SYNTHESIS REPORT FOR YUCCA MOUNTAIN REGION TECTONIC MODELS

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ABSTRACT

The Yucca Mountain Region is located in the transition between the Eastern California Shear Zone to the southwest, the Basin and Range province to the northeast, and the nested Timber Mountain–Claim Canyon caldera complex to the north. Yucca Mountain and Crater Flat are characterized by oblique normal faulting (Fridrich, 1998) that accommodates approximately a WNW-ESE extension. However, the transitional setting of the Yucca Mountain Region has led to the proposal of numerous models to explain its broader tectonic context. The objectives of this report are to (i) reassess the tectonic models evaluated earlier (NRC, 1999) in light of subsequent geologic and geophysical studies; (ii) review three new tectonic models [i.e., the regional right-lateral crustal bending (Wernicke, et al., 2004), the mega rings (Tynan, et al., 2004) and the recently described stateline fault system model (Guest, et al., 2007), which is similar to the earlier Amargosa shear zone model of Schweickert and Lahren (1997)]; and (iii) discuss the reassessment of the potential impact of tectonic models on probabilistic seismic and volcanic hazard assessment.

The descriptions of and bases for proposed tectonic models for the region are reviewed in this report. To simplify review of these models, they are organized into four groups based on their mode of deformation: extension, transtensional, transtensional/extensional, and volcanic. New geologic, geophysical, and geodetic data developed since 1999 are briefly described and evaluated. Geodetic data from a continuously operating geographic positioning system net in the Yucca Mountain area (Wernicke, et al., 2004) and relocation of earthquakes from 1992 to 2002 (Smith, et al., 2003) show promise in constraining existing models or developing a new neotectonic model. A model based on these quantifiable ongoing tectonic processes would more accurately reflect the current tectonic environment of the region. Until additional data are collected and evaluated, all of the previously proposed models, except the Paleozoic synclinorium (Robinson, 1985), the collapsed caldera model (Carr, 1982), and the shallow detachment model of Hamilton (1988) and Scott (1990) are considered viable. It is concluded that there is no preferred tectonic model; instead, a variety of proposed tectonic models should be considered in the assessment of Yucca Mountain. Models that are characterized by long, steeply inclined, and deeply penetrating faults are generally considered to be of greater concern for both seismic and volcanic hazards.

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: No original data were generated for the analyses presented in this report. CNWRA data summarized in this report meet quality assurance requirements described in the CNWRA Quality Assurance Manual. Data used to support conclusions in this report are also taken from documents published by U.S. Department of Energy contractors and supporting organizations; the respective sources of these non-CNWRA data should be consulted for determining the level of quality assurance.

ANALYSES AND CODES: Maps and related Geographic Information System data were generated and plotted by the software ArcView GIS© Version 3.2a (ESRI, 2000) and Oasis montaj© Version 5.1.8(A5) (Geosoft, 2000)—commercially available software maintained in accordance with CNWRA Technical Operating Procedure (TOP)–018, Development and Control of Scientific and Engineering Software.

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1 INTRODUCTION

Understanding the geologic setting of the Yucca Mountain Region was important to the U.S. Nuclear Regulatory Commission (NRC) and Center for Nuclear Waste Regulatory Analyses (CNWRA) staffs' ability to effectively and efficiently review a license application for the potential repository at Yucca Mountain. The geologic setting serves as the framework for understanding site conditions and thus provides a technical basis for assessing the contribution of the natural system to repository safety. One component of the geologic setting is the tectonic setting. The tectonic setting is the consequence of forces within the Earth causing horizontal and vertical crustal movements that (i) result in geologic structures and features, including folds, faults, fractures, the Earth's topography, and volcanoes and (ii) cause earthquakes and volcanic eruptions. These forces are related to or derived from the motion of global crustal plates (Searle, 2005). Within a region, such as the Yucca Mountain Region, tectonic models are developed based on the interpretations of the origins of folds, faults, topography, and igneous features, such as volcanoes, to explain the spatial and temporal development of these features. Often, over the long history of the Earth, a region may undergo a range of deformational forces and be described by a variety of temporally separated tectonic models. The current tectonic model of a region is often referred to as the neotectonic model. A neotectonic period starts when the present-day stress field in the region was first imposed (Stewart, 2005). The direction of maximum horizontal stress in the western United States has gradually rotated 36° to 48° clockwise over the last 22 million years (Bird, 2002). This would be approximately 1.6° to 2.2° of rotation per million years. Because stress field rotation since approximately 22 mya[1] appears to be gradual, there is no clear point that can be identified as the initiation of the present-day stress field in the Yucca Mountain Region. Given this uncertainty, we have arbitrarily chosen 5 mya as the approximate initiation of the present-day stress conditions in the Yucca Mountain Region. This choice is based on the increase in volcanism following a 2.5-million-year hiatus about 5 mya in the Yucca Mountain Region (CRWMS M&O, 1998a). In developing neotectonic models for Yucca Mountain, it is important to characterize and understand geologic and geophysical features and processes reflecting earlier tectonic environments, prior to 5 mya. Such features can influence subsequent tectonic processes (e.g., seismicity, faulting, surface rupture and magmatic pathways). However, to fully characterize the modern tectonic environment at Yucca Mountain, it is also necessary to incorporate features and processes resulting from the current tectonic regime, such as crustal strain measurements (Wernicke, et al., 2004), current seismicity (Smith, et al., 2003), and young geomorphic features (Sims, et al., 2007; McKague, et al., 2006). Thus, the alternative tectonic models assessed here reflect both earlier and current tectonic environments. In the following discussion, no preferred model is identified; instead, a number of proposed tectonic models should be considered for the Yucca Mountain region.

Yucca Mountain is composed primarily of Miocene volcanic tuffs ranging from about 15 to 11 million years in age (Sawyer, et al., 1994). These strata now form east-dipping cuestas bounded by west-northwest-dipping normal faults. Maximum fault displacements are on the order of 400 to 500 m [1,312 to 1,640 ft]. Characterization of the geologic setting of Yucca Mountain requires an understanding of not only the local fault, fracture, and lithologic architecture, but also the nature of the underlying tectonic processes that control active geologic processes in the region. However, because of the transitional setting of the Yucca Mountain Region between the Eastern California Shear Zone and the Basin and Range provinces, sometimes referred to as the Walker Lane (Stewart, 1988), its current tectonic environment is not well constrained. Thus, to capture the varied interpretations of the tectonic setting including

[1]The term "million years ago" (mya) is used frequently throughout this document; therefore the acronym mya has been used.

uncertainties, numerous alternative tectonic models have been proposed and evaluated. These alternative tectonic models are inferred from the geology, geophysics, geodesy, and seismology in the Yucca Mountain Region. In 1999, CNWRA staff identified a number of tectonic models as alternative conceptual interpretations of the Yucca Mountain tectonic setting. These models are summarized in NRC (1999, Table C-1). The U.S. Department of Energy (DOE) summarized their assessment of tectonic models in the Yucca Mountain Site Description (CRWMS M&O, 2000) and considered some of them in the probabilistic seismic hazard analysis (CRWMS M&O, 1998b; Stepp, et al., 2001). While the tectonic setting of the Yucca Mountain Region was discussed during the 1995 probabilistic volcanic hazard analysis (Bechtel SAIC Company, LLC, 2004; CRWMS M&O, 1996) as a method of defining volcanic source zones, tectonic models were not explicitly considered. Based on the Yucca Mountain site description (CRWMS M&O, 2000), O'Leary (2007) recently reviewed proposed tectonic models for Yucca Mountain, Nevada.

The tectonic models proposed for the Yucca Mountain Region have been grouped into four categories based on the fundamental driving mechanism that controls crustal deformation: (i) extension, (ii) extensional/transtensional, (iii) transtension, and (iv) volcanic deformation (Table 1-1). The extension category is further subdivided into three subgroups based on the geometric and kinematic characteristics that result from overall crustal extension: (i) rift (graben), (ii) planar-domino models, and (iii) detachment. In this report, the intermediate and deep detachment models are discussed together. This tectonic model classification is summarized in Table 1-1. This classification is based on the listings of tectonic models in the earlier NRC (1999) and CRWMS M&O (2000) reports and includes the three new models proposed since 2000. The table correlates the models discussed in NRC (1999) and CRWMS M&O (2000). Three of the original 11 models listed in NRC (1999), the Paleozoic synclinorium (Robinson, 1985), Carr's (1982) collapsed caldera model, and the shallow detachment model of Hamilton (1988) and Scott (1990) are listed in Table 1-1 but are not considered further in this report. The Paleozoic synclinorium model is based on a compilation and interpretation of the Paleozoic geology inferred from Yucca Mountain drill hole data and geologic maps of the Paleozoic outcrops in the region. Because of its basis, it does not represent a model of relevance to the current tectonic environment in the Yucca Mountain Region. The collapsed caldera model is not considered viable, because subsequent geophysical surveys (Brocher, et al., 1998; O'Leary, et al., 2002; Perry, et al., 2005a; O'Leary, 2007) do not support a major premise on which it was based (i.e., a caldera beneath Crater Flat). In addition, there have been no active caldera systems in the Yucca Mountain Region in the last 7 million years. Offsets in the pre-Tertiary–Tertiary contact, based on interpretation of a seismic reflection survey across Crater Flat and Yucca Mountain (Brocher, et al., 1998 and O'Leary, 2007), preclude the shallow detachment models of Hamilton and Scott. The same data do not preclude the deeper detachment models. Although not ruled out, the regional detachment model of Wernicke, et al., (1998) was not included in this review because it does not explicitly address the Yucca Mountain region. O'Leary (2007) considers regional detachment faults incompatible with faulting east of Yucca Mountain.

Since 1999, tectonic research, as part of continued site characterization by DOE and independent scientific research conducted by other government agencies and academic institutions, has continued in the Yucca Mountain Region. These research activities have resulted in new geologic and geophysical information, including

- Stratigraphic studies of the valley fill strata in the Amargosa basin gleaned from several sources (e.g., Nye County Nuclear Waste Repository Office, 2006; Murray, et al., 2003, 2002) and the Death Valley Lower Carbonate Aquifer Monitoring Program-Wells (Inyo County Yucca Mountain Nuclear Repository Assessment Office, 2005)

- Aeromagnetic data from the 1999 U.S. Geological Survey (Blakely, et al., 2000) and 2004 DOE (Perry, et al., 2005a, 2004) surveys of Crater Flat and Yucca Mountain

- Geodetic data from the 16 permanent global positioning satellite stations in the Yucca Mountain Region as part of the 53-site Basin and Range Geodetic Network (Bennett, et al., 2002, 1998; Wernicke, et al., 2004, 2000)

- Site geotechnical data used to support earthquake site response studies (Bechtel SAIC Company, LLC, 2002)

- Relocated earthquake foci in the University of Nevada, Reno earthquake catalog (Smith, et al., 2003)

- Teleseismic tomography data from the University of Nevada, Reno (Biasi, 2006)

Since the original staff evaluation of tectonic models in 1999, three new tectonic models have been developed. Wernicke, et al. (2004) proposed a regional right-lateral crustal bending model broadly similar to the earlier model of Schweickert and Lahren (1997), based on continuously recorded data collected from the 16 Yucca Mountain global positioning satellite stations. Tynan, et al. (2004) proposed a mega-rings model based on their interpretation and integration of circular map patterns of large scale geologic and geophysical features in southwestern Nevada and southeastern California. Guest, et al. (2007) recently proposed a model also similar to that of Schweickert and Lahren.

The objectives of this letter report are threefold. First, existing and new tectonic models are reassessed with respect to new geologic and geophysical data. Second, the new regional right-lateral crustal bending model, stateline fault system model, and mega-rings tectonic model are reviewed. Third, the potential impacts of the reevaluated and new tectonic models on seismic and volcanic hazard assessments are discussed.

Table 1-1. Summary of Tectonic Models Discussed in This Report

Authors	Year	Deformation Style	Model Designation	Discussed In	Principal Features or Basis	Model Strengths	Model Weaknesses	Comments
Carr*	1982	Volcanic	Caldera	CRWMS M&O† and NRC‡	Model based on interpretation of Crater Flat drill hole data, topography, and negative gravity anomaly.		Model not supported by subsequent seismic survey.	See Section 1.0.
Carr§	1984	Extensional	Kawich-Greenwater Rift, also known as Amargosa Trough	CRWMS M&O† and NRC‡	Based on interpretation and integration of pre-1998 geology and geophysical observations including alignment of large volcanic centers, north-south-trending region of low gravity, and mapped and inferred large offset bounding normal faults.	Integrates many large regional geologic and geophysical features into a single model.	Some features used to support model are not present (i.e., Prospector-Crater Flat caldera). Does not consider subsequent information including seismic and GPS data.	Model is based on features or processes reflecting an earlier tectonic environment and may not be indicative of the current neotectonic environment. See Section 3.1.2.
Robinson‖	1985	Compressional	Paleozoic Syncline	NRC‡	Model based on interpretation of Paleozoic and/or Mesozoic tectonic environments in Yucca Mountain area.		Model based on pre-Tertiary geology.	See Section 1.0.

Table 1-1. Summary of Tectonic Models Discussed in This Report (continued)								
Authors	**Year**	**Deformation Style**	**Model Designation**	**Discussed In**	**Principal Features or Basis**	**Model Strengths**	**Model Weaknesses**	**Comments**
Hamilton¶	1988	Extensional	Shallow {<2 km [1.2 mi]} Detachment	CRWMS M&O† and NRC‡	Based on interpretation of shallow geologic features and extrapolation of shallow detachments north and west of Yucca Mountain to indicate a shallow detachment between the Paleozoic and Tertiary rocks.		Model not supported by subsequent seismic and geologic investigations.	Similar model also proposed by Scott#. See Section 1.0.
Wernicke**	1988	Extensional	Regional Extensional	CRWMS M&O† and NRC‡	Model based on regional analysis of extension between Colorado Plateau and Sierra Nevada mountains.	Model based on regional explanation of southern Nevada extensional geology.	Does not explicitly address Yucca Mountain Region.	Model is based on features or processes reflecting an earlier tectonic environment and may not be indicative of the current neotectonic environment. See Section 3.1.4.
Young, et al.††	1991	Extensional	Intermediate to Deep Detachment	CRWMA M&O† and NRC‡	Models are based on geometric and kinematic analysis using balanced geologic cross sections with detachments at depths of between 3.5 and 20 km [2.2	Model input used geologic field observations and interpretative geologic cross sections of	Model is based on features or processes reflecting an earlier tectonic environment and may not be indicative of the current	See Section 3.1.4.

