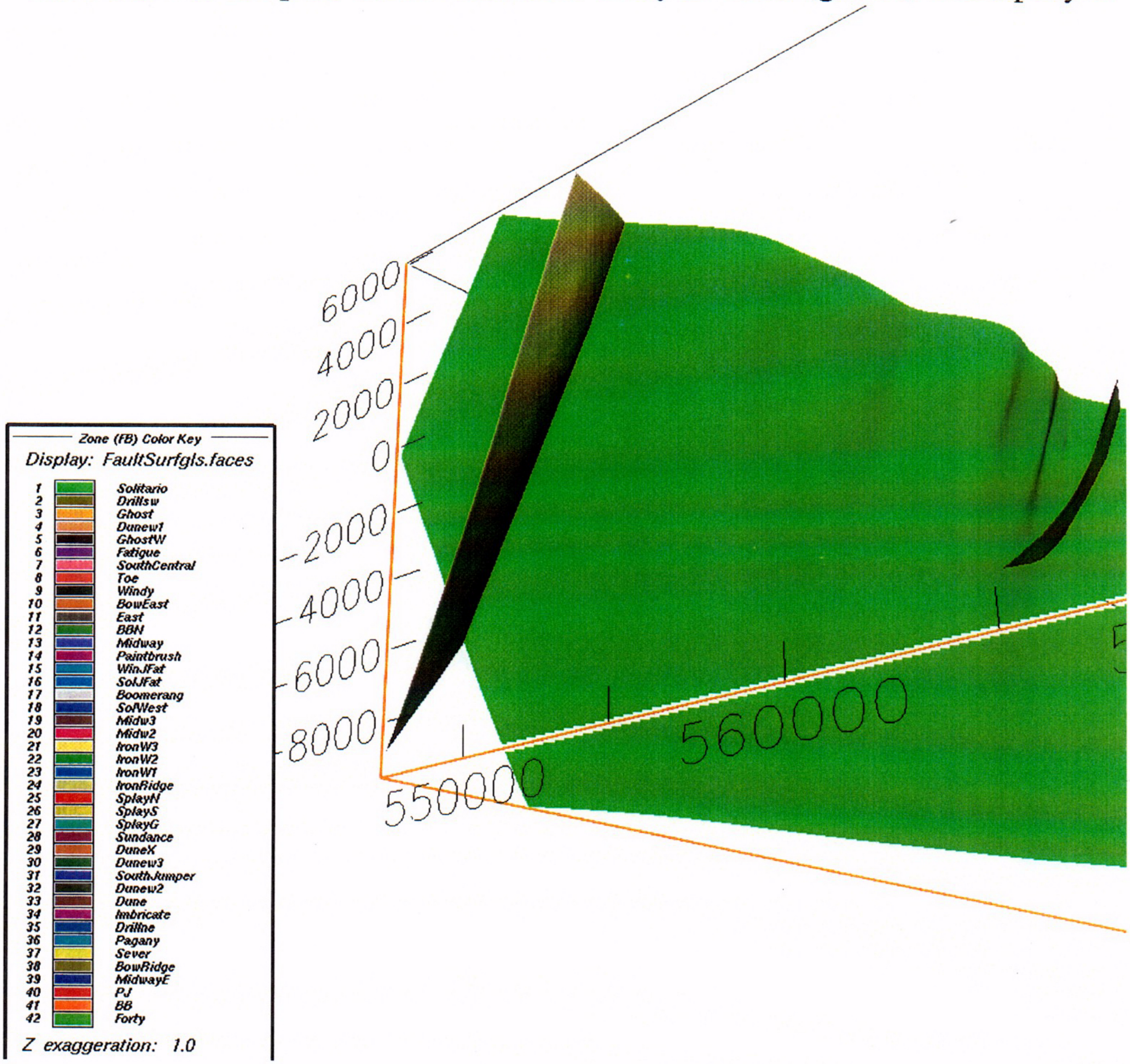
Faults Ironw1, Ironw2, and Ironw3, located in the southwestern corner of GFM3.0, were represented in the model as planar structures extending to the base of the model at -8000 feet. The subsurface geometry of fault Ironw3 in the "Ironw" system was successfully modified to generate a non-planar fault that terminated at a depth no greater than -2000 feet against the Solitario Canyon fault. This test illustrates that it is practicable to alter subsurface geometry of faults in GFM3.0 for incorporating alternative interpretations of fault geometry. Figure 5 illustrates the planar subsurface geometry of Ironw3 as originally represented in GFM3.0 along with non-planar fault Splay S. Figure 6 shows Ironw3 as modified for this test to terminate against the Solitario Canyon fault at a depth no greater than -2000 feet. Fault Splay S is included in the figure to show the similarity between the geometry of Splay S and modified Ironw3.

In summary, the result of this successful test illustrated by Figure 6 proves it is possible to modify GFM3.0 and incorporate alternative interpretations of subsurface fault geometry into the model. Although a detailed explanation of the steps necessary to generate modified fault surfaces is beyond the scope of this letter report, some words of caution are advised. When fault geometries are changed, before running the master sequence (.seq) file in GSB to generate modified .faces files for structure models, it may be necessary to rebuild the fault tree or re-grid horizons in the fault blocks. In particular, if the number of fault blocks is either reduced or increased, as is likely when removing an existing fault or adding a new one in the model, rebuilding the fault tree and re-gridding of horizons in the altered fault blocks are commonly necessary before the .seq file can be used in GSB to calculate .faces files for the suite of structure models (i.e., fault surfaces and blocks and zone surfaces and blocks).

(6) What observations were made relative to representation of faults in GFM3.0 that may require further explanation or clarification?

