4.8 INTEGRATED SITE MODEL

This section describes the integrated site model (ISM) of Yucca Mountain, a three-dimensional representation of the rock layers and faults (geologic framework), rock properties, and mineral distributions in the subsurface. The ISM provides a baseline representation of the geology of the site for use in hydrologic flow, radionuclide transport, repository design, and performance assessment modeling.

Section 4.8.2 discusses the geologic framework model (GFM), Section 4.8.3 discusses the rock properties model (RPM), and Section 4.8.4 discusses the mineralogic model (MM). Additional details for each of the following sections can be found in the corresponding analysis model report (GFM, CRWMS M&O 2000a; RPM, CRWMS M&O 2000b; MM, CRWMS M&O 2000c). Results of the ISM are discussed in the corresponding process model report (CRWMS M&O 2000g).

4.8.1 Integrated Site Model Overview

The ISM consists of three component parts: the GFM, the RPM, and the MM.

Each component part was modeled separately because of the unique data sets and methods required; then the three models were integrated into one spatial model (the ISM). The ISM covers an area of 65 mi.^{2} (168 km^2) centered on Yucca Mountain; however, the RPM (which is based on sparser data) covers a smaller area (Figure 4.8-1). The ISM was developed to provide a consistent volumetric portrayal of the rock layers, rock properties, faults, and mineral distributions in the subsurface of Yucca Mountain for Yucca Mountain Site Characterization Project (YMP) use. Rock layering in the ISM is based on the detailed YMP stratigraphy described in Table 4.8-1. Layers with similar characteristics are combined into modeling units for the primary subsequent uses, which include repository design, hydrologic flow modeling, and radionuclide transport modeling. The subsequent models are, in turn, incorporated into the total system performance assessment.

The interrelationships of the three components of the ISM and their interfaces with subsequent uses are illustrated on Figure 4.8-2. The GFM provides the three-dimensional structure into which the mathematical simulations of rock properties and mineral distributions are integrated, forming the ISM.

4.8.2 Geologic Framework Model

The GFM represents a three-dimensional interpretation of the geology surrounding the area being studied as a potential site for a radioactive waste repository at Yucca Mountain. It consists of the following:

- 50 rock units
- 43 faults
- Area of 65 mi.^{2} (168 km^2)
- Volume of 185 mi.^{3} (771 km^3)
- The repository host horizon and its subdivisions

- The Tertiary-Paleozoic unconformity
- Additional site data.

The boundaries of the GFM (shown on Figure 4.8-1) were chosen to encompass the most widely distributed set of exploratory boreholes (the "WT" series) and to provide a geologic framework over the area of interest for hydrologic flow and radionuclide transport modeling. The 1:24,000-scale bedrock geologic map (Day et al. 1998b) was designed to coincide with the ISM boundaries. The depth of the model is constrained by the deepest contact in the model, the Tertiary-Paleozoic unconformity, which is up to 13,000 ft (3,962 m) below the ground surface.

4.8.2.1 Geologic Framework Model Software

Information on the software used to construct the GFM can be found in CRWMS M&O (2000a).

4.8.2.2 Geologic Framework Model Inputs

The two primary data sources from which the GFM was constructed are the 1:24,000-scale bedrock geologic map of the Yucca Mountain area (Day et al. 1998b) and the stratigraphic contacts identified in boreholes in the map area (CRWMS M&O 2000a, Section 4.1, Table 3). The locations of the boreholes are shown on Figure 4.8-3. The faults modeled in the GFM from the geologic map (Day et al. 1998b) are shown on Figure 4.8-4. Measured stratigraphic sections also were used in developing the model (Figure 4.8-5). Qualified measured sections (solid triangles on Figure 4.8-5) were used as input; unqualified measured sections (plus signs on Figure 4.8-5) were used as corroborative data.

In addition to geologic data, information from geophysical data was used to interpret structures beneath the alluvium in Midway Valley. Based on the gravity and magnetic profiles (Figure 4.8-5), a feature interpreted as a horst (a raised block between two faults) was detected beneath Midway Valley (Ponce and Langenheim 1994, p. 6). Vertical displacements of 246 ft (75 m) were interpreted on the two faults bounding the horst. This feature was integrated with geologic map information during the creation of the bedrock geologic map of the Yucca Mountain area (Day et al. 1998b) and was included in the GFM.

An interpretation (Brocher et al. 1998, pp. 947 to 971) of a regional seismic reflection profile (Figure 4.8-5) was used qualitatively to verify three-dimensional fault geometries and tilted strata in the GFM. The seismic profiles are not sufficient to provide quantitative model input data because of noise and uncertainties regarding rock velocity.

The depth to the top of Paleozoic strata in the GFM was adapted from a gravity inversion study (Majer et al. 1998, Figure 3b). Majer et al. (1998) used gravity data collected along 17 profiles at Yucca Mountain, supplemented by regional gravity data compiled by the USGS for the Nevada Test Site region (Majer et al. 1996, pp. 34-37). In the GFM, the interpreted top of the Paleozoic surface was modified to show vertical displacement along the modeled faults.

4.8.2.3 Geologic Framework Model Methodology

The GFM was constructed using the following general steps:

- Development of grid construction and contouring methodology
- Construction of faults
- Construction of reference horizons
- Construction of isochores
- Assembly of faults and rock layers
- Assessment and iteration.

The GFM stratigraphy was constructed by the thickness (or isochore) method, which consists of adding or subtracting (as appropriate) thicknesses from one or more reference horizons, as illustrated on Figure 4.8-6. This method was chosen for several reasons:

- Mapping thickness is a standard method of mapping and studying volcanic rock units.
- In volcanic units, thickness trends over an area are more predictable than absolute elevations. Thicknesses directly reflect geologic processes and can, therefore, be projected using those processes as guides.
- Because the volcanic strata at Yucca Mountain consist of many units that pinch out, are very thin, or have highly variable thicknesses (creating highly variable differences between the elevations of stratal tops and bottoms), the use of isochores is the most practical method.
- Construction of stratigraphy by isochores is much less time-consuming than the construction of each surface as an elevation grid, and it results in fewer thickness anomalies.

It must be recognized that the isochore maps presented here are the maps used to construct the GFM, and may contain artifacts of the modeling process. A true isochore map (not one constructed for modeling) would not include partial thicknesses caused by faulting; however, for three-dimensional modeling, partial thicknesses must be included to fully account for all three-dimensional relationships around the borehole. In this regard, the model and its components, including isochore maps, structure maps, and cross sections, may differ from results of more traditional analysis of geologic maps. Additionally, many of the isochore maps presented here are composites constructed by adding several isochore grids together. The resulting maps may contain artifacts of the additive process, such as abrupt contour bends and closed contours away from input data. For these reasons, the maps are referred to as "model-isochores" in this section.

4.8.2.3.1 Gridding

A grid is a systematic array of points, or nodes. In three dimensions, a grid forms a surface. Topography is an example of a surface that can be represented by a grid. Gridding is the process of creating a surface (a grid) across an area based on widely and variably spaced input data. Many methods (both mathematical and interpretive) are available for use in creating surfaces in a model. Examples include triangulation, hand contouring, linear interpolation, geostatistical

methods, and various mathematical algorithms. The gridding method used in the GFM is based on a minimum tension mathematical algorithm that calculates a surface passing through the input data. The minimum tension algorithm was chosen because it produces surfaces that have minimal abrupt changes in slope, and is therefore appropriate for representing geologic features produced by fluid-like mechanisms (e.g., deposition of ash-flow tuffs, or hydrologic flow).

In the GFM, the grids represent the geologic surfaces (reference horizons) or unit thicknesses (model-isochores) and are the fundamental building blocks of the model. Grids are also created to define fault planes. For fault planes and reference horizons, each node contains an elevation; for model-isochores, each node contains a thickness. For every grid in the GFM, the minimum tension algorithm was constrained by field data from boreholes, tunnels, measured sections, and the geologic map and interpretive constraints in the form of contour segments (CRWMS M&O 2000a, Section 6.3.2.2). Grid node spacing for all grids except topography is 61 by 61 m (200 by 200 ft). The topographic grid spacing is 30 by 30 m (100 by 100 ft) to more accurately represent details of the ground surface.

As illustrated on Figure 4.8-7, interpretive constraints were used to govern the shapes of grids to produce results that were consistent with the conceptual model. The constraints were in the form of contour segments. The reference horizon, fault, and model-isochore grids in the GFM were calculated with the use of both field data and interpretive contours.

The process for gridding faults, reference horizons, and thicknesses is summarized as follows:

1. The field data were first gridded without any interpretive constraint, and the results were analyzed to determine the best locations for interpretive contours.

2. The grid was then modified by introducing interpretive contours and regridding.

3. The process was iterated until the grid represented the conceptual model being applied by the modeler.

4.8.2.3.2 Construction of Faults

The initial step in fault construction was development of criteria for fault inclusion, which were refined with each model iteration to meet the needs of subsequent users. Inclusion criteria for faults in the GFM were developed to represent the faults needed in subsequent modeling and to limit the faults to a manageable number for modeling purposes. The fault inclusion criteria were as follows:

- In the vicinity of the Exploratory Studies Facility (ESF):
  - The mapped trace length is 1 mi. (1.6 km) or greater, and
  - The maximum vertical displacement is at least 100 ft (30 m), or
  - The mapped fault intersects with the ESF or Cross Drift.

- Outside the vicinity of the ESF:
  - The mapped trace length is 2 mi. (3.2 km) or greater, and
  - The maximum vertical displacement is at least 100 ft (30 m), or
  - Omitting the fault would produce an unacceptable mismatch between the model and the geologic map.

For the GFM, the locations of fault traces were established by the geologic map of the site area (Day et al. 1998b). Vertical fault displacements were estimated from published sources, borehole data, and the geologic map. Vertical fault displacements and geometries were evaluated during technical reviews of each model iteration to incorporate feedback from YMP scientists.

4.8.2.3.3 Construction of Reference Horizons and Thickness Grids

The first reference horizon constructed was at the base of the Tiva Canyon Tuff (top of Tpbt4, the pre-Tiva bedded tuff). This horizon was chosen because of its abundant geologic map and borehole data, and because it is a major lithologic break that is readily identifiable. This reference horizon is illustrated on Figure 4.8-8. To help constrain vertical fault displacements at depth, two additional reference horizons were constructed at the top of the Calico Hills Formation (Ta) and at the base of the pre-Tram Tuff bedded tuff (Tctbt). The grids were constructed using the methods described in Section 4.8.2.3.1.

4.8.2.3.4 Assembly of Faults and Rock Layers

The reference horizon grids, model-isochore grids, and fault grids were combined to produce the final model. In the combination, calculations were performed to determine the intersections of faults and rock units, and this information was stored with each grid. The final model consists of a grid for each rock unit in each fault block and a grid for each fault. The total number of grids in the finished GFM is 2,193, as shown in the following equation:

$$50 \text{ units} \times 43 \text{ fault blocks} + 43 \text{ faults} = 2{,}193 \text{ grids} \qquad \text{(Eq. 4.8-1)}$$

The total does not include the 46 model-isochore grids used to calculate the rock layer grids. Information about how all the grids fit together was recorded in a parameter file called a "sequence" file. The sequence file can be used for subsequent analyses or operations on the model.

4.8.2.3.5 Assessment and Iteration

When the model was assembled, the results were assessed by the developer to determine whether the conceptual model was successfully implemented and the modeling methods were completed correctly. Assessment was performed by visually examining the components of the assembled model. When unsatisfactory results were found, the relevant steps of the modeling process were iterated as necessary to correct the problem.

4.8.2.4 Interpretation of Rock Units

This section provides a description of the geometry and distribution of rock units in the GFM that are important for the ISM, RPM, and MM, as well as the major direct and indirect subsequent uses of the ISM (repository design and hydrologic flow modeling through the unsaturated zone and the saturated zone). Each geologic formation is also described, as well as the Paintbrush nonwelded (PTn) thermal-mechanical/hydrologic unit, the undifferentiated older Tertiary unit (Tund), and the Tertiary-Paleozoic unconformity. Subunits of the formations that are particularly important for ISM uses are also described. Additional details about the stratigraphy of the site are provided in Section 4.5.

4.8.2.4.1 Post-Tiva Units

Post-Tiva rocks are only sparsely encountered in the modeled area. The distribution is based on the geologic map (Day et al. 1998b) and borehole data. South of Yucca Wash, these units are typically preserved in wedges on the downthrown sides of faults. For example, on Figure 4.8-9, a wedge of post-Tiva rocks (grouped with the Tiva Canyon Tuff [Tpc] crystal-rich member) is shown on the downthrown side of the Solitario Canyon fault.

4.8.2.4.2 Tiva Canyon Tuff

The Tiva Canyon Tuff (Tpc) comprises most of the exposed bedrock in the modeled area. The Tpc is thickest in the center of the modeled area and thins to the east, west, and south. Because the top of the formation is eroded over most of the modeled area, a true thickness map cannot be produced. As illustrated on Figure 4.8-10, the crystal-poor, densely welded, vitric subzone (Tpcpv3) is present only in the southwestern part of the area.

4.8.2.4.3 Paintbrush Nonwelded Unit

The major formations of the Paintbrush nonwelded (PTn) unit, the Yucca Mountain Tuff (Tpy) (illustrated on Figure 4.8-11), and the Pah Canyon Tuff (Tpp) (illustrated on Figure 4.8-12), both thicken dramatically to the north and northwest, but are absent over the southern half of the modeled area. In the southern half of the modeled area, the PTn unit is composed of bedded tuffs (Tpbt2, Tpbt3, and Tpbt4), the vitric units of the lower Tpc (Tpcpv1 and Tpcpv2) and the upper Topopah Spring Tuff (Tpt) (Tptrv2 and Tptrv3). In the area west of the ESF, the PTn unit is 75 to 250 ft (23 to 76 m) thick and thickens rapidly to the north to a maximum of more than 550 ft (168 m). A thickness map of the PTn unit is shown on Figure 4.8-13.

4.8.2.4.4 Topopah Spring Tuff

As illustrated on Figure 4.8-14, the Topopah Spring Tuff (Tpt) reaches a maximum thickness of more than 1,200 ft (365 m) along a northwest-southeast axis located in the vicinity of the ESF. The Tpt thins rapidly toward the northeast, reaching a thickness of 0 ft at the far northeastern corner of the modeled area (Day et al. 1998b). To the southeast, the thickness diminishes to less than 700 ft (213 m). To the southwest, the thickness is unconstrained, but could alternatively be interpreted to thicken into the structural low of Crater Flat.

The crystal-rich, densely welded, vitric subzone (Tptrv1) near the top of the Tpt is less than 10 ft (3 m) thick across most of the modeled area, with isolated areas of 0 ft thickness. As illustrated on Figure 4.8-15, the vitrophyre (densely welded, vitric subzone) near the bottom of the formation (Tptpv3) is much thicker, ranging from 46 to 114 ft (14 to 35 m) in the area west of the ESF and from 0 to 115 ft (0 to 35 m) across the total modeled area. It has a thickness of 0 ft only where the formation (Tpt) has a thickness of 0 ft, in the northeastern corner of the modeled area. The thicknesses of both vitrophyre units vary by as much as 300 percent across distances as short as 3,500 ft (1,067 m). The thickness of Tptpv3 in the southwestern corner of the modeled area is unconstrained, but was extrapolated to allow projection to the 155 ft (47 m) thickness in borehole VH-2 in Crater Flat (Carr and Parrish 1985, Table 2), approximately 4 mi. (6 km) west-southwest of the boundary of the modeled area. If the alternative interpretation were used, that the Topopah Spring Tuff thickens into Crater Flat, Tptpv3 would also be expected to thicken in that direction.

The anomalously thin Tptpv3 in borehole WT-1 is due to faulting of the unit. The faulted thickness was used in the model so that all stratigraphic contacts could be honored; if a projected true thickness were used and no fault was explicitly modeled at this rock layer, the model could not honor the rest of the stratigraphic contacts in the borehole. No fault was included at this rock layer because no other information about the fault is available.

The repository host horizon (identified in Table 4.8-1) includes model units RHHtop, Tptpmn, Tptpll, and Tptpln within the Tpt. As illustrated on Figure 4.8-16, the thickness of this unit mimics that of the total Tpt; it reaches a maximum thickness of more than 750 ft (230 m) along the same northwest-southeast axis. The thickness of the unit ranges from 550 to 750 ft (168 to 229 m) in the area west of the ESF, and diminishes to less than 200 ft (61 m) to the southeast.

4.8.2.4.5 Calico Hills Formation

As illustrated on Figure 4.8-17, the Calico Hills Formation (Ta) ranges in thickness from less than 100 ft (30 m) in the south to more than 1,500 ft (457 m) in the northeast. In the northeast, geologic map data provide only a minimum thickness because the base of the formation is not exposed. In the vicinity of the ESF, the formation thickness ranges from less than 40 ft (12 m) to greater than 300 ft (91 m).

4.8.2.4.6 Prow Pass Tuff

As illustrated on Figure 4.8-18, the Prow Pass Tuff (Tcp) is thickest along a north-south axis through the center of the modeled area, reaching a maximum thickness of 636 ft (194 m) in borehole H-4. In the vicinity of the ESF, the formation ranges in thickness from less than 300 ft (91 m) to more than 550 ft (168 m). The formation pinches out to the northeast, according to geologic map data (Byers et al. 1976) that show the overlying Calico Hills Formation in depositional contact with rocks of Devonian age; however, the exact location at which it pinches out against the Tertiary-Paleozoic unconformity is unknown.

4.8.2.4.7 Bullfrog Tuff

As illustrated on Figure 4.8-19, the Bullfrog Tuff (Tcb) is thickest in the southwestern part of the central modeled area, reaching a maximum thickness of 618 ft (188 m) in borehole G-3. In the

vicinity of the ESF, the formation ranges in thickness from 370 ft (113 m) to 618 ft (188 m). Like the overlying Prow Pass Tuff, the Bullfrog Tuff pinches out to the northeast against the Tertiary-Paleozoic unconformity. The exact location at which it pinches out is unknown.

4.8.2.4.8 Tram Tuff

In the GFM, the Tram Tuff (Tct) is the thickest of the formations in the Crater Flat Group. As illustrated on Figure 4.8-20, it is thickest in a north-northeasterly trending axis across the central part of the modeled area. In the vicinity of the ESF, it ranges in thickness from about 620 ft (189 m) to about 1,120 ft (341 m), with a maximum thickness greater than 1,200 ft (365 m) at borehole G-3. The Tram Tuff also pinches out to the northeast against the Tertiary-Paleozoic unconformity. To the northwest, thickness is constrained only by borehole G-2 (see Figure 4.8-3 for borehole locations); however, this borehole may be located on a buried structural high and may not be representative of the regional trend. In the vicinity of borehole G-2, the Tram model-isochore could alternatively be interpreted to show closed contours around the borehole to represent thinning on a structural high.

On Figure 4.8-20, the anomalously thin Tct at borehole p#1 is due to faulting (see Figure 4.8-3 for borehole locations). The faulted thickness had to be used in the model so that all stratigraphic contacts would be honored; if a projected true thickness were used for the Tct in borehole p#1 and no fault was explicitly modeled there, the model would not match the rest of the stratigraphic contacts in the borehole. The thickened Tct would have forced the other contacts to be out of place (as described in Section 4.8.2.3, the model is built by thicknesses, not elevations). No fault was included at this rock layer because no other information about the fault is available. An alternative interpretation is that this fault is the Paintbrush Canyon fault and the Tertiary-Paleozoic contact in borehole p#1 is not a fault (or is another fault).

4.8.2.4.9 Older Tertiary Unit

The elevation of the top of this unit is shown on Figure 4.8-21. The unit thickness was not mapped because it is entirely dependent on the configuration of the Tertiary-Paleozoic unconformity derived from gravity data (Majer et al. 1998, Figure 3b). Therefore, no isochore map was generated during model construction.

4.8.2.4.10 Tertiary-Paleozoic Unconformity

Overview–The configuration of the unconformity between Tertiary and Paleozoic rocks is subject to several interpretations, as described in the GFM analysis model report (CRWMS M&O 2000a, Section 6.4.1.10) and summarized in the following paragraphs. The nature of the GFM is such that only one interpretation could be used, and the interpretation had to cover the entire modeled area. These requirements limited the available sources to one, an interpretation of gravity data (Majer et al. 1998, Figure 3b). This is a recalculation of the Tertiary-Paleozoic unconformity that was initially used in earlier GFM versions. The interpretation incorporated in the GFM also had to be consistent with the other data from boreholes and the geologic map.

The elevation of the Tertiary-Paleozoic unconformity is important for hydrologic modeling because it forms the top of the regional Paleozoic aquifers and aquitards (Carr, M.D. et al. 1986, p. 6). Alternative interpretations are also potentially important because of the range of vertical

differences between the interpreted surfaces, and consequent potential impacts on hydrologic and radionuclide transport modeling. Based on the GFM interpretation, the unconformity occurs 8,000 to 11,000 ft (2,438 to 3,353 m) below the repository host horizon.

In the site area, only one borehole penetrates to the Paleozoic rocks (p#1); therefore, the model relies primarily on the geophysical interpretation (Majer et al. 1998, Figure 3b). The Tertiary-Paleozoic unconformity used in the GFM is illustrated on Figure 4.8-22. The GFM surface includes vertical displacements along the modeled faults, which were not included in the gravity interpretation. Fault displacements on the Tertiary-Paleozoic unconformity were constructed by matching the displacements of the shallower modeled units and displacing the gravity interpretation.

The unconformity forms a high ridge beneath Busted Butte and Fran Ridge in the southeastern model area, falling away to deeper levels to the north and west. At its deepest point in the northwest, the unconformity is 13,000 ft (3,962 m) below ground surface. At its shallowest point beneath Fran Ridge, it is 3,500 ft (1,067 m) below ground surface. The deepening to the west can be explained by the combined down-to-the-west vertical displacement of several known north-trending Tertiary normal faults, but may also be enhanced by erosion and vertical displacement on older, unknown faults. The deepening to the north may be a result of caldera deformation, deposition of the thick Tertiary volcanic pile, and older deformation.

Discussion of Alternative Interpretations–Several interpretations have been made of the Tertiary-Paleozoic unconformity in the vicinity of borehole p#1 (Majer et al. 1998, Figure 7; Brocher et al. 1998, Figures 7, 8, 14; Feighner et al. 1998, Figure 7b). Although they are local interpretations, they coincide with part of the GFM interpretation (Figure 4.8-23). No definitive data (e.g., another borehole or conclusive geophysical data) are available to distinguish between the alternatives; available data permit a variety of interpretations. This section discusses the reason for choosing the interpretation in the GFM over the others.

The GFM was constructed with the interpretation that the Tertiary-Paleozoic contact in borehole p#1 is the Paintbrush Canyon fault, as first interpreted in a U.S. Geological Survey open file report in which the fault was called the Fran Ridge fault (Carr, M.D. et al. 1986, pp. 16, 41, Figure 12). However, because the data are inconclusive, other interpretations of the p#1 borehole data are possible, including an unfaulted unconformity at the Tertiary-Paleozoic contact, correlation of the fault at the unconformity to a fault other than the Paintbrush Canyon fault, or placement of the Paintbrush Canyon fault higher in the borehole at the base of the Tram Tuff.

An important observation is that the geologic map relations in the vicinity of borehole p#1 (Day et al. 1998b) show approximately 700 ft (213 m) of vertical displacement along the Paintbrush Canyon fault and 400 ft (122 m) of vertical displacement on the fault splay that arcs around San Juan Hill south of borehole p#1 (Figures 4.8-3 and 4.8-4). These relations require at least a 1,100-ft (335-m) down-to-the-west vertical displacement in the immediate vicinity of borehole p#1. The interpretation from the borehole report was accepted for the GFM because it was consistent with the geologic map data and formed the most reasonable interpretation in three dimensions.

An alternative interpretation would be the intersection of the Paintbrush Canyon fault at the base of the Tram Tuff in borehole p#1 and no fault at the Tertiary-Paleozoic contact. This configuration is plausible if the Tertiary-Paleozoic contact in borehole p#1 is interpreted as an erosional surface and not as a fault. However, to be consistent with geologic map relations and the borehole report for p#1 (Carr, M.D. et al. 1986, pp. 16, 41, Figure 12), the GFM represents the Tertiary-Paleozoic contact in borehole p#1 as a fault.

The gravity and seismic interpretations that show the Tertiary-Paleozoic unconformity at shallow levels west of borehole p#1 (shown on Figure 4.8-23 as the red, orange, and blue lines) conflict with the geologic map relations discussed previously. The interpretations do not allow for a 1,100-ft (335-m) vertical displacement on normal faults in the vicinity of borehole p#1. Because the GFM could not be constructed using the shallower interpretations and still be consistent with the data from the borehole and geologic map, the shallower interpretations were not used. To construct the Tertiary-Paleozoic unconformity in the GFM, it was necessary to modify the gravity interpretation (Majer et al. 1998, Figure 3b) to be consistent with the data from the borehole and geologic map. This interpretation is shown on Figure 4.8-23 as the dashed line.

Impacts of Alternative Interpretations–The alternative interpretations of the elevation of the Tertiary-Paleozoic unconformity produce marked geometric differences 2 to 4 km (1.2 to 2.5 mi.) east of the ESF. The vertical differences between deep and shallow interpretations are on the order of 3,000 ft (914 m) for a distance of 7,000 ft (2,134 m) along the regional seismic profile west of borehole p#1. This produces a cross-sectional area of approximately 2.1×10^7 ft^2 (1.95×10^6 m^2) and a corresponding volume of disputed pre-Cenozoic rock between the potential repository and the regional Paleozoic aquifers and aquitards. The impacts of this difference on subsequent models would have to be assessed in those modeling activities.

4.8.2.5 Interpretation of Faults

This section presents a discussion of the construction of faults for the GFM. Fault geometries depicted in the GFM were constructed with the use of the methodology described in Section 4.8.2.3.2 and were intended to be consistent with current YMP structural and tectonic models (Sections 4.3 and 4.6); however, the GFM does not extend deep enough to address tectonic model issues or seismic hazards. Patterns of faulting, structural domains, and relative ages of the faults are discussed in Section 4.6. The following sections discuss the particular features of faults modeled in the GFM.

4.8.2.5.1 Fault Curvature

In the GFM interpretation, the dominant faults were shown as slightly curved (dip shallowing slightly with depth) in cross section to be consistent with the cross sections published with the geologic map of the site area (Day et al. 1998b). No quantitative attempt was made to construct precise fault geometries in accordance with structural or tectonic calculations, such as balanced cross sections. The faults could also have been depicted with greater curvature; however, in practical terms, the uncertainty of fault geometries at depth outweighs any fine details that could be applied to the modeled faults.

4.8.2.5.2 Fault Patterns

The north-trending fault system, illustrated on Figure 4.8-4, dominates the model. The largest of these faults are the Solitario Canyon and Paintbrush Canyon faults, both of which displace strata down to the west by more than 1,400 ft (427 m) (Day et al. 1998b). The Windy Wash fault is just as large, but is present only in the far northwestern edge of the model (Day et al. 1998b). Other north-trending faults of note include the Fatigue Wash, Iron Ridge, and Bow Ridge faults, which form major topographic features of the site area. A system of faults beneath Midway Valley produced a series of small horst-graben bedrock structures now buried by alluvium.

Northwest-trending faults also form prominent topographic features in the site area. A series of northwest-trending faults is present in the prominent drainages in the north-central part of the area (Drill Hole, Pagany, and Sever washes). The vertical displacement on these faults is small and not significant in the model. In the southern part of the area, Dune Wash contains a complex pattern of intersecting north-trending and northwest-trending faults (including the Dune Wash fault) that has a maximum vertical displacement of more than 200 ft (61 m). The mapped pattern of faults in Dune Wash is so complex (Day et al. 1998b) that only a few of these faults could be included in the GFM; therefore, the actual structure in Dune Wash is more complex than its representation in the GFM.

4.8.2.5.3 Features of Individual Faults

The Paintbrush Canyon fault (shown on Figure 4.8-4) is the longest of the faults in the GFM and has the greatest Tertiary vertical displacement. The main strand of the fault passes along the west side of Fran Ridge. The U.S. Geological Survey open file report for borehole p#1 called this the Fran Ridge fault (Carr, M.D. et al. 1986, Figure 12) and indicated that it intersects borehole p#1 at the Tertiary-Paleozoic unconformity. This is the interpretation used to construct the Paintbrush Canyon fault in the GFM. The Paintbrush Canyon fault reaches its maximum vertical displacement of approximately 1,400 ft (427 m) at the mouth of Dune Wash, where several faults intersect the Paintbrush Canyon fault and increase the total vertical displacement.

The Solitario Canyon fault changes dip direction at Tonsil Ridge, from west-dipping in the south to east-dipping in the north. The location of Tonsil Ridge is indicated on Figure 4.8-1. Because a grid cannot be constructed to change dip direction as the Solitario Canyon fault does, the fault was generalized in the GFM as a single, west-dipping grid. Interpretations from the model at this location should take this generalization into account. The uncertainties regarding fault dips and locations at great depth are expected to outweigh the potential impacts of the generalization.

The Bow Ridge fault (Figure 4.8-4) is a scissor fault, with its hinge point buried in the alluvium approximately at the mouth of Sever Wash. The constraints of outcrop data and borehole WT#16 require that the fault pass between the borehole and the outcrop to the west and have an apparent down-to-the-east vertical displacement in this area.

Minor faults such as the Ghost Dance, Abandoned Wash, and numerous faults around Dune Wash appear to be secondary features that accommodated strain between the dominant faults (Day et al. 1998b). The intersections of such minor faults with more dominant faults at depth are uncertain; however, the interpretation shown in the GFM is that the Dune Wash, Bow Ridge, and

Midway Valley faults intersect the Paintbrush Canyon fault at depth. The Ghost Dance and Abandoned Wash faults do not intersect any major faults in the GFM, but could at deeper crustal levels below the GFM.

4.8.2.5.4 Faulting and Deposition

In the GFM, model-isochore maps of the Paintbrush Group and older units do not show changes in thickness across faults, although some minor changes could be interpreted from the available data. Data distribution for this kind of detailed analysis is limited. Geologic map relations (Day et al. 1998b) show isolated thickness changes across faults in Solitario Canyon and Fatigue Wash that are associated with pre-Tiva faulting. However, the greatest vertical displacements and tilting of the stratigraphic section appear to have occurred after the deposition of the Tiva Canyon Tuff (Section 4.6). Thickness changes across faults are, therefore, likely to be relatively small in the Paintbrush Group, but are probably more common than indicated by currently available data.

4.8.2.6 Uncertainty

For the GFM, uncertainty is an estimation of how closely the model matches the real world. The primary factor affecting uncertainty in the GFM is distance from the data. Because borehole data are restricted in depth, uncertainty increases with vertical distance below the boreholes and horizontal distance away from them. Likewise, interpretations regarding deep rock units, which have fewer borehole penetrations, have more uncertainty associated with them than those associated with shallow rock units.

Uncertainty was estimated by two empirical methods—an analysis of gridding methods and a piecewise reconstruction of the model. The two methods provide a practical estimation of uncertainty that accounts for data distribution, geologic complexity of the site, and modeling methods. The gridding analysis evaluated the range of geologically reasonable interpretations that could be made between data (i.e., in interpolation). The total range of reasonable interpretations defined the window of uncertainty. The piecewise reconstruction method calculated uncertainty by reconstructing the model one group of boreholes at a time, and using each group to predict the geology for the next group. The uncertainty window for this method was the range in which subsurface geology was predicted for the final group of boreholes.

The results of the two methods agreed closely, suggesting that the methods are appropriate for the data set. The results of uncertainty analysis show that for the vicinity of the ESF, vertical uncertainty for the repository host horizon (as defined in Table 4.8-1) increases from 0 ft at a data point (borehole or tunnel) to ± 40 ft (12 m) at a distance of 3,200 ft (975 m) from the data point. This value is greater for deep units, for which there are less borehole data, and is smaller for shallow units, for which there are more data. Beyond 3,200 ft (975 m) from the data point; uncertainty can be estimated only qualitatively because it is bounded only by conceptual models or distant data.

Uncertainty is summarized as follows:

- Surface to Tptrv1: ± 30 ft (9 m)

- Tptrv1 to Tac (includes repository host horizon): ± 40 ft (12 m)
- Base of Tac to Tctbt: ± 50 ft (15 m).

Uncertainty is higher in areas outside borehole control, particularly in the far corners of the model and in areas of structural complexity (e.g., Midway Valley and Dune Wash).

4.8.2.7 Geologic Framework Model Validation: Predictions for Boreholes and Tunnels

The GFM was validated by predicting the subsurface geology for two boreholes and one tunnel, and assessing the results. Predictions were made for boreholes SD-6 and WT-24 and the Enhanced Characterization of the Repository Block Cross Drift, and the predictions were compared to the actual results. The data from the boreholes and tunnel were later incorporated into the GFM. This section provides a summary of the validation, which is described in more detail in the GFM analysis model report (CRWMS M&O 2000a, Section 6.6).

The predicted depth of stratigraphic contacts for borehole SD-6 and the actual results were compared (CRWMS M&O 2000a, Table 6). Of the 26 predicted contact elevations, 22 (85 percent) were within the expected window of uncertainty. In general, the model meets each validation criterion for the SD-6 predictions. Where contact elevations and thicknesses were not predicted within the expected window of uncertainty, the causes were ascribed to unpredictable geologic features (CRWMS M&O 2000a, Section 6.6.2.1). Because borehole SD-6 is relatively well constrained by surrounding boreholes (Figure 4.8-3), it illustrates the model's predictive capabilities and the effects of geologic variability on model predictions in a constrained area. The data from borehole SD-6 also demonstrate that unknown geologic features can cause outliers that will sometimes exceed the expected window of uncertainty.

Predictions were also made for borehole WT-24. This borehole was located away from existing boreholes when it was drilled, and, thus, provides an assessment of uncertainty for the GFM in a less constrained area. In addition, WT-24 is located in an area that is more stratigraphically and structurally complex than borehole SD-6, so the predictions at WT-24 are expected to be less accurate (i.e., the window of uncertainty is greater due to geologic complexity and lack of subsurface data). The nearest borehole to WT-24 is approximately 975 m (3,200 ft) away (borehole G-2; Figure 4.8-3) and no others are within 1,524 m (5,000 ft). For evaluation purposes, however, the predictions were compared to the maximum uncertainty windows for constrained areas discussed in Section 4.8.2.6.

Twelve of 24 elevation predictions (50 percent) were within the window of uncertainty (CRWMS M&O 2000a, Section 6.6.2.2, Table 7). The causes for the mismatches were determined to result from unpredictable geologic features and cumulative errors (i.e., one mismatch affecting several others), and the model was evaluated as being acceptable for the WT-24 predictions (CRWMS M&O 2000a, Section 6.6.2.2). Borehole WT-24 illustrates the geologic variability expected to be found in less constrained areas.

For the Enhanced Characterization of the Repository Block Cross Drift, the vertical difference between predicted and actual stratigraphic contacts was calculated by the transformation of tunnel stations into elevations, correction for stratal tilt, and subtraction of one from the other. Two of the three contacts were encountered within the expected window of uncertainty for these

horizons at this location (plus or minus 12 m [40 ft]) (CRWMS M&O 2000g, Table 3-1). In the west end of the tunnel, faults with vertical displacements of 3 m to greater than 5 m (10 ft to greater than 16 ft) appear to have caused most of the difference between predicted and actual elevations for the Tptpln contact. Although the faults in the west end of the tunnel were not mapped at the surface, they were not wholly unanticipated because it was known beforehand that structural deformation increases in proximity to the Solitario Canyon fault, and that small faults are present in the mountain. In the Enhanced Characterization of the Repository Block Cross Drift, the Tptpln contact is within 198 m (650 ft) horizontally of the Solitario Canyon fault. As a result, the prediction error for the Tptpln contact, while outside the expected window of uncertainty, can be explained in terms of geologic variability without affecting validation of the model (i.e., the faults are too small to have been included in the model).

The predictions for the Enhanced Characterization of the Repository Block Cross Drift suggest that the GFM will provide predictions of subsurface stratigraphy for future repository tunneling within the expected window of uncertainty. Predictions may be affected on the far western edge near the Solitario Canyon fault and elsewhere if small, unmapped faults like those in the Enhanced Characterization of the Repository Block Cross Drift are encountered at other locations.

In addition to the stratigraphic predictions, a structural prediction was also made. Based on geologic map data, the Solitario Canyon fault was predicted to intersect the Enhanced Characterization of the Repository Block Cross Drift at Station 25+55. The fault was encountered at Station 25+83, indicating that the fault dips slightly more shallowly than predicted. Given that the Solitario Canyon fault has highly variable dip at the surface (Day et al. 1998b), the prediction was evaluated as being adequate. Unlike the stratigraphic predictions, no window of uncertainty was estimated for the fault prediction because of the highly variable nature of fault geometries in the subsurface and the paucity of subsurface data defining them.

4.8.2.8 Limitations and Alternative Interpretations

Appropriate use of the GFM is inherently limited by scale and content. The grid spacing used in the GFM (61 m or 200 ft) discussed in Section 4.8.2.3.1 limits the size of features that can be resolved by the model. Users of the GFM must also consider the data reduction (CRWMS M&O 2000a, Section 6.1) and fault selection criteria (Section 4.8.2.3.2) to determine whether the GFM is appropriate for specific applications.

Because each reference horizon and model-isochore in the GFM is an interpretation, each is non-unique, and other viable interpretations are possible. All interpretations and predictions made by the GFM are bounded by an expected window of uncertainty, and it is implicitly recognized that alternative interpretations that fall within this window would also be considered valid. Changes to the GFM within the expected window of uncertainty would not, therefore, be considered significant. A significant change to the GFM (or a significant alternative interpretation) would be one that exceeds the expected window of uncertainty.

4.8.2.9 Geologic Framework Model Summary

The GFM is one component of the ISM, which also includes models of rock properties and mineralogy. The GFM provides a baseline representation of the locations and distributions of 50 rock layers and 43 faults in the subsurface of the Yucca Mountain area for use in geoscientific modeling and repository design. The input data from the geologic map and boreholes provide controls at the ground surface and to the total depths of the boreholes; however, most of the modeled volume is unsampled. The GFM is, therefore, an interpretation and a prediction tool rather than an absolute representation of reality. The model possesses an inherent level of uncertainty that is a function of data distribution and geologic complexity. Uncertainty in the model is mitigated by the application of sound geologic principles.

The GFM shows the distribution of the rock layers and faults that are of greatest interest to subsequent models. For instance, the PTn unit thickens dramatically to the northwest and thins rapidly southward in the vicinity of the ESF. The repository host horizon is several hundred feet thick in the vicinity of the ESF. The Calico Hills Formation thickens to an unknown maximum thickness toward the northeast. The Tertiary-Paleozoic unconformity, which is the top of the regional Paleozoic aquifers and aquitards, is poorly constrained by data but appears to deepen dramatically from east to west in the vicinity of the ESF. The unconformity is approximately 11,000 ft (3,353 m) below the repository host horizon.

4.8.3 Rock Properties Model

The RPM is the second of three components of the ISM. It describes the distributions of porosity, bulk density, saturated hydraulic conductivity, and thermal conductivity in the subsurface of Yucca Mountain. The RPM was calculated using geostatistical techniques and software, and was then integrated with the GFM to form part of the ISM. Additional details of the RPM are documented in the RPM analysis model report (CRWMS M&O 2000b). The RPM was constructed using geostatistical algorithms that are part of the public-domain GSLIB geostatistical subroutine library (Deutsch and Journel 1992, 1998). Model validation was conducted for the RPM (CRWMS M&O 2000b, Section 6.7).

4.8.3.1 Input Data

Seven different types of data were used as input to the RPM. Each type is discussed in more detail in the RPM analysis model report (CRWMS M&O 2000b, Section 4.1). The first four types are based on actual measurements of rock material properties in the laboratory or on geophysical measurements obtained in the field. The fifth type was derived from in situ geophysical measurements. The remaining two types were input to or derived from the GFM. These inputs are:

- Laboratory core porosity measurements (both relative humidity and oven dried)
- Computed petrophysical porosity data from downhole instruments
- Laboratory measurements of bulk density, matrix-saturated hydraulic conductivity, and thermal conductivity (Section 4.8.3.2.3)

- X-ray diffraction indicators of mineral alteration
- Petrophysical indicators of hydrous-phase mineral alteration
- Observed (measured) lithostratigraphic contacts
- Modeled lithostratigraphic contacts from the GFM.

4.8.3.2 Construction of the Model

This section provides a relatively high-level conceptual description of the geostatistical modeling approach. The methodology has been described in more detail in previous documents (Rautman and McKenna 1997, pp. 6 to 69; CRWMS M&O 2000b, Section 6.7).

4.8.3.2.1 Modeling Philosophy and Conceptual Approach

Because of the sheer scale of the model, measured subsurface data at Yucca Mountain are limited to only a small percentage of the modeled volume. Therefore, numerical models must assume some type of conceptual model for Yucca Mountain in order to assign rock properties to all relevant unsampled points in space. The conceptual model for the site makes use of the fact that Yucca Mountain is composed primarily of layered volcanic tuffs that were tilted and faulted after deposition. The approach to modeling rock properties attempts to strike a balance between the simplification of the hollow shell of the GFM and the great complexity of rock properties that are possible within that shell.

Geostatistical techniques (Deutsch and Journel 1992; Goovaerts 1997) were used to make predictions of heterogeneous material property distributions, consistent with the observed distribution of values in the sample data set. Because the actual properties at unsampled locations are unknown, the predictive process provides an assessment of the geologic uncertainty at unsampled locations. The consequences of geologic uncertainty can then be propagated through subsequent models relevant to assessing the waste isolation potential of a geologic repository at Yucca Mountain.

Figure 4.8-24 illustrates the geostatistical process for combining statistical description with the Monte Carlo generation of multiple replicate models. The replicate models can then be evaluated for performance consequences (Rautman and McKenna 1997, Figure 6). The models need to capture both heterogeneity and spatial correlation; the geostatistical simulation process is intended to do this.

Easily measured and widely distributed porosity data were used as a surrogate for other rock properties (derivative properties) that are of more direct interest for use in subsequent models, such as performance calculations, but for which measured values are relatively few or sparsely distributed. The conceptual assumption is that the spatial variation and trends in both porosity values and the derivative properties will be roughly the same, because all of the rock properties are related to the geologic processes responsible for formation of the rocks.

By assuming that the rock properties of interest were in place before tilting and faulting of rock layers, it is possible to model the properties in undeformed space (Figure 4.8-25). The

undeformed space is referred to as stratigraphic coordinates, and uses the same east-west and north-south coordinates as the boreholes from which the input data came. However, the vertical coordinate is proportional to the thickness of the entire unit. The stratigraphic coordinate concept positions samples from equivalent portions of the overall unit at the same nominal internal position within the rectangular volume.

4.8.3.2.2 Simulation of Porosity

Porosity values on a regular grid, which can be described in stratigraphic coordinates, were simulated using geostatistical techniques. The simulated porosity values were "conditioned" to the measured data (Rautman and McKenna 1997, pp. 11 to 13, 61 to 63). Geostatistical simulation comprises a large class of modeling techniques that can produce complex and reasonable models of rock properties. Simulation may be thought of as an expansion of input data in a stochastic (i.e., statistically random) manner that is also compatible with what is known about the data, including its actual values, statistical properties, and spatial locations. The simulation process assumes that property values at a location will tend to resemble the geologically nearest data value, and that values at progressively farther distances will resemble the data less. This process captures both spatial heterogeneity and spatial correlation. The resulting models exhibit three special statistical properties that are useful in evaluating the effects of geologic uncertainty:

- Known data values (e.g., from borehole samples) are reproduced at locations within the model that are the same as those of the actual samples.
- The full range of measurement variability of the known data values is reproduced.
- The bivariate statistics, or two-point spatial correlation structure, of the input data are reproduced.

The spatially distributed measured porosity data were used to develop a mathematical formulation of spatial continuity (or variability) expressed as a function of the distance and direction between the locations being compared. This mathematical model (or variogram) was provided as an input to the geostatistical simulator. It constrained the generation of simulated porosity values at different distances from the locations of measured porosity data.

The sequential gaussian simulation algorithm that was used to generate porosity values at all unsampled locations within the gridded model volume was implemented as follows (Deutsch and Journel 1992, pp. 123 to 125, 164 to 167):

- Measured porosity data were mapped into the model volume; sample values at a node in the stratigraphic coordinate grid were assigned to that node, and remained fixed.
- A sequential random path was defined to visit each unsampled node only once.
- At each node along this path, a search was conducted for nearby measured data and any previously simulated grid nodes.

- The nearby measured data and any nearby simulated values were then weighted by their geological distance (in contrast to simply their shortest distance), as defined in the stratigraphic coordinate system according to the variogram. Samples that are closer geologically (e.g., samples within the same lithostratigraphic subunit, such as a vitrophyre) were weighted more heavily than samples that may be in closer physical proximity but are geologically more distant (e.g., samples separated by thin interbeds that represent material erupted at a different time and cooled under different pressure-temperature conditions).

- The preceding process produced a locally conditioned, expected range of porosity values (a conditional distribution) for that grid node. A random porosity value was then drawn from that conditional distribution and assigned as the porosity at that node.

- The simulation advanced to the next node along the random path and the process was repeated.

Because porosity values were drawn at random from the conditional distribution at each unsampled grid node, the values obtained in different simulation runs are different. The weighting scheme used to develop the expected conditional distribution at each node in each independent simulation is also different. This is because the path through the three-dimensional grid was different in each successive simulation, and the data-search process considered previously simulated grid nodes as well as measured data (which is nonvarying). At grid locations that are well constrained by consistent measured data, the variability of the simulated values across a suite of simulations is small. However, at grid locations far from any conditioning or measured data, or at grid nodes that are in the vicinity of conflicting measurements, the spread of porosity values is quite broad.

Each of the 50 simulated porosity models is indistinguishable statistically from the others. At grid locations with measured porosity values, each model reproduces these values exactly. The values of porosity across the entire model reproduce the statistics of the input data. Each simulation reflects what is known from site characterization, and as a group they represent a range of geologically plausible porosity values.

4.8.3.2.3 Modeling of Derivative Properties

The volcanic rocks at Yucca Mountain were subjected to depositional and post-depositional processes that produced heterogeneous rock properties. For example, variations of cooling rates caused by local temperature and thickness conditions affected the resulting properties of the rock. Because rock properties can be attributed to geologic processes, they can be modeled by applying knowledge of these processes, and knowledge of the relationships between the resulting rock properties. For example, measurements on samples of densely welded rocks indicate that in addition to low porosity, they exhibit high bulk density, low hydraulic conductivity, and high thermal conductivity relative to other rocks at Yucca Mountain. Establishing and quantifying these relationships is the basis for the modeling of derivative properties. The models of derivative properties (based on porosity as a surrogate) were generated from the individual porosity simulations using a process known as linear coregionalization (Journel and

Huijbregts 1978, pp. 516 to 517; Luster 1985; Altman et al. 1996, pp. 54 to 59; Rautman and McKenna 1997, pp. 63 to 66). These derivative properties are:

- Bulk density
- Matrix-saturated hydraulic conductivity
- Thermal conductivity (for the Topopah Spring welded [TSw] model unit).

This process relates the simulation of the derived property to the mean and variance of the measured property values. Additional details are provided in the RPM analysis model report (CRWMS M&O 2000b, Section 6.4.5).

4.8.3.2.4 Expected-Value (E-type) Modeling

An expected-value model, or "E-type" estimate, is the arithmetic mean of all 50 simulations that were run. Because of the logistical difficulty of presenting 50 simulations for each of 19 unique property/model unit combinations (a total of 950 simulations), the results of the geostatistical simulation of rock properties are discussed in terms of the E-type estimate. These results are discussed in Section 4.8.3.3.

The E-type estimate preserves one of the three statistical characteristics of the simulations—the characteristic of reproducing the input data (Section 4.8.3.2.2). Because the E-type estimate is an average of 50 simulations, the other two statistical characteristics are not preserved. As a result, the E-type estimate grades more smoothly between input data values than do the individual simulations, and the apparent spatial continuity is greater. This effect is typical of virtually all interpolation algorithms (as opposed to simulation algorithms).

4.8.3.3 Model Results

The results of the model are discussed by modeling unit, from the shallowest (Paintbrush nonwelded [PTn]) to the deepest (Prow Pass Tuff [Tcp]). These discussions deal with the E-type models described above.

4.8.3.3.1 Paintbrush Nonwelded Unit

The variability of matrix porosity within the PTn model unit is shown on Figure 4.8-26, in both stratigraphic coordinates and perspective view. As indicated by the projection arrows on the figure, the vertically exaggerated rectangular volume in stratigraphic coordinates is back-transformed to ISM coordinates so that the material property values assume their correct positions within the tilted and faulted strata of Yucca Mountain. Porosity heterogeneity is also presented on Figure 4.8-27.

Porosity values within the PTn model unit are generally high, varying from about 30 percent to more than 60 percent (0.3 to 0.6). A region of low porosity (approximately 10 percent) is shown in the west-central portion of the model area, associated with borehole H-6 (see Figure 4.8-3 for borehole locations). Porosity values appear to be relatively continuous over distances of 5,000 to 10,000 ft (1,524 to 3,048 m), as expected from the variogram model. Porosity trends are generally anisotropic from northwest to southeast (top surface of the block diagram of Figure 4.8-26), also as expected from the variogram model.