Table 1-1. Summary of Tectonic Models Discussed in This Report (continued)								
Authors	**Year**	**Deformation Style**	**Model Designation**	**Discussed In**	**Principal Features or Basis**	**Model Strengths**	**Model Weaknesses**	**Comments**
					and 12.4 mi].	Scott and Bonk‡‡.	neotectonic environment. See Section 3.1.4.	
Schweickert and Lahren§§	1997	Transtensional	Amargosa Shear Zone	CRWMS M&O† and NRC‡	Based on an interpretation of offset of similar Paleozoic structures between Bare Mountain and Striped Hills and vertical rotation measured in southern Yucca Mountain.		No evidence of large right-lateral strike-slip fault at northern or southern margins of Crater Flat or in seismic survey; significant differences in assumed similar Paleozoic structures.	Model is based on features reflecting an earlier tectonic environment and may not be indicative of the current neotectonic environment. See Section 3.3.1.
Fridrich‖‖	1998	Extensional	Planar-Domino Fault	CRWMS M&O† and NRC‡	Based on parallel planar normal faults at Yucca Mountain.	Characterizes an important structural characteristic at Yucca Mountain.	Parallel planar normal faults are components of several models and are not a unique model feature in Yucca Mountain Area.	See Section 3.1.3.
Fridrich¶¶	1999	Transtensional/ Extensional	Crater Flat Basin (pull apart)	CRWMS M&O† and NRC‡	Basis of model is new (1992 to 1996) detailed field mapping west of Yucca Mountain integrated with existing geologic and geophysical data.	Application of new data, including indicators of direction of slip along faults, support a transitional tectonic environment for Yucca Mountain		Although model is based on some features or processes reflecting an earlier tectonic environment, this model may be more indicative of the current neotectonic environment

Table 1-1. Summary of Tectonic Models Discussed in This Report (continued)								
Authors	**Year**	**Deformation Style**	**Model Designation**	**Discussed In**	**Principal Features or Basis**	**Model Strengths**	**Model Weaknesses**	**Comments**
						between the extensional Basin and Range and the strike-slip dominated Eastern California Shear Zone.		than some of the other alternative models because of the incorporation of measured slickenlines orientation. See Section 3.2.1.
Janssen and King##	2000	Extensional	Elastic Viscous Graben	CRWMS M&O† and NRC‡	Two- and three-dimensional numerical and kinematic numerical (boundary element method) modeling to simulate existing topography in Yucca Mountain-Crater Flat-Bare Mountain Region.	Model represents an alternate approach to the assessment of the tectonic environment at Yucca Mountain.	Best fit modeling results requires three assumed relatively large displacement faults, two boundary faults, and one large 3-km (1.9-mi) fault in Crater Flat and predeformational topography.	Model is based on features reflecting an earlier tectonic environment and may not be indicative of the current neotectonic environment. See Section 3.1.1.
Wernicke, et al.***	2004	Transtensional	Regional Right-Lateral Crustal Bending	New	Model based on interpretation of GPS data from Dense Continuous Network in Yucca Mountain Region.	Model is based on interpretation of GPS measurements of ongoing tectonic process in Yucca Mountain area.	For best fit of data, model assumes one or more large strike-slip faults between Death Valley Fault zone and Fortymile Wash. Alternate interpretations of data are possible.	Model is based on ongoing neotectonic processes. See Section 3.3.2.
Tynan, et al. †††	2004	Volcanic	Mega Rings	New	Model is principally based on	Attempts to synthesize	Model not rigorously	Model is based on features

Table 1-1. Summary of Tectonic Models Discussed in This Report (continued)

Authors	Year	Deformation Style	Model Designation	Discussed In	Principal Features or Basis	Model Strengths	Model Weaknesses	Comments
					concentric features surrounding and centered on the Timber Mountain Caldera.	large volume of geologic and geophysical data from Yucca Mountain Region.	assessed.	reflecting an earlier tectonic environment(s) and may not be indicative of the current neotectonic environment. See Section 3.4.1.
Guest, et al. ‡‡‡	2007	Transtensional	Stateline Fault System	New	Model links several proposed northwest-striking, right-lateral strike-slip faults to create a 201-km (125-mi)-long fault system with displacement estimated at southern end.	Similar to Amargosa shear model, but with northwest extension passing southwest of Bare Mountain.	Assumes linkage of a number of inferred strike slip faults. Evidence for northwest extension of fault weak.	Model identifies a potential seismic hazard, but is not a tectonic model for the immediate Yucca Mountain area. See Section 3.3.3.

*Carr, W.J. "Volcano-Tectonic History of Crater Flat, Southwestern Nevada, as Suggested From New Evidence From Drill Hole USW VH-1 and Vicinity." U.S. Geological Survey Open-File Report 82-475. 1982.
† CRWMS M&O. "Yucca Mountain Site Description Document." TDR–CRW–GS–000001. Rev. 01 ICN 01. Las Vegas, Nevada: CRWMS M&O. 2000.
‡ NRC. "Issue Resolution Status Report, Key Technical Issue: Structural Deformation and Seismicity." Rev. 2. Washington, DC: NRC, Division of Waste Management. 1999.
§ Carr, W.P. "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." U.S. Geological Survey Open-File Report 84-854. 1984.
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Table 1-1. Summary of Tectonic Models Discussed in This Report (continued)

Authors	Year	Deformation Style	Model Designation	Discussed In	Principal Features or Basis	Model Strengths	Model Weaknesses	Comments

Scale 1:12,000. 1984.

§§ Schweickert, R.A. and M.M. Lahren. "Strike-Slip Fault System in Amargosa Valley and Yucca Mountain, Nevada." *Tectonophysics*. Vol. 272. pp. 25–41. 1997.

‖‖ Fridrich, C.J. "Tectonic Evolution of the Crater Flat Basin, Yucca Mountain Region, Nevada." U.S. Geological Survey Open-File Report 98-33. 1998.

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††† Tynan, M.C., K.D. Smith, J.M. Savino, and T.J. Vogt. "Mega-Rings Surrounding Timber Mountain Nested Calderas, Geophysical Anomalies: Rethinking Structure and Volcanism Near Yucca Mountain, Nevada." Eos Transactions. Fall Meeting Supplement. Vol. 85, No. 47. Abstract T31A–1256. Poster. American Geophysical Union. 2004.

‡‡‡ Guest, B., N. Niemi, and B. Wernicke. Stateline Fault System: A New Component of the Miocene-Quaternary Eastern California Shear Zone." *Geological Society of America Bulletin*. Vol. 119, No. 11–12. pp. 1,337–1,346. 2007.

2 SYNOPSIS OF NEW INFORMATION

2.1 Geologic Information

Although DOE has not conducted extended geologic field investigations in the Yucca Mountain Region since 1999, site characterization of the geology in the surface facilities area has continued through a drilling and geotechnical program. The geotechnical data include borehole geologic information, seismic velocity and density profiles, and strain-dependent shear modulus and damping measurements. The deepest of the boreholes extend into the densely welded units of the Tiva Canyon tuff, approximately 200 m [656 ft] below ground surface. DOE intends to use these data to develop seismic design response spectra and representative time histories for the surface facilities area. DOE summarized the data collected in this program in 2002 (Bechtel SAIC Company, LLC, 2002). Staff review of those data is documented in Gonzalez, et al. (2004). The review included development of a three-dimensional EarthVision® model of the surface facilities area based on the borehole geological and geophysical data. The model represents the layered, tilted, and faulted stratigraphy in Midway Valley, incorporating the alluvium, nonwelded volcanic units that postdate the Tiva Canyon tuff, and moderately to strongly welded volcanic units of the Tiva Canyon tuff. The geology of the subsurface from the borehole data, EarthVision model, and geotechnical surveys is consistent with nearby mapped geology and with subsurface geologic conditions inferred from geologic interpretations made prior to the boreholes. Tectonic models reviewed in this report are compatible with the new geologic and geotechnical data from the DOE investigations at the surface facility area.

New subsurface information is also available from the Nye County (Nevada) Early Warning Drilling Program (EWDP)[1] (Nye County Nuclear Waste Repository Project Office, 2006), which has drilling projects in Fortymile Wash and the Amargosa Basin. Since the program's initiation, Nye County has drilled 41 boreholes in Fortymile Wash and the northern Amargosa Desert to provide geologic and hydrologic information. Three of the Nye County EWDP wells, NC–EWDP–1DX, NC–EWDP–3D, and NC–EWDP–2DB (Figure 2-1), are especially relevant to understanding the pre-Miocene tuff tectonic setting of Yucca Mountain because they penetrate below the Miocene tuff units of the Southwest Nevada Volcanic Field and include thick sections {greater than 500 m [1,640 ft]} of the underlying upper Oligocene and lower Miocene sedimentary strata. Well NC–EWDP–2DB penetrated Paleozoic bedrock at 884 m [2,900 ft] below ground surface.

Murray, et al. (2003, 2002) correlated the stratigraphy in these three Nye County wells with stratigraphic data collected from surface exposures on the Nevada Test Site and in the eastern Funeral Mountains. That work concluded that the stratigraphy of the Oligocene and early Miocene deposits consists of three main lithostratigraphic units. The lowest unit is a matrix-supported conglomerate with well-rounded, boulder-sized clasts of highly polished quartzite overlain by a few hundred meters of gastropod- and ostracod-bearing limestones. The middle unit consists of several hundred meters {possibly up to 1,000 m [3,281 ft]} of pebble–cobble conglomerate, coarse sandstone, and red siltstone; individual conglomerate beds can be greater than 30 m [98 ft] thick. Above the conglomerate-rich middle unit is a thick section {over 1,000 m [3,281 ft]} of volcaniclastic sandstone and bedded and airfall tuff. This three-unit lithostratigraphy can be correlated across a belt of outcrops that extends from the Frenchman Flat area of the Nevada Test Site west to the Funeral Mountains of eastern California (Figure 2-1). Based on the stratigraphic data from Murray, et al. (2002), these Oligocene to early Miocene strata may be more than 2,000 m [6,562 ft] thick.

[1] The term "Early Warning Drilling Program" (EWDP) is used frequently throughout this document; therefore the acronym EWDP has been used.

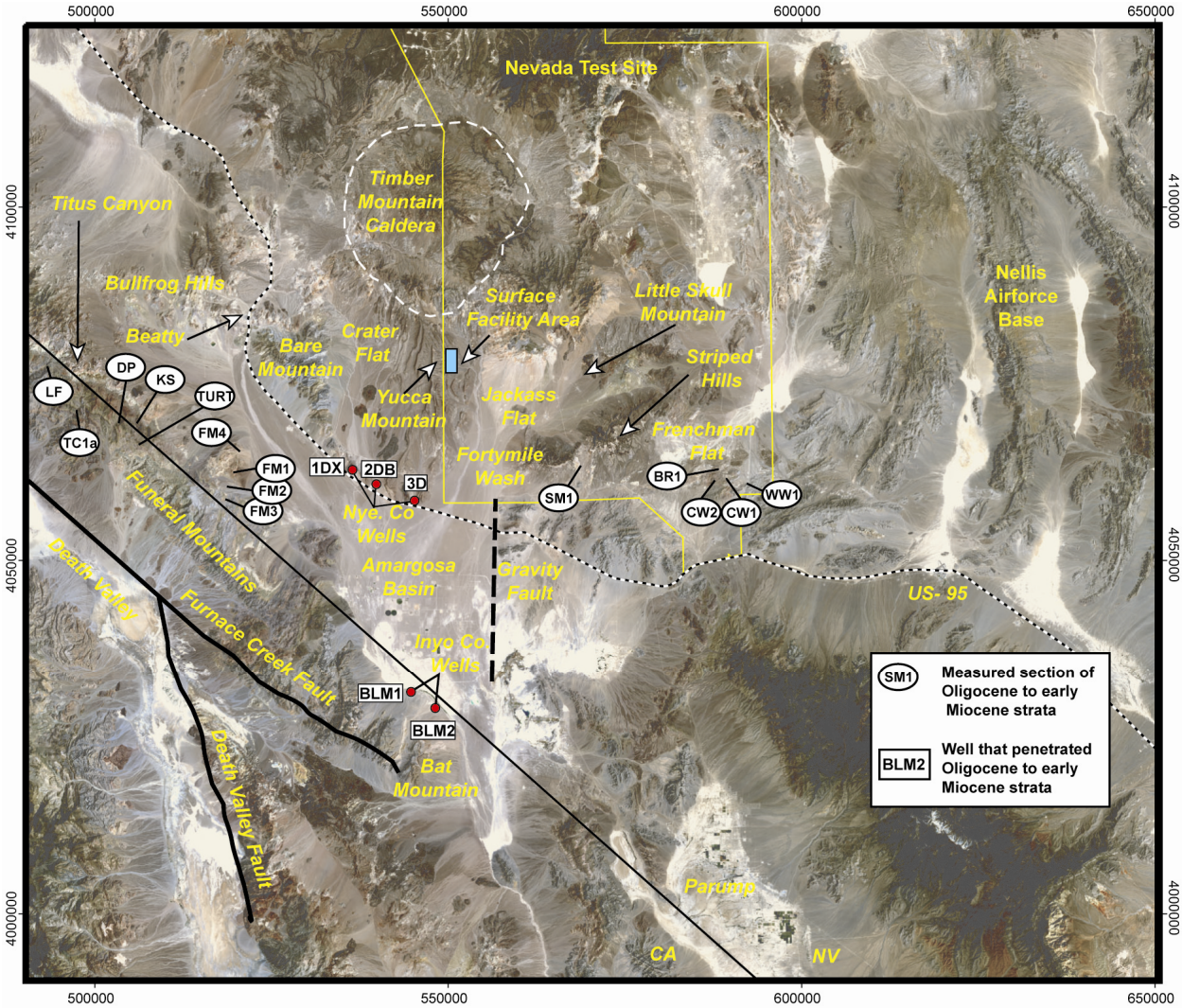

Figure 2-1. Satellite Image of the Yucca Mountain Region Showing the Location of Geographic Features Mentioned in the Text. Locations of the Nye and Inyo County Wells That Penetrated Pre-Miocene Strata, as Well as the Stratigraphic Sections of Murray, et al. (2003, 2002) and Gutenkunst, et al. (2005) Are Also Shown (BR–Burma Road, CW–Cave Wash, DP–Daylight Pass, FM–Funeral Mountains, KS–Keane Springs, LF–Leadfield, SL–Stateline, SM–Skull Mountain, TC–Titus Canyon, TUR–Turtle Canyon, WW–Winapi Wash, and YR–Yellow Ridge). Map Coordinates Are Geographic. Map Projection Is Universal Transverse Mercator (UTM), Zone 11, North American Datum 1983 (NAD83).

Preliminary field studies also suggest that these same three lithostratigraphic units are present in Titus Canyon in Death Valley National Park, California, approximately 100 km [62 mi] west of their occurrence in Frenchman Flat (Gutenkunst, et al., 2005).

Analysis of cuttings from the three Nye County wells south of the Yucca Mountain area shows that these three lithostratigraphic units exist in the subsurface of the Amargosa basin and correlate the Nye County well data to the surface outcrops in the eastern Funeral Mountains (Gutenkunst, 2006; Murray, et al., 2003, 2002). These observations show that the Oligocene to Early Miocene strata constitute a significant fraction of the valley fill in the Amargosa basin.

Murray, et al. (2003) interpreted the lower limestone-rich unit to represent initiation of extension that resulted in the ponding of existing fluvial drainages along the axes of the newly developed extensional basins. The middle conglomerate-rich unit is interpreted to represent development of regional through-going fluvial drainage systems. The upper volcanic-rich unit is interpreted to represent the late phase of extension when attenuation of the crust resulted in widespread regional volcanism north of this area.

These strata therefore provide important constraints on interpretations of nascent extension of the Basin and Range and on structural reconstructions that attempt to restore the region to its preextensional configuration. The presence of basinal strata across the region suggests that extension of the Amargosa basin was well underway by late Oligocene or early Miocene, with strata ranging in age from >27.1 to 11.9 million years (Gutenkunst, 2006). Moreover, the juxtaposition of these strata indicates that subsequent Basin and Range faulting in the late Miocene and Pliocene did not substantially disrupt the overall alignment of these basinal strata as required by tectonic models that envision large-scale Miocene to Pliocene crustal extension of the region by detachment faulting (e.g., Snow and Wernicke, 2000) or large-scale reorganization of crustal blocks by dextral strike-slip fault systems (e.g., Guest, et al., 2007; Schweickert and Lahren, 1997).

The Inyo County scientific drilling program was started in 2002 and reported in 2003 (Jensen, et al., 2003), 2004 (Jensen, et al., 2004), and 2005 (Bredehoeft, et al., 2005). Since the initiation of the Inyo County program, three drill holes have been completed. In addition, gravity, magnetic, and transient electromagnetic surveys were conducted to better define the hydrologic flow path from Amargosa Valley to Death Valley (Jensen, et al., 2004, 2003). Two of the drill holes, BLM #1 and BLM #2, are north and northwest of Bat Mountain along the southwest side of the Amargosa basin (Figure 2-1). Although the drill holes penetrate Oligocene to early Miocene strata, interpretation of the data is incomplete at this time. These data should allow the southward extension of the stratigraphic correlations developed by Gutenkunst (2006) and Murray, et al. (2003, 2002) in the northern Amargosa area. Until the data are interpreted and released, the results of the Inyo County program cannot currently support or preclude any of the proposed tectonic models. In addition, the main areas of data acquisition are located well south and west of Yucca Mountain and will only marginally affect the interpretation of tectonic models of the Yucca Mountain Region.

2.2 Geophysical Data

Geophysical data and associated interpretations provide an important framework for evaluating alternative tectonic models. Although some basic assumptions are used in processing geophysical data, these data generally represent the best available information on subsurface structures at a range of scales. Thus, tectonic models can be tested with geophysical data to determine the correspondence between model interpretation and proposed subsurface structures.