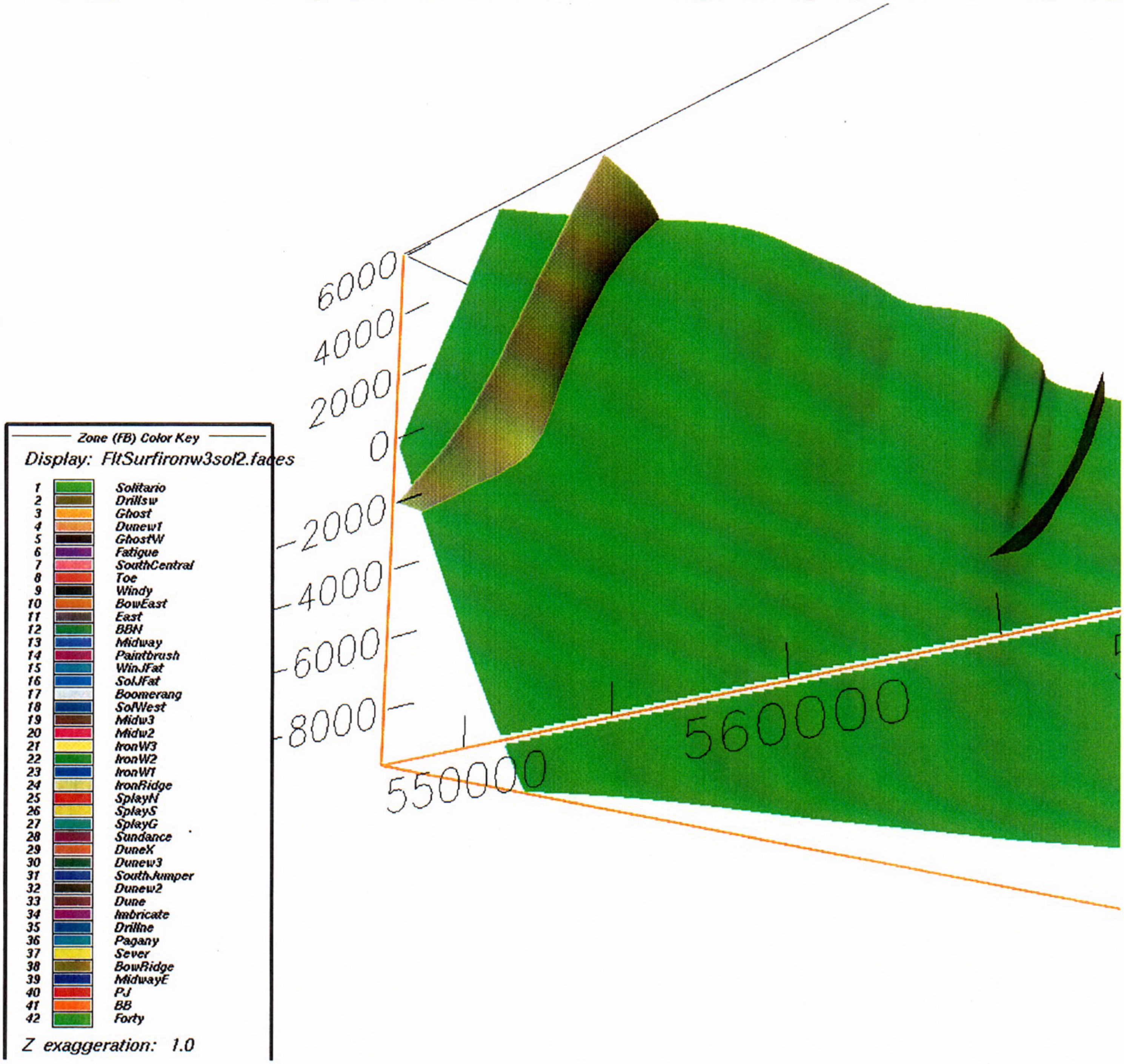
a No northwest-trending structure is included along Antler Wash in the vicinity of borehole H-4 where hydrologic testing suggested some type of connection between H-4 and the C wells. No northwest-trending fault was included in Antler Wash because

Figure 5. Planar fault Ironw3 (tan) as originally included in GFM3.0. Also shown are part of the Solitario Canyon fault (green) and Splay S



C10

Figure 6. Fault Ironw3 (tan) modified to intersect the Solitario Canyon fault (green) no deeper than –2000 feet. Original Splay S is also shown



C11

geologic mapping did not delineate such a structure in rocks at the head of the wash, although a dashed symbol for a northwest-trending fault in Antler Wash is shown on the geologic map of Day, et al (1997). This could be rectified by adding this fault to GFM3.0, although, from H-4 southeast to the C wells, major north-northeast trending faults also occur so that the hydrologic connection is possibly a complex one, at best

b. The imbricate fault zone is presently modeled as a single fault. This representation could also be changed in the model if there is any need to capture more structural complexity in that zone.

c. The Forty Mile Wash fault is included as a prominent structural feature in GFM3.0. Although the presence of this feature and the logic for its inclusion in GFM3.0 has been discussed with R. Clayton, with the history that exists since it was first proposed by Young, et al (1992) based on interpretations from balanced cross sections, the acceptance of the structure by the USGS could perhaps be clarified.

From examination of nine (9) cross sections taken directly from GFM3.0 at traverse locations indicated in Figure 7, additional observations were also made as follows. (Note that the fault labeled as "EHF" in Figure 7 and subsequent cross sections is fault "BowEast" in GFM3.0.)

d. Folding developed in the hangingwall blocks of faults is generally attributed to a curved (i.e., listric) fault geometry at depth (Suppe, 1983; Dula, 1992). Sections 1 (Figure 8) and 8 (Figure 15) through the model appear to illustrate folding of units in hangingwall blocks although GFM3.0 is constructed with essentially planar faults. Explanation of why these units appear to be folded may be helpful. By some interpretations (e.g., Young,et al., 1992), at the depth to which the model was constructed (i.e., 8,000 feet below sea level), the Forty Mile Wash, Paintbrush Canyon, Midway Valley, and Bow Ridge faults would show curved trajectories.

e. The Boomerang Point fault is shown as reversing displacement at depth in Sections 5 (Figure 12) and 6 (Figure 13). This may be due to model construction artifacts or potential uncertainty on the depth to the Paleozoic surface, so clarification may be helpful.

f. The Dune Wash fault is shown to be truncated against the Ghost Dance fault in Section 5 (Figure 12) but not in Section 4 (Figure 11). This observation suggests a change in dip or "flexing" of the Dune Wash fault so some clarification may be useful.

g. Many faults are shown with displacements across the Paleozoic surface that are generally greater than the displacement of the base of the younger Trambt. The exceptions to this are the Solitario Canyon fault in Sections 2 (Figure 9), 3 (Figure 10), 4 (Figure 11), and 9 (Figure 16) and the Forty Mile Wash fault in Section 9 (Figure 16) Increasing differential displacement with depth implies growth in at least the earlier Tertiary sequence, so it may be helpful to clarify whether implied growth is part of the premise for GFM3.0. These displacements for the Solitario Canyon and Forty Mile Wash faults are at the northern and southern edges of the model where well control is