Generally, bulk density (Figure 4.8-28) varies inversely with porosity, as expected from the strong negative correlation coefficient ($r = -0.91$). Bulk density values vary from less than 1.0 to nearly 2.0 g/cm^3 (62.4 to 124.8 lb./ft^3). Densities are generally low across the modeled area. Regions of higher density are associated with borehole H-6 (in the west-central part of the modeled area) and with borehole G-2 (near the northern boundary of the modeled area). At the G-2 locality, density exceeds 1.9 g/cm^3 (118.6 lb./ft^3) at two horizons, presumably corresponding to the Pah Canyon and Yucca Mountain tuffs, which are described as moderately welded in this vicinity (Maldonado and Koether 1983, pp. 57, 59).

Variability in matrix-saturated hydraulic conductivity values is shown on Figure 4.8-29. Hydraulic conductivity values are generally between 10^{-5} and 10^{-7} m/s (3.3×10^{-5} and 3.3×10^{-7} ft/s). Lower conductivities, on the order of 10^{-8} m/s (3.3×10^{-8} ft/s), are modeled in the vicinities of boreholes H-6 and G-2, coincident with the lower matrix porosities in these regions, from which the hydraulic conductivity values are coregionalized.

4.8.3.3.2 Topopah Spring Welded Unit

Heterogeneity of material properties within the TSw model unit is presented on Figures 4.8-30 to 4.8-36. It should be noted that matrix porosity, as indicated on Figures 4.8-30 and 4.8-31, is very low—mostly less than 10 to 15 percent (0.1 to 0.15)—and relatively constant in magnitude across the entire modeled region. This minimal variability is consistent with the definition of this unit as densely welded tuff. Figures 4.8-30 and 4.8-31 show an increased matrix porosity coincident with the major lithophysae-bearing intervals within the unit, and with the crystal-rich, nonlithophysal interval near the top of the unit.

The variability of lithophysal porosity, in contrast to matrix porosity, is shown on Figures 4.8-32 and 4.8-33. Although matrix porosity is generally low in this welded unit compared to that in a nonwelded interval (e.g., the PTn), maximum porosity values within the lithophysal intervals locally exceed 30 to 35 percent. Figure 4.8-33 clearly indicates two such intervals of high porosity, corresponding approximately to the upper and lower lithophysal lithostratigraphic units (Tptpul and Tptpll), separated by a low-porosity (on the order of 10 percent) interval equivalent to the middle nonlithophysal lithostratigraphic unit (Tptpmn). It should be noted, however, that there is a fairly large amount of lateral heterogeneity within each of the elevated porosity intervals. It is the measured porosity data that are responsible for both the apparent layering and the variations within the layers, as simulated values are propagated away from measurements at borehole locations. There are no detailed lithostratigraphic subunits explicitly modeled within the TSw model unit. All property heterogeneities in the RPM are functions of the measured material properties.

Bulk density variability, which is coregionalized from lithophysal porosity, is illustrated in Figure 4.8-34. Density values are typically above 2.0 g/cm^3 (124.8 lb./ft^3) throughout most of the relatively lithophysae-free region. Bulk density is particularly high (approaching 2.5 g/cm^3 [156.1 lb./ft^3]) in the lower parts of the TSw model unit, as indicated by the red colors on the figure. A prominent high-density interval is associated with the lower vitrophyre in the central part of the modeled region (corresponding approximately to lithostratigraphic unit Tptpv3). However, bulk rock density values associated with the upper lithophysal horizon in particular

may be as low as 1.5 g/cm^3 (93.6 lb./ft^3). The alternation of lithophysal and nonlithophysal intervals is clearly illustrated by the bulk density model.

Thermal conductivity is also coregionalized from lithophysal porosity in an effort to predict the thermal conductivity of volumes of rock influenced by the presence of lithophysal cavities. Figure 4.8-35 presents the E-type model of spatial heterogeneity in thermal conductivity. High values of thermal conductivity (greater than approximately 1.3 to 1.4 W/m-K, shown in yellow and orange tones) are associated with the lower portion of the TSw model unit and with the "middle nonlithophysal" lithostratigraphic unit (Tptpmn). Particularly high thermal conductivity values, approaching 1.5 W/m-K, are at the base of the TSw unit. In contrast, the most lithophysal portions of the unit appear to be characterized by bulk rock thermal conductivities of less than 1.0 W/m-K (blue and blue-green tones on Figure 4.8-35).

Variability in matrix-saturated hydraulic conductivity is presented on Figure 4.8-36, coregionalized from the matrix porosity model shown on Figures 4.8-30 and 4.8-31. Matrix conductivities are less than 10^{-11} m/s (3.3×10^{-11} ft/s) through much of the lower part of the model unit. As expected from the higher matrix porosity values associated with the lithophysae-bearing portions of the TSw model unit, matrix hydraulic conductivity values are also higher—10^{-9} to 10^{-10} m/s (3.3×10^{-9} to 3.3×10^{-10} ft/s) (yellow to green tones on Figure 4.8-36)—in these portions of the unit. Some of the higher conductivity values may also be associated with vapor-phase corrosion of the welded tuff within the crystal-rich nonlithophysal unit.

4.8.3.3.3 Calico Hills Nonwelded Unit

Variations in the matrix porosity of the Calico Hills nonwelded (CHn) model unit are presented on Figures 4.8-37 and 4.8-38. Porosity values are generally high (20 to 40 percent [0.2 to 0.4]) throughout the CHn, in contrast to the low porosity values typical of the overlying TSw model unit. In the CHn unit, a mass of particularly high porosity occupies the central portion of the modeled volume. Porosity values locally approach 50 percent within this region.

Variations in bulk density in the CHn model unit are presented on Figure 4.8-39. Density values vary from more than 2.0 g/cm^3 (124.8 lb./ft^3) to less than 1.3 g/cm^3 (81.2 lb./ft^3) depending on location, although the majority of this nonwelded unit exhibits limited variation in bulk density (1.5 to 1.75 g/cm^3 [93.6 to 109.3 lb./ft^3]). Generally, bulk density varies inversely with porosity, as anticipated from the coregionalization relationship.

Heterogeneity in matrix-saturated hydraulic conductivity for the CHn model unit is illustrated on Figure 4.8-40. Although hydraulic conductivity is derived by coregionalization with matrix porosity, the relationship between the two material properties is not completely straightforward because of hydrous-phase mineral alteration (predominantly zeolitic) within the unit. Matrix hydraulic conductivities are typically 10^{-6} to 10^{-7} m/s (3.3×10^{-6} to 3.3×10^{-7} ft/s) (orange to red tones) within the unaltered (vitric) portion of the CHn and typically less than 10^{-11} m/s (3.3×10^{-11} ft/s) elsewhere (blue). The block diagrams on Figure 4.8-40 indicate that vitric (to potentially devitrified) materials are limited to the upper portion of the model unit, and more particularly to the southwestern portion of the modeled volume. The overall geometry is a wedge of vitric (unaltered) material tapering to a feather edge toward the northeast. Zeolitic (altered) rocks are shown in tones of blue underlying and replacing the green-colored through

red-colored volume to the north. The saturated hydraulic conductivity of altered samples is essentially uncorrelated with matrix porosity. The lower portion of Figure 4.8-40 presents cross-sectional views of the hydraulic conductivity field within the model unit and illustrates some of the complex interfingering relationships of altered and unaltered rock types.

4.8.3.3.4 Prow Pass Tuff

Figures 4.8-41 and 4.8-42 present the spatial variability of matrix porosity within the Prow Pass Tuff (Tcp) model unit. Because the Tcp is mostly nonwelded, the porosity values are typically high, varying from 20 to nearly 40 percent (0.2 to 0.4) across large volumes of the model. Lower porosities, typically less than 15 percent, are present along the northern boundary of the modeled volume and as a poorly defined lobate mass that may correspond to the moderately welded portion of this unit, which is generally low within the east-central part of the region.

Variations in bulk density, shown on Figure 4.8-43, correlate with the variations in porosity described above. Densities in excess of 2.1 g/cm^3 (131.1 lb./ft^3) are displayed (in yellow shading to red) along the northern boundary of the model in the vicinity of borehole G-2. Densities on the order of 2.0 g/cm^3 (124.8 lb./ft^3) are also visible in the east-central portion of the block, corresponding to the low-porosity lobe. Elsewhere across the modeled volume, bulk densities are more typically between 1.75 and 2.0 g/cm^3 (109.3 and 124.8 lb./ft^3) (shown in green tones).

Heterogeneity in matrix-saturated hydraulic conductivity is presented on Figure 4.8-44. In a manner similar to the overlying CHn model unit, a bimodal distribution of conductivity values, corresponding to altered and unaltered rock types, is quite prominent. Lower hydraulic conductivity values, typically less than 10^{-10} m/s (3.3×10^{-10} ft/s), are associated with regions affected by hydrous-phase mineral alteration. Higher values of hydraulic conductivity, varying from 10^{-10} to 10^{-7} m/s (3.3×10^{-10} to 3.3×10^{-7} ft/s), are associated with the vitric-to-devitrified regions that are unaffected by alteration. The block diagram on Figure 4.8-44 indicates that the upper and lower margins of the Tcp are essentially completely altered. The cross-sectional views in the lower half of the figure indicate that the unaltered portions of the unit correspond to the devitrified interior of the ash flow.

4.8.3.4 Limitations and Uncertainties

This section presents the limitations and uncertainties associated with the RPM. First, a number of limitations, of both methodology and data, that restrict the accuracy of the models generated by this analysis are described. Next, the results of a stochastic uncertainty analysis are presented in an attempt to quantify the geologic uncertainty that results from sampling limitations (i.e., that it is impossible to sample the entire volume of the mountain).

4.8.3.4.1 Limitations

A number of limitations are best described as limitations of the data, or of the modeling process itself. These limitations include the following:

- Errors and biases in the sampling data used in the analysis
- The use of porosity as a surrogate for other material properties

- The combination of numerous lithostratigraphic units into the four major modeling units
- The effects of faulting and erosion on the use of the stratigraphic coordinate system.

These limitations are discussed in more detail in the RPM analysis model report (CRWMS M&O 2000b, Section 6.6.1).

Errors and Biases in Sampling Data–Measurement error (analytical uncertainty) in the input data is not considered to be a significant source of uncertainty in the RPM. The underlying assumption is that measurement error is small compared to the lateral variability of the rock mass. It is also assumed that any measurement errors are essentially unbiased; some may be a little high, whereas others may be a little low. Statistically, the errors are of mean zero with a small relative variance.

Systematic biases represent a more severe challenge for rock properties modeling that uses a geostatistical approach. Two examples of systematic bias within the data sets used for this modeling activity are known, and are described in the RPM analysis model report (CRWMS M&O 2000b, Section 6.6.1.1). They include measurement sensitivity limits and sampling bias of thermal conductivity values. These biases have been compensated for to some extent during creation of the individual simulated models.

Porosity as a Surrogate–A fundamental limitation of the rock properties modeling effort is the use of porosity as a surrogate for the derivative properties. These derivative properties, such as matrix-saturated hydraulic conductivity, are related to the principal modeled property (porosity) only through a correlation coefficient. The correlation coefficients for each derivative property are based on a limited number of samples, and may introduce uncertainty when applied to the entire modeled volume.

Another limitation induced through the "porosity-as-a-surrogate" mechanism involves some measured hydraulic conductivity values that are not correlated with porosity due to the presence of microfractures (CRWMS M&O 2000b, Section 6.6.1.2). These "out-of-porosity-character" permeability values are modeled as a random overprint imposed only on extremely low-porosity (less than 0.05) grid nodes (interpreted as representing vitrophyres).

Use of Major Stratigraphic Units as Modeling Units–Another limitation of the approach used in development of the RPM is the use of composite major stratigraphic units and an internal "stratigraphic coordinate system" as the geometric basis for modeling. Only four model units are used to represent many different lithostratigraphic subunits (Table 4.8-1). In the transformation of data to stratigraphic coordinates, it is possible that some data are not correctly positioned. Incorrectly positioned data may be correlated to dissimilar (nonequivalent) data, a lithophysal interval to a nonlithophysal interval, for example. If this occurs, uncertainty is increased in the simulations.

This limitation is probably of minimal effect within the major ash-flow units at Yucca Mountain, particularly for the TSw unit, which is effectively an instantaneous deposit of massive proportions. Although the TSw thins southward, the physical and chemical conditions responsible for the current material properties of the rock varied with relative vertical position within the cooling rock mass. The same logical argument applies to a large extent to the Tcp

modeling unit. Multiple-cooling-unit and interbedded intervals are potentially more affected by the use of composite major stratigraphic units.

Effects of Faulting and Erosion–Another limitation related to the use of a stratigraphic coordinate system is the presence of erosional unconformities or within-unit faulting. These conditions will affect the material-property equivalence of rocks assigned to the same stratigraphic (vertical) coordinate. For example, if undetected faulting or erosion juxtaposed rocks of differing material properties and they were sampled in adjacent boreholes, they would be assigned the same stratigraphic coordinate. However, the model compensates for this situation by correctly reflecting the higher variability around the juxtaposed input data. Simulated rock property values near the conflicting data will have greater variability over the 50 simulations run, indicating more uncertainty in the area of undetected faulting or erosion.

4.8.3.4.2 Stochastic Uncertainty Assessment

The rock properties modeling effort was designed to quantify the geologic uncertainty resulting from limited subsurface sampling. This geologic uncertainty translates into uncertainty in the material properties used in subsequent design and performance assessment analyses. The stochastic simulation process generated a total of 950 individual RPMs in this study, each of which reproduced the measured site data and exhibited the full range of heterogeneity and spatial continuity observed in the input data, as described in Section 4.8.3.2. This uncertainty in material properties can then be propagated into uncertainty in subsequent performance analysis, as shown in the conceptual representation of the geostatistical modeling process on Figure 4.8-24. In other words, across multiple simulations it is possible to account quantitatively for the performance or design consequences of geologic uncertainty by propagating plausible variations in material properties through numerical process models (e.g., flow and transport codes) to describe uncertainty in performance measures.

Expectations versus Individual Outcomes–For the E-type models, it should be noted that simply because a value is mathematically the most likely does not mean it is the appropriate value to use for a particular purpose. In fact, the expected value may be an unlikely value for any actual realization or outcome. The mathematical expectation of one-half, where zero is "heads" and one is "tails," does not mean that the most likely result of tossing a coin is to have it stand on edge. In a similar manner, an expected porosity value of 0.20 at a particular grid location does not necessarily imply that 0.20 is the porosity value that should be entered into a numerical flow and transport model at this location. It means that over a large number of individual simulated outcomes, the average simulated porosity at the location, which incorporated values that may have varied from 0.05 to 0.45, was 0.20.

4.8.3.5 Alternative Interpretations

At the time this report was prepared, no alternative interpretations to the RPM methodologies or results were documented.

4.8.3.6 Rock Properties Model Summary

The rock properties model is actually a large suite of individual models that are based on measured input data and use geostatistical techniques to simulate plausible distributions of

porosity, bulk density, saturated hydraulic conductivity, and thermal conductivity in the subsurface at Yucca Mountain. These models reproduce the input data at locations within the model that are the same as the actual sample locations, and preserve the full variability of the data and the spatial correlation structure of the data at simulated locations in each model. Each individual simulation is geologically reasonable, and there is no reason to prefer one over another. This is a measure of geologic uncertainty. The consequences of this geologic uncertainty can subsequently be evaluated by propagating variations in material properties through numerical process models to assess uncertainty in performance measures, such as radionuclide transport times.

4.8.4 Mineralogic Model

The MM is a three-dimensional, weighted, inverse-distance model developed for Yucca Mountain to support analyses of hydrologic properties, radionuclide transport, mineral health hazards, repository performance, and repository design. It was developed specifically for incorporation into the ISM and enables the prediction of calculated mineral abundances at any position in the ISM area. Ten mineral groups or classes were modeled in MM3.0:

- Sorptive zeolites (the sum of clinoptilolite, heulandite, mordenite, chabazite, erionite, and stellerite)
- Nonsorptive zeolite (analcime)
- Smectite and illite
- Volcanic glass
- Tridymite
- Cristobalite and opal-CT
- Quartz
- Feldspars
- Mica
- Calcite.

The model is discussed in detail in *Mineralogic Model (MM3.0)* (CRWMS M&O 2000c) from which the following summary is extracted.

The inputs for the MM consist of stratigraphic surfaces from GFM3.1, quantitative x-ray diffraction analyses of mineral abundances, and the potentiometric surface. The locations of boreholes that were the source of data used in the MM are shown on Figure 4.8-45.

4.8.4.1 Mineralogic Model Methodology

The MM was constructed using the following four sequential steps:

1. The ASCII-format export files from GFM3.1 were modified. Missing values in the vicinity of faults were supplied by interpolation. The missing values occur only in the ASCII-format export files, not in the GFM3.1 model grids.

2. The stratigraphic framework was created from 22 stratigraphic surfaces obtained from GFM3.1.

3. Mineralogic data from boreholes were incorporated into the three-dimensional stratigraphic framework. Quantitative x-ray diffraction analyses of mineral abundance as a function of geographic position (borehole location) and sample elevation were placed within the three-dimensional stratigraphic framework.

4. Mineralogic distribution data for the entire three-dimensional model were calculated using a deterministic, inverse distance weighting function. Measured mineralogic data at each borehole were used to predict mineral abundances at all locations in the model.

The MM consists of 22 volumetric sequences. Two sequences are subdivided to yield a total of 26 model layers. Each layer is represented by 45,756 (186 by 246) grid nodes or cells. For each cell, 16 values are provided, including percentage abundance for the 10 mineral groups, cell volume, cell location (x, y), elevation (z), sequence number, and layer number. Any cell in the model can be queried to obtain these values.

4.8.4.2 Assumptions

For the MM, it was assumed that sample collection methods for drill cuttings did not severely affect the mineral abundance data or the MM predictions based on those data. Therefore, mineral abundance data from drill cuttings were used as input for the MM. It was also assumed that mineralogy within a model unit is spatially correlated. The assumptions are discussed in Section 5 of the *Mineralogic Model (MM3.0)* (CRWMS M&O 2000c).

In addition to assumptions, the MM used certain methodological premises (stratigraphic coordinates and inverse-distance-weighting simulation) upon which the model construction was founded. Details of the application of these assumptions and methodologies are provided in Section 3.4.3 of the *Mineralogic Model (MM3.0)* (CRWMS M&O 2000c)

4.8.4.3 Incorporation of Mineralogic Data from Boreholes

The borehole data were incorporated into the model in a process that involved mapping the elevations of the mineralogic samples onto the stratigraphic elevations obtained from GFM3.1. At each borehole and for each sequence, an arithmetic mean was calculated from the mineralogic data, and these means were used to construct the MM.

The stratigraphic coordinate system was used in the construction of MM3.0. The advantages of the stratigraphic coordinate system are that all mineralogic data are correctly associated with a

sequence and that the stratigraphic relationship of data from differing boreholes is preserved. Mineralogic data were assigned to the correct sequence by making small adjustments to apparent elevations where needed (CRWMS M&O 2000c, Attachment II).

4.8.4.4 Calculation of Mineral Distributions

The final stage of the MM construction used a distance-weighting technique to estimate mineral distributions. Three-dimensional mineral distributions were calculated using an inverse-distance-weighting function that operates solely within sequences. The distance weighting function is defined in the *Mineralogic Model (MM3.0)* (CRWMS M&O 2000c, Section 6.2.4).

4.8.4.5 Model Results

In the following sections, the results of the modeling efforts for MM3.0 are discussed, and the model outputs are illustrated using cross sections and map views of individual surfaces. Results for nonsorptive zeolites (analcime), feldspars, mica, and calcite are not discussed because of their limited impact on radionuclide transport and design issues.

4.8.4.5.1 Sorptive Zeolite Distribution

The distribution of sorptive zeolites at Yucca Mountain plays a role on models of radionuclide retardation and thermohydrologic effects. Zeolite abundance is shown on Figure 4.8-46 as a range of colors from purple (0 percent) to orange (85 percent or greater). Abundance and occurrence of zeolite minerals within the MM model volume (clinoptilolite, heulandite, modenite, chabazite, stellerite, and erionite) are discussed in Section 6.3.2 of the *Mineralogic Model (MM3.0)* (CRWMS M&O 2000c).

Sorptive zeolites occur in varying amounts below the potential repository host horizon in four distinct stratigraphic groups that are separated by nonzeolitic intervals. Zeolite distributions with respect to the potential repository host horizon are displayed on Figures 4.8-47 and 4.8-48. The distribution of sorptive zeolites is closely related to the internal stratigraphy of the tuffs. They occur within the upper vitric, basal vitric, and basal bedded tuff units of each formation of the Crater Flat Group (Tram Tuff, Bullfrog Tuff, and Prow Pass Tuff). The devitrified middle portions of the Crater Flat Group tuffs lack zeolites. The net result is an alternating sequence of zeolitic and nonzeolitic rocks.

The MM also allows the position of zeolite-rich rocks relative to the water table to be examined. In a north-south cross section (Figure 4.8-47), zeolite-rich rocks separate the potential repository host horizon from the water table throughout the section shown. An east-west cross section (Figure 4.8-48) also shows zeolites occurring between the potential repository host horizon and the water table. Further east of this cross section (and east of the potential repository vicinity), faulting displaces the units downward so that Sequence 12 is below the water table and devitrified, nonzeolitic rock from the Topopah Spring Tuff is at the water table.

The progressive development of zeolitization from southwest to northeast is illustrated in a series of map views through the Calico Hills Formation (Tac; Sequence 11) and into the upper vitric Prow Pass Tuff (Tcpuv; Sequence 9) (Figures 4.8-49 through 4.8-54). The transition zone between regions of high (greater than 5 percent) and low (0 to 5 percent) zeolite abundance is an

important feature to model accurately because it may be a zone of enhanced radionuclide sorption below the potential repository. The presence of the zeolites clinoptilolite and mordenite is associated with increased radionuclide sorptive capacity (Vaniman and Bish 1995, pp. 537 to 538). However, the decreased permeability associated with zeolitization of moderately welded to nonwelded vitric tuff (Loeven 1993, Table 6) may inhibit interaction between fluid-borne radionuclides and zeolites in the rock matrix. Within the transition zone, zeolites are present but the rock should be more permeable than completely zeolitized rock would be. This higher permeability may therefore allow the radionuclides better access to sorptive minerals.

There is a striking reduction in zeolite abundance from east to west in the upper half of the Calico Hills Formation. The reduction occurs across a north-south boundary and is well defined in the region of boreholes WT-2 and UZ#16 (Figures 4.8-49 and 4.8-50). The location and abruptness of this transition are very poorly constrained to the north and west of borehole H-5, and moderately constrained to the south between boreholes WT-1 and G-3. Detailed examination of measured zeolite abundance in the lower half of the Calico Hills Formation, from boreholes SD-7, SD-12, and H-6 (Figures 4.8-51 and 4.8-52) indicates that the transition zone may be vertically and horizontally heterogeneous (CRWMS M&O 2000c, Section 6.3.2). This heterogeneity may be caused by a general reduction to the southwest, which has been overprinted by patchy intervals of highly zeolitized Calico Hills Formation.

The bedded tuff below the Calico Hills Formation (Tacbt; Sequence 10) is zeolitized in boreholes SD-7, WT-2, SD-12, and H-5 (Figure 4.8-53). The transition zone to low zeolite abundance is confined to the west and southwest, around boreholes SD-6, H-3, and G-3; however, borehole SD-6 contains about 15 percent smectite and perhaps should be viewed as a part of the zone of abundant sorptive mineralogy.

The upper vitric Prow Pass Tuff (Tcpuv; Sequence 9) has a zeolite distribution similar to that of Tacbt, except that there are data at borehole H-6 indicating abundant zeolites (Figure 4.8-54). In addition, borehole SD-6 lacks both smectite and zeolites, and borehole H-4 has a low abundance of zeolites (10 percent) in this sequence. Zeolitization is complete throughout the MM in Sequence 7 (Tcplv–Tcbuv), which includes the lower vitric and bedded tuffs of the Prow Pass Tuff and the upper vitric unit of the Bullfrog Tuff.

In general, the MM represents the transition zone between zeolitized and nonzeolitized areas as a rather sharp boundary modified by the local effects at particular boreholes. The southwest portion of the area, modeled as a whole, is characterized by low zeolite abundances (less than 10 percent). Values near 0 percent in the Calico Hills Formation (Tac; Sequence 11) are restricted to regions adjacent to nonzeolite-bearing boreholes such as G-3, H-3, and H-5. There is little control on the extrapolation of zeolite data in the northeast, northwest, and southeast regions of the MM. The predicted values of extensive zeolitization in the north are strongly influenced by boreholes such as G-1 and G-2. It is possible that any or all of these regions may be characterized by more moderate values of zeolitization.

4.8.4.5.2 Smectite and Illite Distribution

Smectite is a swelling clay with a high cation-exchange capacity and can be an important factor in calculations of radionuclide retardation (Vaniman et al. 1996). Where present in significant

amounts, it can act as a relatively impermeable barrier to fluid flow. Illites are clays with a higher layer charge than smectites, which reduces their effective cation-exchange capacity and eliminates their impermeable character. At greater depths, illite develops as a prograde product of smectite alteration, particularly in the northern and central portions of the MM (Bish and Aronson 1993, pp. 151 to 155).

Smectite and illite are present in low abundance throughout Yucca Mountain except in some thin horizons and at depth in the region of boreholes G-1 and G-2. The distribution of these minerals with respect to north-south and east-west cross sections constructed through the potential repository is shown on Figures 4.8-55 and 4.8-56, respectively. The X-ray diffraction analyses indicate the presence of smectite in virtually all analyzed samples, although typically in amounts of less than 5 percent. Volumes of smectite and illite increase at depth. Above the water table, there are two zones of up to 75 percent smectite in the Paintbrush Group. One is within the vitric nonwelded section above the Topopah Spring Tuff (PTn, Sequence 20), and the other is at the top of the basal vitrophyre of the Topopah Spring Tuff (upper layer of Sequence 13; Tptpv3–Tptpr2) (zones are too limited to show upon Figures 4.8-55 and 4.8-56). These smectites typically have nonexpandable illite contents of 10 to 20 percent (Bish and Aronson 1993, pp. 151 to 152). Beneath the water table (depths greater than 1,006 m [3,300 ft] below ground surface), there is abundant smectite and illite, but with a much higher illite content of up to about 80 to 90 percent (Bish and Aronson 1993, Figures 3 and 4, pp. 152 to 153). However, the illitic clays occur at such great depths that they are of little importance for transport modeling at Yucca Mountain.

4.8.4.5.3 Volcanic Glass Distribution

Volcanic glass is a highly reactive, metastable material that is readily altered in the presence of water to form assemblages including zeolites and clays. The distribution of volcanic glass relative to the potential repository location is an important factor in evaluating possible repository-induced mineral reactions and assessing their impact on repository performance. Volcanic glass is almost entirely restricted to regions above the water table at Yucca Mountain (Figures 4.8-57, 4.8-58, and 4.8-59). The location of the water table is displayed on Figures 4.8-47 and 4.8-48. The largest deposits of volcanic glass are in the PTn unit (Sequence 20), the lower vitrophyre of the Topopah Spring Tuff (top of Sequence 13; Tptpv3–Tptpv2), and in vitric, zeolite-poor regions of the Calico Hills Formation (Sequence 11; Tac) in the southwestern and western regions of the MM. The distribution of volcanic glass in the Calico Hills Formation is inversely correlated with zeolite abundance. Volcanic glass and zeolite do occur together in the transition zone between high- and low-abundance zeolite.

4.8.4.5.4 Silica Polymorph Distribution

The common silica polymorphs at Yucca Mountain include quartz, cristobalite, opal-CT (short-range cristobalite [C] and tridymite [T] stacking within otherwise amorphous hydrous silica), and tridymite. These minerals could affect potential repository performance because of their chemical reactivity, mechanical response to temperature, and potential impact on human health during mining operations.

Cristobalite and tridymite occur in the potential repository host horizon. Opal-CT is usually found in association with sorptive zeolites. Tridymite occurs above the water table and primarily above the potential repository host horizon, particularly in those parts of the Topopah Spring and Tiva Canyon tuffs where vapor-phase crystallization is common (Figures 4.8-60 and 4.8-61). Pseudomorphs of quartz that replace tridymite in deep fractures and cavities are evidence of the instability of tridymite under low-temperature aqueous conditions. Tridymite occurrences were interpreted as a possible limit on past maximum rises in the water table at Yucca Mountain (Levy 1991, pp. 483 to 484). Volumes of exceptionally high tridymite content are restricted to the upper strata within the Tiva Canyon and Topopah Spring tuffs, but these rarely exceed 20 percent.

Cristobalite is typically a devitrification product that is found in virtually every sample above the water table. As is evident on Figures 4.8-62 and 4.8-63, cristobalite and opal-CT are abundant in the devitrified tuffs of the Paintbrush Group. Occurrences below the Paintbrush Group units are primarily opal-CT in tuffs containing abundant sorptive zeolites. Cristobalite and opal-CT disappear at depth and are replaced by quartz-bearing assemblages. Quartz is common in the lower Topopah Spring Tuff and is abundant at depth in the Crater Flat Group (Figures 4.8-64 and 4.8-65).

4.8.4.6 Model Uncertainties and Limitations

The MM is limited by the distribution of boreholes from which mineralogic data are available. Figure 4.8-45 shows the distribution of boreholes used in developing the MM. The boreholes are confined to the central portion of the model area. Outside of this central area (indicated by the box in Figure 4.8-57), results are poorly constrained. This limitation should be kept in mind when considering the visualizations generated from the MM. The MM is also limited in the vicinity of faults where the resolution of fault geometry is poor. Accurate model results should not be expected adjacent to faults.

Several uncertainties are associated with the MM in regions distant from the boreholes. Given the currently available data, the location of the transition from vitric to zeolitic in the Calico Hills Formation is uncertain. There also is uncertainty related to the nature of the transition. It is unclear whether the depth to zeolitization decreases rapidly and smoothly along a well-defined front, or whether the zeolitized zones are interfingered with vitric zones along a highly irregular front.

The most important limitation of the modeling results is the scarce mineralogic data in the region beyond the western border of the potential repository. The uncertainty in the boundary regions of the MM also is elevated because of the limited number of sampling locations (Figure 4.8-45).

Quantitative mineralogic data from several boreholes were obtained primarily from cuttings rather than cores (all of WT-1 and WT-2, most of H-4, and smaller but important portions of H-3, H-5, and p#1). Drill cuttings have a tendency to average mineral abundance over a finite depth range, and the more consolidated rock fragments may be over-represented with respect to the softer, more friable rock fragments. It is difficult to predict the magnitude of the potential error without obtaining additional mineralogic data. However, the modeling process of the MM uses all of the available data, and this tends to reduce the impact of any single data point.

4.8.4.7 Alternative Interpretations

At the time this report was prepared, no known alternative interpretations to the MM methodologies or results have been documented.

4.8.4.8 Model Validation

Validation to provide the appropriate level of confidence for the MM was based on two criteria. First, the model was required to reproduce the input data. In this validation step, model-generated mineral abundance predictions (output) were compared against the input values at borehole locations where these data were available. The second criterion verified that the model predictions were reasonable, compared to input mineralogy from the surrounding or adjacent borehole sources. This validation step required that the mineral abundance values predicted by the model match the values measured in the adjacent boreholes. Details of the model validation are contained in Section 6.5 of the *Mineralogic Model (MM3.0)* (CRWMS M&O 2000c). For both criteria, the mineralogical abundances predicted by the MM were consistent with the variation observed for the input values. Therefore, in both cases the mineralogical abundances predicted by the model satisfied the model validation acceptance criteria.

4.8.5 Integrated Site Model Summary

The ISM comprises descriptive spatial models of rock layers, faults, rock properties, and mineral distributions in the subsurface of Yucca Mountain. The three types of models (GFM, RPM, and MM) are fully integrated into a spatial model (the ISM).

The GFM component of the ISM portrays the distributions of 50 rock layers and 43 faults. The volcanic units that make up Yucca Mountain are a geometrically complex assemblage of layers that vary in thickness in all directions. The major faults in the GFM form a network dominated by north-trending normal faults with down-to-the-west vertical displacements.

Rock properties were modeled using geostatistical techniques that produced a suite of 50 simulations possessing statistical properties identical to the input data set. The average of the 50 simulations is called the E-type model, and its character is smoother than any individual simulation. The rock property distributions in Yucca Mountain are spatially heterogeneous and complex, and highly dependent on stratigraphy.

The mineralogic model comprises three-dimensional models of mineral abundances in the GFM area within the framework of the GFM. Stratigraphic units in the MM consist of groupings of mineralogically similar units, and include all units modeled in the GFM. The minerals modeled are zeolite, cristobalite, tridymite, quartz, glass, feldspar, calcite, mica, smectite + illite, and analcime. The model of zeolites indicates the presence of zeolites beneath the entire modeled area. Uncertainty in the ISM can be summarized as increasing away from data and with depth.

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4.9 NATURAL RESOURCES

4.9.1 Introduction

This section reviews the assessments of the potential for natural resources within the geologic setting of Yucca Mountain. Natural resource assessments have focused on an area defined as the "conceptual controlled area" because of the requirements contained in the U.S. Nuclear Regulatory Commission regulation, 10 CFR Part 60, to define long-term boundaries for potential radionuclide releases. New requirements (proposed 10 CFR 63 [64 FR 8640]) have obviated the need for defining such an area. However, for the purposes of this summary and the *Natural Resources Assessment of Yucca Mountain, Nye County, Nevada* (CRWMS M&O 2000d), the area being discussed as the "conceptual controlled area" has been renamed the "natural resources site study area" (Figure 4.9-1).

This section includes a brief description of the natural resources—including metallic minerals, industrial rocks and minerals, hydrocarbons (petroleum, natural gas, oil shale, tar sands, and coal), and geothermal energy—known to occur in the region or that could reasonably be postulated to be present based on models of natural resource occurrence and by comparison with other areas of similar geologic setting. The region of similar geologic setting, for purposes of this assessment, is primarily the southern Great Basin. (Section 4.2 contains a discussion of the regional geologic setting).

Resource potential is difficult to predict because it depends on many factors, including economics (supply, demand, and cost of production), the potential discovery of new uses for resources, and the discovery of synthetics to replace natural resources. The evaluation used in this section is based on the present-day use and economic value of the resources; it does not predict future market trends or undiscovered uses for resources.

To provide a natural resource assessment of an area, it is important not only to know the geology of the site, but also the types of economic deposits and resource occurrences in the region. Some general statements concerning economic deposits in the region are presented below. Nevada ranked second in the United States in value of nonfuel (excluding oil, gas, coal, and geothermal) mineral production in 1996 (Nevada Bureau of Mines and Geology 1997, p. 3). Nevada leads the nation in the production of gold, Ag, Hg, and barite (Nevada Bureau of Mines and Geology 1997, p. 3). Gold is Nevada's leading commodity in terms of value (Nevada Bureau of Mines and Geology 1997, p. 3). Brucite, magnesite, clays, gemstones, gypsum, Fe ore, Pb, sand, gravel, and crushed stone are some of the commodities that also were, or are, produced in Nevada. Economic oil deposits occur in Railroad Valley in east-central Nevada. Geothermal resources occur in California and northern Nevada within the Great Basin.

4.9.2 Previous Studies and Assumptions

The Yucca Mountain Site Characterization Project reports on metallic minerals, industrial rocks and minerals, hydrocarbons, and geothermal energy resources were prepared under the quality assurance procedures in effect at the time and described in those reports.

4.9.2.1 Previous Studies

Many recent reports and U.S. Department of Energy-supported investigations are related to the assessment of natural resources at the Yucca Mountain site and, in general, the southern Great Basin. These include a Nevada Test Site resources assessment (Bell and Larson 1982), a Yucca Mountain Site Characterization Project environmental assessment (DOE 1986), the *Site Characterization Plan Yucca Mountain Site, Nevada Research and Development Area, Nevada* (DOE 1988), a land withdrawal evaluation (Castor et al. 1990), a regional compilation of resource deposits and occurrences (Bergquist and McKee 1991), a summary of the status of natural resource assessment for early site suitability (Younker et al. 1992), and a regional preliminary petroleum investigation by the U.S. Geological Survey (Grow et al. 1994).

More recent published reports specific to Yucca Mountain on various resource commodities include geothermal resources (Flynn et al. 1996), industrial rocks and minerals (Castor and Lock 1995), metallic and mined energy resources (Castor et al. 1999; CRWMS M&O 2000f), and hydrocarbon resources (French 2000). In addition, the *Natural Resources Assessment of Yucca Mountain, Nye County, Nevada* (CRWMS M&O 2000d) is a summary of these five reports; these reports provide the major basis for this section.

4.9.2.2 Assumptions

The basic assumption used in this assessment is that resources throughout the Great Basin, including the Yucca Mountain study area, are assessed on the basis of geological, geophysical, structural, and geochemical attributes that can be compared to the attributes of known economic deposits and resource occurrences in the Great Basin. It is also assumed that natural resources within the study area occur within similar geologic settings as those in other parts of the Great Basin. The final assumption is that natural resource assessment is based on established geologic and economic principles, and that these principles provide a valid assessment for the foreseeable future.

4.9.3 Metallic Mineral and Mined Energy Resources

Nevada is known for production of several metallic resources, including gold, silver, copper, mercury, and uranium (Nevada Bureau of Mines and Geology 1997, p. 3). Similarly, the Yucca Mountain region in the southern Great Basin contains deposits or potentially economic occurrences of these metallic minerals (Figure 4.9-1). The presence of these known deposits in the region and the identification of geologic features, including veins, rock alterations, and normal faults, at Yucca Mountain have led some writers to propose that the Yucca Mountain site may have metallic mineral deposits (Johnson and Hummel 1991, p. 15; Weiss et al. 1996, p. 2,081). However, these features are common throughout the southern Great Basin in many localities that do not have economic mineral deposits (Mattson et al. 1992, p. 19). Thus, their presence or absence alone is not considered to be a good indicator for the potential for metallic mineral resources. Extensive site characterization activities, including field studies, drilling, geophysical studies, and geochemical sampling, have been conducted to evaluate the natural resources potential of the site.

4.9.3.1 Comparison of the Geology of the Yucca Mountain Site with Mineralized Areas in the Region

The evaluation of the Yucca Mountain site relies on a comparison of the geology of the Yucca Mountain area to mineralized areas of similar geologic setting (Great Basin). Models of mineral deposition, along with geophysical and geochemical analysis of the Yucca Mountain area, aid in these comparisons.

Rocks found at the surface in the Yucca Mountain area are a relatively unaltered sequence of vitric to devitrified ash-flow tuffs separated by bedded tuffs (Section 4.5). Physical examination of Tertiary volcanic rocks collected at depth in the north part of the Yucca Mountain site contain features that are suggestive of hydrothermal activity, such as clay mineral assemblages, pyrite and barite in veins, and alkali feldspar. However, there is no direct evidence for mineralization of these rocks, and they do not contain known economic precious metal deposits (Castor et al. 1999, pp. 157 to 159). Yucca Mountain drillhole samples were collected from portions of rock core with alteration and vein mineralogy similar to that which has been found elsewhere in some known mineralized areas. However, subsequent geochemical analyses exhibited low concentrations of pathfinder elements, and had low Au, Ag, and base metal contents. (A pathfinder element is an element that might indicate the possible association of more economically viable metallic elements or resources such as gold).

Castor et al. (1990, p. 69) argued that the pattern of faulting in the southwestern part of the site was substantially different from that in precious metal mining districts in the region. Detailed geologic mapping indicates that faults exposed at the surface in the site area are generally subparallel; therefore, fault intersections, which are usually important mineralization controls, are relatively rare in the Yucca Mountain area (Castor et al. 1999, p. 77).

It appears that the alteration and mineralization that followed the deposition of the Paintbrush Group (Section 4.5.4.7), and that are present within a few kilometers of the Yucca Mountain site in the Calico Hills and in Claim Canyon, do not extend into the Yucca Mountain natural resources site study area (Castor et al. 1999, p. 158). Although hydrothermal activity that has produced economic or potentially economic mineralization in the region occurs in volcanic rocks to the west, north, and east of the Yucca Mountain site, no clear evidence exists for extension of these episodes of mineralization into the potential repository area.

The presence of pre-Paintbrush Group hydrothermal activity at depth in the northern Yucca Mountain area has been suggested by Weiss et al. (1996, p. 2,081) to be a potentially important factor in the evaluation of the Yucca Mountain area for epithermal precious metal deposits. The implication is that the younger, relatively unaltered Paintbrush Group rocks in the Yucca Mountain area may overlie, and thus mask, areas of precious metal mineralization in the Crater Flat Group and older rocks. However, analyses of samples obtained from the Paintbrush Group in the northern Yucca Mountain area indicate that, in general, precious metal contents are not elevated or anomalous. Locally higher elevations of precious metal contents demonstrate that local hydrothermal activity took place during Crater Flat Group magmatism but do not provide direct evidence for an episode of precious metal mineralization at that time (Castor et al. 1999, p. 158). Weiss et al. (1996, p. 2,088) noted that Yucca Mountain is not attractive for present-day mineral exploration when compared to the nearby Bare Mountain, Calico Hills, and Wahmonie

areas. However, he stated that similarities in stratigraphy, structure, some vein and alteration mineral assemblages, and geochemistry between the natural resources site study area and some economically mineralized areas are evidence that precious metal deposits could be present (Weiss et al. 1995, pp. 3 to 13; 1996, p. 2,088). Based on the discussions in Castor et al. (1999, p. 177), the potential for volcanic rock-hosted epithermal precious metal deposits at depth (in excess of 700 m or more) in the natural resources site study area cannot be completely ruled out. However, it probably could not be mined economically at such depths. An extensive evaluation of such comparisons was presented in Castor et al. (1999, Section 5.3, pp. 76 to 81).

4.9.3.2 Potential for Economic Metallic Resources at the Yucca Mountain Site

On the basis of studying the geology, mineralogy, petrography, mineral alterations, geophysical data, remote sensing imagery, and results of chemical analyses of samples collected in the Yucca Mountain natural resources site study area by Castor et al. (1999, p. 176) there is little substantive evidence for economic mineralization. Results of geochemical analyses indicate that no ore-grade occurrences of metallic resources have been identified, with the single exception of tin. The estimated reserves of tin, however, are very low. On the basis of field examination, these occurrences appear to be scattered, of minimal size, and of fumarolic origin, and thus have little potential for depth extension. A select sample containing about 3.1 percent tin was collected from one occurrence in the south part of the Yucca Mountain natural resources site study area (Castor et al. 1999, Sections 5.7.2, p. 142, and 6.2.10, p. 165; CRWMS M&O 2000f, p. 4).

Additional work was initiated in fiscal year 1998 to address anomalous values obtained from geochemical analyses for metallic elements, particularly for anomalous values of tin and gold obtained prior to 1998. The work included detailed examination and resampling of surface, underground, and drillhole samples in the Yucca Mountain area.

In the Yucca Mountain area, the only known mass of rock with possible economic levels of tin is found in a shallowly east-dipping zone of silicified rock. Elevated values of tin were used to define a "tin anomaly area" located about 1,500 m (4,921 ft) south of drill holes USW G-3 and USW GU-3 (CRWMS M&O 2000f, p. 4, Figure 1, Plate 1) (Figure 4.9-2). Of the 75 samples collected from the tin anomaly area, only nine contained 25 ppm or more of tin and these are considered clearly anomalous (CRWMS M&O 2000f, p. 7, Appendix 3B). On the basis of geological mapping, an upper estimate of the volume of this rock mass is 1,000 m^3 (1,308 yd^3) (CRWMS M&O 2000f, pp. 7, 29, Figure 2). This is conservatively valued at $200,000, based on current tin prices of less than $4 per pound. This value appears to be too low to cover even the cost of obtaining permits for a modern mining operation (CRWMS M&O 2000f, p. 29).

Gold anomalies as high as 9 ppb were identified in Trench 14 (Exile Hill) in some samples of calcrete (Castor et al. 1999, p. 137). However, because these samples have formed as a result of pedogenic processes (Section 4.4.5) and are of limited extent, they do not represent a potential economic resource. Low level gold anomalies as high as 15 ppb are found in samples of fault gouge and breccia from trenches in the north part of the Yucca Mountain natural resources site study area several hundred meters northwest of borehole USW G-2 (CRWMS M&O 2000f, p. 29) (Figure 4.9-2). These samples contain minor amounts of smectite and show some weak iron oxide staining, but are otherwise unaltered and not mineralized. These weakly anomalous

gold values do not appear to constitute an economic resource. Gold veins exposed in Claim Canyon, north of the site, contain gold anomalies in the 1 ppm range and represent occurrences that are too small in tonnage to be economic resources. The occurrences are found in small banded-quartz veins in an area of altered rock about 800 by 200 m (2,625 by 656 ft) in the Claim Canyon area. There is some potential for low-sulfudation epithermal gold deposits beneath the surface in the Claim Canyon area. The area is located well north of the potential repository site (2 km [1 mi.] north of the north end of the Yucca mountain natural resource study area). The potential for gold mineralization for the Claim Canyon area remains unproven with current information (CRWMS M&O 2000f, p. 30, Figure 4).

The highest amount of U found at the site (63 ppm; Castor et al. 1999, p. 170) is far below what would be considered ore in today's market (at least 1,000 ppm), and the likelihood of economically mineable, concealed U deposits at Yucca Mountain is extremely low (Castor et al. 1999, pp. 170, 177).

4.9.4 Industrial Rocks and Minerals Resources

The Yucca Mountain region contains many occurrences of economic or potentially economic industrial rocks and minerals (Castor and Lock 1995, p. 1). The Great Basin terranes include resources of alunite, basalt, feldspar, gemstones, gypsum, kyanite, lithium, mica, pyrophyllite, quartz and quartzite, salt (salines and brines), sandstone, silica sand, sodium compounds (sodium carbonate and sulfate), sulfur, turquoise, and wollastonite.

Deposits with past or current production in the region near Yucca Mountain include borate minerals, building stone, clay, construction aggregate, fluorspar, silica sands, and zeolites (Figure 4.9-3) (Castor and Lock 1995, p. 1). The potential for industrial mineral resources in the Yucca Mountain natural resources site study area was assessed by Castor and Lock (1995) and the following discussions are summarized from their report and CRWMS M&O (2000d).

Most of the industrial mineral production in the region surrounding the Yucca Mountain site has originated from four mining districts: Bare Mountain, Bullfrog, Ash Meadows, and Death Valley (Castor and Lock 1995, p. 3). The first two districts produced primarily precious metals, whereas Ash Meadows and Death Valley are solely industrial mineral districts (Castor and Lock 1995, p. 3). The Bare Mountain, Bullfrog, and Ash Meadows districts are shown in Figure 4.9-1. The region of the Death Valley district is shown on Figure 4.9-3 and is located near Furnace Creek.

Barite, clay minerals, fluorite, and zeolites have been identified in samples from Yucca Mountain (e.g., Caporuscio et al. 1982, p. 1; Scott and Castellanos 1984, pp. 58 to 62; Bish 1989, pp. 1 to 2; Broxton, Bish et al. 1987, p. 89). Building stone, construction aggregate, limestone, pumice, silica, and vitrophyre/perlite can also be found at Yucca Mountain and are discussed below.

4.9.4.1 Barite

Barite occurs sporadically in core from boreholes at the site (Castor and Lock 1995, p. 60). Minor amounts of barite found in boreholes occur in some thin veins at depths of 1,200 m (3,937 ft) or more beneath the surface of Yucca Mountain. However, the Yucca Mountain area

is considered to have little or no potential for barite production because these barite occurrences are minor, of limited extent, and occur at such great depths.

4.9.4.2 Building Stone

Considerable amounts of Tertiary ash-flow tuff are accessible at the surface for use as building stone (Castor and Lock 1995, p. 55). The likelihood of excavation of this ash-flow tuff for building stone depends on intangible factors, including future demand for particular colors and textures of stone. The tuff at the site does not appear to have unique properties, either physical or aesthetic, that would make it especially valuable as a decorative dimension stone when compared with tuffs outside the Yucca Mountain site that are abundant in the region and located closer to current population centers.

4.9.4.3 Clay

Both sepiolite and smectite group clays have been identified in samples from Yucca Mountain. Sepiolite occurs in extremely small amounts and cannot be considered an economic resource (Castor and Lock 1995, p. 26). Although smectite is ubiquitous, it occurs in relatively small quantities at the Yucca Mountain site except for two zones of smectite enrichment. The uppermost zone occurs between the Topopah Spring and the overlying Tiva Canyon tuffs. Based on an evaluation, it is not considered an economic resource because the extent of the resource is not of sufficient size to make it marketable given the large extent of readily available clay resources in the region (Castor and Lock 1995, p. 26). The deep zone does not crop out within the natural resources site study area but has been located in boreholes at depths greater than 305 m (1,000 ft). Most of the calculated subeconomic resource is too deep to make acceptable strip ratios for clay mining. In addition, the grade of most of the material at locations shown on Figure 4.9-3 is insufficient to compete with readily available sources of clay in the region (Castor and Lock 1995, p. 28).

4.9.4.4 Construction Aggregate

The canyons and alluvial fans at the Yucca Mountain site contain minor amounts of high-quality construction sand and gravel (Castor and Lock 1995, p. 47). Most of the detritus in these sands and gravels is probably sound, durable welded ash-flow tuff; however, some structurally inferior nonwelded and bedded tuff fragments are probably also present. Abundant welded ash-flow tuff bedrock exposures at the site undoubtedly include material that has adequate soundness and durability for many of the uses of crushed stone. For concrete aggregate, alkaline reactivity problems that are commonly associated with silicic rhyolite may make sand, gravel, and bedrock deposits at the site less desirable. It should be noted that any use of these materials would only involve surface-disturbing activities that would not be likely to affect the functioning of a repository. Under present circumstances, the Yucca Mountain site has little or no potential for production of construction aggregate (Castor and Lock 1995, p. 49). Large amounts of sand and gravel and bedrock that are usable for construction aggregate are present closer to the Las Vegas area. However, if repository rail service into Las Vegas were used for haulage, the potential for crushed stone production from Yucca Mountain cannot be discounted (CRWMS M&O 2000d, p. 58).

