3.8 THREE-DIMENSIONAL INTEGRATED SITE MODEL

3.8.1 Introduction

3.8.1.1 Purpose and Scope

The 3-D Integrated Site Model for Yucca Mountain is a representation of the geology of the site that supports development of flow and transport models, the design of a geologic repository, and provides a framework to view and understand other spatial geologic data (namely, rock properties). This subsection discusses the 3-D Integrated Site Model version ISM2.0 (CRWMS M&O 1997e) which represents a snapshot in time of data and interpretations at the time of its construction. The model covers an area of about 166 square km (64 square miles) surrounding the Yucca Mountain Conceptual Controlled Area in southwestern Nevada (Figure 3.8-1). The model boundaries are (in Nevada State Plane coordinates): 224,942 to 239,878 m north, and 166,726 to 178,003 m east (738,000 to 787,000 ft north, and 547,000 to 584,000 ft east). These model boundaries were chosen to encompass the most widely distributed set of exploratory boreholes, the WT series, and to provide a geological framework over the area of interest for unsaturated zone flow and radionuclide transport models. The Integrated Site Model includes 37 rock units between the ground surface and the top of Paleozoic strata approximately 3,050 m (10,000 ft) below land surface. Table 3.8-1 shows the geologic horizons in the model and their correlation to stratigraphic and thermal-mechanical layering schemes. This set of horizons was selected to portray the geology of the site and to meet the needs of YMP hydrologic and transport models. Stratigraphic horizons are consistent with the YMP Reference Information Base Section 1.12(a): Geologic/Lithologic Stratigraphy, and are based on the YMP stratigraphy (Table 3.8-1) of Buesch, Spengler et al. (1996a) and Sawyer, D.A., Fleck et al. (1994). The relation of these stratigraphic units to others used in the project is shown in Table 3.5-2.

The Integrated Site Model consists of two major parts: a geologic framework model and a set of rock properties and mineralogic models. This section describes only the geologic framework model; rock properties models (Rautman 1997) and mineralogic models (Chipera, Carter-Krogh et al. 1997) are discussed in Subsections 5.3.1.1.8 and 6.1.3.4, respectively. The structural geology of the site is discussed in Subsection 3.6. The geologic framework model is an interpretation of the spatial position and geometry of rock layers and faults. The Integrated Site Model is subsequently used by other modelers to evaluate processes such as fluid flow, radionuclide transport, and thermal response.

The geologic framework incorporates data from lithologic logs, measured sections, geologic maps, seismic profiles, and gravity and magnetic profiles. Every measured data point is recognized explicitly in model construction. The model also incorporates interpretations of specific features from gravity and magnetic profiles. To aid construction of the framework, working groups of Principal Investigators from YMP participant organizations collaborated to interpret geologic data to guide framework model construction as it progressed. The Principal Investigators discussed issues including fault geometries, rock unit shapes, depositional features, and locations of features based on geophysical surveys in a series of workshops and meetings. The results were incorporated in the model to the extent possible.

The various process models use the Integrated Site Model geologic framework as abstracted to suit modeling requirements; in other words, each will use a unique subset of rock units from the Integrated Site Model, and some will generalize faults to be vertical as required for calculations.

The Integrated Site Model is a living model, intended to incorporate new site data and the results of ongoing activities as they become available, as well as to incorporate feedback from hydrologic, transport, and Performance Assessment modelers to better meet modeling requirements. The current Integrated Site Model represents the total scope of intended 3-D modeling, and future Integrated Site Models are not anticipated to be altered significantly in content or complexity but rather in refinement of details.

In digital format, the Integrated Site Model consists of more than 2,700 files containing data and surfaces representing rock unit contacts, input data files, faults, and isochore maps. (An isochore is the thickness of a rock unit as measured in a borehole. Because most boreholes at Yucca Mountain are approximately vertical, this approximates a vertical thickness map, and is therefore similar to–but distinct from–an isopach map). From the digital model, cross-sections, maps, views, and predicted values can be obtained via the appropriate software (Earthvision Integrated Site Model 3.1 or higher). Model components can also be exported as ASCII files for incorporation in other modeling software.

3.8.1.2 Previous Work

The Integrated Site Model builds on a 3-D framework model of lithology and rock properties, Integrated Site Model 1.0 (CRWMS M&O 1996g), a lithostratigraphic model of the central block of the repository, YMP.R2.0 (Buesch, Nelson et al. 1996), and a regional site model (Zelinski 1995). The Integrated Site Model is more comprehensive in detail and content than any previous model. The primary changes from Integrated Site Model 1.0 to Integrated Site Model 2.0 are as follows:

- Dipping fault geometries modeled (Integrated Site Model 1.0 assumed vertical faults)
- More faults included (44 versus 26)
- New Paleozoic unconformity (Majer et al. 1996b) included
- Qualified Earthvision software used as the primary tool
- Volumetric model visualization constructed
- Refined isochore and structure maps included
- Updated borehole lithostratigraphic contacts included.

An extensive effort was made throughout Integrated Site Model development to ensure that properties modeling, geologic studies, and performance assessment requirements were met. The Integrated Site Model 2.0 updates Integrated Site Model 1.0 where new information is available, including the Paleozoic surface (Majer et al. 1996b), the geologic map of the central block area (Day, et al. 1996a), preliminary information from the geologic map of the site area (Day et al. 1997 et al.), borehole lithostratigraphic contacts (Spengler 1996), and conclusions from the tectonics synthesis report (Whitney 1996). The framework model was also planned in consultation with investigators involved with both hydrological and thermal performance studies, and repository design engineers.

The geologic model of the potential repository primary area used in M&O design engineering (YMP.M03; CRWMS M&O 1997d) incorporates faults and surfaces from the Integrated Site Model and the two models are consistent over their common areal coverage. The design model was created using software (Lynx) which originated in the mining industry and is more suited to the input and output needs of subsurface tunnel design. On the other hand, Earthvision software used to construct the model provides capabilities needed for an integrated model of geology and rock properties that are not provided in Lynx software. The Integrated Site Model geologic framework includes data from all boreholes, while the design model YMP.M03 includes only data from carefully selected boreholes; hence the two modeling efforts are complementary rather than parallel.

3.8.1.3 Definitions

A few definitions and concepts are presented below to establish a basis for discussion:

Layering Scheme–Employed to divide or group rocks in accordance with some end-use purpose. Examples of layering schemes are formal stratigraphy (that has gone through the formal USGS approval process), informal stratigraphy (which includes the members, zones, and subzones used here), thermal-mechanical units, and hydrogeologic units. Each scheme may require different groupings of the same rocks for a different purpose. These schemes are not mutually exclusive or contradictory.

Model–A representation of an object or system. Specifically, the Integrated Site Model is an interpretive representation of selected, simplified, and edited parts of the geology at Yucca Mountain. It resides on a computer as a large set of files, combinations of which can be displayed on the computer screen. Some of these files are displayed in the figures of this report. Most files are in a software-specific format, but can be translated to generic forms (such as tables of ASCII text) for input to other software systems. Most files containing volumetric model components, however, are in software-specific binary formats which can not be translated to other software systems.

Dynamic or Process Model (such as numerical models of fluid flow or radionuclide transport)–Representation of the variation of selected process variables with time based on input parameters and the geologic framework and properties models.

Geologic Framework Model–Interpretation of the static geometries of rock units. This representation includes fault surfaces and the contact surfaces between rock units. Rock unit volumes occupy the space between these surfaces.

Properties Model–Contains representations of selected properties (such as porosity or density) within the context of the geologic framework, as interpreted from scattered data points and interpolated and extrapolated according to geostatistical principles.

Three-dimensional Model–Contains interpretations for every point in the volume within the model's lateral and vertical boundaries.

Performance Assessment–Analysis and interpretation of linked dynamic models to predict the ability of the potential repository system to satisfy established health and safety criteria.

3.8.2 Input Data

3.8.2.1 Geologic Data

Geologic inputs to the modeling process include borehole lithologic logs, borehole survey data, maps of geology and topography, measured sections (vertical transects of stratigraphy measured at the surface), and model elements from previous framework models.

The primary input data for the geologic framework are lithologic logs for one hundred boreholes (locations shown in Figure 3.8-2). These data and their reference documents and quality status are summarized in Appendix A of CRWMS M&O 1997e. These data include non-Q data collected prior to the inception of the YMP quality assurance program and Q data collected under the approved quality assurance program. For most boreholes, some lithostratigraphic contacts are taken from a recent document by the USGS, which is an extensive review and update of a select group of older borehole lithostratigraphic contacts (Spengler 1996).

Several types of borehole information were used by Principal Investigators to determine the spatial coordinates of lithostratigraphic contacts, including rock property measurements from drill core, downhole orientation and geophysical surveys, and downhole video observations (Buesch, Spengler et al. 1996a). Downhole video and geophysical logs were especially valuable in determining lithostratigraphic contacts where core was not available.

Borehole location data were received from the Technical Database and are non-Q. Borehole lithostratigraphic information is consistent with the Yucca Mountain Project Stratigraphic Compendium (CRWMS M&O 1996e), which summarizes information from many sources, and the YMP Reference Information Base Section 1.12a: Geologic/Lithologic Stratigraphy.

Geologic mapping by the USGS (Day et al. 1996a) was the primary source of surface geologic information for the central part of the model (the potential repository block). Where necessary, selected geologic information was digitized from a preliminary release of information from the Site Area Geologic Map (Day et al. 1997). This information includes the surface trace of major faults and selected points along stratigraphic contacts, although the primary source for fault trace locations outside the central block was the "Map Showing Fault Activity in the Yucca Mountain Area" (Simonds et al. 1995). Lithologic contacts from Exploratory Studies Facility mapping were incorporated for the North Ramp area (Barr et al. 1996).

3.8.2.2 Geophysical Data

Seismic, gravity, and magnetic profiles provided important information for construction of the geologic framework in the Integrated Site Model (CRWMS M&O 1997e; Langenheim, Ponce et al. 1993; Ponce 1996; Ponce, Kohrn et al. 1992; Ponce, Langenheim et al. 1993). Where specific interpretations are given in source documents, these have been incorporated in the model. For example, gravity and magnetic profiles detected a feature interpreted as a horst (a raised, faulted block) beneath Midway Valley (Ponce, Langenheim et al. 1993). The authors interpreted fault offsets of 50 m (164 ft) on the two faults bounding the horst. This feature is included in the ISM as integrated with geologic map information by the USGS for this activity.

Seismic reflection profiles (Brocher, Hart et al. 1996; Majer et al. 1996) have been used to formulate 3-D fault geometries and interpret tilted strata.

The depth to the top of Paleozoic strata in the Integrated Site Model was calculated from gravity data (Majer et al. 1996b). This surface also was modified to tie to faults, and is discussed in detail in Subsection 3.8.4.1.

3.8.2.3 Model Elements from Other Sources

The most recent Exploratory Studies Facility and repository layouts are incorporated into the framework model for display in plan maps and cross-sections. The repository layout plan available during creation of the Integrated Site Model is shown in Figure 3.8-1 (CRWMS M&O 1996f). The layout is being updated. The repository and Exploratory Studies Facility layouts are Q data.

3.8.3 Construction of the Model

3.8.3.1 Modeling Assumptions

A basic set of geologic assumptions was employed in geologic framework model construction as discussed by working groups of YMP geologists and geophysicists. The key assumptions are listed here:

- Relations between faults in the vertical dimension are generally reflected in their map-view geometries. In other words, when fault B splays from fault A in map view, it is also likely that fault B splays from fault A in the vertical dimension. A broad observation throughout the Basin and Range structural province, this concept helps bound uncertainties in 3-D fault network creation by providing a geometric guide.

- Lithophysal zones are more or less stratiform at the scale of the model, although the amount of pore space varies horizontally and vertically. This is supported by rock properties modeling of porosity (see 5.3.3.1.1.8).

- Within a fault block, lithostrata can be interpolated between and extrapolated away from hard data points using sound geologic principles applicable to volcanic terranes. In other words, standard contouring techniques were applied. For example, a linear interpolation was used to continue thickness trends between control points (during hand-contouring) and thickness and structural trends constrained by data were extrapolated into areas of no data.

3.8.3.2 Layering Schemes

The rock layers at Yucca Mountain can be described and defined by various layering schemes. Rock layers in the Integrated Site Model adhere to the stratigraphic hierarchy and subdivision system detailed in Reference Information Base item 1.12a: Geologic/Lithologic Stratigraphy, which is derived from Buesch, Spengler et al. (1996a) and Sawyer, D.A., Fleck et al. (1994). This layering scheme is the current Yucca Mountain Project standard, and model users should refer to Subsection 3.5 and Table 3.5-2 to become familiar with stratigraphic names. Rock units are subdivided into groups, formations, members, zones, and subzones which serve as the basis of reference for all YMP layering schemes.

The table of lithostratigraphic contacts in Appendix A of Clayton et al. (CRWMS M&O 1997e) lists the measured depths to the *tops* of rock units; similarly, the Integrated Site Model considers contacts as rock unit *tops* and the name of each surface in the model is the name of the top of a rock unit. This should be kept in mind when dealing with most USGS lithologic logs, which name contacts as rock unit *bottoms*, and names are accordingly shifted. Rock units included in the Integrated Site Model are correlated with the stratigraphic nomenclature and thermal mechanical units listed in Table 3.8-1. Extensive descriptions of each rock unit can be found in Buesch, Spengler et al. (1996a) and Reference Information Base item 1.12a. Lithologic logs and stratigraphic descriptions from numerous documents are compiled in the YMP Stratigraphic Compendium (CRWMS M&O 1996e) and are discussed in Subsection 3.5 of this document.

The top of the Repository Host Horizon does not coincide with any defined stratigraphic horizon, but is 5 to 40 m (a few tens to over a hundred feet) above the Tptpul/Tptpmn stratigraphic contact (CRWMS M&O 1997d). No attempt is made here to extrapolate this surface across the entire site area. The top of the Repository Host Horizon is the only widely-used rock boundary that does not closely coincide with a stratigraphic contact defined in Reference Information Base Item 1.12a.

3.8.3.3 Modeling Methods

The Integrated Site Model was constructed using Earthvision software version 3.1 (manufactured by Dynamic Graphics Inc., Alameda, California) running on a Silicon Graphics Indigo 2 computer.

A lengthy process of data preprocessing (i.e., data compilation, arrangement, and translation into the required input formats) preceded actual model construction. As data were compiled and analyzed prior to model construction, issues invariably arose which required some kind of resolution with the Principal Investigators. Such issues included the nature of a contact, clarification of interpretations of seismic profiles, and interpretive geologic concerns. Integrated Site Model developers contacted the appropriate Principal Investigators and worked out resolutions.

The geologic framework model construction process followed these general steps:

- Construction of faults
- Construction of structure surface on base of Tpbt4 (the pre-Tiva Canyon bedded tuff)
- Construction of isochore maps of all units
- Assembly of the faults
- Assembly of the rock layers
- Create faulted grids
- Create 3-D model
- Assessment and iteration

The details of the steps above are discussed in the following sections.

3.8.3.3.1 Construction of Faults

Faulting is discussed in Subsection 3.6. Because of the purpose and scale of the 3-D geologic model, it should not be used as a rigorous representation of the discussions in Subsection 3.6, and the content of figures from the model may differ from those in Subsection 3.6.

Creation of fault surfaces for the Integrated Site Model required a significant amount of feedback from YMP scientists. The criteria for fault inclusion/exclusion were developed first. The resulting set of faults was then analyzed for completeness and applicability. The locations of fault traces were then established using USGS geologic maps (Day et al. 1996a; Simonds et al. 1995). Fault offsets were then estimated from published sources and preliminary cross-sections.

Fault surfaces were constructed as contour maps. The mapped surface trace for each fault was explicitly honored in surface construction, as were borehole intercepts. The contour map was then converted into a rectilinear grid of x,y,z values for use in the modeling software, tightly constrained to honor the contour values. The Earthvision software's minimum tension surface-generating algorithm's freedom to extrapolate was limited by the distribution of hand-drawn contours.

Faults with dip directions that change along strike (Bow Ridge and Solitario Canyon faults) were constructed in two pieces, one dipping in each direction. The two segments were brought together as near vertical as mathematically possible, and passed through each other. Earthvision software includes a feature that ignores a fault once it crosses to the "wrong"side of another fault, resulting in apparently continuous Solitario Canyon and Bow Ridge faults.

3.8.3.3.2 Construction of a Structure Surface on Base of Tpbt4

This surface was hand-contoured, honoring all borehole and outcrop data (Figure 3.8-3). Offsets along faults were estimated from outcrop information and cross-sections. Feedback from YMP Principal Investigators was incorporated in an iterative process. The contours were then converted to a rectilinear grid, tightly constrained to honor the contour values to the degree allowed by the grid spacing.

The base of Tpbt4 was selected because it is commonly shown on the quadrangle geologic maps, which group Tpbt4 with the Tiva Canyon Tuff–this is the major reason for the change from Integrated Site Model 1.0, where the top of Tpbt4 (which is not shown on the geologic maps) was used for structural control. The contact may be difficult to determine in outcrop and boreholes, but is commonly identified in borehole lithologic logs without condition (i.e., without indication of uncertainty); therefore, the distribution of data points available (especially on geologic maps of the model area margins) made it a desirable contact. Normally, a 3-D model would be built upward from a deep control surface, but we chose a shallow unit to build downward from Tpbt4 because of the sparseness of deeper drillholes. Tpbt4 is penetrated and identified in most boreholes.

3.8.3.3.3 Construction of Isochore Maps of All Units

Isochore (thickness in borehole) maps were hand-contoured, honoring all borehole and outcrop data. Correction was made for inclined boreholes. A linear interpolation was used to estimate thicknesses between boreholes in hand-contouring. Feedback from YMP Principal Investigators was incorporated iteratively. Contours were converted to rectangular grids, tightly constrained to honor the contour values.

Isochore maps for welded and nonwelded units in the Prow and Bullfrog Tuffs were gleaned from existing data. Units described as poorly, partly, or nonwelded are grouped in the nonwelded units. Those described as moderately or densely welded are grouped in the welded units.

3.8.3.3.4 Assembly of the Faults

A logic tree was created to provide a hierarchy for fault intersections (i.e., which faults truncate which) and to establish the stratigraphic sequence for use in the software. The faults were assembled first without any stratigraphy, and the results checked. Fault construction was then iterated until no interpretive or data issues remained. The following are the criteria used to include faults in the Integrated Site Model:

- Outside of the repository area, faults which have over 30 m (100 ft) of vertical displacement and a (3200 m) 2 miles or greater mapped surface trace length were included. These are referred to as block-bounding faults (Day et al. 1996a).

- Within the repository area, faults with a mapped vertical offset of greater than 30 m (100 ft) or a 1600 m (1 mile) or greater mapped surface trace length were included.

- Faults that exert local control on the geologic map cartography, such that leaving the fault out would result in a mismatch between the model and published geologic maps, were included.

A thorough discussion of faulting and deformation at Yucca Mountain can be found in Whitney (1996) chapters 1 through 4 in Volume 1 (Seismotectonic Framework and Characterization of Faulting at Yucca Mountain) and in Subsection 3.3 of this report. No attempt is made here to summarize this information.

3.8.3.3.5 Assembly of the Rock Layers

Assembling the rock layers consists of inputting the previously constructed isochore maps of each rock layer in proper stratigraphic order. As part of this process the Earthvision software requires that the top of each rock layer be defined either as an unconformity or as a depositional surface. In the Integrated Site Model the topographic surface and the top of Tiva undifferentiated (an eroded surface commonly overlain by alluvium or Rainier Mesa Tuff) were defined as unconformities; all others were defined as depositional.

3.8.3.3.6 Create Faulted Grids

The next step–which technically completes the model-building process–was to create faulted grids for each rock layer boundary. The software uses the fault logic tree to assemble the isochore maps into the proper sequence and determine fault block boundaries. Each horizon is then broken into pieces, one piece for each fault block, and is labeled with the fault block name. This step results in creation of separate digital files for each horizon in each fault block and internal bookkeeping of how the pieces all fit together. Fault offsets are clean breaks with no draping or connectivity of contact horizons across the fault surface. These files are exported to flow and transport modelers and performance assessment.

3.8.3.3.7 Create 3-D Model

An additional step was performed purely for visualization, display, editing, inspection, and interpretation. In this step, a 3-D visual representation of the model was created from the faulted surfaces constructed in the previous step. In Earthvision software parlance, the visualization is called a "faces"file and has the suffix of "faces." The term "faces" is an analogy to crystal faces, which form layer upon layer within a crystal lattice and are therefore similar in form to the grids and surfaces created in Earthvision. The faults and rock units were connected in space by a proprietary form of triangulation that produces surfaces that can be displayed on the computer screen. Rock layers, faults, and fault blocks can be displayed individually or in combinations as desired. An example is shown in Figure 3.8-4.

3.8.3.3.8 Assessment and Iteration

The results of the above steps were examined and corrections made. Input data files were displayed against the gridded or assembled horizons and faults to check for inconsistencies. Where inconsistencies were found, the root cause was determined and the appropriate correction taken (usually in the form of recontouring). Three-dimensional visualization proved to be a powerful editing tool by quickly revealing data input errors or interpretive inconsistencies.

3.8.3.4 Limitations, Error, and Uncertainty

The basic limitation of the Integrated Site Model in accurately portraying the subsurface geology (as would be tested by new drillholes or tunnels) is data distribution. In typical modeling environments in the mining or oil and gas field exploitation industries (the closest analogues to Yucca Mountain site characterization), primary data inputs–usually boreholes–are more or less regularly distributed across the model area and to the depth of interest, and features of interest are frequently targeted in data acquisition. At Yucca Mountain, only one borehole penetrates to the deepest stratigraphic horizon of interest (the Paleozoic carbonate aquifer, borehole p#1). Only 10 boreholes penetrate to the base of the Tram Tuff, and these are scattered irregularly over 166 square km (64 square miles). As a result, most of the volume of the Integrated Site Model is not well constrained by data and the rest of the volume must be interpreted. Areas of least constraint are north of Yucca Wash, east of Fortymile Wash, in Crater Flat, in the south-central area, in the four corners of the model area, and below the top of the Calico Hills Formation. We believe, however, that the effects of this limitation have been minimized by application of sound geological mapping techniques and principles employed in the process of building the model from a series of structure and thickness maps. Because thickness maps show trends that originate from geologic processes, application of sound geologic principles in map construction should minimize spatial uncertainty; however, there is no way to remove all uncertainty in extrapolating away from data points and the locations of rock units and faults at unconstrained points are interpretive.

Undersampling of geologic features introduces additional uncertainty which limits the model's predictive capabilities. YMP boreholes are not located in every fault block; neither do they intersect faults at depth (with a few exceptions). Most fault offsets are unconstrained at depth because paired boreholes on either side of faults do not exist. As a result, modeled stratigraphic thicknesses and elevations at depth in fault blocks in which no boreholes are located have a slightly higher uncertainty, and modeled fault offsets at depth have increased uncertainty.

The interpretive nature of the structure and isochore maps from which the model is built also introduce a degree of uncertainty. Given the same data points, many contouring interpretations are possible and equally valid as long as they honor the data. Depositional concepts can be applied to mitigate uncertainty due to contouring. The differences between contouring interpretations are nearly always small compared to the vertical uncertainty with depth, and so the effects on the model due to differing contouring interpretations is also small in relation to the total spatial uncertainty in the model.

Vertical error introduced by the minimum tension extrapolation algorithm used in Earthvision is small at input data points. Our investigations show that for a typical gridding application, minimum tension gridding errors are typically less than 0.16 m (0.5 ft). In this investigation, a minimum tension surface was generated for a set of data points, and then the difference between the data points and the generated surface was calculated. Where poorly constrained or forced to deal with widely varying values over short distances, the minimum tension algorithm required us to insert added control contours.

Spatial uncertainty in the final model is also a function of distance from known data points such as boreholes, the Exploratory Studies Facility tunnel, and the topographic surface. Additional factors which increase uncertainty are the presence of faults and changes in dip; i.e., uncertainty increases each time a fault is crossed and each time dip changes away from a known data point. These uncertainties can be mitigated by application of sound geologic principles. Uncertainty in the framework model can thus be generalized as increasing with depth and distance from boreholes and increasing across faults and dip changes, and is mitigated where assumed geologic principles are not violated. A quantitative assessment is not attempted here.

Vertical resolution of the finished model (i.e., its ability to accurately represent input data) is a function of several factors. The first factor is the scale of the maps both used as input and generated for structure and isochores. At the scale of the maps used to create the model (1:6,000 to 1:24,000) and the contour intervals used (3 m or 10 ft for isochores, 30 m or 100 ft for structure contours), our experience shows that data input errors of a meter or two (less than about 7 ft) have minimal impact on the maps, except thickness maps of very thin units. Expected vertical errors for borehole lithostratigraphic contacts are on the order of a meter or less (in most cases) as described in the numerous cited references in *Yucca Mountain Project Stratigraphic Compendium* (CRWMS M&O 1996e), and so would not be expected to impact the model in any discernible way. The second factor is grid spacing used to construct surfaces. Where input data points are closer together than the grid spacing (100 ft in Integrated Site Model 2.X updates), all can not be honored and an averaging is performed. This is the case with boreholes UZ-1 and UZ-14, UZ-7 and UZ-7a, a#1 and b#1, and c#1-3. Grid spacing also affects the results of contouring. Where input contour points are closer together than the grid spacing, some averaging is performed and the contours are not exactly honored.

Horizontal resolution of the model is also difficult to quantify, but at the scale of the maps used to construct the model errors of 10 m (about 30 ft) would not be detected unless the data point were placed on the wrong side of a fault, which is a possibility for several boreholes located close to faults. No such errors have been detected.

3.8.4 Model Results

Maps of structure and thickness that were produced to support hydrologic and transport modeling, performance assessment, site suitability, and design engineering studies are important interpretive products of framework model development. These products provide means to interpret the geologic history of the site; however, it must be realized that a significant amount of geologic interpretation went into map creation, and the maps and other model components must be used strictly as interpretive products.

3.8.4.1 Interpretation of Rock Units

The following section interprets the geometries and distributions of rock units as represented in the 3-D geologic framework model. Depositional histories of the rock units are described in detail elsewhere (see Buesch, Spengler et al. 1996a; CRWMS M&O 1996e). While construction of the model requires interpretations of geologic processes (faulting, erosion, and volcanism), the focus here is on interpretations which can be made based on geometry and distribution.

The thickness of a specific volcanic unit such as those represented in the model is a function of the original topography onto which the unit was deposited, proximity to the source caldera, and structural history (Smith, R.L. 1980). Unit thicknesses are also locally controlled by post-eruption erosion. The 3-D model helps provide quantitative constraints on the regional variation of the units, and, as such, the physical properties of the host rocks for the potential repository area. As reviewed by Sawyer, D.A., Fleck et al. (1994), the Claim Canyon Caldera was the source for most of the volcanic units in the Paintbrush Canyon Group. The ultimate source for the Topopah Spring Tuff, however, has been a topic of discussion. M.D. Carr et al. (1986) proposed a source west of Yucca Mountain in the Crater Flat area, and Sawyer, D.A., Fleck et al. (1994) contend that the Claim Canyon caldera, which is north and northwest of Yucca Mountain, could have been the source for most of the entire group. The source caldera for the Calico Hills Formation was northeast of Yucca Mountain (Sawyer, D.A., Fleck et al. 1994). The source caldera(s) for the Prow Pass, Bullfrog, and Tram Tuffs is (are) uncertain (Sawyer, D.A., Fleck et al. 1994).

The Rainier Mesa Tuff of the Timber Mountain Group (Sawyer, D.A., Fleck et al. 1994) is typically preserved on the downthrown sides of normal faults. This unit has been used in constraining the younger limit of major faulting in the area (11.6 Ma; Fridrich, Whitney et al. 1996); however, in-progress mapping may alter this interpretation (Day et al. 1997).

The Comb Peak Rhyolite crops out in a few exposures in the northern part of the model area, where it reaches a maximum thickness of a few hundred feet (over 60 m) above an unconformity which places it in contact with units as old as the Calico Hills Formation (Day et al. 1998b). Notice that in 3-D view color keys (e.g., Figure 3.8-4), the Comb Peak rhyolite is shown out-of-sequence above the Rainier Mesa Tuff for internal modeling logistical reasons. The related ignimbrite unit (Tpki; tuff unit "x") is not modeled, but is grouped with the Rainier Mesa Tuff.

The Tiva Canyon Tuff is relatively thinner to the north of Yucca Wash and thickens southward. This unit becomes thickest in the repository area, and then thins southward in the Busted Butte area (Day et al. 1996a).

The lower densely welded vitric unit of the Tiva Canyon Tuff (Figure 3.8-5) is present only in the south-central and west-central part of the model area, and farther to the southwest in Crater Flat in boreholes V.-1 and V.-2. The distribution of this unit between the V. boreholes and Yucca Mountain is not known, but the isochore contours in Figure 3.8-5 leave a possible connection open. Because densely welded vitric units have low porosity, this unit could be of considerable local importance in hydrologic modeling.