GFM version 3.0

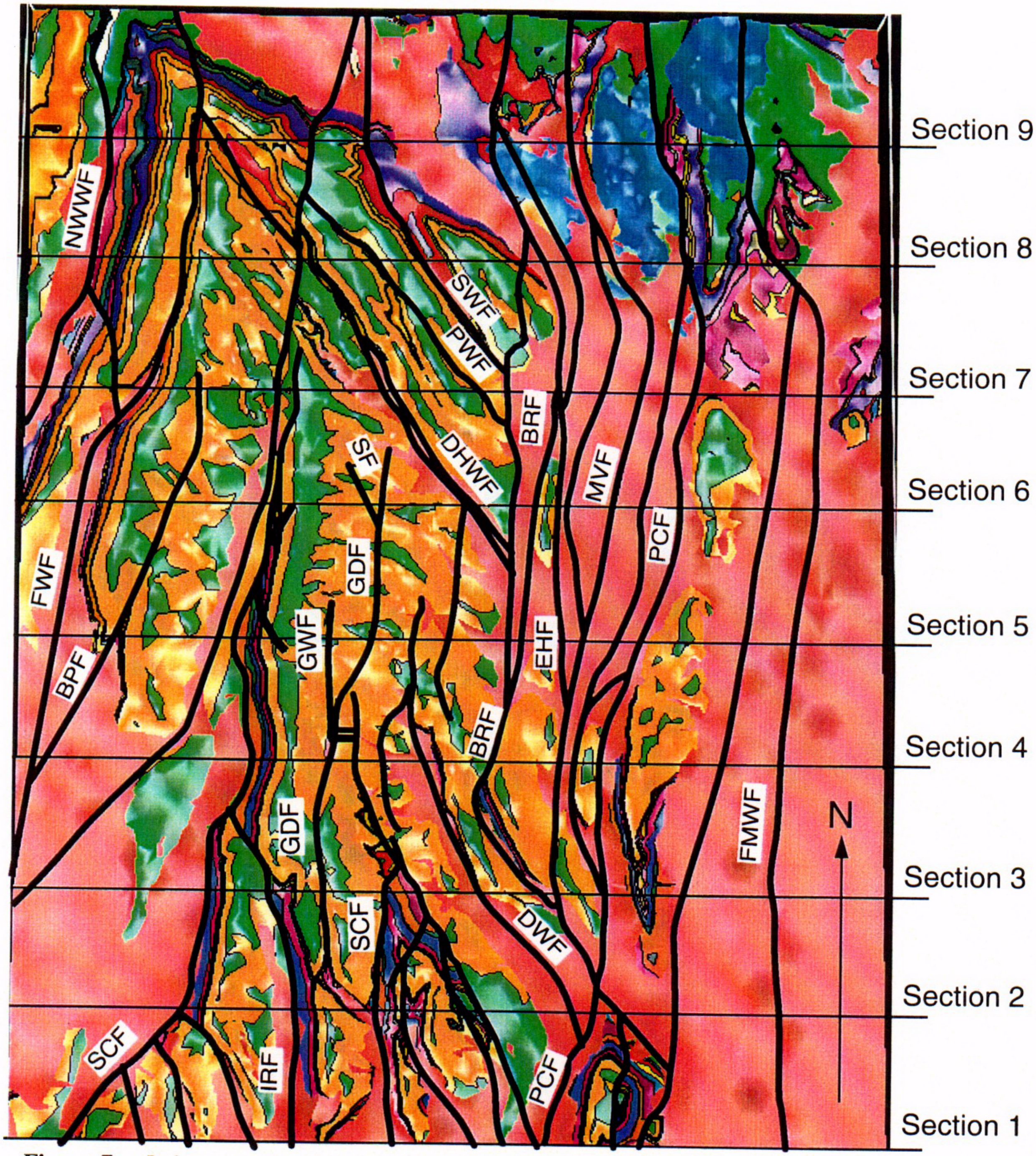


Figure 7 – Index map showing locations of sections 1 to 9 across GFM Version 3.0 as shown in figures 8 to 16.

C12

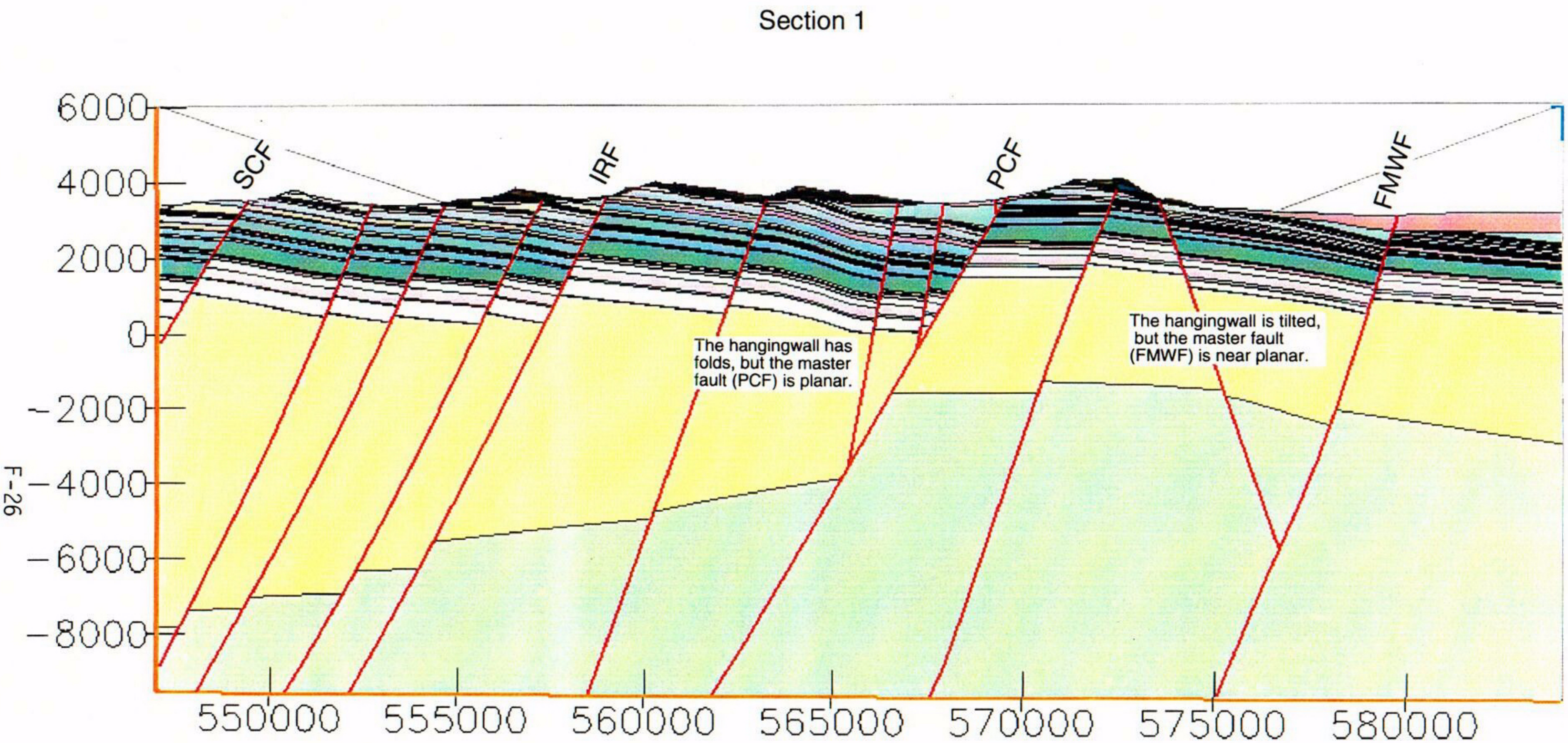


Figure 8 – Cross section 1. This section illustrates folding in the hangingwall of the PCF without curvature in the associated fault plane. Slight curvature of the FMWF may not be sufficient to produce tilting as shown in the hangingwall. See Figure 7 for location.