4.9.4.5 Fluorite

Small amounts of fluorite have been identified in core and cuttings from boreholes in the Yucca Mountain natural resources site study area (Castor and Lock 1995, p. 19). Fluorite-bearing veins in the volcanic stratigraphic sequence at the site are thin and contain only small amounts of fluorine. No fluorite was identified during the surface appraisal performed for the natural resources assessment (Castor et al. 1990, p. 71). Although fracture-coating fluorite was found in core at depths as shallow as 318 m, thicker veins that carry fluorite (up to 1 cm [0.4 in.] thick) occur at or below 970 m (3,182 ft). None of the reported occurrences of fluorite found in core and cuttings from the natural resources site study area are of sufficient grade or tonnage, or at a shallow enough depth, to constitute an economic resource (Castor and Lock 1995, pp. 20 to 21).

4.9.4.6 Limestone

Limestone or dolomite, although abundant in the surrounding region, does not crop out in the Yucca Mountain natural resources site study area (Day, Potter et al. 1998a), but does occur at depths greater than 1,240 m (4,068 ft) east of the site at drill hole USW-25 p#1 (Carr, M.D. et al. 1986, pp. 16 to 17) (Figure 4.9-2). Given its low unit value, economic extraction of limestone and dolomite is not possible at these depths. The Yucca Mountain natural resources site study area is considered to have no potential for production of limestone or dolomite (Castor and Lock 1995, p. 89).

4.9.4.7 Pumice

No occurrences of economic pumice or pumicite are known to occur in the Yucca Mountain natural resources site study area, and the pumiceous material that is present in the Paintbrush Group appears to be too consolidated or impure for commercial use. In addition, large resources of domestic pumice and pumicite are readily available in a relatively stable, long-term market. Therefore, it is highly unlikely that new pumice or pumicite mines will be opened in the near future. The potential for pumice or pumicite production from the Yucca Mountain site is considered to be low (Castor and Lock 1995, p. 71).

4.9.4.8 Silica

Neither the thin silica veins encountered in drill holes nor the impure siliceous breccia found on the surface can be considered to have commercial significance as sources of silica (Castor and Lock 1995, p. 77). Volumetrically significant deposits of high-grade silica are not known to occur at the Yucca Mountain site and it is not considered to have any potential for silica production.

4.9.4.9 Vitrophyre/Perlite

The geologic environment for vitrophyre/perlite is glassy silicic domes, flows, or intrusions. No exposures or drillhole intercepts of this geologic environment have been recorded in the Yucca Mountain natural resources site study area, although these rocks are present a few kilometers to the north in the rhyolite of Fortymile Canyon (Scott and Bonk 1984, p. 1). The site contains some dense vitrophyric welded ash-flow tuff layers that may contain expandable perlite; however, it is unlikely that these layers will be mined because they occur at depth and there are

large quantities available in near-surface locations outside the Yucca Mountain area (Castor and Lock 1995, pp. 65 to 67).

4.9.4.10 Zeolites

A large subeconomic resource of zeolite is present at Yucca Mountain (Castor and Lock 1995, p. 40); however, the stratigraphic units that contain this estimated resource do not crop out within the Yucca Mountain natural resources site study area (Day, Potter et al. 1998a). Although zeolitized rock may reach the surface along the northeast border of the natural resources site study area, the zeolite, for the most part, is covered by a considerable thickness of tuff (about 500 m [1,640 ft]) containing little or no zeolite. Because zeolite deposits are mined by open-pit methods, the amount of overburden is an important factor. The zeolite subeconomic resource at the Yucca Mountain site occurs at depths that render commercial extraction unlikely. The deposit is economically unattractive when compared with the large amounts of readily extractable, higher grade zeolite elsewhere in the western United States.

As noted by Papke (1972, pp. 27 to 28), zeolite deposits of the type that are present in tuff at Yucca Mountain are extensive in Nevada and have economic potential only for uses that require impure materials of relatively low unit value. Given their low commercial value, relatively low grades, and the unfavorable mining situation, it is not likely that zeolites at the Yucca Mountain site will be commercially attractive in the foreseeable future (Castor and Lock 1995, p. 41).

4.9.5 Hydrocarbon Resources

Hydrocarbons are compounds containing the elements hydrogen and carbon. They may exist as solids, liquids, or gases. Hydrocarbon resources include oil, natural gas, tar sands, oil shale, and coal resources that can be economically extracted.

Brief discussions on oil and gas potential are presented as part of general resource evaluations in Bell and Larson (1982, p. 19) and Castor et al. (1990, pp. 72 to 73). Papers by Aymard (1989), Chamberlain (1991), Barker (1994), Grow et al. (1994), Cashman and Trexler (1995), and Trexler et al. (1996) have presented information aimed more directly at making an evaluation. Numerous papers on commercial and noncommercial occurrences are in Schalla and Johnson (1994) and other publications of the Nevada Petroleum Society. The following section is based primarily on French (2000) and CRWMS M&O (2000d). Local wells in the vicinity of the Yucca Mountain site reviewed for hydrocarbon potential are shown in Figure 4.9-4.

4.9.5.1 Oil and Gas

The conditions of source, reservoir, trap, and seal that characterize petroleum accumulations of the Great Basin are present, with variations, in the Yucca Mountain area. Most of the variations, however, indicate that the accumulation of oil and gas at the potential repository site is not likely (French 2000, p. 34).

Mississippian age and Tertiary age source rocks have generated the oil that is commercially produced in the Great Basin (French 2000, p. 34). Likewise, potential source beds have been identified in the Mississippian stratigraphy of the Yucca Mountain area. However, based on the conodont color alteration index of Ordovician-Silurian samples obtained from borehole

UE-25p#1, Mississippian source rocks at Yucca Mountain are at an advanced state of maturity compared to counterparts in the area of Railroad and Pine valleys (CRWMS M&O 2000d, pp. 69, 131). This complicates the identification of a generation site in the vicinity of Yucca Mountain. Whereas the generation of oil is a relatively recent and ongoing process in the producing areas, accumulations at Yucca Mountain that originated from Mississippian source rocks would likely be a product of generation from a site that was folded and faulted during periods of tectonic deformation. Section 4.2 contains a discussion of regional tectonic history, and Tables 4.2-1 and 4.2-2 illustrate the timing of deformation relative to sediment deposition. Tertiary source rocks are present in the Yucca Mountain area, but little is known about them. They may be present in the Crater Flat basin, where they could be buried adequately for generation of oil and gas to occur. Comparable circumstances exist in Railroad Valley, where early Tertiary source rocks have generated the oil produced at Eagle Springs Field, and in the Great Salt Lake, where oil from Neogene age source rocks is produced.

Reservoir rocks of the Yucca Mountain area compare favorably with those of the producing areas of the region. Paleozoic carbonate rocks, early Tertiary limestone, middle Tertiary ash-flow tuffs, and late Tertiary debris slides and basalt are proven reservoirs in the region and have counterparts in the vicinity of Yucca Mountain. In addition, cavernous porosity is present in a wider range of stratigraphy around Yucca Mountain than in the producing areas.

The most important sealing horizon in the Great Basin, the unconformity at the base of the valley fill, is absent at Yucca Mountain. An unconformity is present in Crater Flat, where it could act as a seal for accumulations in volcanic rocks, but it is dissimilar to the unconformity of the producing areas. Because Crater Flat basin began to form during the deposition of the Tertiary volcanic sequence, these rocks became part of the basin-fill section. Consequently, the unconformity is difficult to identify as a discrete horizon representing a single continuous span of time at Crater Flat. This contrasts sharply with Railroad Valley, where there is a significant time break between the cessation of deposition of volcanic strata and the onset of deposition of syntectonic basin-fill sediments (French 2000, p. 16).

Faults present at Yucca Mountain are similar to productive fault-block traps elsewhere in the Great Basin. Certain special circumstances, like the faulted debris slides that produce at Kate Spring Field, have been eroded from Yucca Mountain, but are present in the Crater Flat basin to the west.

The basic elements of a viable petroleum system are present in the Yucca Mountain area; therefore, the petroleum potential is not zero (French 2000, p. 39). In comparing the Yucca Mountain area to known producing fields in the region, the area that could contain a potential generation site with a volume of potential source rock is limited compared with the productive basins in the region. In addition, one of the important seals of the region is not well developed in the Yucca Mountain area. The conditions of source, reservoir, trap, and seal that characterize petroleum accumulations of the Great Basin are present, with variations, in the Yucca Mountain area. Most of the variations, however, indicate that the accumulation of hydrocarbons at the potential repository site is not likely (French 2000, p. 34). Thus, the area of Yucca Mountain is considered to have low potential for the accumulation and preservation of liquid petroleum (Grow et al. 1994, p. 1314).

4.9.5.2 Tar Sands

Tar sands are not exposed in rocks at or in the area surrounding Yucca Mountain, and it is extremely unlikely that they would be concealed at depth below Yucca Mountain (Castor et al. 1999, p. 172). In the unlikely event that tar sands were present at Yucca Mountain, they would have to be found in the Paleozoic marine rocks that occur at depths of 1,800 to 2,100 m (5,906 to 6,890 ft) or greater beneath Yucca Mountain (Brocher et al. 1998, Figure 7). Conventional recovery methods for tar sands require surface mining and processing of large volumes of rock. Mass mining underground at such depths is not economically feasible now or in the foreseeable future.

4.9.5.3 Oil Shale

The kinds of Paleozoic rocks that underlie the Yucca Mountain site are not known. In addition, it is not certain if rocks with a depositional environment compatible with the depositional environment of known oil shales are even present at depth under Yucca Mountain. Even if they are, they have probably been heated, with consequent loss of hydrocarbons. In the unlikely event that oil shales of some richness do occur under Yucca Mountain, the minimum depth to such rocks in the Yucca Mountain area is at least 1,800 to 2,100 m (5,906 to 6,890 ft) beneath the Yucca Mountain site (Brocher et al. 1998, Figure 7). Such speculative deposits would have to be mined by underground methods at those depths, which is unlikely until other, more cost-effective energy sources (including rich surface oil shales in the United States) are near exhaustion. Economic conditions in the United States have not yet warranted exploitation of rich oil shales, such as those exposed at the surface in the Green River Formation of Wyoming. Thus, if any oil shales are present at the Yucca Mountain site, exploitation is not economically feasible for the foreseeable future (Castor et al. 1999, p. 173).

4.9.5.4 Coal

There are no reports of coal deposits in the vicinity of Yucca Mountain (Castor et al. 1999, p. 174). It seems unlikely that any coal beds of significance would not have been discovered because coal was actively sought during early mining and mineral exploration of the western United States.

Economic coal deposits are usually found in lacustrine deposits. No coal or coal-bearing Tertiary sedimentary rocks have been encountered in drill holes on and adjacent to Yucca Mountain (Castor et al. 1999, p. 175). In the Yucca Mountain area, rocks younger than about 15 Ma are almost entirely volcanic in character, consisting of Miocene ash-flow tuffs, flows, and associated bedded pyroclastic rocks. No significant lacustrine units from this sequence are known in the site area (Section 4.4.3.3; Table 4.4-3). Regionally, no known coal is present in the Paleozoic strata and if it were to occur at the Yucca Mountain site, it would have to be located at depths greater than 1,800 to 2,100 m (5,906 to 6,890 ft) (Brocher et al. 1998, Figure 7). Economic extraction at these depths would not be feasible in the foreseeable future.

4.9.6 Geothermal Resources

The term "geothermal" pertains to the heat of the earth's interior. Geothermal energy is extracted from the earth's internal heat. Near-surface internal heat can be exacerbated by several

processes, including subsurface magma chambers, crustal thinning, and convective groundwater flow. An economic geothermal resource must have, at a minimum, a continual source of heat and fluid (groundwater), a way to reheat the fluid after its heat has been drawn off during commercial use or to heat new fluid if the fluid is not reused, and a pathway to get the heated fluid to the power generation plant or other user. Geothermal resources can be assessed on the basis of geologic indicators: for example, the presence or absence of late Tertiary or Quaternary volcanism; abnormally high heat flow; geysers, fumaroles, mud volcanoes, and thermal springs; siliceous sinter; elevated silica content of spring water; the sodium/potassium ratio in spring water; and porosity and permeability of reservoir rocks (Flynn et al. 1996, p. 1). Electrical, magnetic, gravity, airborne infrared, and other geophysical surveys may be used. The sections below are based primarily on Flynn et al. (1996) and CRWMS M&O (2000d).

4.9.6.1 Potential for a Magmatic Heat Source

Magma bodies below larger calderas (more than 10 km [6.2 mi.] in diameter) cool slowly and may be heat sources for up to 2 m.y. (Wohletz and Heiken 1992, p. 160). Silicic volcanism in the Yucca Mountain area ended more than 11 Ma, so there is little potential for a heat source from this mechanism. Minor volumes of recent basalts (Section 12.2) are present, but because these occurrences are of small volume and occur in isolated pockets there is little potential for a heat source to yield economic geothermal resources at Yucca Mountain.

4.9.6.2 Hydrology and Heat Flow

The temperature gradient at Yucca Mountain is low or below average. Heat flow at Yucca Mountain is less than 60 and as low as 30 mW/m^2 (Sass, Lachenbruch, Dudley et al. 1988, pp. 36 to 37, Table 5), which is much less than the Basin and Range average (100 ± 20 mW/m^2) or the regional heat flow (about 85 mW/m^2) (Sass, Lachenbruch, Dudley et al. 1988, p. 44). For deep holes (approximately 300 to 600 m [984 to 1,968 ft] deep) with minimal hydrologic disturbance, the temperature gradient is on the order of 30°C/km (139°F/mi.) (Sass, Lachenbruch, Dudley et al. 1988, pp. 38 to 39, Table 6). The highest temperature measured at Yucca Mountain is 62°C (144°F), at about 1,800 m (5,906 ft) depth in borehole USW H-1 (Sass, Lachenbruch, Dudley et al. 1988, Appendix I, p. 73, Figure 1-13) (Figure 4.9-2). Temperatures, thermal gradients, and heat flow at Yucca Mountain vary over small distances vertically and laterally (i.e., small wavelength), indicating dominance of relatively shallow hydrologic factors (Sass, Lachenbruch, Dudley et al. 1988, pp. 24, 31, 42). The water table at Yucca Mountain is generally 500 to 700 m (1,640 to 2,297 ft) beneath the surface, and the temperature at the water table ranges between 29° and 39°C (84° and 102°F) (Sass, Lachenbruch, Dudley et al. 1988, Appendix I, pp. 66, 67, 69 to 81, Figures 1-6, 1-7, 1-9 to 1-21).

4.9.6.3 Indirect Indications of Potential Geothermal Systems

In addition to direct observations of a geothermal system, the presence of a potential geothermal system can be assessed through indirect observations of thermal springs and spring deposits, stable isotopes, and chemical geothermometers. There are no geysers, fumaroles, or hot springs nearby and the lack of siliceous spring deposits at Yucca Mountain suggests that no thermal fluids from high-temperature reservoirs have discharged to the surface in the study area in the last 1.6 m.y. (Flynn et al. 1996, p. 28).

Because there are no active surface thermal features in the Yucca Mountain natural resources site study area such as hot springs and fumaroles, the discussion of a detailed relationship between gravity and geothermal activity is speculative at best (Flynn et al. 1996, p. 65). Available information on spring deposits in the southern Great Basin indicates that presently flowing or preexisting springs are or were only moderately warm (probably 30° to 40°C [86° to 104°F]). There is no indication from geological, geophysical, geochemical, and drilling data that the area surrounding the Yucca Mountain site has potential for anything but low-temperature geothermal resources, and those only at depth (Flynn et al. 1996, p. 92).

Results documented in Flynn et al. (1996, p. 92) and CRWMS M&O (2000d, pp. 98 to 100, 135 to 136) indicate that thermal resources at Yucca Mountain are classed as low temperature (defined as being within the range of 25° to 90°C [77° to 194°F]) and occur at depths in excess of 400 m (1,312 ft). Chemical analyses of fluids throughout the area and in various lithologic formations indicate that the water is nonthermal in origin. Geophysical data, including gravity, magnetic, seismic, and heat flow data, failed to delineate any systematic structural evidence for a thermal anomaly. Hydrological data indicate that thermal fluids, where they exist, are restricted to faults, fractures, breccia zones, and the deep Paleozoic carbonate aquifers. Compared with the physical attributes of geothermal systems that have been developed in other parts of the Great Basin, no economically viable resources were identified within the Yucca Mountain area. Some surface geothermal manifestations were identified within a 50-mi. (80-km) radius of Yucca Mountain, but, based on the present level of development, recreational uses are the only likely applications (Flynn et al. 1996, p. 92).

4.9.7 Summary

4.9.7.1 Metallic Mineral Resources

On the basis of extensive sampling and geochemical and mineralogical analyses by Castor et al. (1999), CRWMS M&O (2000f), and previous work, the Yucca Mountain natural resources site study area contains no identified metallic mineral or uranium resources. In addition, on the basis of detailed study of the geology, geochemistry, mineralogy, mineral alteration, and geophysical data and remote sensing, the Yucca Mountain site is considered to have little or no potential for deposits of metallic minerals or uranium resources that could be mined economically now or in the foreseeable future. Geological and geochemical comparisons between the Yucca Mountain natural resources site study area and metal mining districts in the region indicate substantial differences in the geologic and the geochemical patterns observed for precious metals, base metals, and pathfinder elements (Castor et al. 1999).

Additional work to investigate anomalous tin values indicates that the value of any potential deposit appears to be too low to cover even the cost of obtaining permits for a modern mining operation (CRWMS M&O 2000f, p. 29). Anomalous values of gold obtained from surface samples in the natural resources site study area formed as a result of pedogenic processes and do not represent an economic resource. Other weakly anomalous gold values obtained from fault gouge and breccia do not appear to constitute an economic resource. The potential gold mineralization in the Claim Canyon area remains unproven by current information and, in any case, is located well north of the Yucca Mountain site study area.

4.9.7.2 Industrial Rocks and Minerals Resources

Many of the industrial rock and mineral commodities occur in the Great Basin but not at Yucca Mountain. Although barite, clay minerals, fluorite, limestone, perlite, and zeolites have been identified in samples from Yucca Mountain, these occurrences are minor and at depths too great to be economic (Castor and Lock 1995, pp. 93 to 96).

It is possible that alluvial deposits at the site could be used as concrete aggregate for local construction and that some of the Tertiary tuff could be used as building stone. However, neither the alluvial deposits nor the tuff have any properties or features that would make them more marketable than other deposits readily available and closer to processing plants and end users. Under present circumstances, the Yucca Mountain site has little or no potential for production of construction aggregate (Castor and Lock 1995, p. 47).

4.9.7.3 Hydrocarbon Resources

In comparing the Yucca Mountain area to known producing fields in the region, the area that could contain a generation site with a volume of potential source rock is limited. In addition, one of the important seals of the region, the unconformity at the base of valley fill, is not well developed in the Yucca Mountain area and is absent from the natural resources site study area. Under the structural interpretation presented in Section 4.8 (Figure 4.8-22), the most attractive exploration target for hydrocarbons in Paleozoic strata in the Yucca Mountain area has been at least partly evaluated by borehole UE-25p#1. Potential traps that involve Tertiary rocks have been partly evaluated by various boreholes drilled to investigate the repository site (French 2000).

The conditions of source, reservoir, trap, and seal that characterize petroleum accumulations of the Great Basin are present, with variations, in the Yucca Mountain area. Most of the variations, however, indicate that the accumulation of hydrocarbons at the potential repository site is not likely (French 2000, p. 34). The area of Yucca Mountain is considered to have low potential for the accumulation and preservation of liquid petroleum as well (Grow et al. 1994, p. 1,314).

It is extremely unlikely that tar sands, oil shale, or coal occur as economic resources at the Yucca Mountain site. If tar sands, oil shale, and coal were to be associated with Paleozoic marine rocks underlying the Tertiary volcanic rocks at Yucca Mountain, they would occur at depths greater than 1,800 m (5,906 ft). Economic extraction at these depths would not be feasible in the foreseeable future.

4.9.7.4 Geothermal Resources

Results documented in Flynn et al. (1996, p. 92) indicate that thermal resources at Yucca Mountain are low temperature (from 25° to 90°C [77° to 194°F]) and occur at depths in excess of 400 m (1,312 ft). There are no geothermal discoveries near the Yucca Mountain natural resources site study area and there are no potential users located at or near the site. Chemical analyses of fluids throughout the area and in various lithologic formations indicate that most waters are nonthermal in origin. Geophysical data, including gravity, magnetic, seismic, and heat flow data, failed to delineate any systematic structural evidence for a thermal anomaly.

Hydrological data indicate that thermal fluids, where they exist, are restricted to faults, fractures, breccia zones, and the deep Paleozoic carbonate aquifers. Compared with the physical attributes of geothermal systems that have been developed in other parts of the Great Basin, no economically viable resources were identified within the Yucca Mountain area. Some surface geothermal manifestations were identified within a 50-mi. (80-km) radius of Yucca Mountain, but, based on the present level of development, recreational uses are the only likely applications (Flynn et al. 1996, p. 92).

4.10 SUMMARY

The geology of Yucca Mountain and the surrounding region provides the framework for understanding water flow and transport at and from the potential radioactive waste repository. Geologic studies also provide the basis for assessing economic resources and geologic hazards. The detailed geologic studies of the site provide critical input for engineering and design of the potential repository.

Geologic Setting–The regional geologic setting for Yucca Mountain is discussed in Section 4.2. It is based solely on published studies that have been ongoing since the late 1800s. The region lies in the north-central part of the Basin and Range Physiographic Province, within the northernmost subprovince commonly referred to as the Great Basin, which encompasses nearly all of Nevada, as well as adjacent parts of Utah, Idaho, Oregon, and California. The mountain ranges of the Great Basin, like Yucca Mountain, are mostly tilted fault-bounded blocks that may extend for more than 80 km (50 mi.) in length, and are generally 8- to 24-km (5 to 15 mi.) wide. Relief between valley floors and mountain ridges is typically 300 to 1,500 m (984 to 4,921 ft), and valleys occupy approximately 50 to 60 percent of the total land area.

The current tectonic setting of Yucca Mountain results from extensional tectonism and magmatism active during the middle and late Cenozoic Era and is fundamentally controlled by plate tectonic interactions at the western margin of the North American continent. Three regional tectonic domains characterize the tectonic setting within 100 km (62 mi.) of Yucca Mountain: the Walker Lane domain, which includes the site; the Basin and Range domain, to the northeast; and the Inyo-Mono domain to the west and southwest. These domains represent structurally bounded blocks of crust, each of which is characterized by a deformation history that differs substantially from adjacent domains.

Yucca Mountain lies within the Walker Lane domain, which is an approximately 100-km-wide (62-mi.-wide) structural belt along the western side of the Basin and Range province. The domain extends northwestward from the vicinity of Las Vegas, subparallel to the Nevada-California border. The domain is generally characterized as an assemblage of crustal blocks separated by discontinuous northwest-striking right-lateral faults and northeast-striking left-lateral faults.

Regional Stratigraphy and Lithology–A complete summary of rock stratigraphic units appropriate to regional scale discussions is presented in Section 4.2.2. In brief, the important elements of the regional and site stratigraphy can be grouped as Cenozoic and pre-Cenozoic units. Within the pre-Cenozoic grouping, Precambrian rocks are made up of two major assemblages: an older, metamorphosed basement assemblage, and a younger, metasedimentary assemblage, the uppermost unit of which grades upsection into Cambrian strata. These rocks are only exposed south and west of Yucca Mountain; the nearest outcrops are located at Bare Mountain, the Bullfrog Hills, the Funeral Mountains, and the Spring Mountains. Both assemblages of Precambrian rocks tend to retard groundwater flow except where the rocks are faulted or fractured. The older assemblage consists chiefly of quartzofeldspathic gneisses and quartz-feldspar-mica schists of metasedimentary or metaigneous origin. The rocks are typically intruded by migmatitic veins or larger, deformed bodies of granite or pegmatite.

Paleozoic rocks in the Yucca Mountain region include three lithosomes: a lower, Cambrian through Devonian carbonate lithosome; a middle, Mississippian fine-grained siliciclastic lithosome; and an upper, Pennsylvanian to mid-Permian carbonate lithosome. The lower carbonate lithosome represents deposition in a deep marine setting. These rocks dominate exposures west, south, and east of Yucca Mountain. By late Devonian time, these conditions were interrupted by the Antler Orogeny, the main result of which, in the Yucca Mountain region, was an influx of marine clay, silt, and sand into the depositional record. Rocks from this period have a similar distribution to those of the earlier Paleozoic, but are much less voluminous. Carbonate deposition was reestablished in Pennsylvanian time across much of the region. This lithosome is best displayed east of Yucca Mountain. The carbonate lithosomes form important aquifers in southern Nevada and the siliciclastic lithosome forms a regionally important aquitard.

Mesozoic strata are not present near Yucca Mountain, and therefore are not a factor in the hydrologic or tectonic phenomena relevant to Yucca Mountain. Regionally, they are dominantly continental and shallow marine sediments with minor Cretaceous plutonic rocks (such as those in the northeastern part of the Nevada Test Site). Structurally, the Mesozoic sequence records some compressional tectonism, as represented by regional thrusting.

Cenozoic rocks of the Yucca Mountain geologic setting fall into three groups: pre-middle Miocene sedimentary rocks that predate creation of the southwestern Nevada volcanic field, the middle to late Miocene volcanic suite that constitutes the southwestern Nevada volcanic field; and Plio-Pleistocene basalts and basin-fill sediments. The last two groups are of major importance in the immediate vicinity of Yucca Mountain.

The explosive volcanism that led up to and culminated in the formation of the southwestern Nevada volcanic field is the most significant depositional event of the Cenozoic Era with respect to Yucca Mountain. It resulted in the formation of six major calderas in the vicinity of Timber Mountain between about 15 to 7.5 Ma, created the rocks of Yucca Mountain, and brought to a close the regional deposition that spans the domains of the Yucca Mountain geologic setting. The record of regional tuff deposition begins within the sedimentary Oligocene rocks. True tuff deposition began less than 1 m.y. later and is first documented in the eastern part of the Nevada Test Site. The general succession of tuff and lava units that form Yucca Mountain is described in Section 4.5.4.

Plio-Pleistocene deposits consist of alluvial sediments and infrequently erupted basalts. The basaltic eruptions represent a continuation of the activity during the late Tertiary. Following the episode at 3.7 Ma, a subsequent basaltic eruption occurred between 1.7 and 0.7 Ma. It consisted of four cinder cones aligned north-northeast along the axis of Crater Flat. This episode spatially overlaps the eruption area of the earliest (11.3 Ma) basaltic episode.

The most recent basaltic volcanism created the Lathrop Wells Cone, which is composed of fissure eruptions, spatter and scoria cones, and aa flows. The Lathrop Wells Cone complex has been dated at about 80 ka. A complete description of basaltic volcanism can be found in Section 12.2.4, along with the discussion of volcanism as a possibly disruptive event.

Regional Structure and Tectonic Deformation–The geologic setting of Yucca Mountain is characterized structurally by two distinctly different styles of tectonic deformation: an earlier

shortening "mountain building" style of regional folding and overthrusting, and a later extensional "basin forming" style of regional normal and strike-slip faulting. The shortening style is restricted entirely to pre-Cenozoic rocks. It records orogenic events that occurred during Paleozoic deposition, and a peak event that occurred in the Mesozoic and terminated marine deposition. Shortening deformation of Precambrian age also is recorded in Proterozoic and older rocks, but no orogenic pattern has been determined from the sparsely exposed rocks.

The earliest mountain-building event (orogeny) that had an effect on Paleozoic rocks of the Yucca Mountain geologic setting is the Antler Orogeny. Antler orogenic deformation is expressed chiefly by the Roberts Mountains overthrust belt, which is located well to the north of Yucca Mountain. The Antler Orogeny is significant in the Yucca Mountain region for two reasons: the fine-grained, terrigenous lithology of the Eleana (and especially the Chainman Shale) lithosome forms a major Paleozoic aquitard north and east of Yucca Mountain; and the subsequent juxtaposition of three distinct but coeval facies (Antler-derived clastic debris, black Chainman Shale, Mississippian and older carbonates) aids in recognizing the structural configurations that formed during the subsequent Sevier-Cordilleran Orogeny.

Models for the Current Tectonic Setting–The current tectonic regime, and the one that dominated during formation of the southwestern Nevada volcanic field, is extensional. Within this general tectonic setting, several classes of tectonic models have been proposed to explain the structural features observed at Yucca Mountain and vicinity (Section 4.3). They include a caldera model for Crater Flat; simple shear models with detachment faults at depth; pure shear models, which have been applied to the Basin and Range province because of the horst-and-graben-like structure; and lateral shear models, expressed as strike-slip faulting, which is noted as an important extensional mechanism throughout the Walker Lane and the Inyo-Mono domain to the west and is at the heart of pull-apart models.

None of these models fits well with all the available data. For example, seismic profiling across Crater Flat fails to identify either detachment faults or caldera structures. Likewise, paleomagnetic studies demonstrate that some deformation at Yucca Mountain occurred around a vertical axis of rotation, probably about 12.7 Ma, which is inconsistent with a pure shear model unless the strike-slip faulting is hidden beneath the alluvium in Crater Flat.

Surficial Deposits and Processes–Surficial deposits in the Yucca Mountain region are discussed in Section 4.4. These deposits form an important component of the valley-fill aquifer. Most surficial deposits are composed of alluvium, but hillslopes are typically covered with a thin veneer of colluvium. Eolian deposits are generally a minor component of the surficial deposits, except for the massive star dune at Big Dune, and sand ramps, such as those that flank Busted Butte. Southwest and south of Yucca Mountain, minor spring and marsh deposits have been mapped and studied for paleohydrologic implications. The ages of surficial deposits range from less than 1 to more than 760 ka, but most deposits exposed at the surface were deposited during the last 100 k.y.

Opaline and carbonate deposits, occurring both as slope parallel and as fracture fillings, have raised concerns about possible catastrophic rises in the water table. Evidence regarding the origin of these deposits is discussed in Section 4.4.5. Available data include field relation, mineralogic and textural data, major and minor element data, stable isotope data, radiogenic

tracer isotope data, and paleontologic data. In 1992, the National Research Council concluded that a sedimentary, low-temperature origin from descending meteoric water was supported, rather than an origin involving upwelling of thermal water from deep within the crust. The panel also evaluated the theoretical basis for the model of upwelling water and concluded that there is no theoretical reason to believe that it could happen and that there was no evidence that a similar phenomenon has occurred elsewhere. Continued study by the Yucca Mountain Site Characterization Project has not changed these conclusions.

Site Geology–The stratigraphy of the site is discussed in Section 4.5. Neogene volcanic rocks, consisting mostly of pyroclastic-flow and fallout tephra deposits with minor lava flows and reworked materials, dominate the exposed stratigraphic sequence at Yucca Mountain. The central portion of Yucca Mountain is essentially a dip slope formed by rocks of the Paintbrush Group dipping gently to the east, generally less than 10°. The volcanic section has been studied in whole or in part in 57 boreholes and 37 measured sections. The potential repository horizon and the access to it are entirely within the Paintbrush Group, which consists of four formations. Each formation is primarily composed of pyroclastic-flow deposits that are interstratified with small-volume pyroclastic-flow and fallout tephra deposits, and, locally, lava flows and secondary volcaniclastic deposits from eolian and fluvial processes. The lowermost formation is the Topopah Spring Tuff. This unit, or, more specifically, a subunit referred to as TSw2, forms the host rock for the potential radioactive waste repository, and therefore is one of the most intensely studied formations at Yucca Mountain.

The Topopah Spring Tuff has a maximum thickness of about 375 m (1,230 ft) in the vicinity of Yucca Mountain. The formation is divided into two members: a lower crystal-poor member and an upper crystal-rich member. Each member is divided into numerous zones, subzones, and intervals based on variations in depositional features, such as crystal content and assemblage, size and abundance of pumice and lithic clasts, distribution of welding and crystallization zones, and fracture characteristics. The Topopah Spring Tuff is compositionally zoned with an upward chemical change from high-silica rhyolite in the crystal-poor member to quartz latite in the crystal-rich member.

The uppermost unit of the Paintbrush Group is the Tiva Canyon Tuff, which is a large-volume, regionally extensive, compositionally zoned (from rhyolite to quartz latite) tuff sequence that forms most of the rocks exposed at the surface of Yucca Mountain. Thicknesses of those portions of the formation penetrated in boreholes or observed in outcrops range from less than 50 m to as much as 175 m (164 to 574 ft). The formation has a lower crystal-poor member and an upper crystal-rich member similar to that discussed above for the Topopah Spring Tuff.

Rocks from the upper nonwelded Topopah Spring Tuff through the nonwelded base of the Tiva Canyon Tuff form an important hydrologic unit known as the Paintbrush nonwelded (PTn) unit. This unit consists of volcaniclastic units with ash-flow tuffs that vary from nonwelded to moderately welded. This lithology results in a much greater porosity than the rocks above and below it and a much lower degree of fracturing. The hydrologic significance of these features is discussed in Section 8.9.

The spatial and temporal patterns of faulting and fracturing of the volcanic bedrock are the fundamental elements of the structural geology of the potential underground repository at Yucca

Mountain. Documentation and discussion of these patterns is presented in Section 4.6 and is based on geologic mapping, which in turn is based on the detailed stratigraphy. The geologic mapping studies were conducted at scales of 1:2,400 to 1:24,000, using either U.S. Geological Survey or Yucca Mountain Site Characterization Project topographic base maps. Bedrock maps were prepared using formational boundaries for scales of 1:24,000; zonal contacts were used for more detailed mapping. Faults with 5 m (16 ft) (or more) of offset were recorded on the 1:24,000 mapping, whereas faults with 1 to 5 m (3.3 to 16 ft) of displacement were mapped in the more detailed studies.

The area mapped at 1:24,000 is informally referred to as the "Yucca Mountain site area." The term "site area" corresponds to the 12- by 14-km (7.5- by 8.7-mi.) area, extending from The Prow on the north to Busted Butte on the south, and from Windy Wash on the west to Fortymile Wash on the east. In general, the detailed geology of the potential repository is addressed by geologic mapping and fractured rock mass studies within a smaller area known as the Central Block, whereas the subregional context for the geology of the potential repository is found in the site area.

The structural geology of Yucca Mountain is controlled by block-bounding faults spaced 1 to 4 km (0.6 to 2.5 mi.) apart. In the site area, these faults include (from west to east) the Windy Wash, Fatigue Wash, Solitario Canyon, Bow Ridge, and Paintbrush Canyon faults. The Dune Wash and Midway Valley faults are also block-bounding faults, but differ from the other block-bounding faults in that they have no evidence of Pleistocene movement. The block-bounding faults commonly dip 50° to 80° to the west, with scattered dips of 40° to 50° and 80° to 90°. A subordinate component of left-lateral displacement is commonly associated with these faults as determined from slickenside orientations. The orientation, amount of offset, and nature of the associated deformation varies from north to south (and to some degree from west to east) within the site area.

Displacement is transferred between block-bounding faults along relay faults, which intersect block-bounding faults at oblique angles, providing an intrablock kinematic link between the bounding structures. As such, the relay faults are significant components of the block-bounding fault systems, particularly (but not exclusively) in the southern half of Yucca Mountain. Most of these relay faults are actually complex zones of faulting. Through most of the site area, block-bounding faults strike to the north and relay faults strike to the northwest, whereas south of the site area block-bounding faults strike to the northeast and relay faults strike to the north. This is in part a reflection of vertical axis rotation discussed above.

Within structural blocks, small amounts of strain are accommodated along intrablock faults. In many cases, intrablock faults appear to represent local structural adjustments in response to displacements on the block-bounding faults. In some cases, intrablock faults are expressions of hanging-wall or footwall deformation that affects the blocks within a few hundred meters of the block-bounding faults. Other intrablock faults, such as the northwest-trending narrow grabens in the southeast part of the Central Block, accommodate strains in narrow zones between overlapping tips of block-bounding faults. Such intrablock faults may have evolved into relay faults at the higher magnitudes of horizontal extension that are present in the southern part of Yucca Mountain.

Ten structural domains within the site area can be defined, each characterized by a distinctive structural style. These structural domains all lie within the more regional Crater Flat tectonic domain. The term "structural domain" is used to denote an area characterized by a particular structural pattern that is distinct from that of adjacent areas. The distinctive structural patterns that characterize individual domains may include the nature and intensity of faulting as well as magnitude and direction of stratal dips.

Detailed mapping has shown that some postulated faults either do not exist or are minor in nature. Geophysical and geologic data indicate that the main north-trending faults exposed north of Yucca Wash continue southward beneath Quaternary deposits to the southern part of Midway Valley. This observation argues strongly against the presence of a major structure beneath Yucca Wash, as well as any effect that such a structure might have on groundwater flow at Yucca Mountain. Results of studies of small faults in the immediate vicinity of the potential repository, such as the Sundance and Ghost Dance faults, are presented in Section 4.6.4.

Fractured rock mass studies include detailed studies of the distribution of fractures in natural exposures, cleared pavements, boreholes, and underground excavations. Fractures were mapped at scales of 1:240 and greater (typically 1:120 and 1:125). The largest volume of fractured rock mass data comes from the detailed mapping of the Exploratory Studies Facility, an 8-km-long (5-mi.-long), 7.6-m-diameter (25-ft-diameter) tunnel completed in 1997. Results of fracture studies are summarized in Section 4.6.6.

Applications of fracture data include hydrologic flow, development of surface infiltration models, numerical simulations of discrete fracture networks, and calculations of bulk rock permeability for use in equivalent continuum models of the unsaturated zone. Fracture data at Yucca Mountain are also used to characterize the fracture network for mechanical stability of the potential repository, and to better understand the paleostress history of Yucca Mountain.

Fractures are generally of three types: early cooling joints, later tectonic joints, and joints caused by erosional unloading. Cooling and tectonic joints have similar orientations, but can be distinguished because cooling joints are smoother. Both sets of joints form two orthogonal sets of steeply dipping fractures and a subhorizontal set.

Fracture intensity and connectivity have the strongest influence on groundwater flow within the volcanic rocks. Values for these variables are greatest in the densely welded tuffs, least in the nonwelded units, and intermediate in the lithophysal zones. Hydrologic models require that the width and hydraulic properties of fault zones be defined in order to evaluate the influence of faults on flow pathways. The total width of the fault zone may include an area around the fault plane, here called a zone of influence, in which fracture intensity is higher, or some other parameter, such as orientation, changes in response to the presence of the fault. Within the Exploratory Studies Facility, the zones of influence vary from 1 to 7 m (3.3 to 23 ft) and, in a general way, correlate with the total displacement on the fault. The amount of deformation associated with the faults is also dependent upon the lithology of the units involved in the faulting. Nonwelded to partly welded portions of the crystal-poor vitric zone of the Tiva Canyon Tuff apparently can accommodate a greater amount of extensional strain before failing by fracture than brittle, densely welded rocks.

The database for the site includes numerous measurements of physical properties of Paintbrush Group rocks (Section 4.7). Large-scale data include rock quality, hardness, and key block analysis from the Exploratory Studies Facility, and weathering characteristics from outcrops. Laboratory data include mineralogy (including health-related minerals, such as polymorphs of silica and erionite), density and porosity, thermal conductivity and expansion, heat capacity, static and dynamic elastic constants (expressed as Young's modulus and Poisson's ratio), confined and unconfined compressive stress, tensile and shear strength, and rock mass properties of strength and elastic moduli. Horizontal in situ stress is generally low, with minimum and maximum stresses nearly equal, which indicates a weak horizontal anisotropy for in situ stress.

The site geologic framework is presented in an integrated site model (Section 4.8). The model is a three-dimensional interpretation of currently available data for the spatial relations of rock layers and faults. Similar models for mineralogy and rock properties are also presented. Together, these models form the framework for hydrologic flow and transport models for the unsaturated and saturated zones.

Economic Resources–Nevada is a major producer of non-fuel minerals, and the southern Great Basin is a favorable geologic province for several types of economic deposits. Furthermore, the volcanic rocks at Yucca Mountain are found in a region known to have some areas of strong fracturing and hydrothermal alteration of rocks. These types of features can be associated with known economic deposits. Section 4.9 summarizes the results from a combination of literature searches, fieldwork, geophysical surveys, and petrographic and geochemical analyses to evaluate natural resource potential at Yucca Mountain. It is concluded that the Yucca Mountain natural resource study area contains no identifiable economic metallic mineral, energy (e.g., oil, gas, coal), or industrial mineral/rocks resources. Furthermore, this area is judged to have low or little potential for deposits of these resources that could be mined economically either at present or in the foreseeable future.

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4.11.2 Codes, Standards, Regulations, and Procedures

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29 CFR 1910. Labor: Occupational Safety and Health Standards. Readily available.

64 FR 8640. Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, Nevada. Proposed rule 10 CFR 63. Readily available.

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4.11.3 Source Data, Listed by Data Tracking Number

GS940308315215.006. Uranium, Thorium, and Lead Analyses of Calcite-Silica Drill Cores USW G-1, G-2, G-3 and G-4 and Water Samples from Yucca Mountain Vicinity. Submittal date: 03/14/1994.

GS960908314224.020. Analysis Report: Geology of the North Ramp - Stations 4+00 to 28+00 and Data: Detailed Line Survey and Full-Periphery Geotechnical Map - Alcoves 3 (UPCA) and 4 (LPCA), and Comparative Geologic Cross Section - Stations 0+60 to 28+00. Submittal date: 09/09/1996.

GS960908314224.022. Exploratory Studies Facility - Main Drift, Comparative Geology Cross Section Along Main Drift, Station 28+94.76 to Station 55+00. Submittal date: 09/17/1996.

GS970808314224.016. Geology of the South Ramp – Station 55+00 to 78+77, Exploratory Studies Facility, Yucca Mountain Project, Yucca Mountain, Nevada. Submittal date: 08/27/1997.

GS990908314213.001. Geophysical Logs and Core Measurements from Forty Boreholes, Including Corrected Magnetic Susceptibility for UE-25 A #1. Submittal date: 09/10/1999.

MO0002YMP98116.001. Locator Map for Cross Sections A-A' and B-B'. Submittal date: 02/26/2000.

MO0003YMP98121.001. Bullfrog Hills Detachment Geology. Submittal date: 03/22/2000.

MO0004YMP00004.001. Fault Systems. Submittal date: 04/14/2000.

MO0004YMP00005.001. Bedrock Geologic Map of Central Block Area, Yucca Mountain, Nevada. Submittal date: 4/15/2000.

MO0004YMP00016.000. Sample Locations and Selected Boreholes Within the Yucca Mountain Natural Resources Site Study Area. Submittal date: 04/04/2000.

MO0004YMP98110.002. Miocene Volcanic Bedrock. Submittal date: 04/26/2000.

MO0004YMP98111.002. Yucca Mountain Area Geologic Maps. Submittal date: 04/13/2000.

MO0004YMP98114.005. Bedrock Geologic Map of the Central Block Area, Yucca Mountain, Nevada. Submittal date: 04/15/2000.

MO0004YMP98120.002. Locations of Metal Mining Districts and Metal Mines in the Region. Submittal date: 04/04/2000.

MO0004YMP99033.003. Fault Types in the Vicinity of Yucca Mountain. Submittal date: 04/15/2000.

MO0004YMP99060.002. Distribution of Structural Domains in the Yucca Mountain Area. Submittal date: 04/15/2000.

MO0004YMP99063.001. Industrial Mineral Occurrences in the Vicinity of Yucca Mountain. Submittal date: 04/01/2000.

MO0006YMP00063.000. Walker Lane Belt in Relation to Physiographic Subdivisions of the West-Central and Southern Great Basin. Submittal date: 06/21/2000.

MO0006YMP00067.000. Pleistocene Depositional Basins and Drainage Features. Submittal date: 06/26/2000.

MO0006YMP98118.003. Physiographic Subdivisions of the Yucca Mountain Area. Submittal date: 06/19/2000.

MO0006YMP98119.002. Boreholes and Measured Surface Sections in the Vicinity of Yucca Mountain. Submittal date: 06/30/2000.

MO0006YMP99059.001. Potential Repository Site Investigation Area. Submittal date: 06/20/2000.

MO0006YMP99064.000. Local Wells Used in Hydrocarbon Resource Assessment. Submittal date: 06/26/2000.

MO9510RIB00002.004. RIB Item: Stratigraphic Characteristics: Geologic/Lithologic Stratigraphy. Submittal date: 06/26/1996.