Gravity surveys measure density variations in the upper 15 km [9.3 mi] of the crust and can delineate different rock types, deep sedimentary basins, or linear structures such as faults. Although most regional gravity surveys in the Yucca Mountain Region were conducted prior to 1999 [e.g., Healey, et al., (1987)], Morin and Blakely (1999) and Ponce, et al. (2001, 1999) conducted additional gravity surveys in areas of sparse data coverage. These newer data are integrated with existing regional gravity data by Ponce, et al. (2001), who describe the data processing methods using a final isostatic gravity anomaly map (Figure 2-2).

Several major tectonic features are represented in the gravity anomaly data. Relative to a standard rock density of 2,670 kg/m^3 [166.7 lb/ft^3] (Ponce, et al., 2001), pre-Cenozoic crystalline and carbonate rocks such as those at Bare Mountain in the footwall of the Bare Mountain fault have high densities {i.e., >2,700 kg/m^3 [>168.6 lb/ft^3]} and form many of the prominent gravity highs (Figure 2-2). Miocene calderas of the Southwest Nevada Volcanic Field form a large, negative gravity anomaly (Figure 2-2). A thick sequence of relatively low density volcanic and sedimentary rock dominates the upper crustal section beneath these anomalies. A prominent gravity low trends south-southeast from the Miocene calderas, representing a deep structural basin that is filled with sedimentary and pyroclastic deposits (e.g., Snyder and Carr, 1984). This basin, which is commonly referred to as the Amargosa Trough (Fridrich, 1999) or Amargosa basin (Murray, et al., 2003), extends southward to the Greenwater Range and may extend northward from the Miocene calderas into the Kawich Valley–Reveille Range (e.g., Carr, 1990). Yucca Mountain is located within the Amargosa Trough (Figure 2-2).

Aeromagnetic surveys detect subtle variations in the strength of remanent magnetization in shallowly buried rocks. The resulting patterns of magnetic field strength produce magnetic anomaly patterns that can be modeled to yield information on the shape, depth, and character of buried volcanoes and intrusions (e.g., O'Leary, et al., 2002). Other rocks with high remanent magnetization include welded tuff deposits. In areas such as the Yucca Mountain Region where normally and reversely polarized welded tuffs occur, deposition and faulting of these deposits can produce complex magnetic anomaly patterns that represent details of buried geologic structures.

Although numerous aeromagnetic surveys were conducted in the Yucca Mountain Region prior to 1999 (e.g., Kane and Bracken, 1983), integration of these surveys into coherent regional patterns only occurred recently (Ponce and Blakely, 2001). The remanent magnetizations in the Miocene tuffs and Miocene and younger basalts are very strong and tend to swamp the magnetic signatures of the aeromagnetic and ground magnetic surveys. Broad magnetic highs (Figure 2-3) are generally associated with large igneous intrusions or widely distributed volcanic rocks. In the Yucca Mountain area (Figure 2-3), patterns of linear anomalies with short wavelengths represent faulted tuffs associated with the Miocene calderas of the Southwest Nevada Volcanic Field. Broad regions with positive magnetic anomalies represent thick accumulations of igneous rock; circular negative or positive anomalies represent basaltic volcanoes, such as Red Cone and Black Cone in Crater Flat or Anomaly B in the Amargosa basin (Figure 2-3). Most pre-Cenozoic rocks in this area have low remanent magnetization and produce weakly negative magnetic anomalies that do not express geologic structures.

The U.S. Geological Survey collected an integrated set of high-resolution aeromagnetic data in the Amargosa Desert–Death Valley region during the summer of 1999 (Blakely, et al., 2000). These data are used primarily to support ongoing geologic and hydrologic studies for the Death Valley groundwater flow system, but also support interpretations of tectonic models in the Yucca Mountain Region. High frequency anomalies extending south from the caldera boundaries represent detailed patterns of north-trending faults that displace normal and reverse

polarity tuffs. Some prominent anomalies coincide with inferred or mapped locations of caldera boundaries, which may be poorly represented by gravity data (e.g., Figure 2-2). In addition, buried basaltic volcanoes are likely represented by some isolated anomalies within the Amargosa Trough, as discussed in Hill and Stamatakos (2002) and O'Leary, et al. (2002). The DOE's magnetic anomaly drilling program has confirmed the presence of basaltic material at several magnetic anomalies (Perry, et al., 2005b, 2006b; Stamatakos, et al., 2007). Analyses of sample data (e.g., age dates, geochemistry, and petrography) from this effort will add additional constraints on the tectonic models. Tectonic models reviewed within this report are compatible with the new geophysical data.

2.3 Geodetic Data

The results of geodetic surveys in southwestern Nevada and southeastern California provide information that further constrains the current tectonic framework in the Yucca Mountain Region. The results of geodetic surveys conducted through 1998 were discussed in NRC (1999). Prior to mid-1999, geodetic data were based on either optical or campaign-style global positioning satellite survey measurements. The results of these earlier global positioning satellite campaign surveys (1992–1998) ranged from 50 ± 9 nstrain (nanostrains/yr) (Wernicke, et al., 1998) to 23 ± 10 nstrain (Savage, et al., 1999). This is on the order of 12 to 25 times greater than the strain rates indicated by geologic methods that rely on long-term cumulative slip rates across faults (Connor, et al., 1998). Starting in mid-1999, a dense cluster of 16 continuous recording global positioning satellite sites was established in the Yucca Mountain Region (Wernicke, et al., 2004, Figure 2). The Yucca Mountain network of stations is linked to the larger Basin and Range Geodetic Network (Bennett, et al., 2002, 1998; Wernicke, et al., 2000). Wernicke, et al. (2004) reported the results of the network over the first 3.75 years of its operation. Interpretation of the results for the Yucca Mountain Region suggests a strain rate of 20 ± 2 nstrain/yr in a N 20° W direction (Wernicke, et al., 2004). An evaluation of the Yucca Mountain dense cluster network indicated velocity uncertainties of between 0.1 and 0.2 mm/yr [0.004 and 0.008 in/yr] (Davis, et al., 2003). Because of the preliminary (3.75 years of accumulated data) nature of the global positioning satellite data, it was not considered in the review of the tectonic models in this report.

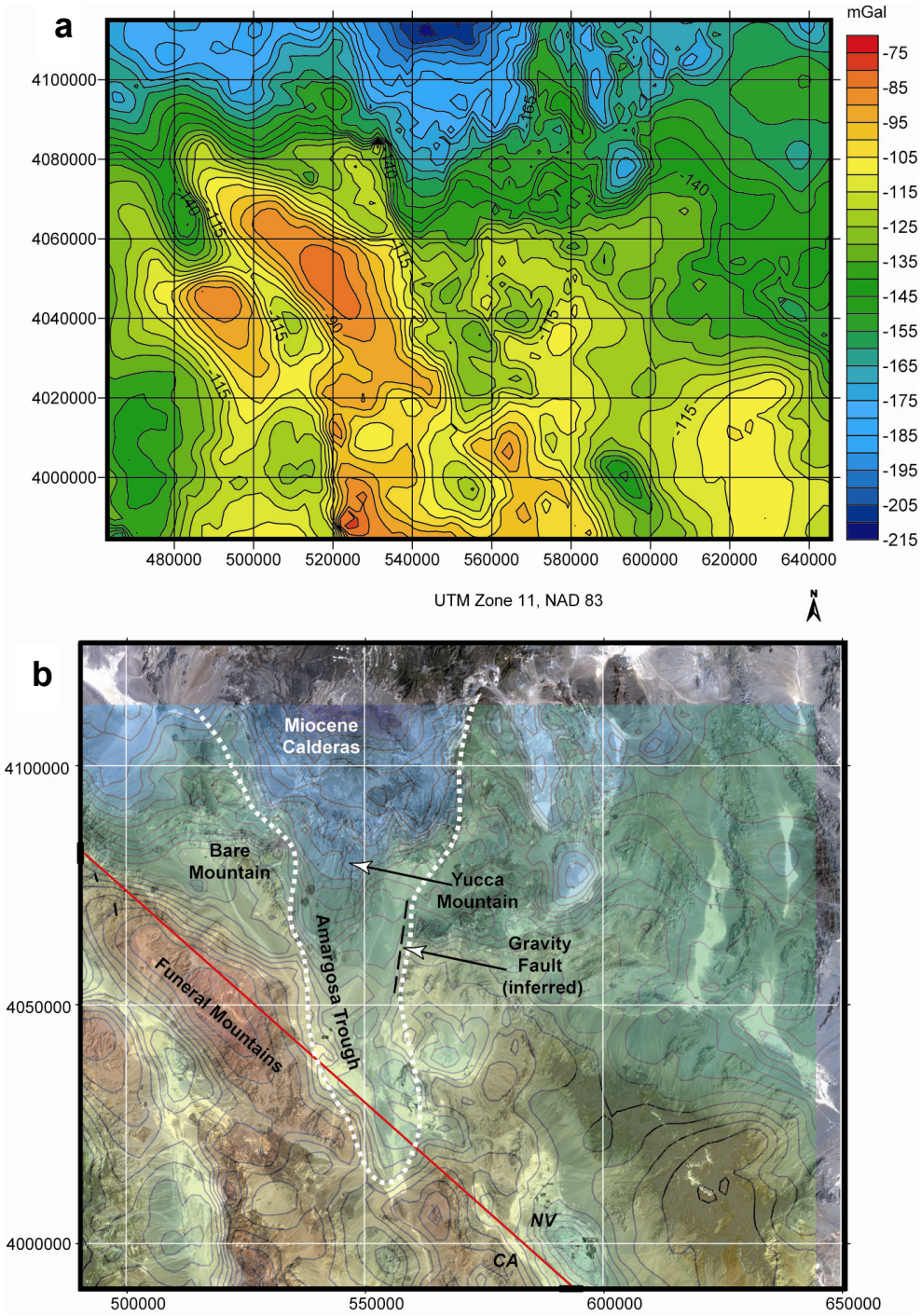

Figure 2-2. (a) Bouguer Gravity Map Based on the Data From Ponce, et al. (2001). (b) The Same Gravity Map Overlain on the Satellite Image Used in Figure 2-1. Inferred East and West Boundaries of Amargosa Trough (Carr, 1990) Indicated by Dotted Lines. Map Coordinates Are in Universal Transverse Mercator (UTM), Zone 11, North American Datum 1983 (NAD83) Projection.

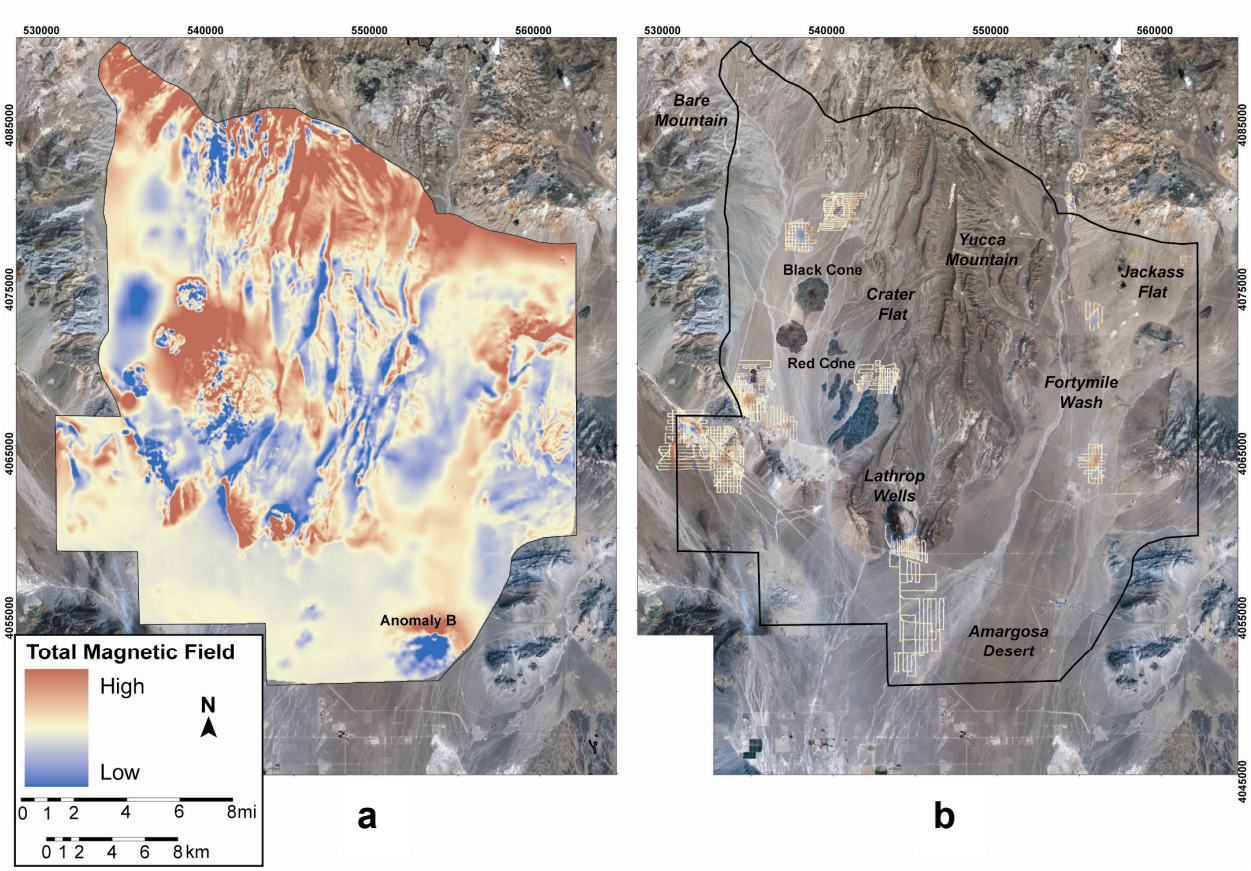

Figure 2-3. (a) Magnetic Anomaly Map Based on the DOE Aeromagnetic Data as Reported in Perry, et al. (2004) Overlain on the Satellite Image Used in Figure 2-1. (b) Locations of CNWRA Ground Magnetic Surveys (Hill and Stamatakos, 2002; Magsino, et al., 1998). Map Coordinates Are in Universal Transverse Mercator (UTM), Zone 11, North American Datum 1983 (NAD83) Projection.

3 TECTONIC MODELS

3.1 Introduction

At least 13 tectonic models have been proposed for the Yucca Mountain area since 1982 (Table 1-1). They are based on an assortment of interpretations of geologic, geophysical, and geodetic data from the Yucca Mountain Region and reflect the education, training, and experience of the models' authors. Of the 13 models in Table 1-1, 3 are considered not viable because the subsequent acquisition of new data does not support their validity. The remaining tectonic models are discussed next. As there is no single preferred tectonic model for the Yucca Mountain area, all models should be appropriately considered. O'Leary (2007) makes a similar assessment of proposed tectonic models.

The following discussions of the models are abbreviated. For fuller discussions, refer to original publications referenced in Table 1-1 and throughout the report.

3.2 Extensional Models

As summarized in Table 1-1, four tectonic models compose the suite of reviewed extensional tectonic models for the Yucca Mountain Region. Each model represents an alternative in the nature, style, and age of extensional deformation that in turn affects interpretations about the natural hazards at the site. For example, some models, such as the rift model, interpret large normal faults that extend to the base of the seismogenic crust, which is approximately 15 km [9.3 mi] deep in the Yucca Mountain Region. Because earthquake moment magnitude scales directly with the rupture area of the fault surface, the large normal faults envisioned in these models would constitute a large surface area available for rupture, and thus the seismic hazard assessment would indicate larger moment magnitudes than models in which the normal faults may only extend partially into the seismogenic crust (see Section 4.1).

3.2.1 Elastic-Viscous Graben Model

Description

The elastic-viscous graben model of Janssen and King (2000) is based on mechanical and kinematic numerical modeling using boundary element methods (Figure 3-1). Two- and three-dimensional models are used. The geometric portion of the two-dimensional, or cross-sectional model, consisted of seven planar faults. Two faults are model boundary faults and are not shown in Figure 3-1b. To improve their results, Janssen and King (2000) introduce a fault they refer to as the Crater Flat Fault into their model. While improving the results, it does not produce the required uplift of Yucca Mountain. Two-dimensional shear zone modeling in plan view is used to simulate strike-slip components of Yucca Mountain faulting. A simplified set of eight faults, including the inferred Crater Fault and the two boundary condition faults, is used in the three-dimensional modeling. The material properties portions of the models consist of a 12-km [7.5-mi]-thick seismogenic crust overlying a ductile lower crust.