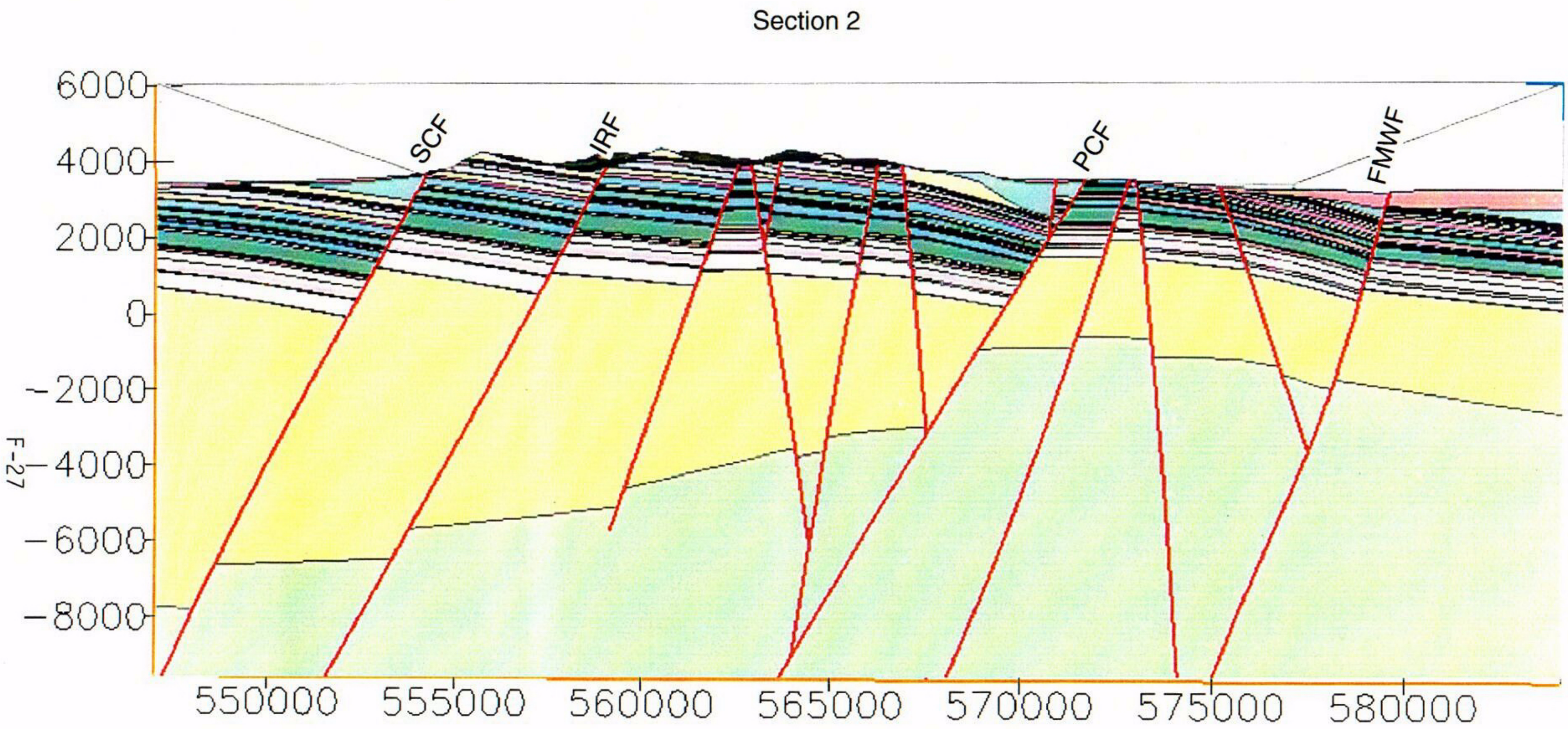


Figure 9 – Cross section 2. See Figure 7 for location.