The Pah Canyon and Yucca Mountain Tuffs thicken dramatically to the northwest and pinch out southward in the repository area (Figures 3.8-6 and 3.8-7). The Yucca Mountain Tuff is thickest on the south side of Yucca Wash at the northern end of Yucca Mountain, but is absent north of Yucca Wash. Either the tuff was eroded north of Yucca Wash without fault offset, or it simply thinned abruptly against a paleotopographic high and was not deposited.

Thermal mechanical (and hydrogeologic) unit PTn (the non- to partly-welded units between the Tiva Canyon and Topopah Spring Tuff densely welded interiors) is thinnest a mile or so south of the potential repository area and thickest toward the Prow (Figure 3.8-8).

The Topopah Spring Tuff upper densely welded vitric subzone (Tptrv1) is generally less than about 3 m (10 ft) thick across the model area. Data distribution permits a wide variety of contouring interpretations, including thickness changes arranged in pods or axes. The contoured interpretation included in the Integrated Site Model depicts trends (axes) of thickness changes.

Some rock units within the Topopah Spring Tuff disappear to the north or south, causing the over- and underlying units to merge. In particular, the upper and lower lithophysal zones pinch out to the north and become indistinct in their physical characteristics at the northern and extreme southern model area limits.

The Topopah Spring Tuff contains a lithic-rich unit (Tptf) which is present only in the northern part of the model area and straddles the contact between the crystal-rich and crystal-poor members (Buesch, Spengler et al. 1996a). The unit is comprised of 10 to 50 percent lithic clasts, which range locally up to 1 to 2 m in diameter. Clast types include crystal-poor welded tuff, flow-banded lava flows, and fine- to medium-grained quartz monzonite (Lipman et al. 1966; Spengler and Fox 1989).

Like the Tiva Canyon Tuff, the Topopah Spring Tuff thins dramatically north of Yucca Wash (Christiansen and Lipman 1965), becomes thicker to the south in the repository area, and thins again southward (Day et al. 1996a; Figure 3.8-9). In the northern part of the model area near borehole G-2 the Topopah Spring Tuff is 288 m (946 ft) thick. In the repository area, the Topopah thickens to over 335 m (over 1,100 ft), then thins to 244 m (800 ft) in the area near borehole WT-1.

The thickness of the Topopah Spring Tuff lower densely welded vitric subzone (Tptpv3; Figure 3.8-10) varies widely across the model area. The interpretation shown depicts thickness trends where possible, and local thickening at certain boreholes. Some of the differences shown are believed to reflect the heterogeneous borehole contact data set, where the differences are most pronounced in vitric units.

The Calico Hills Formation (Figure 3.8-11) is a sequence of interbedded, nonwelded ashflows, bedded tuffs, and rhyolitic lavas that have been grouped into several subunits that are recognizable throughout the model area (Moyer and Geslin 1995). For the purpose of modeling rock properties, the Calico Hills Formation is treated as part of the CHn thermal-mechanical-hydrogeologic unit. It is 250 m (819 ft) thick in drillhole USW G-2 and rapidly becomes thinner to the west (less than 91 m [300 ft] thick at Prow Pass) and is less than 30 m [100 ft] thick at the south and west edges of the model area.

The Prow Pass Tuff (Figure 3.8-12) welded and lower nonwelded zones show a north-south-trending lobe or axis of thickening that approximately coincides with the Nevada Test Site boundary (Moyer and Geslin 1995).

Both total thickness of the Bullfrog Tuff and the thickness of the welded zone (Figure 3.8-13) show a thickening trend to the southwest. The welded interior of the unit is 135 m (481 ft) thick in borehole G-3.

The Tram Tuff (Figure 3.8-14) thins rapidly to the north from Drill Hole Wash. The unit has an axis of thickening extending from the head of Drill Hole Wash southward to drillhole G-3.

On the western side of the model area, the Prow Pass Tuff and older units dip moderately to the east, more steeply than the shallower units. This geometry is shown in the regional seismic profiles where the east-dipping reflections are interpreted as artifacts (Brocher, Hart et al. 1996). The results of the 3-D model suggest that the reflections are real, and that they represent the east-dipping lower Tertiary units.

Interpretation of the Paleozoic Unconformity–Two representations of the top of the Paleozoic surface are incorporated in the geologic framework model. One is derived from the geophysical (gravity) interpretation of the unconformity at the top of the Paleozoic rocks by Majer et al. (1996b), which does not incorporate offset by the major block-bounding faults (Figure 3.8-15). The other is the same surface with interpretive offset along block-bounding faults (Figure 3.8-16). The two interpretations differ by as much as 5,000 ft locally beneath the potential repository area where major fault offset interpretations create the difference.

An interpretation of deep seismic profiles (Brocher, Hart et al. 1996) that places a fault with major pre-Topopah offset (age unknown) under the repository block is not included in the Integrated Site Model. There are four reasons for this decision. First, the interpreted fault lies near the intersection of two profiles and is most apparent when the two profiles are joined; interpretation of the fault is equivocal on the individual profiles. Second, it would not be consistent with regional observations to assume that a major fault in a favorable orientation would have become inactive while nearby parallel faults (e.g., Solitario Canyon fault, Paintbrush Canyon fault) reached their peak activity. Third, the seismic signature of Paleozoic rocks intersected by borehole p#1 along the seismic profile cannot be carried to the west because the Paleozoic-Tertiary contact in p#1 is a fault contact (the Paintbrush Canyon fault; down to the west) and the amount of offset of the Paleozoic rocks along this fault is not known. Finally, there are problems in trying to reconcile the interpreted fault with the Paleozoic unconformity calculated by inversion of gravity data (Majer et al. 1996b; Figure 3.8-17). The gravity interpretation places the down-to-the-west scarp farther east than the seismic interpretation (Figure 3.8-17; the seismic scarp is at the west end of the green line), and provides a viable tie to known faulting not possible with the seismic interpretation. The gravity interpretation provides a satisfactory interpretation because it places the highly reflective parallel reflections in the lower Tertiary units rather than in the highly deformed Paleozoic units, which would not be expected to produce organized reflections. The Integrated Site Model incorporates the interpretation by Majer et al. (1996b) because of its better tectonic and geometric fit with the rest of the model. The approximate location of the Integrated Site Model Paintbrush fault is dashed in Figure 3.8-17.

3.8.4.2 Interpretation of Faults

The overall pattern of faulting at Yucca Mountain is that of increasing fault offsets, fault density, and stratal tilt to the southwest (Fridrich, Whitney et al. 1996). Faults within the model area can be classified as north-south trending block-bounding (a significant deformation boundary), northwest-southeast trending high-angle, or intra-block (or non-block-bounding; Day et al. 1996b). The block-bounding faults in the Integrated Site Model are the Paintbrush Canyon, Bow Ridge, Solitario Canyon, Fatigue Wash, and Windy Wash faults (see Subsection 3.3). All others that are considered intra-block faults, and probably play minor roles in the overall deformation of the mountain. A more extensive discussion of faulting is given in Subsection 3.6.

Fault geometries were established through a series of workshops over a period of two years with the U.S. Geological Survey Yucca Mountain Project Branch Tectonics and Structure groups, and generally represent the favored conceptual (tectonic) models discussed in Subsection 3.3. The fault geometries were constructed from field data (geologic maps, gravity profiles, and boreholes) in addition to the conceptual models. Because of the limited boundaries and depth of the geologic model, however, it does not represent many of the details of the tectonic model such as projection of faults to seismogenic depth or intersection with faults outside the model boundaries. Use of the geologic model to draw conclusions about or distinguish between competing models would not be appropriate because of these limitations.

The northerly-trending fault system appears to have been dominated by a few faults, namely the Solitario Canyon and Paintbrush Canyon faults. The Windy Wash fault is also a major structure, but only a small part of it is present in the model volume. The Bow Ridge and Fatigue Wash faults bound blocks, but do not have offsets as large as the Solitario Canyon and Paintbrush Canyon faults. The large blocks of rock between the block-bounding faults were subjected to widespread fracturing which produced variably abundant faults with minor offsets. To match borehole p#1 and the Paleozoic surface, we interpret the Paintbrush Canyon fault as dipping 60 degrees in the upper kilometer and 50 degrees below that, and that the Paintbrush Canyon fault is one of the major contributors to the down-to-the-west downstep in the Paleozoic unconformity.

The main strand of the Paintbrush Canyon fault passes along the west side of Fran Ridge (Figure 3.8-1). Previous documents have labeled this segment as the Fran Ridge fault and have shown the Paintbrush Canyon fault bowing west around the boomerang-shaped hill between Fran Ridge and Bow Ridge (Carr, M.D. et al. 1986; Scott, R.B. and Bonk 1984). Modeling in three dimensions and accounting for geologic mapping and the fault intercept in borehole p#1 require that the main strand of the Paintbrush Canyon fault be located on the west side of Fran Ridge and that the fault to the west have small offset and be tied to the system of faults beneath Midway Valley (Figure 3.8-1).

The Solitario Canyon fault is a scissor fault, with its hinge point located on Tonsil Ridge (the ridge north of Drill Hole Wash). South of the hinge, the fault offset is down to the west; north of the hinge it is down to the east on geologic maps (Day et al. 1996a). At the north end of the model area on the south side of Yucca Wash the Solitario Canyon fault has 60 m (200 ft) of offset with the east side downthrown (Day et al. 1996a). Southward, offset decreases to zero at Tonsil Ridge, then reverses to west-side-down in Solitario Canyon. The fault splays into three major strands at the southern end of the model area.

The Bow Ridge fault is also a scissor fault, with its hinge point buried in the alluvium approximately east of Sever Wash. Constraints of outcrop and borehole WT#16 require that the fault pass between the borehole and Isolation Ridge and have a down-to-the-east sense of offset (see Day et al. 1996a). The fault is interpreted to continue north of Yucca Wash (Day et al. 1998b).

West side down normal faulting with concomitant tilting (a result of fault dips which shallow with depth) was apparently most active after deposition of the Rainier Mesa Tuff. The Integrated Site Model shows an angular unconformity between the Rainier Mesa Tuff and the Tiva Canyon Tuff, but new mapping data show that in the model area, the unconformity may not be severe (Day et al. 1997).

Intra-block faults (Day et al. 1996b) such as the Ghost Dance, Abandoned Wash, and numerous faults around Dune Wash appear to be secondary features that accommodated strain (including minor vertical-axis block rotation) between the dominant faults. Their intersections with more dominant faults at depth are uncertain, but the interpretation shown in the Integrated Site Model is that faults on the east side of the model area (Dune Wash faults, Bow Ridge, Midway Valley faults) intersect the Paintbrush Canyon fault at depth. The Ghost Dance-Abandoned Wash system's disposition at depth is unknown, but they do not intersect any major faults within the Integrated Site Model volume.

Isochore maps of the Paintbrush Group and older units do not indicate systematic thickening on the downthrown sides of northerly-trending faults, although data distribution for this kind of analysis is quite poor. Most fault offset and tilting of the stratigraphic units appears to have occurred after emplacement of the Paintbrush Group volcanics (Fridrich, Whitney et al. 1996).

Isochore and structure contour maps show no significant changes in thicknesses or elevations within the Paintbrush Group across the northwesterly faults in Drill Hole, Pagany, and Sever washes. Although these faults are shown in the previous YMP.R2.0 framework model (Buesch, Nelson et al. 1996) and on published geologic maps, they were not significant factors affecting the geometry of rock units in the Integrated Site Model. They are, however, included in the Integrated Site Model for potential use in other studies.

Drillhole data are too sparse to diagnose possible offsets in deeper strata or changes in offset with depth. The Paintbrush volcanics which cover the Yucca Mountain area were deposited on significant topographic relief (Fridrich, Whitney et al. 1996). Borehole distribution is too sparse to permit a detailed analysis. The length and prominence of topographic lineaments suggests persistent structures which may extend to depth, but their effect on the geometry of deeper rock units can not be modeled without more data.

The interpreted Paleozoic unconformity (Figure 3.8-16) suggests the presence of a down-to-the-east fault buried beneath the western edge of Jackass Flats that continues northward beneath Fortymile Wash. Geophysical profiles have suggested no significant fault under Fortymile Wash (Ponce, Kohrn et al. 1992), but if the buried fault or fault system is pre-Paintbrush Group or even older, it may not have produced the geophysical signatures expected by offset of Paintbrush Group tuffs (in particular, the Topopah Spring Tuff).

3.8.5 Summary

The Integrated Site Model is a flexible modeling system suitable for creating customized models of geology, rock properties, and mineralogy. The geologic framework portion of this model provides insights to the geology of Yucca Mountain.

The Integrated Site Model is consistant with the favored tectonic model described in Subsection 3.3. The depositional units modeled include several with widely-varying thicknesses (Yucca Mountain and Pah Canyon Tuffs) and several units that are very thin but widely distributed (Paintbrush Group bedded tuffs, Topopah Spring Tuff vitric zones). The Tiva Canyon Tuff lower densely welded vitric unit is only locally present in the south-central and west-central part of the model area. Lithophysal zones in the Topopah Spring thin and disappear to the extreme northern and southern margins of the model area. The Topopah Spring Tuff becomes thinner abruptly near Yucca Wash, and there contains a xenolithic unit which becomes thicker to the north and straddles the crystal-rich/crystal-poor member boundary.

The Paintbrush Group and Crater Flat Group rocks are underlain by older Tertiary rocks which are thicker than the two groups combined, and which are thickest in the north and west part of the model area. The older Tertiary rocks are poorly known or constrained by data from borehole penetrations. The unconformity between Paleozoic and Tertiary rocks is penetrated by borehole p#1 in the Paintbrush Canyon fault plane. The Paleozoic rocks form a high north-trending ridge beneath the southeastern part of the model area beneath Fran Ridge and Busted Butte which reaches maximum elevations slightly below sea level as interpreted from gravity modeling. The Paleozoic unconformity is probably offset down to the west by the Paintbrush and related faults and the Solitario Canyon fault farther west, but gravity data do not provide sufficient resolution to make an assessment with any confidence. The actual amount of offset on the Paintbrush Canyon fault is not known, but could exceed 1,190 m (3,900 ft) based on the general structure of the gravity-derived Paleozoic unconformity surface.

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3.9 VOLCANIC HAZARDS

Assessment of the volcanic hazard at Yucca Mountain builds on the knowledge of the late Tertiary and Quaternary history of igneous activity. Investigations were performed to determine the ages and character of past volcanic episodes, and to understand that tectonic setting with which they and Yucca Mountain are associated. Founded upon this extensive base of data, analyses, and interpretation, a Probabilistic Volcanic Hazard Assessment was carried out to determine the likelihood of igneous activity intersecting the volume of the potential repository. The mean value of the aggregate probability distribution is 1.5×10^{-8} events/year, with a 90 percent confidence interval of 5.4×10^{-10} to 4.9×10^{-8}. This probability distribution, along with information on the potential effects of igneous activity, provides one input for evaluating the ability of the site to contain and isolate high-level nuclear waste.

The program to understand igneous activity and volcanism in the vicinity of Yucca Mountain supports the need to describe and assess the site (10 CFR 60.21(c)(1)) and to analyze the geology of the site (10 CFR 60.21(c)(I)(ii)(A)). In addition, it provides the basis for assessing the existence of potentially adverse conditions (10 CFR 60.122(c)(3) and (15)), and if they exist, characterizing the extent to which they detract from the ability of the site to isolate waste (10 CFR 60.21(c)(I)(ii)(B)). The results of the program will be used to address the NRC's key technical issues on igneous activity.

3.9.1 Overview of Late Cenozoic Volcanism in the Great Basin and Relationship to Tectonic Setting

The Great Basin (encompassing most of the Northern Basin and Range province) was affected during the middle and late Cenozoic Era by extensional tectonism and magmatism caused by plate tectonic interactions at the western margin of the North American continent. As a result, the Great Basin is a region of thinned lithosphere, high heat flow, active faulting, seismicity, abundant thermal springs, and the widespread distribution of late Cenozoic volcanic rocks (Figure 3.9-1) (e.g., Eaton 1982; Crowe, Perry et al. 1995).

Volcanism in the Great Basin can generally be divided into two stages: a silicic episode involving eruption of large volume ignimbrites (Oligocene to middle Miocene) and a basaltic episode involving increasingly smaller volumes of basalt (mid-Miocene to Quaternary). These two stages of volcanism also correlate in a general way with crustal extension rate: high rate of extension during the time of the silicic episode, low and declining rate of extension during the period of basaltic volcanism. Large-volume silicic volcanism (the "ignimbrite flare-up") is considered to be due to a large flux of basaltic magma into the crust (Johnson, C.M. 1991; Best and Christiansen 1991), as a result of reactivation of the mantle wedge above a steepening subducted slab following the slowing of subduction rates after the Laramide (Coney and Reynolds 1977; Cross and Pilger 1978; Lipman 1980). Basaltic intrusion, convection in the underlying mantle wedge, and thick crust inherited from the Laramide created an unusually hot crust by the end of the Oligocene epoch. Thermally weakened crust is considered a prerequisite for large-magnitude ductile extension in the Basin and Range province in the late Oligocene to early Miocene (Morgan, P. et al. 1986). The extensional collapse of over-thickened and thermally weakened crust followed the slowing of subduction and easing of compressional forces at the continental margin (Coney 1987). Coupled with decreased basalt flux into the crust beginning in the late Oligocene (from breakdown of the mantle wedge), the thinned crust would begin to cool (Perry, DePaolo et al. 1993).

Overall cooling of the Cordilleran crust in late Cenozoic time is consistent with slowing of extension rates, changes in style of deformation, and transition to the eruption of basalt. Two overlapping phases of extensional deformation are recognized during the Cenozoic:

- An early, mid-Tertiary phase characterized by high strain rates, a shallow brittle-ductile transition, shallow fault penetration, and eruption of voluminous intermediate to silicic volcanic rocks

- A late, Miocene-Pleistocene phase (Basin and Range event) characterized by lower strain rates, deeply penetrating faults, the establishment of modern Basin and Range structural styles, and bimodal eruptions of basalt and high-silica rhyolite (Christiansen and Lipman 1972; Zoback et al. 1981; Eaton 1982; Morgan et al. 1986; Coney 1987; Keller et al. 1990; Armstrong and Ward 1991)

The high strain rates characteristic of Oligocene extension required a hot and thermally weakened crust, while lower strain rates and associated deep, high-angle faulting are consistent with a cooler, more brittle, and mechanically stronger crust (Morgan et al. 1986). Cooling of the crust is considered to favor the eruption of basalt because cooling of the crust increases crustal density on a regional scale (enhancing buoyant ascent of basaltic magma), contamination or mixing with more silicic crustal magmas is inhibited, and basaltic magmas intruded into brittle crust would have access to deeper crustal fractures that would favor rapid ascent without differentiation (Perry, DePaolo et al. 1993).

3.9.2 Oligocene-Miocene Silicic Volcanism

Intermediate to silicic calc-alkaline Cenozoic volcanism began in the Northern Great Basin during the late Eocene and gradually swept south, ending in Southern Nevada by the late Miocene (Stewart et al. 1977; Armstrong and Ward 1991). The Yucca Mountain region marked the southern limit of silicic time-transgressive volcanic activity in the Great Basin, with the formation of the southwestern Nevada volcanic field. This southward sweep is thought to be related to declining plate convergence rates and steepening of the dip of the subducted slab, resulting in activation of the asthenospheric mantle wedge and generation of basaltic magma to fuel crustal magmatic systems (Cross and Pilger 1978; Lipman 1980; Best and Christiansen 1991). Isotopic studies of zoned ignimbrite systems suggest that an equal or greater volume of basaltic magma derived from the mantle was required to generate these ashflow tuffs, through fractional crystallization of basalt and mixing of basalt with melted crustal wallrock (Johnson, C.M. 1991; Perry, DePaolo et al. 1993). Eruption of calc-alkaline ashflow tuffs reached a peak in the Central Great Basin between 30 to 20 Ma (the "ignimbrite flare-up"), when >50,000 km^3 of tuff was erupted (Best and Christiansen 1991). The period of most voluminous silicic volcanic activity in the Yucca Mountain region occurred between about 15 to 11 Ma (Figure 3.9-2, Sawyer, Fleck et al. 1994). Large-magnitude extension also migrated southward during the Cenozoic (Crowe, Perry et al. 1995), although less systematically than silicic volcanism. The timing of extension and silicic volcanism may not be well correlated in any particular area; extension locally may predate, be contemporaneous with, or postdate silicic volcanism (Axen et al. 1993; Sawyer, D.A., Fleck et al. 1994).

3.9.3 Miocene-Quaternary Basaltic Volcanism

The initiation of true basaltic volcanism in the Great Basin and the Basin and Range Tectonic Province as a whole began in the early to middle Miocene (<17 Ma, Figure 3.9-1) and generally postdates major silicic volcanism and periods of high extension rate in any particular region. Basaltic volcanism in the Great Basin and adjoining regions has exhibited systematic trends in location, composition, and eruption volume through time. These trends can be related to both tectonic processes in the crust and melt generation processes in the underlying mantle.

Figure 3.9-1 shows the distribution of basaltic rocks in the Western United States (excluding the Columbia Plateau) during two time periods: 16 to 5 Ma, from near the inception of basaltic volcanism to the end of the Miocene; and 5 to 0 Ma, from the end of the Miocene to the present. Basaltic volcanism was concentrated increasingly along major physiographic margins with time, in particular along the margins of the Great Basin and the Colorado Plateau. Post-Miocene eruption of basalt within the Great Basin interior has been sparse, with the notable exception of a band of post-Miocene basalt that extend from Death Valley to Lunar Crater in Central Nevada, including the basalts in the vicinity of Yucca Mountain (Crowe, Vaniman et al. 1983). The migration of basaltic volcanism to the margins of the Great Basin correlates with increased extension and seismicity in these areas, indicating that the stress regime and local strain rate exert a broad control on the location of basaltic eruptions. (Christiansen and McKee 1978).

In the southwestern United States, in general, basaltic volcanic fields that erupted the largest volumes and had the highest eruption rates are associated with the Colorado Plateau margin (Taos, Cerros del Rio, San Francisco, Springerville, Zuni-Bandera, Mount Taylor; Perry et al. 1998b). Many of these basalt fields erupted tholeiitic basalt in addition to alkalic basalt, indicating higher degrees of partial melting at shallower mantle depths compared to the Great Basin/Basin and Range interior. Basalt fields in the interior of the Basin and Range have volumes that seldom exceed a few tens of cubic kilometers, while fields along the Colorado Plateau boundary have volumes of 100 to 300 km^3 (San Francisco, Springerville, Zuni-Bandera, Taos). Long-term eruption rates for several volcanic fields on the Colorado Plateau margin exceed 50 km^3/Ma, while rates for fields within the Basin and Range are <20 km^3/Ma (Perry et al. 1998b). The volume and eruption rates of basalt fields of the Colorado Plateau margin suggest higher production rates of basaltic magma in the mantle beneath these areas, compared with mantle beneath the Basin and Range interior. The eruption rate for the past 5 Ma cycle of basaltic activity near Yucca Mountain is among the lowest of volcanic fields in the Western United States (Perry et al. 1998b), and basaltic volcanism is minor compared to other regions of the Western United States (Figure 3.9-1).

3.9.3.1 Data Acquisition and Methodology

Geologic Mapping–The units of the young post-caldera basalts have been the focus of detailed field studies, including trenching and standard geologic mapping at scales of 1:24,000 to 1:4000 (Faulds et al. 1994; Crowe, Perry et al. 1995; Fleck et al. 1996; Perry et al. 1998a). In all cases, Quaternary volcanic centers have been mapped in greater detail than Pliocene centers.

Geochronology–Early determinations of the age of basalts in the Yucca Mountain region were obtained by the K-Ar method. This method is generally accurate and reproducible for basaltic rocks older than about 1 Ma; rocks younger than 1 Ma are generally more difficult to accurately date due to the low amount of radiogenic argon present in the rocks. In recent years, the K-Ar method has been increasingly replaced by the use of the $^{40}Ar/^{39}Ar$ method. The $^{40}Ar/^{39}Ar$ method has generally been used to date basalts older than 1 Ma. For younger basalts (e.g., Sleeping Butte and Lathrop Wells), the $^{40}Ar/^{39}Ar$ method has been supplemented by the use of cosmogenic ^{3}He, U-Th disequilibria and thermoluminescence (Perry et al. 1998a), because of the difficulty of dating young basaltic rocks using the $^{40}Ar/^{39}Ar$ method and the need to independently confirm the results of any one method.

The increased level of detail study given to geologic and geochronologic data as the age of basalt centers decreases is a purposeful attempt to focus the work on assessment of the Pliocene and Quaternary volcanic history of the Yucca Mountain region. It is this part of the geologic record that provides the most important basis for assessing volcanic hazard.

Comparison of K-Ar and $^{40}Ar/^{39}Ar$ data for Post-Miocene Basalts–The most extensive studies to date post-Miocene basalts of the Yucca Mountain region were carried out as part of Nevada Test Site studies by the USGS using the K-Ar method (Fleck et al. 1996) and as part of the YMP by Los Alamos National Laboratory using the $^{40}Ar/^{39}Ar$ method (Perry et al. 1998a). Comparison of the results of these studies serves as an independent check on the reproducibility of age determinations obtained for post-Miocene basalts of the Yucca Mountain region. Mean age comparisons are generally good for basalt episodes between 1 and 5 Ma, with a maximum difference in mean age determinations of about 8 percent for the basalt of Buckboard Mesa (Table 3.9-1, Figure 3.9-3). Even where mean age determinations are in agreement, however, there is uncertainty in what the true age distribution of a given volcanic episode is. For example, the Quaternary basalt centers of Crater Flat can be interpreted as all having the same age of ~1 Ma, or alternatively, there may be a systematic decrease in eruption age from north to south in Crater Flat (Figure 3.9-4). For the two youngest volcanic episodes (Sleeping Butte and Lathrop Wells) agreement is poorer (~20 to 40 percent difference), which is considered to reflect the difficulty of dating young (<1 Ma) basalts using these methods.

In the case of the Sleeping Butte centers, only a few age determinations have been attempted, and the data are insufficient to assess which age determination is more correct. The difference of ~70 ka in the age determinations does not significantly impact volcanic recurrence rate calculations for probability calculations (Crowe, Wallmann et al. 1998b).

The age of the Lathrop Wells volcanic center has been debated for a number of years (Turrin et al. 1991, 1992; Wells, S.G., McFadden et al. 1990a; Wells, S.G., Crowe et al. 1992). Recent $^{40}Ar/^{39}Ar$ dates (Perry et al. 1998a) on both basalt whole-rock samples and tuff xenolith sanidine samples are reproducible and indicate an age of ~75±10 ka. This age is consistent with U-Th disequilibria and ^{3}He dates (Perry et al. 1998a) and ^{36}Cl dates (Zreda et al. 1993) measured at Lathrop Wells, indicating that the true age of the Lathrop Wells center is between about 70 and 90 ka. In further discussions of post-Miocene volcanism, ages obtained within the YMP by Los Alamos are considered the preferred ages.

Geochemistry–Major element, trace element, isotopic, and mineral chemistry data have been obtained for all basalt units of the young post-caldera basalts (Bradshaw and Smith 1994; Perry and Straub 1996; Fleck et al. 1996; Perry et al. 1998b). Major and trace element chemistry were analyzed by X-ray fluorescence and instrumental neutron activation analysis (e.g., Perry and Straub 1996). Isotopic compositions of strontium, neodymium, and lead were measured by solid-source mass spectrometry (Perry and Straub 1996). Mineral chemistry was analyzed by electron microprobe.

3.9.3.2 Basaltic Volcanism in the Yucca Mountain Region

In the Yucca Mountain region, silicic volcanism of the southwestern Nevada volcanic field (see Figure 3.9-1) and peak extension rates in the Southern Great Basin, occurred simultaneously at approximately 15 to 10 Ma (Wernicke, Axen et al. 1988; Scott, R.B. 1990; Carr, W.J. 1990). The commencement of basaltic volcanism occurred during the latter part of this period, as extension rates waned, and relatively small-volume basaltic volcanism has continued into the Quaternary period (Figure 3.9-2). In terms of eruption volume, the 15 million-year history of the southwestern Nevada volcanic field is viewed as a magmatic system that peaked between 13 to 11 Ma, with the eruption of over 5000 km^3 of ashflow tuffs, and has been in decline since, with relatively minor volumes of basalt erupted since 11 Ma ago (Figures 3.9-2). Approximately 99.9 percent of the volume of the southwestern Nevada volcanic field erupted by about 7.5 Ma ago with the eruption of tuffs from the Stonewall Mountain volcanic center, the last active caldera system of the southwestern Nevada volcanic field (Figure 3.9-5). The last 0.1 percent of the erupted volume of the southwestern Nevada volcanic field consists entirely of basalt erupted since 7.5 Ma ago (Sawyer, D.A., Fleck et al. 1994; Crowe, Perry et al. 1995). In terms of relative volumes, therefore, the southwestern Nevada volcanic field is considered to have virtually ceased eruptive activity since about 7.5 Ma ago (Figure 3.9-5).