Basis

The current topography between Bare Mountain and Yucca Mountain is simulated using a boundary element modeling approach. The boundary element models consist of a two-layer crust, cut by 75° dipping normal faults. Best fit models require additional features including two boundary faults or crustal attenuation east and west of Yucca Mountain or at Yucca Mountain

volcanic underplating or preexisting topography. Also required is a fault, with approximately 2 to 3 km [1.2 to 1.9 mi] of throw, beneath Crater Flat.

Summary

The boundary element model can successfully match the topography of the Yucca Mountain Region; however, the best match requires an inferred westward-dipping fault west of the Windy Wash fault that penetrates the brittle crust and has about 2 to 3 km [1.2 to 1.9 mi] of displacement. For a best fit, it was also necessary to assume either attenuation of the crust to the east and west of the Yucca Mountain Region, uplift of the whole Yucca Mountain Region, or a prefaulting topography.

3.2.2 Rift Model

Description

The Kawich-Greenwater rift (Carr, 1990) is a north-trending volcano-tectonic rift (Figure 3-2) that extends from the Greenwater Range in the south to the Kawich Range north of the Nevada Test Site. The rift is characterized by faulted margins, a trough of low gravity Figure 2-2), and the occurrence of several large volcanic centers along its axis. In the Yucca Mountain–Crater Flat area, Carr (1990) proposes that the rift-bounding faults are normal faults with the eastern fault coincident with the gravity fault of Winograd and Thordardson (1975) and the western margin marked by the Bare Mountain fault. Carr (1990) states that the presence of young basalts in the rift zone and of Quaternary faulting that rifting is continuing, albeit at a much slower rate than in the past. Brocher, et al. (1998), on the basis of interpretation of a seismic reflection profile across Crater Flat and Yucca Mountain, proposed a similar rift model. That model was composed of an array of east-dipping normal faults west of the Solitario Canyon fault and a west-dipping array east of and including the Solitario Canyon fault.

Basis

The Kawich-Greenwater rift model is based on the interpretation of geologic and geophysical data, generally at a regional scale. These data include

- An alignment of large volcanic centers including the Greenwater, Crater Flat–Prospector Pass (see Section 1), the Timber Mountain–Claim Canyon Oasis Valley, Silent Canyon (beneath Pahute Mesa), and Kawich volcanic centers
- A north-south trending zone of gravity lows
- A thick {>4 km [>2.5 mi]} fill of Miocene volcanic rocks within the proposed trough
- Low levels of natural seismicity within the rift
- Coincidence of the rift with part of the Death Valley–Pancake Range basalt belt of Crowe, et al. (1980)
- Mapped or inferred large offset rift-bounding normal faults

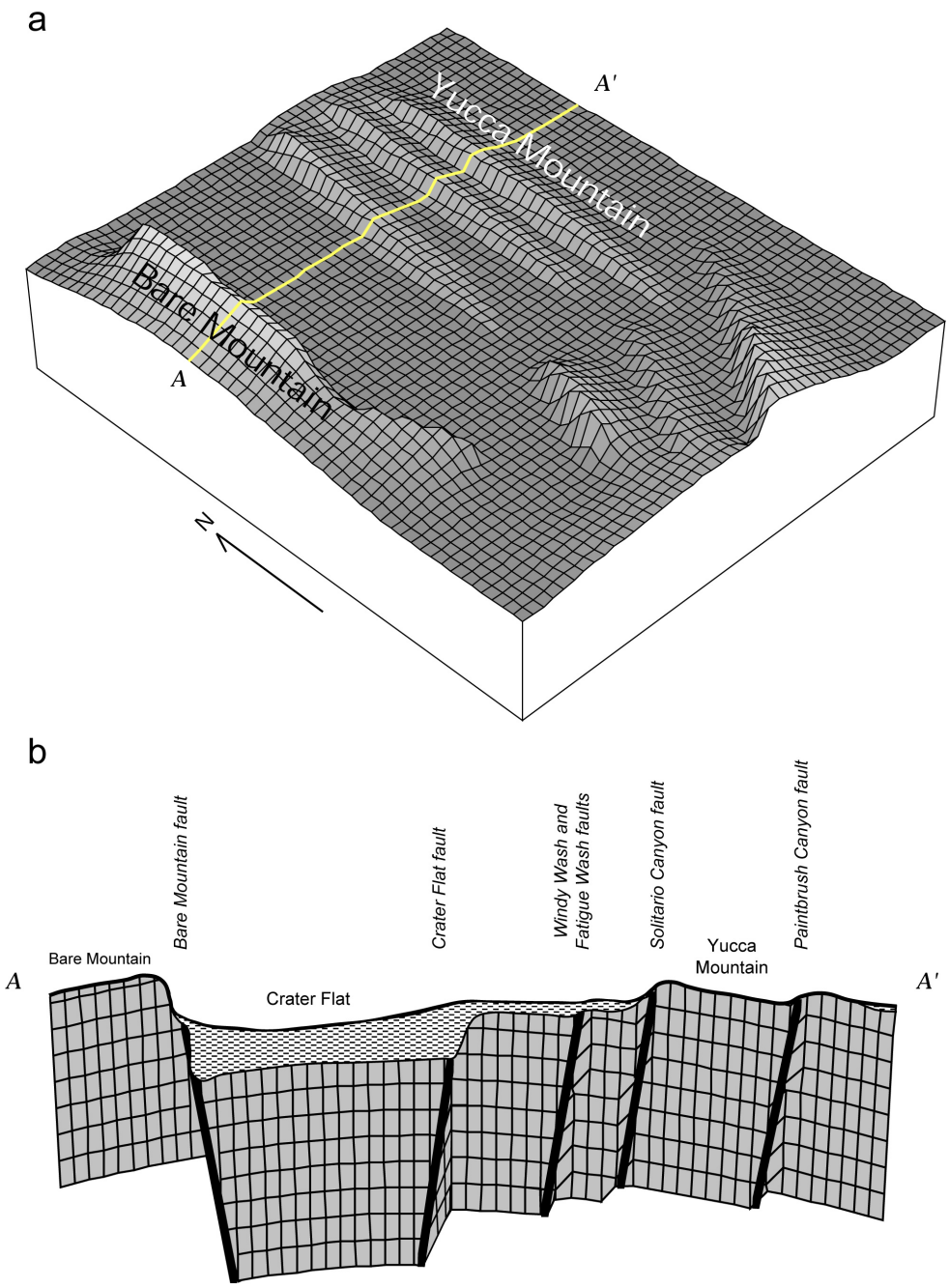

Figure 3-1. Results of Numerical Model of Yucca Mountain Area. (a) Three-Dimensional Interpretative Model of Results of Numerical Modeling Showing Surface Deformation. Ridges, East to West, Correspond to Displacement Along the Paintbrush Canyon, Solitario Canyon, Windy Wash/Fatigue Wash, and Bare Mountain Faults. (b) Interpretive Cross Section of Results Along A-A' Line of Section (After Janssen and King, 2000).

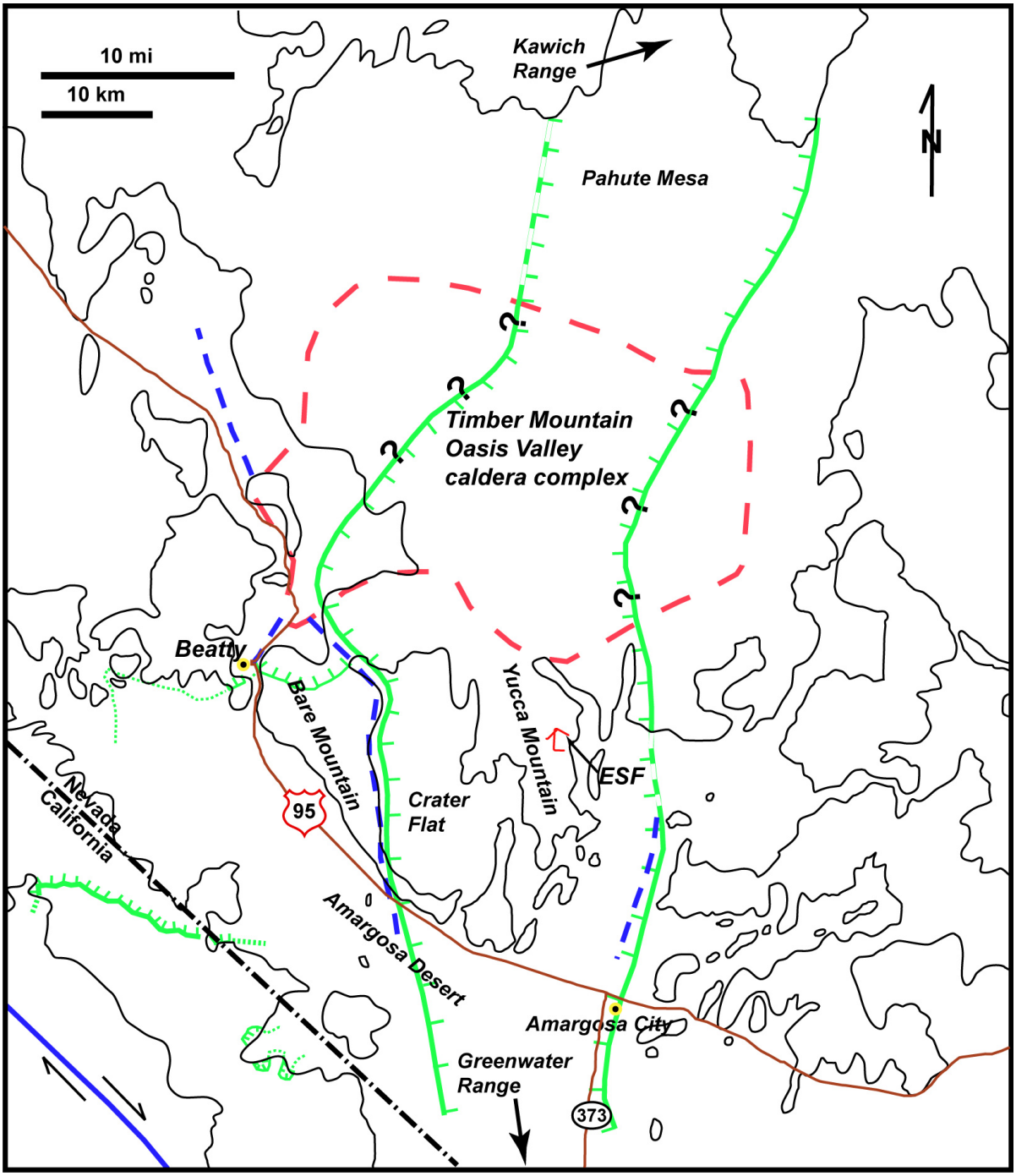

Figure 3-2. Kawich-Greenwater Rift After Carr (1990)

Summary

The Kawich-Greenwater rift model is viable, although one of its identifying characteristics is questionable (i.e., the Crater Flat–Prospector Pass volcanic center) (see Section 1). In this model, the interior faults as well as the bounding faults are considered to penetrate deeply into the crust and thus be capable of producing large earthquakes or serving as conduits for magma ascent.

3.2.3 Planar-Domino Model

Description

The planar-domino model, also called the tilted domino model (Fridrich, 1998), is based on nearly parallel fault strikes and similar westward fault dips in the Crater Flat basin (Figure 3-3).

Movement along these faults results in eastward-dipping strata. The faults are assumed to penetrate the full thickness of the crust. To generate planar-domino-like faults, several mechanisms have been proposed, including movement along a detachment fault and plastic flow of the asthenosphere. Fridrich (1999, 1998) proposes that within the Crater Flat basin a pure dip-slip planar-domino model was modified by northwest-directed dextral shear and oroflexural bending along a northwest-trending axis (see Section 3.2.1).

Brocher, et al. (1998) support a planar-domino-like model, based on their interpretation of seismic reflection, magnetic, and gravity data from Crater Flat and Yucca Mountain. They interpret the data to indicate a closely spaced series of nearly planar, moderately to steeply dipping faults across Crater Flat and Yucca Mountain. Their interpretation differs from Fridrich's model in that east of the Solitario Canyon Fault the faults dip east, while west of the Solitario Canyon fault they dip west, in an antithetic relationship with the Bare Mountain fault. The interpretation of the seismic data is also compatible with a deep detachment with a roll-over structure into the Bare Mountain Fault (Brocher, et al., 1998, Figure 6).

Basis

This model is based on geologic mapping within the Crater Flat basin that shows the near parallelism of the strikes of faults, the similarity of stratal dip in the blocks between the faults, oblique slickenlines on fault surfaces, and paleomagnetic measurements indicating southward-increasing clockwise rotation of interfault blocks.

Summary

The planar-domino model is an independent alternative model but could be considered a component of other tectonic models. The classic mechanism for generating planar-domino faults has been plastic movement in the asthenosphere at the base of the brittle crust; however, other processes such as movement along a horizontal detachment fault or rifting could also generate similar dipping parallel faults. The planar-domino model is also a component of the Crater Flat basin model (see Section 3.2.1). Planar-domino faults characteristic of this model are considered to penetrate the brittle crust and therefore are capable of generating large earthquakes or serving as conduits for magma ascent.

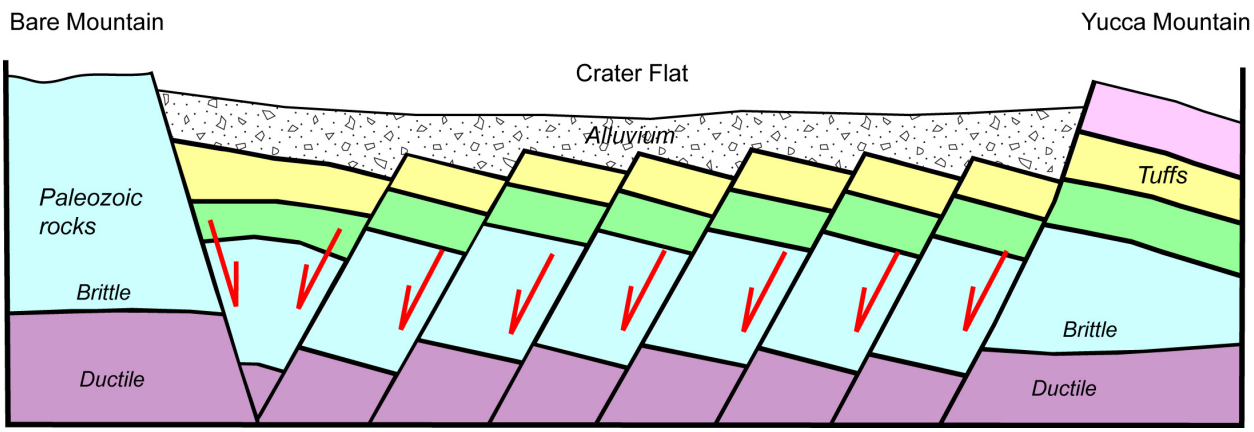

Figure 3-3. Crater Flat Planar-Domino Model

3.2.4 Detachment Models

Description

Detachment models are based on the common interpretation that overall extension of the crust is ultimately transferred to slip or flow along a nearly horizontal surface at depth (Figure 3-4).

A range of depths has been proposed for the location of the horizontal detachment surface from shallow to deep (Table 1-1) (Figure 3-5). At the Earth's surface, fault slip may be partitioned among many smaller faults that sole into the master detachment at depth. This arrangement of faults therefore suggests a strong kinematic relationship between the master fault and smaller faults—one in which slip on the master detachment would essentially control slip on the subordinate faults.

Basis

Hamilton (1988) and Scott (1990) (see Section 1-0) first proposed shallow {1 to 4 km [0.6 to 2.5 mi]} detachment faults at Yucca Mountain, stating these faults developed as part of a large west-dipping regional detachment system. Maldonado (1990) demonstrated extreme Miocene extension, detaching on at least two crustal levels, in the Bullfrog Hills north and west of Bare Mountain. These detachment fault models (Hamilton, 1988; Scott, 1990; Young, et al., 1992) were predicated upon a west-dipping extensional system detaching at various depths from 4 to 12 km [2.5 to 7.5 mi]. The current geologic setting, in which the Precambrian through lower Paleozoic block of Bare Mountain forms the western edge of Crater Flat, was interpreted as the result of the isostatic rise of Bare Mountain, effectively severing the highly extended western hanging wall of the detachment system from the much less extended eastern part represented by Crater Flat and Yucca Mountain. Although seismic data does not support shallow detachment models, tectonic models with deeper detachment faults are not ruled out (Brocher, et al., 1998).