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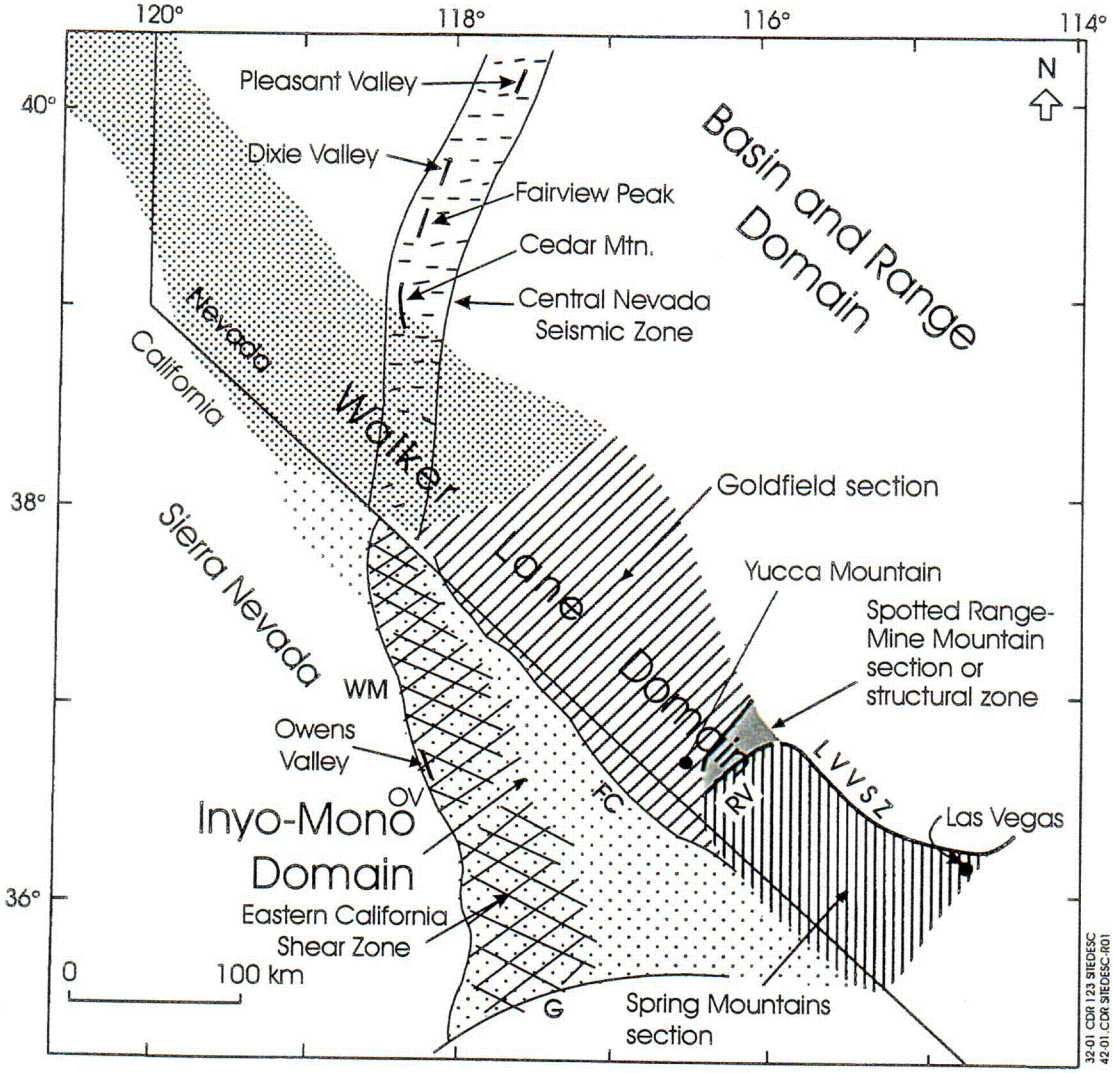
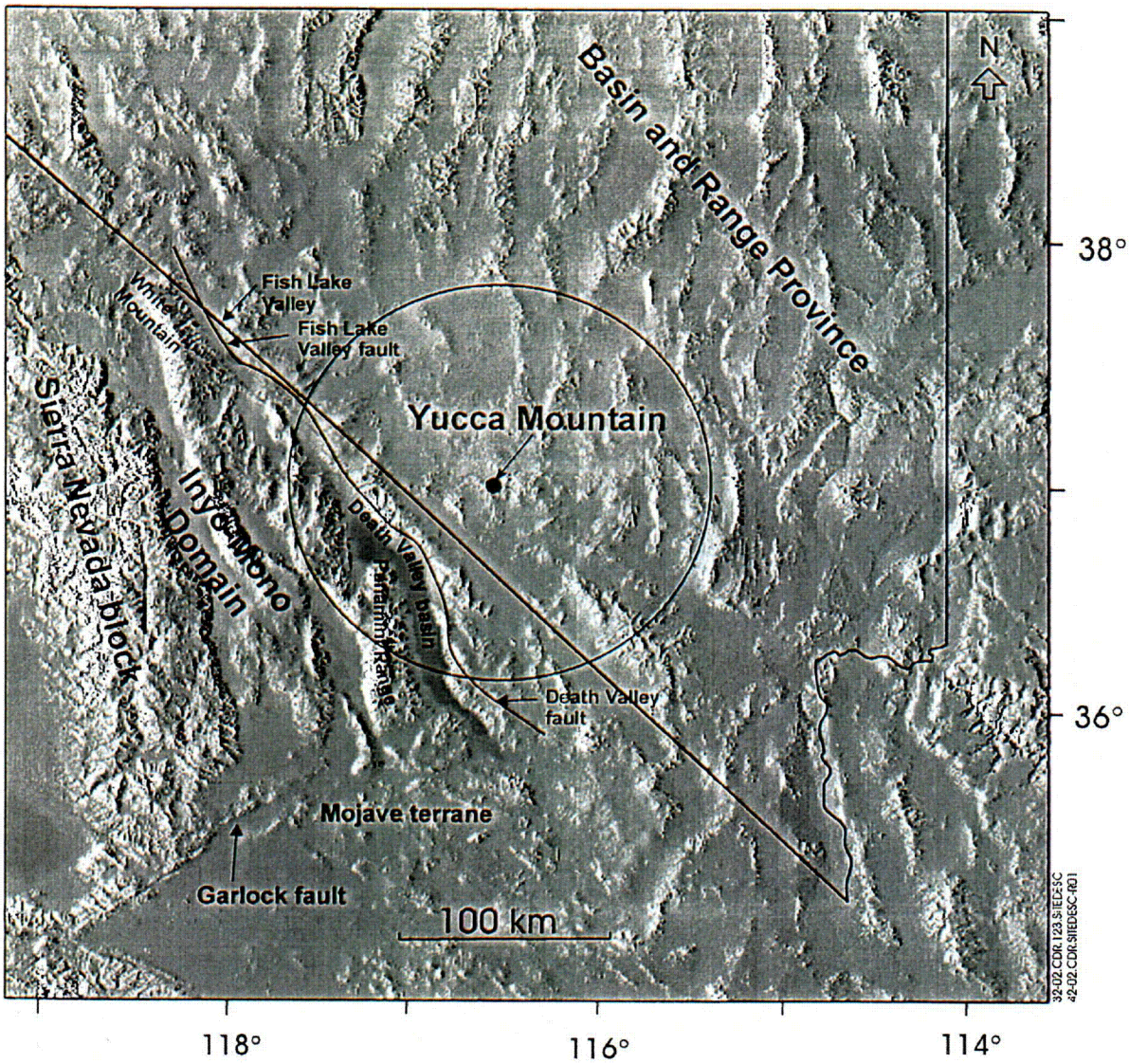


Source: After Stewart (1988)

NOTE: FC = Furnace Creek fault, G = Garlock fault, LVVSZ = Las Vegas Valley Shear Zone, OV = Owens Valley fault, RV = Rock Valley fault, WM = White Mountain fault

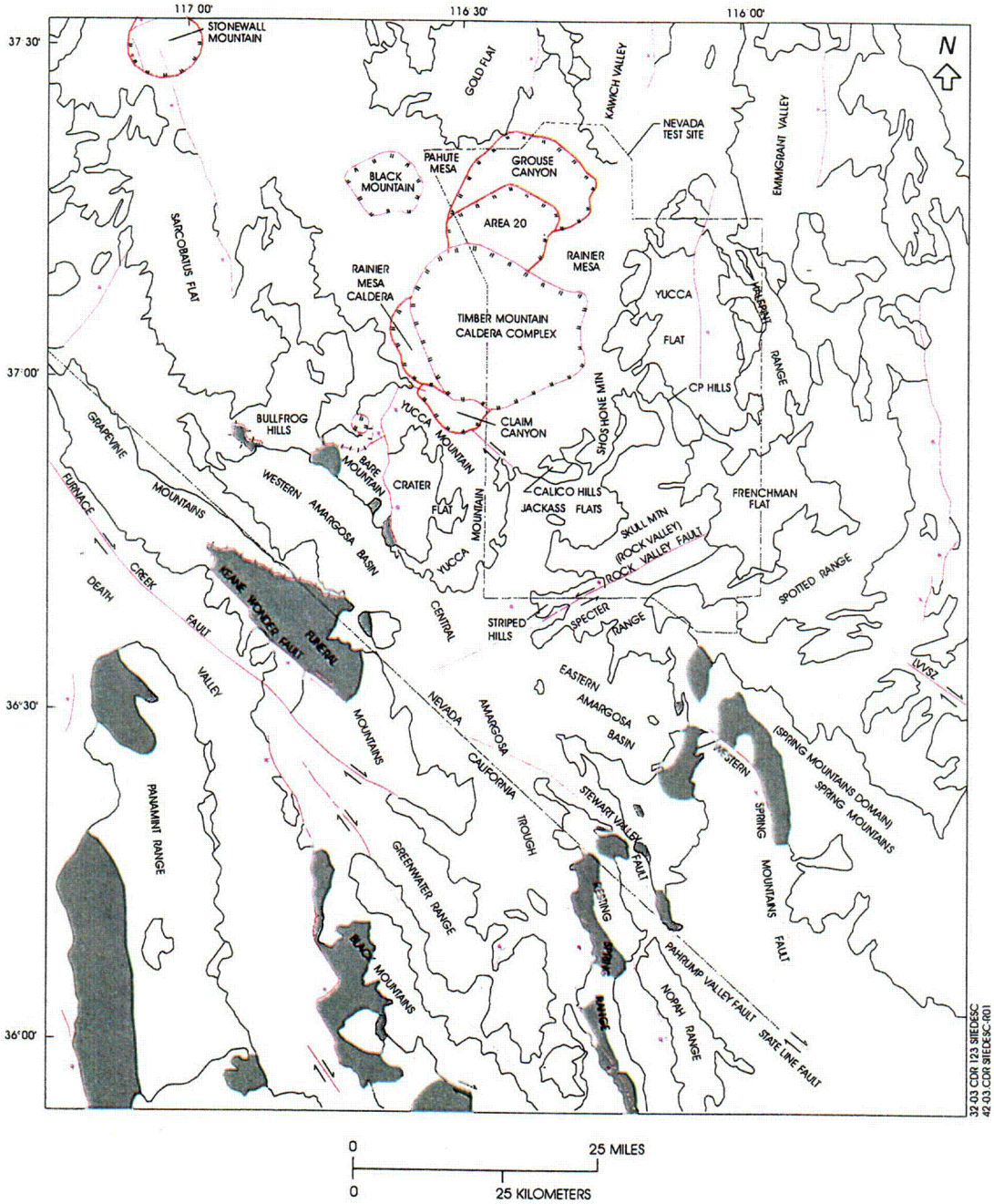
Figure 4.2-1. Regional Tectonic Domains for Yucca Mountain and Surrounding Environs, plus Sections of the Walker Lane and Zones of Historical Seismic Activity



Source: After O'Leary (1996, Figure 8.2)

NOTE: Circle encloses 100-km radius area centered on Yucca Mountain. Light screen shows the Walker Lane and, to the west of Death Valley Basin, the Inyo-Mono domain.

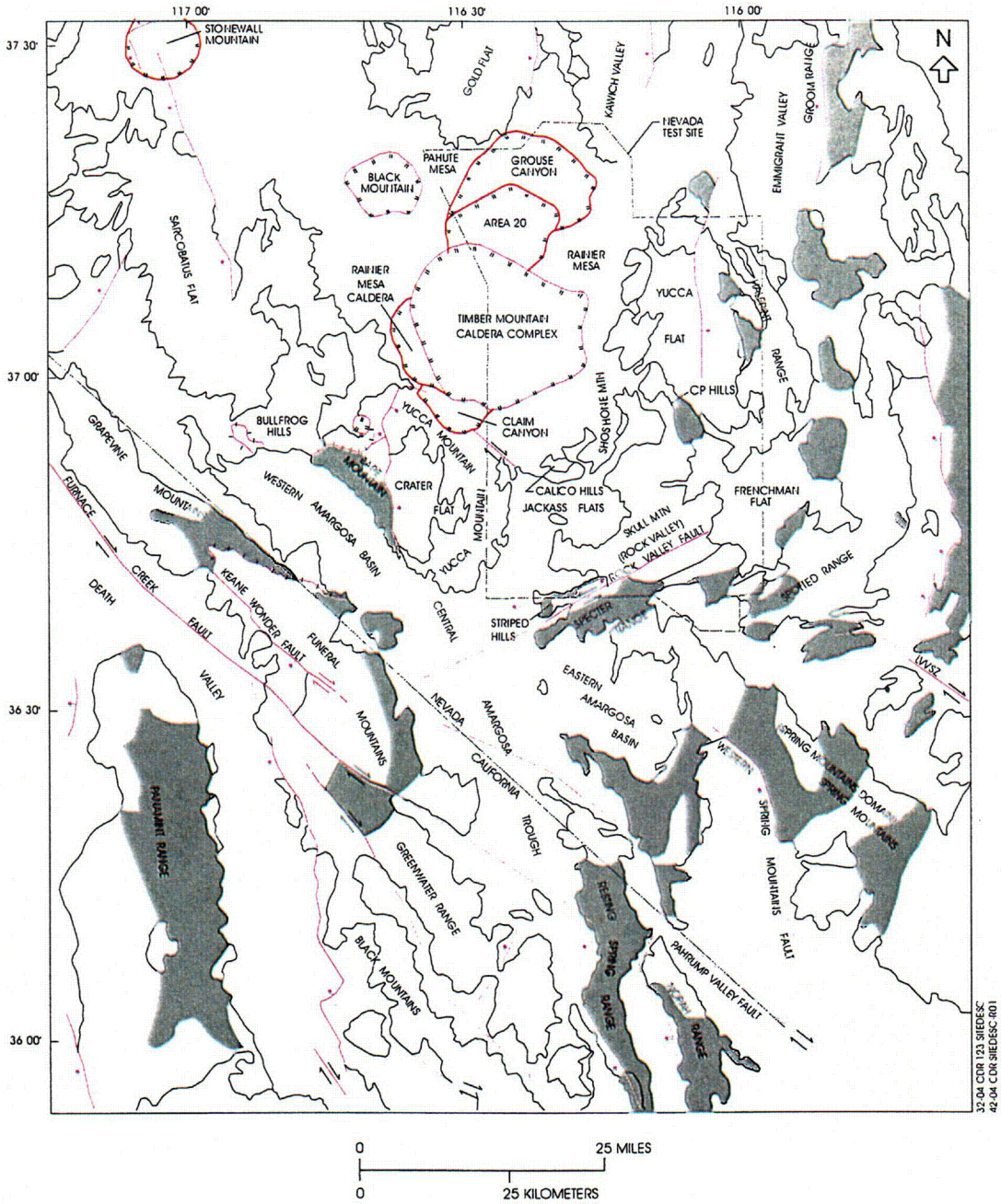
Figure 4.2-2. Geologic Setting of Yucca Mountain



Sources: Burchfiel et al. (1983, Figure 2), Carr and Monsen (1988, p. 50), Stewart and Carlson (1978), Tschanz and Pampeyan (1970, Plate 2), and Jennings (1977)

NOTE: Surface exposures are shown by shading. For faults, bar and ball are shown on the downthrown side; relative lateral movement is shown by arrows. Caldera margins are shown by double bar symbol.

Figure 4.2-3. General Distribution of Surface Exposures of Crystalline Precambrian Rocks in the Yucca Mountain Geologic Setting

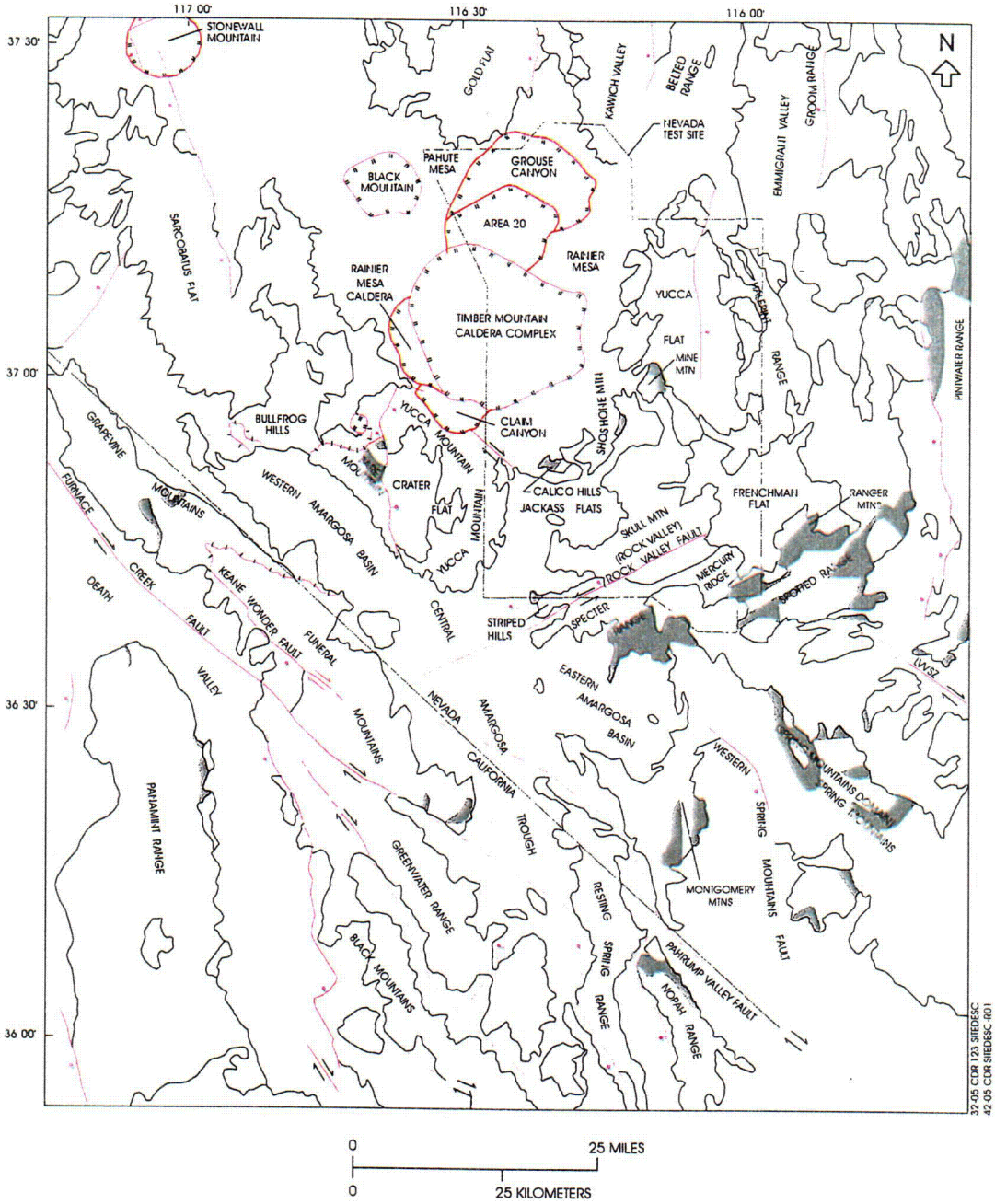


Sources: Frizzell and Shulters (1990), Stewart and Carlson (1978), Tschanz and Pampeyan (1970, Plate 2), Jennings (1977)

NOTE: Surface exposures are shown by shading. Precambrian portions of the Wood Canyon Formation are shown on this figure but not on Figure 4.2-3. For faults, bar and ball are shown on the downthrown side; relative lateral movement is shown by arrows. Caldera margins are shown by double bar symbol.

Figure 4.2-4. General Distribution of Surface Exposures of Cambro-Ordovician Rocks in the Yucca Mountain Geologic Setting

C04

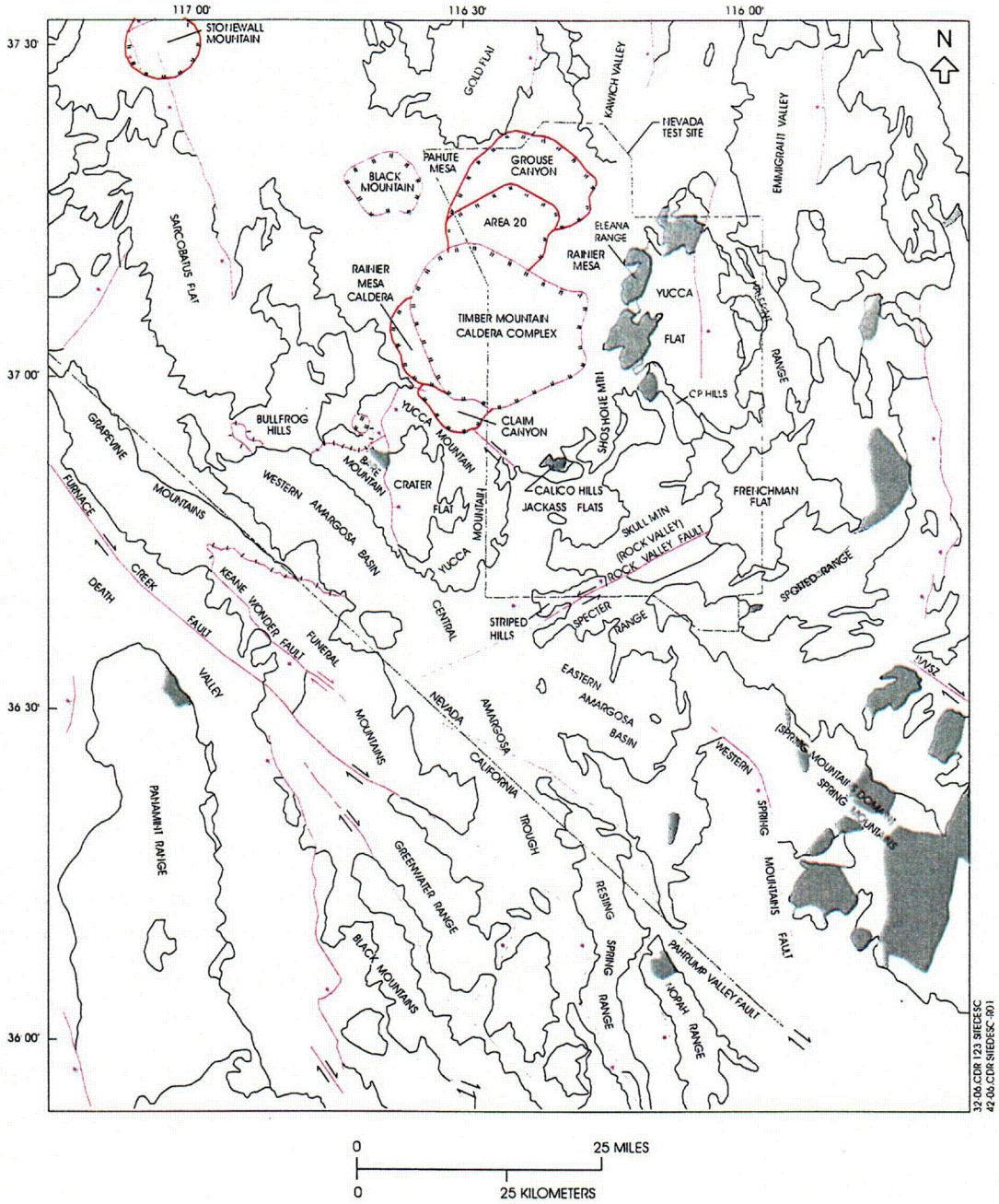


Sources: Frizzell and Shulters (1990), Stewart and Carlson (1978), Tschanz and Pampeyan (1970, Plate 2), Jennings (1977)

NOTE: Surface exposures are shown by shading. For faults, bar and ball are shown on the downthrown side; relative lateral movement is shown by arrows. Caldera margins are shown by double bar symbol.

Figure 4.2-5. General Distribution of Surface Exposures of Siluro-Devonian Rocks in the Yucca Mountain Geologic Setting

C05

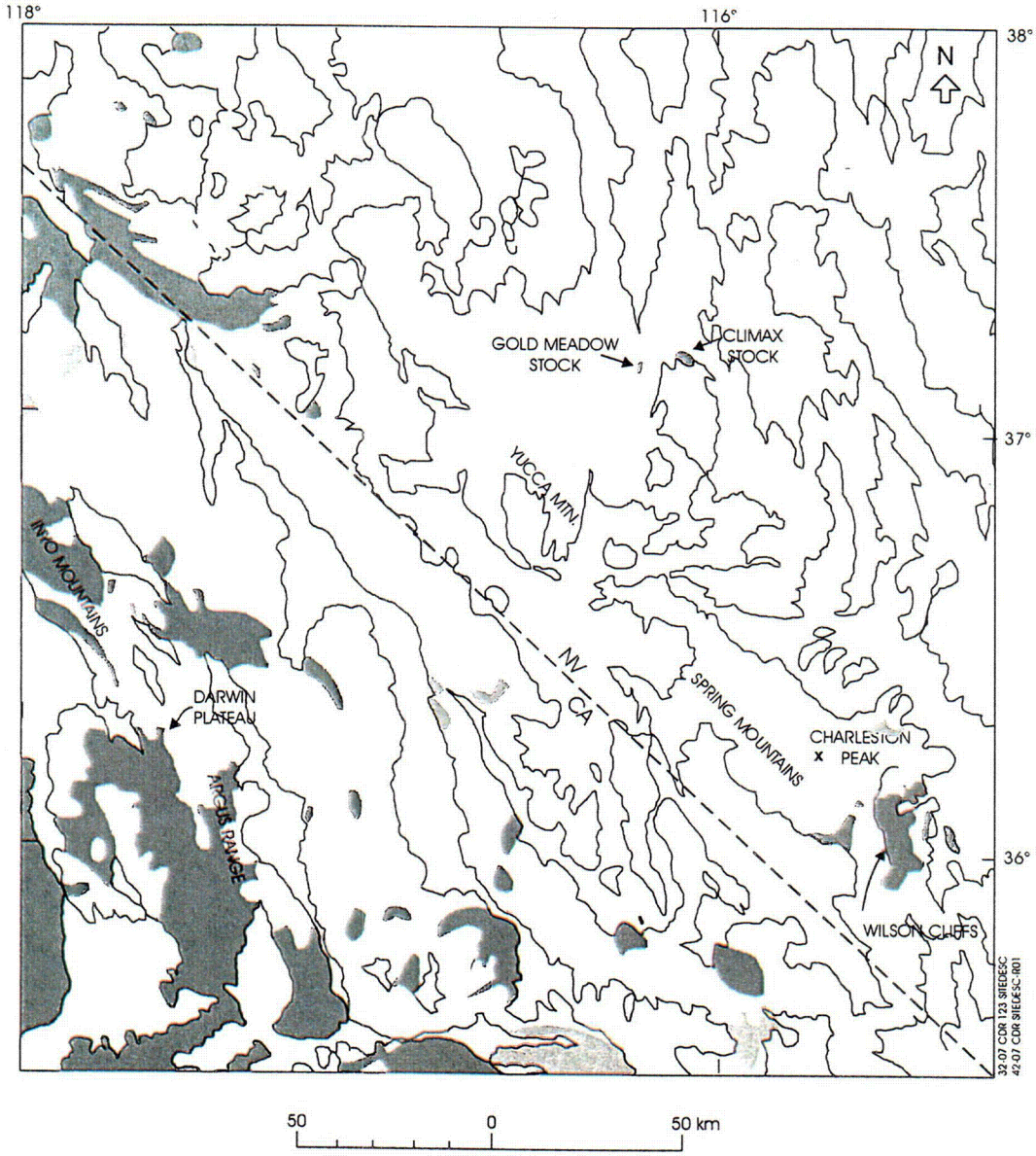


Sources: Frizzell and Shulters (1990), Stewart and Carlson (1978), Tschanz and Pampeyan (1970, Plate 2), Jennings (1977)

NOTE: Surface exposures are shown by shading. For faults, bar and ball are shown on the downthrown side; relative lateral movement is shown by arrows. Caldera margins are shown by double bar symbol.

Figure 4.2-6. General Distribution of Surface Exposures of Carboniferous and Permian Rocks in the Yucca Mountain Geologic Setting

C06

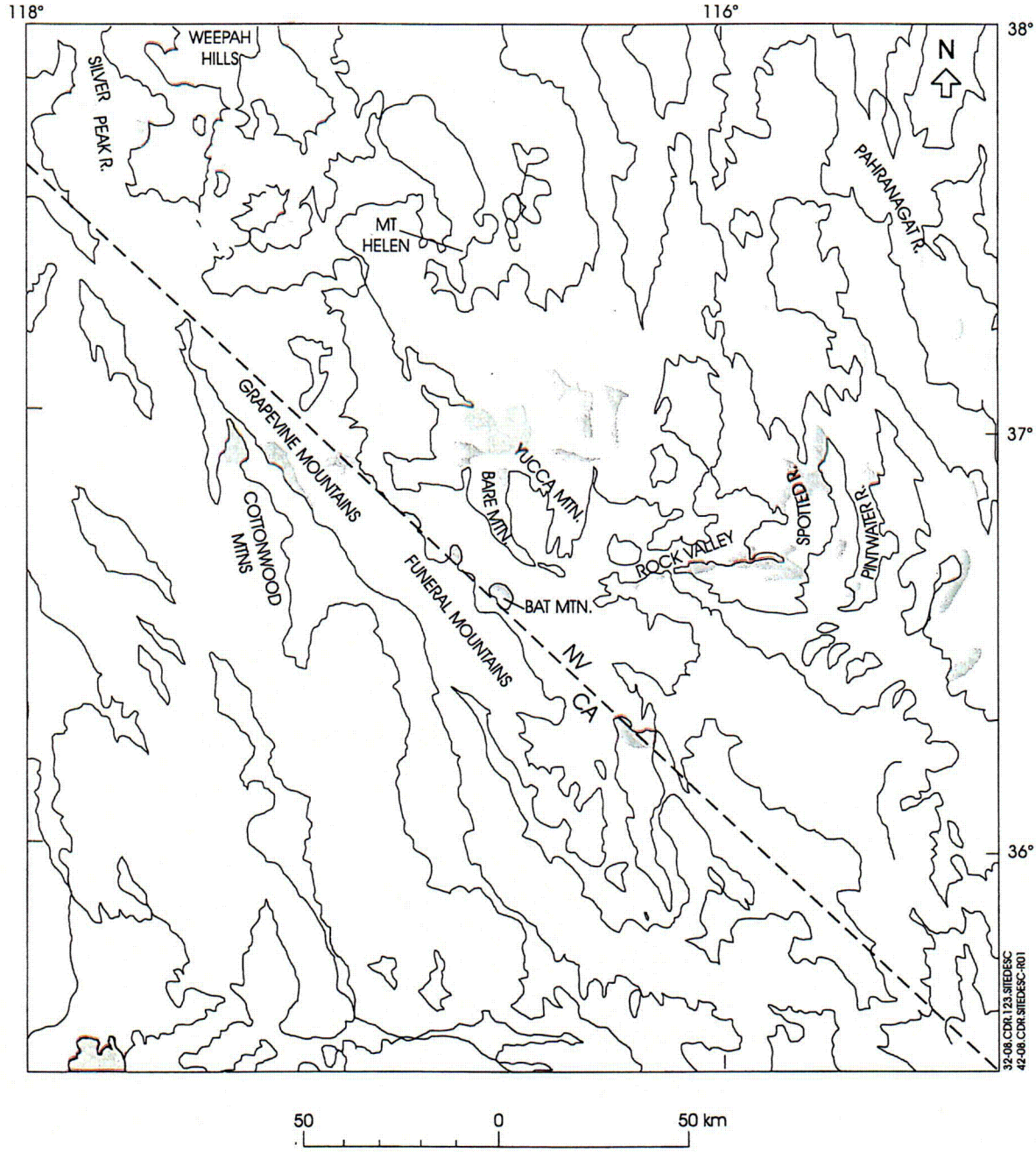


Sources: Frizzell and Shulters (1990), Stewart and Carlson (1978), Tschanz and Pampeyan (1970, Plate 2), Jennings (1977)

NOTE: Surface exposures are shown by shading.

Figure 4.2-7. General Distribution of Surface Exposures of Mesozoic Rocks (Igneous and Sedimentary) in the Yucca Mountain Geologic Setting

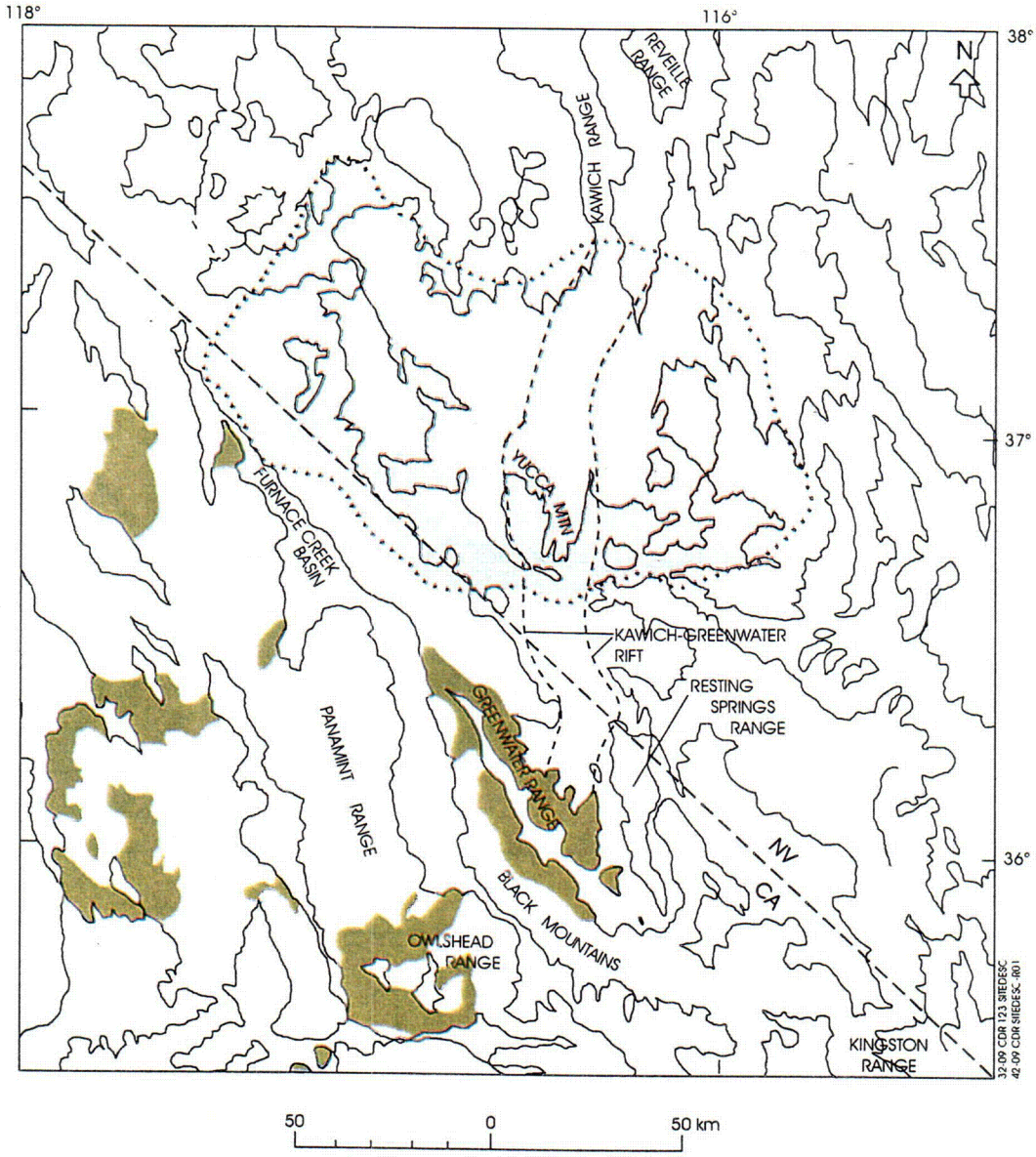
C07



Sourcse: Frizzell and Shulters (1990), Stewart and Carlson (1978), Tschanz and Pampeyan (1970, Plate 2), Jennings (1977)

NOTE: Surface exposures are shown by shading.

Figure 4.2-8. General Distribution of Surface Exposures of Tertiary Sedimentary Rocks in the Yucca Mountain Geologic Setting

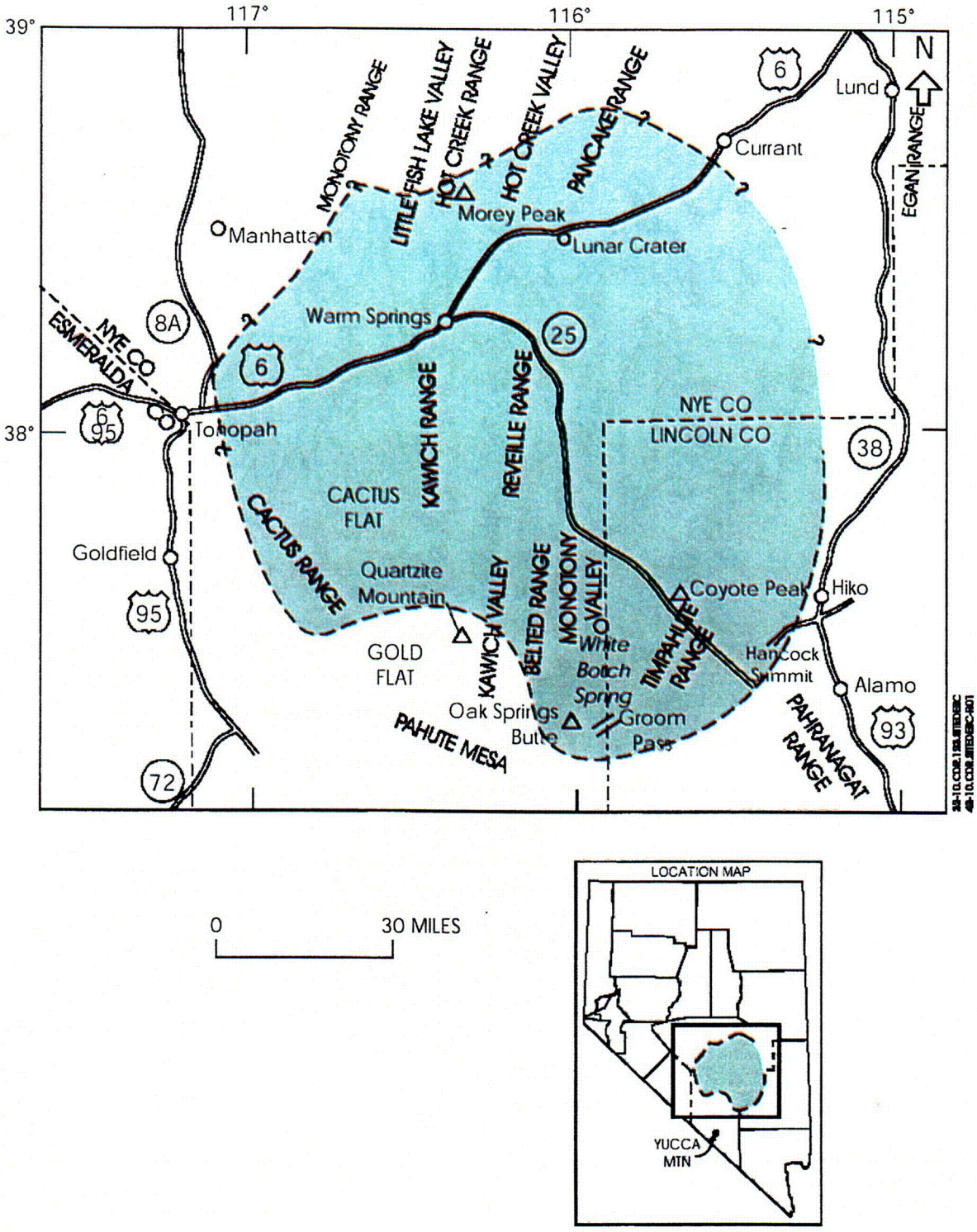


Source: Carr (1988, Figure 4-1), Carr (1990), Jennings (1977)

NOTE: Dashed lines indicate approximate borders of the Kawich-Greenwater rift of Carr (1990). The Kawich-Greenwater rift is also discussed in Section 4.3. The dotted boundary indicates the general extent of the southwestern Nevada volcanic field; brown shading indicates coeval igneous rocks of the Inyo-Mono domain.

Figure 4.2-9. General Extent of the Southwestern Nevada Volcanic Field and Coeval Igneous Rocks of the Inyo-Mono Domain

C09

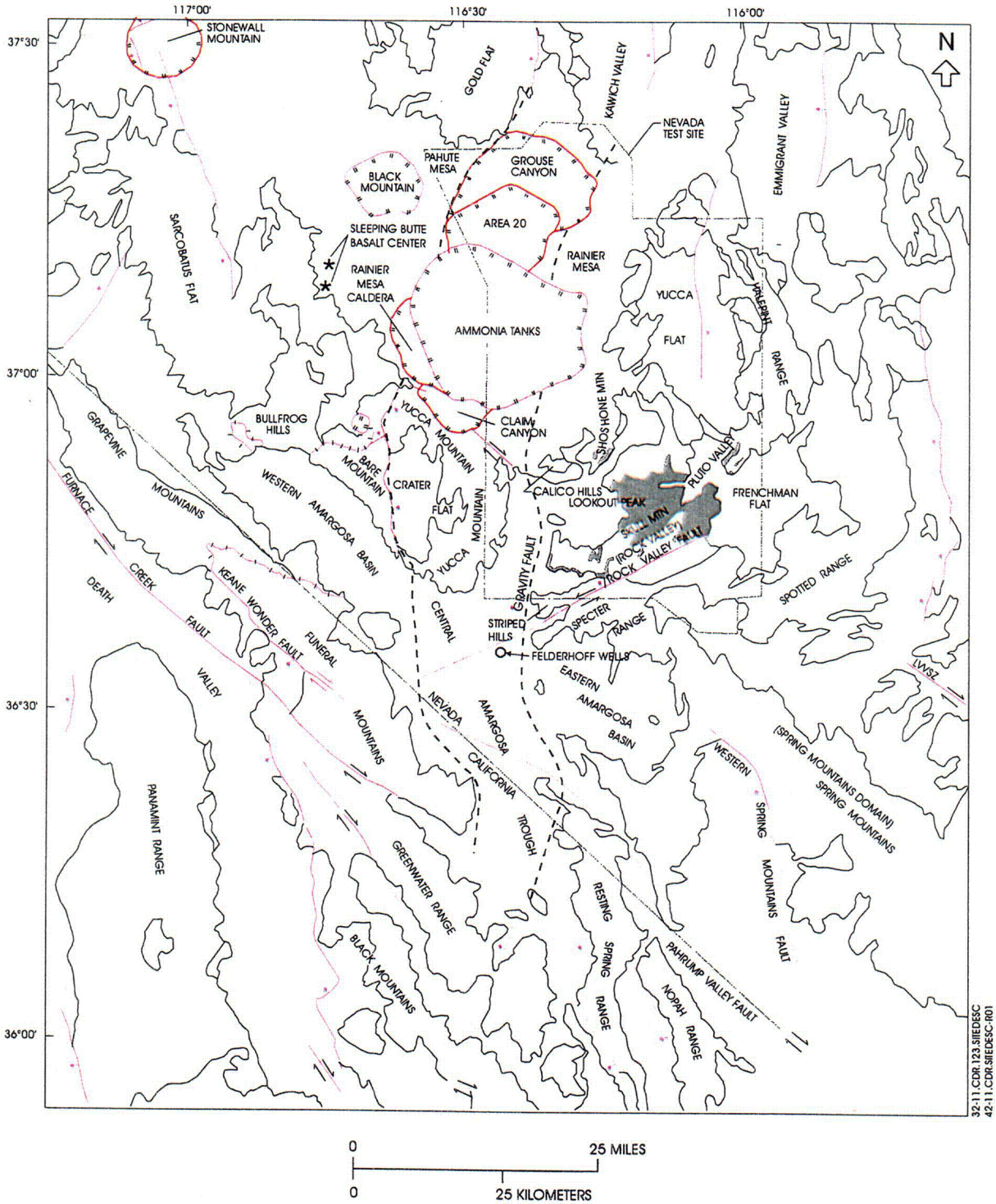


Source: Ekren et al. (1971)

NOTE: Shading indicates Monotony Tuff.

Figure 4.2-10. General Distribution of the Monotony Tuff

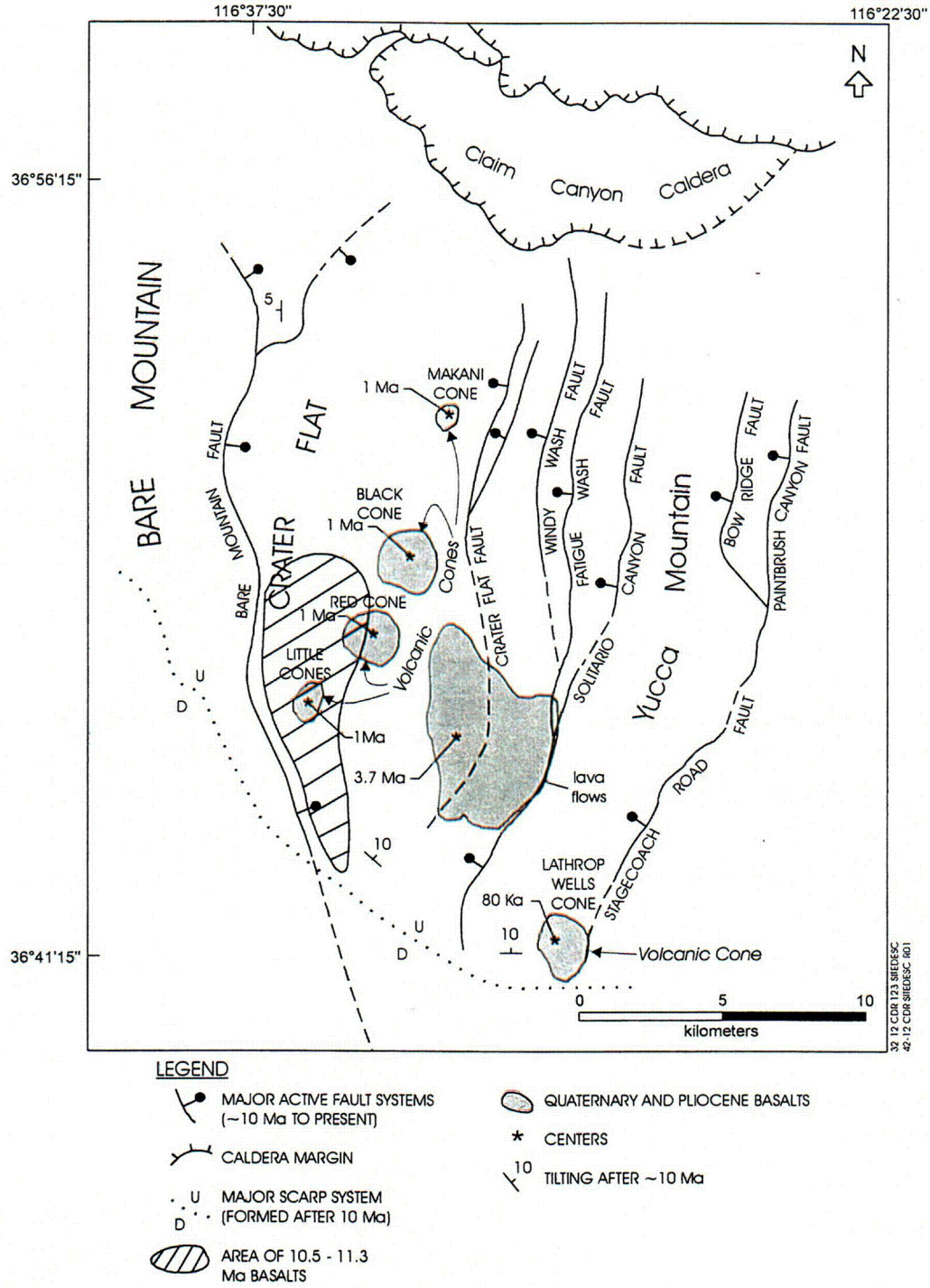
C10



Source: Carr, Grow, and Keller (1995), Carr (1990, p. 285)

NOTE: Surface exposures are shown by shading; dashed lines show approximate borders of the Kawich-Greenwater rift. For faults, bar and ball are shown on the downthrown side; relative lateral movement is shown by arrows. Caldera margins are shown by double bar symbol.

Figure 4.2-11. General Distribution of Surface Exposures of the Wahmonie and Salyer Formations



Source: Modified from Fridrich (1998)

NOTE: For faults, bar and ball symbol shown on downthrown side.