The post-caldera basalts of the southwestern Nevada volcanic field consist of basalts erupted since formation of the Stonewall Mountain volcanic center (7.5 Ma), the most distal of the southwestern Nevada volcanic field calderas. This definition of post-caldera basalts differs slightly from that of Crowe, Perry et al. (1995) who considered post-caldera basalts as old as ~ 9 Ma, which postdate formation of the Black Mountain caldera, the youngest caldera of the central southwestern Nevada volcanic field caldera cluster. Using the definition of Crowe, Perry et al. (1995), which applies to the main portion of the southwestern Nevada volcanic field, post-caldera basalts can be divided into two episodes: older post-caldera basalts and younger post-caldera basalts. The older post-caldera basalts erupted between about 9 and 7.2 Ma, while the younger post-caldera basalts erupted between about 4.8 and 0.08 Ma. The time interval of about 2.5 Ma between these episodes is the longest eruptive hiatus of basalt in the Yucca Mountain region during the last 9 Ma. This eruptive hiatus also marks a distinct shift in the locus of post-caldera basaltic volcanism in the Yucca Mountain region to the southwest (Figure 3.9-6). The basalts of the older post-caldera basalts and younger post-caldera basalts are thus both temporally and spatially distinct. This observation emphasizes the importance of considering the age and location of the younger post-caldera basalts (~ the past 5 Ma of the volcanic history of the Yucca Mountain region) when calculating the volcanic hazard to the potential Yucca Mountain repository (e.g., Crowe and Perry 1989; Crowe, Perry et al. 1995; Crowe, Wallmann et al. 1998b; Ho, C.-H. 1991, 1995; Ho, C.-H., Smith et al. 1991; Connor and Hill 1995; CRWMS M&O 1996h).

The basalts of the younger post-caldera basalts comprise at least six episodes of volcanism that occur within 50 km of the proposed Yucca Mountain repository (Figure 3.9-7). The total eruption volume of the younger post-caldera basalts is about 6 km^3. The volume of individual episodes has decreased progressively through time, with the three Pliocene episodes having volumes of approximately 1 to 3 km^3 each and the three Quaternary episodes having a total volume of ~0.5 km^3 (Figure 3.9-2, inset).

Quaternary basalt in the Yucca Mountain region erupted along a north-northwest trending alignment (Crater Flat Volcanic Zone of Crowe and Perry 1989) that lies to the south, west, and northwest of the potential repository (Figure 3.9-7). Eight Quaternary scoria cones occupy this alignment, representing either seven or eight eruptive centers. All of the Quaternary centers are similar in that they are of small volume (~0.1 km^3 or less), and typically consist of a single main scoria cone surrounded by a small field (=1 km in extent) of *aa* basalt flows.

3.9.3.3 Geochemistry and Petrology of Yucca Mountain Region Basalts

The geochemistry of Yucca Mountain region basalts gives insight into mantle source characteristics, the fraction of melt generated in the mantle as a function of time, and ascent history. A large geochemical database that includes major elements, trace elements, and radiogenic isotopes exists for basalts of the Yucca Mountain region (Vaniman, Crowe et al. 1982; Perry and Straub 1996; Bradshaw and Smith 1994; Fleck et al. 1996; Perry et al. 1998b). Basalts of the Yucca Mountain region are classified as alkali olivine basalts, as are most post-Miocene basalts in the interior of the Great Basin.

Alkali olivine basalts have high total alkalis ($Na_2O + K_2O$) and are generated at relatively great depth by small degrees of partial melting (Jaques and Green 1980). Experimental data (Takahashi 1980; Takahashi and Kushiro 1983) indicate that alkalic basalts compositionally similar to those of the Great Basin equilibrated at pressures of 14 to 20 kb, equivalent to a depth of 45 to 65 km. Magnesium/iron ratios of basalts in the Yucca Mountain region are relatively low, indicating significant fractionation of olivine and pyroxene in route to the surface. On average, Pliocene basalts have slightly higher magnesium/iron ratios than Quaternary basalts (Perry et al. 1998b). If this difference is significant, it indicates that higher extension rates in the Pliocene favored more rapid transit to the surface with less opportunity for fractional crystallization.

Post-Miocene basalts of the Yucca Mountain region vary widely in concentrations of incompatible trace elements, which reflect differences in the composition of the mantle and the conditions of mantle melt generation beneath the Yucca Mountain region. Concentrations of La and Th and La/Th ratios, for instance, vary considerably, in some cases even within individual volcanic centers (Perry et al. 1998b). An important observation concerning the genesis of basalts in the Yucca Mountain region is that basalts younger than about 3 Ma have higher concentrations of many incompatible trace elements (e.g., Sr, Th, U, La, Ce) than older basalts (Vaniman, Crowe et al. 1982; Farmer et al. 1989; Fleck et al. 1996). For melting of mantle source rocks, elements such as La and Th are diagnostic of relative degrees of partial melting (e.g., high percentage of partial melt = low concentration of La and Th). These criteria can only be used as a broad guideline, since source heterogeneity also has to be taken into account. However, the three Pliocene basalt centers (Thirsty Mesa, SE Crater Flat, Buckboard Mesa) (Figure 3.9-7) have generally lower La and Th concentrations than Quaternary centers, implying larger degrees of partial melting of the mantle source, an interpretation that is consistent with their higher eruption volumes. The combination of decreasing eruptive volume through time and the geochemical data discussed above indicates that the intensity of mantle melting processes beneath the Yucca Mountain region is waning. Fleck et al. (1996) observed that the increase in incompatible elements through time is also valid when the time frame is extended to include basalts of Miocene age (<11 Ma), and concluded that a general decrease through time in the amount of partial melting of the mantle source is the most reasonable explanation (cf. Perry and Crowe 1992; Perry et al. 1998b).

Neodymium, strontium and lead isotopic data have been obtained for most of the post-Miocene volcanic centers of the Yucca Mountain region (Farmer et al. 1989; Perry and Straub 1996; Fleck et al. 1996; Perry et al. 1998b). The high $^{87}Sr/^{86}Sr$ (~0.707) and low ϵ_{Nd} (~ -10) of the Yucca Mountain region basalts are unusual for alkali basalts of the Western United States and are interpreted as reflecting the isotopic composition of a lithospheric mantle source (Farmer et al. 1989; Fleck et al. 1996; Perry et al. 1998b). A lithospheric source is consistent with a relatively shallow generation depth of 45 to 65 km, as previously discussed. Bradshaw et al. (1993) and Feuerbach et al. (1993) infer that isotopically similar basalts from the Lake Mead area are generated due to passive extension of shallow, volatile-enriched lithospheric mantle. The predominance of a lithospheric source in this region and the relatively small volumes of basalt erupted argue against the presence of an anomalously hot, deep-seated mantle plume as the driving force behind volcanism (Bradshaw et al. 1993).

Crater Flat Volcanism–Basaltic volcanism at Crater Flat occurred in three episodes at approximately 3.7, 1, and 0.08 Ma (Figure 3.9-7). All of the basalt erupted at Crater Flat are alkalic (Vaniman et al. 1982), indicating relatively small degrees of partial melting in the mantle throughout the lifetime of the field. The volume of alkali basalt erupted through time has decreased, from ~1.5 km^3 in the oldest cycle (including the basalt of Amargosa Valley) to ~0.1 km^3 at the youngest center, Lathrop Wells (Crowe, Wallmann et al. 1998b). The relatively long lifetime of the Crater Flat field, combined with the small volume of erupted material, results in one of the lowest eruptive rates of any basaltic volcanic field in the southwestern United States (Perry et al. 1998b).

Although declining volumes through time indicate a waning magmatic system, the normative compositions of basalt from different episodes (Vaniman, Crowe et al. 1982) do not clearly indicate a shift to more undersaturated compositions (and hence, smaller degrees of partial melting) through time. Differences in normative composition appear to be related more to fractionation history (e.g., amphibole removal) than differences in degree of partial melting (Vaniman, Crowe et al. 1982).

Another factor bearing on the evolution of the Crater Flat field is changes in the fractionation depth of magmas through time which is probably related to changes in magma chamber depth (Perry and Crowe 1992). Lavas of the oldest episode contain plagioclase, olivine, and clinopyroxene phenocrysts, while lavas of the younger episodes contain only olivine. Experimental studies of alkali basalt (Knutson and Green 1975; Mahood and Baker 1986) indicate that clinopyroxene will crystallize early in the crystallization sequence relative to plagioclase, at pressures exceeding 8 kb. The lack of plagioclase in lavas of the younger episodes indicates fractionation at high pressure, within the lower crust or upper mantle. The high strontium (which partitions into plagioclase) of the younger episodes also indicates that plagioclase was not an important fractionating phase in the younger episodes. Scandium (which partitions into clinopyroxene) is lower in the youngest episodes relative to the oldest episode, indicating fractionation of clinopyroxene at high pressure. In contrast, lava of the oldest episode contains plagioclase phenocrysts, relatively low strontium, and relatively high scandium (Vaniman, Crowe et al. 1982), indicating fractionation at low pressure where plagioclase and olivine dominate fractionation. These relationships indicate that magma chambers were relatively shallow (middle to upper crust) at 3.7 Ma but were deep (lower crust or upper mantle) during the younger two episodes (Perry and Crowe 1992). This interpretation implies a decreased generation rate for basaltic magma in the Quaternary. Fleck et al. (1996) noted that the higher abundances of plagioclase phenocrysts in older basalts extends to basalts of late Miocene age and likewise concluded that younger basalts equilibrated at higher pressure, consistent with a reduced magma flux into the crust.

3.9.3.4 Eruptive History of Yucca Mountain Region Quaternary Basaltic Centers

The decrease in eruption volumes between Pliocene and Quaternary volcanic centers in the Yucca Mountain region corresponds to a change in predominant eruption style. Pliocene eruptions were predominantly of Hawaiian type, with small ratios of pyroclastic deposits to lava flows. In the Quaternary, volcanic centers formed predominantly by Strombolian-type eruptions with larger ratios of pyroclastic deposits relative to lava flows compared to Pliocene centers (Crowe, Perry et al. 1995; Crowe, Wallmann et al. 1998b). The change to higher pyroclastic deposits/lava flow ratios in the Quaternary is consistent with smaller fractions of basaltic melt generated in the mantle. Compared to large volume melts, small volume mantle melts are high in volatile constituents (H_2O, CO_2) that favor high pyroclastic deposit to lava flow ratios.

Monogenetic versus Polycyclic Volcanism–An intriguing aspect of the eruptive history of the Quaternary volcanic centers of the Yucca Mountain region is whether their eruption history lasted days to years (*monogenetic*) or thousands to tens of thousands of years dominated by long periods of inactivity (*polycyclic*). Determining whether Quaternary volcanic centers are monogenetic or polycyclic has potential impact on assessing volcanic hazard. First, if volcanic centers are polycyclic, volcanic events in the Yucca Mountain region cannot be considered to be randomly distributed spatially. Once a polycyclic volcano has formed, subsequent volcanic events are more likely to occur at the same volcano for a period of time. Thus, if the late Quaternary Lathrop Wells center were polycyclic, with eruptions extending into the Holocene, subsequent eruptions in the Yucca Mountain region would be more likely to reoccur at Lathrop Wells (Figure 3.9-7).

Ideally, determining whether a particular volcano is monogenetic or polycyclic should be a simple matter of dating different volcanic deposits using generally accepted geochronology methods, or identifying unequivocal field evidence of significant time intervals between eruptions. In practice, determining whether age differences exist between deposits at Quaternary volcanoes is uncertain using standard geochronology techniques because ages determined for young volcanic deposits often have poor reproducibility or large errors, and field observations are rarely subject to a single interpretation (e.g., Whitney and Shroba 1991; Wells, S.G., McFadden et al. 1991). Consequently, these uncertainties must be considered in the volcanic hazard assessment.

The possibility of polycyclic volcanism in the Yucca Mountain region was first introduced by Wells, S.G., McFadden et al. (1988, 1990a), who observed soils between scoria deposits south of the

Lathrop Wells cone, suggesting significant time intervals between emplacement of the scoria deposits. Subsequent field, geochronologic, and geochemical studies could not disprove the hypothesis that Lathrop Wells was polycyclic (Crowe, Perry et al. 1995) and it remains a viable alternative hypothesis to monogenetic volcanism despite vigorous scientific challenge (Turrin et al. 1991, 1992).

The most recent studies at Lathrop Wells combining new geochronology and field studies weaken the evidence for polycyclic volcanism and suggest that the center formed in a single episode about 70 to 90 thousand years ago (Perry et al. 1998a). Field evidence for monogenetic volcanism at Lathrop Wells include apparent erosional unconformities between eruptive units and the origin of scoria deposits on the south side of the Lathrop Wells cone (Perry et al. 1998a). This field evidence also is considered uncertain and its resolution must be considered in the volcanic hazard assessment.

Bradshaw and Smith (1994) and Smith, E.I., Blaylock et al. (1996) have concluded that both Red Cone and Black Cone of the Quaternary Crater Flat (Figure 3.9-7) volcanic episode are polycyclic, with eruptions that spanned 100 to 150 ka.

3.9.3.5 Geophysical Evaluations Related to Yucca Mountain Region Basaltic Volcanism

Geophysical studies can potentially provide constraints on the location of basaltic volcanism by identifying the subsurface relationship between crustal structure and volcanism, or by directly identifying intrusive bodies in the crust. Magnetic and seismic data have been the most useful in understanding the location of basaltic volcanism in the Yucca Mountain region.

Aeromagnetic data have been gathered at a variety of scales in the Yucca Mountain region (summarized in Crowe, Fridrich et al. 1998a; see also Connor et al. 1997). A number of aeromagnetic anomalies in the Yucca Mountain region have been interpreted as buried or partially buried basaltic centers (Kane and Bracken 1983; Crowe 1986; Langenheim 1995; Connor et al. 1997). Two anomalies, in Western Crater Flat and the northern Amargosa Valley (Figure 3.9-8), have been drilled and confirmed to be buried basalt with ages of ~11 Ma and 3.8 Ma, respectively (Crowe, Perry et al. 1995).

The most recent seismic reflection studies across Crater Flat show that the Crater Flat basin is an asymmetric graben that is deepest to the west and south (Brocher, Hart et al. 1996). Most of the basalts of Crater Flat are above the deepest part of the basin, suggesting a correlation between the location of basalts in the Yucca Mountain region and areas of most active tectonism (see discussion in next subsection).

Teleseismic data gives some insight into the physical state of upper mantle basalt sources beneath the Yucca Mountain region. Low upper mantle seismic velocities beneath much of the Basin and Range province suggest that the upper mantle contains a small percentage of partial melt. Ascent of this melt through the crust to produce basaltic volcanism may depend partly on where local extensional stresses are conducive to magma ascent (Smith, R.L. and Luedke 1984).

Against the general background of small melt fractions in the Basin and Range mantle, three northeast-trending zones of enhanced partial melting have been proposed based on identification of low-velocity mantle anomalies (Spence and Gross 1990; Dueker and Humphreys 1990; Humphreys et al. 1992). The northernmost and southernmost of these zones correspond to pronounced magmatism: the Snake River Plain - Yellowstone zone and the Jemez zone of the southeastern Colorado Plateau margin (Figure 3.9-1). The middle zone extends from Central Utah to Southern Nevada and corresponds with surface volcanism in the St. George area of Utah (Dueker and Humphreys 1990) and the Crater Flat area of Southern Nevada (Evans, J.R. and Smith 1992). Biasi (1996) reported new teleseismic data and teleseismic tomography interpretations which indicate that no low-velocity zone attributable to magma bodies exists within the crust beneath Yucca Mountain or Crater Flat. Small amounts of partial melt within the mantle (>45 km depth) cannot be ruled out beneath Southern Crater Flat and adjacent portions of Amargosa Valley.

The volume of basaltic volcanism associated with the St. George zone is far less than the zones to the north and south. At Crater Flat, in particular, 4 Ma of basaltic volcanism has produced only about 2 km^3 of basalt. If the low-velocity anomaly beneath Crater Flat does represent a higher volume of partial melting relative to the rest of the Basin and Range, the observed small volume that has erupted suggests that the local extensional stress regime does not strongly favor magma ascent and eruption.

3.9.3.6 Structural Controls on Basaltic Volcanism

Numerous tectonic models have been proposed for the Yucca Mountain region in the past 15 years. These models have been reviewed and evaluated by Crowe, Perry et al. (1995) and O'Leary (1996) and will not be reviewed further here.

A preferred tectonic model for the Crater Flat domain (which includes the Crater Flat basin and the Yucca Mountain range) has emerged that accounts for many of the structural, geophysical, paleomagnetic and volcanic features of the Yucca Mountain region (O'Neill et al. 1992; Fridrich and Price 1992; Fridrich, Dudley et al. 1994; Crowe, Perry et al. 1995; O'Leary 1996; Fridrich, Whitney et al. 1996; Crowe, Fridrich et al. 1998a). The Crater Flat domain (Figure 3.9-8) is one of many tectonic domains that comprise the Walker Lane tectonic belt, a north-northwest trending zone characterized by discontinuous north-northwest–trending dextral strike-slip faults (O'Leary 1996).

The Crater Flat domain is modeled as an oblique pull-apart basin with a minimum of extension and vertical-axis rotation to the northeast, with both increasing strongly to the southwest (Fridrich 1998). An important internal feature of the Crater Flat domain is a north-northwest trending hinge-line based on paleomagnetic data that separates the domain into northeast and southwest subdomains (Figure 3.9-8). The hinge-line corresponds approximately to the contour of 20 degrees clockwise rotation of Tiva Canyon Tuff (Fridrich, Whitney et al. 1996), with greater rotation present to the southwest. The southwestern subdomain, between the hinge-line and the Bare Mountain fault, is characterized by larger fault displacements, higher slip rates on faults, greater stratal tilting, and much greater subsidence than the northeastern subdomain (Fridrich, Whitney et al. 1996). Taken together, this evidence indicates that the southwest corner of Crater Flat is presently the most tectonically active part of the Crater Flat domain. The identification of buried lava flows at Little Cones in southwestern Crater Flat is consistent with a high rate of subsidence in this part of Crater Flat during the past 1 Ma (Connor et al. 1997).

In light of the preferred tectonic model, it is significant that all post-Miocene volcanism in the Crater Flat domain has occurred within the southwest subdomain, where extensional deformation has been greatest (Figure 3.9-8). This observation suggests that upper crustal structure in the southwest subdomain is more conducive to volcanism and that future volcanism is more likely to occur here than in the northeastern subdomain that includes the potential repository at Yucca Mountain (Fridrich, Whitney et al. 1996; Crowe, Fridrich et al. 1998a).

3.9.3.7 Evidence for Simultaneous Faulting and Volcanic Eruption

In an extensional tectonic environment magma may ascend through the crust along fractures which serve as pathways for magma ascent. In the case of basaltic volcanism, the formation of fracture pathways releases seismic energy that typically results in earthquakes with a maximum magnitude of M 4.0 to 5.0 (Yokoyama and De la Cruz-Reyna 1990). Volcanogenetic earthquakes may, however, trigger larger tectonic earthquakes on nearby faults that have sufficient strain accumulation.

In the Yucca Mountain region, basaltic ash has been found as a dilute to concentrated component in fissure fillings and stratabound alluvial horizons exposed by trenching of several faults near Yucca Mountain. The basaltic ash consists of 0.1 to 0.5 mm glass shards containing phenocrysts of olivine and microcrystals of plagioclase. The glass shards have sharp edges indicating minimal abrasion from surface transportation. Correlation of these ashes (or ash) to the contemporary eruptive source has been used to constrain the age of the ash and, therefore, provide information about the slip history of a fault (Perry et al. 1998b). The most concentrated occurrence of ash in a trenched fault exposure was found in Trench 8 across the trace of the Solitario Canyon fault (Ramelli, Oswald et al. 1996). This ash occurs at the bottom in a 65 cm wide fissure that represents the largest recorded Quaternary displacement event (>1 m) on the Solitario Canyon fault (Ramelli, Oswald et al. 1996).

Pure ash separates were analyzed for trace elements by Instrumental Neutron Activation Analysis and compared to the composition of all Quaternary eruptive centers in the Yucca Mountain region (Perry et al. 1998b). These geochemical comparisons leave little doubt that the ash found in the Solitario Canyon fault (Trench 8), the Windy Wash fault (Trench CF3), the Fatigue Wash fault (Trench CF1), and the Stagecoach Road fault (Trench T1) originated from the eruption of the Lathrop Wells volcanic center, south of Yucca Mountain (Perry et al. 1998b). Based on geochronology results from Lathrop Wells, the age of this ash is ~75±10 ka. (Perry et al. 1998a). This conclusion is consistent with geochronology results from stratigraphic units exposed in Solitario Canyon fault Trench 8 (Ramelli, Oswald et al. 1996).

A direct date of the ash sample from Solitario Canyon fault Trench 8 using the $^{40}Ar/^{39}Ar$ method yielded a plateau age of 0.86±0.16 Ma (Perry et al. 1998b). This age is consistent with ages of the Quaternary basalt centers in Crater Flat, all of which have ages near 1 Ma. Examination of the ash sample by scanning electron microscope, however, shows that ~0.5 percent of the dated sample consists of Miocene, high-K rhyolitic glass (Perry et al. 1998b) that is optically cloudy and difficult to distinguish from the basaltic glass. It is likely that this high-K contaminant is the cause of the erroneously old $^{40}Ar/^{39}Ar$ age.

3.9.4 Eruptive and Subsurface Effects of Basaltic Volcanism

Studies of the eruptive and subsurface effects of basaltic volcanism have been conducted to provide bounds on the quantity of debris likely to be entrained by a rising magma intersecting the potential repository. Knowledge of such effects support the evaluation of disruptive event scenarios as part of the analysis to assess a repository's long-term performance. Of particular interest are estimates of the amount of debris that would be entrained by magma rising through a repository and the effects such magma would have on the geochemical and geohydrological processes operating in its vicinity. Information on the rate of occurrence for rising magma intersecting a repository is discussed in Subsection 3.9.5.

3.9.4.1 Analog Studies of Eruptive Centers

Field studies were conducted at Lucero volcanic field in New Mexico and the San Francisco volcanic field in Arizona (Figure 3.9-1). Due to the geologic setting of these volcanic fields, the quantity of debris entrained by rising magma can be related to strata at depth below the volcanoes. The data provide bounds on the quantity of debris that can be entrained into rising magma per meter along the volcanic plumbing, for a range of eruption mechanisms including Strombolian, hydrovolcanic, and effusive.

Upper-crustal xenoliths erupted from small-volume basaltic volcanoes of the Lucero volcanic field in west-central New Mexico (Valentine and Groves 1996) and of the San Francisco volcanic field in north-central Arizona (Valentine, Woldegabriel et al. 1998) were studied to assess the relative importance of various entrainment mechanisms. Total xenolith volume fractions were found to range from 0.3 to 0.9 in hydrovolcanic facies to $<10^{-4}$-10^{-2} in most Strombolian facies.

The volcanoes erupted through thick, well-characterized sequences of Paleozoic and lower Mesozoic sedimentary rocks, so that in some cases erupted xenoliths could be correlated with sedimentary units and hence, depth ranges. The abundance of xenoliths from a given subvolcanic unit was divided by that unit's thickness to obtain an average entrainment rate (xenolith volume fraction derived per unit depth in the conduit). For small basaltic eruptions driven primarily by the expansion of magmatic volatiles (Strombolian and Hawaiian eruption styles), entrainment rates were found to range from zero to $\sim 10^{-4}$/m, and were typically within the range of 10^{-8} to 10^{-6}/m. Entrainment was found to be most sensitive to the mechanical properties of the wall rocks, and is thought to depend mainly on brittle failure related to offshoot dikes, pore pressure buildup, and thermal stresses (Valentine and Groves 1996; Valentine, Woldegabriel et al. 1998). Entrainment rates in the uppermost few hundred meters of the earth's crust can be much higher for hydrovolcanic explosion mechanisms, which are driven by interaction of hot magma with surface or groundwater (Valentine, Woldegabriel et al. 1998). For this type of eruption, rates can range as high as 10^{-4} to 10^{-3}/m. These entrainment rates are averaged over thicknesses of individual stratigraphic units beneath the volcanoes; local entrainment rates could be higher (Valentine and Groves 1996; Valentine, Woldegabriel et al. 1998).

3.9.4.2 Effects of Basalt Intrusions on Silicic Tuffs

Field Studies–This subsection reports studies of alteration of silicic pyroclastic rocks by shallow basaltic intrusions. Two sites were chosen for study because combined they are good analogs for the various rocks in the vadose zone at Yucca Mountain and allow us to constrain the type and spatial scale of alteration that would accompany a basaltic intrusion into the potential repository. The two sites are the Slanted Buttes area of Paiute Ridge, Eastern Nevada Test Site, where variably vitric and zeolitized silicic tuffs (some of which correlate to those at Yucca Mountain, some 40 km away) were intruded by basaltic dikes and sills; and Grants Ridge, New Mexico.

At Grants Ridge a thick sequence of unconsolidated rhyolite ignimbrite, fallout, and reworked volcaniclastic deposits were intruded by a basaltic plug that fed a scoria cone eruption. Erosion of the site has since produced a natural cross-section through the scoria cone, its feeding system, and the pyroclastic host rocks. Data were gathered on geochemical and mineralogical alteration effects at both sites. The studies show that alteration is limited typically to within 5 to 10 m of the intrusion (Valentine, Woldegabriel et al. 1998).

Slanted Buttes (Paiute Ridge) Site–Vitric and zeolitized tuffs of middle-Miocene age intruded by shallow high-alumna alkali basalt magmas developed localized contact metamorphic zones at Slanted Buttes in the northeastern part of the Nevada Test Site (Valentine, Woldegabriel et al. 1998). The sill and dikes were probably intruded into a shallow, unsaturated environment a few hundred meters from the paleosurface as indicated by reconstruction of stratigraphy above the intrusions (Valentine et al. 1993; Ratcliff et al. 1994). The depth of intrusion was comparable to the potential repository environment at Yucca mountain. At two dikes, each of similar width (~9-m wide), the contact metamorphic zones were found to range from 0.5 to about 6 m wide on either side of the dikes. The dike responsible for the localized thermal zone (0.5 m) is about 2 km from a basaltic plug, whereas the other one is within 100 m. The contact aureole beneath a 45 m thick sill localized and extends to about 5 m below the sill. The sill is an offshoot from a dike and is about 1 km away from a plug. Shallow emplacement into an unsaturated environment may be responsible for the localized nature of the contact metamorphic zones (Valentine, Woldegabriel et al. 1998).

Silicic and zeolitized tuffs within the contact aureoles were found to be either devitrified and/or fused and quenched to form vitrophyres. Within the contact zone, the vitric component of the Ammonia Tanks Tuff of the Timber Mountain Group was totally replaced by feldspar, quartz, and cristobalite. The Tiva Canyon Tuff of the Paintbrush Group beneath the sill were found to contain a vitrophyre and a devitrified zone side by side and a clinoptilolite-rich tuff occurs about 3 m away. Variations in major, trace, and rare earth elements are subtle except for water content.

Based on the natural analog studies, there is no indication for extensive hydrothermal circulation and alteration, brecciation and deformation related to magmatic intrusion into the vitric and zeolitized tuffs. Field and analytical evidence from the localized contact metamorphic aureoles and devitrification of the silicic tuffs adjacent to the intrusion, minimal hydrothermal alteration, and presence of low-temperature minerals at close proximity to the intrusions also suggest insignificant effects of the shallow basaltic intrusions on the vitric and zeolitized tuffs (Valentine, Woldegabriel et al. 1998).

Grants Ridge Site–A study was conducted at Grants Ridge, New Mexico (Figure 3.9-1), to assess the effects of contact metamorphism on poorly consolidated late Pliocene ashflow tuffs and overlying volcaniclastic layers that were intruded by a basaltic plug and capped by thick scoria deposits (Valentine, Woldegabriel et al. 1998). The area is characterized by a northeast-trending discontinuous mesa. The plug responsible for the widespread basaltic lavas capping the mesa is located in the northeastern part of this discontinuous mesa (termed East Grants Ridge) about 12 km southwest of Mt. Taylor, New Mexico (Figure 3.9-1).

Physical features (e.g., color variation and degree of compaction), mineralogical, and chemical data from the silicic tuffs around the basaltic plug indicate variable thermal effects. Despite the size of the basaltic intrusion (~150 m wide), the contact metamorphic zone developed around the basaltic plug is only about 5 m wide. The poorly-cemented ashflow tuff along the contact aureole is baked, fused, deformed, and injected with basalt lava. This thermal effect gradationally decreases away from the intrusion. Variation in color and the degree of compaction of the silicic ashflow tuff provide evidence for the localized nature of the thermal effect (Valentine, Woldegabriel et al. 1998).