C14

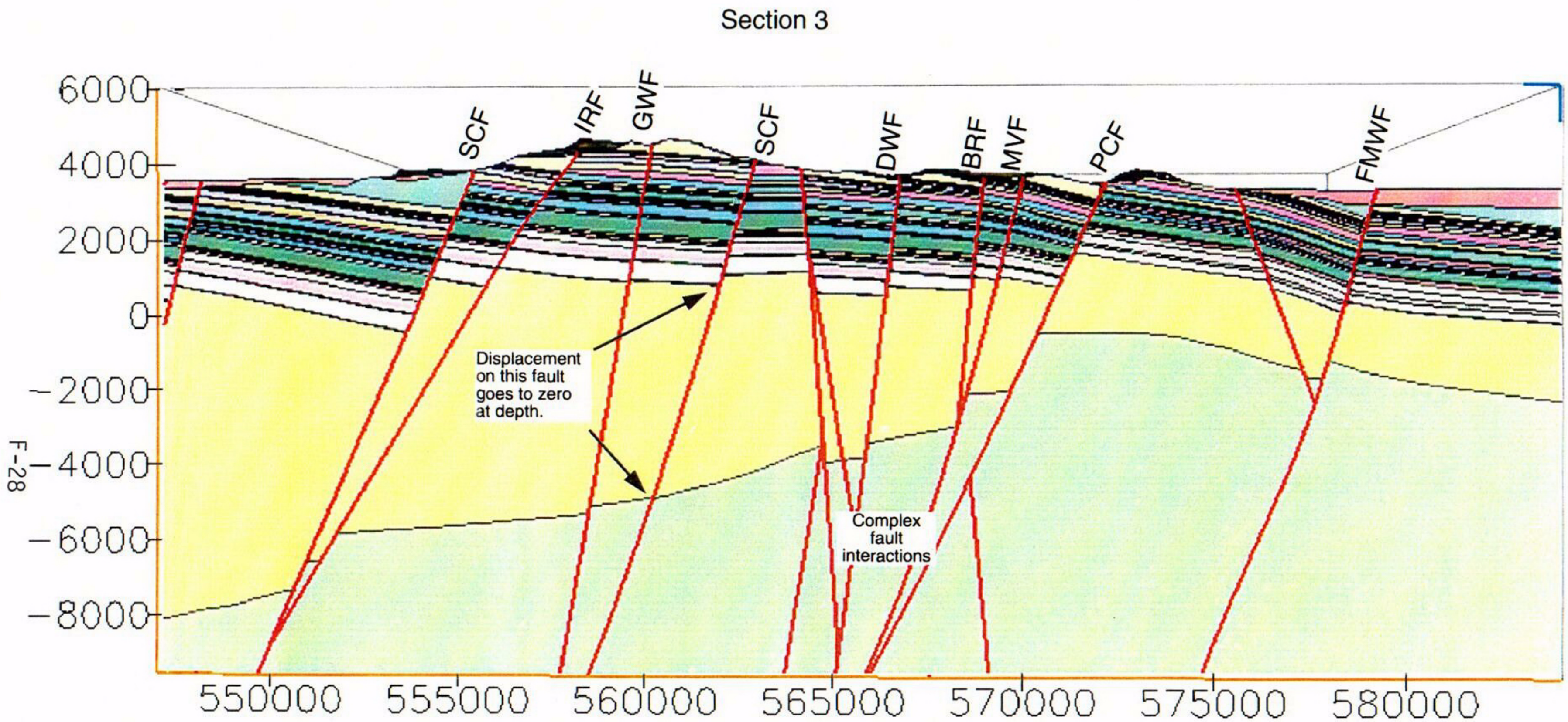
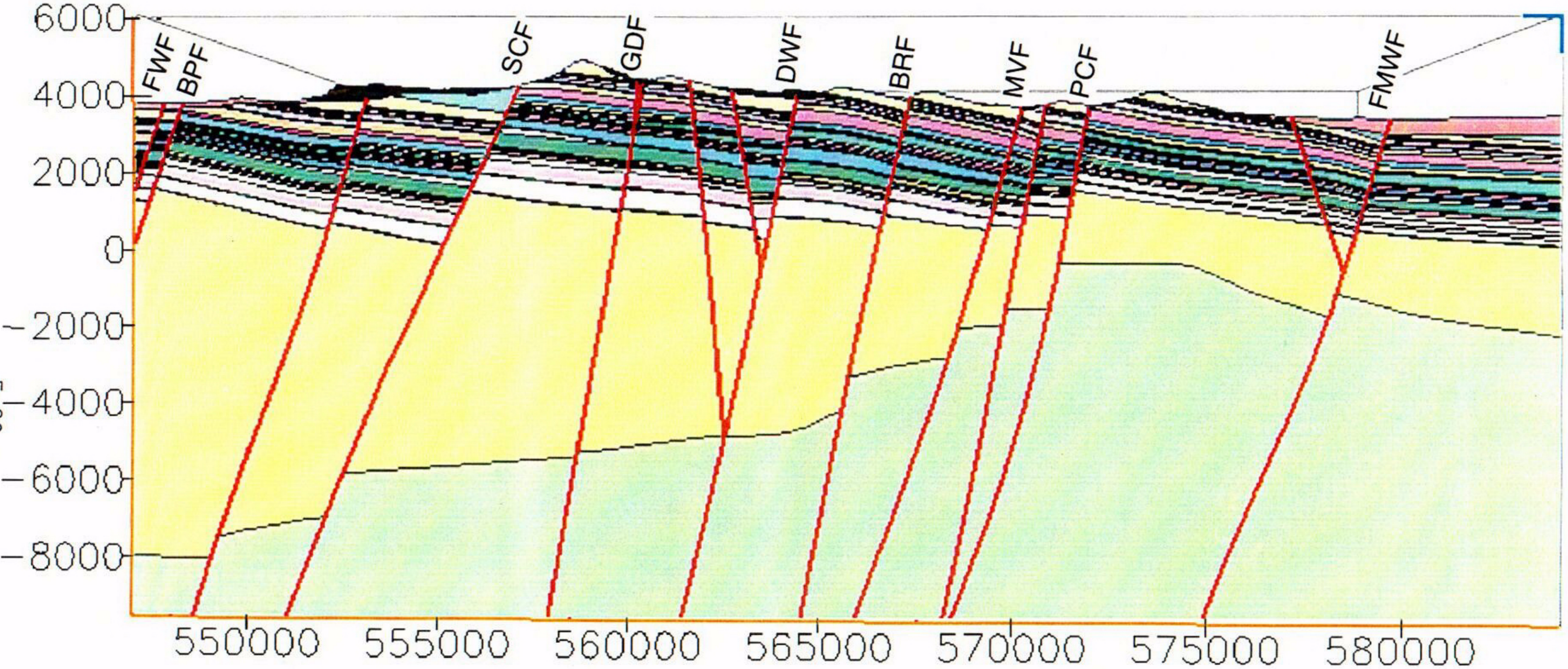


Figure 10 – Cross section 3 illustrates complex fault geometries, including fault displacement decreasing with depth (SCF), faults that are terminated updip by other faults, and crossing fault geometries. See Figure 7 for location.

C15

Section 4



F-29

Figure 11 – Cross section 4. The DWF fault is continuous through model stratigraphy in cross section 4, and is discontinuous in cross section 5 (Figure 12). See Figure 7 for location.