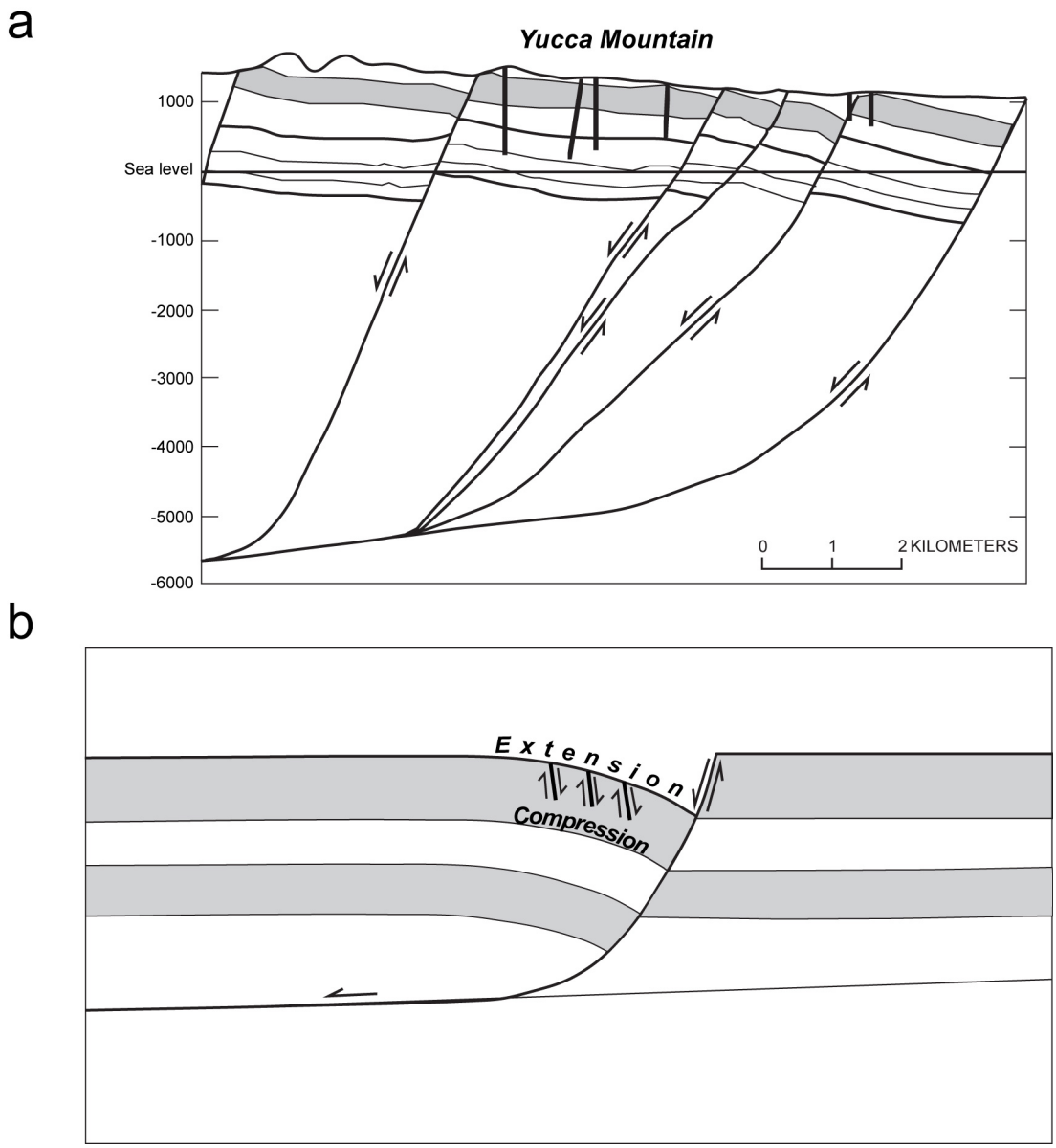

Figure 3-4. Detachment Fault Model. (a) Master and Secondary Faulting Merging With Near Horizontal Detachment Fault. (b) Roll-Over Structure in Hanging Wall of Detachment Fault.

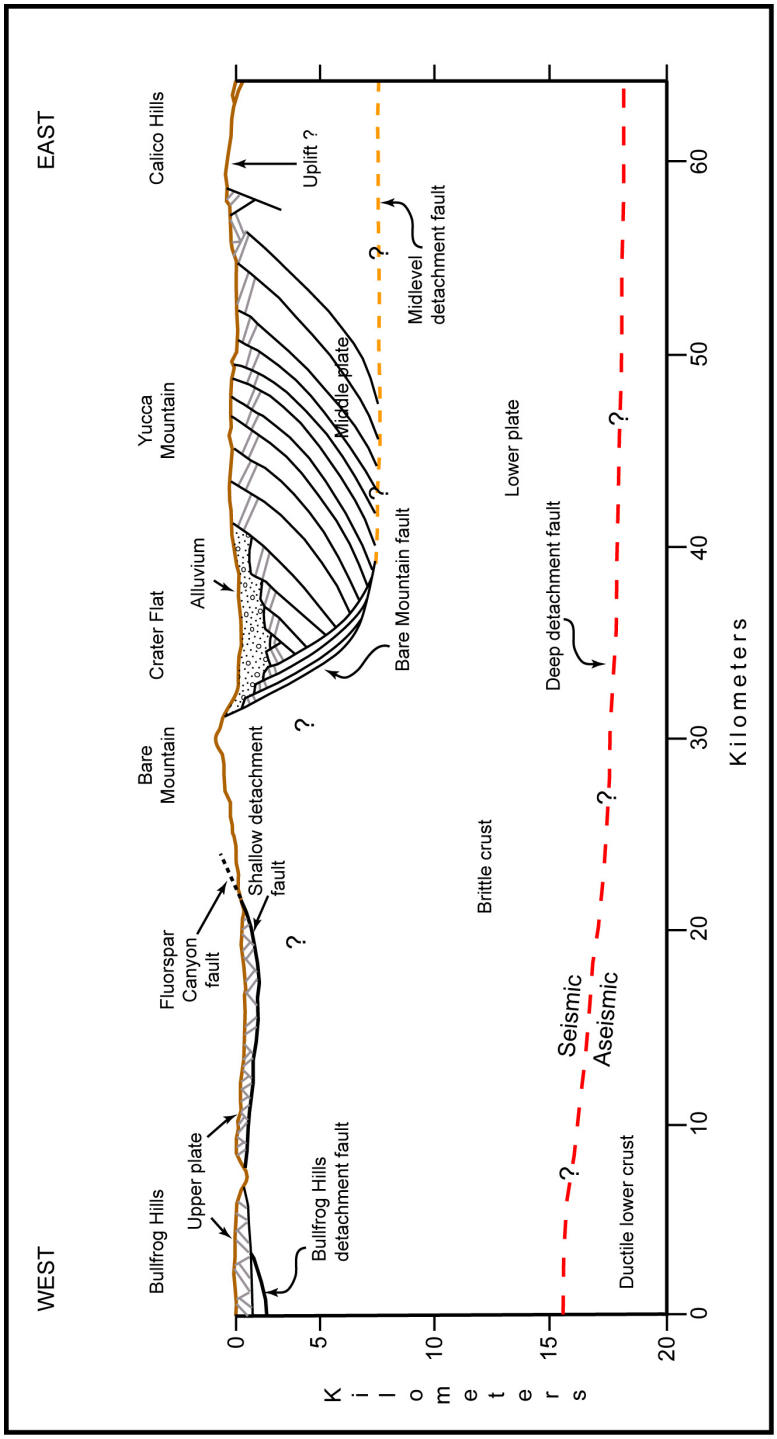

Figure 3-5. Schematic Illustration of Detachment Surfaces of Multiple Depths (Modified From Scott, 1990). A Midlevel Detachment Fault (Young, et al., 1992) Is Shown Extending East From the Bare Mountain Fault, and a Regional Deep Detachment (Ferrill, et al., 1996) Is Shown Between the Brittle and Ductile Crust. The Bare Mountain Fault Is Shown as Merging Into the Midlevel Detachment Fault, But Could Merge with a Deeper Detachment.

In contrast, Carr and Monsen (1988) and Gilmore (1992, Figure 2) proposed that Crater Flat and Yucca Mountain developed in response to displacement on the east-dipping listric Bare Mountain fault, which forms the eastern edge of Bare Mountain. This interpretation agrees with that of Faulds, et al. (1994), based on geologic mapping in Crater Flat and western Yucca Mountain. These listric (shallowing dip with depth) interpretations imply that Crater Flat basin is a half-graben controlled by displacement on the Bare Mountain fault resulting in a roll-over structure east of the fault (Ferrill, et al., 1996; Scott, 1990). The authors suggest the faulting at Yucca Mountain accommodates outer arc extension required by the bending (roll-over) of the fault's hanging wall (Figure 3-4b). Depending on the interpretations of fault dips at Yucca Mountain and the deformation mechanism of the hanging wall, depth to the listric Bare Mountain fault is estimated to be between 7 and 15 km [4.3 and 9.3 mi]. Details of half-graben models are described in Ferrill, et al. (1996).

Summary

None of the new geologic, geophysical, or geodetic information collected at Yucca Mountain or Crater Flat challenges the validity of the reviewed detachment models. Thus, these models remain viable conceptual models to explain the tectonic evolution of Yucca Mountain. Movement along the Bare Mountain fault may cause coseismic movement along the smaller secondary faults. The shallow penetrating secondary faults (Figure 3-4b) do offer potential pathways for magma ascent in the upper crust (see Section 4.2) (Parsons, et al., 2006).

3.3 Transtensional Models

Transtensional or strike-slip tectonic models are based on geologic and geodetic data that are interpreted as indicating large horizontal movement across a long vertical fault or fault system. In all models, the Pahrump-Stateline fault system is a major component. A notable difference between the models is the projection of the northwest extension of the fault system. It has been placed beneath Fortymile Wash (Wernicke, et al., 2004), Crater Flat (Schweickert and Lahren, 1997), and southwest of Bare Mountain (Guest, et al., 2007).

3.3.1 Amargosa Shear-Zone Model

Description

Schweickert and Lahren (1997) propose the presence of an Amargosa Desert fault system beneath Yucca Mountain and Crater Flat that connects with the Stewart Valley–Pahrump–Stateline fault system to form a >200-km [>124-mi]-long dextral strike-slip shear zone in southeastern California and southwestern Nevada (Figure 3-6). This Amargosa shear zone has an estimated total displacement of 30–40 km [19–25 mi] with as much as 24 km [15 mi] occurring since approximately 12.75 Ma. To explain the absence of surficial geologic features indicative of transtensional faulting, the authors propose a two-level detachment system where the primary dextral slip is localized in the pre-Cenozoic basement rocks. The overlying Cenozoic stratigraphy is decoupled from the underlying basement and undergoes distributed shear (rotation) and extensional normal faulting.

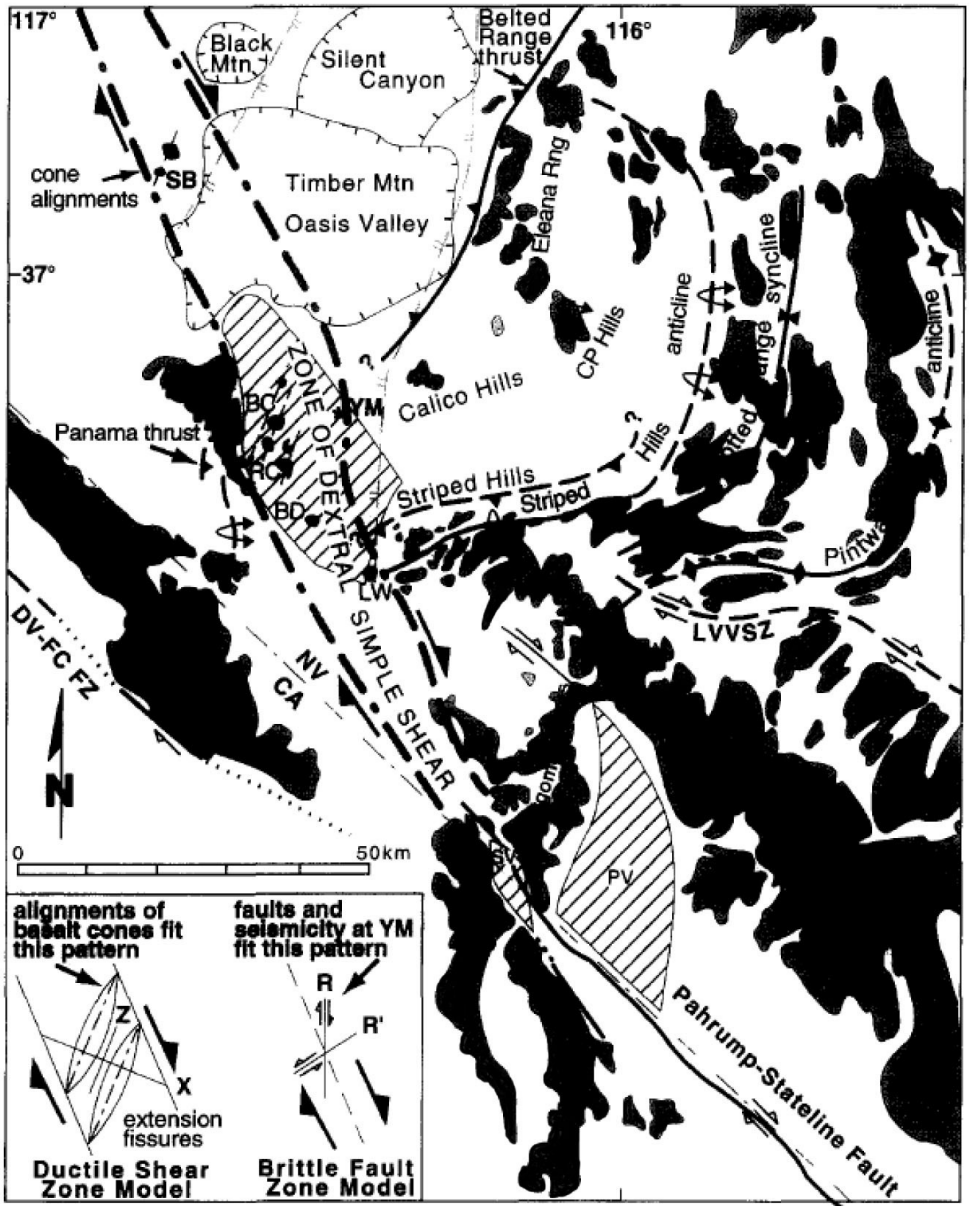

Figure 3-6. Amargosa Shear Model Modified From Schweickert and Lahren (1997)

Basis of Model

Schweickert and Lahren (1997) use several lines of geological and geophysical evidence to support their Amargosa shear-zone model:

- A series of elongated gravity lows connects the southern Amargosa valley region with the Yucca Mountain and Crater Flat areas.

- An east-west oriented seismic reflection line the U.S. Geological Survey collected showed evidence for two faults south of Yucca Mountain. While the U.S. Geological Survey (Brocher, et al., 1993) interprets these as normal faults, Schweickert and Lahren (1997) conclude that the westernmost fault is a subvertical strike-slip fault.

- Detailed mapping and structural analyses of Proterozoic and Paleozoic rocks at Bare Mountain record the presence of north-south dextral strike-slip faults.

- The alignment of more than 30 springs along the Ash Meadows–Pahrump–Stateline fault system, together with seven Quaternary and Pliocene volcanic cones, supports the occurrence of the fault zone.

- Paleomagnetic data at Yucca Mountain and Sleeping Butte record clockwise vertical-axis rotations.

- Late Quaternary to Holocene activity on faults between Pahrump Valley and Crater Flat is supported by small scarps south of Ash Meadows.

Summary

The data used to develop the models are generally applicable to the other proposed models. However, the assumption that the faults underlying Crater Flat connect with the Pahrump–Stateline fault system and the necessity of a two-level detachment fault make this a more complex model. Detailed analysis of paleomagnetic data and fault data by Stamatakos and Ferrill (1998) challenges some of the supporting data for this model. After reviewing the evidence Schweickert and Lahren (1997) presented, Stamatakos and Ferrill (1998) argued that the bulk of Schweickert and Lahren's geological and geophysical evidence data could be most readily explained by extension or oblique extension rather than strike-slip deformation.