Variations in mineralogical and geochemical compositions are consistent with the changes in color and compaction of the silicic rocks. The volcanic glass, water composition, fluorine, chlorine, and iron contents increase away from the intrusion. Conversely, the amount of re-crystallized minerals and the alkali contents are higher along the contact (Valentine, Woldegabriel et al. 1998).

The field and laboratory data suggest that the effect of the intrusion on the unwelded pumice-rich ashflow tuff was minimal. Because devitrification is generally enhanced by aqueous solution, the abundance of volcanic glass within a short distance (~5 m) from the intrusion suggests a dry environment. Thus, in the absence of aqueous solutions, the width of the contact metamorphic aureole is generally confined to a narrow zone regardless of the size of the intrusion (Valentine, Woldegabriel et al. 1998).

Modeling Studies–The purpose of this work was to estimate the spatial scale over which an intrusive event can have a significant effect on the potential Yucca Mountain high-level waste repository (Valentine, Woldegabriel et al. 1998). The approach was based on simplified numerical simulations of thermally induced convective flow of air where the thermal driving force is the heat from magmatic intrusions (Valentine, Woldegabriel et al. 1998). In an unsaturated zone, such as at the potential repository site, the pore fluid that is likely to have the largest spatial scale of thermally driven flow is air, and these calculations thus result in a conservative estimate of spatial scale of subsurface effects.

The modeling study indicates that magmatic intrusions in an unsaturated tuff would not cause significant convection at horizontal distances greater than about 2.5 km (Valentine, Woldegabriel et al. 1998). Intrusion gas was found to travel less than about 500 m laterally and the horizontal distance over which an intrusion affects convective airflow was found to be less than 2.5 km. These findings make sense considering that while it is easy to move large volumes of air, because of the very low density of air, those volumes carry very little energy. Further, the small amount of heat being physically transported by the air is dissipated by conduction through the matrix, which rapidly damps the convective motion.

3.9.5 Volcanic Hazard Calculations

The major goal of volcanism studies has been to assess the probability that magmatic processes will disrupt the potential repository during the isolation period of waste containment. The probability of magmatic disruption is expressed as the annual probability of occurrence of a magmatic event (recurrence rate) multiplied by the probability that, given an event occurs, it will intersect the repository (disruption or intersection probability).

3.9.5.1 Recurrence Rate

The recurrence rate is expressed as the annual probability that a new volcanic center will form within the Yucca Mountain region (Crowe, Perry et al. 1995). Calculating the recurrence rate based on the past volcanic record depends on the time frame chosen in which volcanic events have occurred and the number of volcanic events that occurred in the time frame of interest. During the Pliocene and Quaternary (last 5 Ma), for instance, 16 volcanic events have occurred, based on "most likely" event counts in the Yucca Mountain region (Crowe, Wallmann et al. 1998b). These values give a simply calculated recurrence rate of $\sim 3\times10^{-6}$ events/year. Crowe, Perry et al. (1995) summarizes calculated recurrence rates that had been published prior to 1995. The entire range of calculations are encompassed by values of 10^{-5} to 10^{-6} events/year, with mean estimates of homogeneous and nonhomogeneous recurrence models ranging from 2.2×10^{-6} (minimum models) to 6.1×10^{-6} (maximum models) events/year.

Crowe, Wallmann et al. (1998b) recognized that during the time period of the young post-caldera basalt, there have been both long and short-duration repose intervals between basaltic episodes, and that it may be inappropriate to use arbitrary time frames to assess recurrence rates. The last million years in the Yucca Mountain region has been characterized by increasingly short-duration repose periods, that correspond to a maximum recurrence rate of 3.3×10^{-6} events/year.

Additional perspective on the possible magnitudes of recurrence rate in the Yucca Mountain region can be gained by considering that volcanism would not be of regulatory concern if no volcanic events occurred within the Quaternary. The minimum recurrence rate possible is therefore based on one volcanic event within the Quaternary, which gives a recurrence rate of $\sim 6\times10^{-7}$ events/year. Based on the volcanic record of the Yucca Mountain region, the maximum recurrence rate possible in the Yucca Mountain region is less than that of the most active Quaternary basaltic volcanic fields in the Basin and Range interior, such as the Lunar Crater and Cima Volcanic Fields (Figure 3.9-1). These fields have recurrence rates ranging from $\sim 1\times10^{-5}$ to 5×10^{-5} (Crowe, Perry et al. 1995). Thus the volcanic recurrence rate for the Yucca Mountain region must lie between $\sim 6\times10^{-7}$ and 5×10^{-5}.

3.9.5.2 Disruption Probability

The disruption or intersection probability is a dimensionless number (repository area/source zone area) that expresses the probability that, given a volcanic event, the potential repository system will be disrupted. The major uncertainty in determining the disruption probability is the choice of appropriate volcanic source zones, which depends on incomplete scientific understanding of why volcanism occurs in specific places within the Yucca Mountain region, the Great Basin, or the Western United States as a whole.

Crowe, Wallmann et al. (1998b) ran simulations using seven volcanic source zones that represent the range of source and structural zones that have been proposed for the Yucca Mountain region in order to bound the disruption probability. These zones are:

- The Quaternary Crater Flat volcanic zone (Crowe and Perry 1989)
- The Pliocene and Quaternary Crater Flat volcanic zone (Crowe and Perry 1989)
- The Pliocene and Quaternary Yucca Mountain region (Crowe, Johnson et al. 1982; AMRV of Smith, E.I., Feurbach et al. 1990)
- The Quaternary Crater Flat Pull-Apart Basin (Fridrich 1998)
- The Pliocene and Quaternary Crater Flat Pull-Apart Basin, which is identical to (D) but extends to the south to include aeromagnetic anomalies in the Amargosa Valley (Langenheim 1995)
- The Walker Lane Shear zone
- The northeast-trending Structural zone (Smith, E.I., Feurbach et al. 1990; Carr, W.J. 1990)

Maximum disruption probabilities for each alternative zone are obtained by Crowe, Wallman et al. (1998b) using a potential repository footprint of 51 km^2, derived by adding a 2.5 km standoff distance (distance at which an intrusion would have no effect on the repository, Valentine, Woldegabriel et al. 1998) to each side of the estimated boundary of a low-temperature repository (Wilson et al. 1994). A comparable area is derived using the viability assessment reference design. The mean estimates of the maximum disruption probabilities range from 2×10^{-3} for the Quaternary Crater Flat Volcanic Zone to 4×10^{-2} for the Pliocene and Quaternary Yucca Mountain Region. The important parameters that effect the disruption probability calculation are dike length, dike orientation, volcanic source zone model, and event distribution within a particular source zone (Crowe, Wallmann et al. 1998b).

An additional parameter that could affect the disruption probability is the position of source zone boundaries in cases where the position of the source zone boundary is uncertain and lies near the boundary of the potential repository. For these cases, it is important to establish the sensitivity of the position of the east or northeast boundary (the boundary nearest the repository) of a volcanic zone on the disruption probability. Crowe, Wallmann et al. (1998b) analyzed the sensitivity of uncertain source zone boundaries on the disruption probability by varying the lengths of dikes generated within source zones. For example, increasing dike lengths from 10 to 14 km has approximately the same affect as assigning an uncertainty of 4 km to the position of a source zone boundary. For most source zones, the uncertainty of the boundary has only a small effect on the disruption probability. The greatest effect is for the case of the Quaternary Crater Flat Pull-Apart Basin source zone (approximately the southwest subdomain of the Crater Flat domain, Figure 3.9-8), where increasing the dike length by 4 km increases the disruption probability by a factor of about 3 (Crowe, Wallmann et al. 1998b).

3.9.5.3 Probability of Magmatic Disruption of a Repository

The probability of magmatic disruption of a repository is expressed as the annual probability that a volcanic event will disrupt (or intersect) a repository, given that a volcanic event occurs during the time period of concern. The magmatic disruption probability thus combines the recurrence rate and the disruption probability, taking into account uncertainties in each value.

Prior to 1996, there were three alternative sources of published probability calculations (Crowe, Perry et al. 1995; Ho, C.-H. 1995; Connor and Hill 1995). The results of these calculations are summarized in Table 3.9-2. The calculations of Crowe, Perry et al. (1995) and Connor and Hill (1995) result in almost identical results ($\sim 10^{-8}$ events/year), while the calculations of C.-H. Ho (1995) result in higher probabilities of disruption ($\sim 7\times10^{-6}$ events/year). The upper end of the probability range of C.-H. Ho (1995) is predicated by restricting future volcanism to an extremely small volcanic source zone (75 km^3) that encloses the potential repository, a decision that is not justified based on the current structural understanding of the Yucca Mountain site (Crowe, Perry et al. 1995; Fridrich, Whitney et al. 1996).

Finally, Crowe, Wallmann et al. (1998b) conclude, using sensitivity analysis, that the maximum probability of magmatic disruption of a repository is 8-9$\times10^{-8}$ events/year (or $\sim 10^{-7}$). This value corresponds to the upper 90 percent confidence intervals for the highest individual mean estimates of the Probabilistic Volcanic Hazard Assessment (discussed below).

3.9.5.4 Probabilistic Volcanic Hazard Assessment

In 1995 and 1996, the DOE conducted a Probabilistic Volcanic Hazard Assessment to determine the probability of intersection of the potential repository by volcanic processes (CRWMS M&O 1996h). The assessment brought together a panel of ten experts that represented a wide range of expertise in the fields of physical volcanology, volcanic hazards, geophysics and geochemistry. Through a series of four workshops and two field trips, the experts were presented all of the available data pertaining to volcanism and volcanic processes in the Yucca Mountain region and to alternative interpretations of process and modeling parameters by scientists representing DOE, the USGS, the State of Nevada, and the NRC consultants. The goal of the Probabilistic Vocanic Hazard Assessment was to arrive at a defensible distribution of frequency of volcanic intersection that reflects the current scientific understanding of volcanic processes in the Yucca Mountain region, and in particular, the uncertainty in the volcanic hazard due to both scientific knowledge and data uncertainty (CRWMS M&O 1996h).

Each of the ten experts independently arrived at a probability distribution that typically spanned ~2 orders of magnitude of the annual probability of intersection. From these individual probability distributions, an aggregate probability distribution was computed that reflects the uncertainty across the entire expert panel (Figure 3.9-9; CRWMS M&O 1996h). The mean value of the aggregate probability distribution is 1.5×10^{-8} events/year, with a 90 percent confidence interval of 5.4×10^{-10} to 4.9×10^{-8}. The mean value translates to a probability of about 1 in 7,000 that the potential repository will be disrupted by a magmatic event during the 10,000 year isolation period. The major contributions to the uncertainty are the uncertainty in estimating event rates (because of uncertainty in the number of events) and the uncertainty in understanding the location of future volcanic events (i.e., source zones). The mean value of 1.5×10^{-8} events/year arrived at by the Probabilistic Vocanic Hazard Assessment are almost identical to values arrived at independently by previous researchers (Crowe, Perry et al. 1995; Connor and Hill 1995, Table 3.9-2).

Using most likely event count data from the Probabilistic Vocanic Hazard Assessment, Crowe, Wallmann et al. (1998b) explored the sensitivity of the probability of intersection assuming that aeromagnetic anomalies in the Amargosa Valley and Crater Flat, as well as the estimated number of undetected volcanic events, all represent Quaternary volcanic events. These assumptions lead to a revised count of eight Quaternary events and a revised probability of intersection of about 2.5×10^{-8} events/year, a value that is not significantly higher than previous estimates (Crowe, Perry et al. 1995; CRWMS M&O 1996h).

3.10 SEISMICITY AND SEISMIC HAZARDS

The assessment of seismic hazards at Yucca Mountain focuses on characterizing the potential vibratory ground motion and fault displacement that will be associated with future earthquake activity in the vicinity of the site. The evaluation of these hazards serves as a basis to define inputs for the preclosure seismic design of a potential geologic repository (YMP 1995e). The evaluation also provides information that can be used in evaluating the impact of different tectonic scenarios on the ability of the repository to contain and isolate waste during the postclosure period.

Seismic hazards at Yucca Mountain are assessed probabilistically (YMP 1994). The assessment is founded on the evaluation of a large database that incorporates information on all known seismic sources in the Yucca Mountain region including their maximum earthquakes, source geometry, and earthquake recurrence. Much of this information is based on the detailed history of past earthquakes on nearby Quaternary faults. The historical earthquake record and information on the attenuation of ground motion are also important components of this database. The seismic hazard assessment considers tectonic models that have been proposed for the Yucca Mountain vicinity (see Subsection 3.3) and information from analog sites in the Basin and Range Province to characterize the patterns and amounts of fault displacement. The probabilistic assessment explicitly incorporates uncertainties in the characterization of seismic sources, fault displacement, and ground motion. The resulting hazard calculations thus represent a sound basis for seismic design and performance assessment by reflecting the interpretations that are supported by data along with the associated uncertainties in those interpretations.

The assessment of seismic hazards at Yucca Mountain, and the associated collection, compilation, and interpretation of supporting data, contributes to addressing a number of requirements in 10 CFR 60. In addition to supporting the general requirements of 10 CFR 60.21 to describe and assess the site, including an analysis of the geology of the site, the information presented in this subsection will provide the basis for demonstrating the adequacy of the investigations and evaluations of potentially adverse conditions set forth in 10 CFR 60.122. This information also addresses the NRC's key technical issues on Structural Deformation and Seismicity.

This subsection on seismicity and seismic hazards first presents the data and interpretations that support the hazard assessment, followed by a description of the hazard assessment and its results. The subsection begins by describing the approach used to compile the historical earthquake record for the Yucca Mountain region. This is followed by a description of the seismicity within 300 km of the site, including its distribution and characteristics. Next, information on prehistoric earthquakes is presented including a description of all known and suspected Quarternary faults in the Yucca Mountain region. (It should be noted that the information presented in this section, particularly the characterization of seismic sources, does not necessarily represent the interpretations of the experts involved in the Probablistic Seismic Hazard Analyses Project (Subsection 3.10.9). The experts seismic source characterizations are summarized in Subsection 3.10.9.2.) Empirical and numerical modeling results of ground motion in the Yucca Mountain region are then discussed. Finally, the integration of these data and interpretations into probabilistic seismic hazard analyses for vibratory ground motions and fault displacement and a deterministic ground motion evaluation are described.

When referring to earthquake magnitudes, the following scales are cited and abbreviated as such: M_L Richter local; M_w moment; M_s surface wave; m_B body wave; M_c or M_d coda duration; M_I intensity-based; and M unspecified.

3.10.1 Earthquake Record

Seismic hazard evaluations rely on having a description of the temporal and spatial distribution of earthquakes (both prehistoric and historical), their magnitudes, and an evaluation of how these relate to the seismotectonic processes of the region. Seismically active regions around the world are characterized by the occurrence of many small magnitude ($M < 5$) earthquakes that typically recur much more frequently than the rare but potentially more hazardous larger magnitude events. These larger earthquakes produce potentially damaging strong ground shaking and often result in geomorphic expression at the earth's surface either through primary and secondary surface faulting or other local deformation. Variations of a power law distribution of earthquake magnitudes form the basis for estimating earthquake recurrence from the historical record of earthquake activity within a given region. The process may also involve relating the historical seismicity to the Quaternary history of surface faulting and possibly geodetic estimates of the regional strain budget to define and characterize seismic sources. The temporal and spatial occurrence of earthquakes for a given region is evaluated from two sources: the historical (instrumental and reported effects) and prehistoric (paleoseismic) earthquake records.

3.10.1.1 Prehistoric Earthquake Record

The identification and documentation of earthquakes occurring prior to historical times is possible by studying the geologic record of past events. Larger events that rupture to the surface often leave geological evidence in the form of offset strata and characteristic earthquake-related deposits. Geologic fault studies at Yucca Mountain reveal that the return times of large magnitude earthquakes are on the order of tens of thousands of years (Whitney and Taylor 1996), much longer than the 130-year period encompassed by the historical record of the Yucca Mountain region. Thus, the prehistoric earthquake history of the Yucca Mountain site spans at least the past several hundred thousand years and is particularly important for probabilistic seismic hazard assessments because it extends the record for larger magnitude events.

Geologic and geomorphologic studies of faulted deposits are the basis for identifying the occurrence of large-magnitude surface-rupturing earthquakes and evaluating their size, age, and occurrence rate. Aerial photographs were examined to locate and map evidence of Quaternary faulting, commonly seen as a fault scarp or small slope change produced by faulting of geologically young colluvial and alluvial deposits at the ground surface. Typically these deposits are Quaternary in age, which spans approximately the past 2 million years (2 Ma). At the most promising locations, trenches were excavated across the fault scarps, and the late to middle Quaternary soils and stratigraphy were mapped specifically to document the size and age of surface-faulting displacement events. The ages of critical deposits were determined where possible, using appropriate geochronologic techniques, to assess the timing of past earthquakes. Fault slip rates were estimated from the age of offset geological deposits and the amount of fault displacement. The prehistoric earthquake record has been constructed from the results of these paleoseismic and geochronologic studies, and is discussed in Subsection 3.10.6.

3.10.1.2 Historical Earthquake Record

Information on historical seismicity in the Yucca Mountain region is obtained by:

- Compiling and reassessing the historical earthquake record for the southern Great Basin and adjacent regions
- Monitoring the seismicity at Yucca Mountain and the surrounding region with both local and regional seismographic networks

For both seismic monitoring and the compilation of past activity, attempts were made to identify seismic events that were not earthquakes, such as chemical explosions associated with mining activities in the region and underground nuclear explosions at the Nevada Test Site. Aftershocks of the Nevada Test Site blasts and earthquakes induced by reservoir impounding (e.g., Lake Mead) were also identified.

Current seismicity at Yucca Mountain is monitored by the southern Great Basin Digital Seismic Network consisting of 27 high-dynamic range, three-component, telemetered digital seismographs sited within 50 km of the site. Data from the network are transmitted in near-real time to a semi-automated computer-based data acquisition system. The continuous record of ground motion from all stations is archived and can be accessed for later reprocessing and analysis. Earthquake data are processed and evaluated by seismologists to compile and publish a yearly catalog for the region that includes hypocentral locations, magnitudes, and, for some events, focal mechanisms.

In addition to the record of current seismicity, the historical record also includes events instrumentally recorded by more limited distributions of seismographs particularly prior to about 1978, and earthquakes known only through non-instrumental means. The compilation and assessment of felt reports and related damage and effects, form the primary basis for documenting the occurrence of many historical earthquakes.

3.10.2 Historical Seismicity of the Yucca Mountain Region

The region of interest for assessing probabilistic seismic hazards at Yucca Mountain is a function of earthquake magnitude and the rate of earthquake occurrence. Because earthquake ground motions attenuate with distance, the farther an earthquake occurs from Yucca Mountain, the larger it must be to contribute significantly to the hazard at the site. At a distance of 100 km from Yucca Mountain, earthquakes must reach a size on the order of M_w 8 to produce median peak horizontal ground accelerations of 0.1 g at the site (Pezzopane 1996). Similarly, if distant earthquakes are infrequent, ground motions from closer events of similar or lesser size will be more significant to the probabilistic hazard at the site. Thus, as distance from Yucca Mountain increases, seismic hazard studies focus on the longer and more active faults.

Although the focus of the hazard studies is the area within 100 km of Yucca Mountain, the historical seismicity within 300 km of Yucca Mountain is considered and described in the following subsections. This examination allows the seismicity of the Yucca Mountain vicinity to be evaluated within a broader regional context and provides an appropriate basis for the characterization of "background" earthquakes as part of the probabilistic seismic hazard analyses. The following subsection describes the historical seismicity of the Yucca Mountain region.

3.10.2.1 History of Seismographic Network Monitoring

Seismic monitoring of the southern Great Basin began in the early 1900s with isolated stations installed and operated by the University of California Berkeley and the University of Nevada Reno. Later, networks of stations were installed to monitor and study specific areas such as the Nevada Test Site, portions of the western U.S., and globally. Milestones in monitoring are presented in Table 3.10-1. Networks that are relevant to assessing seismicity of the southern Great Basin are listed in Table 3.10-2.

Seismic Monitoring Before 1979–In the early 1900s, the first seismographs were in operation in California (Richter 1958) (Figure 3.10.1a). One of the earliest seismograms was from a drum recorder operating in 1911 at University Nevada Reno, and this record was used to refine the location and magnitude for the largest historical earthquake within 100 km of Yucca Mountain, the 1916 M_L 6.1 Death Valley, California, earthquake (Gross, S. and Jaumé 1995). The development and installation of seismographs accelerated from 1932, and standardization of earthquake magnitude scales and an improvement in earthquake location techniques soon followed. The detection capability for earthquakes in the western Basin and Range Province in the early and mid-1900s improved with increasing number of seismograph stations in California (Figure 3.10-1b). A seismograph station established at Tinemaha, California in 1929 by the California Institute of Technology was the first seismic monitoring equipment installed in the southern Great Basin (Figure 3.10-1b).

From 1936 to 1940, seismographs were installed in the Lake Mead area near Las Vegas due to a number of felt earthquakes following the filling of Lake Mead (Mead and Carder 1941; Jones, A.E. 1944; Anderson, L.W. and O'Connell 1993). In 1973, A.M. Rogers and Lee (1976) deployed a microearthquake network in the Lake Mead area and recorded approximately 1,300 small magnitude earthquakes during the short deployment.

Underground nuclear testing began in 1951, and in 1961 the National Oceanic and Atmospheric Administration (formerly the U.S. Coast and Geodetic Survey) began monitoring the seismicity around the Nevada Test Site (King et al. 1971) (Figure 3.10-1c). By the late 1960s, several regional stations were operating in Nevada, and were augmented by stations in southern Utah and eastern California. A network of 18 telemetered stations was installed in 1968 in the eastern and southern Nevada Test Site. In the 1970s, Sandia and Lawrence Livermore National Laboratories upgraded and expanded the regional network coverage with the installation of several stations for the purposes of supporting the nuclear testing program.

The USGS Yucca Mountain Analog Network, 1979-1992–In 1979, the USGS established a 47-station seismograph network out to a distance of 160 km from Yucca Mountain in support of YMP efforts (Figure 3.10-2a). In 1981, six seismograph stations at Yucca Mountain were added to the network. The network was based on the analog technology of the 1970s and was the primary source of earthquake data in the southern Great Basin from 1979 through October 1995. Stations were initially configured with vertical-component 1 Hz sensors and horizontal components were added at a few sites in late 1984. The network was operated at a high gain or sensitivity in an attempt to record any microseismicity (M<2) associated with potentially active faults near Yucca Mountain. Magnitudes were usually estimated with coda duration (time of the earthquake signal) and coda decay methods for larger events, and these methods were then calibrated to M_L. By the late 1980s, some stations with horizontal components were operated at a low gain in order to preserve on-scale records and to calibrate coda-amplitude magnitudes with standard magnitude scales (Rogers, A.M., Harmsen, Meremonte 1987).

In September 1992, maintenance and operation of the analog network were transferred to the University of Nevada Reno Seismological Laboratory. All seismic data from the analog and digital stations operating in the southern Great Basin are now telemetered along a microwave network to University of Nevada Reno. Radio links are used to telemeter the signals from the remote seismograph sites to the regional microwave network. At University of Nevada Reno, earthquakes are located and M_d calculated for all events, and M_L for many events greater than M_d 2.

Three-Component Digital Network Near Yucca Mountain, 1995-Present–A high dynamic range, three-component digitally telemetered network, in operation since 1995, is currently the primary seismic network at the Yucca Mountain site. The digital network only spans a radius of 50 km out from Yucca Mountain (Figure 3.10-2b) in contrast to the 160 km-radius area covered by the analog network. At the time of this report, 24 stations of the planned 28-station network are in operation. The digital network has enabled a decrease in the magnitude detection threshold in the Yucca Mountain block from about M_L 0.5 to about M_L -1.0 during times of low cultural noise. The regional detection threshold is approximately M_L 1.0, a decrease of 0.5 to 1.0 magnitudes units from the earlier analog network capabilities. Earthquake location accuracy has improved due to the recording of horizontal component S-wave arrivals.

Other Regional Seismic Networks–Other regional seismic networks on the edges of the southern Great Basin contribute data for earthquake monitoring in the Yucca Mountain region. To the north, the University of Nevada Reno operates their statewide regional network which monitors seismicity in northern and central Nevada and areas along the state border with California such as Mammoth Lakes. The University of Utah operates a number of stations in southern Utah and the California Institute of Technology operates stations in the southern Owens Valley and Ridgecrest, California, areas. Northern Arizona University operates a small network of five analog telemetered stations around Flagstaff, Arizona.

3.10.2.2 Historical Seismicity Catalog for Yucca Mountain

As part of the Probabilistic Seismic Hazard Analyses Project, a catalog of historical and instrumental earthquakes was compiled for the region within 300 km of the potential repository site at Yucca Mountain (USGS 1998). This region includes all of the relevant and potentially relevant seismic sources (Pezzopane, Bufe et al. 1996; McKague et al. 1996). The resulting combined catalog contains 271,223 earthquakes of approximately M_L 1 and greater from 1868 to 1996. All known magnitudes are listed in the catalog. Figure 3.10-3 shows events of M_w >3.5 or maximum Modified Mercalli (MM) intensity greater than III in the catalog. The earthquake catalog for Yucca Mountain was compiled from several sources including the catalogs of Meremonte and Rogers (1987), the Decade of North American Geology, University of Nevada Reno, University of California Berkeley, California Institute of Technology, and USGS for eastern California and the Great Basin (Table 3.10-3) (USGS 1998).

Catalog completeness has improved significantly with time, but the catalog is still considered to be complete for historical events of M_w 5.5 and larger for the 100-km radius area around Yucca Mountain (Rogers, A.M., Harmsen, Corbett et al. 1991). Estimated periods for which the Yucca Mountain catalog is complete for the southern Great Basin as a function of magnitude interval are provided in Table 3.10-4.

The accuracy of information in the historical catalog is affected by several variables especially the great variability in seismic network coverage over time. The spatial distribution of seismicity in the 300-km catalog is a function of the density of seismographic network coverage in a particular region over time and is somewhat an artifact of the more thoroughly represented aftershock sequences of the modern period. For example, a significant portion of the catalog is derived from a recent series of moderate-sized earthquakes, aftershock sequences, and volcanic swarm activity in the Mammoth Lakes, California area. This modern sequence began in 1978 and has continued to the present. Although these events figure prominently in terms of the number of earthquakes in the catalog, they represent an insignificant portion of the total moment release along the western Basin and Range in the past two decades. The total deformation or strain release represented by this sequence is minor in comparison to that of the large magnitude ($M_w > 6.5$) historical earthquakes of the Central Nevada Seismic Belt (Wallace, R.E. 1977, 1984). For example, the Cedar Mountain earthquake of 1932 occurred prior to complete seismic instrumental coverage, and therefore only the larger aftershocks were recorded (therefore relatively few) despite its large energy release.

Earthquake Magnitude Scale–Since the Yucca Mountain catalog was compiled from several source catalogs, each using a variety of different magnitude scales that also changed with time, a uniform magnitude scale was required in order to compute the earthquake recurrence for the region. In addition, it was necessary to assign magnitudes to historical earthquakes that occurred prior to calibrated seismographic instrumentation. Such magnitude estimates are usually based on the felt area or the maximum Modified Mercalli intensity. This is particularly problematic in the Basin and Range Province where settlement and population growth have been erratic and sparse due to the boom and bust nature of mining operations and the rugged environment. For each earthquake within the catalog, a M_w was estimated from the best available magnitude. Published relationships between seismic moment (M_o) and M_w and M_L were used when available. A detailed description can be found in USGS (1998).

Identification of Nevada Test Site Explosions and Induced Seismicity–Nevada Test Site explosions and their induced earthquake aftershocks and reservoir-induced seismicity events at Lake Mead were identified in the earthquake catalog. Nuclear explosions were identified and flagged in the catalog using a list provided by D. Oppenheimer (USGS, written communication, to I. Wong, Woodward-Clyde Federal Services, August 1996), information provided by T. Hauk of Lawrence Livermore National Laboratory, and with a listing of the Announced United States Nuclear Tests (DOE 1994). Nevada Test Site aftershocks were identified and flagged using a space-time window. The Lake Mead area induced seismicity was identified but not removed from the catalog (Anderson, L.W. and O'Connell 1993; Rogers, A.M. and Lee 1976). It is unlikely that earthquakes in the Lake Mead area will contribute significantly to ground motion hazard at the Yucca Mountain site.

3.10.2.3 Significant Earthquakes and Earthquake Sequences

The historical and instrumental earthquake record within 300 km of Yucca Mountain (Figure 3.10-3) includes the reported earthquakes of the southern Basin and Range Province, and portions of the southern Sierra Nevada and Mojave Desert in California. The catalog contains all reported felt and instrumentally located earthquakes from the late 1800s to the present, including a few magnitude (M_w >5) that are located slightly outside of the 300 km radius region, as discussed below. These are included because they are associated with surface ruptures that form important historical analogues for assessing fault displacement hazards at the potential repository site (Pezzopane and Dawson 1996).