Figure 4.2-12. Late Neogene and Pleistocene Features at and near Yucca Mountain

C12

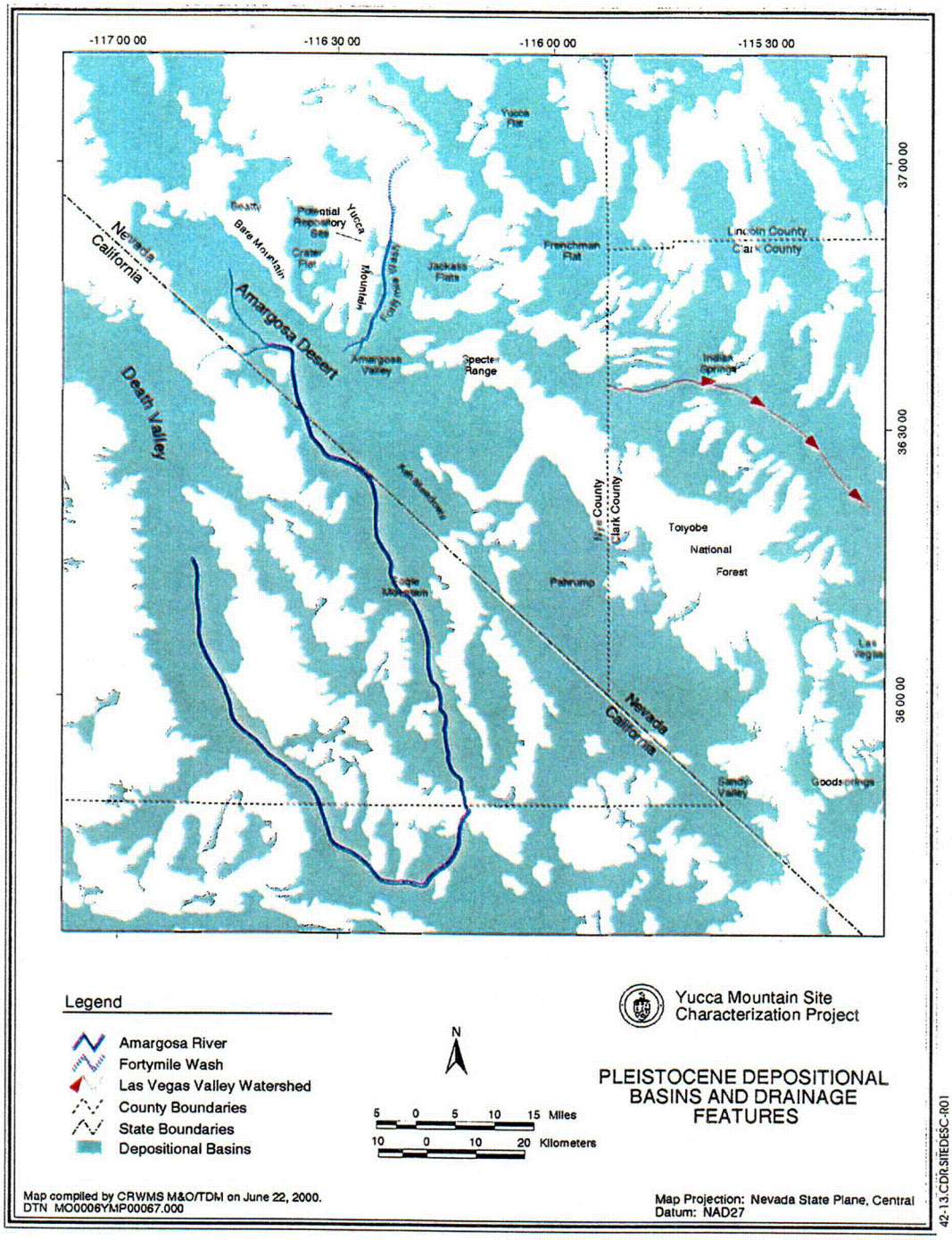
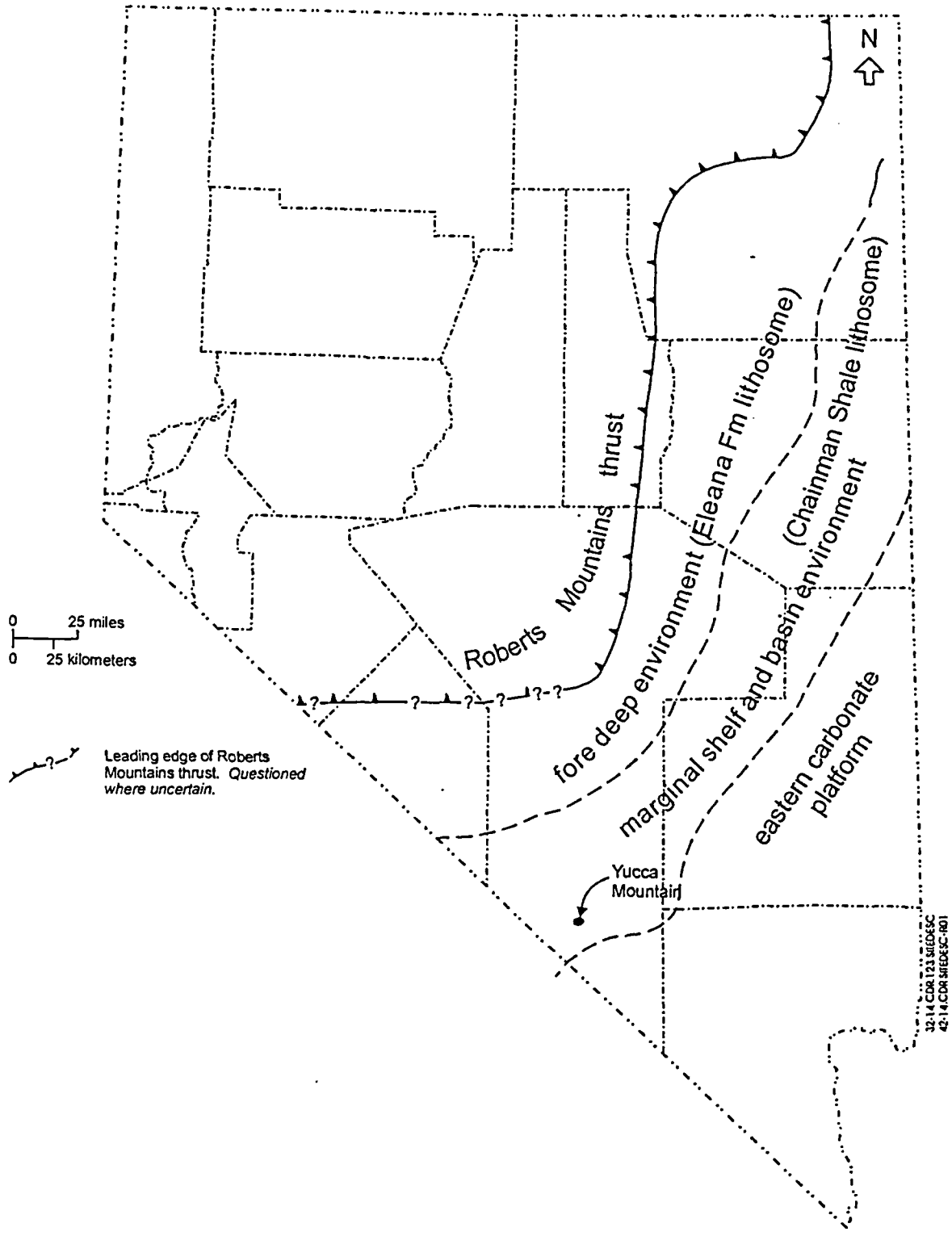


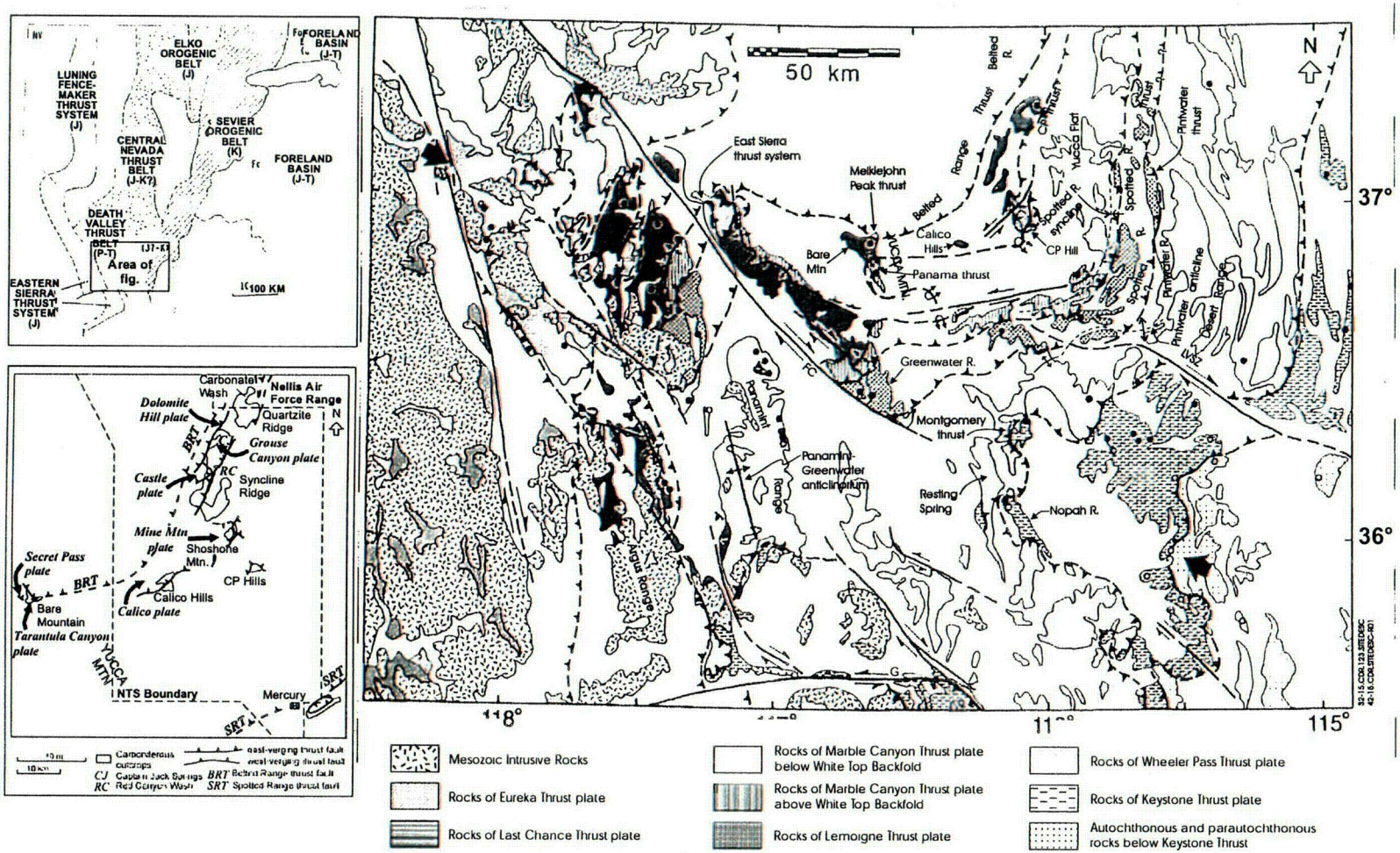
Figure 4.2-13. Pleistocene Depositional Basins and Drainage Features

C13



Sources: Stewart (1980); Trexler et al. (1996)

Figure 4.2-14. Generalized Location of Antler Orogenic Features

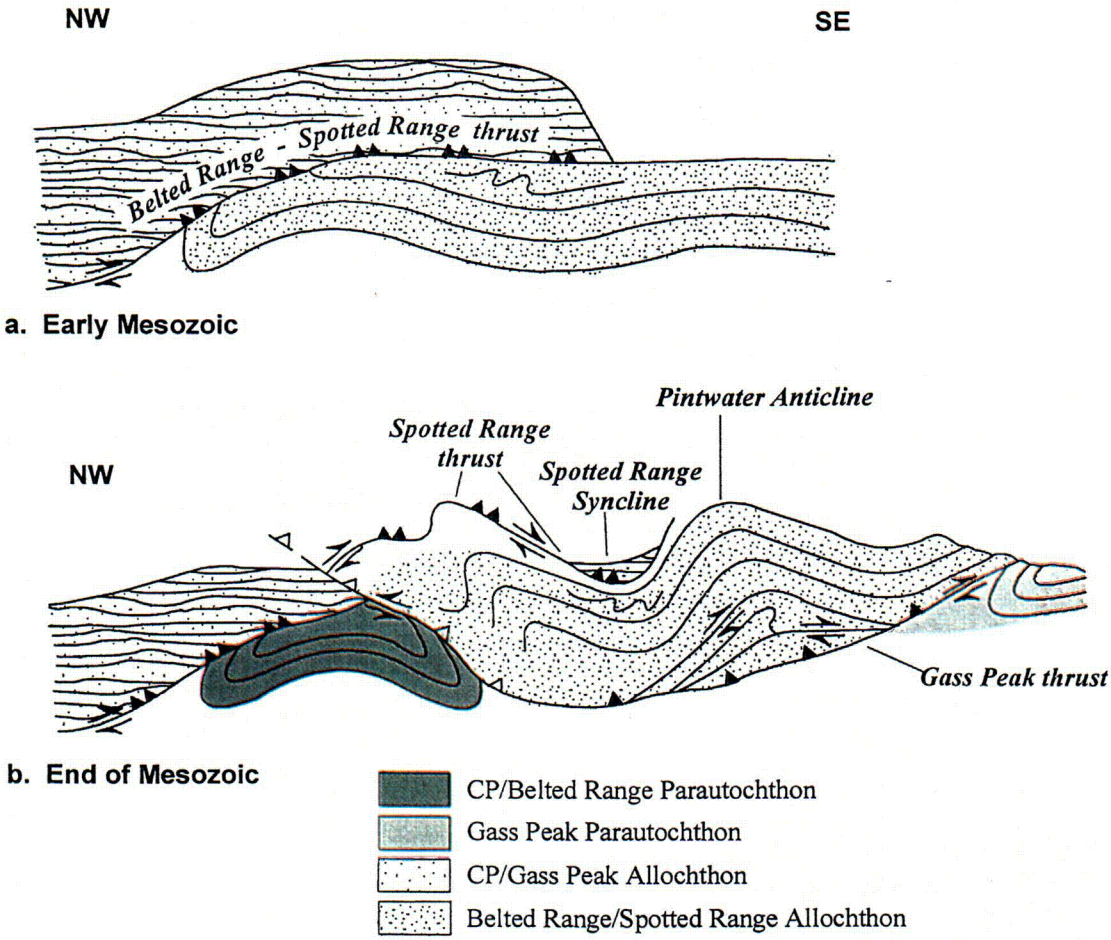


Sources: Snow (1992); Taylor et al. (1993); Trexler et al. (1996)

NOTE: Fault traces are dashed where covered; teeth point to overthrust (upper) plate; double-arrowed "U" indicates overturned fold.

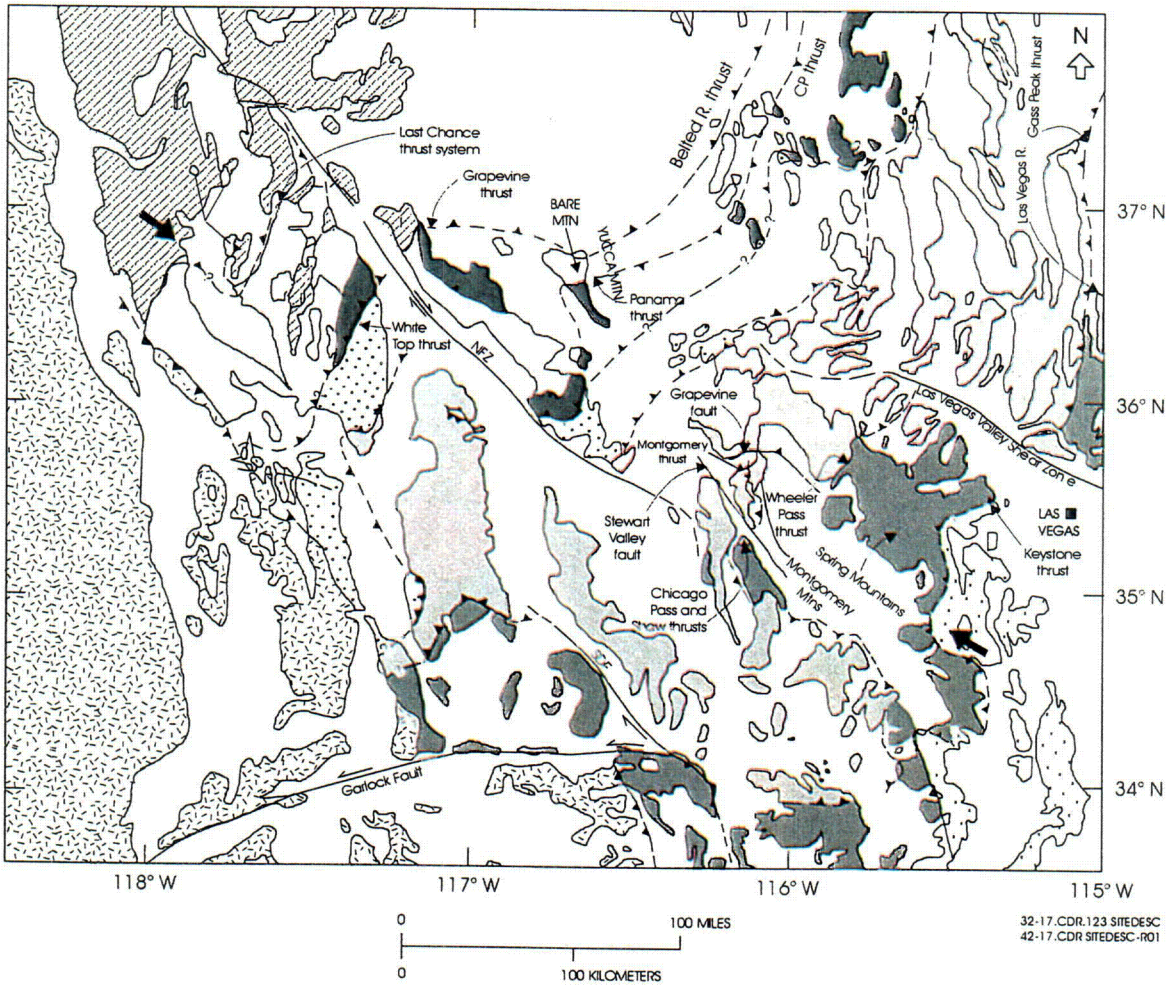
Figure 4.2-15. Structures of the Central Nevada and Sevier Thrust Zones

C14



Source: Caskey and Schweickert (1992)

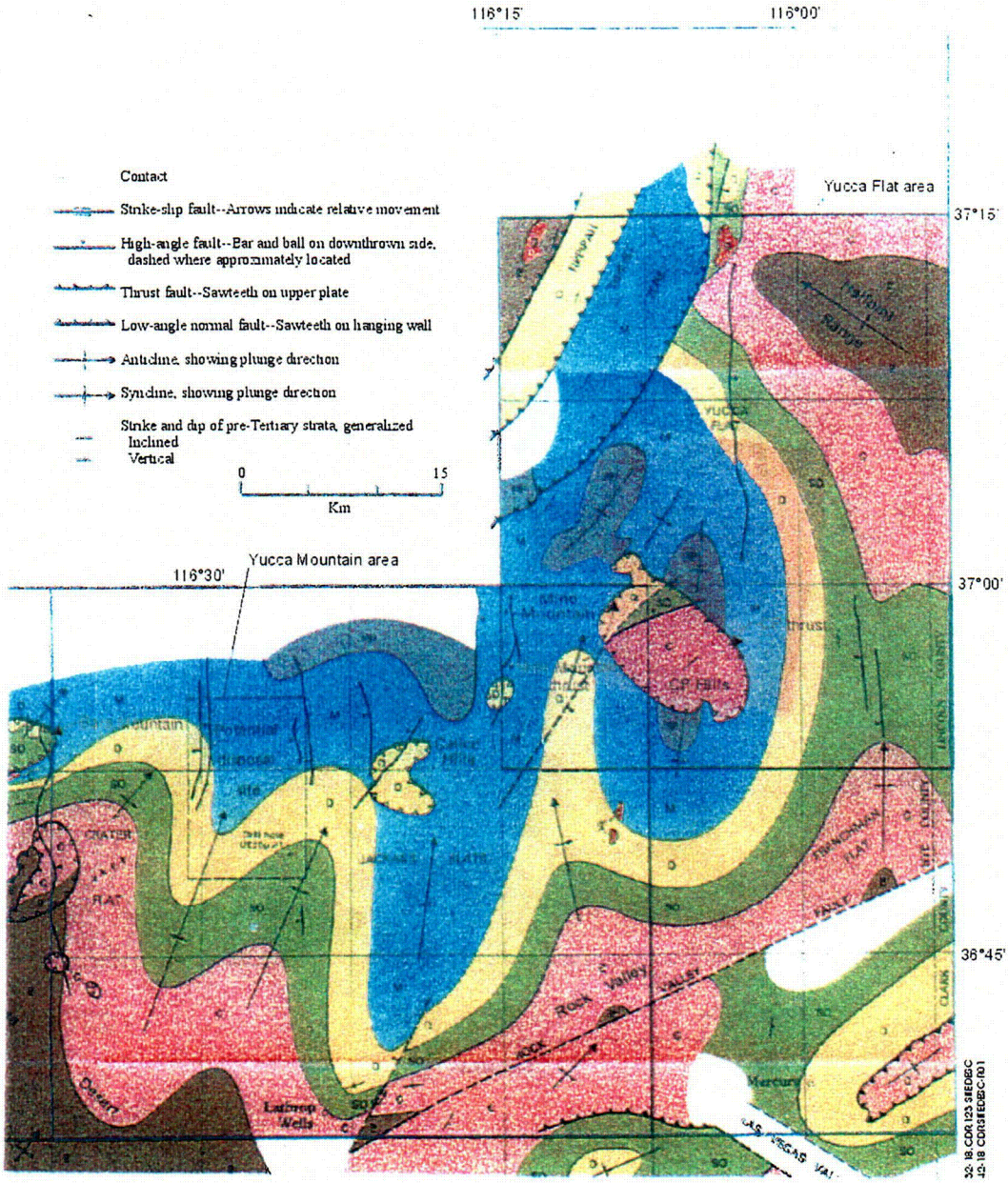
Figure 4.2-16. Schematic Cross Section Showing Kinematic Relationships among Thrusts



Sources: Wernicke, Snow et al. (1988); Burchfiel et al. (1983)

NOTES: Bar stipple (along left side of figure) is Sierra Nevada block; diagonal rule is rock above the Last Chance thrust; no pattern is rock below the Last Chance and White Top thrusts; dark gray is rock above the White Top thrust; dot stipple is rock below the White Top thrust; light gray is rock above the Wheeler Pass, Gass Peak, Chicago Pass, and Shaw thrusts; medium gray is rock between the Wheeler Pass and Keystone thrusts; and x-pattern (lower right part of figure) is rock below the Keystone thrust.
SDF = Southern Death Valley fault; NFZ = Northern Death Valley-Furnace Creek fault zone.

Figure 4.2-17. Correlative Thrusts of the Yucca Mountain Setting



Legend:

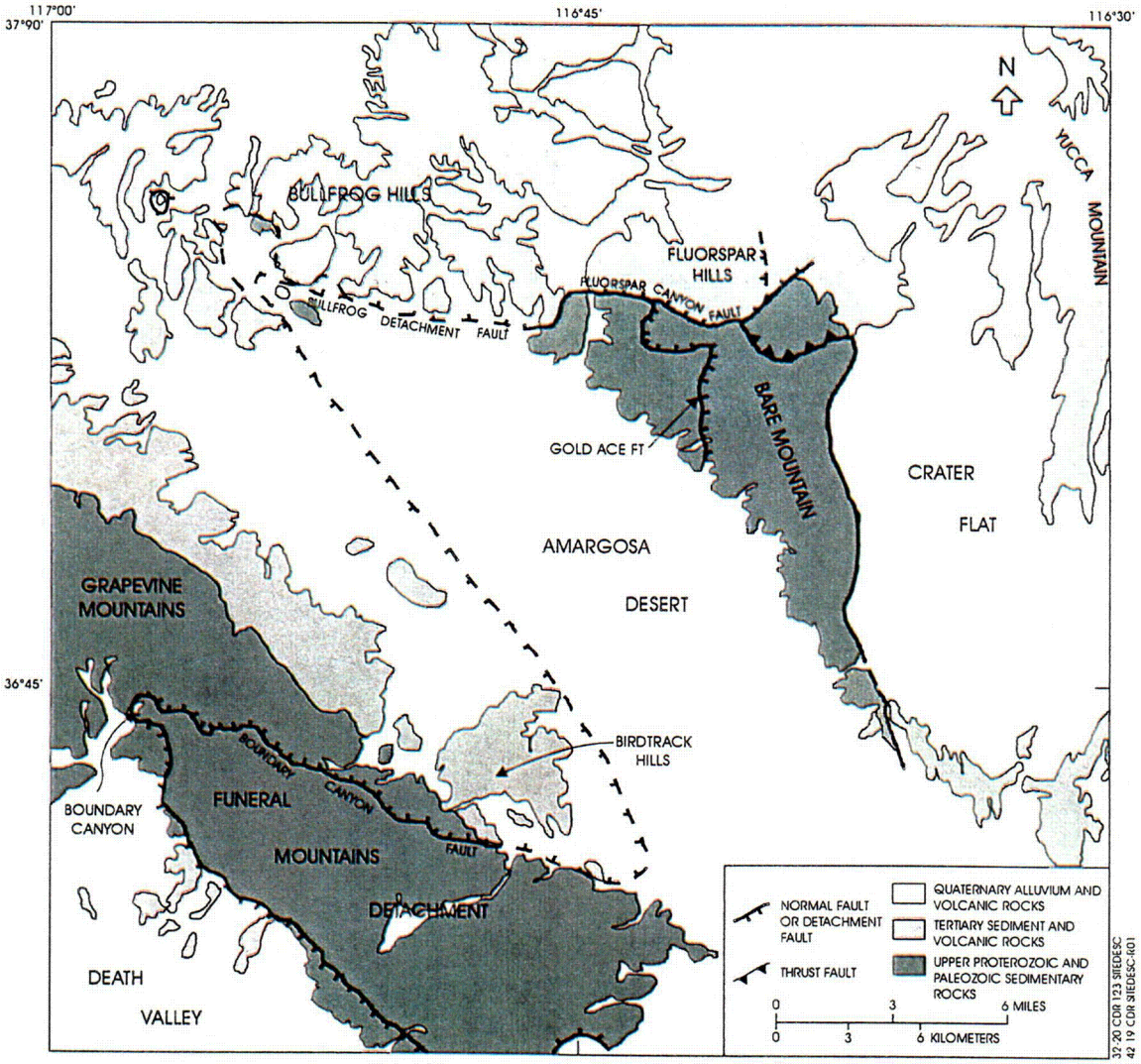
Proterozoic (P, brown)	Cambrian (C, pink)	Siluro-Ordovician (SO, green)
Devonian (D, yellow)	Mississippian (M, blue)	Permian-Pennsylvanian (PP, purple)

Source: Robinson (1985)

NOTE: Marginal legibility of some text on the figure does not affect the purpose of the figure; relevant information is conveyed by the colors.

Figure 4.2-18. Mesozoic Folding of the Yucca Mountain Area

C17



Source: Hoisch (1995)

Figure 4.2-19. Funeral Mountains Detachment

C18

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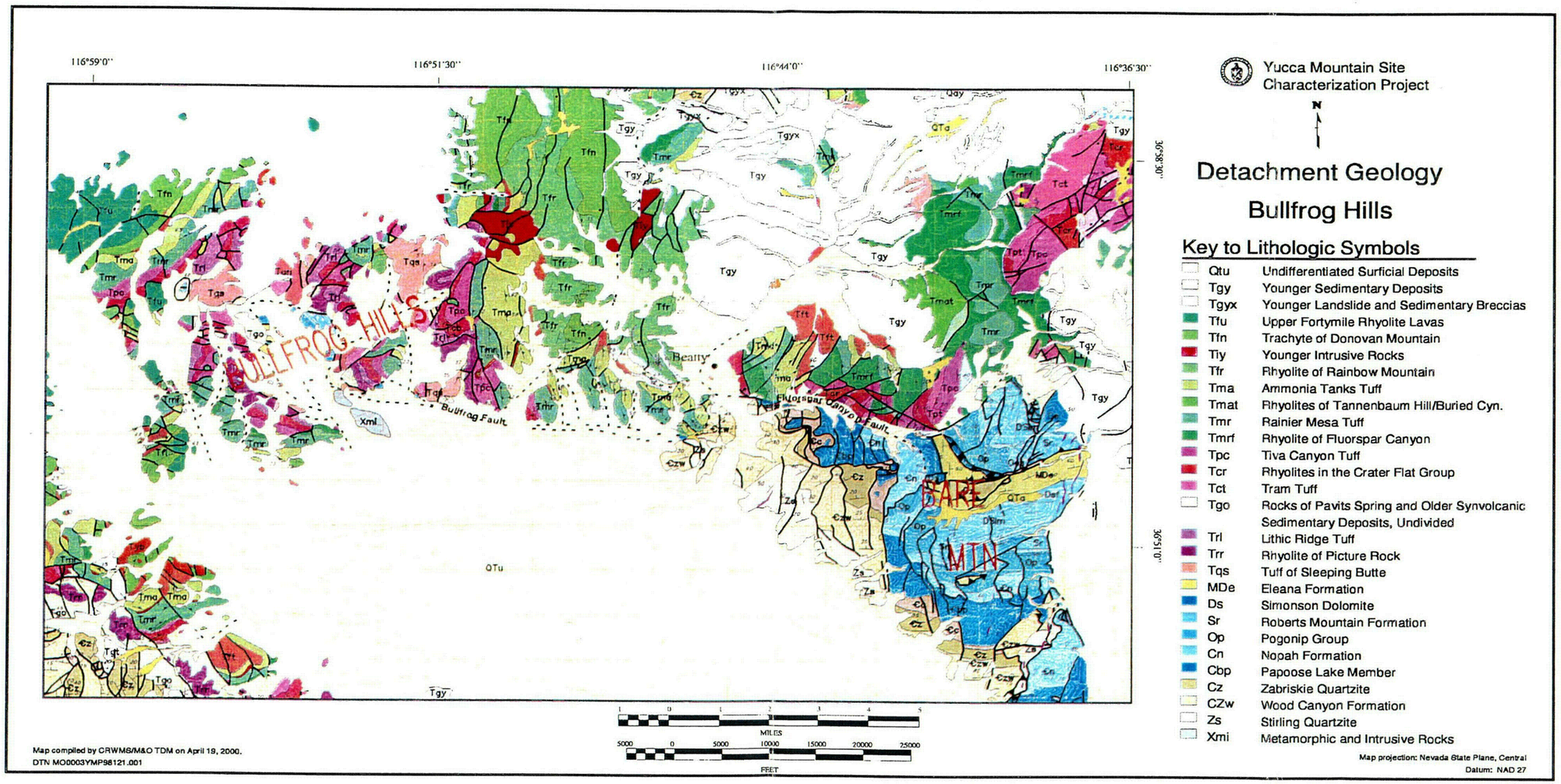

NOTE: The purpose of this figure is to show the location of the Bullfrog and Fluorspar Canyon faults with respect to Bare Mountain and other high-angle faults. Details of the geology, some of which may not be completely legible, are not important to the purpose of the figure.

Figure 4.2-20. Bullfrog Hills Detachment Geology

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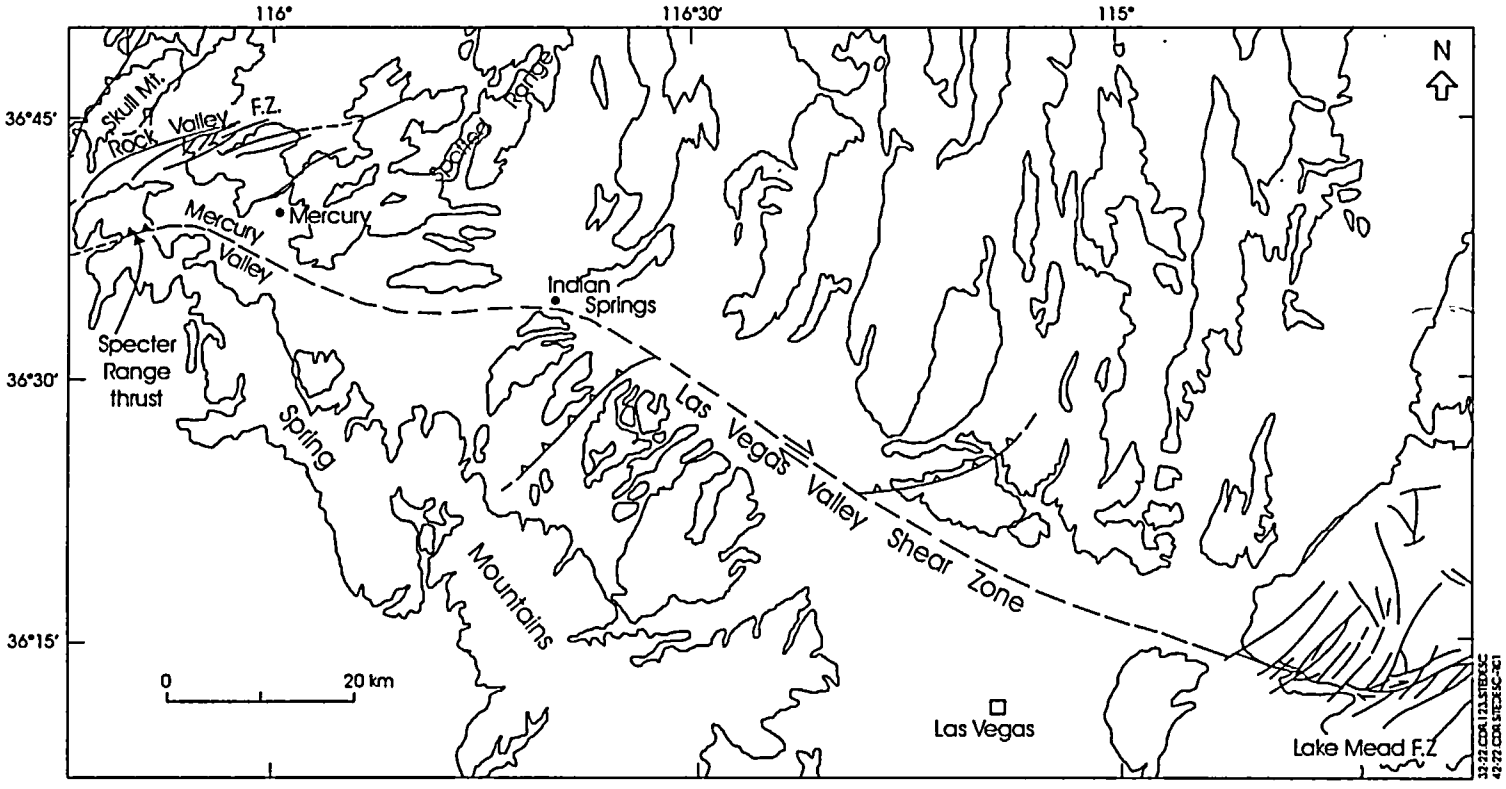
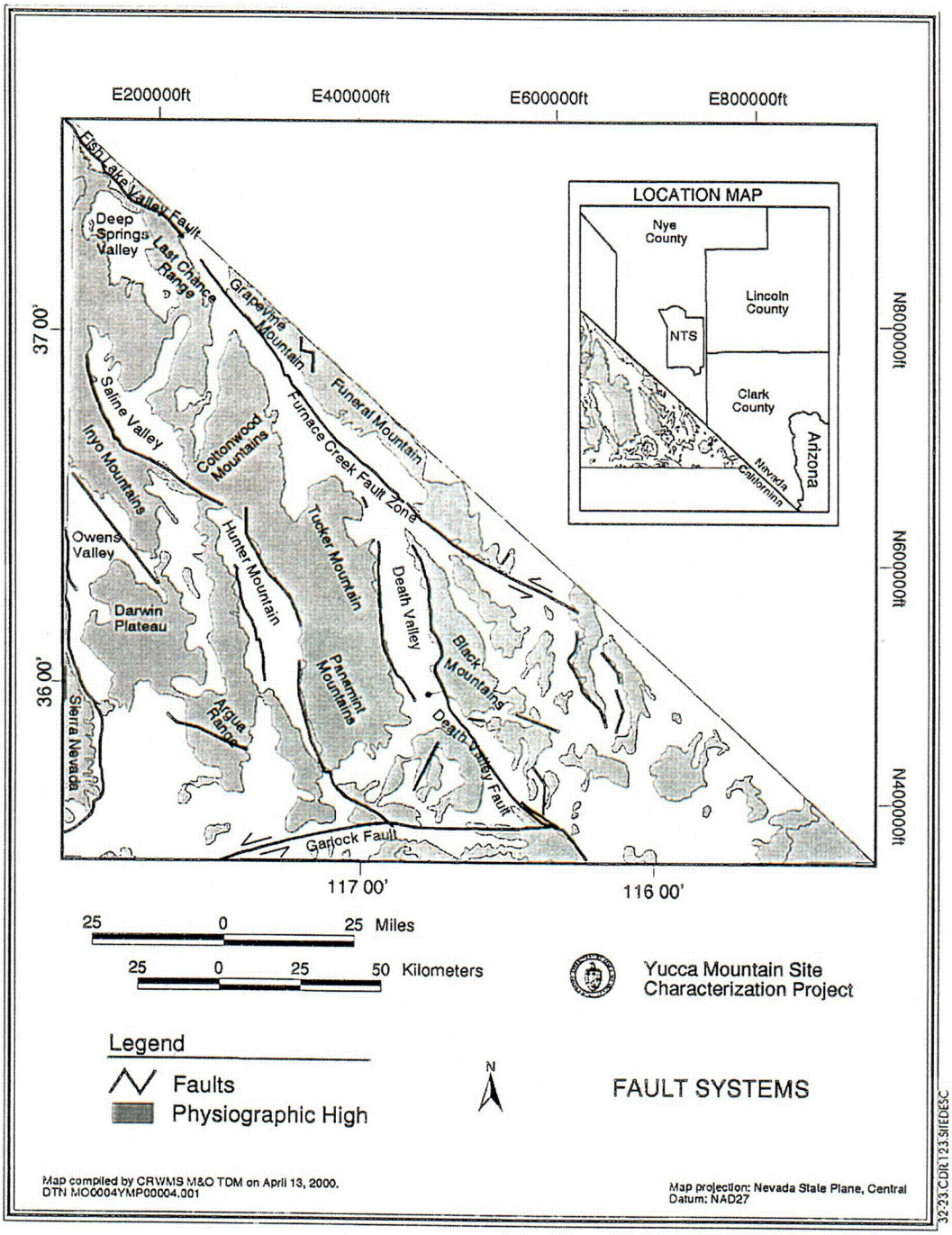


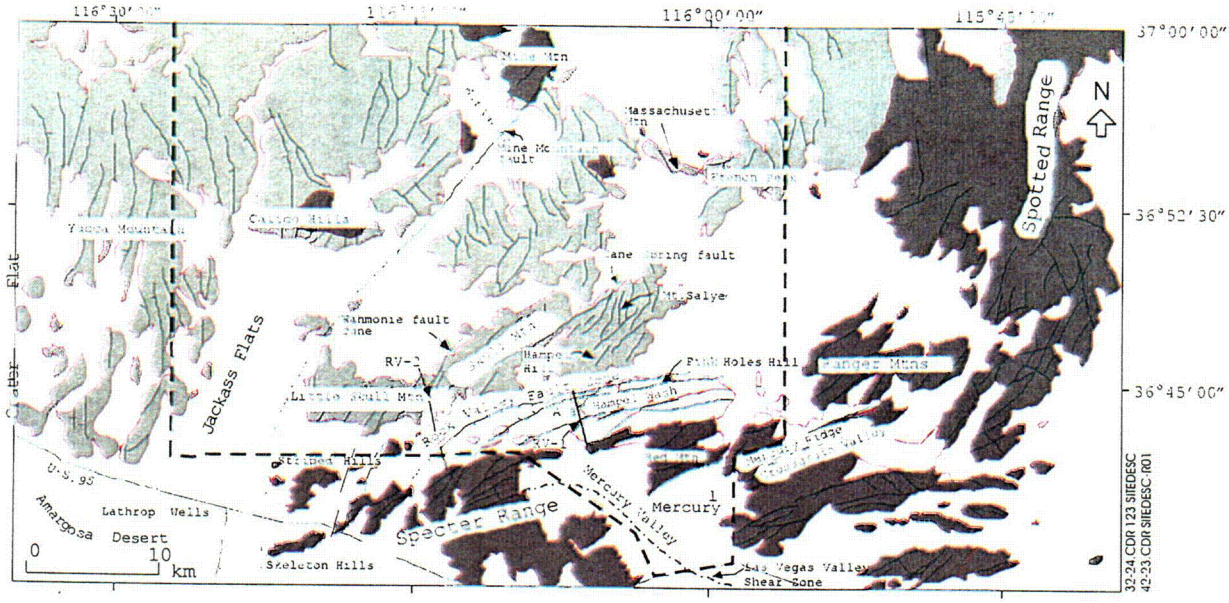
Source: Burchfiel (1965)

Figure 4.2-21. Las Vegas Valley Shear Zone



Sources: Wernicke et al. (1986); Piety (1996)

Figure 4.2-22. Major Faults of the Inyo-Mono Domain



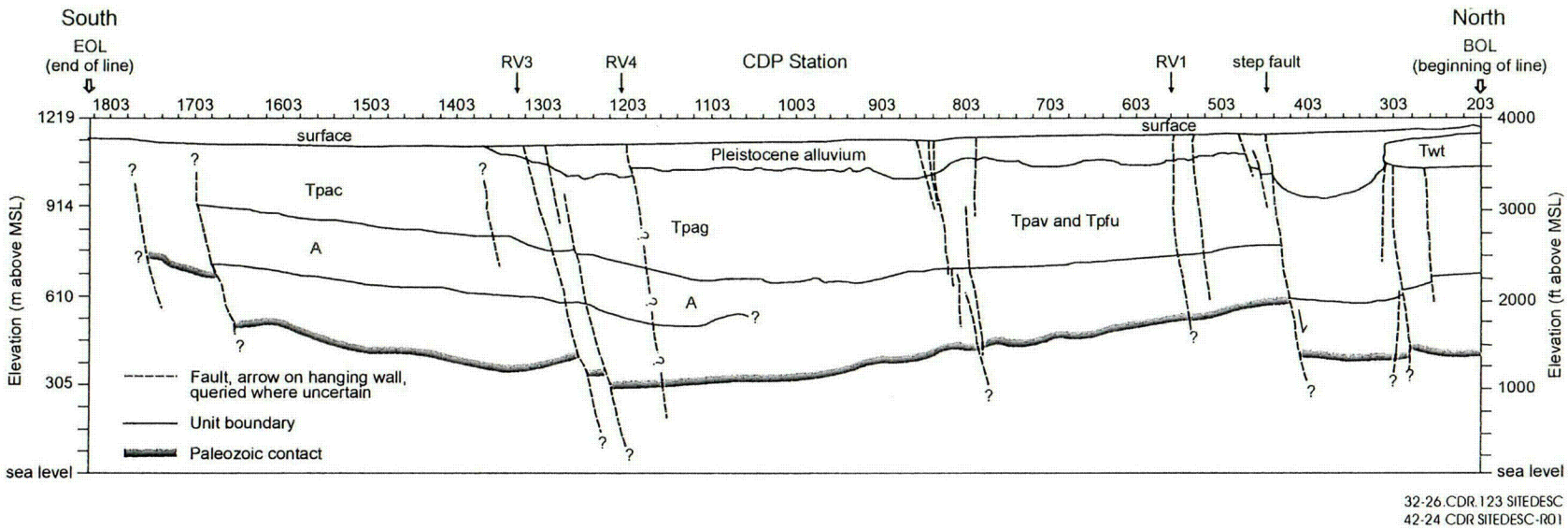
Legend

- Nevada Test Site perimeter
- fault; location and extent generalized; dash on down side; dotted where projected
- locations of trenches (Yount et al. 1987) on fault trace (A B)
- Las Vegas Valley shear zone
- Seismic profile lines
- Holocene and Pleistocene surficial deposits
- Tertiary (chiefly upper Miocene) volcanic rocks
- Tertiary (middle to upper) volcanics and volcaniclastic sediments, fluvial and lacustrine rocks of Pavits Spring (Hinrichs 1968)
- Upper Oligocene lacustrine carbonates, marls, lesser tuffs, and roundstone gravels (rocks of Winapi Wash)
- Paleozoic to Precambrian undifferentiated; chiefly carbonates, lesser quartzites and shales

Sources: Hinrichs (1968); Frizzell and Shulters (1990)

Figure 4.2-23. General Geology of the Rock Valley Fault Zone

C21

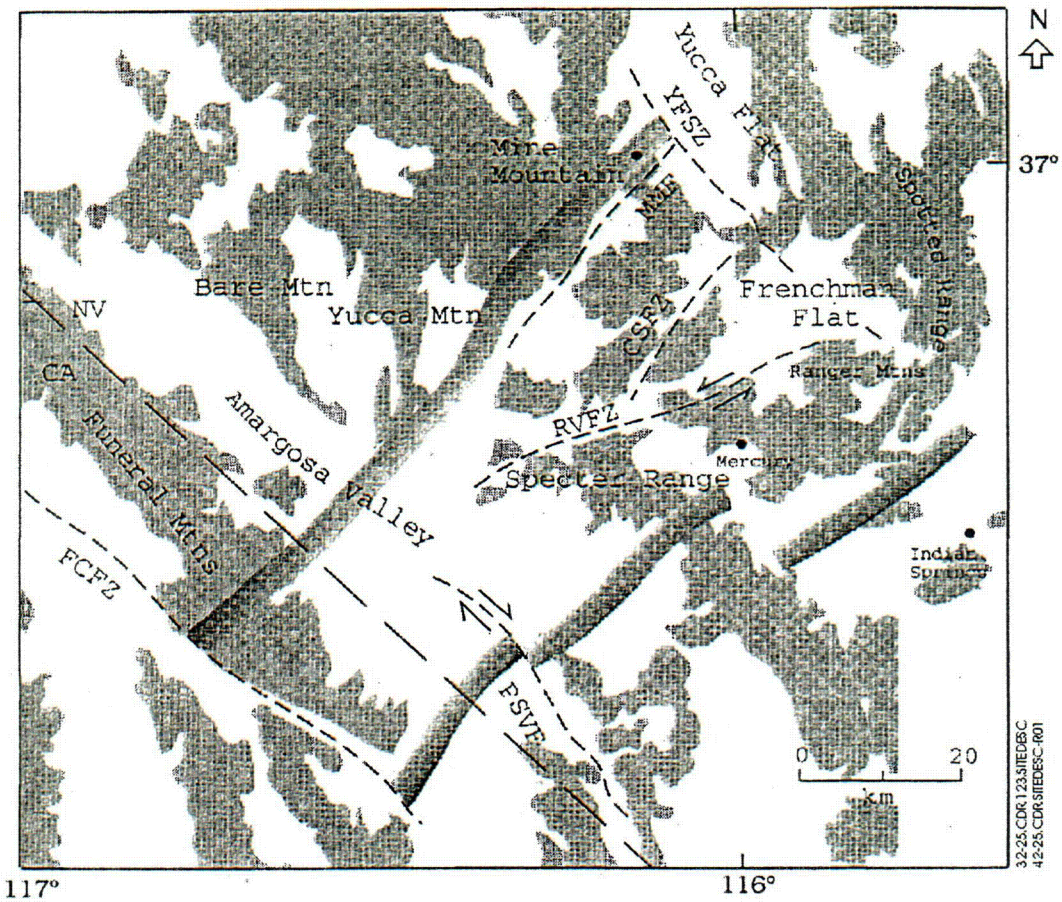


Source: Coe et al. (1996, Figure 4.13.2)

NOTE: No vertical exaggeration. RV1, RV3, and RV4 indicate major fault strands of the Rock Valley fault zone; BOL indicates beginning of line (northern end). Tpac, Tpag, Tpav, and Tpfu are subunits of Pavits Spring. Twt is the Wahmonie formation; A is the highly reflective part of Tpac, at underlying rock units.

Figure 4.2-24. Interpretation of Seismic Reflection Profile across Rock Valley

C22



Source: Carr (1984)

NOTES: CSFZ = Cane Spring fault zone
FCFZ = Furnace Creek fault zone
MMF = Mine Mountain fault zone
PSVF = Pahrump-Stewart Valley fault zone
RVFZ = Rock Valley fault zone
YFSZ = Yucca Frenchman shear zone

Figure 4.2-25. Spotted Range-Mine Mountain Structural Zone Depicted by Northeast-Trending Shaded Borders

C23

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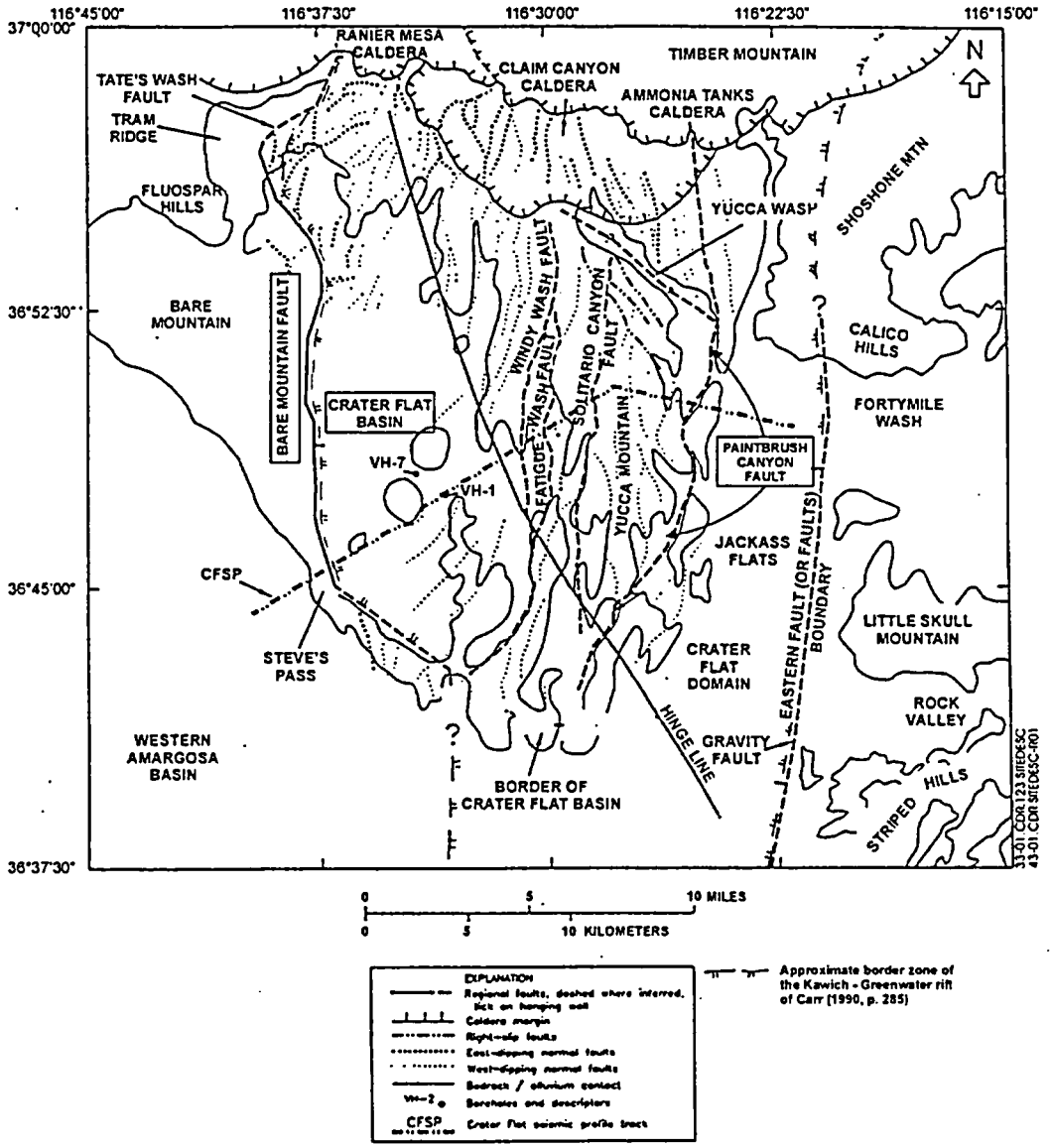

Source: After Fridrich (1999, Figure 3)

NOTE: The Gravity fault forms the eastern boundary and the Bare Mountain fault forms the western boundary of the Crater Flat Domain. The Paintbrush Canyon fault is considered to be the eastern limit of the normal fault system that characterizes Yucca Mountain.