3.3.2 Regional Right-Lateral Crustal Bending Model

Description

Wernicke, et al. (2004) conclude from analysis of the dense continuous Yucca Mountain area global positioning satellite network data that north-northwest (N 20° W)-oriented dextral shear is accumulating at a rate of 20 ± 2 nstrain/yr, which is equivalent to approximately 1.2 mm/yr [0.05 in/yr] across a 60-km [37-mi]-wide region (Figure 3-7). Based on the global positioning systems data and its interpretation, Wernicke, et al. (2004) propose that right-lateral shear is required for the western Great Basin with respect to the central Great Basin, with the boundary located east of Yucca Mountain and west of the Striped Hills and Little Skull Mountain (i.e., Fortymile Wash). Using a simple elastic half-space model of strain accumulation, Wernicke, et al. (2004) tested two strain models: (i) a single-fault model representative of the Death Valley–Furnace Creek fault zone and (ii) a two-fault model that contained the Death Valley–Furnace Creek Fault Zone and an unidentified fault with a right-lateral strike-slip

component east of Yucca Mountain (Figure 3-7). The authors concluded that the two-fault model fit their data better than the single-fault model. An example of the two-fault model Wernicke, et al. (2004) proposed, for which the global positioning satellite data provide a reasonable fit, is a two-fault strike-slip model with approximately 2.8 mm/yr [0.11 in/yr] of slip in the Death Valley–Furnace Creek fault system and 0.9 mm/yr [0.035 in/yr] slip on an unmapped northward extension of the Stateline–Pahrump–Amargosa Desert fault systems. This is similar to that proposed by Schweickert and Lahren (1997), but east rather than west of Yucca Mountain. Another aspect of the model, as suggested earlier (Wernicke, et al., 1998), is the periodic migration of strain in the Yucca Mountain area, with a change in the strain rate occurring about 1997.

Basis of Model

The regional right-lateral crustal bending model is based on geodetic velocities calculated from position estimates derived from a global positioning satellite network with 16 sites densely clustered near Yucca Mountain and an additional 16 sites sparsely distributed in the surrounding area. The network was monitored daily from mid-1999 to early 2003 (approximately 3.75 years), and positional data were collected every 30 seconds. These data are then fitted against several numerical models, and Wernicke, et al. (2004) concluded that the data best fit a two-fault model.

Summary

This model is based on recent geodetic data, which are of very high quality.[1] Along with other models, this model must be evaluated based on these data and future global positioning satellite data.

At the request of Center for Nuclear Waste Regulatory Analyses (CNWRA), Drs. T.H. Dixon and P. LaFemina[2] reviewed Wernicke, et al. (2004). Their review concluded that

- the numerical analysis of the single-fault model was too simple, and a more thorough numerical model should include more realistic representation of faults, earthquake cycle effects, and vertical and lateral changes in the rheological structure of the Earth;

- alternate sites for their reference frame should be evaluated, as demonstrated by LaFemina, et al. (2005), who showed that alternate reference locations resulted in velocity vectors of different magnitudes and directions; and

- based on a statistical F-test, the two-fault model was not warranted at the 95 percent confidence interval, and statistically there is no difference between the one- and two-fault models. In addition, Dixon and LaFemina[3] believe the proposed regional strain migration is not warranted by the global positioning satellite data at this time.

Wernicke, et al. (2004) recognized that east of Yucca Mountain there is no obvious northwest extension of the last mapped trace of the Pahrump–Stateline fault. In addition, the northward extension of the Amargosa Desert fault system Schweickert and Lahren (1997) proposed is west of Yucca Mountain and thus cannot serve as the second fault as Wernicke, et al. (2004) proposed.

[1] Personal communication (January 14) with P.C. LaFemina and T.H. Dixon. Review of Wernicke, et al. (2004). University of Miami, Florida—Rosentiel School of Marine and Atmospheric Sciences. 2006.
[2] Ibid.
[3] Ibid.

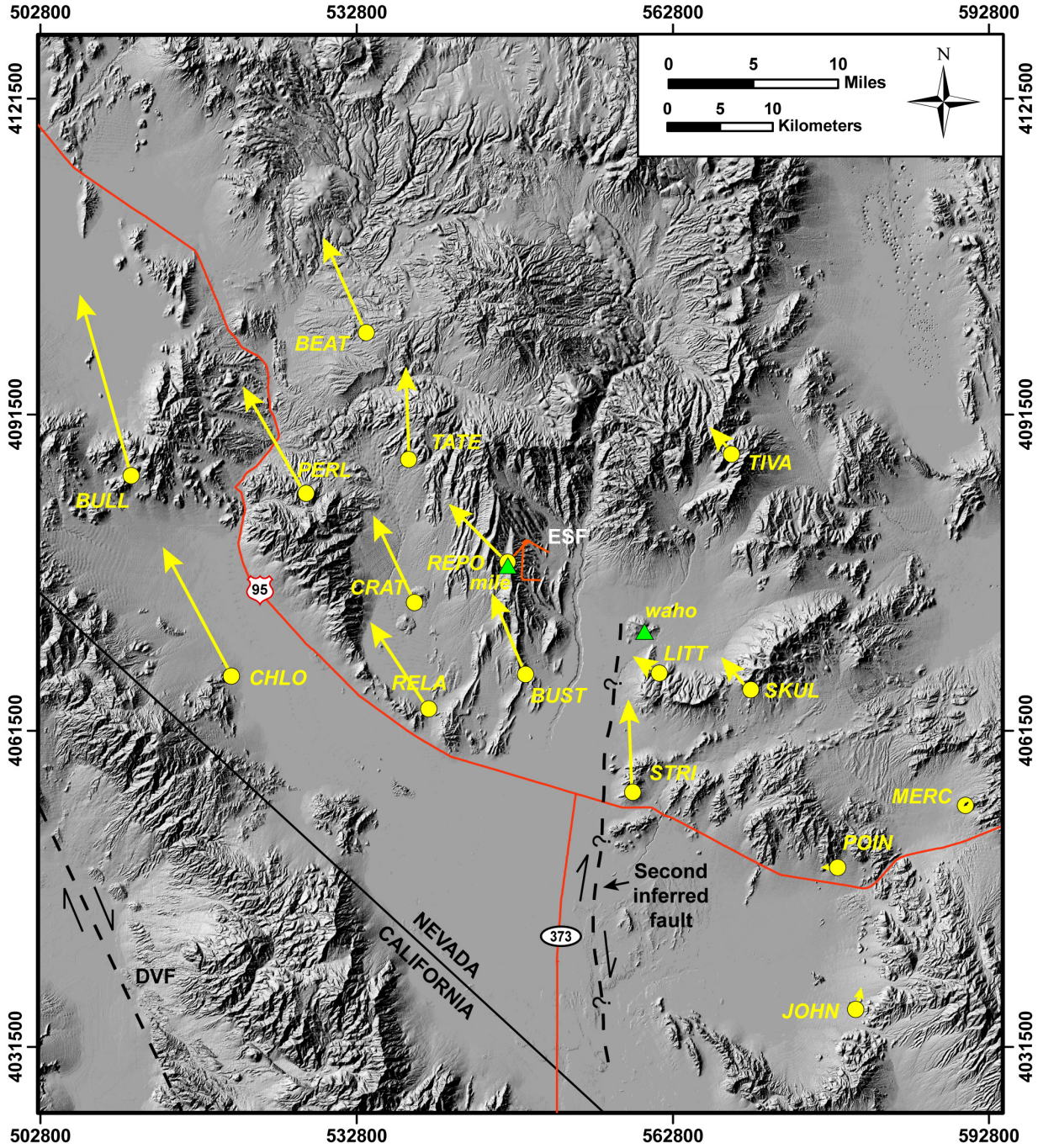

Figure 3-7. Right-Lateral Crustal Bending Model, After Wernicke, et al. (2004), With Location and Direction of Movement of Global Positioning Systems Stations Shown by the Arrows. Wernicke's Best Interpretation of the GPS Data Requires the Death Valley Fault (DVF) and a Second Inferred Strike-Slip Fault, Whose Location May Be Coincident With the Location of the Gravity-Inferred Normal Fault of Winograd and Thordardson (1975).

3.3.3 Stateline Fault System Model

Description

The stateline fault system model of Guest, et al. (2007) is similar to both of the preceding transtensional models, but focuses exclusively on the Stateline Fault System east of Death Valley. The Stateline Fault System is defined as a 200-km [124-mi] active dextral shear zone that is the easternmost fault in the Eastern California Shear Zone.

Basis

The stateline fault system tectonic model is based on connecting together, in a continuous zone, a number of previously described faults, including the Pahrump fault (Louie, et al., 1998; Piety, 1996), Pahrump fault zone (Liggett and Childs, 1973; Stewart, 1988; Wright, 1989), Pahrump Valley fault zone (de Polo, 1998; Hoffard, 1991), Stewart Valley fault, (Burchfiel, et al., 1983; Carr, 1984; Stewart, et al., 1968), Amargosa River fault zone (Anderson, et al., 1995; de Polo, 1998; Donovan, 1991; Piety, 1996), Stateline fault (Hewett, 1956), the Mesquite fault segment of the Stateline Fault System (Guest, et al., 2007), and the Carrara (Highway 95) fault (Stamatakos, et al., 1997). In addition, Guest, et al. (2007) utilize geological, geochemical, and geologic data to characterize the Stateline Fault system. Near the southern end of the fault system, the authors recognize Black Butte and Devils Peak have similar ages (13 mya) and trace elements signatures, but are displaced by the fault 30 to 40 km [18.6 to 24.9 mi]. The authors use these data to estimate the rate of displacement {2.3 ± 0.35 mm/yr [0.09 ± 0.01 in/yr]} along the fault. However, if this displacement occurred since the initiation of the Eastern California Shear Zone (10–6 million years ago), the estimated slip rate increases to 3–5 mm/yr [0.12–0.2 in/yr], respectively. Guest, et al. (2007) recognize these slip rates are not consistent with (i) current global positioning systems data on the northern segment of the fault system and (ii) the absence of geologic features indicative of active faulting along much of the proposed trace of the Stateline Fault System. Guest, et al. (2007) explain the discrepancy in slip rate as due either to (i) temporal variation of strain along the Stateline Fault System or (ii) underestimation of the geologic slip rate. They attribute the absence of surface features indicative of active faulting to the projection of the Stateline Fault System through many basins with soft, easily erodeable valley fill.

Summary

The stateline fault system model differs from the Amargosa shear zone model (Schweickert and Lahren, 1997) and the crustal bending model (Wernicke, et al., 2004) in that the northwestward extension of the fault is projected to be southwest of Bare Mountain, along the Carrara Highway 95 Fault (Stamatakos, et al., 1997) rather than beneath Crater Flat or Fortymile Wash. The fault is about 21 km [13 mi] southwest of Yucca Mountain, and should be considered in seismic analysis, but because of the separation {21 km [13 mi]}, it is not a concern for volcanic hazard analysis.

3.4 Extensional/Transtensional Model

The Crater Flat pull-apart model is a hybrid model that has elements of both extensional and transtensional deformation (Fridrich, 1999).

3.4.1 Crater Flat Pull-Apart Model

Description

Fridrich (1999) proposed that Yucca Mountain and Crater Flat are part of the late Cenozoic Crater Flat structural basin that formed as a result of a combination of east-west to southeast-northwest extension accompanied by northwest dextral shear resulting in oroflexural bending along a northwest axis or hingle line across the basin (Figure 3-8). In this model, the basin extends eastward from the Bare Mountain fault to the northward extension of the gravity fault of Winograd and Thordardson (1975) east of Fortymile Wash (Figure 2-2b). The basin is dominated by Quaternary and younger alluvium and Miocene tuffs from calderas located north of the basin. The tuffs have been tilted to the east and southeast by westward- to northwestward-dipping normal faults (Figure 3-8). Fridrich (1999) proposed that the variations in the amount of extension and the degree of vertical axis rotation within the basin cause it to resemble a triangular pull-apart basin. This is the result of its location on the flank of the Timber Mountain–Claim Canyon caldera complex at the boundary of the Walker Lane Belt (Eastern California Shear Zone) and the northern Basin and Range province and just east of a major region of extreme extension (the Bullfrog Hills). Fridrich interprets the geologic data as indicating a progressive decline in tectonism over the last 10 million years.

Basis of Model

The Crater Flat pull-apart model is based on interpretation of detailed geologic mapping (Fridrich, 1999) west of Yucca Mountain and preexisting geologic and geophysical data at Yucca Mountain. Paleomagnetic data provide information on vertical axis rotation of intrafault blocks across the proposed hinge line (Fridrich, 1999).

Summary

This model is based on mapped structural data collected in areas of exposed Miocene tuffs west of Yucca Mountain. The tectonic model the author presented for the period from 13 to 10 Ma is well defined. The author admits the subsequent and current tectonic environment is not well defined, except for the evidence of significantly reduced deformation since 10 Ma.

3.5 Volcanic Models

3.5.1 Mega-Rings Model

Description

The mega-rings model consists of a large {approximately 80–100 km [50–62 mi] in diameter}, roughly circular area of structural transition surrounding the Timber Mountain caldera complex (Tynan, et al., 2004) (Figure 3-9). The area of structural transition is bounded by the Las Vegas shear zone to the southeast, the Mojave block to the south, the Walker Lane to the northwest, and the north-south features of the Basin and Range to the north. Tynan, et al. (2004) based the mega-rings model on observed regional physiography, tomographic images, seismic

patterns, and structural relationships that define a series of concentric circular or semicircular structures centered on the Timber Mountain caldera.

Basis for Model

The system of mega-rings covers an area approximately the size of the Yellowstone and Toba, Indonesia, calderas and may have additional volcanic eruptions and structural features similar to Valles Caldera, New Mexico, and large volcanoes on Venus. Tynan, et al. (2004) believe that mega-rings are substantiated by (i) arcuate structural features based on Landsat images and seismic tomographic data; (ii) rift-bounding fault systems indicated by north/south linear trends of microseismicity; (iii) age, distribution, and type of volcanic eruption; (iv) hydrologic basins mimicking the ring system; (v) interpretation of mantle and crustal velocity, isostatic gravity, and tomography; (vi) area thermal regime; and (vii) stress and strain data. The seismic tomographic data is interpreted to indicate a mantle velocity anomaly located beneath Timber Mountain and extending to the upper mantle. Tynan, et al. (2004) interpret the data to indicate that the overall structure is a deep-seated fundamental feature of the area.

Summary

The mega-rings model was proposed in 2004, and because it assimilates a large number of geological and geophysical features, it needs to be carefully assessed. Many features on which this model is based are also explained by other tectonic models, and because of this commonality, this model will have little effect on probabilistic seismic hazard analysis.

Tynan, et al. (2004) conclude that post-mid-Miocene basalts commonly occur either within and adjacent to the older rhyolitic caldera moats or marginal to the outer rings of the mega-rings system, leaving an intervening zone that is devoid of basaltic material. Yucca Mountain is within this zone. However, the Solitario and nearby basaltic dikes seem to refute this hypothesis.