Several M_w >5.5 events are listed in the earthquake catalog which are located within 100 km of Yucca Mountain. The earliest entry is the 1916 M_L 6.1 (M_s 5.9) Death Valley event (Gross, S. and Jaumé 1995) (Figures 3.10-3 and 3.10-4). Of earthquakes greater than M_w 5.5 in the 100-km compilation, only five events occurred outside of the areas of underground nuclear explosions and can be unequivocally designated as tectonic in origin. All of these tectonic M_w >5.5 earthquakes, except the 1992 Little Skull Mountain earthquake are near the Death Valley-Furnace Creek fault zone, and all occurred prior to 1966 (Figure 3.10-4). Many M_w >4 earthquakes within 100 km also occur near the Furnace Creek fault system, the most active tectonic feature in this region.

The significant historical seismicity in the 300-km Yucca Mountain region is described below and illustrated in Figures 3.10-3 to 3.10-5.

1872 Owens Valley, California, Earthquake–Possibly the largest historical earthquake in the Basin and Range Province, M_w 7.8, occurred in 1872 along the Owens Valley fault zone in Eastern California. Numerous aftershocks over M_I 6 (based on felt reports) followed the earthquake but there is no instrumental record of the sequence. The magnitude was estimated from felt area and surface rupture dimensions. There has been limited seismicity in much of the central Owens Valley since.

One of the most recent and detailed investigations of the 1872 earthquake rupture was conducted by Beanland and Clark (1994). The 1872 earthquake produced a 100 ± 10-km long zone of surface faulting along the entire length of the Owens Valley, from southern Owens Lake to north of Big Pine, California. Vittori et al. (1993) describe additional faulting and deformation related to the 1872 event within and south of Owens Lake. Other reported geologic effects included: fissures and cracking as far north as Bishop, California (Stover and Coffman 1993); liquefaction, especially in the area of Owens Lake; and rockfalls and landslides in Yosemite Valley and as far away as the White Mountains (Beaty and dePolo 1989).

1916 Death Valley Earthquake–The 1916 M_L 6.1 Death Valley is the largest earthquake to occur within 100 km of Yucca Mountain. Townley and Allen (1939) describe it as the strongest earthquake of the year based on its seismograms; however, due to its remote location, no damage was reported and it was only felt at intensity Modified Mercalli IV at Rhyolite. S. Gross and Jaumé (1995) relocated the earthquake by comparing waveforms recorded during the Little Skull Mountain earthquake with a heliocorder recording of the 1916 event from the Reno seismograph station. The revised location suggests that the 1916 earthquake was in the Death Valley fault zone. They suggested a revised magnitude of M_s 5.9 based on amplitude of the signal on the 1916 heliocorder record.

The 1932 Cedar Mountain Earthquakes–The 1932 M_L 7.2 Cedar Mountain and the 1954 M_w 7.1 Fairview Peak and M_w 6.8 Dixie Valley earthquakes occurred within the Central Nevada Seismic Belt northwest of Yucca Mountain (Slemmons et al. 1965; Caskey et al. 1996; Rogers, A.M., Harmsen et al. 1991) (Figure 3.10-5). Teleseismic waveform data models show that the 1932 Cedar Mountains earthquake was a multiple source, consisting of at least two subevents of M_w 6.8 and M_w 6.6 (Doser 1988). The extent of surface faulting indicates a M_L 7.2 for the earthquake (Slemmons et al. 1965), but the distribution of faulting and waveform data are consistent with a multiple source interpretation (Caskey et al. 1996).

The Cedar Mountain earthquake produced widely distributed surface faulting. Gianella and Callaghan (1934) recognized a zone of rupture approximately 60 km in length by 14 km in width. dePolo et al. (1994) recognized additional ruptures at the southern end of the faulted area which increased the rupture length to as much as 80 km and the width to as much as 17 km. Individual rupture zones are typically several hundreds of meters in length, and the longest extend for up to 16 km. Surface ruptures such as left-stepping *en echelon* fissures and fractures, mole tracks, and swell and depression morphology collectively indicate lateral slip. Right-lateral displacements range from 0.5 to 1.5 m, and the maximum single-trace right-lateral displacement was 2.0 $\pm$ 0.5 m (dePolo et al. 1994). Many of the ruptures associated with the Cedar Mountain event occurred along identifiable pre-existing scarps. Geologic effects induced by the event include liquefaction, changes in spring and well flows, and cracking in alluvium in the epicentral area, and landslides in the adjacent ranges. An analysis of the rupture pattern and tabulation of the geological effects can be found in Pezzopane and Dawson (1996).

1934 Excelsior Mountains Earthquake–The 1934 M_L 6.3 (M_w 6.1) Excelsior Mountains, Nevada earthquake took place in the Mono Lake-Excelsior Mountains region of the west-central Walker Lane in Nevada and eastern California, a source of continuing seismicity (Figure 3.10-3). The region is characterized by scattered, persistent microseismicity and northeast-striking, left-lateral and left-oblique-slip faults (Stewart 1980; dePolo et al. 1993).

The Excelsior Mountains event occurred on a northeast-striking fault and produced left-oblique fault ruptures (Callaghan and Gianella 1935; Carr, W.J. 1974; dePolo et al. 1993). The poorly-constrained focal mechanism and depth of this event show a predominantly normal fault source with a shallow to moderate dipping fault plane (8° to 40°) with a subordinate left-oblique-slip component (Doser 1988; Doser and Smith 1989). Left-lateral slip is consistent with the sense of displacement on faults north of the Excelsior Mountains (Garside 1982).

The 1934 Excelsior Mountains earthquake produced a 1.5- to 1.7-km long scarp along a pre-existing bedrock fault in the Excelsior Mountains. The north side of the fault is downdropped relative to the south side, and forms an uphill-facing scarp. The ruptures follow an older fault trace across the ridges on the south side of Excelsior Mountain, but along part of its length, the 1934 earthquake may have ruptured previously unfaulted rock. Open *en echelon* fissures with scarp heights ranging from 15.3 cm to 46 cm indicate possible left-lateral movement along the fault. Reported geologic effects include numerous rockfalls, fissures that formed in alluvium, and changes in spring flows in nearby marshes.

1947 Manix, California, Earthquake–The M_w 6.5 Manix earthquake produced faulting along a 4-km section of the Manix fault zone (Buwalda and Richter 1948) (Figure 3.10-3). The left-lateral displacements of up to 5 cm on a northeast-striking fault contrast with the many northwest-striking, right-lateral faults elsewhere in the Mojave Desert (Dokka and Travis 1990). Other reported geologic effects include cracking along the banks of the Mojave River and a report of liquefaction near the Mojave River (Richter 1947; Stover and Coffman 1993).

1954 Fairview Peak Earthquake–The M_w 7.1 Fairview Peak and the M_w 6.8 Dixie Valley earthquakes occurred in December of 1954 within a period of 6 minutes. The southern portion of the aftershock zone of the Fairview Peak event lies at the edge of the 300-km region and minor seismicity continues to occur there (Figure 3.10-3). The Fairview Peak earthquake probable initiated at the northern end of the 1932 Cedar Mountains rupture zone. The focal mechanism determined by Doser (1986) and Doser and Smith (1989) has a nodal plane that aligns with the overall strike of the surface rupture, dips 60° ± 5°E, and the slip vector is predominantly right-lateral strike-slip.

The Fairview Peak earthquake ruptured several faults along a discontinuous 64 km zone (Caskey et al. 1996). The longest of the individual faults is the Fairview fault, which is approximately 32 km long. The sense of displacement is normal-right-oblique, with a maximum vertical displacement of 380 cm and maximum right-lateral displacement of 290 cm along the Fairview fault, resulting in a net surface displacement of 460 cm. Both the Phillips Wash and Fairview faults have displacements that are east-side down, whereas the West Gate, Gold King, and Louderback faults exhibit west-side down displacements. Normal/right-oblique-slip occurs along portions of the Louderback Mountains and West Gate faults, whereas the Gold King fault shows dominantly normal slip, and the Phillips Wash fault exhibits normal/left-oblique-slip. The average surface displacement over the entire zone is estimated to be 100 cm. The normal-oblique-slip observed for this event may represent a transition zone between right-lateral displacements in the south (i.e., 1872 Owens Valley and 1932 Cedar Mountain earthquakes) and the normal faulting in the north (i.e., 1915 Pleasant Valley and 1954 Dixie Valley events). The slip vector of the Fairview Peak event differs from the mostly normal slip recorded in earlier Quaternary deposits.

1954 Dixie Valley Earthquake–The 1954 Dixie Valley earthquake ruptured the northern portion of the 100-km long zone of surface faulting produced by the Fairview Peak-Dixie Valley earthquake sequence (Figure 3.10-3). Surface faulting from the Dixie Valley earthquake formed a 46-km long zone, which at the southern end lies parallel to the surface faulting from the Fairview Peak earthquake along the opposite side of the valley. Displacements related to the Dixie Valley earthquake are normal, down to the east, with a maximum vertical displacement of 280 cm and an average surface displacement of 92 cm. Caskey et al. (1996) determined that the fault dips at relatively low angles of 25° to 35°E. near the surface, but the nodal plane of the focal mechanism of Doser (1986) indicate the fault dips 60° ± 20°E at seismogenic depths. Reported geologic effects include spring flow changes, water fountains, and liquefaction, landslides, rockfalls, mudflows, and fractures in alluvium (Caskey et al. 1996; Slemmons 1957).

1975 Galway Lake, California, Earthquake–The Galway Lake earthquake (Figure 3.10-3) produced surface faulting along a 6.8-km long section of the Galway Lake fault zone (Hill, R.L. and Beeby 1977). Surface ruptures are expressed primarily as left-stepping *en echelon* fractures, shattered ground, and mole tracks. The surface rupture zones range in width from 1 to 100 m. Displacements were mostly right-lateral, generally between 0.2 and 0.5 cm with a maximum single-trace displacement of 1.5 cm. Rare vertical separations between 0.5 and 1 cm lack a consistent sense of displacement. Reported geologic effects include mass downslope movement of rocks in the epicentral area.

1979 Homestead Valley, California, Earthquake–The Homestead Valley earthquake (Figure 3.10-3) produced a 3.25-km long zone of surface ruptures, discontinuous left-stepping *en echelon* cracks, and mole tracks (Hill, R.L., Treiman et al. 1980). Displacements were mostly right-lateral, with a subordinate dip-slip displacement, and down to the east. A maximum right-lateral single-trace displacement of 7.5 cm was observed along the northern half of the primary rupture zone, and a maximum vertical displacement of 4 cm was observed in the southern part of the rupture zone. Other reported effects include rockfalls and slumping along stream channels.

1980 Mammoth Lakes Earthquake Sequence–The 1980 sequence of four M_L >6 earthquakes produced surface faulting along small faults in the Long Valley caldera and along the Hilton Creek fault, a Sierra Nevada frontal fault system (Clark et al. 1982; Taylor, G.C. and Bryant 1980; Hill, D.P., Wallace et al. 1985) (Figure 3.10-3). The zone of surface faulting stretches for 16 km from near McGee Creek on the Hilton Creek fault, across the caldera margin and into the caldera. Normal displacements on ruptures in the Long Valley caldera form a graben with west- and east-facing scarps. Vertical displacements on faults within the caldera are generally less than 5 cm, and many of the surface ruptures are only ground surface cracks. Vertical to east-side-down displacements of 20 cm occurred on the Hilton Creek fault but may have been enhanced by slumping. Many ruptures occurred on surface fault traces, although there is controversy as to whether the surface faulting was a direct manifestation of seismogenic faulting at depth. Slip on the Hilton Creek fault may have been triggered by other earthquakes in the sequence or these features may only represent surficial ground failure rather than faulting. Reported geologic effects include widespread rockfalls and landslides, lurch cracks, and liquefaction in the Mammoth Lakes region (McJunkin and Bedrossian 1980). Boulders as large as 7.6m x 6m x 4.5m were dislodged, and the majority of earthquake-related injuries were caused by the rockfalls (Bryant 1980).

1981 Mammoth Lakes Earthquake Sequence–A 1981 swarm of earthquakes culminated with a M_w 5.6 (M_s 5.8) event that produced small surface displacements along faults that ruptured during the 1980 Mammoth Lakes earthquake sequence (Figure 3.10-3). Extensional cracks were observed at three places and the maximum vertical displacement was 10 to 20 mm. Geologic effects reported include liquefaction, rockfalls, and changes in geyser and spring behavior in the Mammoth Lakes region (W. Bryant, California Division of Mines and Geology, written communication to S.K. Pezzopane, USGS, 1995).

1986 Chalfant Valley Earthquake Sequence–The Chalfant Valley sequence occurred near the White Mountains beneath the Volcanic Tablelands, 15 km east of the Long Valley caldera (Smith, K.D. and Priestley 1988; dePolo and Ramelli 1987; Lienkaemper et al. 1987) (Figure 3.10-3). The sequence is associated with three distinct faulting events (M_w 6.3, M_w 5.8 and M_w 5.5) that occurred over a period of 11 days. All three of these earthquakes had predominantly strike-slip motion. The mainshock (M_w 6.3) occurred in the hanging wall block of the White Mountains fault zone, and was the largest earthquake in the Central Nevada Seismic Belt since the 1954 Fairview Peak-Dixie Valley earthquakes.

K.D. Smith and Priestley (1997) performed a detailed relocation of the earthquakes and determined the source parameters of the primary events. Static stress drops of 87, 26, and 23 bars, respectively, for each of the three primary events (M_w 5.8, M_w 6.3, and M_w 5.5) were determined from the teleseismic moment and from rupture areas estimated from the aftershock activity. The primary characteristic of the sequence is the conjugate fault geometry with left-lateral slip for the initial M_w 5.8 event, followed 24 hours later by right-lateral slip during the mainshock (Smith, K.D. and Priestley 1997; Savage, J.C. and Gross 1995). Mainshock rupture extended for 12 to 15 km on a northwest-striking, southwest-dipping (55°) fault plane. Surface fracturing in the Volcanic Tablelands area was confined to the hanging wall of the mainshock fault plane. A peak horizontal acceleration of about 0.46 g was recorded at a sediment site on an alluvial fan about 12 km northeast of the mainshock epicenter.

The Chalfant sequence produced surface ruptures along the White Mountains fault zone and within the Tableland fault system west of the White Mountains. Surface ruptures along the White Mountains fault zone stretched for 12 ± 2 km, whereas cracks and open fissures in loose sand along pre-existing faults in the Tableland fault system are widely scattered, discontinuous, and occurred in a broad zone as much as 26 km in length. Surface ruptures along the White Mountains fault zone have right-lateral displacements with a maximum single-trace displacement of 5 cm. The total right-lateral displacement across the zone in the same area is about 11 cm. Although extensive fracturing occurred at the surface along mapped Holocene faults in the Volcanic Tablelands area, it is uncertain whether any of this is primary rupture. Lienkaemper et al. (1987) concluded that faulting along the White Mountains zone was associated with the mainshock, whereas dePolo and Ramelli (1987) concluded that surface faulting was probably sympathetic slip. Reported effects include small landslides and numerous small rockfalls that occurred within the epicentral area (Stover and Coffman 1993).

1992 Landers, California, Earthquake–The June 28, 1992 Landers earthquake produced 85 km of surface ruptures distributed over five major faults and several minor faults as far as 60 km from the primary rupture zone (Sieh et al. 1993; Hart, E.A. et al. 1993) (Figure 3.10-3). Rupture occurred over portions of five principle faults (Johnson Valley, Landers, Homestead Valley, Emerson, and Camp Rock) connected by a series of right-steps. Displacements are mostly right-lateral, with a maximum displacement of 610 cm. The maximum vertical slip was 100 cm or more, and left-lateral displacements of up to 50 cm occurred mostly along east-trending faults. Geologic effects include widespread rockfalls and ground fissuring (Barrows 1993).

Dreger (1994) modeled the mainshock rupture at long periods and interpreted the source to consist of two subevents of seismic moments $2x10^{26}$ and $6x10^{26}$ dyne-cm. Rupture directivity effects were one of the more important aspects of the Landers event, and most likely contributed to the triggering of seismicity including the Little Skull Mountain earthquake to the north (Valesco et al. 1994; Anderson, J.G., Brune et al. 1994).

1993 Eureka Valley, California, Earthquake Sequence–The 1993 M_w 6.1 Eureka Valley earthquake produced extensive cracking and minor surface ruptures on faults of the Eureka Valley (G. Peltzer, written communication to S.K. Pezzopane, U.S. Geological Survey, 1995) (Figure 3.10-3). Satellite interferometry data analyzed by Peltzer and Rosen (1995) showed a maximum displacement of 3 cm in the southeast part of the epicentral region. Surface ruptures along west-dipping faults were mostly discontinuous cracks that extended 4 to 5 km, with vertical displacement of up to 2 cm over about 100 m observed by S. Hecker (U.S. Geological Survey) and S.K. Pezzopane (U.S. Geological Survey) in verbal communication, 1993).

The Eureka Valley earthquake occurred on a northeast-striking (N10°E), west-dipping (43° ± 5°W) normal fault. The Eureka Valley mainshock hypocenter was constrained to a 11.8-km depth (K. Smith (University of Nevada, Reno), verbal communication with S.K. Pezzopane (U.S. Geological Survey), 1996), nearly identical to the Little Skull Mountain earthquake. The aftershock zone for the Eureka Valley earthquake extended approximately 20 km, whereas the Little Skull Mountain aftershock zone extended only about 10 km, suggesting either a low stress drop for the mainshock or initiation of activity on faults near the source area (K. Smith (University of Nevada, Reno), verbal communication with S.K. Pezzopane (U.S. Geological Survey), 1996).

3.10.2.4 Areas of Significant Seismicity

In the following, we discuss specific areas of significant seismicity which occur within the 300-km Yucca Mountain region. The areas are shown in Figures 3.10-4 and 3.10-5.

Coso Volcanic Field and Ridgecrest, California, Area–The Ridgecrest, California, area and the Coso volcanic field north of Ridgecrest have been the locations for a series of M_L 5 earthquakes and extended aftershock sequences beginning in 1994 and ongoing small-magnitude seismicity in the Coso volcanic field. Earthquake sequences in the Ridgecrest area occurred in 1938, 1961, and 1982 (Roquemore et al. 1996; Hauksson et al. 1995). The 1982 sequence produced cracking along the Little Lake fault zone, which lies east of the Airport Lake fault zone.

A M_d 5.3 earthquake of August 17, 1995, produced a 1-km long zone of discontinuous surface cracking along a fault trace that ruptured again in a M_d 5.4 event on September 20, 1995 (Figure 3.10-3). The September 20, 1995 earthquake produced surface faulting along 2.5-km of the Airport Lake fault zone, expressed mostly as left-stepping *en echelon* fractures and scarps with a maximum vertical displacement of 1 cm and a maximum right-lateral displacement of 0.8 cm.

Garlock Fault, Southern Sierra Nevada, Southeastern California –The trace of the Garlock fault in southeastern California is outlined by concentrated zones of seismicity and microseismicity (Figure 3.10-5). It includes the northeastern extent of mainshock rupture and aftershock activity of the 1952 M_w 7.5 Kern County, California, earthquake which was the result of rupture on the white Wolf fault (Ellsworth 1990) (Figure 3.10-3). The Kern County earthquake, however, triggered slip on sections of the Garlock fault, and nearby moderate to large magnitude events are sometimes associated with increased levels of seismicity on creeping segments of the fault.

Mammoth Lakes-Chalfant Valley-Bishop, California–The Mammoth Lakes, California volcanic area, within and adjacent to the Long Valley caldera, has been the location of a series (1940-present) of moderate sized (M_L 5 to 6) earthquakes, aftershock sequences, and volcanic related earthquake swarms (Hill, D.P., Wallace et al. 1985) (Subsection 3.10.2.3) (Figure 3.10-3). Several middle 0Pleistocene and younger eruptions since the late Pleistocene (~ 750 ka) of the Long Valley caldera shaped the physiography of the Mammoth Lakes-Chalfant Valley-Bishop, California area (Bailey and Koeppen 1977). Foreshock-mainshock-aftershock sequences (mainshocks M_L >6) in the caldera and volcanic earthquake swarms in and adjacent to the caldera have numbered in the tens of thousands from 1980 to present (Hill, D.P., Ellsworth et al. 1990).

A recent series of moderate-sized earthquakes began in October 1978 and culminated with four M_L 6+ earthquakes during a 48 hour period from May 25 to May 27, 1980 (Cramer and Toppozada 1980; Lide and Ryall 1985) (Subsection 3.10.2.3). The activity continued with the 1984 M_w 5.8 Round Valley and 1986 M_w 6.3 Chalfant earthquakes (Priestley et al. 1988) (Subsection 3.10.2.3). Swarm-like earthquake activity and occasional tremor activity around the caldera was accompanied by inflation of a resurgent dome (Savage and Clark, J.C. 1982; Ryall and Ryall 1983; Aki 1984b; Cockerham and Pitt 1984; Denlinger and Bailey 1984; Rundle and Whitcomb 1984; Savage, J.C. and Cockerham 1984; Hill, D.P., Ellsworth et al. 1990).

An earthquake swarm under Mammoth Mountain near the town of Mammoth Lakes in 1989 included a number of deep, low frequency earthquakes that may have been associated with magma movement (Julian 1983; Julian and Sipken 1985; Pitt and Hill 1994; Wallace, R.E. 1984). The recent series of moderate-sized earthquakes show strike-slip motion, but dominantly normal offsets occur on Holocene faults that bound the Sierra Nevada and White Mountains.

Mojave Desert–The Mojave Desert, approximately 150 to 200-km south of Yucca Mountain, contains several zones of persistent seismicity (Figure 3.10-5). The 1992 M_w 7.3 Landers earthquake was the largest surface-faulting event observed in the region (Subsection 3.10.2.3). The Landers earthquake occurred in the southern Mojave Desert, where broad zones of right-lateral and minor normal faults splay northward from the San Andreas, distributing 8 to 10 mm/yr of right-lateral motion along the Eastern California Shear Zone (Savage et al. 1990). In comparison to the Basin and Range Province, seismicity in the Mojave Desert region is shallower with more surface faulting events and predominantly strike-slip motion (Ellsworth 1990). Other notable events previously described include the 1947 Manix, 1975 Galway Lake, and 1979 Homestead Valley earthquakes (Subsection 3.10.2.3 and Figure 3.10-3).

Mono Lake-Excelsior Mountains Area–Faults in the Excelsior-Mono domain of Stewart (1988), could be analogous to the structural domain of the northeast-striking Rock Valley, Wahmonie, Cane Springs, and Mine Mountain fault systems in the south-central Nevada Test Site area. These domains disrupt the north-northwest-striking grain of the Walker Lane. Faults near Excelsior Mountains and in the Nevada Test Site region are zones of persistent seismicity (Figure 3.10-5) and may represent structural transition zones fundamental to the processes of strain accommodation within the Walker Lane Belt.

Nevada-Utah-Arizona Borders Area–The 1966 M_L 5.5 to 6.1 Clover Mountains earthquake occurred near the Nevada-Utah-Arizona borders and was marked by an extended aftershock sequence (Boucher et al. 1967; Beck, P. 1970) (Figure 3.10-3). T.C. Wallace et al. (1983) determined a nearly pure strike-slip mechanism for the mainshock from regional records, consistent with the short-period mechanism of Boucher et al. (1967). No surface rupture was reported. E.R. Anderson (USGS, verbal communication, to K. Smith, University of Nevada, Reno, 1995) investigated the area and noted that the local structural grain was characterized by east-west-striking faults which are not consistent with the right-lateral strike-slip mechanism for the mainshock.

The 1902 M_I 6.0 Pine Valley (Smith, R.B. and Arabasz 1991) and 1992 M_L 5.9 St. George (J. Pechmann, University of Utah, verbal communication to S.K. Pezzopane, USGS, 1997) earthquakes occurred east of the Clover Mountain sequence in Utah (Figure 3.10-3). Only one aftershock larger than M 2.5 was recorded for the St. George sequence. This is an area of generally low seismicity and the moderate and larger sized earthquakes are associated with the Colorado Plateau-Basin and Range transition zone.

Northern Amargosa Valley–Sarcobatus Flat–Seismicity in the Northern Amargosa Valley is distributed in the vicinity of Beatty and the Bullfrog Hills, some of which may be related to mining (Vortman 1991) (Figure 3.10-4). In Sarcobatus Flat, earthquakes have occurred in four clusters since the beginning of instrumental monitoring (Rogers, A.M., Harmsen, Carr et al. 1983; Rogers, A.M., Harmsen, Meremonte 1987). These clusters, which lie 10 to 20-km apart, trend north along the length of the valley. Focal mechanisms for the three southern clusters suggest right-lateral slip along northeast-trending structures. These mechanisms are anomalous with respect to general trends observed in the southern Great Basin (Figure 3.10-8), and represent local variability in the tectonic stress field. The fourth cluster, in the northern part of the valley shows normal faulting on a northeast-trending fault (Rogers, A.M., Harmsen, Meremonte 1987). These mechanisms are anomalous with respect to the general trends observed in the southern Great Basin (Figure 3.10-8) and may represent local variability in the tectonic stress field.

Northern Death Valley Area–Seismicity associated with the Furnace Creek fault zone in Northern Death Valley is distributed over a much larger area than the mapped surface traces of the faults (Figures 3.10-4 and 3.10-5). Epicenters extend northeast from the northern end of the Furnace Creek fault through the Gold Mountain-Mount Dunfee region. The largest recent event in this area was a M_L 4 at Gold Mountain. The focal mechanism for this event shows left-lateral slip. In 1983, a northeast-trending cluster of events occurred near Mount Dunfee. A composite focal mechanism for these earthquakes suggests left-oblique normal faulting on a northeast-striking plane (Rogers, A.M., Harmsen, Meremonte 1987).

Northern Nevada Test Site–The northern region of Nevada Test Site includes the Timber Mountain caldera, Pahute Mesa, Rainer Mesa, and Yucca Flat. These areas experienced considerable earthquake activity associated with nuclear testing, in contrast to seismicity that is tectonic in origin in the southern part of the Nevada Test Site (Figure 3.10-4). Discriminating naturally-occurring earthquake activity from events associated with underground nuclear explosions is problematic (Subsection .10.5.1). The relative number of artificial and induced earthquakes in the testing areas suggests that the natural seismicity of the region is close to the background activity of the southern Basin and Range Province (Vortman 1991). In 1979 and 1983, several swarms of microearthquakes occurred in the region, apparently unrelated to the underground nuclear explosion. Two sequences occurred during the period of active testing in the vicinity of Dome Mountain and Thirsty Canyon (Rogers, A.M., Harmsen, Carr 1981; Rogers, A.M., Harmsen, Meremonte 1987). Focal mechanisms indicate mainly right-lateral strike-slip faulting on north-trending structures and normal faulting on northeast-trending structures.

Pahranagat Shear Zone Area–The Pahranagat shear zone, located between the 1966 Clover Mountains sequence area and the northern Nevada Test Site (Figure 3.10-5), has been a constant source of M 3 to 4 earthquakes over the recent period of seismic monitoring. This level of seismicity appears to be characteristic of active northeast-striking faults or structural zones within the Basin and Range Province. High-angle, strike-slip focal mechanisms are consistently reported in this region. The Clover Mountains, St. George, and Pine Valley earthquakes and the Pahranagat shear zone activity comprise most of the events located within the eastern half of the Southern Nevada Seismic Belt of the southern Great Basin (Rogers, A.M., Harmsen, Corbett et al. 1991).

3.10.3 General Features of the Instrumental Seismicity in the Southern Great Basin

The more recent instrumentally-recorded seismicity in the southern Great Basin is generally expressed in clusters of earthquakes distributed in an east-west belt between latitude 36 and 38°N, referred to here as the Southern Nevada Seismic Belt (Figure 3.10-5). The earthquake clusters are diffusely distributed around mapped faults, covering areas larger than the surface projections of the rupture. Most events are not readily associated with the surface traces of known faults. These clusters may align with local structural grain, and composite and single event focal mechanisms (see below) suggest that the P- and T-axes planes correlate with regional stress directions inferred from other data.

The comparison of the energy release maps for the pre-1978 and post-1978 periods show that, averaged over decades, the seismically active zones appear to be releasing moment at about the same rates. Rogers, A.M., Harmsen, Corbett et al. (1991) show that the historic rate of occurrence of the largest earthquakes ($M_w > 7$) in the Central Nevada Seismic Belt west and northwest of Yucca Mountain is larger by an order of magnitude than is indicated by geologic evidence. R.E. Wallace (1987) noted evidence in the western Basin and Range Province of active periods lasting hundreds to thousands of years are followed by quiescent periods of 10,000 to 30,000 years. On a larger distance but shorter time scale, Bufe and Toppozada (1981) described a period of relative quiescence encompassing both California and western Nevada and extending from 1960 to 1980. The current active period for $M < 6$ also encompasses the same large region, as characterized by Bufe (1992).