C16

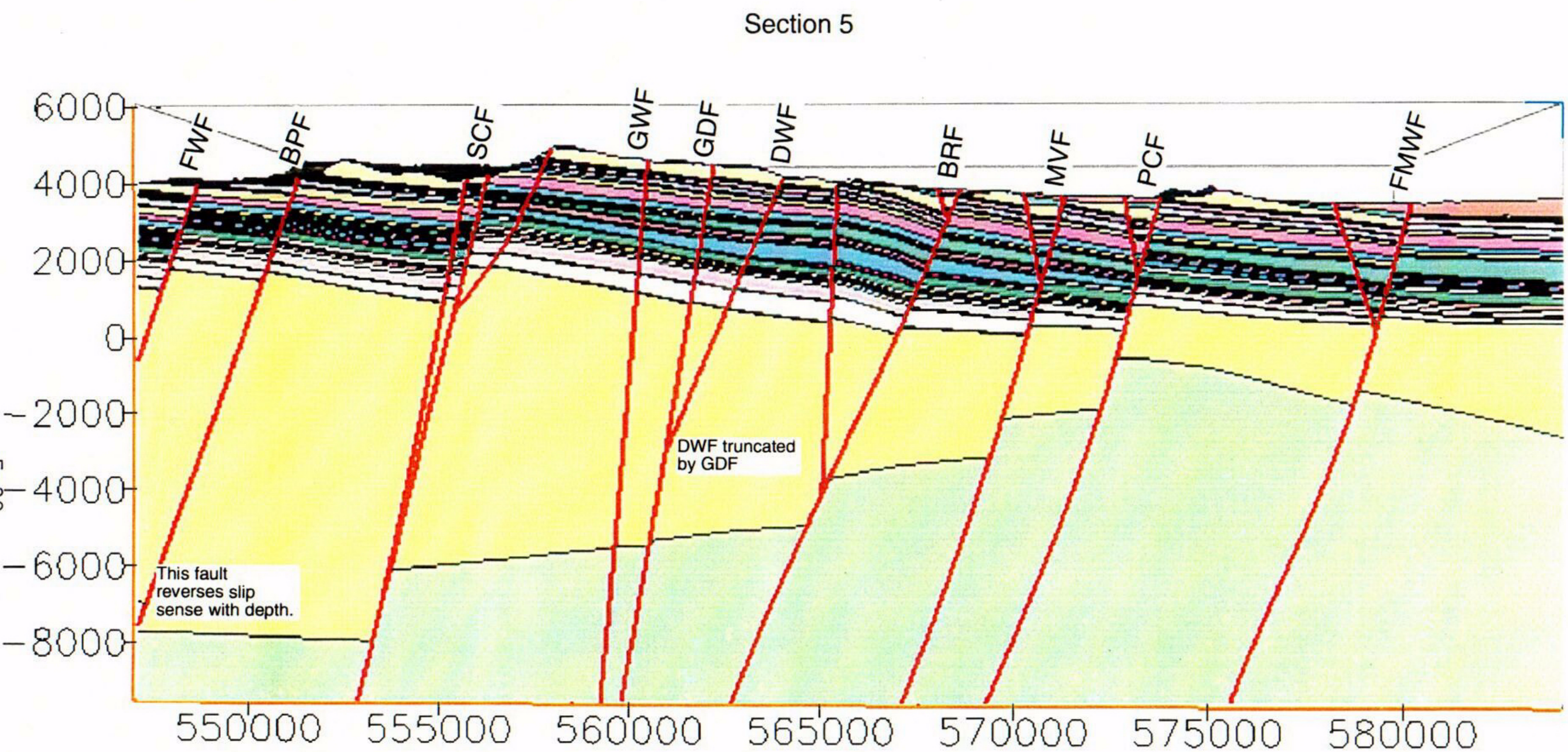


Figure 12 – Cross section 5 illustrating truncation at depth of DWF fault by GDF fault and reverse of slip sense with depth of BPF fault (see also Figure 13). Section 4 (Figure 11) shows DWF fault continuous through model stratigraphy. See Figure 7 for location.

C17

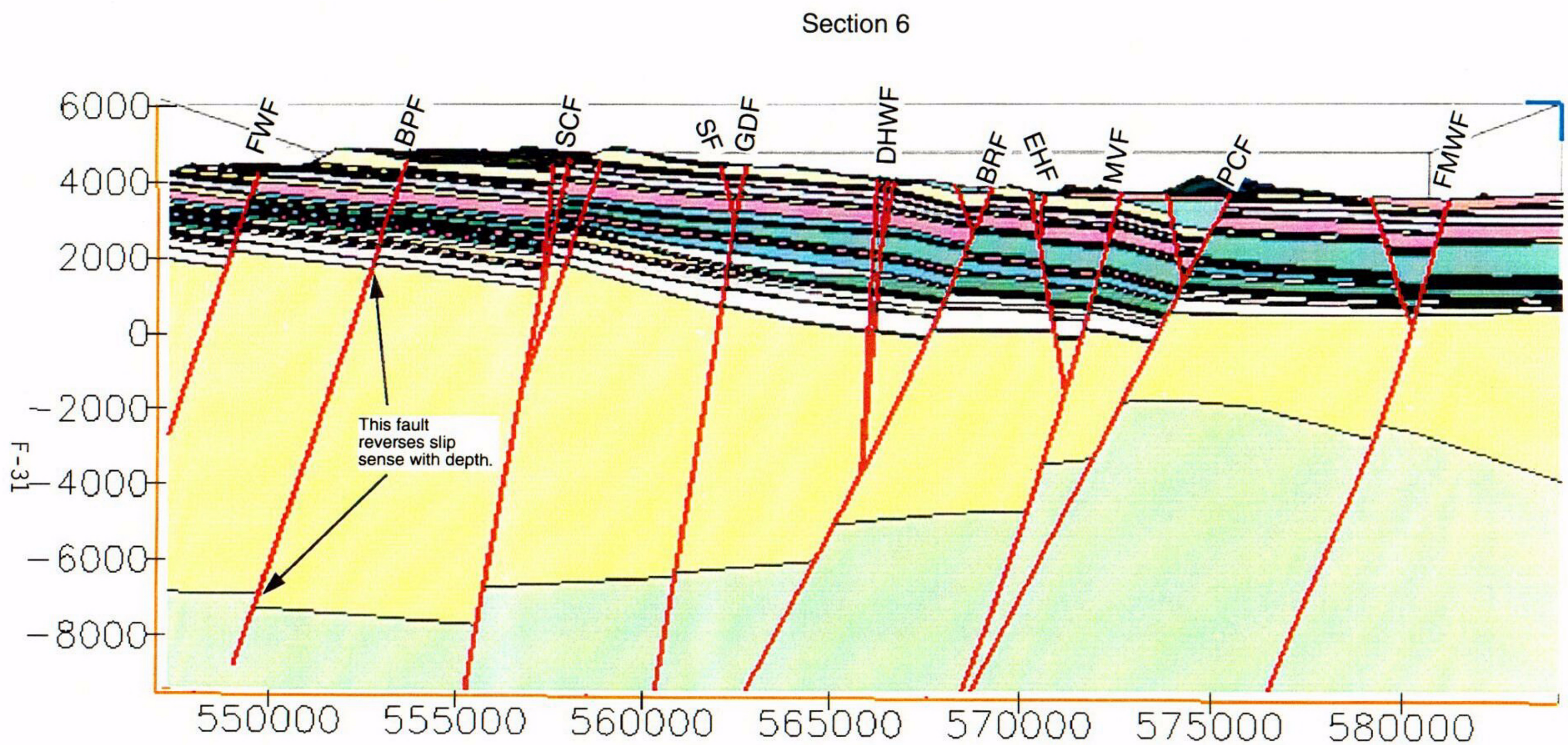


Figure 13 – Cross section 6 illustrating reverse of slip–sense at depth of BPF fault (see also Figure 12). See Figure 7 for location.