Figure 4.3-1. Crater Flat Domain and Its Inferred Bounding Structures

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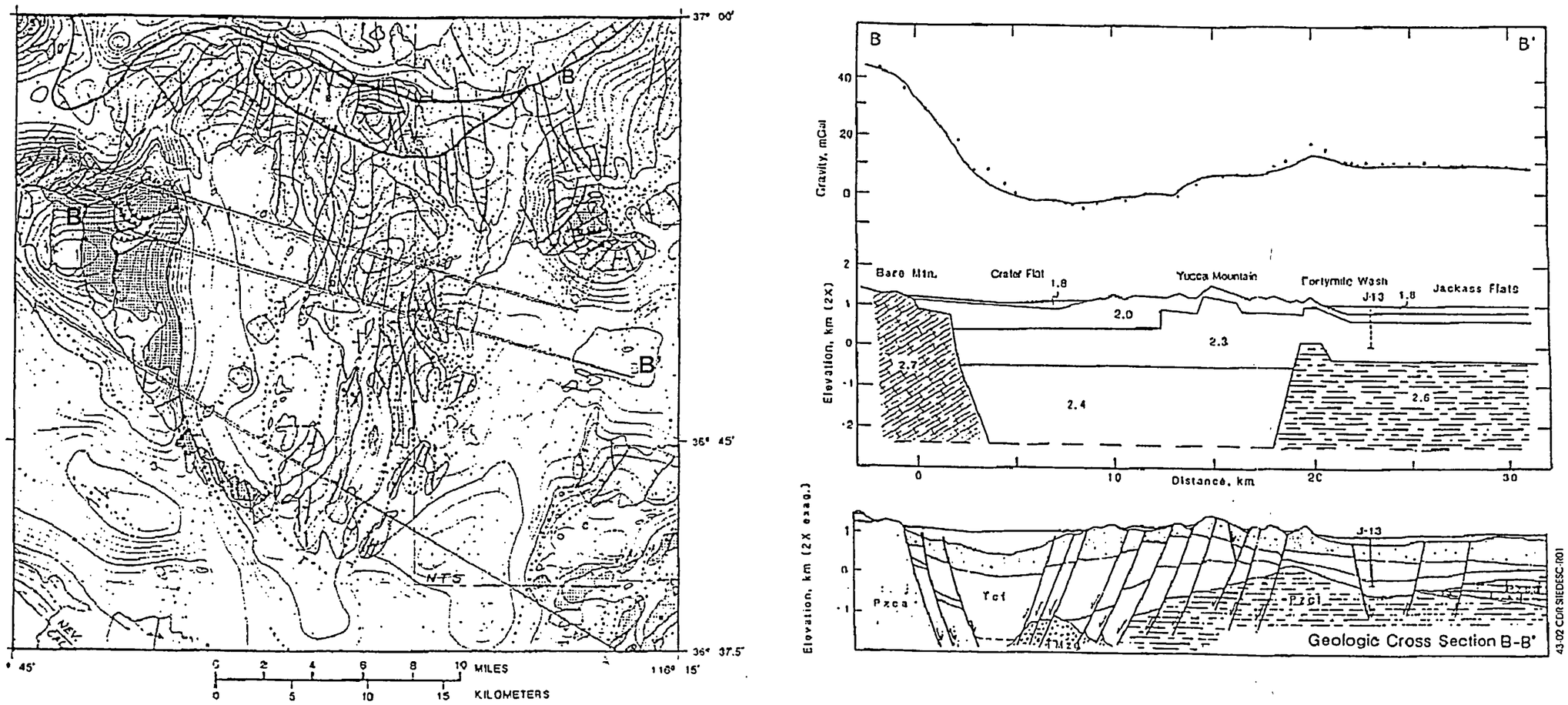

Source: Snyder and Carr (1982, Figures 7, 9, 12)

NOTE: Map shows residual gravity anomalies (contour interval 2 mGal) with superimposed geologic features of Crater Flat domain and cross section lines. Gravity modeling profile B-B' shows calculated gravity (curve) and observed values (points). Model patterns indicate Paleozoic rocks; numbers are densities in g/cm^3; USGS well J-13 location shown. Interpretive geologic cross section shows lower and middle Paleozoic carbonate rocks (Pzca), upper Paleozoic clastic rocks (Pzcl), Mesozoic granite (TMzg), and Crater Flat Tuff (Tcf).

Figure 4.3-2. Residual Gravity Anomalies with Superimposed Geologic Features of Crater Flat Domain and Cross-Section Lines

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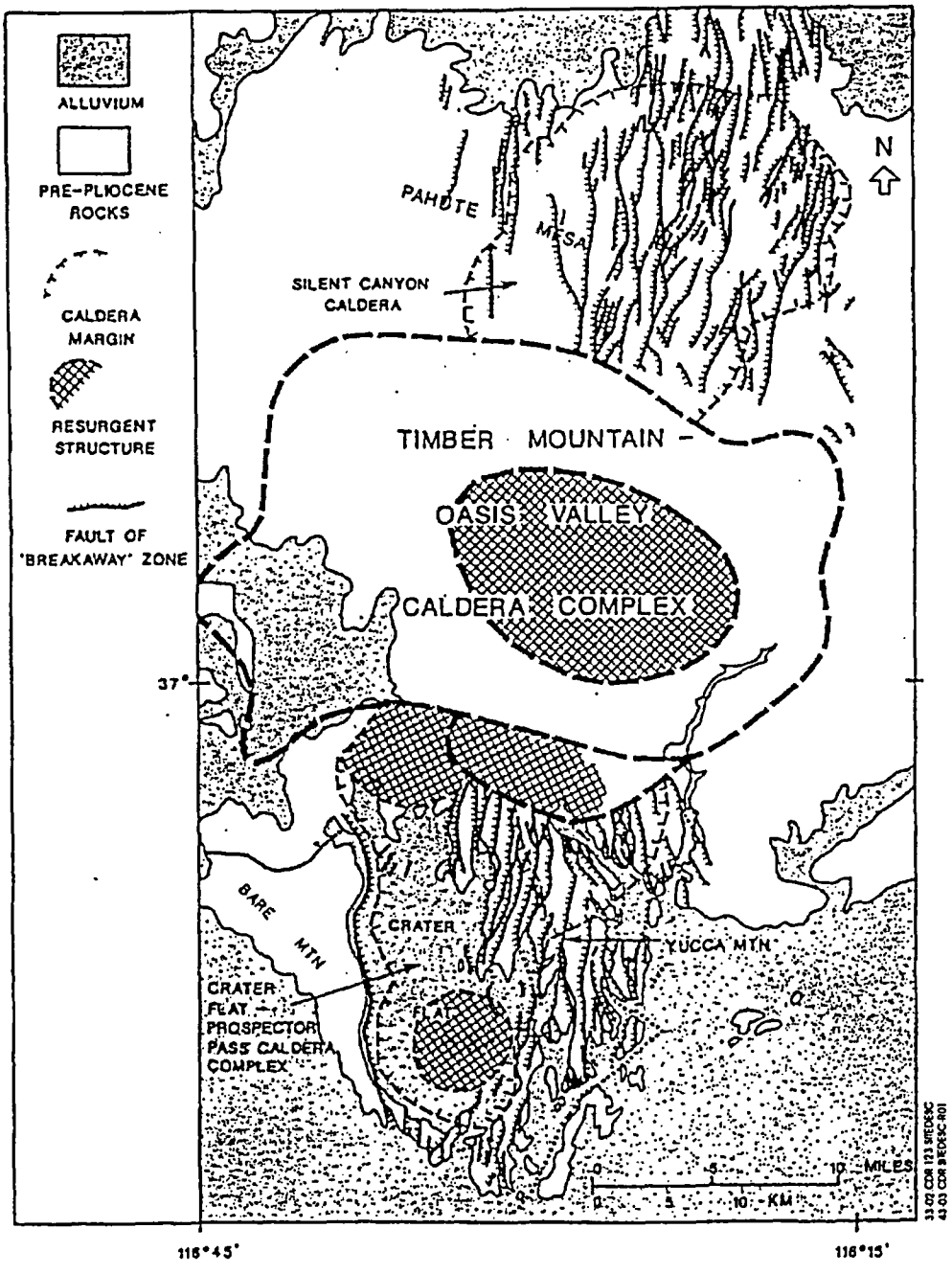
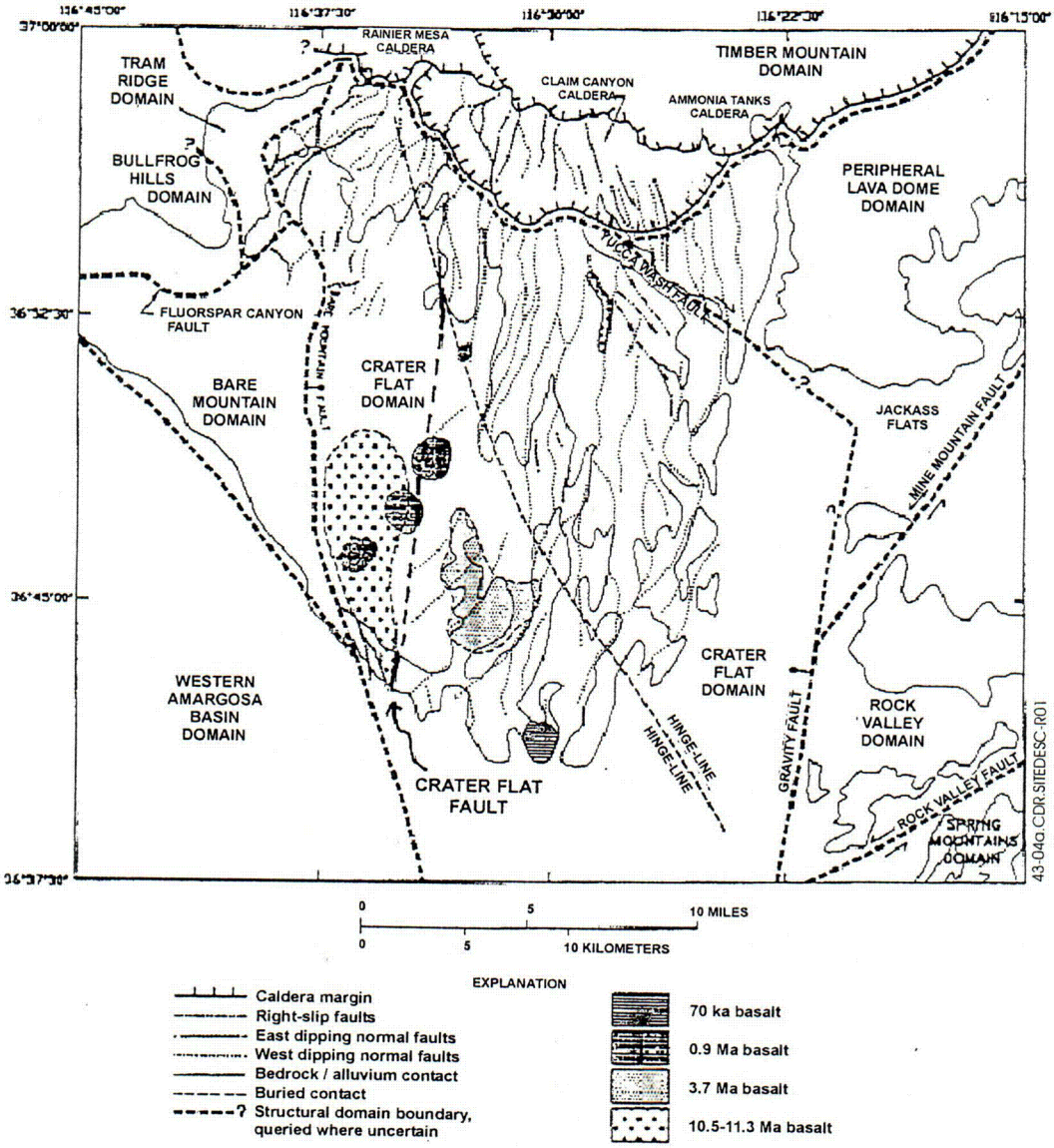


Source: Carr (1990, p. 293)

Figure 4.3-3. Coaxial Fault Sets of Yucca Mountain and Pahute Mesa Separated by Caldera Complex

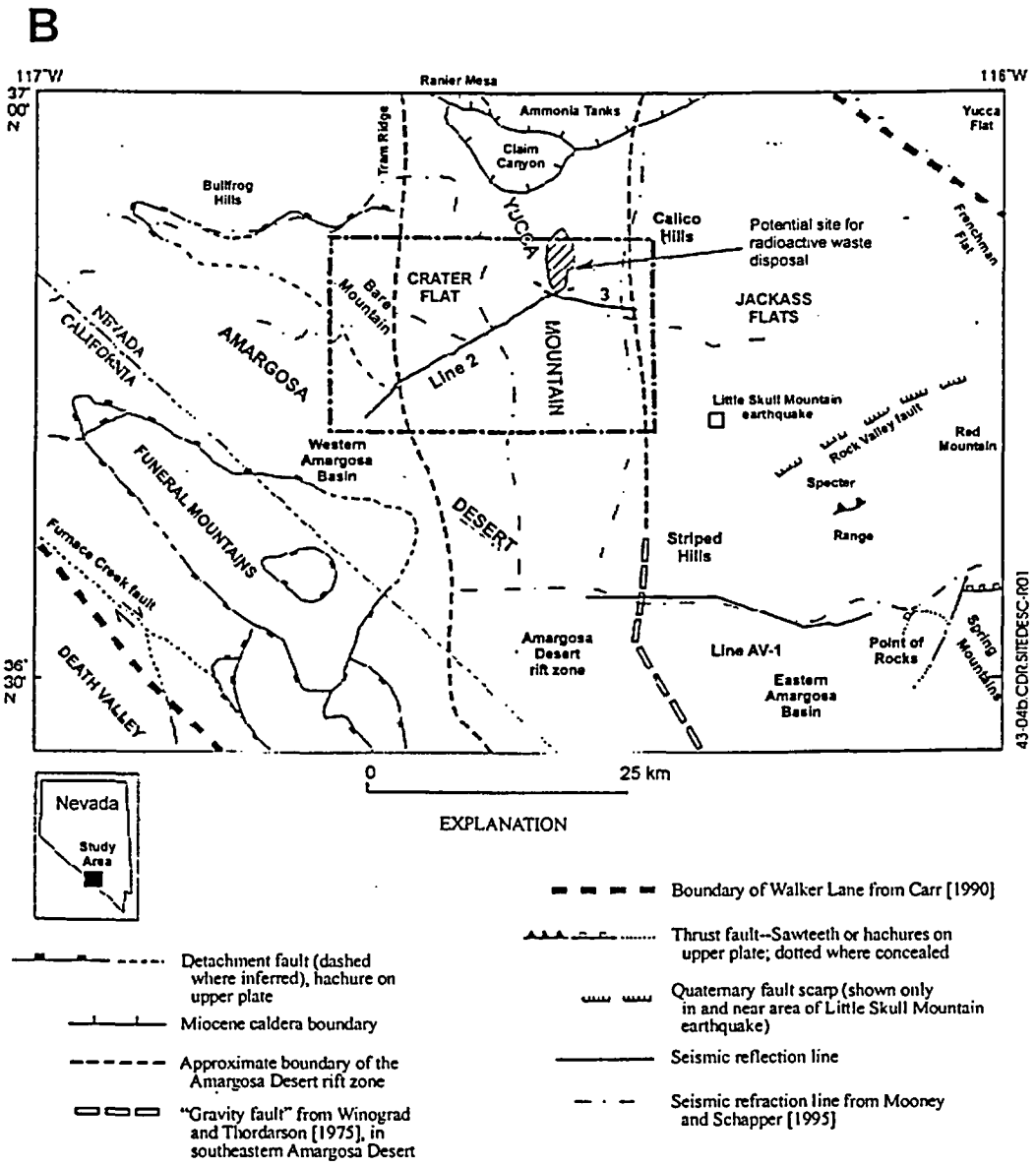
A



Source: Interpretations of the eastern boundary of the Crater Flat domain for Part A are from Fridrich (1999) and for Part B, Brocher et al. (1998). The Amargosa Desert rift zone (Part B) is equivalent to the Kawich-Greenwater rift of Carr, W.J. (1990, Figure 3.2-9).

NOTE: Part A is a map showing structural domains and domain boundaries of the Yucca Mountain region and internal fault structures of the Crater Flat basin and selected parts of adjacent domains.

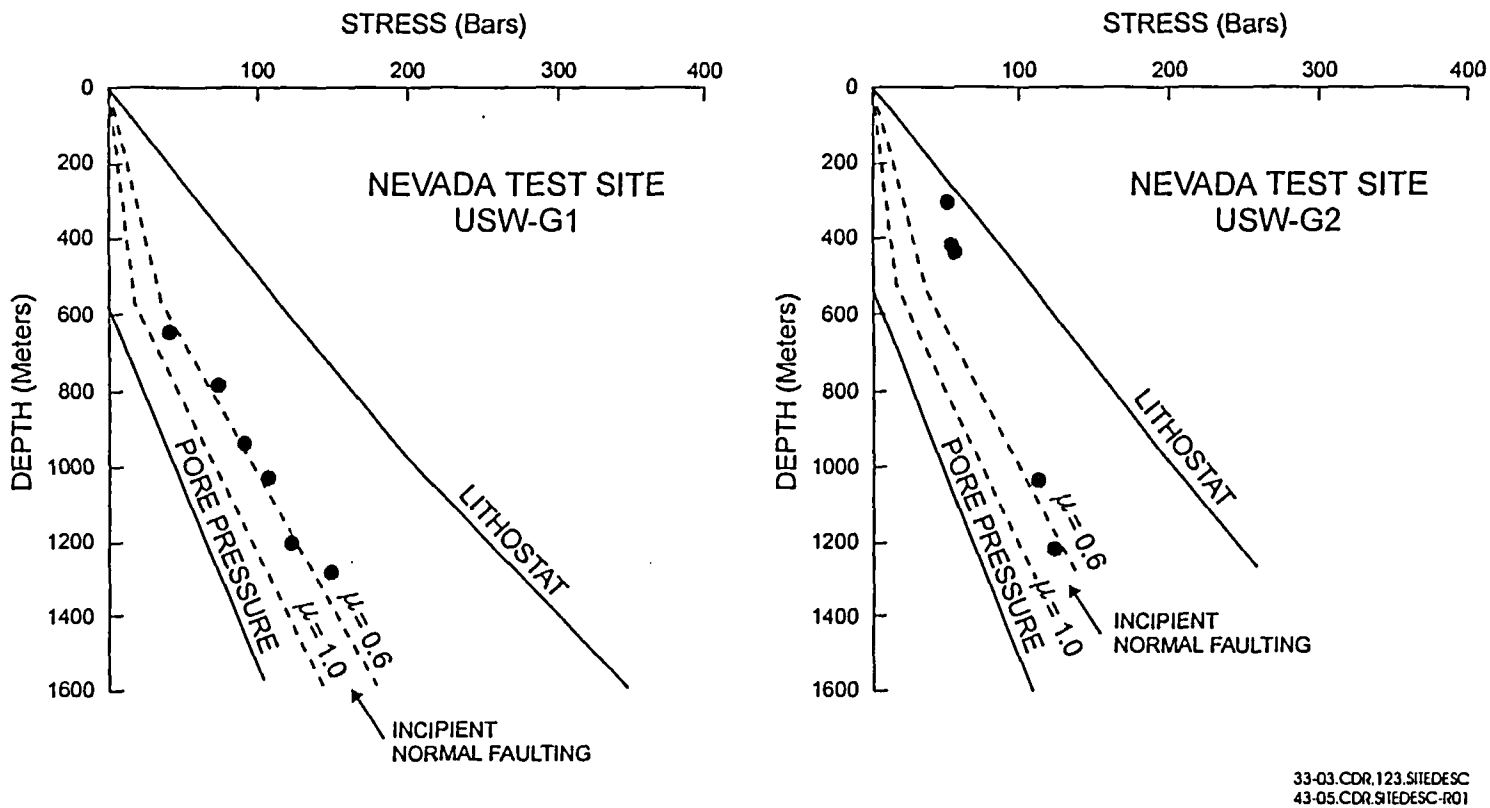
Figure 4.3-4. Interpretations of the Eastern Boundary of the Crater Flat Domain



Source: Interpretations of the eastern boundary of the Crater Flat domain for Part A are from Fridrich (1999) and for Part B, Brocher et al. (1998). The Amargosa Desert rift zone (Part B) is equivalent to the Kawich-Greenwater rift of Carr, W.J. (1990, Figure 3.2-9).

NOTE: Part B is a map showing relation of seismic lines 2, 3, and AV-1 to Bare Mountain, Crater Flat, Yucca Mountain, and other structures described in the text. Square shows the epicenter of the 1992 Little Skull Mountain earthquake (Harmsen 1994). Inset shows location of study area in Nevada.

Figure 4.3-4. Interpretations of the Eastern Boundary of the Crater Flat Domain (Continued)

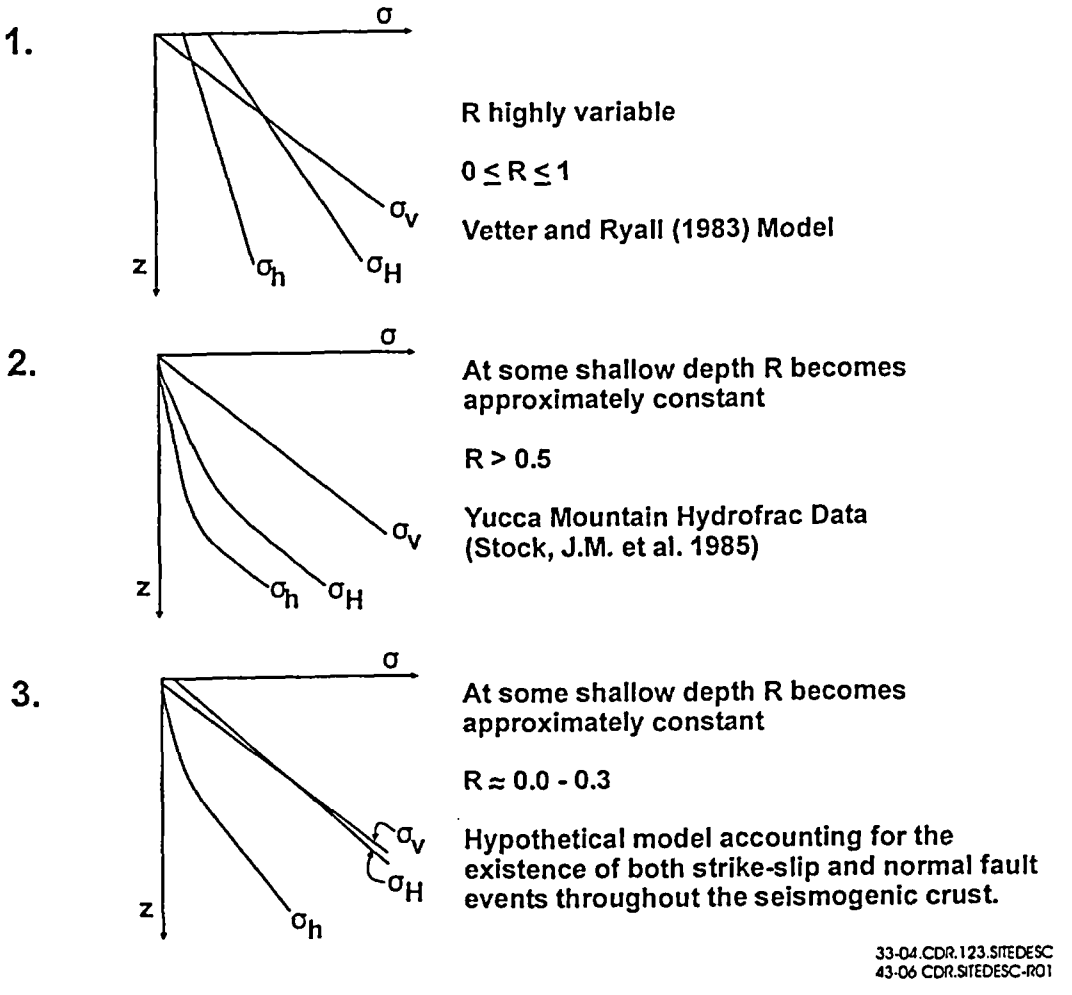


Source: USGS (1984, Figure 40)

NOTE: Black dots denote stress value measurements. Dashed lines show boundaries of fault instability for values of the coefficient of friction, μ, of 0.6 and 1.0. Faults are stable for stress values to the right of the dashed lines. Note that three values fall close to the stability boundary for normal faults that have a typical μ=0.6 (Byerlee 1978).

Figure 4.3-5. Least Principal Compressive Stress (σ_3) Values Measured from Boreholes USW G-1 and USW G-2 at Yucca Mountain

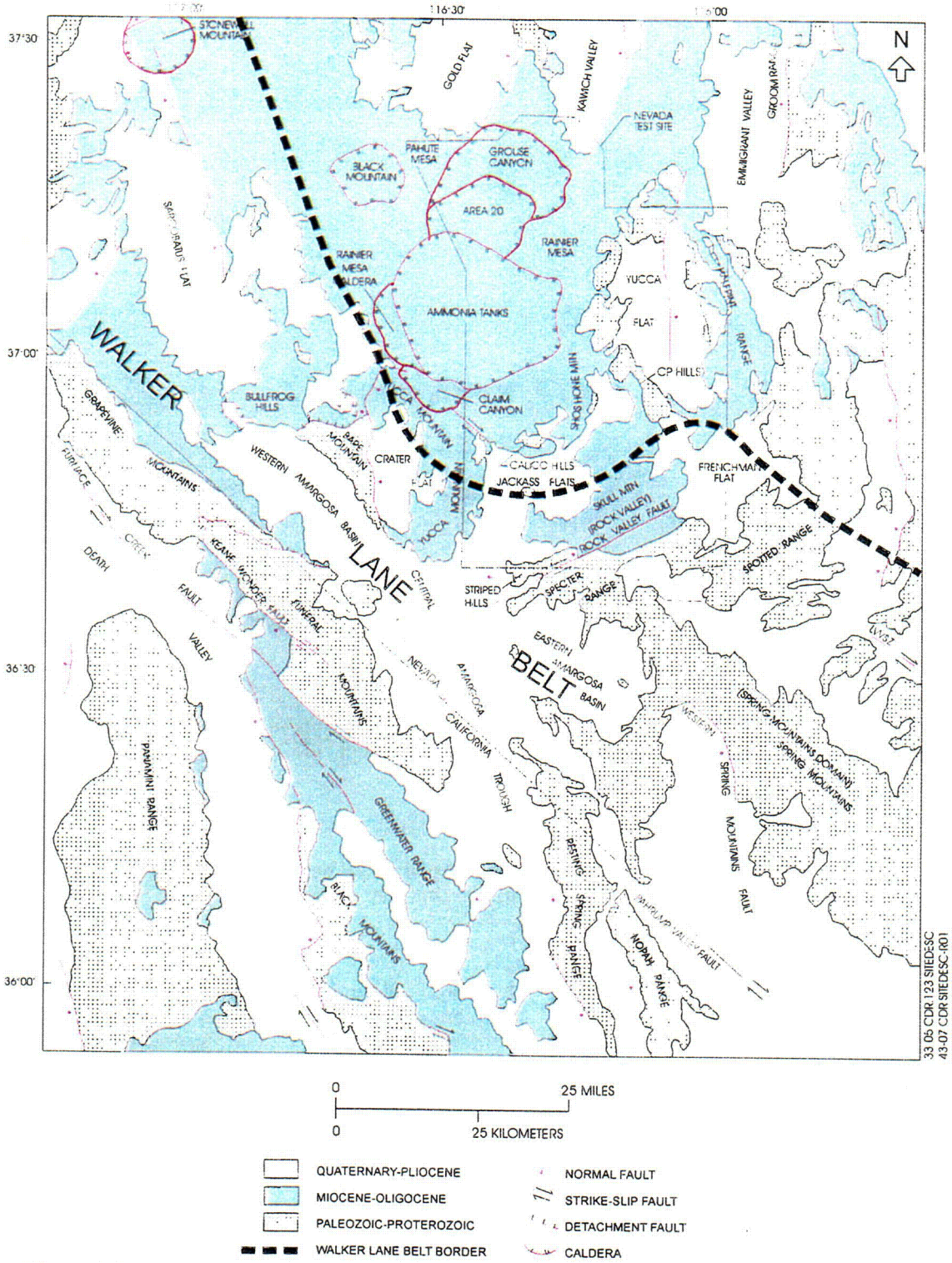
$$R = \frac{\sigma_1 - \sigma_2}{\sigma_1 - \sigma_3} = \frac{\sigma_v - \sigma_H}{\sigma_v - \sigma_h}$$



Source: Rogers, Harmsen, and Meremonte (1987, Figure 43)

NOTE: Figure shows how vertical stress (σ_v) and horizontal stress (σ_h,σ_H) components might vary with crustal depth (z); model 3 shows σ_v and σ_H to be axially symmetric. R is the stress ratio.

Figure 4.3-6. Models of Stress Distribution with Depth

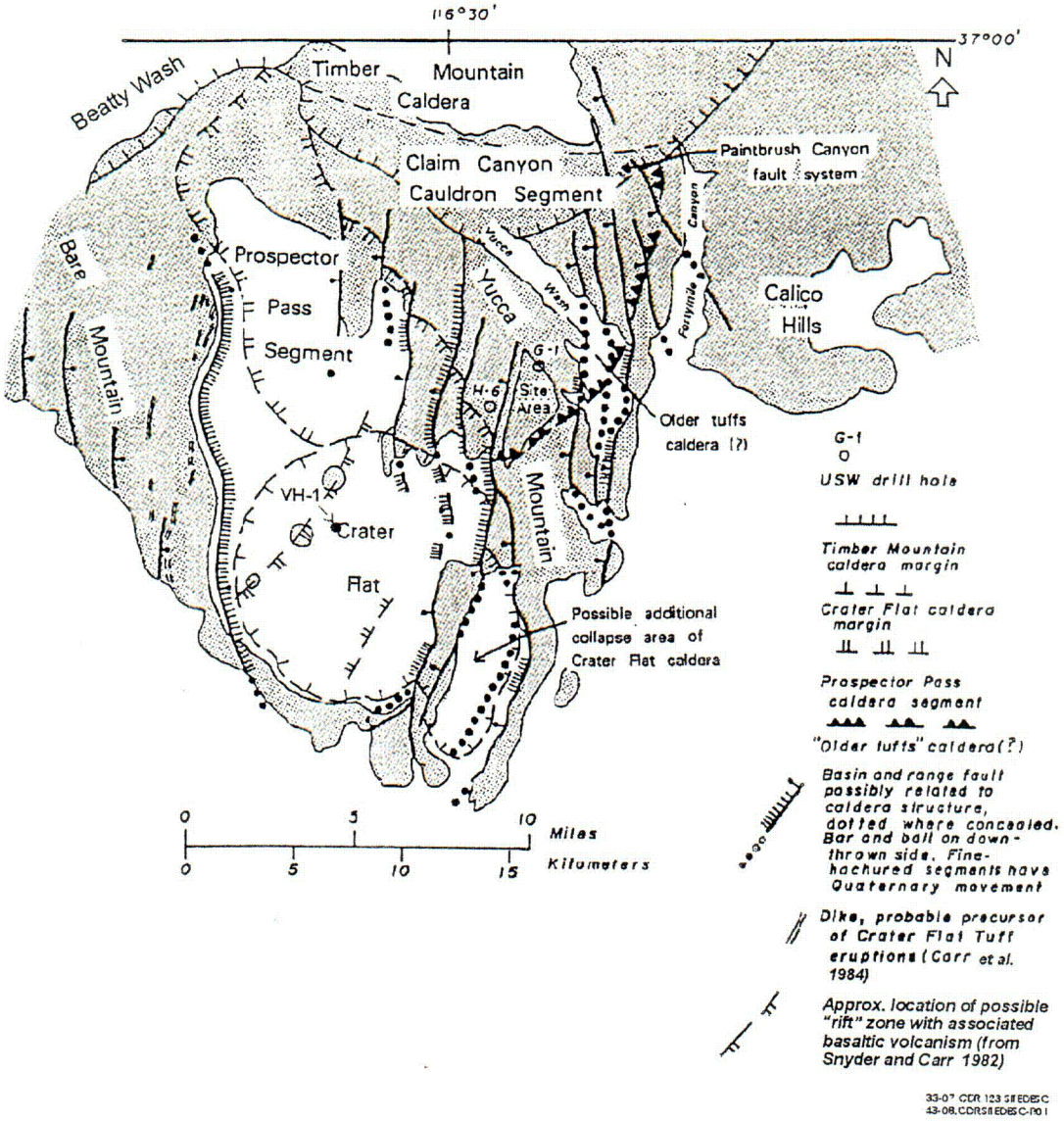


Source: Minor, Hudson et al. (1997, Figure 1)

NOTE: Heavy dashed line indicates eastern border of Walker Lane.

Figure 4.3-7. Eastern Border of Walker Lane

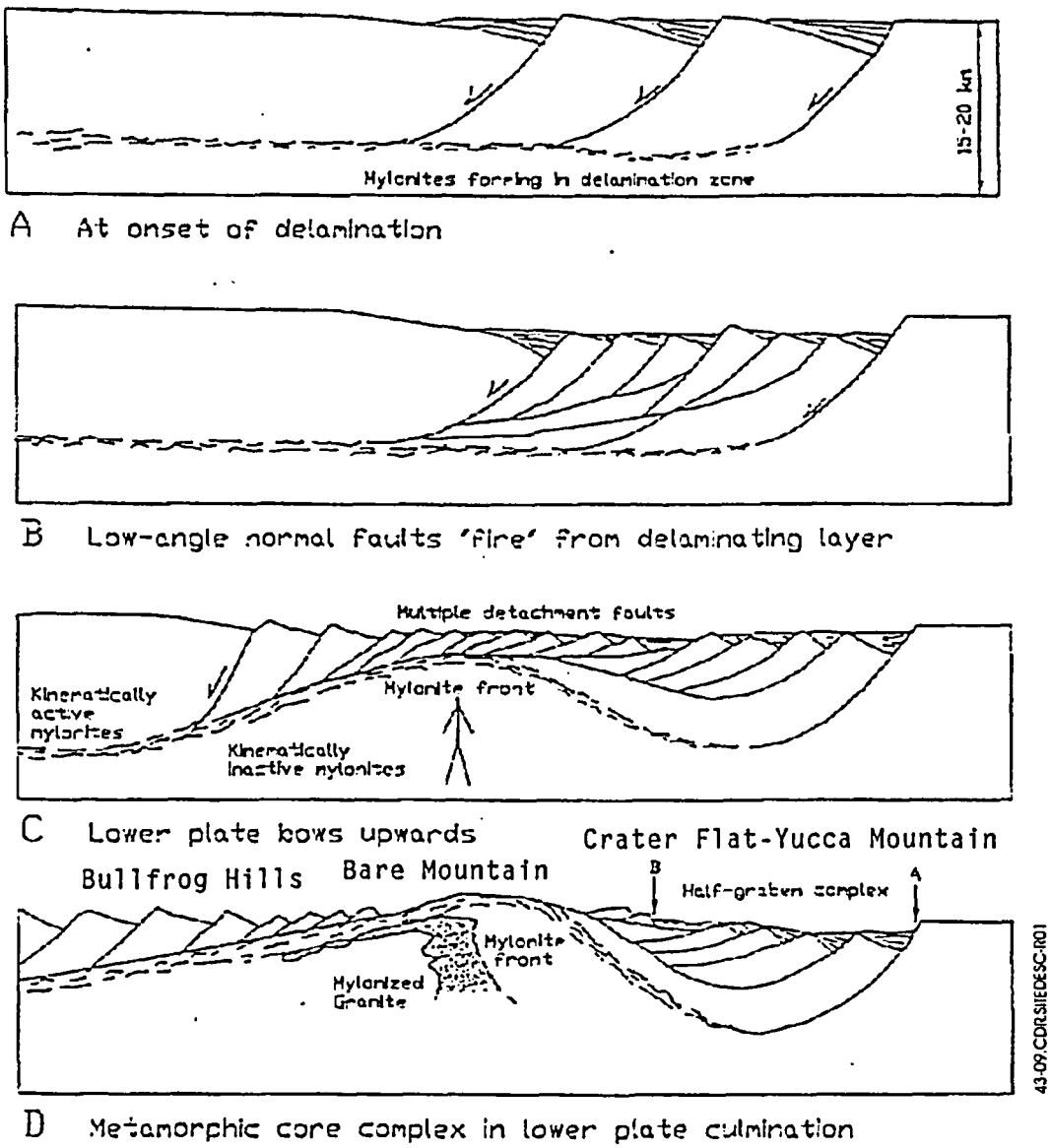
C25



Source: W.J. Carr (1984)

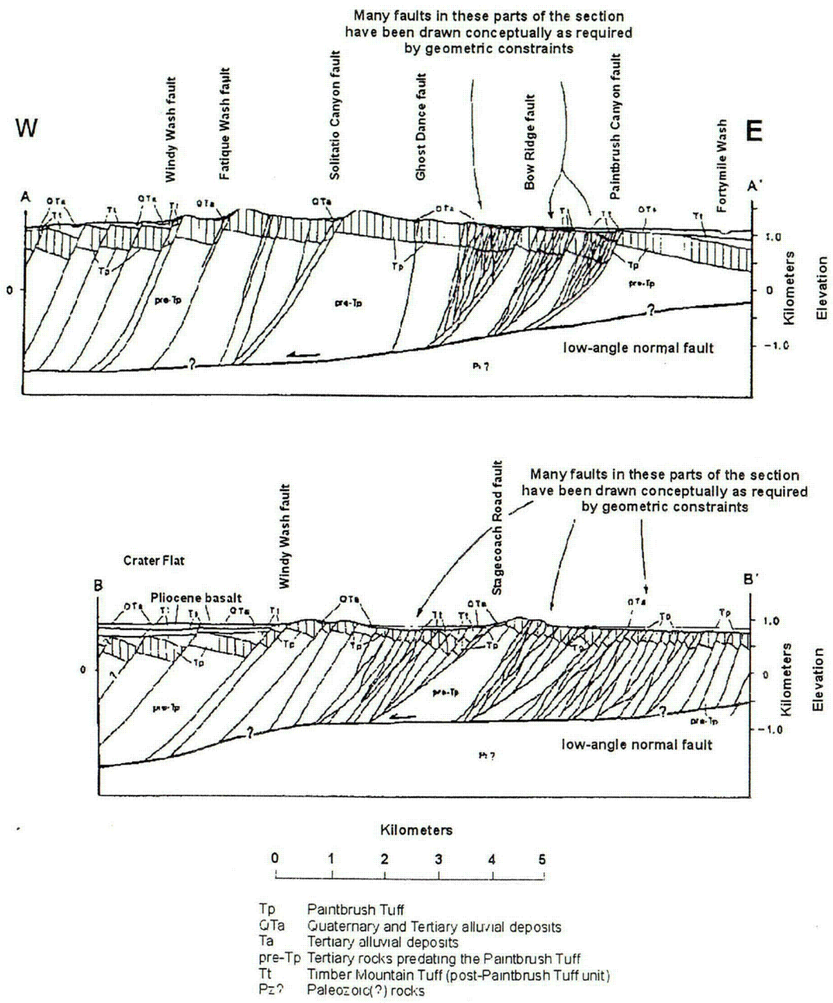
Figure 4.3-8. Size and Extent of Inferred Calderas beneath Crater Flat and Yucca Mountain

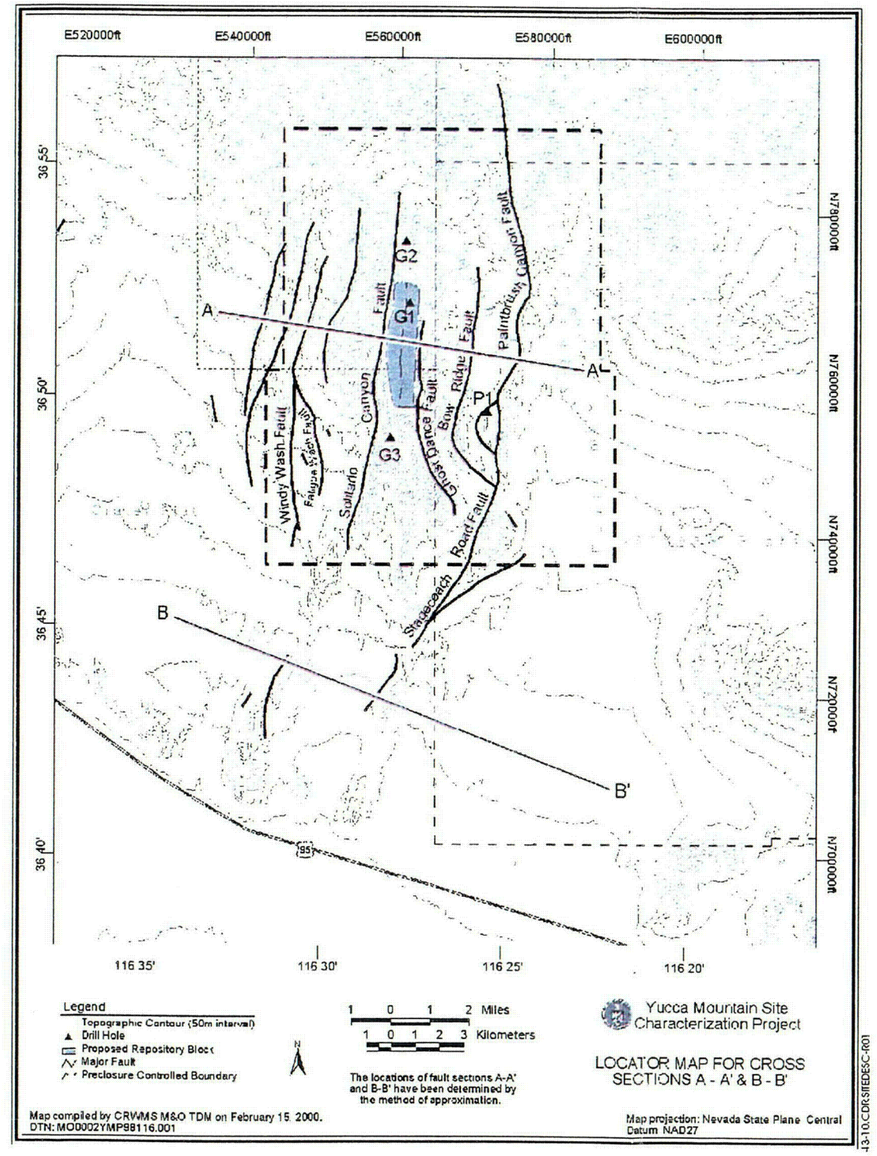
C26



Source: From Simonds and Hamilton (1995, Figure 1-4)

Figure 4.3-9. Rolling Hinge Model with Reference to Bare Mountain and Crater Flat





Source: R.B. Scott (1990)

NOTE: Fault names that are marginally legibile on the map can be found on the cross sections.

Figure 4.3-10. Cross Sections of Yucca Mountain Showing Inferred Shallow Detachment Fault

C27

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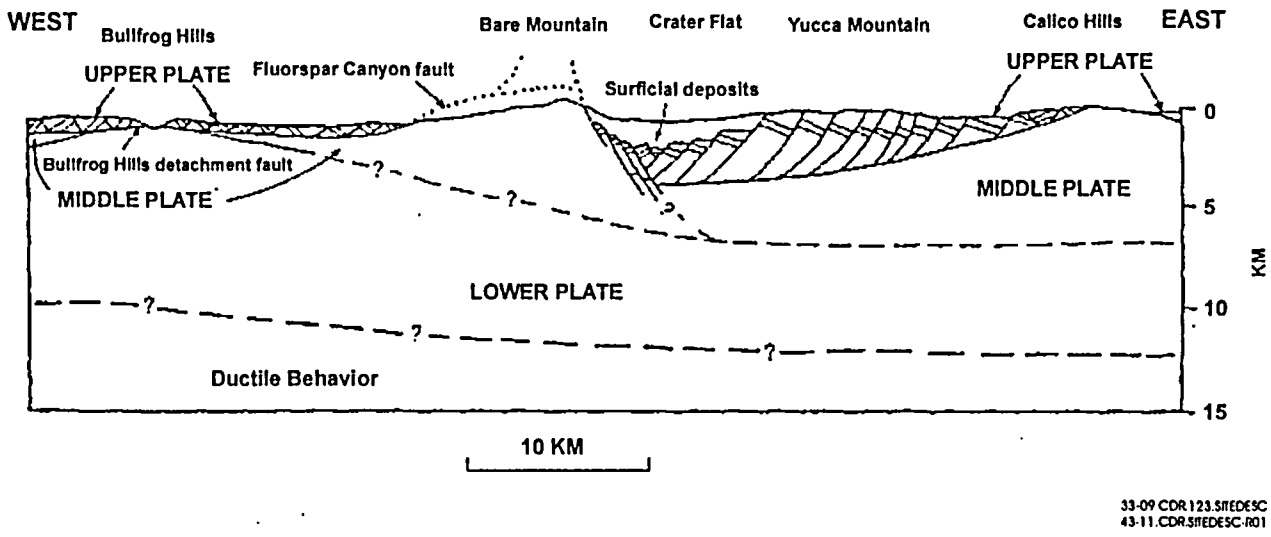
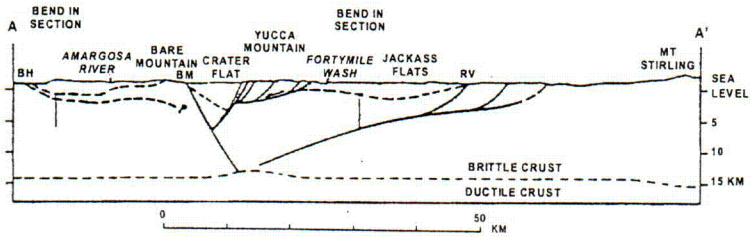


Source: R.B. Scott (1990)

Figure 4.3-11. Conceptual Cross Section Showing Inferred Levels of Detachment beneath Yucca Mountain



EXPLANATION

Faults dotted where concealed

Quaternary surficial deposits

Tertiary volcanic and sedimentary rocks

Paleozoic and Proterozoic sedimentary and metamorphic rocks

Map

Strike-slip arrows indicate relative movement

Normal hachured on downthrown side where known

Low-angle extensional hachures on upper plate

Cross Section

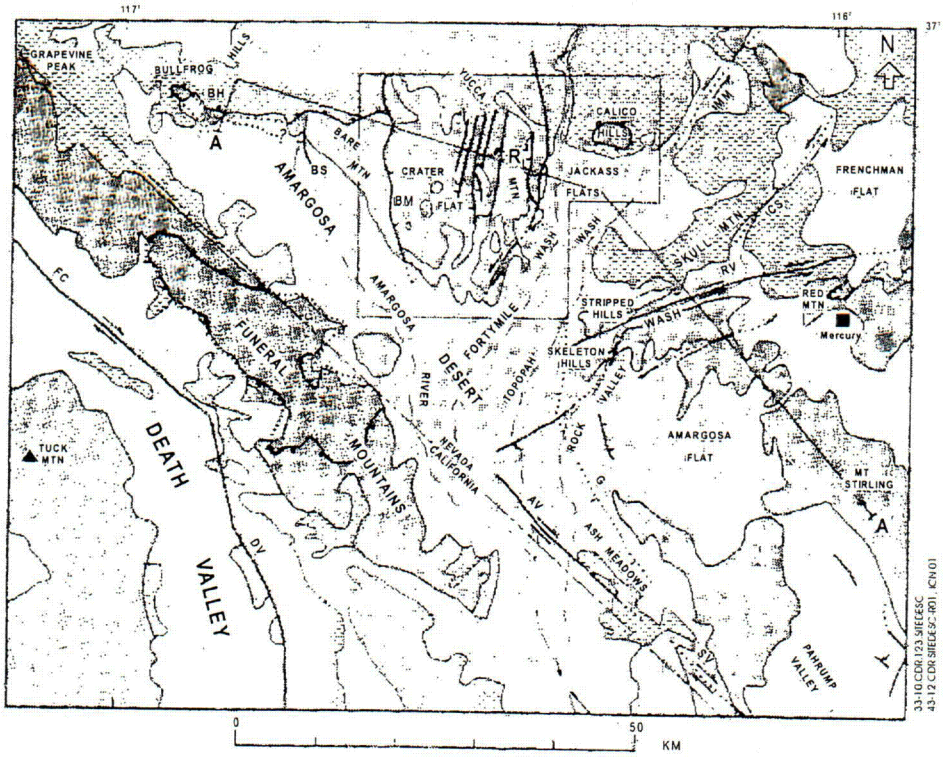
Inferred or known to be Quaternary

Probably pre-Quaternary

Transition zone

Map features

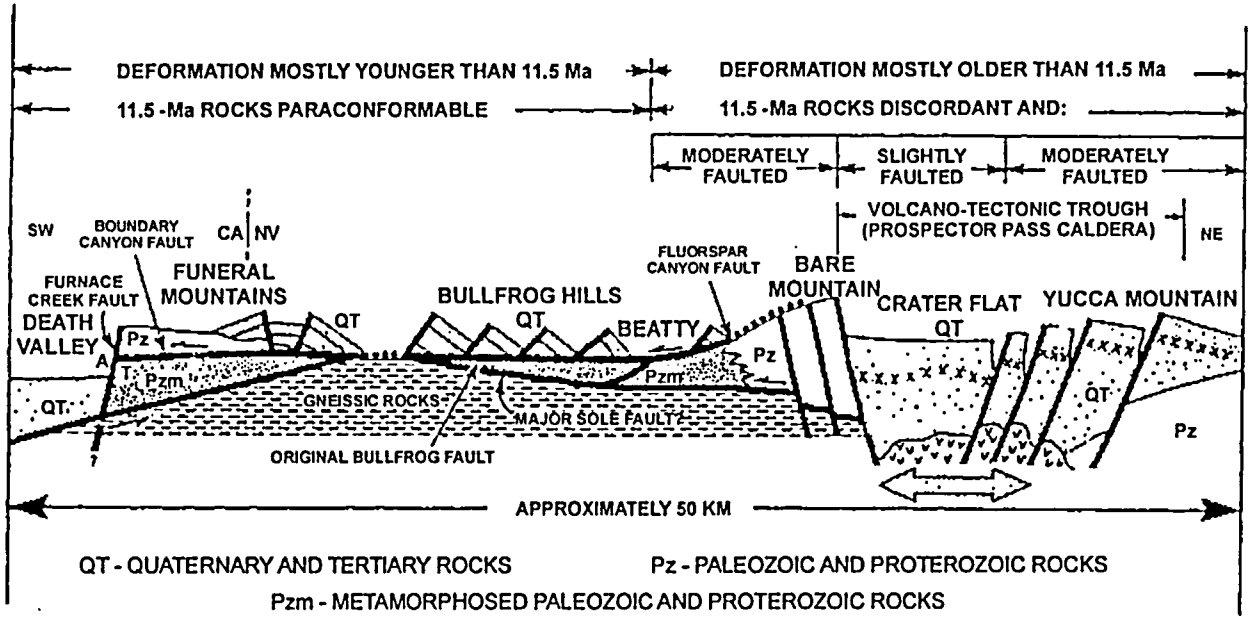
FC Furnace Creek fault
DV Death Valley fault
BH Bullfrog Hills core complex of McKee (1983)
BS Beatty scarp
BM Bare Mountain fault
Pahrump fault zone
AV Amargosa Valley fault
SV Stewart Valley fault
G Gravity fault
MM Mine Mountain fault
CS Cane Springs fault
RV Rock Valley fault
R Repository (potential)



Source: After Fox and Carr (1989)

Figure 4.3-12. Detachment Structures Inferred near Yucca Mountain

C28



Source: W.J. Carr (1990)

Figure 4.3-13. Model of Crustal Extension from Death Valley to Yucca Mountain

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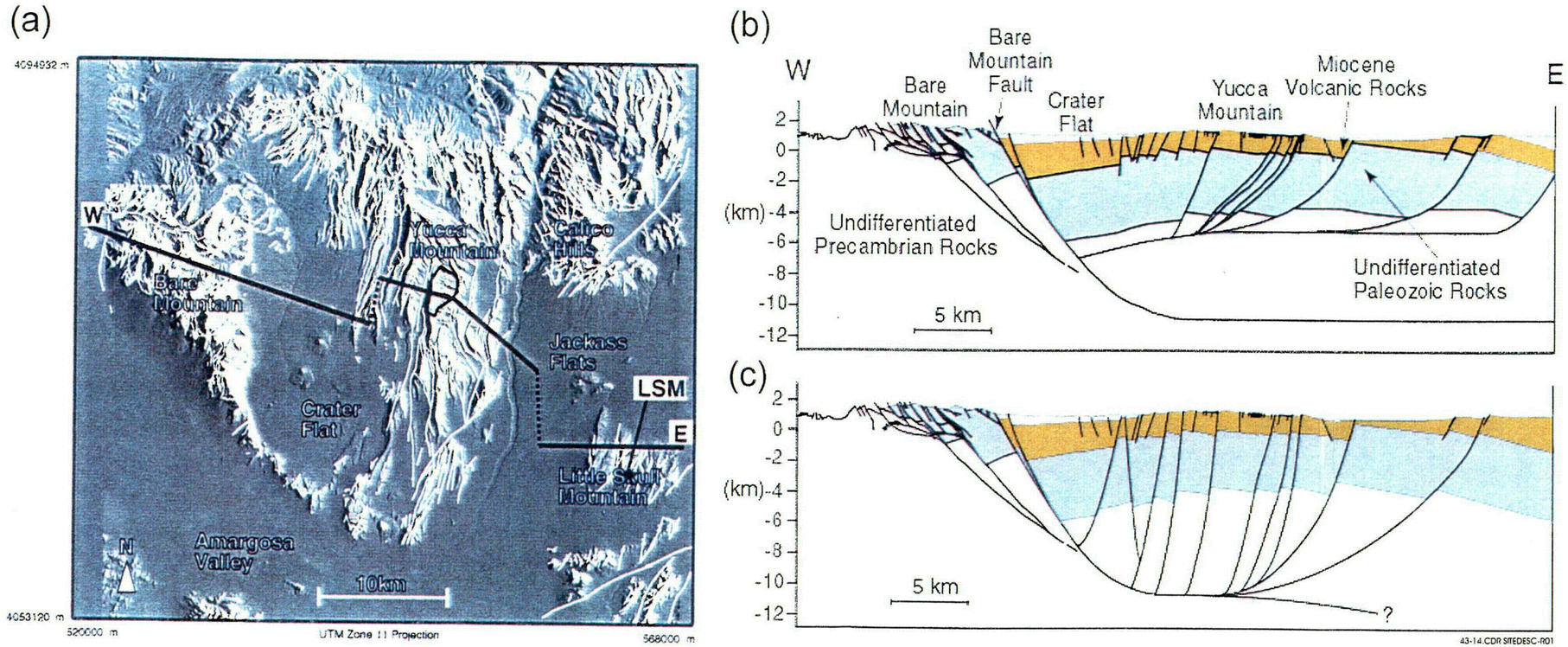

Source: From McKague et al. (1996, pp. 3-4, 3-11)

NOTE: Part (a) is a digital elevation map of the Crater Flat domain. The line segments (W-E) show composite trace of cross sections illustrated in Parts (b) and (c). Map coordinates are UTM. Part (b) shows the shallow detachment fault system. Part (c) shows the deep detachment fault system.