3.10.3.1 Seismogenic Depths

Earthquake hypocenters in the southern Great Basin are predominantly between 5 and 15-km depth as illustrated in Figure 3.10-6. The histogram is dominated by the Little Skull Mountain sequence which now comprises 20 to 30 percent of the seismicity catalog for the southern Great Basin in the Nevada Test Site area. The Little Skull Mountain hypocenters were mainly between 5 and 12-km depth, and the distribution peaks near the lower portion of the seismogenic zone. The sequence was well recorded and depth constraints were very good. A.M. Rogers, Harmsen, Meremonte (1987) showed that the seismicity in the southern Great Basin is distributed between about 2 and 15 km, with less at about 4 km. The 1993 Rock Valley sequence occurred at depths less than 3 km, as determined using near-source (less than one focal depth) three-component digital recorders in the immediate epicentral area (Shields et al. 1995).

Rogers, A.M., Harmsen, Carr et al. (1983) showed that most of the seismic energy released in the southern Great Basin occurs at depths less than 12 km, but this study represents a very short period of time (1978 to 1987) where there was minimal moment release. Several larger magnitude earthquakes have been reported to nucleate deeper than 15 km, although these events occurred early in the instrumental record and the hypocenters may not be well constrained (Doser and Smith 1989). Nucleation depths ranging from 10 to 20 km have been determined from waveform modeling for several major mainshock earthquakes in the Basin and Range Province, including the 1954 Dixie Valley, Nevada, earthquake, the 1959 Hebgen Lake, Montana earthquake, and the 1983 Borah Peak, Idaho earthquake, all of which are associated with surface faulting on range-bounding normal faults (Doser 1986, 1988; Doser and Smith 1989). Critical to the estimation of maximum moment from a particular structure is whether rupture can propagate to these depths, which would not necessarily correspond to hypocentral depth.

Earthquakes in the southern Great Basin also tend to distribute in vertical tubular-shaped clusters rather than along planar fault zones. A.M. Rogers, Harmsen, Meremonte (1987) interpreted this distribution of hypocenters to be activity at the intersections of faults. These vertically distributed localized clusters of seismicity locate between 10 and 15 km depth.

3.10.3.2 Focal Mechanisms

Focal mechanisms of earthquakes of M_L >3.5 within the southern Great Basin from 1987 to 1997 are shown in Figure 3.10-7. These mechanisms plus others and hypocentral alignments indicate that right-lateral slip on northerly trending faults is today the predominant mode of stress release near the site. However, faulting on east-northeast (left-lateral) and northeast (normal) faults has been observed as well as oblique slip on structures of intermediate orientation with the appropriate dip angles (Figure 3.10-7). Geologic evidence of fault movement at Yucca Mountain reflects multiple tectonic episodes of faulting over millions of years and under the influence of different stress regimes (see also Subsections 3.3.1.7 and 3.6.2.3.7), and thus is not always consistent with these contemporary observations. The principal extensional (minimum compression) stress axes inferred from earthquake mechanisms trends northwest and plunges approximately horizontal (Figure 3.10-8). The principal compressional (maximum compression) stress axes from earthquake mechanisms are concentrated along a belt (girdle) that sweeps from vertical (normal faulting) to northeast and horizontal (strike-slip faulting) (Figure 3.10-8). Thus regional stress orientations indicate north-south and east-west orientations for high-angle fault planes with right-lateral slip on the north-striking and left-lateral slip on the east-west striking surfaces. Normal and oblique slip are indicated on fault surfaces with orientations intermediate to these directions. The style of faulting determined from the focal mechanisms is not a function of depth.

Harmsen and Rogers (1986) analyzed the stress field from a set of regional earthquake focal mechanisms. The presence of both strike-slip and dip-slip mechanisms in particular localities was interpreted to indicate an axially symmetric stress field, in which the intermediate and maximum compressive stresses are nearly equal (Harmsen and Rogers 1986). They suggested that because no large earthquakes were present in the data set, that movement along a variety of fault plane orientations was accommodated by an ample number of small preferably-oriented faults. A.M. Rogers, Harmsen, Meremonte (1987), A.M. Rogers, Harmsen, Corbett et al. (1991), and Bellier and

Zoback (1995) also discuss and analyze the modern stress field in regions of Nevada near Yucca Mountain.

3.10.4 Seismicity in the Vicinity of Yucca Mountain

The southern portion of the Nevada Test Site around Yucca Mountain is a more seismically active region than other areas in the southern Great Basin (Figure 3.10-4). Most of the seismicity in this region, including the 1992 M_L 5.6 Little Skull Mountain earthquake, is concentrated around the Rock Valley, Mine Mountain, and Cane Springs fault zones, and around the southern boundary of the Timber Mountain caldera (Figure 3.10-9). Some of the activity near the eastern Nevada Test Site boundary, particularly the 1971 Massachusetts Mountain earthquake and 1973 Ranger Mountain swarms (Figure 3.10-4), may have been triggered following the initiation of testing in the Yucca Flat area, but there are considerable numbers of small to moderate earthquakes related to natural tectonic strain release (Gomberg 1991a, 1991b).

A wide, northeast-trending cluster of seismicity centers on the Rock Valley fault zone. This area includes the 1971 M_L 4.6 Massachusetts Mountain earthquake, the 1973 Ranger Mountains sequence, the 1992 M_L 5.6 Little Skull Mountain earthquake, the 1993 Rock Valley sequence, and other earthquake clusters (Harmsen 1993a, 1993b; Meremonte, Gomberg et al. 1995; Shields et al. 1995; K.D. Smith et al., *The 1992 Little Skull Mountain Earthquake Sequence, Southern Nevada Test Site*, U.S. Geological Survey Open File Report, in press) (Figure 3.10-4). Seismicity in the Rock Valley zone extends along the Mine Mountain system and to the south, subparallel to the South Specter Range fault (Anderson, R.E., Bucknam et al. 1995).

Earthquakes within the immediate vicinity (20 km) of Yucca Mountain are shown in Figure 3.10-9. In this area, as elsewhere in the Great Basin, there is little correlation between the distribution of epicenters and Quaternary faults. The earthquakes have focal depths ranging from near-surface to 5 to 12 km. Focal mechanisms of earthquakes near Yucca Mountain are strike-slip to normal oblique-slip along moderately to steeply dipping fault planes (Figure 3.10-9). The nodal planes are consistent with right-lateral faulting on north to north-northwest striking planes or normal left oblique-slip on northeast- to east-striking faults, and are similar to regional focal mechanisms (Rogers, A.M., Harmsen, Meremonte 1987).

A zone of quiescence at Yucca Mountain is apparent in all studies of seismicity in the southern Great Basin (Figure 3.10-9). D.H. von Seggern and J.H. Brune (*Seismicity in the Southern Great Basin, 1868-1992*, U.S. Geological Survey Open File Report, in press) relocated two M 3.5 earthquakes that occurred in 1948. The initial locations of these two events, previously reported as being located at Yucca Mountain, were constrained by first motion data at California seismic stations. The waveforms and S minus P times at the regional stations operating in 1948 were more consistent with a source near the Rock Valley fault zone rather than at Yucca Mountain. By a comparison of waveforms from Little Skull Mountain aftershocks and heliocorder records from the Caltech station for a well located 1948 Rock Valley area event, they concluded that the two 1948 events most likely occurred in the Rock Valley area and not at Yucca Mountain. D.H. von Seggern and J.H. Brune (*Seismicity in the Southern Great Basin, 1868-1992*, U.S. Geological Survey Open File Report, in press) concluded that the three events were most likely part of one localized earthquake sequence in the Rock Valley area. S. Gross and Jaumé (1995) also analyzed a number of small events that were in the historical catalog and reported to be in Yucca Mountain block from 1978 to 1992 by reviewing the archived waveform data. They noted that some of the events were incorrectly identified as earthquakes and a list of them is included in their report.

Brune et al. (1992) and Gomberg (1991a, 1991b) showed that the Yucca Mountain zone of quiescence is a real feature of the seismicity and not an artifact of network design or detection capability. An experiment in high resolution monitoring of seismicity at the potential site by Brune, J.N. et al. (1992) also confirmed the existence of the quiescent zone. Modeling of the strain field in southern Nevada by Gomberg (1991a) suggests that this area is not accumulating significant strain, and that Yucca Mountain is an isolated block within the structural framework of the southern Great Basin. Other than the 1992 Little Skull Mountain event, the largest earthquake near Yucca Mountain after the inception of the southern Great Basin Seismic Network in 1978 was an M_L 2.1 event, which occurred on November 18, 1988, and was located 12 km north-northwest of the potential repository at a depth of 11 km (Harmsen and Bufe 1992).

Paleoseismic events on a number of major faults at Yucca Mountain (Subsection 3.10.6) have very long return times and strain may accumulate a long time between large surface-rupturing earthquakes on the faults. There may be little or no microseismicity on the faults during this long strain build-up. Many faults in the Great Basin with paleoseismic evidence for prehistoric surface-rupturing earthquakes have little or no associated historical seismicity.

3.10.4.1 The 1992 Little Skull Mountain Sequence

The largest and most significant earthquake recorded by the southern Great Basin Seismic Network since its establishment in 1979 was the June 29, 1992 M_L 5.6 Little Skull Mountain earthquake (Lum, P.K. and Honda 1992; Harmsen 1994; Walter 1993; Meremonte, Gomberg et al. 1995; K.D. Smith et al., *The 1992 Little Skull Mountain Earthquake Sequence, Southern Nevada Test Site*, U.S. Geological Survey Open File Report, in press) (Figures 3.10-4 and 3.10-9). This event produced a horizontal ground acceleration of 0.21 g at Lathrop Wells about 11 km from the epicenter. The earthquake caused minor damage to the Yucca Mountain Field Operations Center in Jackass Flat which was located on the surface projection of the buried fault. The event was felt throughout the region. The earthquake appears to have been triggered by the 1992 Landers event that occurred approximately 20 hours earlier (Subsection 3.10.5.2).

The Little Skull Mountain earthquake initiated at a depth of 11.7 km, and the rupture was confined between 5 and 12 km depth. Fault rupture propagated unilaterally from southwest to northeast for about 6 km, and the epicenter of the mainshock plots near the southwestern end of the aftershock zone. There was no evidence of primary or secondary surface rupture. Rockfalls along the south-facing cliffs of Little Skull Mountain were observed shortly after the earthquake. The distribution of rockfalls was found to be consistent with the ground shaking predicted from the source model and provided a means of calibrating the distribution of ground shaking in the epicentral region (Brune, J.N. and Smith 1996). The earthquake occurred on a northeast-striking fault plane dipping steeply to the southeast (Harmsen 1993b, 1994; Meremonte, Gomberg et al. 1995; K.D. Smith et al., *The 1992 Little Skull Mountain Earthquake Sequence, Southern Nevada Test Site*, U.S. Geological Survey Open File Report, in press) and involved normal slip with a small left slip component. Table

3.10-5 is a compilation of short-period and waveform-based focal mechanisms and reported seismic moments for the Little Skull Mountain earthquake.

There were three aftershocks of M_L >4. None of these occurred on the mainshock fault plane but on adjacent off-fault structures accommodating the stress change from mainshock rupture. These events also triggered stations of the Blume and Associates strong motion network in Las Vegas. The first M_L 4 aftershock occurred in the coda of the mainshock and the location could only be constrained to be east of the mainshock epicenter. Focal mechanisms for two of the four M_L 4+ events show northeast-trending, southeast-dipping fault plane solutions.

The Little Skull Mountain earthquake could not be correlated with any mapped faults, although the aftershocks coincide with the projections of the Wahmonie, Cane Springs, and the Mine Mountain fault systems into the Rock Valley fault zone. Dip angles determined for the mainshock fault plane from the short-period focal mechanisms vary from 65°, consistent with the early aftershock activity, (K.D. Smith et al., *The 1992 Little Skull Mountain Earthquake Sequence, Southern Nevada Test Site*, U.S. Geological Survey Open File Report, in press; Harmsen 1993b, 1994) to 56° (Harmsen 1993b, 1994). The dip of structures in the Little Skull Mountain area has implications for the orientation of faults at depth in the Yucca Mountain site area.

The Little Skull Mountain earthquake occurred in an area of persistent recent seismicity, present throughout the recording period of the Southern Great Basin Network (Figure 3.10-9). This may be a zone of stress concentration, accommodating strain from fault systems throughout the south-central Nevada Test Site area. The Rock Valley fault zone is the primary Quaternary fault system in this group and has the most associated seismicity. The Little Skull Mountain mainshock epicenter plots directly along the crest of Little Skull Mountain, or at hypocentral depth at the base of the seismogenic zone potentially near an intersection with the Rock Valley fault system.

The sequence was recorded on a number of portable digital seismographs deployed in the epicentral area by the USGS (Meremonte, Cranswick et al. 1993) and the University of Nevada Reno (Sheehan et al. 1994). These data were used to develop high quality locations for the special aftershock studies (K.D. Smith et al., *The 1992 Little Skull Mountain Earthquake Sequence, Southern Nevada Test Site*, U.S. Geological Survey Open File Report, in press) and contributed to ground motion modeling in the Probabilistic Seismic Hazard Analyses Project (USGS 1998) (Subsection 3.10.9).

3.10.4.2 Earthquakes in the Rock Valley Area

Following the Little Skull Mountain earthquake, there was an increase in earthquake activity in the southern Rock Valley fault zone (Smith, K.D., Shields et al. 1996; Shields et al. 1995; O'Leary 1996; Coe, Oswald et al. 1996). Only two M 3+ earthquakes were included in the southern Great Basin Seismic Network earthquake catalog from 1979 until the Little Skull Mountain sequence. Since Little Skull Mountain, three M 3.5+ earthquakes, and the sequence of very shallow, small magnitude (M_d ≤3.8)earthquakes in mid-1993 occurred in southern Rock Valley. This activity is diminishing, suggesting that the Little Skull Mountain event may have in part triggered the increased Rock Valley activity (Smith, K.D., Shields et al. 1996).

The shallow sequence of earthquakes in 1993 was recorded on a near-source portable digital instrument. This station recorded over 500 earthquakes, of which only 140 triggered the regional seismic network and could be located. S minus P times for the events averaged about 0.5 sec at this station and relocations of the earthquakes place them at a depth of only about 2 km. The largest event of the sequence (M_d 3.8) also occurred at 2 km depth. Stress drops were on the order of 10 bars for all of the larger events. A cluster of earthquake activity also occurred southeast of the Rock Valley fault zone in the Spotted Range in late 1993. This was the most active cluster of seismicity in the region east of the Nevada Test Site since the 1973 Ranger Mountain sequence but was confined to a small volume and included only one earthquake greater than M 3.

3.10.4.3 1995-1996 Microearthquakes at Yucca Mountain

From May 1995 through September 1996, a sequence of fifteen microearthquakes occurred in and around the Yucca Mountain block (Table 3.10-6) (Smith, K.D., Shields et al. 1996; Brune, J.N. and Anooshehpoor 1996; von Seggern and Smith 1997). These earthquakes triggered at least three stations of the three-component digital network, and three of them were large enough to trigger the older, less sensitive analog net. The events ranged from M -0.76 to 0.72 in size. These microearthquakes occurred throughout the Yucca Mountain block and all had focal depths between 5 and 10 km. Short-period focal mechanisms were determined for four of the earthquakes. Although there was not enough information from the focal mechanism data to unequivocally correlate the earthquakes with specific mapped faults, the solutions are consistent with normal to normal-oblique-slip on faults with orientations similar to several Quaternary faults mapped at the surface. Although small earthquakes ($M < 1$) were occurring at the rate of about one per month from 1995 to 1996, as of March 1997, none have been observed directly within the Yucca Mountain block since August 12, 1996 (Table 3.10-6). This suggests that the restricted time period of the sequence is not strictly a function of the installation and detection threshold of the digital network at the site.

3.10.5 Induced and Triggered Seismicity

Identification of induced events is necessary to properly evaluate the distribution, characteristics, and recurrence of natural tectonic seismicity for the probabilistic seismic sazard analyses. Seismological analyses by the USGS and University of Nevada Reno routinely attempt to distinguish between the natural tectonic seismicity of the region and seismicity induced by human activities, including underground nuclear explosions, their collapses and aftershocks, chemical explosions associated with testing and mining activity, and seismicity associated with the filling and subsequent level changes of Lake Mead.

The occurrence of at least one event, the 1992 Little Skull Mountain earthquake, appears to have been triggered by seismic waves from a large distant earthquake. This type of earthquake triggering has implications for the failure condition of faults in the area. Chemical blasting may have triggered seismicity in the Bullfrog Hills west of the Bare Mountain fault and in various mining sites around the region. The Nevada Test Site is the site of nuclear testing and the level of seismic activity may reflect tectonic release following the underground nuclear explosions. The area around Lake Mead has experienced high levels of microseismicity related to filling of the reservoir behind Hoover Dam.

3.10.5.1 Earthquakes Triggered by Underground Nuclear Explosions

Large underground nuclear explosions (~1 Mt) have been known to trigger release of natural tectonic strain (Wallace, T.C. et al. 1983, 1985). Future testing potentially could induce displacements on faults in the Yucca Mountain site vicinity, but little co-seismic release and related effects have been observed beyond 5 to 10 km from even the largest nuclear blasts (1 Mt). The nearest underground nuclear explosion testing area to Yucca Mountain is the Buckboard area approximately 25 km to the northeast. Future underground nuclear explosions would probably not be close enough to trigger seismicity on local faults at Yucca Mountain.

Vortman (1991) proposed that small-magnitude earthquakes are dominantly induced by dynamic stresses associated with seismic energy generated during the explosion and seem to be due to the altered static stress field resulting from the explosion. That is, some events are triggered by the arrival of the underground nuclear explosion phase, others appear to be responding to changes in an altered stress field caused by the explosion. An underground nuclear explosion may cause a stress change of several bars, a fraction of the lithostatic stress in the hypocentral region. Some of the southern Great Basin may be in a state of critical stress in which a small perturbation in the load on a fault, such as underground nuclear explosion-induced stress changes, could cause the release of accumulated tectonic strain.

Portable instruments recorded about 2,500 earthquakes greater than M 2.0 from December 1968 through December 1970 following the Benham shot, including several nuclear explosions. Hamilton, R.M., Smith et al. (1971) reported that 94 percent of the events with well constrained focal mechanisms were shallower than 5 km, but some events were as deep as 8 km. Focal mechanisms show normal slip on north- to northeast-striking fault planes, implying a down to the west-northwest sense of motion for these earthquakes. Extensive aftershock sequences followed several underground nuclear explosions in the Pahute Mesa area from 1968 through 1970 (Hamilton, R.M., Smith et al. 1971). These sequences were not confined to the shot locations but were distributed along several mapped faults as far as 15 km from the shot points. Aftershocks of underground nuclear explosions also occurred in the Yucca Flat and Rainier Mesa areas on the eastern Nevada Test Site, although they are not as numerous as the triggered earthquakes in the Pahute Mesa area. An increase in seismicity occurred in the 1970s following the initiation of underground testing in the southeastern Nevada Test Site south and east of Yucca Flat.

3.10.5.2 Other Triggered Earthquakes

The triggering of aftershocks by underground nuclear explosions at the Nevada Test Site and the continued occurrence of induced seismicity near Lake Mead suggest that a number of faults in the southern Great Basin may be near failure. There is strong evidence that the Little Skull Mountain earthquake was triggered by the Landers earthquake 225 km to the south less than 24 hours earlier. An increase in microearthquake activity in the vicinity of Yucca Mountain was observed beginning in the coda of the Landers event (Anderson, J.G., Brune et al. 1994). The activity accelerated over the next 23 hours, culminating in the Little Skull Mountain main shock, perhaps indicating that the Little Skull Mountain region was near failure and that the Landers earthquake advanced the time of rupture.

The Landers earthquake also apparently triggered smaller earthquakes in the western United States as far away as the Yellowstone Caldera (Hill, D.P., Reasenberg et al. 1993). Following the Landers mainshock, Johnston et al. (1995) observed a transient strain change associated with an increase in seismicity at the Long Valley Caldera. The occurrence of the Landers earthquake produced a unprecedented increase in seismicity in the Eastern California Shear Zone (Roquemore and Simila 1994) and in the Sierra Nevada-Great Basin boundary zone, prompting several studies of the possible triggering mechanisms. The specific mechanism involved remains uncertain, but the dynamic strain associated with the propagation of long-period surface waves from the Landers earthquake may have initiated a failure process involving fluids or sympathetic slip or creep (Hill, D.P., Reasenberg et al. 1993; Bodin and Gomberg 1994). J.G. Anderson, Brune et al. (1994) proposed that dynamic stresses resulting from surface waves from the Landers earthquake initiated the Little Skull Mountain sequence, and Gomberg and Bodin (1994) have proposed a model in which static strain was propagated through interconnecting fault systems, ultimately triggering failure of the fault at Little Skull Mountain.

Perturbations in the timing of earthquakes as a results of tectonic or non-tectonic triggers have no impact on probabilistic hazard estimates which assumes earthquakes behave in a Poissonian manner, but they may affect the timing of earthquakes where near-failure conditions exist. The earthquakes probably would occur at some later time, as evidence suggests that some faults in the southern Great Basin may be at a critical stress state, but the amount of time in which the failure process is accelerated is uncertain.

3.10.5.3 Lake Mead Area

Since 1936, Lake Mead, the reservoir impounded by Hoover Dam, has been the site of induced seismicity (Anderson, L.W. and O'Connell 1993; Rogers, A.M. and Lee 1976). Microseismicity continues to the present day in the Colorado River area east of Las Vegas, Nevada. The following is a summary from L.W. Anderson and O'Connell (1993).

The first felt earthquakes in the Lake Mead area occurred in 1936 one year after the filling of Lake Mead. There had been no instrumentation at Lake Mead and there is no record of microseismicity in the area prior to 1936. Based on records of Lake Mead earthquakes at Caltech stations, magnitudes have been revised from those based on felt reports. Only one M_L 5 event occurred although there are several of M_L 4.9. A special study (Rogers, A.M. and Lee 1976) in 1973 using portable instruments resulted in the location of about 1,000 small earthquakes in the Lake Mead zone of seismicity. The largest events recorded were M_L 3. Hypocentral depth estimates were better constrained than in previous studies. Depths ranged from near the surface to 13 km with most of the activity between 2.5 and 9.5 km depth and with a peak at about 5 km. First motion focal mechanisms from the A.M. Rogers and Lee study (1976) show a range of mechanism with a preference for strike-slip motion and northwest extension consistent with the regional stress field. A recalculation of the recurrence relations by Anderson, L.W. and O'Connell (1993) using the A.M. Rogers and Lee (1976) magnitude estimates show a b-value of 1.29 for the Lake Mead seismicity as compared to a b-value of 0.9 estimated from a regional (200 km) declustered catalog. A swarm of five M >3 earthquakes (main event M 3.7) in the Eldorado Mountains area near Henderson, Nevada, was also followed by the deployment of portable seismographs by the USGS. Focal mechanisms determined from that study also showed a range of normal, oblique and strike-slip solutions consistent with the known regional extension direction.

3.10.6 Prehistoric Earthquakes at Yucca Mountain

Prehistoric earthquake studies have been conducted to determine the magnitude and frequency of surface-rupturing on active faults in the Yucca Mountain area. These studies provided some of the background and input information necessary for the seismic source characterization component of the Probabilistic Seismic Hazard Analyses Project for Yucca Mountain (Subsection 3.10.9). The seismic source models developed for the evaluation are fully described in the *Probabilistic Seismic Hazard Analyses for Fault Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada* (USGS 1998), whereas this subsection solely summarizes much of the prehistoric earthquake information considered in developing these models.

3.10.6.1 Prehistoric Earthquake Data

Investigations were conducted to identify faults in the Yucca Mountain area that have evidence of Quaternary displacements (Reheis 1991, 1992; Reheis and Noller 1991; Dohrenwend, Menges et al. 1991; Dohrenwend, Schell et al. 1992; Anderson, R.E., Bucknam et al. 1995; Anderson, R.E., Crone et al. 1995; Piety 1996). These studies were reconnaissance in nature, consisting of a combination of literature research, photo interpretation, and field traverses to evaluate offset geomorphic surfaces and fault scarps. These studies identified 88 faults with known or suspected Quaternary activity within a 100-km radius of the potential repository site at Yucca Mountain (Figure 3.10-10). Summaries of each of these faults are presented in Subsection 3.10.6.8.

Studies have also been conducted of faults at and near Yucca Mountain including detailed field mapping and compilation of faults at Yucca Mountain with known or suspected Quaternary activity (Simonds et al. 1995; Whitney and Taylor 1996). This work identified the location and surface characteristics of the mapped faults and identified locations where Quaternary displacement is evident. Specific physiographic and structural evidence for Quaternary displacements was identified and mapped. Bedrock faults that lack evidence for or against Quaternary displacements also were mapped (Scott, R.B. and Bonk 1984; Scott, R.B. 1992).

Displaced or disturbed alluvial and colluvial deposits record late Quaternary faulting along nine local faults in the Yucca Mountain area (Figure 3.10-11). These include, from west to east: the Northern and southern Crater Flat, Windy Wash, Fatigue Wash, Solitario Canyon, Iron Ridge, Stagecoach Road, Bow Ridge, and Paintbrush Canyon faults. Estimates of several paleoseismic parameters for local site faults including information on fault lengths, probable rupture lengths, and geometric relations between faults are primarily based on the map compilation of Simonds et al. (1995).

The Quaternary faults at Yucca Mountain share common characteristics (see Subsection 3.6). They bound east-dipping fault blocks and displace bedrock down-to-the-west; displacement is dominantly dip-slip with varying amounts of left-oblique slip. Sections of some of the faults, particularly those on the west side of Yucca Mountain, are associated with piedmont fault scarps developed in basin-fill alluvium. Displacement increases to the south along each north-trending fault. Fault lengths (with evidence of Quaternary movement) range from less than 2 km to about 28 km. The faults are closely spaced with inter-fault distances on the order of 0.5 to 2 km measured perpendicular to strike.

The faults at Yucca Mountain display anastomosing patterns in plan view (Figure 3.10-11). Numerous bifurcations and splays are indicated by the merging and branching of individual fault strands. These patterns indicate that many of the faults or fault splays are structurally interconnected along strike. The overall pattern suggests that the faults on the east and west sides of Yucca Mountain represent two major subparallel interconnected fault systems. How these systems are kinematically related to one another is not obvious from the mapping or from geophysical data; however, a number of factors suggest that distributive faulting events, i.e., simultaneous rupture on more than one individual fault, have occurred on both the east and west sides of Yucca Mountain. Fault characteristics that support distributive faulting include:

- Close spacing between faults
- The interconnectedness of many faults
- The timing of paleoseismic events (summarized in Subsection 3.10.6.3 and Pezzopane et al. 1996)
- The patterns of principal and distributed faulting observed on historical earthquake ruptures in the Great Basin (Pezzopane and Dawson 1996)

Prehistoric earthquakes have been interpreted based on displacement and timing of surface ruptures at specific locations. A total of 52 exploratory trenches and natural exposures have been excavated, cleaned, and logged in the past 20 years as part of seismotectonic investigations in the Yucca Mountain site area (Swadley et al. 1984; Whitney and Taylor 1996). Forty of these trenches and exposures are located across the nine faults described above, that display evidence of Quaternary activity in the Yucca Mountain site area. The remaining 12 trenches were situated across bedrock faults in the central repository block, which lack direct evidence for Quaternary activity. Twenty-eight trenches at the site display clear evidence for Quaternary displacement in deposits that are displaced or deformed across the fault traces (Figure 3.10-11). The other trenches lack evidence of Quaternary displacements, either because the trench did not intersect a fault in surficial deposits, or undisturbed deposits were found to overlie a bedrock fault. Trenches that expose unfaulted Quaternary deposits above bedrock faults also provide information on the length of surface ruptures. An additional 11 trenches were excavated across the Bare Mountain and the Rock Valley faults located within a 20-km radius of the site. All of these trench sites exposed displaced Quaternary deposits.

The number of sites trenched on an individual fault varies from two to eight. Trenches were placed where geomorphic characteristics suggested that maximum and (or) most recent displacement could be studied. For this reason, trench data only provide minimum rupture lengths for the faulting scenarios discussed below and in Subsection 3.10.6.3.

Paleoseismic data on Quaternary faults collected or interpreted at each trench site includes: fault geometry; the character and ages of Quaternary surficial deposits and soils interacting with the fault; the number, amounts, and ages of individual surface displacement events; prehistoric earthquake recurrence; and fault slip rates (Allen 1986; Schwartz, D.P. 1988; dePolo and Slemmons 1990; Reiter 1990; Coppersmith 1991). Paleoseismic data are summarized in Tables 3.10-7 and 3.10-8, based on the detailed descriptions of individual trench investigations presented in Whitney and Taylor (1996).