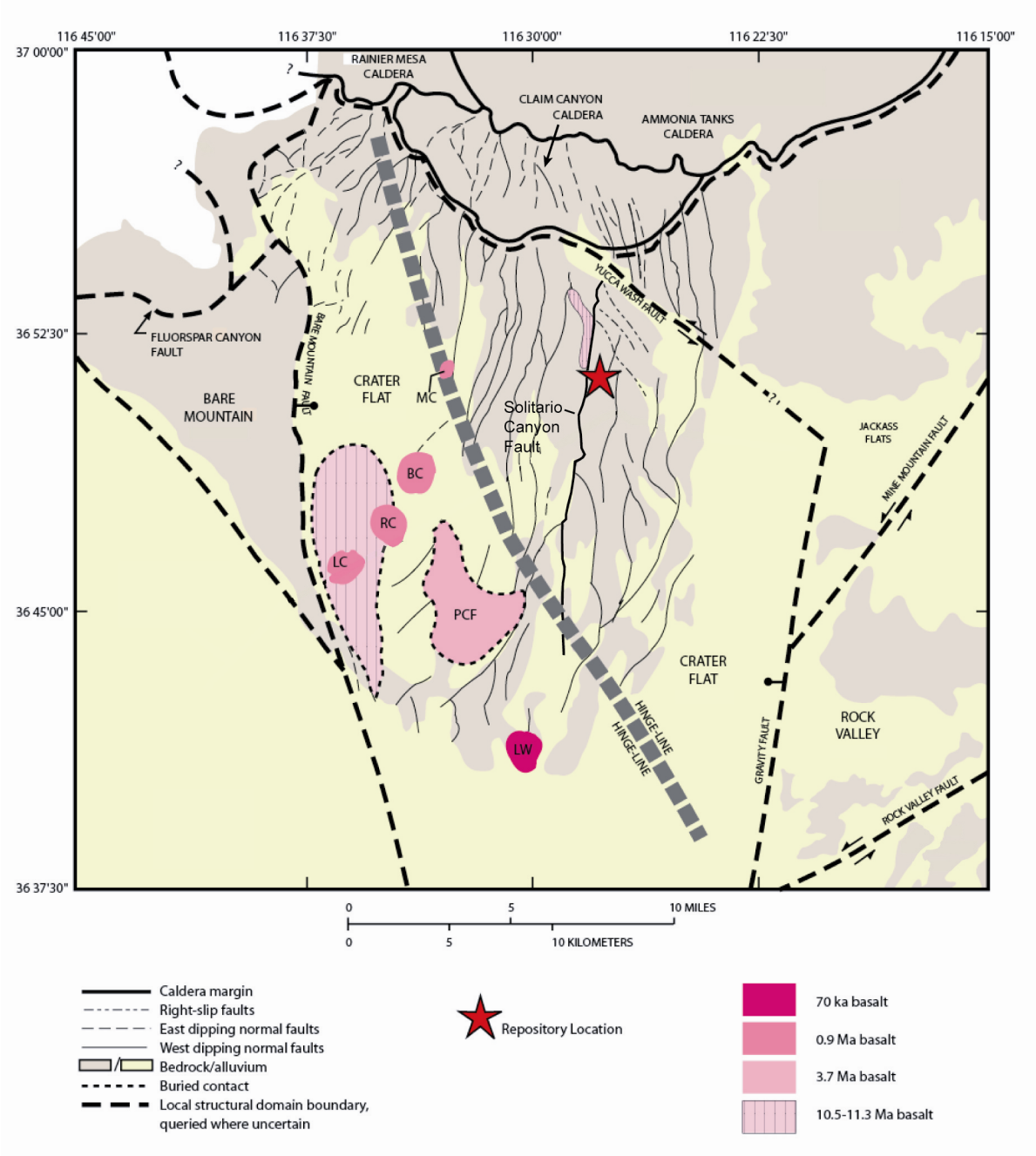

Figure 3-8. Crater Flat Pull-Apart Model Modified From Fridrich (1999). (MC–Makani (Northern) Cone; BC–Black Cone; RC–Red Cone; LC–Little Cone; PCF–Pliocene Crater Flat Volcanics; and LW–Lathrop Wells Cone)

Figure 3-9. Mega-Rings Model After Tynan, et al. (2004)

4 APPLICABILITY OF MODELS TO NATURAL HAZARD ANALYSIS

4.1 Probabilistic Seismic Hazard Analysis

Probabilistic seismic hazard analysis is used to determine the probability of exceeding a predetermined ground motion at a site in a given future time period (Cornell, 1968; Sevy, et al., 2002). Probabilistic seismic hazard analysis involves three steps: (i) designation of appropriate seismic source models, (ii) determination of appropriate ground motion models, and (iii) probabilistic calculations. Tectonic models influence the identification and selection of appropriate source models. A seismic source model includes a description or estimation of potential earthquake magnitude, its range of potential locations, and an inferred seismic recurrence rate. These parameters are determined by the tectonics of the region. In some regions, the applicable tectonic model is clearly defined; however, as discussed in Section 1, in the Yucca Mountain Region, where the tectonic environment is not clearly defined, a number of tectonic models have been proposed.

The significance of the magnitude, location, and rate of seismic activity will vary depending upon proposed source models. Source models or tectonic models, which are of most concern at Yucca Mountain, are those with faults capable of initiating large magnitude events, are near Yucca Mountain, and are the source region of earthquakes with a relatively high recurrence rate.

Each of these input parameters (i.e., earthquake magnitude, closeness, and seismic rates) can vary depending upon the assumed tectonic model. Large magnitude earthquake events are characterized by large rupture areas along the faults and thus include faults that are long and/or penetrate through the brittle crust, which is approximately 15 km [9.3 mi] thick in the Yucca Mountain area. The closest approach of a potential earthquake is a function of a fault's location relative to Yucca Mountain and the fault's orientation relative to the local *in-situ* stress field (Ferrill, et al., 1999; Morris, et al., 1996). The location and strike of major faults in southern Nevada are well known (Piety, 1996). Most of these faults are oriented such that their slip tendencies are high (McKague, et al., 1996) and thus have a higher potential to be sites for earthquakes. The seismic rate is a function of the regional strain rate and is actively being quantified by global positioning satellite studies (Savage, et al., 1999; Wernicke, et al., 2004). However, seismic rate is not inherently a function of regional strain rate measured by global positioning systems. As discussed in Connor, et al. (1998), aseismic strain can account for deformation, and long-term fault displacements that are inconsistent with extrapolation of short-term global positioning systems strain rates to geologically significant times.

Most of the proposed tectonic models (Table 1-1) are based on the interpretations or inferences that require one or more long deeply penetrating fault with the potential for large earthquakes. They are also characterized by numerous additional faults that are shorter, less penetrating, and have smaller displacements. These faults are commonly closer to the proposed surface facilities. However, future movement along them would probably be the result of coseismic motion in response to movement along major faults such as Bare Mountain or Pahrump–Stateline faults.

The current seismic hazard assessment for Yucca Mountain (e.g., CRWMS M&O, 1998b) assumes traditional planar-shaped, domino-style faults. Estimates of the maximum magnitude earthquake derived from empirical fault-scaling relationships (e.g., Wells and Coppersmith, 1994) thus consider fault planes that cut the entire thickness of the brittle crust {about 15 km [9.3 mi] in southwestern Nevada}. In contrast, because the outer arc bending structural models incorporate outer arc extension of the hanging wall, normal faults observed at the surface do not

necessarily cut through the entire seismogenic crust and many lose displacement (tip) downward. Hence, the effective area for fault rupture on faults that do not reach the base of the seismogenic crust is reduced over those that penetrate the crust.

When detachment models, such as those defined by Young, et al. (1992) and Ferrill, et al. (1996), are applied to the Crater Flat basin, there is a structural link between the faults at Yucca Mountain and slip on the Bare Mountain fault. This is because the Bare Mountain fault is the master normal fault of the Crater Flat basin, and Crater Flat and Yucca Mountain compose the hanging wall above the Bare Mountain fault (see Figure 3-5). By inference, a large earthquake on the Bare Mountain fault could lead to coseismic or postseismic deformation at Yucca Mountain.

The majority of displacement (strain) presently observed across the Bare Mountain fault occurred in the Middle to Late Miocene, from 12 to 11 mya (Fridrich, 1999). Since 11 mya, the average slip rate on the fault has remained low, probably near the 0.06-mm/yr [0.002-in/yr] average rate previously derived for the past 1 mya, based on progressive burial of the Little Cones (Stamatakos, et al., 1997). Thus, the recently proposed slip rates of 1–2 mm/yr [0.04–0.08 in/yr] for the fault based on global positioning satellite results (Wernicke, et al., 2004, 1998) are either the result of monument movement error (e.g., Savage, et al., 1999), represent a geologically recent spike of increased crustal strain (e.g., Connor, et al., 1998; Wernicke, et al., 2004), or slow migration of strain through the region (Wernicke, et al., 2004). There is not enough cumulative displacement across the fault remaining after the 12–11 mya pulse to allow for a 1 to 2-mm/yr [0.04 to 0.08-in/yr] rate to be long lived {i.e., 1 mm/yr [0.04 in] would result in 11 km [6.8 mi] of displacement over an 11 million year period.}

The mega-rings model (Tynan, et al., 2004) is based on interpretations of a number of local and regional geologic and geophysical features. It does not speak to strain changes that might alter earthquake recurrence rates. Thus, this model introduces no new feature that would change the existing probabilistic seismic hazard analysis.

The right-lateral crustal bending model (Wernicke, et al., 2004) suggests active slip or creep on one (Pahrump–Stateline fault) or more faults between the Death Valley–Furnace Creek fault zone and the striated hills. In addition, this interpretation of the dense continuous global positioning satellite network data suggests that the Pahrump–Stateline fault extends into Jackass Flat, which, although other authors have inferred faulting in the area to support their models (Carr, 1990; Fridrich, 1999; Guest, et al., 2007), is not supported by surface evidence of active faulting. Geophysical data do not support significant vertical or horizontal offset beneath Fortymile Wash, although electrical (Ponce, et al., 1992) and seismic (Brocher, et al., 1998) data may indicate small faults on either side of the wash near Fran Ridge and Busted Butte.

The new geodetic data constrains crustal strain rates and direction of movement. However, these data are subject to alternate interpretations of extension direction, from N 60° W (LaFemina, et al., 2005; Savage, et al., 1999) to N 20° W (Wernicke, et al., 2004). Such data must be considered in future assessments of models. The same recommendation is applicable to new and relocated seismic data. Because both geodetic and seismic data relate to the current neotectonic setting at Yucca Mountain, continued accumulation and analysis of both data sets will constrain proposed models and perhaps lead to new models.

4.2 Implications for Probabilistic Volcanic Hazard Analysis

A probabilistic approach has been used to estimate the occurrence of a volcanic eruption or igneous intrusion at Yucca Mountain (Connor and Hill, 1995; CRWMS M&O, 1996;

Ziegler, 2005). Yucca Mountain represents the first site where long-term probabilistic volcanic hazard analysis has been performed. Although elements of the Yucca Mountain geology and geophysics were used, explicit tectonic models were not considered in the probabilistic volcanic hazard analysis by NRC (Connor and Hill, 1995) or by the experts for the first probabilistic volcanic hazard analysis by DOE (CRWMS M&O, 1998a). For volcanism to occur, the necessary physical and chemical conditions needed for magma generation must exist in the mantle, and a path must be established between this magma source and the Earth's surface. Both these sets of conditions together with the style and frequency of igneous activity are determined by the tectonic setting.

The occurrence of the basaltic cinder cones establishes that the generation of basaltic magma has occurred sporadically over the last 12 million years in the Yucca Mountain Region and as recently as 76,000 years ago (Heizler, et al., 1999). Although not required for the development of volcanic conduits, preexisting zones of weakness may provide pathways to the surface that can control the ascent of basaltic magma. The large number of faults (Figure 4-1) with strikes and dips (Figure 4-2b) favorable for dilation, and hence intrusion, in the Yucca Mountain area, especially between Bare Mountain and Fortymile Wash, offer potential pathways for magma ascent to the surface. However, not all preexisting faults provide optimal pathways. Using dilation analysis and the current orientation of the regional *in-situ* stress field, Ferrill, et al., (1997) conclude that faults oriented north to northeast striking (approximately 355–065°) (Figure 4-1) and with steep (60–90°) dips (Figure 4-2b) have a high dilation tendency and are optimally oriented for intrusion by magma. The magma pathway does not need to be a major block-bounding fault. Steeply dipping antithetic and synthetic faults in the hanging walls of major normal faults offer more favorable paths because they have steeper dips (Figure 4-2c). In the Yucca Mountain Region evidence suggests that faults have influenced surface and near-surface igneous activity. A basaltic dike intrudes along the Solitario Canyon fault, and cinder cones (and their remnants) strongly inferred to occur in association with faults include Northern (Makani) Cone (Magsino, et al., 1998); Black, Red, and Little Cones (Perry, et al., 2006b); Paiute Ridge volcanic center (Valentine and Krogh, 2006); and Lathrop Wells (Perry, et al., 2005a). Perry, et al. (2006a) show (Figure 4-3) a magnetically inferred, north-south-striking, west-dipping fault in close association with Black Cone. Although no faults are shown in close association with either Red or Little Cones, they may have originated along north-striking faults that are unresolved by the magnetic survey. Perry, et al. (2005a) interpret the Lathrop Wells Cone as being intruded along a northwest-striking fault at or near the intersection with a northeast-trending fault; however, because of its recent age (76 ka), the orientation of the preferred magma ascent pathway would most likely reflect the current state of *in-situ* stress and intrusion along the northeast-trending Raven Canyon fault (Nye County Nuclear Waste Regulatory Project Office, 2005, Figure 6.3-1; Potter, et al., 2002).

Local perturbations in the regional stress field at the time of emplacement can result in unexpected dike orientations. For example, those with northwest strikes that are at a high angle to the maximum horizontal regional stress seem to have unfavorable indications for intrusion. In Figure 4-4, dikes mapped by Day, et al. (1998a,b) in the Little Prow area at the north end of Solitario Canyon are shown. In the upper left quadrant of the figure, dikes are shown intruded along a northwest-trending, southwest-dipping fault system. At the time (11 mya) of the Solitario Canyon dike intrusion and, presumably, the northwest trending dikes, the direction of the least principal horizontal stress would have been oriented approximately east-west and a northwest oriented fault system would have provided a less likely pathway for magma intrusion than a north-south orient fault. However, this northwest-striking fault system is the result of extension across a ramp structure across Jet Ridge between the Solitario Canyon fault and the Fatigue Wash fault (Ferrill and Morris, 2001; Ferrill, et al., 1996). This ramp structure resulted in a local disturbance within the regional stress field at the time of its formation and provided a

northwest-striking pathway for magma. Note that the smaller northwest-trending dikes occur in the hanging wall of the cross ramp fault, probably along small more steeply dipping antithetic faults or fractures.

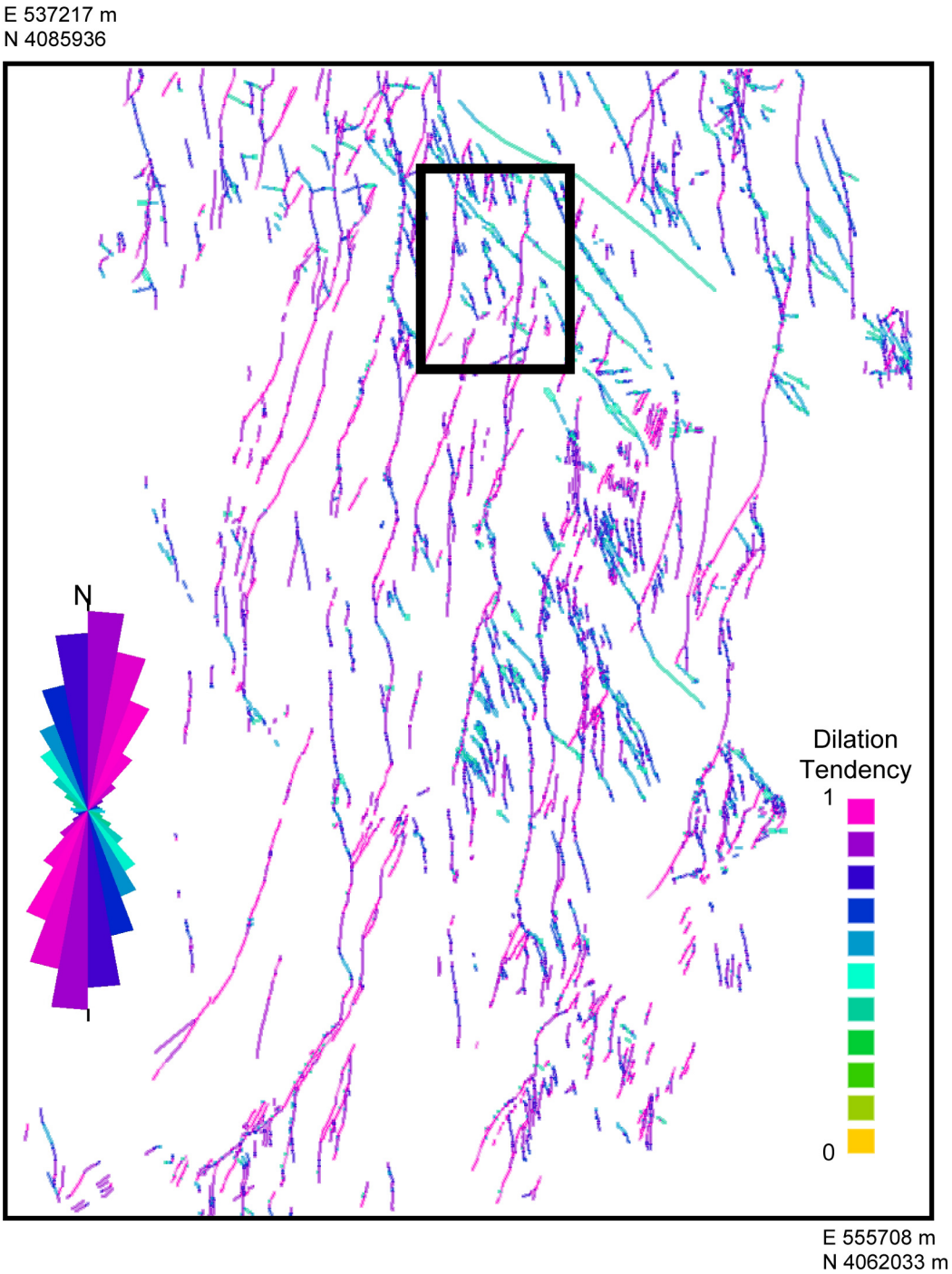

Figure 4-1. Dilation Tendency of Faults in Yucca Mountain Region With a Stress State Where δ_1 Is Vertical, 85 Megapascal (MPa); δ_2 Is Horizontal With Azimuth 025°, 55 MPa, and δ_3 Is Horizontal With Azimuth 115°, 18 MPa (Stock, et al, 1985). Those With Purple and Blue Colors Have High Dilation Tendency and Would Offer Low Energy Paths for Magma. Box Outlines Map Area Shown in Figure 4-4.