Figure 4.3-14. Alternative Interpretive Cross Sections across Crater Flat Domain

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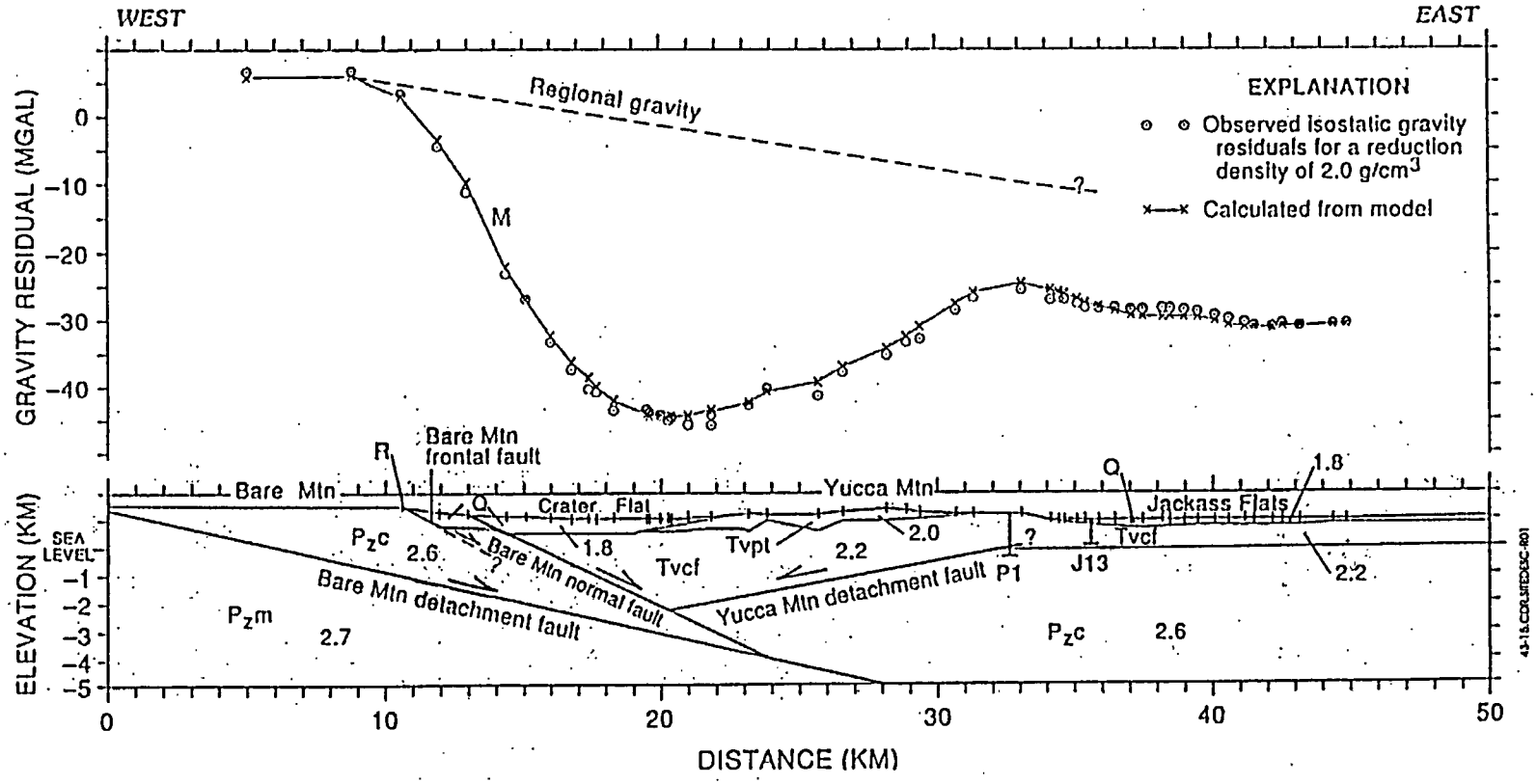
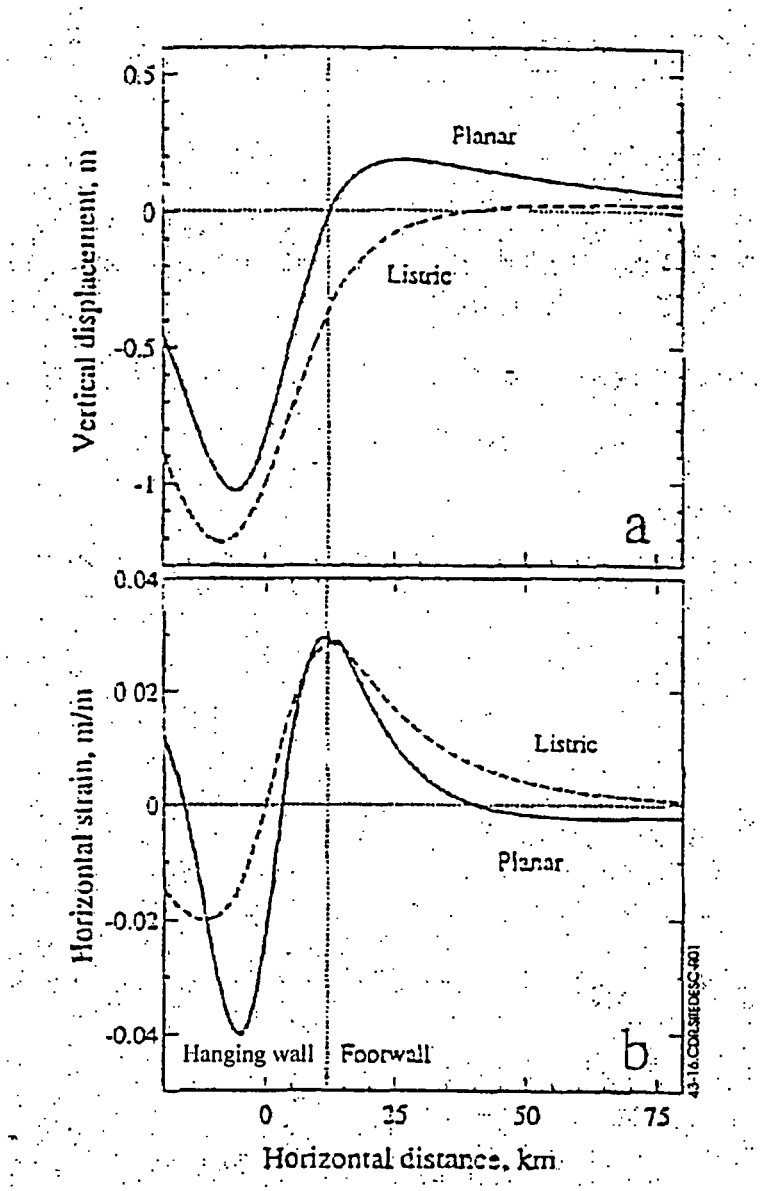


Source: Oliver and Fox (1993)

NOTES: Numbers within units are densities in g/cm^3 assumed in the model. No vertical exaggeration. Q, Quaternary alluvium; Tvpt, Paintbrush and Timber Mountain Group tuffs; Tvcf, Crater Flat Tuff and older volcanic rocks; P_zc, Paleozoic carbonates; P_zm, lower Paleozoic schist and gneiss; R, Bare Mountain range front; M, maximum gravity gradient.

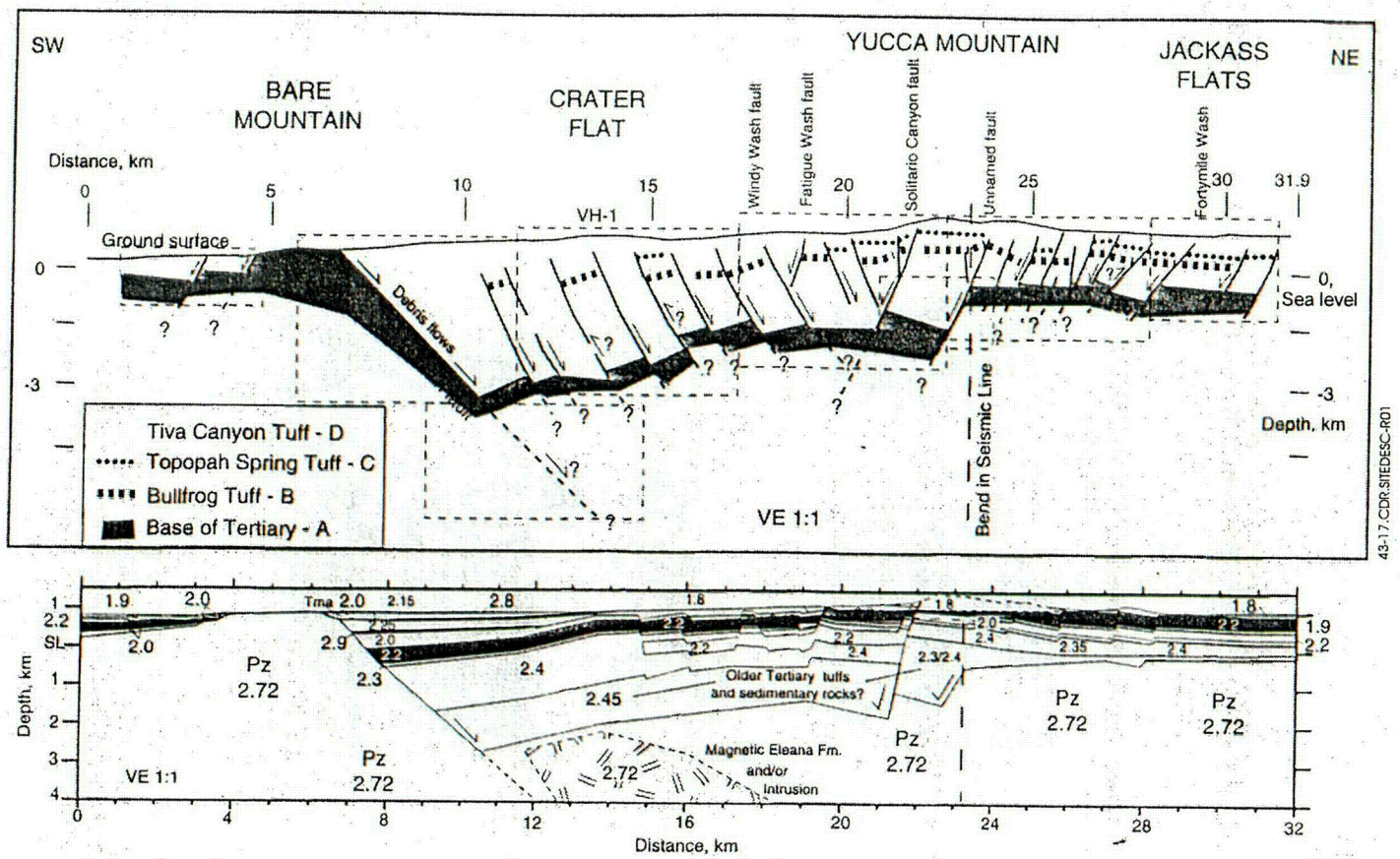
Figure 4.3-15. Interpreted Detachment Faults under Yucca Mountain as Modeled Using Gravity Data



Source: Bruhn and Schultz (1996, p. 3410, Figure 8)

NOTE: Part (a) presents vertical displacement; part (b), horizontal strain. The planar fault footwall undergoes significant uplift. Positive values of horizontal strain indicate extension; negative values indicate compression.

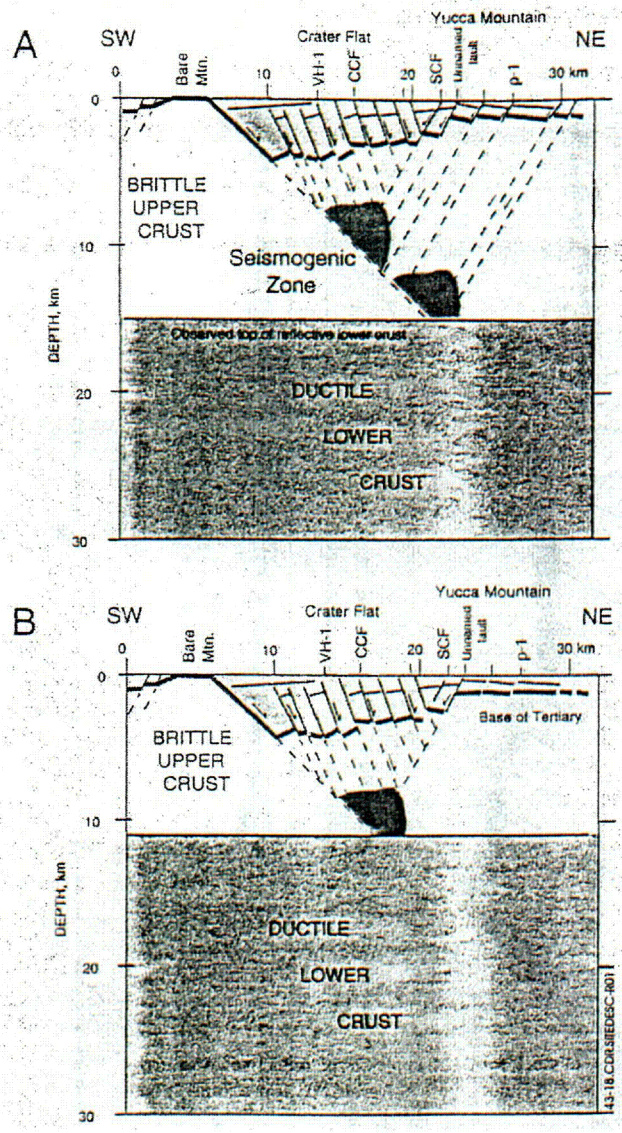
Figure 4.3-16. Vertical Displacement and Horizontal Strain at Earth's Surface for a Planar Fault and a Listric Fault at Initiation of Slip



Source: Brocher et al. (1998, p. 955)

NOTE: Interpretation of seismic reflection profile for Crater Flat (Figure 4.3-1) shows inferred east- and west-dipping fault domains. Gravity model shows asymmetry of Crater Flat basin; layer densities in g/cm^3.

Figure 4.3-17. Interpretation of Seismic Reflection Profile for Crater Flat

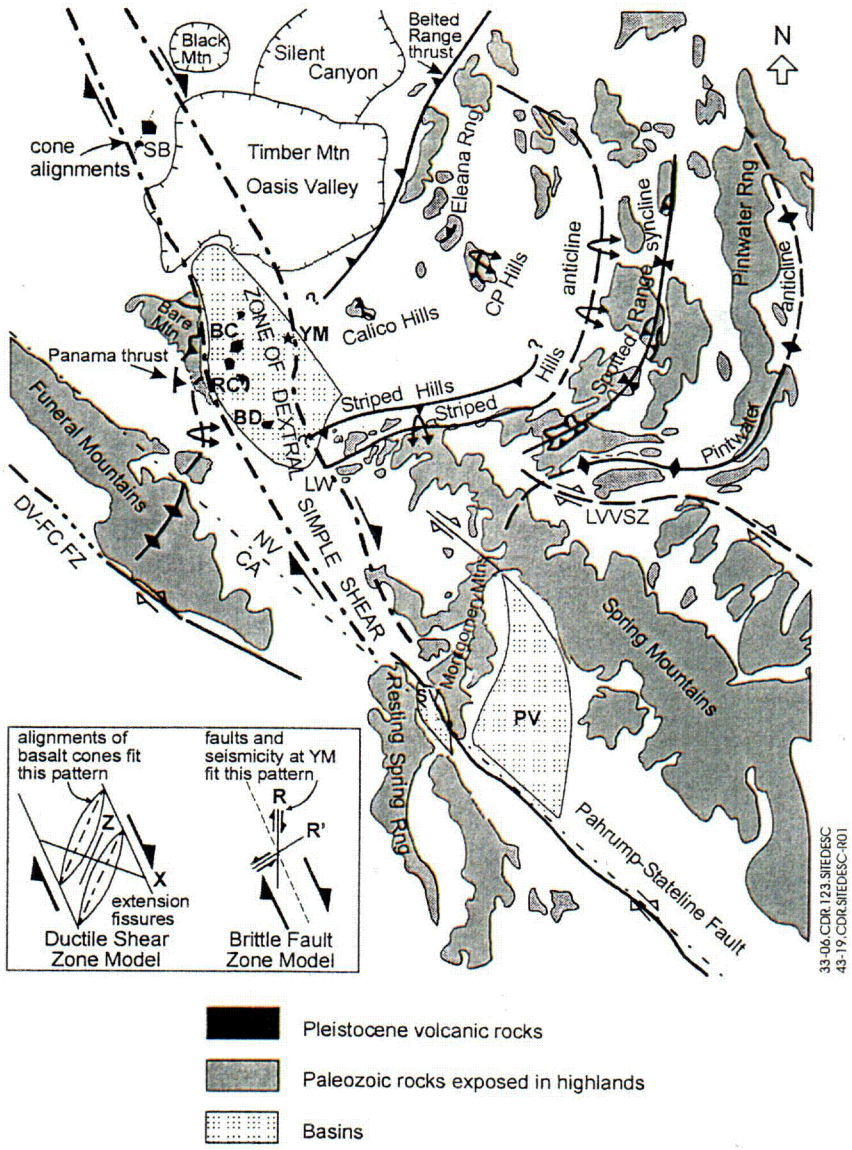


Source: Brocher et al. (1998, p. 968)

NOTES: This tectonic model of Crater Flat basin is based on seismic reflection profile interpretation (Figure 4.3-17). Part (A) depicts present fault configuration. Part (B) depicts middle Miocene fault configuration. (Black areas in brittle upper crust are not explained by Brocher et al. [1998].)
VH-1 = location of VH-1 borehole, CCF = Central Crater Flat fault, SCF = Solitario Canyon fault, p-1 = location of p#1 borehole.

Figure 4.3-18. Tectonic Model of Crater Flat Basin Based on Seismic Reflection Profile Interpretation

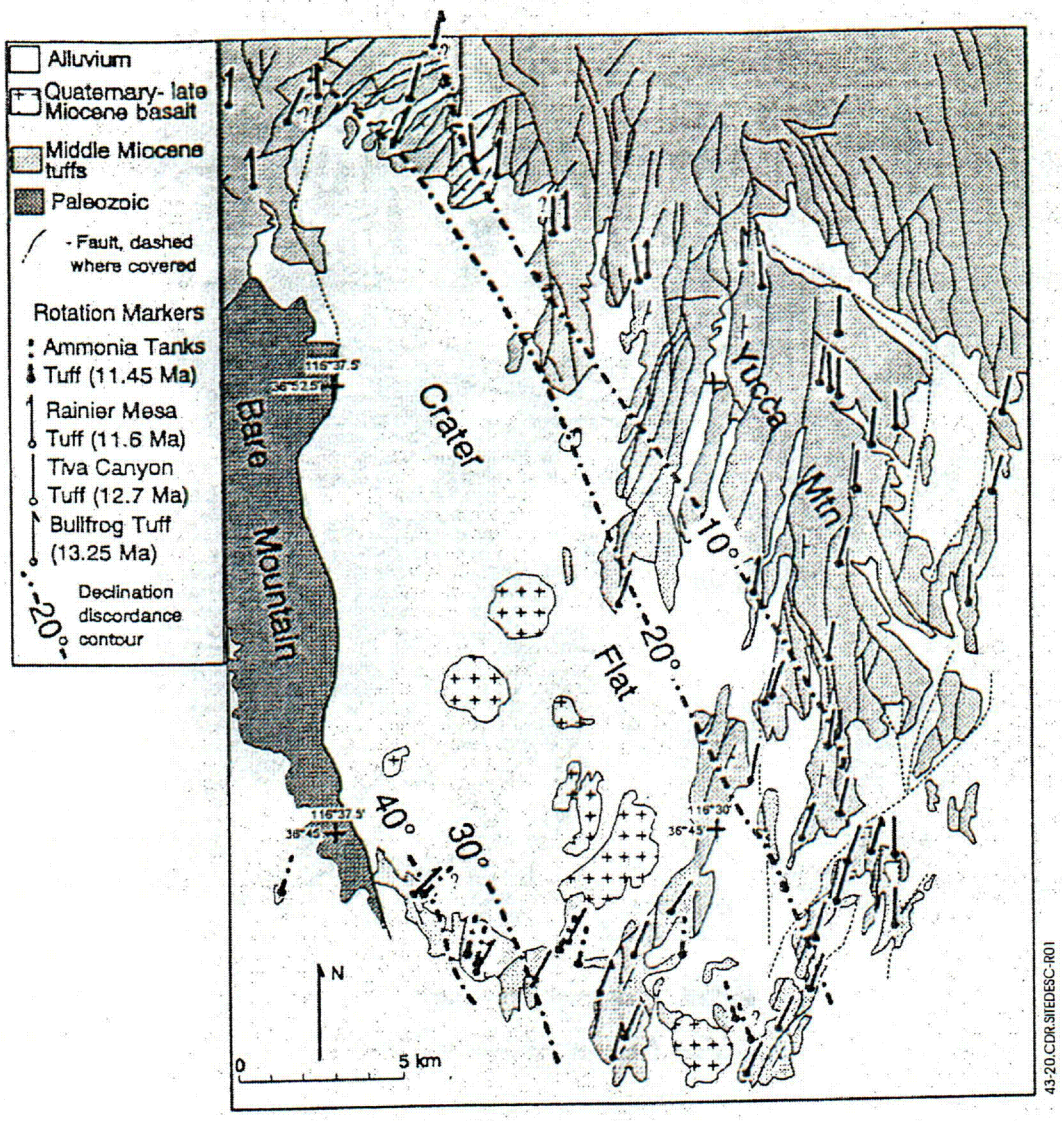
C31



Source: As inferred by Schweickert and Lahren (1997, Figure 1)

NOTE: BC = Black Cone; LVVSZ = Las Vegas Valley Shear Zone; PV = Pahrump Valley; RC = Red Cone; SB = Sleeping Butte; and YM = Yucca Mountain; BD = Big Dune cone; LW = Lathrop Wells cone; DV-FCFZ = Death Valley-Furnace Creek fault zone.

Figure 4.3-19. Amargosa Desert Fault System



Source: Minor et al. (1997, p. 18)

NOTE: Geologic map of Crater Flat basin with locations of paleomagnetic sites and the associated declination discordances of their tilt-corrected site mean directions. Discordance values indicated by amount of deviation of discordance indicators from true north. Declination discordances are queried if the sites have inclination discordances of greater than 10°. Also shown are contours of equal clockwise declination discordance (dotted lines).

Figure 4.3-20. Paleomagnetic Data from Yucca Mountain–Crater Flat

C33

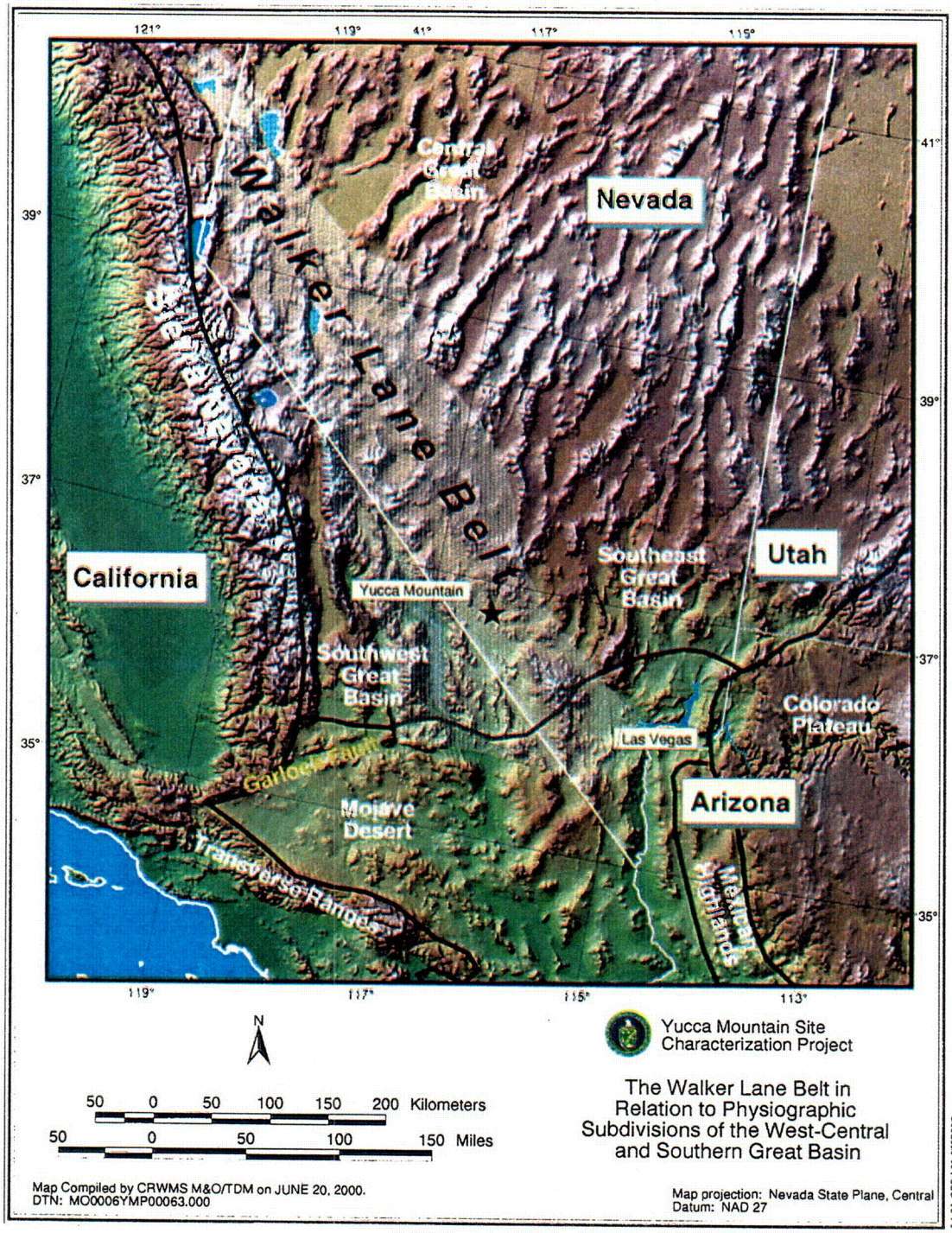


Figure 4.4-1. Approximate Locations of the Physiographic Subdivisions of the West-Central and Southern Great Basin

C34

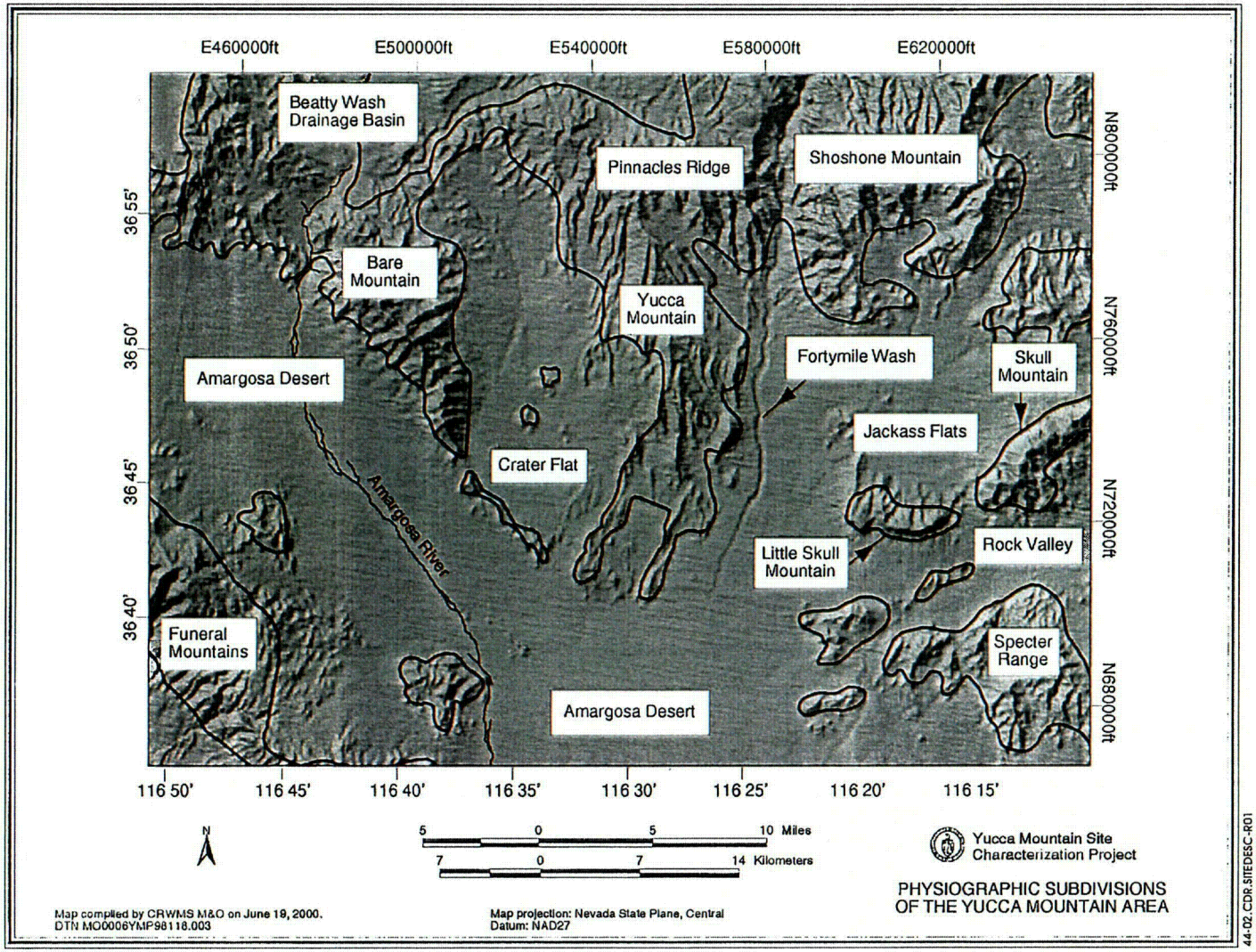
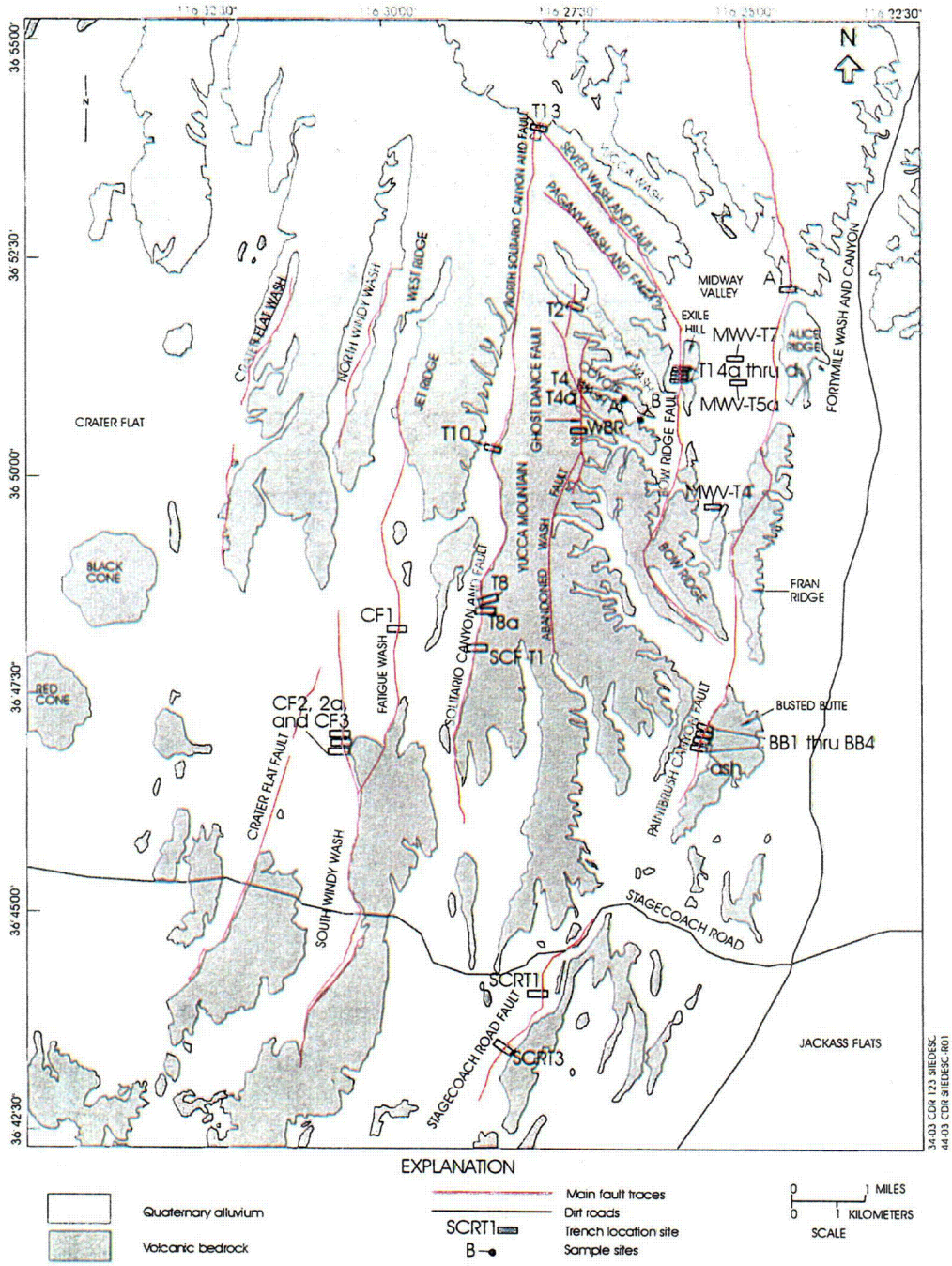


Figure 4.4-2. Physiographic Features of the Yucca Mountain Area

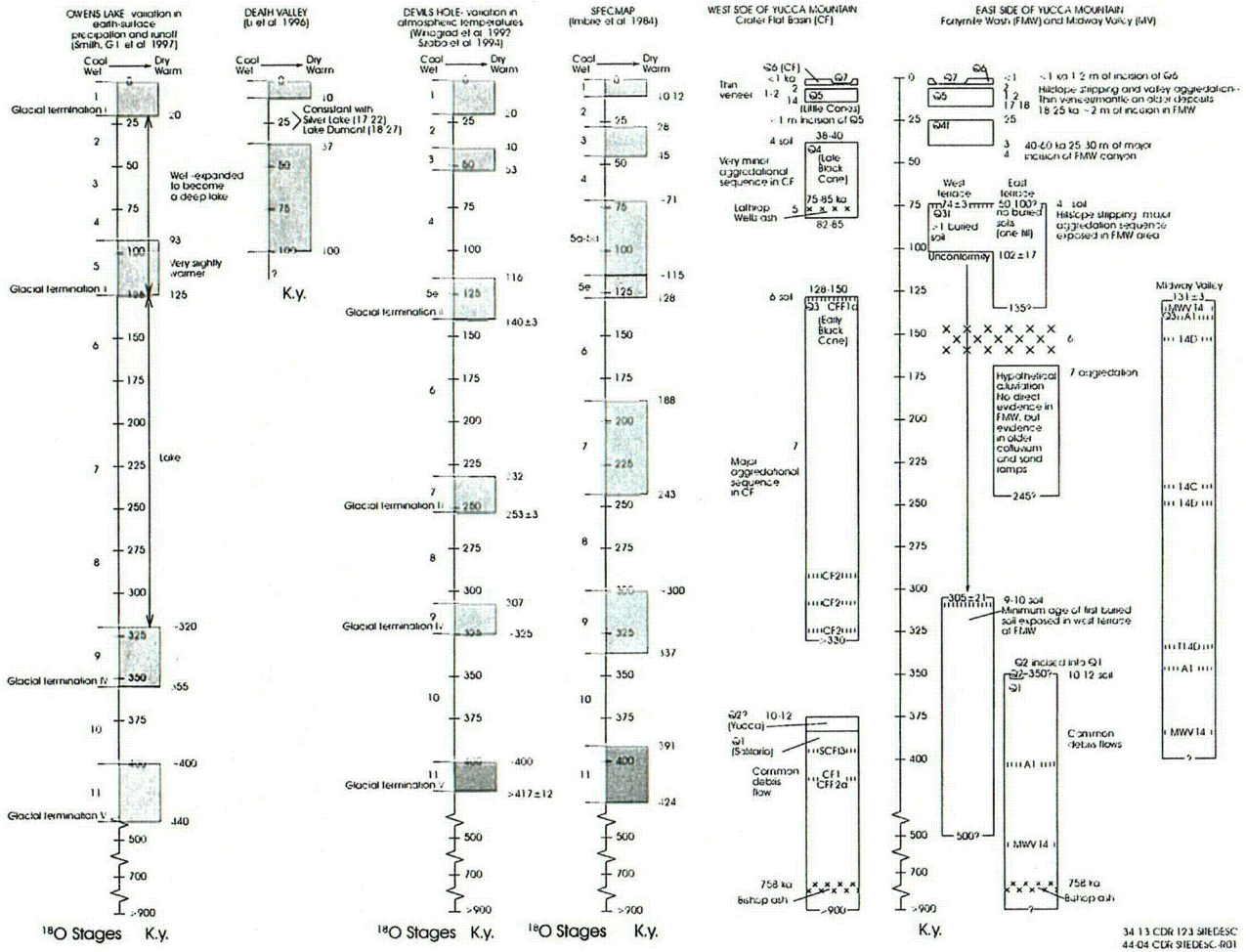
C35



Source: Whitney and Taylor (1996, Figure 4.0.1)

Figure 4.4-3. The Yucca Mountain Region Showing Trench Locations and Local Place Names

C36



Sources: Located at top of each column and Whitney and Taylor (1996).

Figure 4.4-4. Age Ranges of Quaternary Stratigraphic Units in the Yucca Mountain Vicinity Compared to Regional Climatic Records

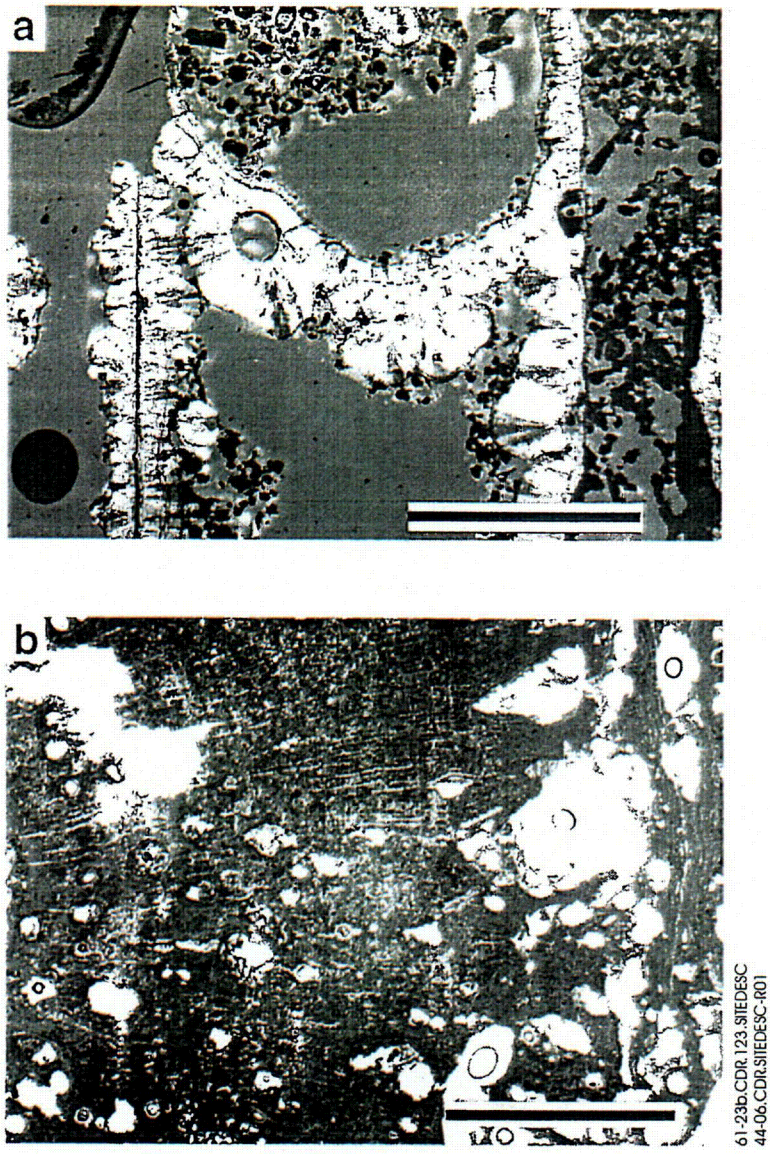
C37

34-04 CDR 123 SIEDESC
44-05 CDR SIEDESC-R01

Source: YMP (1993, Figure 2)

NOTE: Bull's-eye targets are spaced on a 1-m grid (only one is shown). Bottom of trench is approximately 4 m below original land surface.

Figure 4.4-5. The South Wall of Trench 14 Showing Pedogenically Derived Calcite and Opaline Silica Veins



Source: Vaniman et al. (1995, Figure 14)

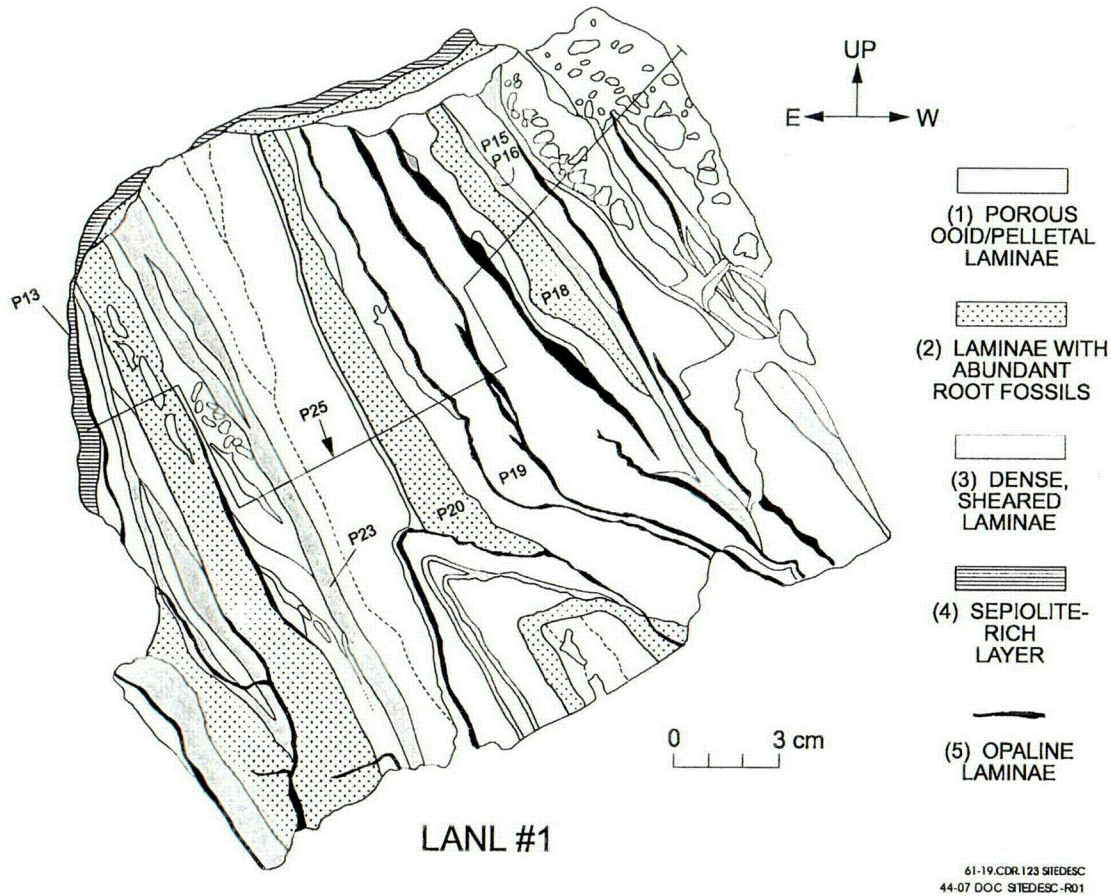
NOTES: (a) Fossilized plant stem from the Nevares Spring mound (LANL#762). Stem walls (vertical) provided nucleation sites for radial-fabric calcite; concave-upward meniscal forms can occur both within and between stems. Note the abundance of loosely cemented bacterial clumps.