C18

Section 7

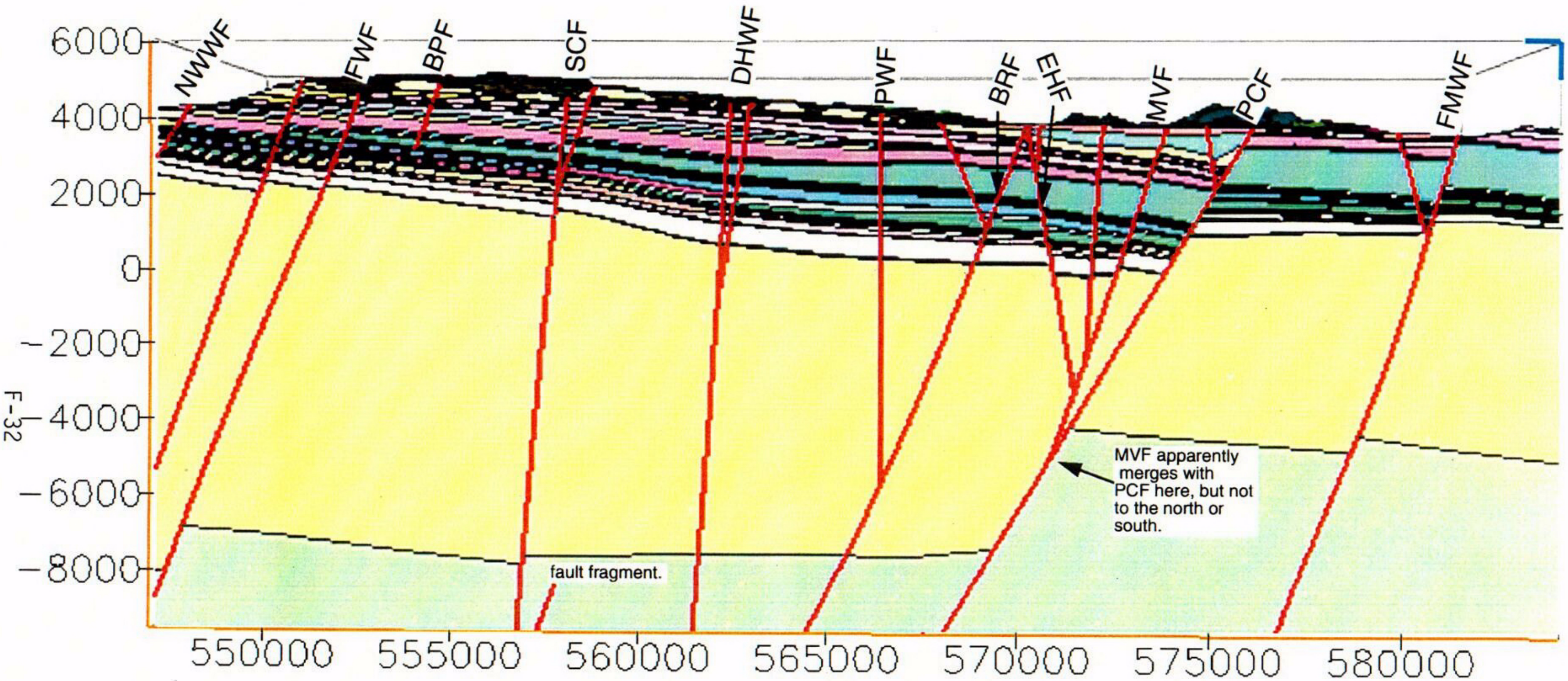


Figure 14 – Cross section 7 illustrates merging of MVF with PCF at depth. These faults do not merge in cross sections 6 (Figure 13) and 8 (Figure 15). Fault fragment terminates updip. See Figure 7 for location.