Data were collected at each trench or exposure using a prescribed set of basic logging procedures. The walls were first cleaned to allow identification and mapping of fault deformation and the stratigraphy and soil relations of surficial deposits. Structures, stratigraphic contacts, and soil-horizon boundaries were identified and flagged, and the relative position of flagged features were measured and plotted on trench logs using one of three methods: manual gridding and plotting, theodolite measurement, and close-range photogrammetry (Hatheway and Leighton 1979; Fairer et al. 1989; Coe, Taylor et al. 1991). Several example logs are shown in Figure 3.10-12a to d. Deformational features, stratigraphic units, and soils were measured and described and where possible, stratigraphic units and soils related to faulting events were sampled for geochronologic dating. Samples were collected from deposits and soils, and analyzed in the laboratory. The logs and field data then were integrated to derive paleoseismic interpretations of the stratigraphic position and amount of fault displacements, fault recurrence, and fault slip rates.

The terms "event" and "rupture scenario" are used in a specific context in this report. Table 3.10-7 is a listing of the "events" recognized from paleoseismic studies at Yucca Mountain. Event refers to an specific coseismic surface rupture, or prehistoric earthquake, interpreted at a given time at a specific site on a fault and may include either displacement or only fracturing with no displacement. An event commonly is associated with a distinct stratigraphic horizon, or event horizon, in trench exposures that represents the land surface at the time of the prehistoric earthquake. As mentioned previously, however, some of the events at Yucca Mountain may not be separate individual prehistoric earthquakes, but instead, may be associated with a single earthquake with distributive rupture on several adjacent faults. An attempt has been made to correlate events in time from different sites on all the different Yucca Mountain faults, and these possible distributive-rupture prehistoric earthquakes are referred to as rupture scenarios. Identification of rupture scenarios is discussed in more detail in Subsection 3.10.6.3 and Pezzopane, Bufe et al. (1996).

Individual fault displacement events were identified in trench wall exposures using several criteria:

- Abrupt increases in the amount of offset or backtilting of marker horizons or units across the fault
- Recognition of buried deposits or features, such as scarp-derived colluvial wedges or debris-filled fault fissures, which commonly are associated with surface ruptures (Nelson, A. 1992)
- Upward termination of fractures, fissures, or shears at the base of a stratigraphic horizon

There commonly were uncertainties in identifying at least a few rupture events at a given site due to ambiguities and complexities in structural and stratigraphic interpretations. Thus a qualitative rating of the confidence in identification of events is listed in Table 3.10-7 for some faults. In some trenches paleoseismic reconstructions are primarily dependent on interpretations of fault-related colluvial deposition in the hanging wall adjacent to the fault, not offset Quaternary deposits, which may have resulted in overestimation of the number of events. Direct measurement of offset Quaternary units is available only from six trenches and natural exposures, because most trenches are located where faults separate bedrock from colluvium. Not all events are present in the stratigraphic record because of a number of factors including poor stratigraphic definition, pedogenesis, deformational overprinting, and erosion or nondeposition of units. The completeness of event recognition varies from site to site and generally decreases with increasing age of deposits.

Alternative geologic processes may be interpreted from deposits and structures observed in fault trenches at Yucca Mountain. These include: (1) independent fault rupture; (2) distributed faulting; (3) triggered slip; (4) aseismic strain such as fault creep and folding; (5) mass movements, possibly induced by earthquakes or volcanic eruptions; (6) fissures and compaction related to groundwater fluctuations or pore water volume changes, possibly induced by local earthquakes, volcanic eruptions, or climate changes; (7) mechanical piping associated with groundwater fluctuations, possibly induced by local earthquakes, volcanic eruptions, or climate changes; (8) bioturbation from tree, brush, and plant roots, animal and insect burrows; (9) expansive effects associated with pedogenic carbonate accumulation and crystallization, especially in the fault zone, on the footwall, or near the bedrock-alluvium contact; (10) channeling and hillslope erosion along old bedrock faults; and (11) deposition due to climatic change. Within the context of the recognized geologic, hydrologic, and seismotectonic setting of Yucca Mountain, all of these mechanisms could produce or enhance some of the fault-related features exposed at Yucca Mountain. Some mechanisms (1 and 2) occur during only moderate-to large-magnitude local earthquakes, whereas others (3, 5, 6 and 7) could be associated with almost any sized local or regional earthquake. A number of mechanisms (5 through 11) are non-tectonic processes that probably have operated at different times and to differing degrees at Yucca Mountain. Distinguishing which of these processes is responsible for a specific feature or deposit may be difficult because similar-looking features such as cracks may have originated by different processes. Thus care must be taken to consider these uncertainties in deciphering the paleoseismic history for Yucca Mountain.

Despite the uncertainties, there is good evidence for recurrent mid-late Quaternary fault displacement activity, in the form of at least two, and as many as eight, individual displacement events, at most sites on the block-bounding Quaternary faults in the Yucca Mountain site area (Tables 3.10-7 and 3.10-8). These events are associated with discrete fault displacements interpreted to be related to either individual or scenario prehistoric earthquakes (see Subsection 3.10.6.4). Paleoseismic interpretations suggest that many of the events are due to fracturing and fissuring with no detectable offset, and that such events are nearly as common as displacement events. These interpretations have led to inferences that the fracturing events, if tectonic in origin, are either the record of relatively frequent, small to moderate-magnitude earthquakes that do not produce measurable rupture at the surface, or they are a record of distributed faulting and fracturing produced by rarer, larger-magnitude, surface-rupturing earthquakes on any one of several closely spaced nearby faults.

3.10.6.2 Fault Slip Rates

Fault slip rate is the time-averaged rate of displacement on a fault stated in units of millimeters per year. Slip rate is an important paleoseismic parameter; it is a standardized measure of activity on the fault which can be directly used for comparing the activity of many different faults. Fault slip rates are calculated by dividing the amount of cumulative net slip by the age of a specific faulted deposit or horizon. Fault slip rates were computed at each trench site from measurements of the observed net displacement of one or more dated units. Minimum, maximum, and preferred slip rates were calculated at each site. These vary over a large range of values. The range of slip rates reflects uncertainties in both age control and displacement measurements.

In practice, attention must be directed at the relative time spans included in slip rate calculations (McCalpin 1995). Meaningful slip rates should span at least several seismic cycles, as indicated by multiple displacement events. This is particularly important for long recurrence, low-slip faults such as those observed at Yucca Mountain. Fortunately deposits as old as middle to late Quaternary are exposed at most trench sites (Subsection 3.10.6.3). These deposits provide sufficiently long paleoseismic records to yield valid average fault slip rates. At Yucca Mountain, slip rates are average values derived from the oldest faulted units with adequate age control, which typically are displaced by two, and commonly three or more, events.

The spatial distribution of fault slip rate measurements for local faults at Yucca Mountain is determined by the distribution of trench sites which had suitable paleoseismic data (Figure 3.10-11). One to four slip rate determinations were computed for each of the Quaternary faults at Yucca Mountain, as well as the nearby Bare Mountain and Rock Valley faults. The level of study of known and suspected Quaternary faults at distances greater than about 25 km from Yucca Mountain is lower, except for the large, high slip rate Death Valley and Furnace Creek faults. Trench-derived paleoseismic data best suitable for slip rate calculations are not available for most regional faults. Instead more crude estimates, in some cases order of magnitude, are derived from the observed offset of geomorphic surfaces with generalized ages from soil stratigraphy. The morphology and distribution of alluvial fan surfaces adjacent to the range front has been applied to calculating Quaternary slip rates on the Bare Mountain fault (Ferrill et al. 1996, 1997), but results from these analyses are controversial (Anderson, L.W., Klinger, Anderson 1997).

Estimates of slip rates for faults at Yucca Mountain vary from 0.001 mm/yr to 0.04 mm/yr (Figure 3.10-13, Table 3.10-8; Subsection 3.10.6.8; see Whitney and Taylor [1996] for more detailed discussions). Most slip rates cluster around 0.002 to 0.003 mm/yr and 0.01 mm/yr. Slip rates for regional faults in the southern Basin and Range Province range over several orders of magnitude from 0.00001 mm/yr to as large as 4 to 8 mm/yr for the very active Furnace Creek fault (Klinger and Piety 1996; Subsection 3.10.6.8).

Even given the uncertainties in measurements, the rates of fault displacement at Yucca Mountain are low to very low. For example, faults with slip rates of 0.01 mm/yr or less are associated with extremely low rates of activity in a classification of active faulting developed by Slemmons and dePolo (1986). The slip rates observed at Yucca Mountain fall within the moderately low to low activity fault classification in a regional scheme developed by dePolo (1994) that uses slip rates to categorize the activity of normal faults in the Basin and Range tectonic province. The fault slip rates on faults at Yucca Mountain are equal to or are less than the lowest values in a regional compilation of slip rates developed by McCalpin (1995) from fault studies in the entire Basin and Range Province. Only slip rates from the Pitaycachi fault in the southern part of the Basin and Range Province are in the same general range of values as the Yucca Mountain faults, although it should be emphasized that paleoseismic investigations capable of providing slip rates rarely have been conducted on faults with these low rates of activity.

A crude pattern is evident in the spatial distribution of slip rates among the faults at Yucca Mountain (Figure 3.10-13). Slip rates are generally lowest at northern sites, intermediate at central sites, and the highest rates are observed at the southernmost site. This suggests a very general tendency for a southward increase in slip rates among the study localities along faults at Yucca Mountain. This southern gradient in the level of Quaternary tectonism mimics other late Cenozoic tectonic patterns at Yucca Mountain. For example, the cumulative amount of offset of bedrock units generally increases to the south both along a given fault and among faults at Yucca Mountain (Scott, R.B. 1990). Similarly the total amount of extension across all of the faults increases to the south in the Yucca Mountain area (C.J. Fridrich, USGS, written communication to S.K. Pezzopane, USGS, 1995; Fridrich, Whitney et al. 1996), as does the amount of paleomagnetic rotation of volcanic rocks (Rosenbaum et al. 1991; Hudson, M.R., Sawyer et al. 1994).

A comparison can be made between long- and short-term slip rates on two faults, the Stagecoach Road and southern Windy Wash faults (Whitney, Menges et al. 1996). Long-term rates have been calculated from offsets of two volcanic units dated at 8.5 to 3.7 Ma. These units are displaced approximately 100 m vertically across the southern ends of these two faults. These offset units yield long-term slip rates of 0.017 to 0.027 mm/yr over Plio-Quaternary time. These values are generally similar, and within the same order of magnitude, as the late Quaternary slip rates of 0.01 to 0.03 mm/yr computed for these faults from the paleoseismic data. Volcanic units of differing ages display similar amounts of offset, relationships that suggest a possible 2 to 4 my hiatus in significant faulting on both faults in the Pliocene. Fox and Carr (1989) suggested such a hiatus may have occurred in the Crater Flat basin, and that basin extension and faulting resumed with the 3.7 Ma episode of volcanism, a hypothesis supported by the analysis of Fridrich, Whitney et al. (1996) as well.

3.10.6.3 Timing of Surface-Displacement Events and Possible Distributive Rupture Scenarios

The timing of surface-ruptures forms the basis for developing prehistoric earthquake recurrence models and is critical for correlating displacements among faults in distributive faulting scenarios. Ages of offset units must be determined to compute fault slip rates as well. The timing of individual events at a given site is constrained by ages of faulted and unfaulted deposits and soils either exposed in trenches excavated across the fault, or located adjacent to the surface trace of the fault.

The ages of faulting events are best constrained at trench sites where stratigraphic or soil units have been sampled and successfully dated. In some cases the units dated are features, including scarp-derived colluvial wedges on the hanging wall or fissure fills or carbonate laminae in fault zones, that can be directly associated with a faulting event. More typically the age control markers in trench exposures are faulted or unfaulted deposits or soils which have been dated, and which stratigraphically overlie or underlie the event horizon. This type of age control only provides upper and lower temporal bounds on the rupture event, and includes an unknown amount of time between the dated units and the event itself. In some cases this intervening amount of time can be estimated at least crudely by the degree of soil development on deposits in the stratigraphic interval.

Displacement-event ages for regional faults have been estimated from one or more geomorphic characteristics, including the surface expression of the fault, fault scarp morphology, and relationship of the fault to adjoining Quaternary surfaces and deposits that have age assignments based on surface morphology or soil development.

Table 3.10-7 gives maximum and minimum age estimates for each event interpreted at trench sites where direct age control is available. Also, refer to Whitney and Taylor (1996). The indirect bracketing relationships between age control and events described above in part accounts for the wide time range given for most of the events. Additional uncertainty in event ages is due to error associated with the bounding age determinations themselves. Wherever possible, preferred dates or ranges of ages in Table 3.10-7 are based on available geologic constraints additional to the bounding dates of trench units. Where this was not possible, a midpoint or mid-range of the bounding dates was chosen to represent the preferred age of the event.

The ages of faulted and unfaulted units and soils are based on geochronologic studies. An ongoing integrated program was initiated in 1992 to provide specific geochronologic control for paleoseismic investigations at Yucca Mountain (Paces, Menges et al. 1994; Paces et al. USGS, written communication, QT Dating Milestone Report 3GCH510M September 1995). This program employs two basic dating techniques: thermoluminescence analysis of fine-grained, polymineralic sediment, and U-Th disequilibrium series (U-series) analyses of pedogenic carbonate-silica laminae and clast rinds, matrix soil carbonate, and rhizoliths (carbonate-replaced root casts). These techniques have undergone extensive testing, development and refinement during the course of the studies. Additional geochronologic constraints are provided by correlations of trench deposits and soils with a composite Quaternary chronosequence of surficial deposits in Yucca Mountain developed in previous and ongoing studies (summarized in Subsection 3.4.3 and Whitney, Taylor et al. 1996; see also Taylor, E.M. 1986; Peterson, F.F. 1988; Hoover, D.L. 1989; Wesling et al. 1992; John Wesling, Geomatrix, written communication to Yucca Mountain Project Branch (YMPB) Staff, QT Map of Midway Valley, September 1993; Lundstrom, Wesling, Swan et al. 1993; Lundstrom, Wesling, Taylor et al. 1994; Peterson, F.F., Bell et al. 1995). Age assignments for map units in this regional chronosequence are based on a number of geochronologic techniques, including ^{14}C dating of charcoal, ^{14}C and cation ratio dating of rock varnish on geomorphic surfaces, thermoluminescence dating, and U-series disequilibrium and U-trend dating of soil carbonate. Some age-dating techniques such as U-trend dating of soil carbonate, which were used earlier in the Project, have since been found to be unreliable. Data from these techniques have not been used in the geologic site characterizations. Compilations of all Quaternary age determinations completed in the Yucca Mountain area as part of both trench-specific and regional stratigraphic studies are included in Table 3.4-2 and Table 4.1.4-1 of Whitney, Taylor et al. (1996).

The distribution and quality of geochronologic control of displacement-event ages varies widely on faults studied in the Yucca Mountain area. Samples for dating have been collected from mapped lithologic units and soils at almost all trench sites that contain evidence for paleoseismic events. Thus there are at least one, and commonly two or more, data sites on all of the Quaternary faults in the Yucca Mountain vicinity that have been trenched (see earlier discussion; Figure 3.10-11). The number of samples collected varies widely among sites, although typically at least several, and locally as many as twelve dates were determined at a single locality. Individual age determinations vary widely in quality and resolution. This primarily reflects intrinsic problems in the sampling and analysis of the materials available in the trenches, which commonly included loose sand and silt (thermoluminescence) and porous impure secondary carbonate (U-series). The quality of dates obtained in the study generally has improved with time due to continual refinement of sampling and laboratory procedures. The reliability and precision of U-series ages particularly has improved after 1994 with use of mass spectrometry analysis of very small, precise samples and more robust materials such as secondary silica rinds on clasts.

The geochronologic studies have revealed that the deposits and soils exposed in trenches vary greatly in age from late Holocene (1 to 2 ka) to early Pleistocene (1 Ma). Trenches have exposed deposits that range as old as 400 ka on the Windy Wash and Fatigue Wash faults, to 750 ka (Bishop ash in natural exposures) on the Paintbrush Canyon fault, to over 900 ka (U-series dated soil) on the Solitario Canyon fault. Quaternary stratigraphy mapped in the trenches provides an unusually long record of preserved paleoseismic activity for characterization of the long recurrence, low slip rate faults present at Yucca Mountain. However, the resolution and completeness of the paleoseismic record of faulting events decreases with increasing age. In particular, fewer events are recognizable and the geologic context of those identified is more poorly understood in deposits older than 500 ka; this results from incompleteness of older stratigraphic records, deformational overprinting by younger events, and commonly poorer resolution in older age control. The inventory is most complete and the timing data of highest quality for displacement events within the past 150 ka. Thus this time interval is emphasized in developing recurrence models and rupture scenarios.

Nine rupture scenarios that accommodate distributive displacements on more than one fault during a single prehistoric earthquake are developed for the main Quaternary faults at Yucca Mountain, including the Bare Mountain fault (Figure 3.10-14 and Table 3.10-8). Methods for identifying scenarios and the characteristics of each scenario are described in detail in Pezzopane, Whitney et al. (1996). The scenarios are based on correlations of event timing data within the past 150 ka at individual trench sites on each of the faults. The scenario correlations are developed from simple probability distribution plots with three basic shapes (boxcar, triangle, and trapezoid) which represent the minimum, maximum, and preferred timing constraints for a given event at each site, using the timing data in Table 3.10-7. The event timing distributions are superposed upon one another and a simple average is calculated from the number and sum of the overlapping distributions. Peaks in the cumulative probability density function occur at times where more than one event's distribution function overlaps with another event's timing. At times where two or more events overlap, the cumulative average is higher than where no events overlap. Thus, the shape and overall range of the cumulative distribution characterizes the resultant event correlations and their timing distributions for the different recurrences presented here. Scenarios identified in this manner are then tested for reasonableness using other geologic constraints such as correlations of deposits and soils offset by the event at the trench sites involved in the scenario, the spatial association of these sites, and the structural and geophysical relationships of faults in the scenario. Preferred ages for all of the nine rupture scenarios thus identified are listed in Table 3.10-8. The correlations are rated also as high, moderate or low on the basis of both geochronologic and geologic constraints.

3.10.6.4 Displacements Per Event

Displacements per event are an important paleoseismic parameter for estimating the maximum magnitude of prehistoric earthquakes (see Subsection 3.10-7). The most precise displacements per event were estimated directly from trench log data. Between one and six measurements of displacement are available for a given event along the faults at and adjacent to the Yucca Mountain area. Fewer data on displacements per event are available for regional faults and the estimates generally are less precise. They are based primarily on the projected measurement of geomorphic surfaces across topographic scarps or the surface trace of the faults (Subsection 3.10.6.8).

Displacement-per-event data were obtained from trench logging in the following manner. Where possible, displacements associated with each faulting event were determined directly by measuring the displacement of marker horizons across the fault, and then subtracting the amount of offset related to any younger events identified higher in the stratigraphic section. This procedure could not be used if different deposits were present on opposite sides of the fault. At some sites, for example, late Quaternary deposits on the hanging-wall block are faulted against much older deposits or bedrock on the footwall block. Several different methods were used in this situation. In some cases rupture amounts were derived from the thickness of fault-related colluvial wedges, which may result in minimum estimates commonly 50 to 80 percent of the actual surface displacement (Swan et al. 1980; Machette et al. 1992; Nelson, A. 1992). An alternative method involved measurement of the vertical separation between a displaced event horizon in the hanging-wall block and the stratigraphically highest faulted unit on the footwall block. Displacements per event were then derived by subtracting from this measurement, the offsets related to events stratigraphically higher in the hanging-wall block. A similar technique used the stratigraphic thickness of deposits between successive event horizons on the hanging-wall block as a maximum estimate for the displacement associated with the stratigraphically lower event. Measurement uncertainties, inherent in all of these methods, are included in the range of displacements reported. The resolution of displacement-per-event measurements generally decreases with increasing age due to the propagation of measurement error for successively older displacements in an event sequence.

The dip-slip values of single-event displacements were adjusted in two ways to derive net-slip displacements. The amount of normal-oblique slip was calculated for any site that contained possible slip indicators, such as slickenlines on bedrock shears that are related to Quaternary deformation, or, less reliably, striations on carbonate coatings within the fault zone. At some sites, units are deformed near the main fault zone either by backtilting towards the fault surface, and/or by development of antithetic grabens. The effects of this secondary deformation were removed by projection of displaced horizons into the fault zone from undeformed sections of the hanging wall and footwall prior to measuring displacements on the main fault. All measurement uncertainties were incorporated in derivations of net single displacements. Slip indicators clearly associated with Quaternary displacements were rarely observed. Consequently studies in Whitney and Taylor (1996) report dip-slip estimates of single displacements that do not consider probable modest components of lateral slip. The few slip indicators observed increased displacement amounts by factors of 1.1 to 1.7.

Tables 3.10-7 and 3.10-8 includes maximum, minimum, and preferred estimates of displacements for each event. Most of the uncertainty in the estimates result from the measurement uncertainties noted above. Preferred values are based on additional geologic constraints and/or the judgment of the investigator. Preferred displacements per event vary from 3 to 167 cm. Fracture events with no detectable offsets are also identified in the table. Disregarding all events older than 500 ka, there are 12 events for which the preferred per-event displacements are equal to or greater than 50 cm or for which the maximum displacements are equal to or greater than 100 cm. These displacement events form the basis for one of the inter-event recurrence models (Model 1) described in Subsection 3.10.6.6. Displacements per event are slightly larger (150 to 367 cm) for the Rock Valley and Bare Mountain faults. Available estimates of single-event displacements for regional faults are in the general range of those for site faults, with the exception of displacements of 240 to 470 cm on the Death Valley-Furnace Creek fault system.

Single-event displacements are also tabulated for each of the nine scenarios of distributive faulting at Yucca Mountain described in the previous subsection. Paleoseismic displacements are compiled and plotted against position along the faults, providing a crude slip distribution for each scenario earthquake (see Pezzopane, Whitney et al. 1996). A projection scheme is used where the along-trace fault lengths and the paleoseismic study sites were projected onto a north-south plane using a join line at 36°50"N. Displacements associated with the rupture scenario are plotted at the projected position on this line of the site where they were measured. Generally, several scenarios exhibit asymmetrically-shaped slip distributions, with displacements increasing to the south. At least one scenario (Scenario U) displays a more symmetric triangular shaped distribution, whereas scenarios V and S appear to be relatively flat. Table 3.10-9 contains the largest preferred displacement reported at any site in the scenario, a parameter used for calculating prehistoric earthquake magnitudes (see Subsection 3.10.6.7).

3.10.6.5 Rupture Length Constraints

The length of coseismic surface rupture is an important parameter used to define the maximum magnitudes of prehistoric earthquakes. Estimated rupture lengths for prehistoric earthquakes are restricted by surficial mapping data, the locations of trenches, and displacement-event timing data. Although, as noted previously, trench sites generally were located on the basis of criteria other than rupture length constraints. The length of a rupture was determined by the lateral extent that a given event could be traced along and among faults. In some cases this was accomplished by using event correlations between sites based on similarities in ages and other supportive geologic criteria (see Subsection 3.10.6.3). Rupture lengths may be equivalent to the total length of the fault, or may be restricted to a specific portion, or segment, of the fault, as discussed below.

The lengths of individual faults have been measured along the curvilinear traces of all site and regional faults in the Yucca Mountain area (Tables 3.10-7 and 3.10-11, Subsection 3.10.6.8; also Table 11-1 in Pezzopane 1996; Piety 1996). Maximum, minimum, and preferred lengths are given in Table 3.10-7 for the site faults; the variations in fault length reflect the manner in which specific disconnected sections of mapped fault traces could be linked together. The lengths of individual site faults vary from < 2 to 28 km. Fault lengths in the region surrounding the site range from several kilometers to more than 300 km for the Death Valley-Furnace Creek-Fish Lake fault system. The total measured length of a fault represents its maximum rupture potential. This is considered to be a reasonable assumption, especially for short faults at Yucca Mountain with mapped lengths of 5 to

30 km based on the relationships of D.L. Wells and Coppersmith (1994) and Pezzopane and Dawson (1996).

Lengths of faults determined from mapped surface traces of faults do not always correspond to the length of surface rupture associated with earthquakes. Coseismic rupture may be segmented; that is, confined to a particular section of the fault by geometric irregularities or other physical characteristics of the fault zone (Aki 1979, 1984a; Schwartz, D.P. and Coppersmith 1984, 1986; Schwartz, D.P. 1988). As noted above, segmentation of fault rupture can be demonstrated reliably only by analysis of timing constraints on displacement events from multiple sites along a fault or system of faults. Rupture segmentation is considered likely on most of the long regional faults, although adequate timing data for faulting events generally is not available to precisely define segment boundaries and lengths.

The presence of rupture segmentation on local Yucca Mountain faults is not well established. As noted above, comparisons with analogue historical earthquakes, and particularly those in the Basin and Range Province, suggest that rupture segmentation is unlikely on such short faults (Wells, D.L. and Coppersmith 1994; Pezzopane and Dawson 1996). However, possible fault segments based on geometric complexities are identified on at least three of the local site faults: Paintbrush Canyon, Solitario Canyon, and Windy Wash (Table 3.10-7). The distribution and resolution of data concerning faulting events is not sufficient to uniquely constrain any rupture segmentation. Most of the segments are very short (5 to 10 km) and are considered unlikely to rupture independently; however the displacement timing data suggests that the entire lengths of the faults may not have ruptured in all displacement events. In order to account for possible rupture segmentation on site faults, minimum rupture lengths were determined for all of the scenario ruptures based on the distribution of sites containing that event.

Maximum and minimum lengths were estimated for all nine rupture scenarios proposed for distributive faulting on local site faults at Yucca Mountain (Subsection 3.10.6.3; Table 3.10-8). The fault trace lengths and paleoseismic study sites associated with each scenario were projected into a common plane using the same projection technique described earlier for scenario displacements. This method provided a way to obtain composite rupture lengths for scenario events that span more than one Quaternary fault at Yucca Mountain. The projection method used here has some inherent distortion and may overestimate rupture length by 1 or 2 km. Minimum rupture lengths are derived from the northern-most and southern-most trenches with displacement event data for a particular scenario. For faults without trench data to constrain the extent of minimum rupture length, the end points of rupture length are considered to be the northern-most and southern-most trenches along other faults included in the same scenario. In most cases this procedure results in a partial or segmented rupture length relative to the entire length of the projected fault system. Note that on some faults, estimates for minimum rupture length incorporate paleoseismic data where there is negative evidence for an event at a site along a fault, thus making rupture length on that fault shorter than what would be obtained using the trench to trench method. Maximum rupture lengths were estimated using the longest fault or combination of faults based on the preferred fault length measurements listed in Table 3.10-7. Maximum scenario rupture lengths were derived by assuming that the entire fault ruptured, if any study site on the fault had evidence of the scenario event. As with minimum rupture lengths, estimates using total fault length can be superseded by paleoseismic data where there is negative evidence for an event at a trench location along a fault. Thus, in a few cases, the maximum rupture length is shorter than the length of any individual fault involved in the scenario rupture.

3.10.6.6 Recurrence Intervals

Recurrence interval is defined in this subsection as the time interval between successive surface-rupturing prehistoric earthquakes. It is an important temporal measure of fault behavior in seismic hazard analysis. Recurrence intervals were computed for individual faults at all sites with paleoseismic data on the number and timing of prehistoric earthquake events. Individual recurrence intervals were determined where adequate age control exists to isolate the relative timing of specific pairs of faulting events. This procedure is most precise where the dated units are colluvial wedges or fissures that can be associated closely with the faulting events, although this situation occurs rarely in the Yucca Mountain region. More commonly dated deposits formed at some unknown time between successive events and only bracket two or more events. In this case, an average recurrence interval was calculated by dividing the time between the age constraints by the number of possible intervals between events. Uncertainties in both the dating of units (reported as $\pm 2\sigma$) and the number of possible events were incorporated in the reported ranges of recurrence intervals. Recurrence intervals typically are shorter for the late Quaternary because more small displacement events are preserved and can be detected in the youngest deposits in the trenches, and these commonly have the best age control.

At least one and commonly two or more estimates of recurrence intervals were made along individual faults at Yucca Mountain (Whitney and Taylor 1996). Average recurrence intervals on individual faults are 30 to 100 ky; preferred average recurrence of events is 40 ky (Table 3.10-8). Long recurrence intervals are consistent with the relatively small number of observed displacements in middle Pleistocene deposits. The range in values for recurrence intervals between specific events is similar, although in a few cases they are as low as 13 ky (e.g., Stagecoach Road fault) or less (e.g., Rock Valley fault) and approach as much as 100 to 200 ky, with a wide error margin related to poor resolution in event age control. Average recurrence intervals of 10 to 30 ky were estimated for the Stagecoach Road and Rock Valley faults, but these estimates are poorly resolved due to poor constraints on the dating of some events.