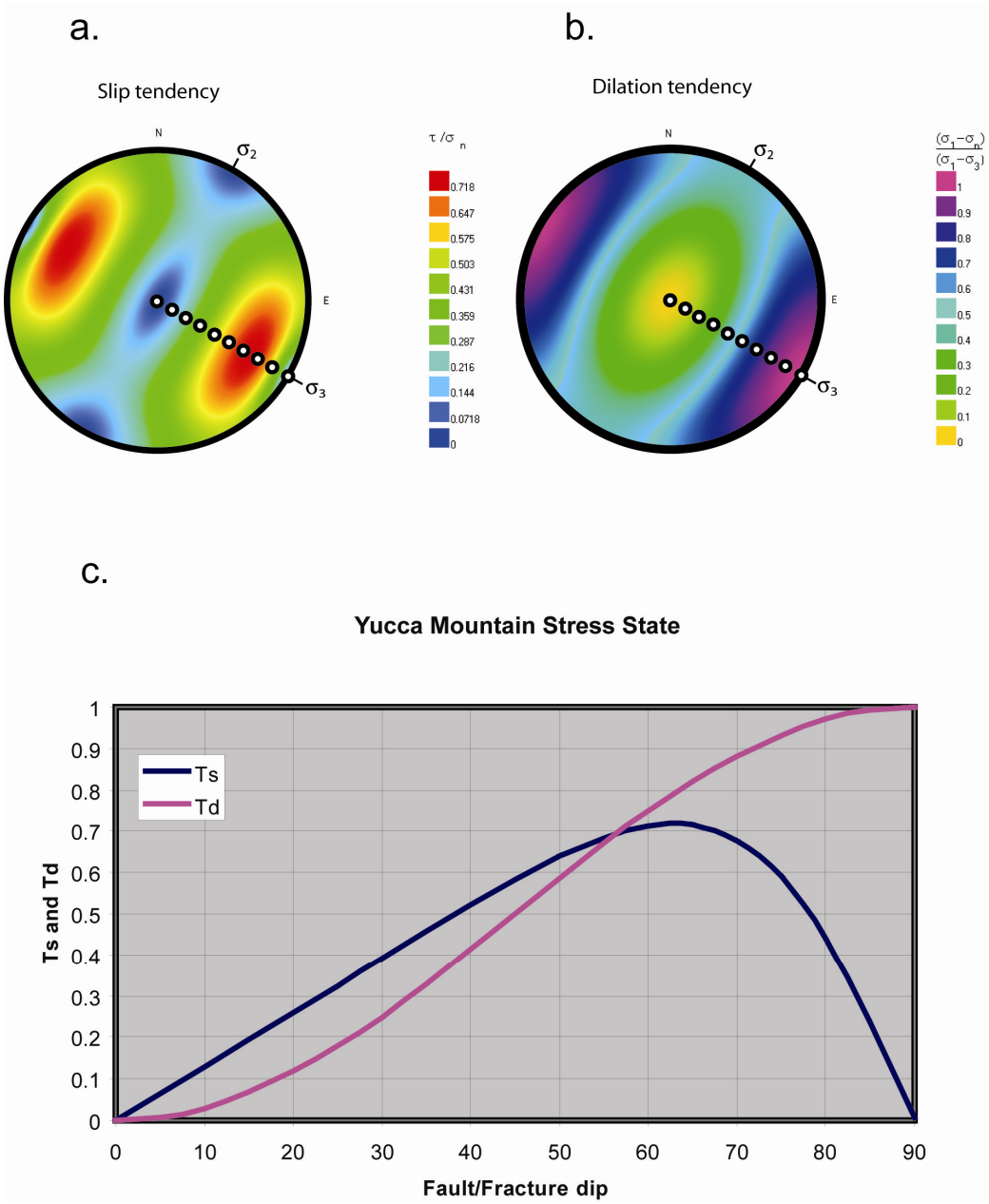

Figure 4-2. Slip (T_s) and Dilation (T_d) Tendencies for Stress Field in Yucca Mountain Area. (a) Slip Tendency Plot for Stress Conditions in Yucca Mountain Area. Hot Colors Indicate Orientations With a High Slip Tendency and (b) Dilation Tendency Plot for Stress Conditions in Yucca Mountain Area. Purple to Blue Colors Indicate Orientations With High Dilation Tendency, (c) Plot of Slip and Dilation Tendency Versus Dip for Faults/Fractures Oriented Perpendicular to δ_3 (Minimum *In-Situ* Stress). Lines of Circles, Spaced at 10° Increments on (a) and (b), Are Parallel to δ_3. Stress Condition Used in Analysis is δ_1 Vertical; δ_2 = 68% of δ_1, Horizontal at 030°; δ_3 = 26% of δ_1, Horizontal at 120°. See Ferrill, et al. (1997).

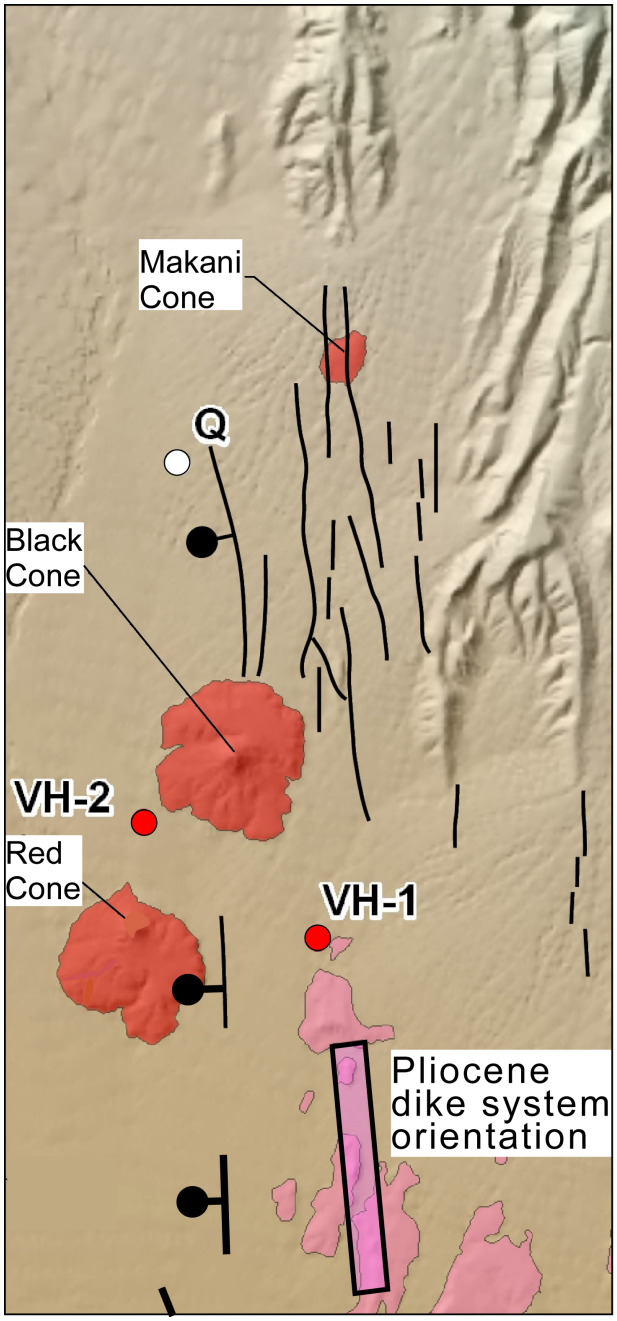

Figure 4-3. Normal North-South-Trending Faults (Black Lines) Interpreted From Aeromagnetic Data in Crater Flat. Red, Black, and Makani Cinder Cones Are in Close Association With Normal West-Dipping Faults or in the Hanging Walls of Such Faults. Q Is Location of a Buried Basalt Lava Flow (Perry, 2005a); VH-1 and VH-2 are Locations of Deep Bore Holes To Help Define the Subsurface Volcanic Features in Crater Flat. After Perry, et al. (2006b). Q Represents Aeromagnetic Anomaly That Drilling Showed To Be Four Lava Flows Separated by Breccia and Scoria (Perry, et al., 2006a).

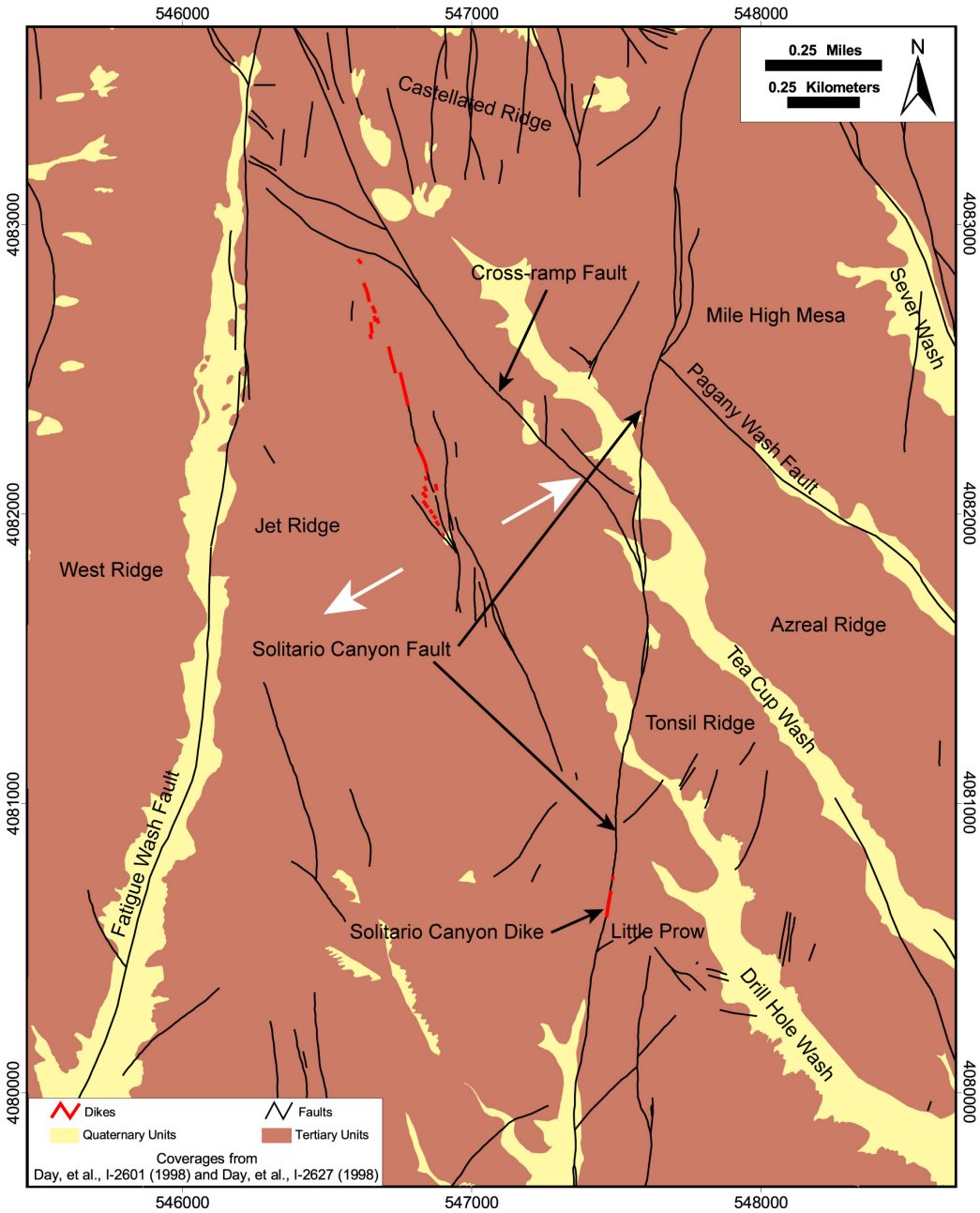

Figure 4-4. Map of Faults in the Little Prow Area of Yucca Mountain, Nevada. Basaltic Dikes Are Indicated in Red. The 11-mya-Old Solitario Canyon Dike Occurs Along the Solitario Canyon Fault Near the Bottom of the Figure. Other Basalt Dikes Occur Along a Cross Ramp Extensional Fault System Between the Solitario Canyon and Fatigue Wash Faults. White Arrows Indicate Approximate Orientation of the Local Minimum Stress During Development of Fault System. Maps Modified from Day, et al. (1998a,b). Location of Map Shown on Figure 4-1. See Text for Details.

5 SUMMARY

Currently there are at least 10 tectonic models proposed for the Yucca Mountain Region. Most are based on satisfying one or a few selected geologic or geophysical features or characteristics. Based on deformation style they can be placed into one of four categories: (i) extension, (ii) transtensional, (iii) extensional/transtensional, or (iv) volcanic. Many of the models are based on experience in other tectonic regimes or on concepts that are difficult to confirm in the Yucca Mountain Region. Grouping the models into the four categories makes it possible to generalize their characteristics with less concern for unique individual features. While more clearly defined tectonic models explain tectonic environments to the northeast and southwest, a single neotectonic model has yet to be agreed upon for the Yucca Mountain Region. The traditional Basin and Range Great Basin with its predominantly north-south-striking dip-slip faults occurs immediately north and east of the Yucca Mountain Region, while the Eastern California Shear Zone with its large northwest-striking, right-lateral strike-slip faults occurs to the south and west. Yucca Mountain occurs in the transition between these definitive tectonic areas and is further complicated by an extensive period of massive volcanism in the middle to late Miocene that resulted in large collapsed calderas, the remnants of which add complexity to the Yucca Mountain Region.

6 CONCLUSIONS

As a result of geologic and geophysical data acquired since 2000, most tectonic models included in NRC (1999) and CRWMS M&O (2000) documents have not changed or needed to be modified since last reviewed. Three new models—the regional right-lateral crustal bending model, the stateline fault system model, and the mega-rings model—have been proposed.

Although the intensity of geological and geophysical work has been reduced at Yucca Mountain, some ongoing projects such as strain analysis with the dense cluster global positioning satellite network and seismic monitoring will continue to provide information that may constrain existing tectonic models at Yucca Mountain or result in new models for consideration. Development of neotectonic models based on ongoing geologic and geophysical processes will lead to an improved understanding of the tectonic environment at Yucca Mountain.

Many of the proposed tectonic models are based on geology or geophysics that reflects an older tectonic environment and may not be relevant to the current tectonic setting at Yucca Mountain. While the actual tectonic setting at Yucca Mountain may not be well known, indications are the strain rate, while still being quantified (Wernicke, et al., 2004), is less than during the period of maximum deformation 12–10 mya (Fridrich, 1999; Murphy, et al., 2003).

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