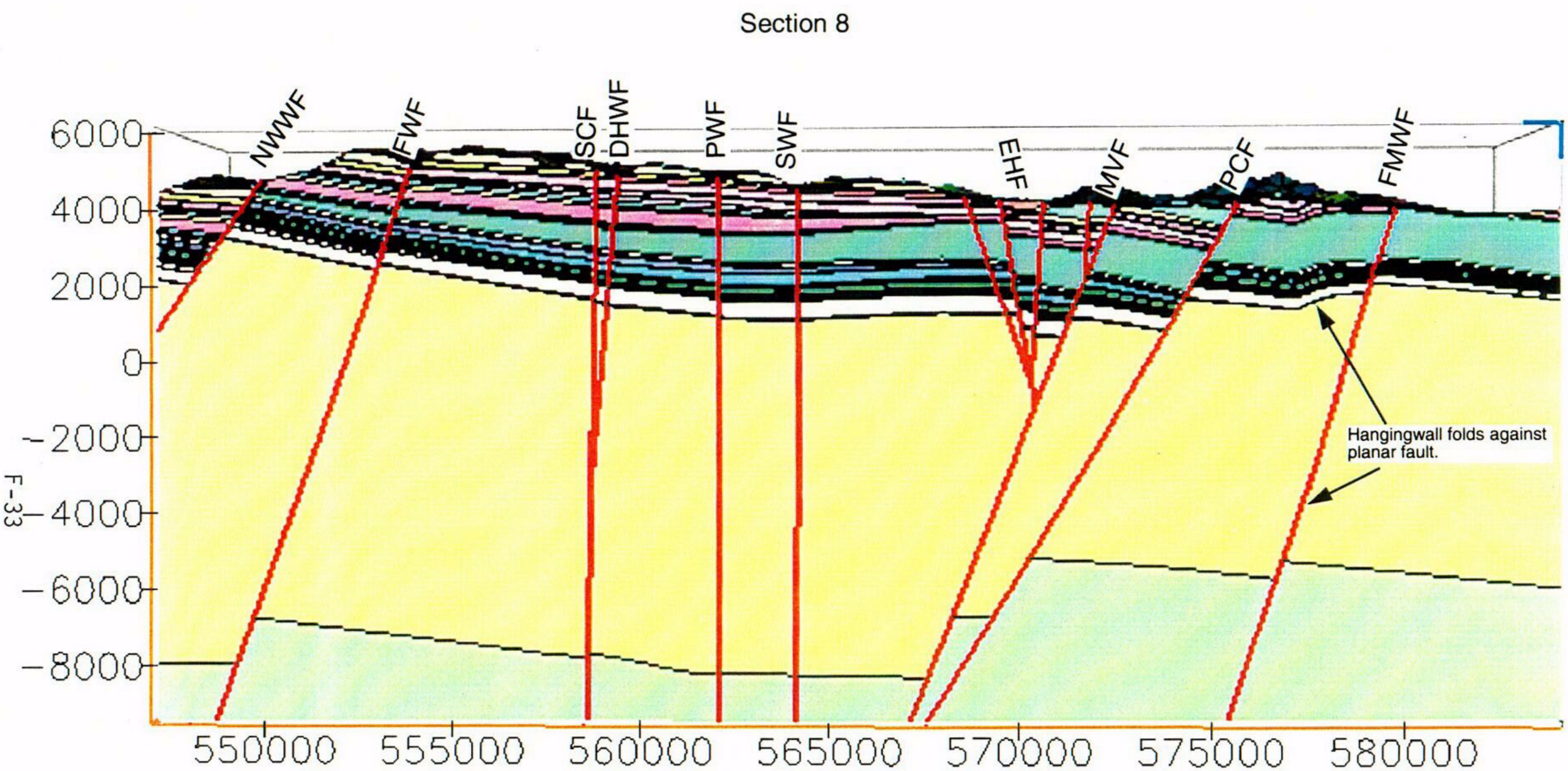


Figure 15 – Cross section 8 illustrating folded beds in the hanging wall of FMWF without curvature of associated fault surface. See Figure 7 for location.

Section 9

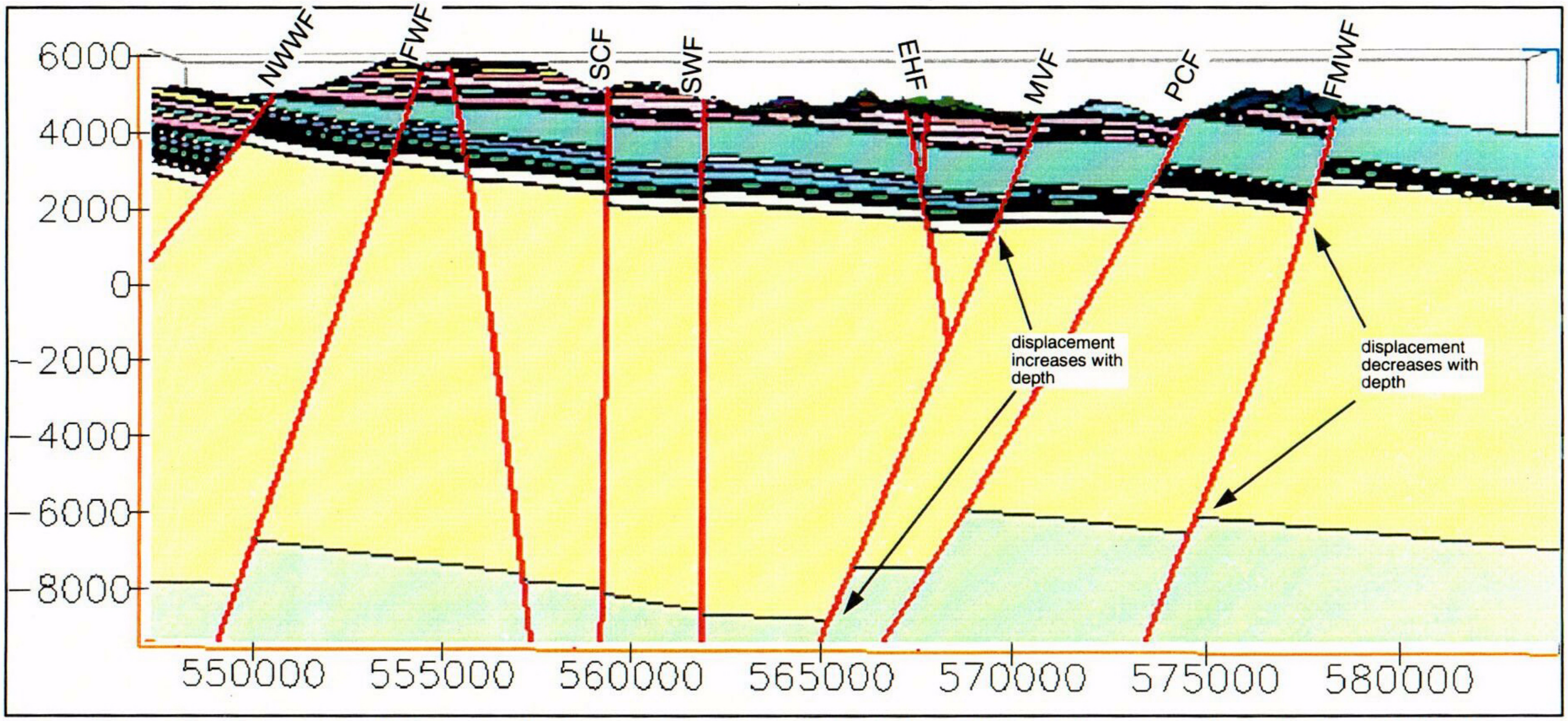


Figure 16 – Cross section 9 illustrating displacement increasing with depth along MVF and decreasing with depth along FMWF. See Figure 7 for location.

C21

minimal and may reflect sparse data. Effects of sparse data may also be reflected in GFM3.0 as greater discrepancies between the data and the extrapolations made by EarthVision software for depths to stratigraphic horizons (See Figure 5 in Part I) Consider clarifying what uncertainties are associated with the estimates to the depth of the Paleozoic surface.

In Yucca Flat, the mean depth differences between depth estimates based on gravity and actual tags of the Paleozoic rock surface at 38 drill holes was 30m +/- 88m. (Brethauer, et al., 1981). At Yucca Mountain, only a few boreholes can be used to define the Paleozoic surface. (Ue25 p-1 is the only borehole that penetrates this surface. A few other holes, such as G-1 and Gu-3, while not penetrating the surface do constrain its depth.) This information suggests that, as a minimum, only offsets greater than 100 m can be used as control for the location of faults intersecting the Paleozoic surface, and displacements of less than 100 meters may be artifacts of model construction. Consider clarifying whether artifacts of modeling are an influence in this case.

h. Complex interactions between faults with opposing dip (e.g., Section 3, Figure 10) are likely in the Yucca Mountain area (Brocher, et al. 1998) and may be important influences on groundwater flow (Ferrill, et al. 1998). Variable displacement values between different units at the same position along a given fault and beheaded faults without a continuation across the offsetting fault are examples of complex fault interactions. Consider clarifying whether these complex interactions are real or modeling artifacts.

APPENDIX G

GLOSSARY

[TO BE DEVELOPED FOR REVISION 2, FY99]