(b) Fossilized root from the seep at Site 199 (LANL#251). Radial fabric extends from root center at left to concentric fabric at root rim on right. Note that fine-scale cell structure is very poorly preserved because fossilization is principally by bacterial clumps of about 30 μm.

Scale bar = 2 mm.

Figure 4.4-6. Photomicrographs of Stem and Root Fossils from Spring Deposits

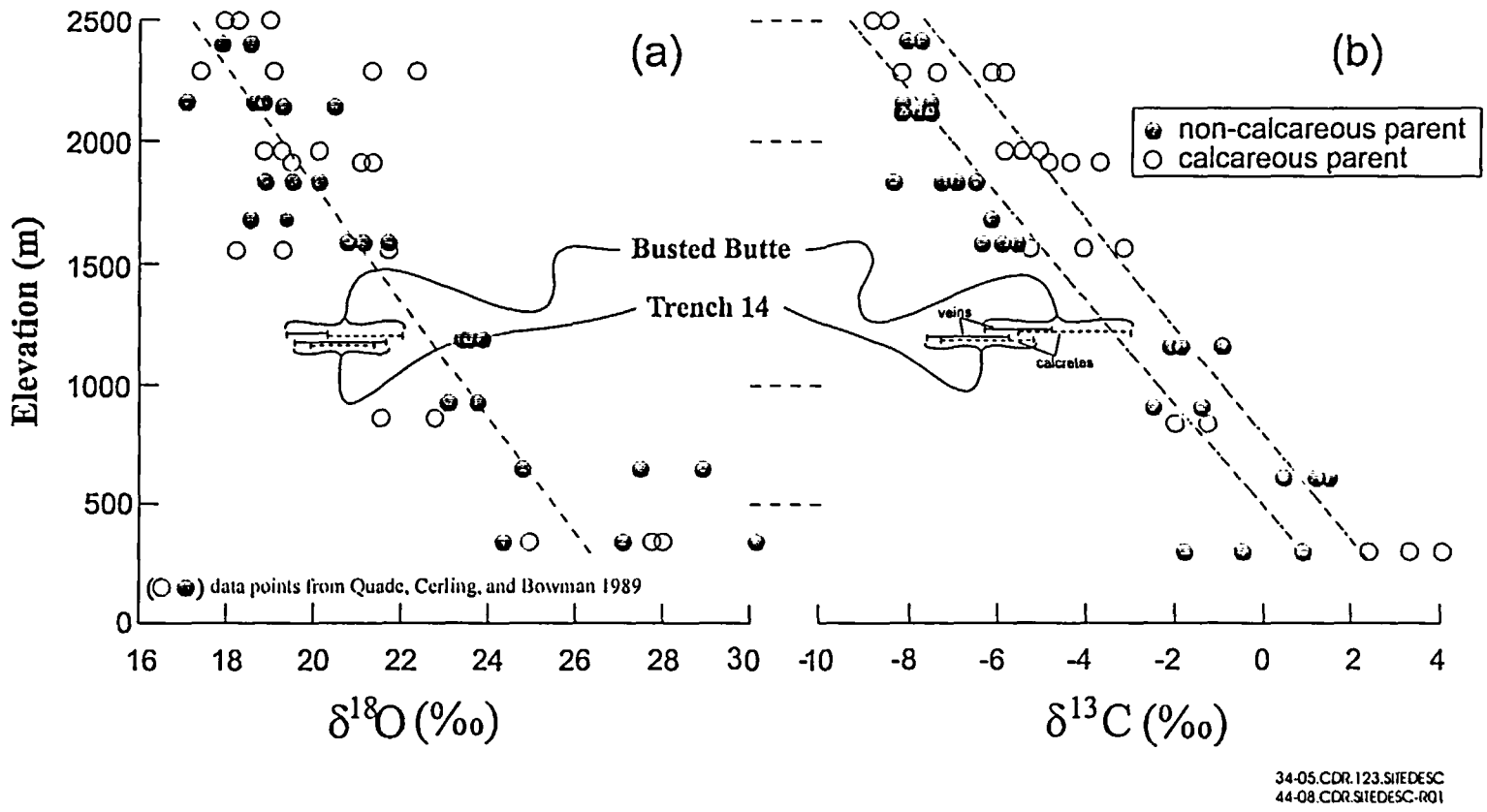
C39



Source: Vaniman et al. (1995, Figure 20)

NOTE: This detailed map of sample block LANL#1 shows the distribution of calcrete lamina types. Numbers beginning with P represent powders for which mineralogical and chemical data have been obtained (Vaniman, Chipera, and Bish 1995); P25 is a channel sample representing the entire block.

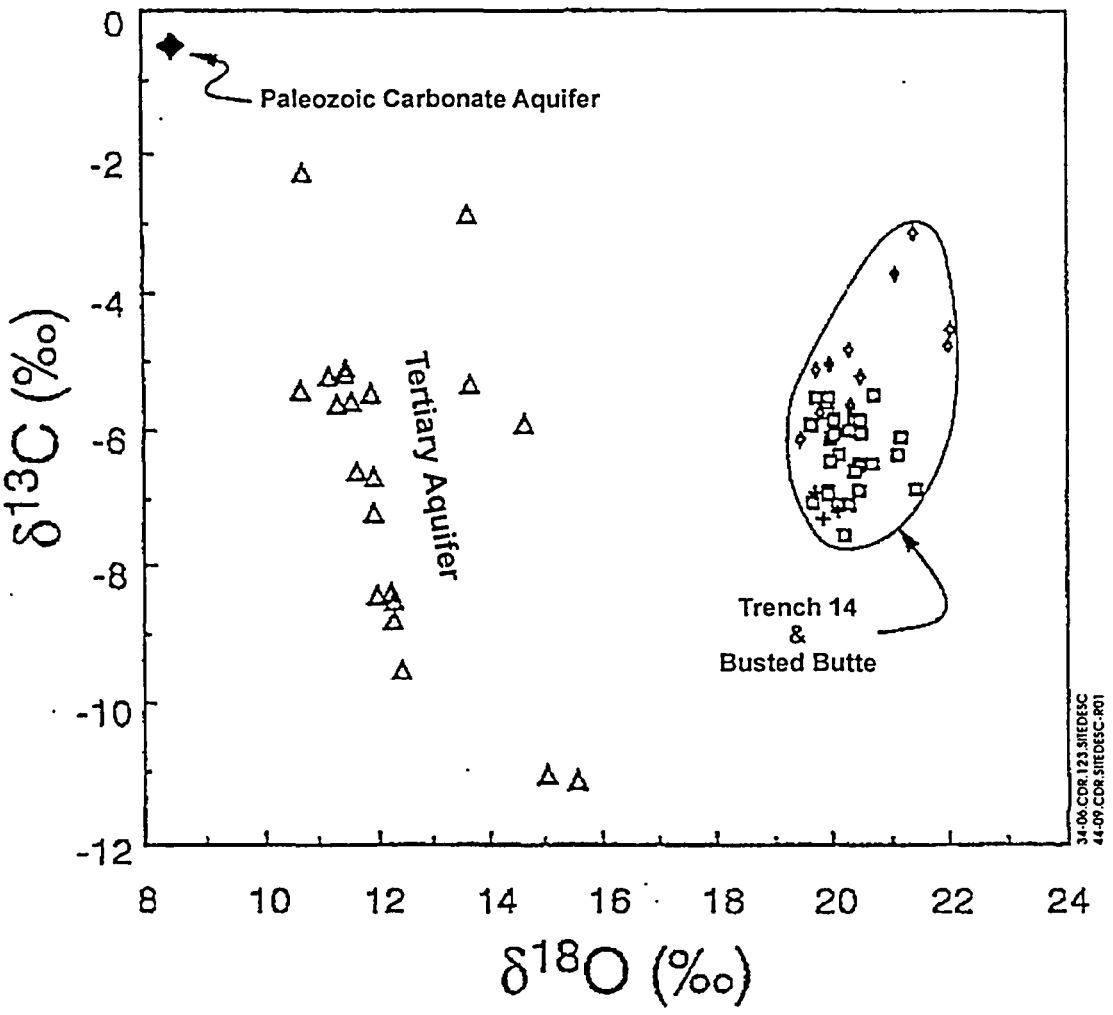
Figure 4.4-7. Calcrete Laminae Types from Trench 14



Source: Stuckless, Peterman et al. (1992)

NOTE: Stable isotopic compositions are reported as the per mil (‰) deviations of the samples from international standards Standard Mean Ocean Water (for O) and Peedee Cretaceous formation Belemnite (for C).

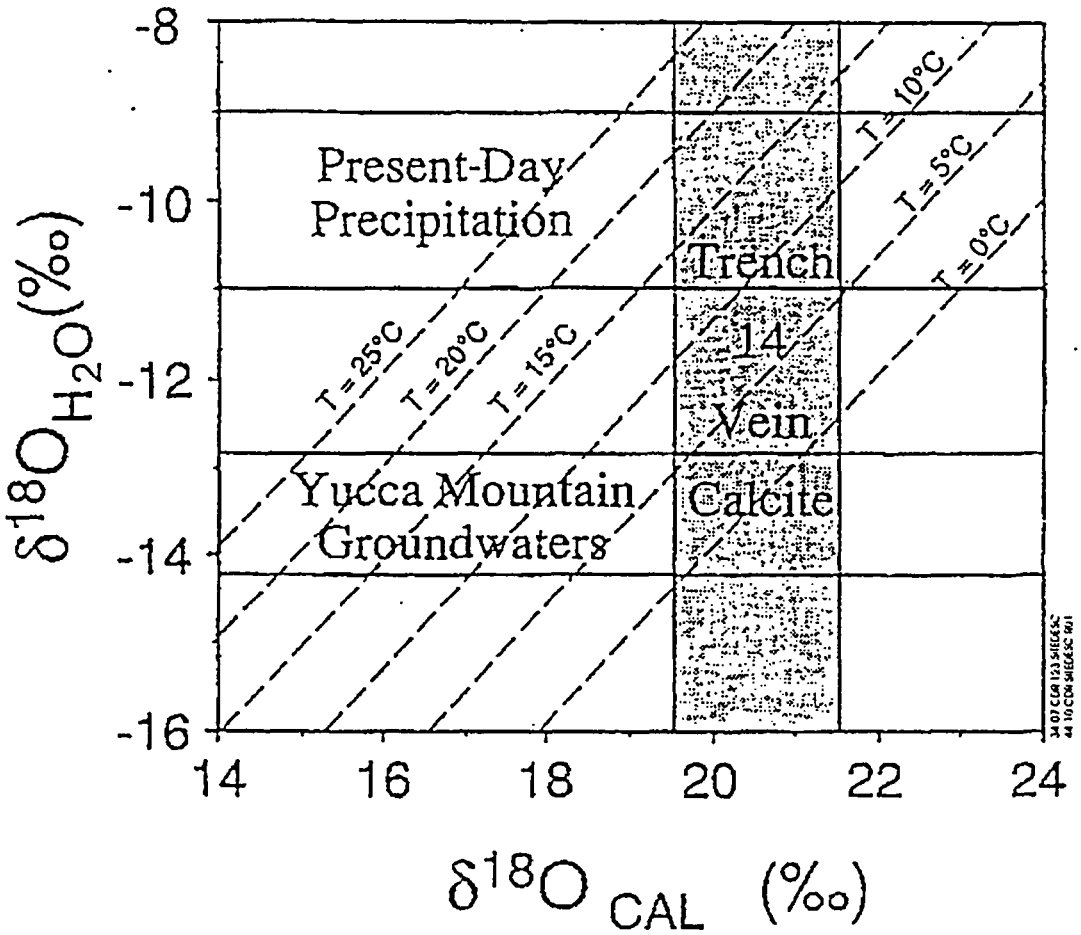
Figure 4.4-8. Isotopic Composition of Oxygen and Carbon in Pedogenic Carbonate as a Function of Elevation



Source: Stuckless, Peterman et al. (1992)

NOTE: Shown are carbonates from Trench 14 (squares), Busted Butte (diamonds), and breccia cement (plus signs). Triangles and diamonds represent calculated compositions of calcite that would crystallize at equilibrium from Yucca Mountain groundwater assuming present-day temperatures and measured water compositons (triangles = Tertiary aquifer, diamonds = Paleozoic aquifer). Stable isotope compositions are reported as the per mil (‰) deviations of samples from the international standards Peedee Cretaceous formation Belemnite (for C) and Standard Mean Ocean Water (for O)

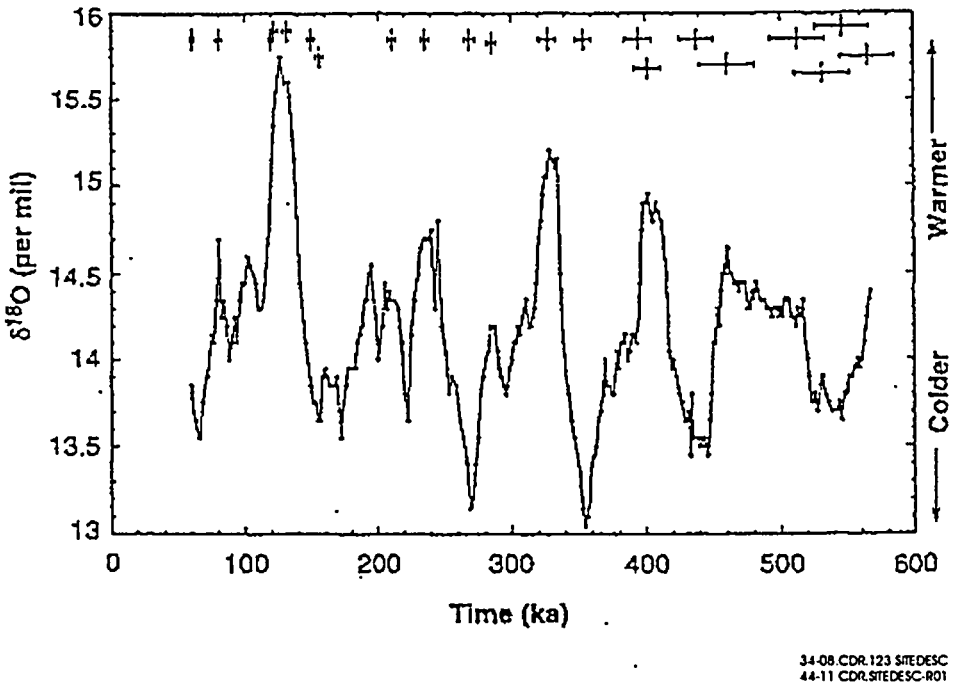
Figure 4.4-9. Observed Isotopic Composition of Oxygen and Carbon for Yucca Mountain Area Carbonate Samples Compared to Calculated Compositions



Source: Stuckless, Peterman et al. (1992)

NOTE: Also shown are the fields of composition of modern precipitation, groundwater, and calcites from Trench 14. Stable isotope compositions are reported as the per mil (‰) deviations from the international standard Standard Mean Ocean Water.

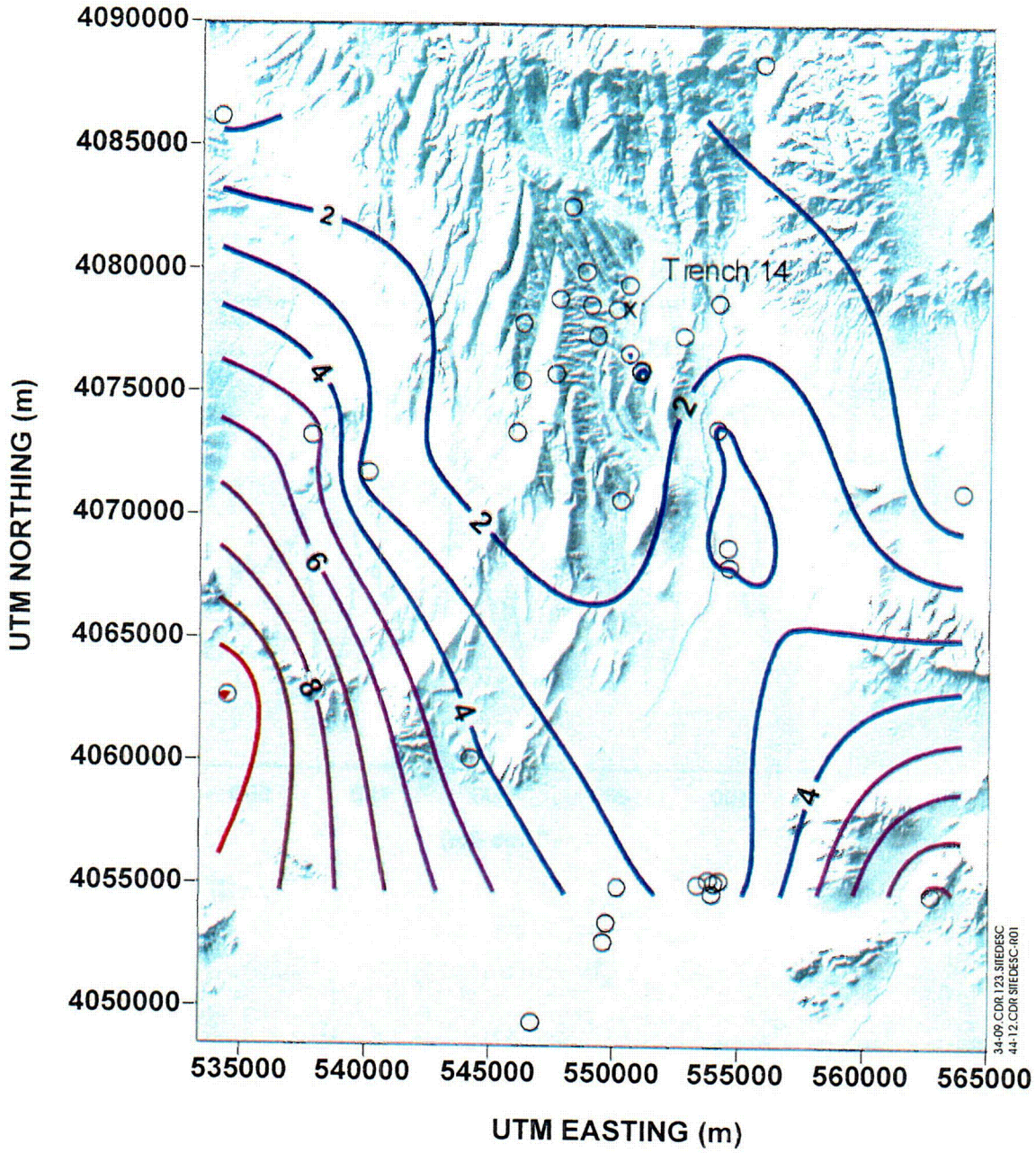
Figure 4.4-10. Isotopic Composition of Oxygen in Water and Calcite Crystallized in Equilibrium with Water as a Function of Temperature



Source: Winograd, Coplen et al. (1992)

NOTE: Ages of dated samples are shown as crosses along the top of the figure with two sigma errors indicated by the width of the cross.

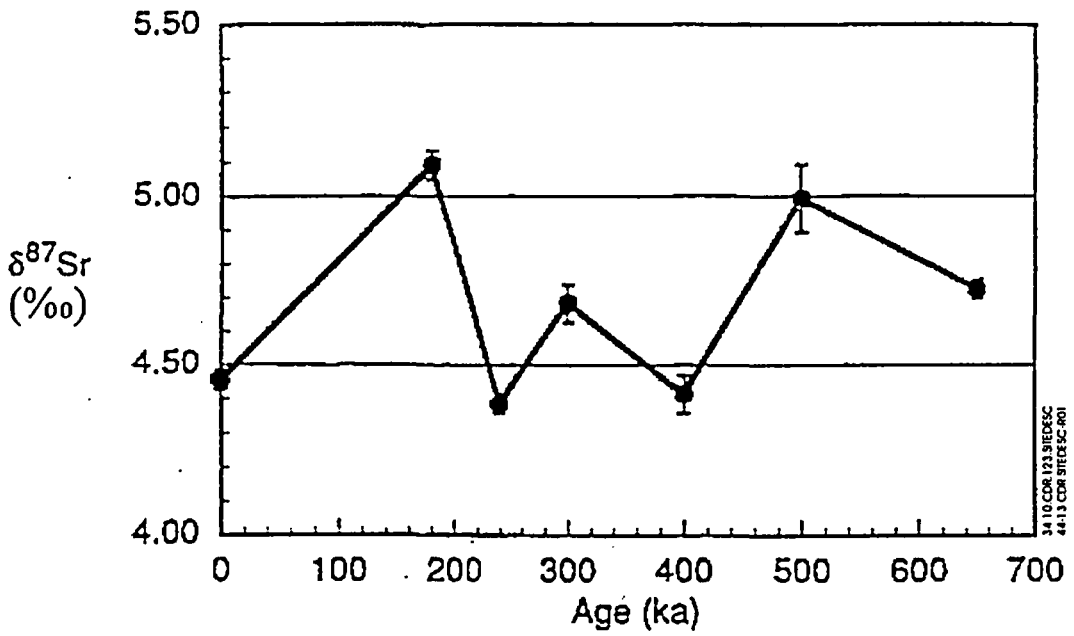
Figure 4.4-11. Variation of Oxygen Isotopic Composition of Calcite at Devils Hole



Source: Data from Paces (1995)

NOTE: Circles represent data points. Water samples are from wells or springs in the Tertiary aquifer.

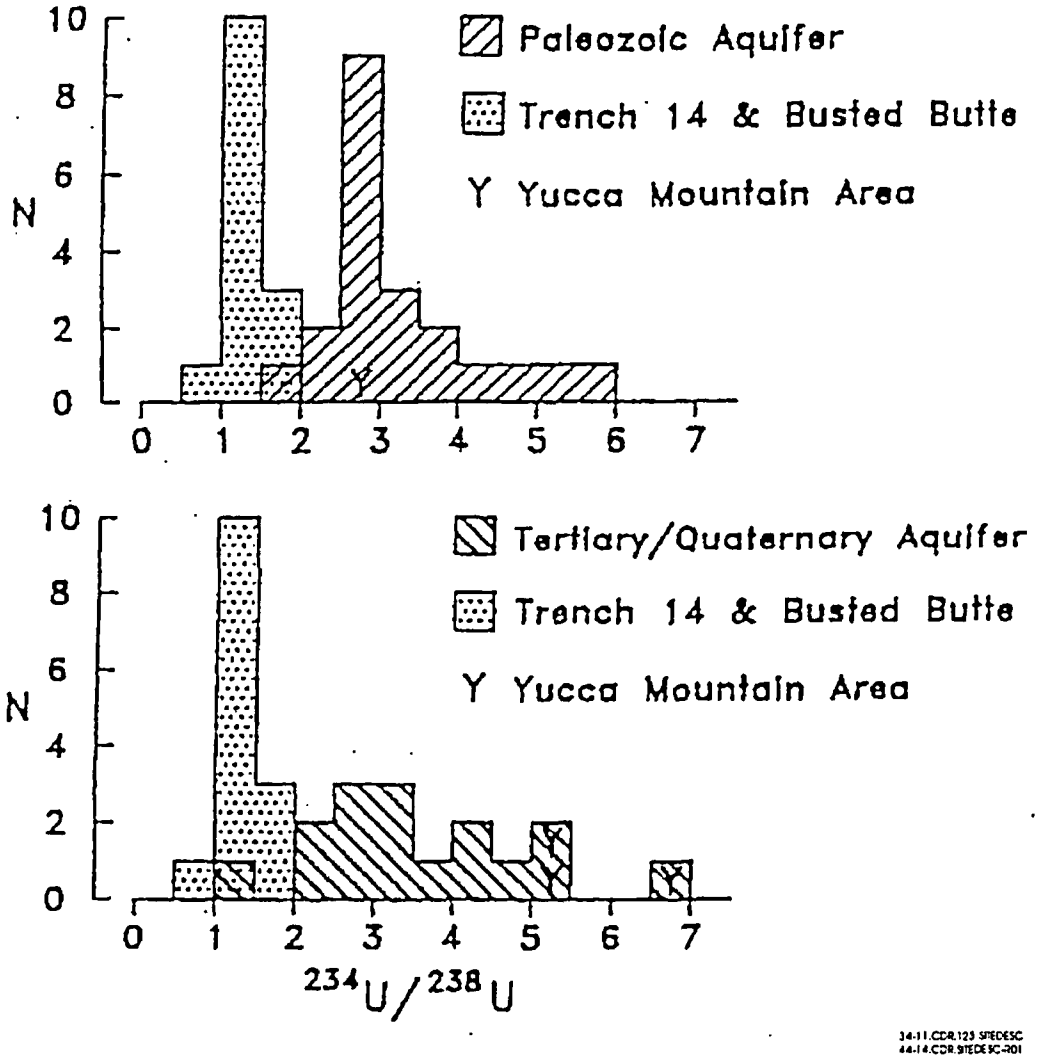
Figure 4.4-12. Isotopic Composition of Strontium (in Delta Strontium-87 Units) in the Tertiary Aquifer



Source: Marshall et al. (1990)

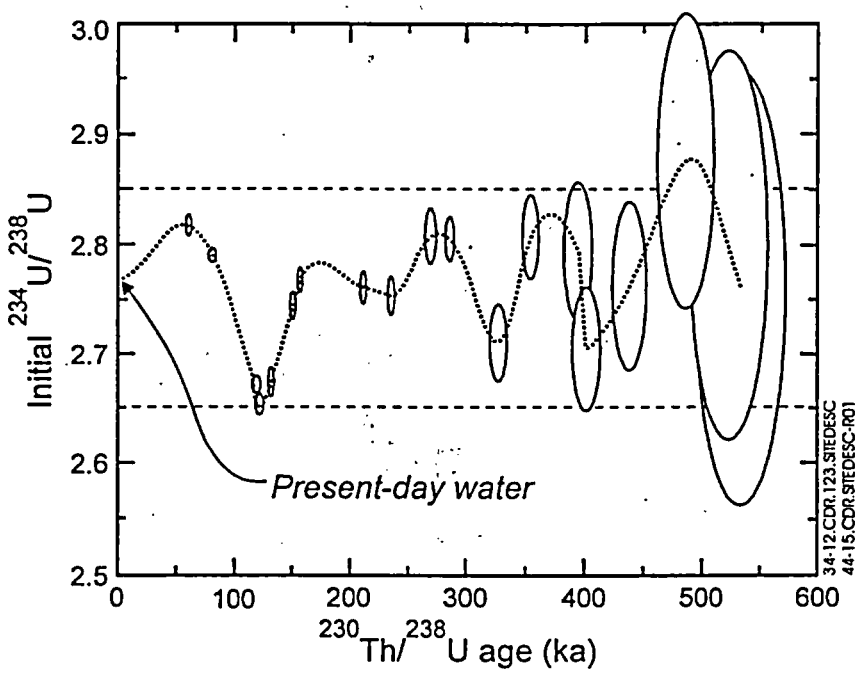
NOTE: Analytical error for strontium (95 percent confidence level) is shown by vertical error bars.

Figure 4.4-13. Variation in the Isotopic Composition of Strontium in Calcite from Devils Hole as a Function of Time



Source: Stuckless, Peterman et al. (1992)

Figure 4.4-14. Isotopic Composition of Uranium in Water and Carbonates from Trench 14 and Busted Butte



Source: Ludwig et al. (1992)

NOTE: Two-sigma uncertainties are indicated by the ellipses. Estimated maximum variation in initial $^{234}U/^{238}U$ shown by dashed horizontal lines.

Figure 4.4-15. Variation in the Isotopic Composition of Uranium in Calcite from Devils Hole as a Function of Time

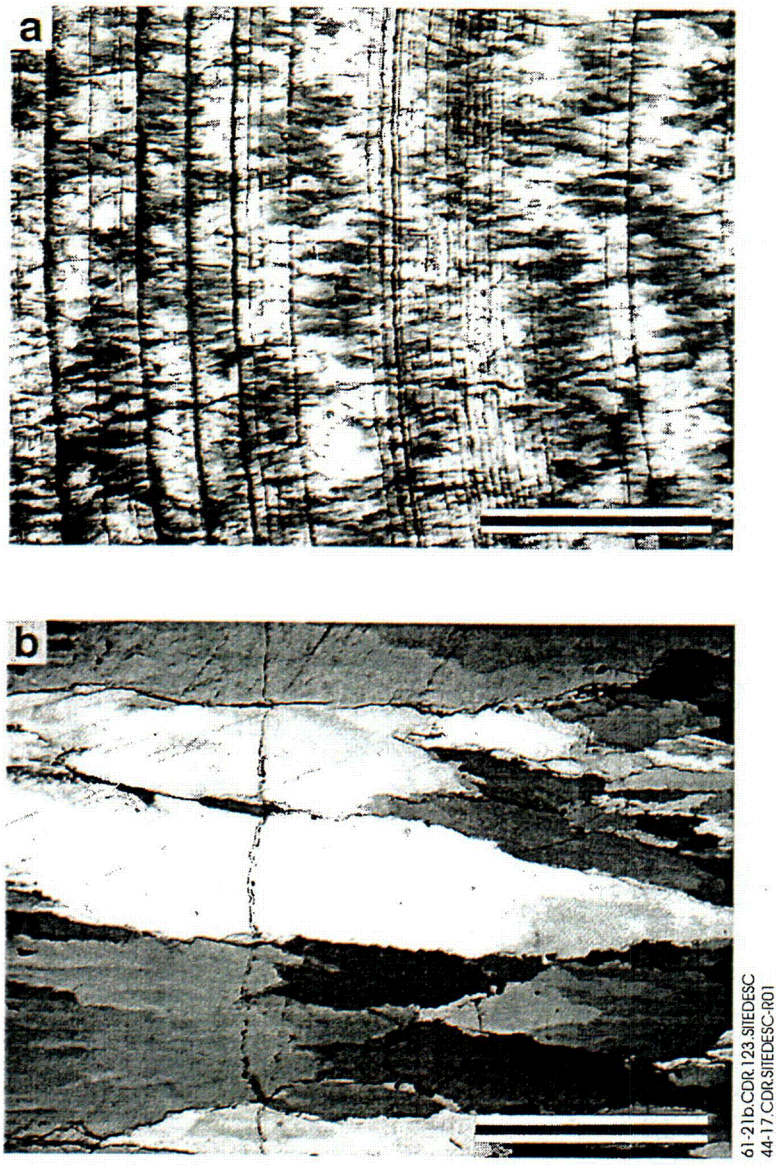
61-20.CDR.123.SITEDESC
44-16.CDR.SITEDESC-R01

Source: Vaniman et al. (1995, Figure 11)

NOTE: Scanning electron micrograph of equant whewellite crystals in root sample LANL #351 (inner part of creosote bush root). Scale bar is 200 μm.

Figure 4.4-16. Scanning Electron Micrograph of Whewellite Crystals in Root Sample

C42



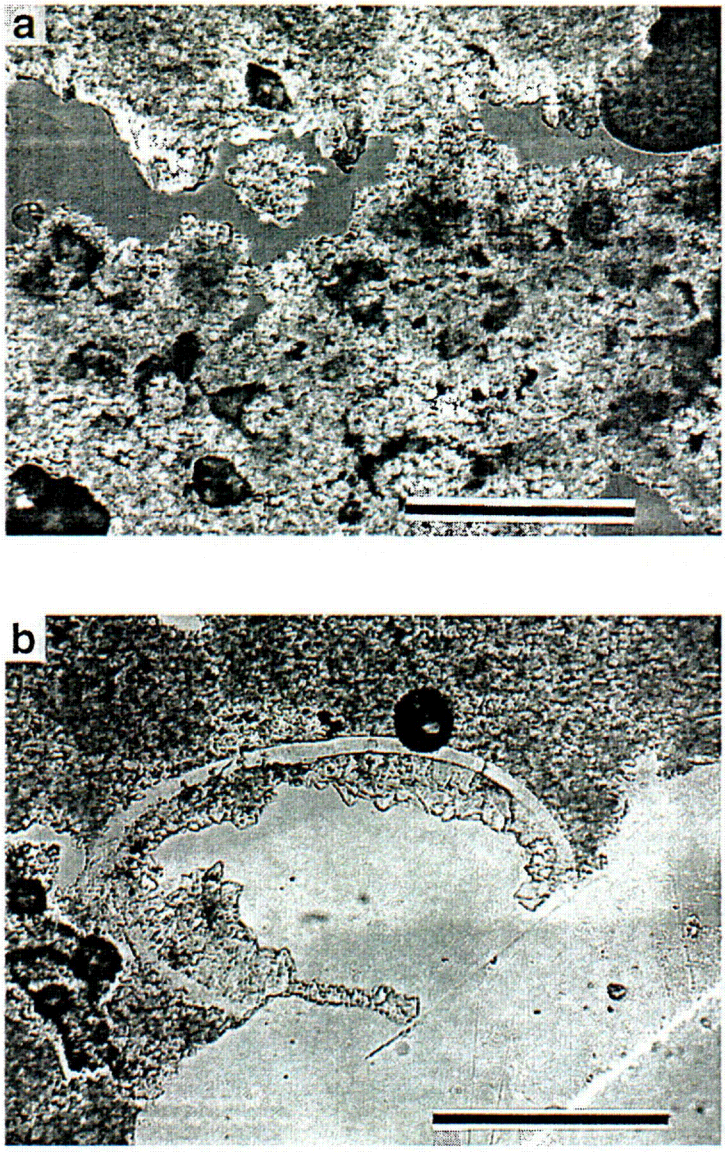
Source: Vaniman et al. (1995, Figure 12)

NOTE: Both photomicrographs are from the same thin section of a single sample (LANL #755). Scale bars in both photomicrographs are 2 mm.

(a) Fibrous-structure vein calcite

(b) Massive vein calcite from Travertine Point

Figure 4.4-17. Photomicrographs of Calcite Veins



Source: Vaniman et al. (1995, Figure 13)

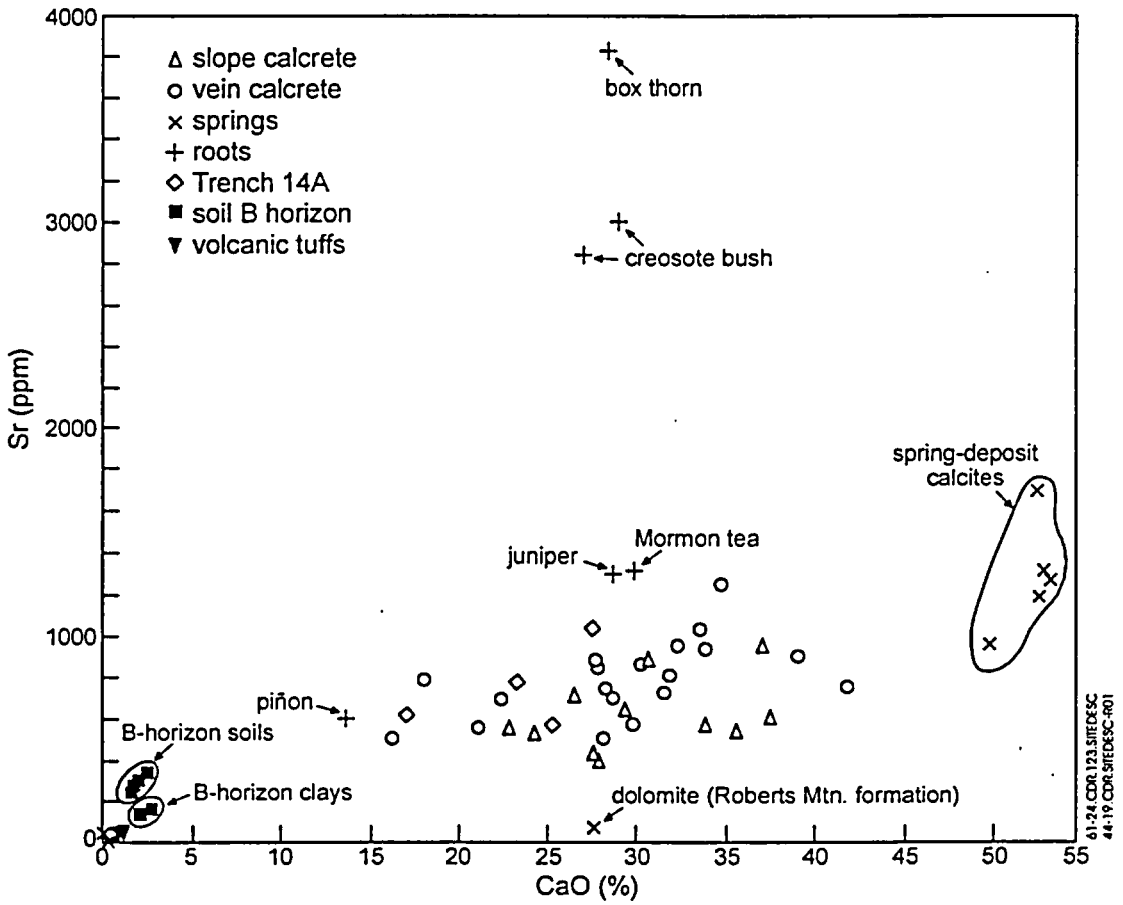
NOTE: Calcite forming the ostracode shell is exceptionally strontium rich; microspar lining the interior of the ostracode shell is magnesium rich. Scale bars in both photomicrographs are 200 μm.

(a) Bacterial clumps (Chafetz and Folk 1984)

(b) Ostracode fossil from the Nevares Spring mound (LANL #760)

Figure 4.4-18. Photomicrographs of Bacterial Clumps and Ostracode Fossil

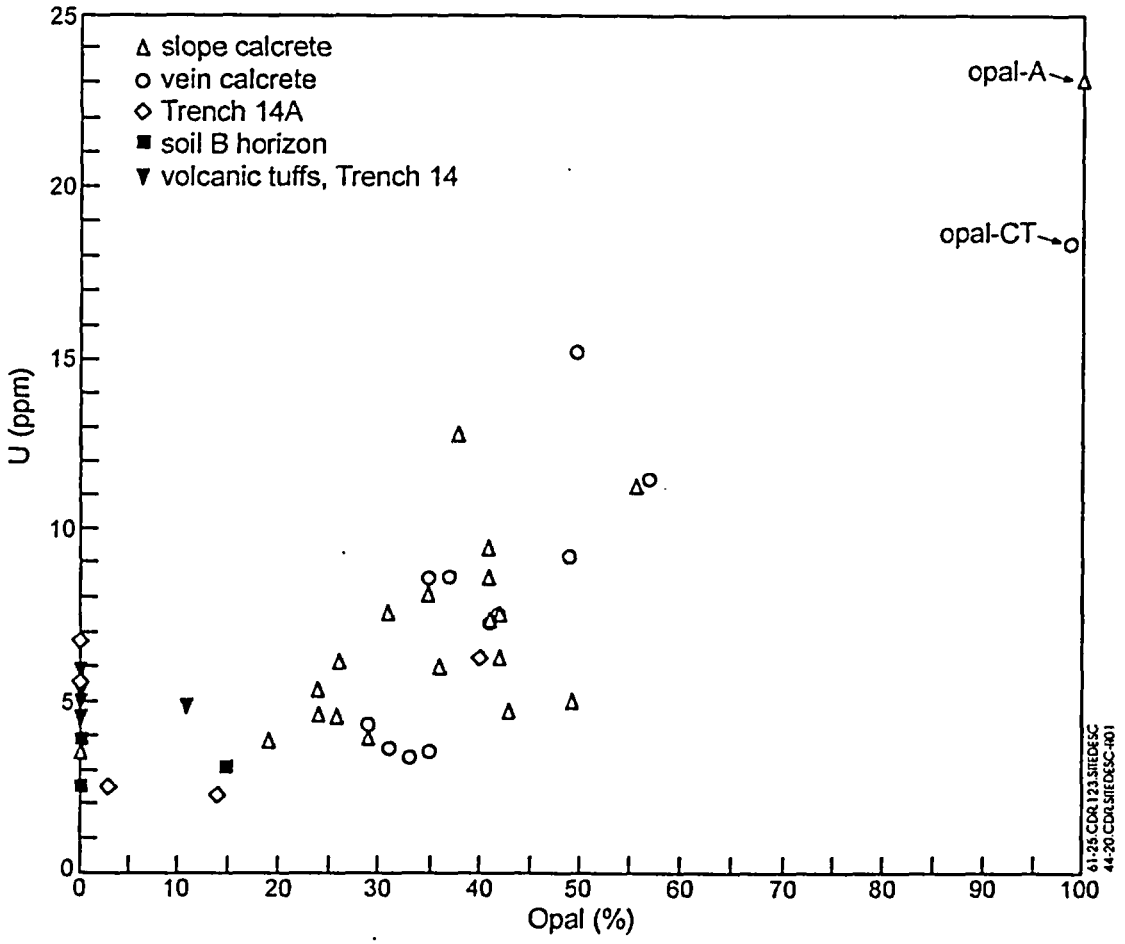
C44



Source: Vaniman et al. (1995, Figure 28)

NOTE: The plot shows strontium concentration in parts per million versus CaO percentage content of slope and vein calcrete, root ash, and spring-deposit samples. Note the very high strontium/CaO ratio for some ashed root samples (box thorn and creosote bush) from Exile Hill. The Trench 14A values represent three vein and one slope calcrete samples.

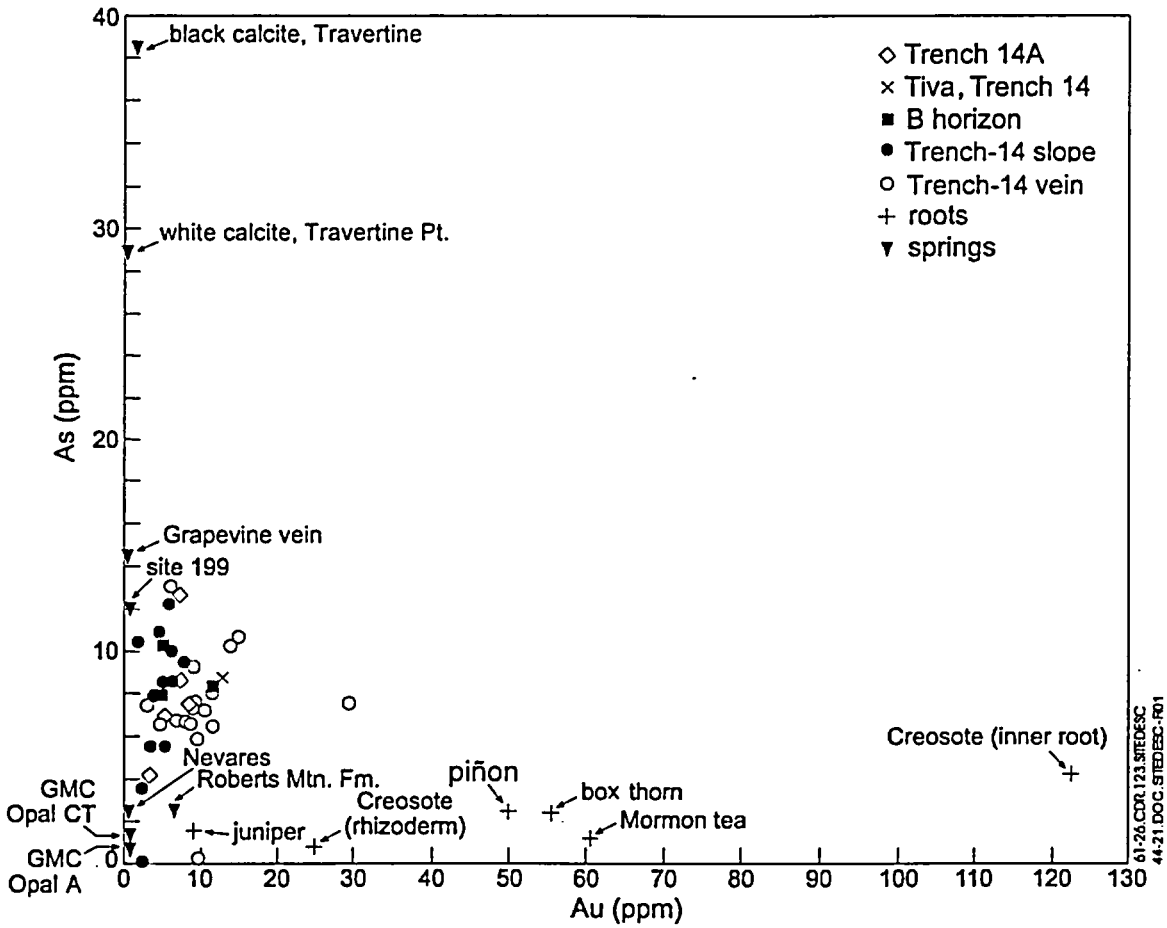
Figure 4.4-19. Strontium Concentration as a Function of Calcium Oxide Percentage for Yucca Mountain Area Samples



Source: Vaniman et al. (1995, Figure 29)

NOTE: The plot shows uranium concentration in parts per million versus opal percent content of slope and vein calcrete, B soil horizon, and wall-rock tuff samples from Trench 14 and of calcrete and wall-rock tuff samples from Trench 14A. Note the general correlation between uranium and opalization.

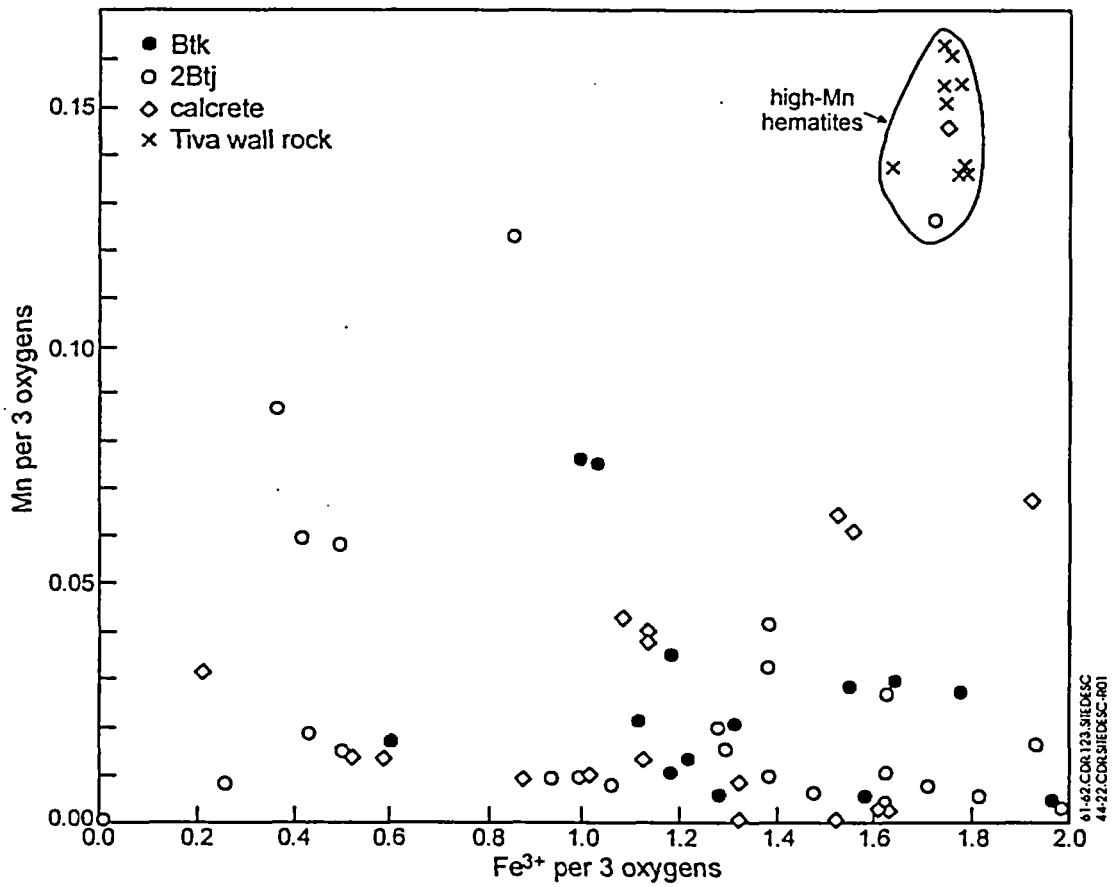
Figure 4.4-20. Uranium Concentration as a Function of Opal Percentage in Yucca Mountain Area Samples



Source: Vaniman et al. (1995, Figure 32)

NOTE: The plot shows arsenic concentration versus gold concentration, both in parts per million, for spring deposits and data from Exile Hill. Note low gold and high arsenic content of several calcite samples from spring deposits.

Figure 4.4-21. Arsenic Concentration as a Function of Gold Concentration for Yucca Mountain Area Samples



Source: Vaniman et al. (1995, Figure 34)

NOTE: The plot shows FeO versus MnO in fine-grained hematite fragments of the B soil horizon, calcretes, and hematite-altered Tiva Canyon Tuff at Trench 14. Hematites of the B horizon and calcretes are more aluminum rich and manganese poor than those of the tuff.

Figure 4.4-22. Ferrous Oxide versus Manganese Oxide in Fine-Grained Hematite Fragments