Estimates of recurrence intervals were obtained for regional faults on less precise data for the number and ages of events. Recurrence intervals vary greatly from 100 ky to as low as 0.5 to 1.5 ky for the Death Valley and Furnace Creek faults (Subsection 3.10.6.8).

Because earthquakes have occurred at different times on the Quaternary faults in the Yucca Mountain site area, the potential repository site experiences local earthquakes, on average, more frequently than the average recurrence interval of any given fault. Three recurrence models are presented in Pezzopane, Whitney et al. (1996) to describe the composite prehistoric earthquake events on multiple Quaternary faults in the site area. One of these recurrence models explicitly incorporates the rupture scenarios for distributive faulting discussed previously in Subsection 3.10.6.3.

Recurrence model 1 is based on the displacement data, where each large-displacement prehistoric earthquake, on each fault, is considered to be an independent seismic event. Events estimated to be older than 500 ka, or those recognized to be old or have poorly constrained ages were omitted. Disregarding the older events, there are 12 events for which the preferred displacements are equal to or greater than 50 cm or the maximum displacements are equal to or greater than 100 cm (see Subsection 3.10.6.4). Eight events out of these 12 large-displacement events occurred between 15 ka and 150 ka, the remaining four events are older than 200 ka, and U-series dated soils indicate they are younger than 500 ka. Initially disregarding the individual event timing data, if the 12 events occurred within 485 ky (500 ky - 15 ky = 485 ky), it is assumed there are 11 intervals of time, each of the same length, and the average recurrence interval is 44 ky (Table 3.10-10). Considering that 8 events occurred within 135 ky (150 ky - 15 ky = 135 ky), assuming there are 7 equal time intervals between earthquakes, the average recurrence interval is 19 ky. However, some of the large-displacement events are interpreted to likely correlate with each other; thus, model 1 probably does not accurately represent actual fault behavior.

Recurrence model 2 treats the data in Table 3.10-8 as though each interpreted paleoseismic event, including events characterized by fracturing and small offsets (0 to 15 cm), on each fault is an independent earthquake. Thirty-nine events have been identified (Table 3.10-7, within the past 500 ky); this includes all events recognized at all sites, even those events from different sites along the same fault. This disregards the fact that many of the paleoseismic events recognized from fault to fault are correlative in time. Using model 2, average recurrence rates for these fracturing to large-displacement events is approximately 13 ky (Table 3.10-10). Given the numerous, closely-spaced and anastomosing (in map view) faults at Yucca Mountain, this model is considered unlikely because individual sites on a single fault commonly rupture together, and more than one fault participates in a single earthquake with distributive ruptures.

Recurrence model 3 represents an attempt at correlating the events in time using the stratigraphic and geochronological constraints from the trench studies to develop the nine scenario ruptures described previously (Subsection 3.10.6.3; Table 3.10-8; Pezzopane, Whitney et al. 1996). Nine events in 150 ky yields an average recurrence interval of 17 ± 5 ky (Table 3.10-9). The time interval between individual scenario events in model 3 varies from 7 ± 3 to 25 ± 10 ky.

3.10.6.7 Magnitude Distribution

Estimates of the magnitudes of local prehistoric earthquakes are derived from empirical relations using paleoseismic displacements and rupture lengths for faults with known or suspected Quaternary activity. Magnitudes also were estimated for regional faults that have sparse paleoseismic data. These analyses use the empirical magnitude-rupture relations of D.L. Wells and Coppersmith (1994) developed for maximum single-event displacement and/or surface rupture lengths for all fault slip types. The Wells and Coppersmith relations were chosen because they fit well the magnitudes and surface displacements of 24 earthquakes with associated surface-faulting located in extensional provinces of the western United States, primarily the Basin and Range Province (Pezzopane and Dawson 1996; Section 9.2, Figure 9-13).

The maximum earthquake magnitude was evaluated for all faults with known or suspected Quaternary activity in the Yucca Mountain region as part of a regional study to determine relevant sources for seismic hazard analysis (see Subsection 3.10.8.1; also Pezzopane 1996). The maximum earthquake is the estimated size of the largest earthquake that could occur on a fault in the present tectonic regime. Maximum earthquakes were estimated using the empirical relationships between moment magnitude and surface rupture length of D.L. Wells and Coppersmith (1994). Fault lengths were used because this parameter could be more reliably and consistently measured for all faults in the region regardless of whether any paleoseismic data were available to estimate fault displacement. The analysis used maximum fault length (the entire mapped or inferred length), and the conservative assumption that the entire length ruptures during a single earthquake (i.e., no segmentation). As noted earlier (Subsection 3.10.6.5), surface rupture commonly occurs on portions of long, segmented faults. Using the length of fault segments as the measure of earthquake size would reduce the estimated maximum magnitude. Maximum magnitudes computed in this analysis range from M_w 5.1 to 7.9 for faults within a 100-km radius of the potential repository site (see Subsection 3.10.8.1 and Table 11-1 of Pezzopane 1996). These results will be superseded by maximum magnitude distributions provided as part of the probabilistic seismic hazard analyses (Subsection 3.10.8).

More detailed estimates of prehistoric earthquake magnitudes are available for site faults that use the paleoseismic information summarized in this subsection (Pezzopane, Whitney et al. 1996). Specifically, paleomagnitudes were computed for events in all three recurrence models described above using the D.L. Wells and Coppersmith (1994) relation between maximum surface displacement and moment magnitude. The preferred paleoseismic displacements (Table 3.10-7) were used with the magnitude-maximum displacement relation because:

- Only the largest displacement events were selected (model 1).
- The maximum event displacements from all available trench data were selected for each fault, and investigators reported preferred displacement values that tended toward maximums.
- Trenches were sited at points where fault scarps displayed maximum apparent offset, and thus probably are closer to maximum displacements than average.

Prehistoric earthquake magnitudes calculated for recurrence model 2 vary from M_w 5.6 to 6.9. The range in values is large because this model includes all events at all sites with a great amount of variation in single displacements. The twelve large displacement events in recurrence model 1 yield a more restricted range of magnitude estimates between M_w 6.4 and 6.9 . Magnitudes computed from displacements assigned to the nine scenario ruptures of recurrence model 3 range from M_w 6.2 to 6.9 (Table 3.10-9), values similar to those derived from the large single-fault events of model 1.

The largest preferred displacement value measured on an individual fault or at a single site involved in each distributed rupture scenario was used to calculate moment magnitude (Table 3.10-7). The displacements across the faults involved in each scenario were not summed because the smaller displacements on related faults are considered to be distributed secondary ruptures. This assumption may not be appropriate for scenario U because both east and west side faults may have moved simultaneously, and if these structures penetrate to seismogenic depths as individual rupture surfaces, the displacements and the rupture areas should be summed in order to estimate the magnitude. If the west and east side faults are considered to merge at shallow depth, the magnitude of U should be estimated by summing the displacements across all the faults. Summing displacements on the west side faults for scenario U provides an estimated total displacement of 2 m, which corresponds to a M_w 6.9.

The relation between surface rupture length and M_w of D.L. Wells and Coppersmith (1994) also was applied to compute magnitudes from the minimum and maximum rupture lengths of each rupture scenario in recurrence model 3. Rupture lengths for each scenario were measured from the composite fault lengths and distribution of trench sites with the event using the projection method described in Subsection 3.10.6.5 (Table 3.10-7). Magnitudes based on minimum and maximum scenario rupture lengths range from M_w 6.2 to 6.7. The minimum and maximum rupture length magnitudes differ by as much as 0.5 magnitude units, and commonly by only 0.2 to 0.3 magnitude units. The scenario rupture lengths are considered first approximations because they depend directly upon how individual faults and fault segments are combined into rupture zones, which is subject to differences of interpretation. Maximum scenario rupture lengths were estimated on the conservative assumption that the entire fault length ruptures during the event.

Figure 3.10-15 shows a comparison of the scenario magnitudes derived from rupture lengths with those derived from displacement data. If magnitudes derived from scenario rupture lengths were the same as magnitudes derived from displacement data, the points would plot along the diagonal line. However, in almost all scenarios, the maximum rupture lengths provide magnitudes more equivalent to those derived from displacement data than the minimum rupture lengths magnitudes.

Preferred scenario magnitudes listed in Table 3.10-9 were derived by considering the single displacement data and the scenario rupture length data independently, and assessing which values (rupture lengths or displacements) were most reasonable given the geological constraints. Preferred scenario magnitudes range from M_w 6.2 to 6.9, not unlike those derived in recurrence model 1.

3.10.6.8 Descriptions of Known and Suspected Quaternary Faults in the Yucca Mountain Region

One of the primary objectives of the YMP is to identify faults with known or suspected Quaternary activity that may have a potential impact on the design and performance of a high-level radioactive waste facility. Included within the region of interest, generally within a 100-km radius of the potential repository site, are diverse types of faults represented by: the long, continuous, high slip-rate, oblique- and strike-slip faults of the Eastern California shear zone west of Yucca Mountain; the potentially long, mostly discontinuous, moderately active normal- and oblique-slip faults of the Walker Lane belt northwest and south-southeast of Yucca Mountain; and the intermediate length, moderately segmented, and moderately active range-bounding normal faults typical of that part of the Basin and Range Province that lies east and northeast of Yucca Mountain.

Several investigations of regional scope were conducted to identify and characterize faults, and to present evidence as to their Quaternary history; these investigations include Reheis (1991, 1992), Reheis and Noller (1991), Dohrenwend, Menges et al. (1991), Dohrenwend, Schell et al. (1992), Piety (1996), Anderson, R.E., Bucknam et al. (1995), and Anderson, R.E., Crone et al. (1995). Numerous fault studies of a more local nature have also been conducted at and near Yucca Mountain, including detailed mapping of the geologic relations exposed in trenches at selected localities. The results of these studies are briefly described here but are discussed in considerably more detail in Whitney and Taylor (1996). Faults near the potential repository that have been investigated by trenching include: Bare Mountain, Bow Ridge, Crater Flat, Fatigue Wash, Ghost Dance, Midway Valley, Paintbrush Canyon, Rock Valley, Solitario Canyon, Stagecoach Road, and Windy Wash faults (Table 3.10-7). Descriptions of faults within and adjacent to the immediate site area (generally within 10 km) are based on the results of recent large-scale mapping along the fault traces, logging of trenches, and geochronological studies, as well as a detailed compilation of fault data presented by Simonds et al. (1995).

During the course of fault investigations in the Yucca Mountain region approximately one hundred individual faults were considered as possible sources of seismicity and potentially significant levels of ground motion (see Subsection 3.10.8.1; Pezzopane 1996). Calculations to determine which faults may have the capability of generating at least 0.1 g peak horizontal acceleration at the 84th percentile level of confidence (a standard commonly used for seismic design basis ground motions for critical facilities) further identified those features that should be taken into specific account for evaluating fault displacement and ground motion hazards at Yucca Mountain. As a result, 67 faults, or combinations of faults, have been distinguished as "relevant" or "potentially relevant" sources of seismicity, depending on whether there is demonstrable or only questionable evidence of Quaternary movement (Table 3.10-10). Two or more closely related faults that are aligned end to end are combined in some cases because, if ruptures were to occur simultaneously along their entire length, the resulting ground motion would be substantially greater than if rupture occurred on only one of the faults (see Table 3.10-11, and Pezzopane 1996).

The summary descriptions presented here focus on the evidence for Quaternary activity. It should be emphasized that the delineations of known and suspected Quaternary faults are strongly dependent on the information contained in published literature. In particular, there are many limitations associated with combining short, individual fault traces (or tectonic-related geomorphic features) into one fault and implying a single seismotectonic source of a certain length and age; where uncertainties exist, the maximum mapped lengths are given in the fault descriptions. Many faults in the region are poorly exposed, but even where well exposed or trenched, a complete sequence of Quaternary deposits is rarely preserved with which to accurately date the history of Quaternary fault movements.

The faults are listed alphabetically in the following. Approximate age ranges of various time intervals are: Holocene: <10 ka; late Quaternary: <128 ka; late Pleistocene: 10 to 128 ka; middle Quaternary/middle Pleistocene: 128 to 760 ka; early Quaternary/early Pleistocene: 760 ka-1.6 Ma; late Tertiary: 1.6 to 5.0 Ma. In many cases, specific age limits within the Quaternary have not been determined (or reported), hence surficial deposits or fault movements are stated only as being Quaternary in age. Fault distances refer to the distances between the closest point on the surface trace of a given fault to both the controlled area boundary and the center of the potential repository at Yucca Mountain. Fault lengths refer to the maximum length of a given fault zone as reported or shown on maps in published references (e.g., Piety 1996), and represents the total length of the mapped or inferred fault zone (see Table 3.10-11). Unless otherwise indicated, the following descriptions for regional faults are taken from Piety (1996) and the field reconnaissance work of R.E. Anderson, Bucknam et al. (1995) and R.E. Anderson, Crone et al. (1995). The Piety (1996) compilation is an excellent synthesis of most of the data available for characterizing regional faults, and contains an extensive list of published references.

Fault Descriptions–The following known or suspected Quarternary faults and some of their seismic source parameters are listed in Table 3.10-11 by increasing minimum distance to Yucca Mountain and are shown in Figures 3.10-10 and 3.10-11.

Also included in the following discussion are a few local faults which exhibit no evidence for Quaternary activity (e.g., Ghost Dance fault) but are presented here because of potential regulatory interest.

Amargosa River fault–The 15 km long Amargosa River zone is a diffuse band of scarps extending northwest across the central part of Ash Meadows, about 38 km southwest of Yucca Mountain. Scarps have small vertical offsets (1 to 3 m) and unknown amounts of horizontal offset, but the only strong evidence for Quaternary activity is a strike-slip offset on one of the faults, the movement probably occurring during the late Pleistocene (Anderson, R.E., Crone et al. 1995). R.E. Anderson, Crone et al. (1995) estimate the age of the most recent event to be more than 10 k.y.

Amargosa River-Pahrump faults–If the Amargosa River-Pahrump fault systems (see description of Pahrump fault in a later subsection), which have a combined length of about 130 km, were extensions of one another and acted seismically as a single feature, the estimated values for the maximum moment magnitude and peak acceleration would be greater than the estimated values for either one figured separately (see Pezzopane 1996).

Area Three fault–The Area Three fault is located in the east-central part of Yucca Flat, about 44 km east-northeast of the repository area. Total fault length may be as much as 12 km, depending upon whether individually mapped shorter fault segments are all connected. Structural and stratigraphic relations indicate Quaternary activity; the latest movement is perhaps as young as Holocene (Fernald et al. 1968; Swadley and Hoover 1990). Some displacements of surficial deposits were triggered by underground nuclear explosions.

Ash Meadows fault–The Ash Meadows fault consists of discontinuous lineaments and subdued scarps that extend north-south for at least 30 to 40 km, and possibly as much as 60 km, along the eastern side of the Amargosa Desert through Ash Meadows. At its northern end the fault zone, which exhibits normal dip-slip movement, is about 34 km southeast of the potential repository site. At one locality, the largest of two multiple-event scarps has 3.4 m of surface offset on middle or early Pleistocene deposits and 1.8 m of surface offset on late Pleistocene alluvium (Anderson, R.E., Crone et al. 1995). More typically scarp offsets attributed to the most recent event range from 0.7 to 1.5 m, and commonly <1 m; the age of this event is considered late Pleistocene based on scarp morphology and the estimated age of the youngest offset geomorphic surface. Based on these measurements, a maximum slip rate is 0.1 mm/yr, but a lower slip rate of <0.01 mm/yr is indicated for smaller scarps along most of the Ash Meadows fault. The recurrence of surface-rupturing events is at least 15 to 20 ky, and more likely > 50 ky (Anderson, R.E., Crone et al. 1995).

Bare Mountain fault–The Bare Mountain fault is a generally north-trending, east-dipping (50°-70°), normal-oblique slip (right-lateral) fault that forms the structural boundary between Bare Mountain to the west and Crater Flat basin on the east (Reheis 1988; Monsen et al. 1992). The fault is approximately 16 km long and lies about 14 km west of the potential repository site. There is no direct indication of the total amount of bedrock offset that has occurred along the Bare Mountain fault because it is located within surficial deposits for most of its length. In several places, Quaternary deposits are displaced at the surface, and fault scarps are developed in late Pleistocene alluvial fans (Anderson, L.W. and Klinger 1996). One to two surface rupturing events are interpreted at three trench sites excavated on the fault trace. Estimates of the average preferred single displacements are in the range of 80 to 150 cm. Available data indicate that the most recent surface rupturing event occurred no more recently than 14 to 21 ka, and could be as old as 100 ka. The recurrence of moderate to large surface rupturing events appears to be on the order of tens of thousands to a hundred thousand years or more. The late Quaternary slip rate interpreted from paleoseismic data at the trench sites is quite low, on the order of 0.01 mm/yr (Anderson, L.W., and Klinger 1996; Anderson, L.W., Klinger et al. 1996). Ferrill et al. (1996) infer a somewhat higher slip rate on at least the southern end of the fault, on the order of 0.06 mm/yr (J. Stamatakos, Southwest Research Institute, oral communication to C.M. Menges, USGS October 1996), based on more indirect and controversial methods using variations in the morphology and distribution of alluvial fan surfaces adjacent to the range front (Ferrill et al. 1997; Anderson, L.W., Klinger et al. 1997).

Belted Range fault–The Belted Range fault is a generally north-trending normal fault with a maximum length of 54 km; it is located about 55 km north of Yucca Mountain. Total displacement exceeds 610 m, down to the west. Quaternary displacement is expressed by a relatively continuous 22-km long zone of well-defined scarps on alluvium (Anderson, R.E., Bucknam et al. 1995). Total surface offsets on these scarps ranges from 0.6 m on the youngest faulted alluvium to 11.3 m on the older alluvium. Scarps with less than 1 m of surface offset are probably the result of a single faulting event, whereas many of those with larger offsets show evidence of multiple displacements. The most recent movement along the Belted Range fault is probably early Holocene to latest Pleistocene based on scarp morphology and the surface characteristics of the youngest offset alluvial fans (Anderson, R.E., Bucknam et al. 1995). Poorly constrained estimates of slip rates since late Pleistocene time vary from 0.01 to 0.1 mm/yr, but the timing data are too poorly resolved to determine recurrence intervals.

Black Cone fault–The Black Cone fault, northeast of Black Cone in the central part of Crater Flat, lies about 8.5 km west of the potential repository. This down-to-the-east normal fault offsets Quaternary deposits of middle to late Pleistocene age (Faulds et al. 1994), locally producing subtle scarps with as much as 0.5 m topographic relief (Simonds et al. 1995). The Black Cone fault trends north to northwest for a distance of about 7 km; no trenches have been excavated across it to provide data on recurrence or slip rates during the Quaternary.

Boomerang Point fault–The Boomerang Point fault is a 5-km long north- to northeast-trending dip-slip fault mapped by Scott, R.B. and Bonk (1984) along the west side of Boomerang Point in the western part of the site area. Dip of the fault averages about 75 west, and down to the west displacement in the mid-Tertiary volcanic rocks is about 30 m. There is no evidence of displacement of Quaternary surficial deposits that conceal the fault at its southern end.

Bow Ridge fault–The Bow Ridge fault is a prominent north-striking, west-dipping, normal-oblique slip fault about 10 km long that lies in the eastern part of the potential repository site area. The fault trace is buried beneath alluvium and colluvium for most of its extent along the western margin of Midway Valley; the best topographic expression of the structure occurs where a 760-m ong section follows the base of the west side of Exile Hill, although the fault is buried by colluvium with no detectable fault scarp (Simonds et al. 1995; Menges and Whitney 1996b; Menges, Taylor et al. 1997). Tertiary volcanics are displaced about 125 m down-to-the-west at this locality. The fault dips 65°E to 75°E west, and net displacement is left oblique. Several trenches and the Exploratory Studies Facility expose a complex fault zone in highly fractured Tertiary volcanic bedrock and colluvial deposits that have been subjected to multiple faulting events during Quaternary time. At least two and possibly three surface rupturing events are developed in late to middle Pleistocene colluvial deposits at trench 14D (Menges and Whitney 1996b; Menges, Taylor et al. 1997). A minimum age of 48 ± 20 ka is established for the most recent surface rupturing event. Measured displacements range from 14 to 44 cm for individual faulting events, and from 30 to 70 cm for all events. Average recurrence intervals vary from 70 to 215 ky (preferred range, 100 to 140 ky); recurrence intervals between individual events vary more widely from 40 to 350 ky, with preferred values of 90 to 270 ky Average slip rates are 0.002 to 0.007 mm/yr with a preferred value of 0.003 mm/yr (Menges and Whitney 1996b; Menges, Taylor et al. 1997).

Bullfrog Hills fault zone–The Bullfrog Hills fault zone includes several north-to-northwest-trending faults in the Bullfrog Hills area, about 38 km northwest of the potential repository. Total length of any one of the faults is a maximum of 7 km, others are only about 4 km. Where displacements have been observed, they are found to be down to the southwest. Parts of all faults have been mapped either as being concealed by Quaternary deposits, or as faulted contacts between Tertiary bedrock and Quaternary alluvium (Cornwall and Kleinhampl 1964; Cornwall 1972).

Buried Hills faults–The Buried Hills faults includes several north-trending discontinuous faults in a zone that extends for a total distance of about 26 km. The faults, located 53 km east of Yucca Mountain, show both down-to-the-east and down-to-the-west displacements. Based largely on air photo interpretation, faults in the Buried Hills faults are shown primarily as weakly to moderately expressed lineaments and scarps on surfaces of Quaternary and Tertiary deposits (Reheis 1992). In a few places, faults are also portrayed as juxtaposing Quaternary alluvium against bedrock (Dohrenwend, Menges et al. 1991).

Cane Spring fault–The Cane Spring fault is a northeast-trending, left-lateral fault that is part of the Spotted Range-Mine Mountain structural zone. This zone also includes the Mine Mountain, Rock Valley, and Wahmonie faults. The Cane Spring fault lies about 29 km east of the potential repository, and, depending on how many individual faults are included, may be as much as 27 km in length. Tertiary volcanic rocks are displaced largely by left-lateral strike-slip movement accompanied by a smaller component of vertical movement; however, the total amount of displacement has not been determined. The Cane Spring fault is generally shown as being concealed by Quaternary alluvium, except for sections portrayed on various geologic maps as fault contacts between Tertiary bedrock and younger Tertiary or early Quaternary surficial deposits (Ekren and Sargent 1965; Cornwall 1972; Swadley and Huckins 1990). Although recent studies do not indicate Quaternary activity (D.W. O'Leary, USGS, written communication, Draft Milestone Report, Cane Springs and Rock Valley fault zone 1996), the Cane Spring fault is classed as a relevant fault because of its close proximity to faults of known Quaternary activity (e.g., Rock Valley, Mine Mountain) and because historical seismicity has occurred in the vicinity of the fault (see Figure 3.10-9; Pezzopane 1996).

Carpetbag fault system–The Carpetbag fault system, located about 43 km northeast of Yucca Mountain, is comprised of several subparallel north-striking, steeply east-dipping, normal-oblique fault strands in a zone about 30 km long; the faults are largely concealed at the surface, and their total length is derived from geophysical studies and other subsurface imaging techniques. Vertical displacement of Tertiary volcanic rocks is 600 m, and the amount of right-lateral slip could be even greater, accounting for as much as 1,500 m of horizontal extension. Evidence for several episodes of fracturing (and perhaps minor faulting) of Quaternary age were interpreted from the uranium-series dating of secondary $CaCO_3$ in fracture-fill deposits (Shroba et al. 1988a, 1988b). The approximate times of fracturing were 30 ka, 45 ka, 65 ka, 100 ka, 125 to 130 ka, and 230 ka. However, no significant surface rupturing appears to have occurred during the last 130 ky and possibly during the last 2350 ky. The slip rate along Carpetbag fault system between about 30 ka and 125 to 130 ka or earlier has been nearly zero; no evidence of fracturing or faulting has been recognized for the last 30 ky The average recurrence interval for fracture producing events is inferred to be about 25 ky during the last 125 to 130 ky. Of special interest is the creation of a scarp 1.5 m high along part of the fault system that resulted from an underground nuclear explosion at Yucca Flat (Carr 1974; Shroba et al. 1988a).

Checkpoint Pass fault–The Checkpoint Pass fault, which lies 44 km east-southeast of Yucca Mountain, trends northeast to east for a distance of 8 km. Displacements are left-lateral strike-slip in part, but some segments show dip-slip down-to-the-west movement. In places the fault is shown as juxtaposing Quaternary alluvium against bedrock (Dohrenwend, Menges et al. 1991); in other places, it is shown as being concealed by alluvial deposits of Quaternary and Tertiary age (Barnes, Ekren et al. 1982).

Cockeyed Ridge-Papoose Lake fault–Two northwest-trending normal faults in a segmented zone about 21 km long comprise the Cockeyed Ridge-Papoose Lake fault. The faults are located 53 km east-northeast of the site area. Most of Cockeyed Ridge-Papoose Lake fault is shown as faults in Quaternary deposits and as weakly expressed lineaments or scarps on surfaces of Quaternary deposits (Reheis 1992).

Crater Flat fault system–The Crater Flat fault system consists of two fault zones located 6 km west of the potential repository. The Northern Crater Flat fault zone is marked by two subparallel, northeast-trending strands that are 300 to 600 m apart and have a combined length of about 18 km. The trace of the southern Crater Flat fault zone is characterized by a northeast-trending basalt-alluvium contact, fractured carbonate-cemented alluvium, subtle scarps in alluvium, and a linear stream channel (Simonds et al. 1995; Menges and Whitney 1996a). However abrupt changes in orientation, differences in geomorphic expression, and contrasts in paleoseismic history revealed in trenches (Coe 1996b; Taylor, E.M. 1996) suggest that the two faults are separate structures, although it is still possible, but less likely, that they may be different segments of a single fault zone. The orientation and paleoseismic history of the southern Crater Flat fault in particular suggests that it may be a southwest splay of the Windy Wash fault. The amount of down-to-the-west displacement of bedrock along the Crater Flat fault system is unknown; a slickenside measurement on one of the individual faults indicates a moderate left-lateral component of slip on a 70° west-dipping fault plane (Simonds et al. 1995). There is evidence that three paleoseismic events occurred on the southern fault zone during the Quaternary, with preliminary age estimates of 3 to 7 ka, 10 to 60 ka, and 130 to 250 ka (Taylor, E.M. 1996). Single displacement amounts vary between 2 and 32 cm, with preferred estimates of 10 to 20 cm. The preferred estimate of total vertical displacement is 48 cm, which yields a vertical slip rate of 0.002 mm/yr. Preliminary timing data suggests recurrence intervals of 5 to 60 ky. Three to five events are interpreted in middle to early Pleistocene alluvium on the Northern Crater Flat fault, with the earliest possibly Holocene or latest Pleistocene in age (Coe 1996b). Single displacements on the fault range from 0 to 50 cm, although local graben formation and backtilting reduce the cumulative net tectonic displacement to 100 cm maximum. This produces slip rates of <0.0023 mm/yr, although this number may be refined pending results of additional dating. Preliminary recurrence intervals are estimated in the range of 120 to 160 ky (Coe 1996b).

Crossgrain Valley fault zone–The northeast-trending, 9-km long Crossgrain Valley fault zone lies 48 km southeast of Yucca Mountain. Displacement is chiefly left-lateral strike-slip with a down-to-the-northwest dip-slip component. The Crossgrain Valley fault zone has surficial expression on surfaces of both Quaternary and Tertiary deposits, and several sections are shown as moderately to strongly expressed lineaments or scarps on surfaces of Quaternary deposits (Reheis 1992; Dohrenwend, Menges et al. 1991). In other places, faults are variously shown as forming the contact between alluvium and bedrock or as being concealed beneath the alluvium (Barnes, Ekren et al. 1982).

Death Valley fault–The Death Valley fault is a north-northwest-striking, down-to-the-west normal fault that lies along the west side of the Black Mountains and the east side of Death Valley. The fault, whose nearest point is about 55 km southwest of the potential repository site, has a total length of 100 km, which includes the southernmost segment sometimes called the southern Death Valley fault. Late Pleistocene and Holocene fault scarps are prominent along the Death Valley fault, and evidence for Holocene activity is abundant. Recent studies (Klinger and Piety 1996) indicate that three and possibly four ground-rupturing events have occurred along the central portion of the fault in about the last 2 to 4 ky. Based on scarp morphology and offset of a 200 to 2,000-year-old surface, the age of most recent faulting may be nearly historic. The scarps are west-facing, heights range from 5 to 9.4 m, and maximum vertical displacement of late Pleistocene surfaces is 15 m. Scarp heights interpreted to be the result of several large-magnitude earthquakes indicate that the average event height is about 2.4 m, and the surface rupture length for such events is estimated to be about 45 km. A right-lateral offset of 35 km on an alluvial fan was measured along the southern Death Valley fault, and total vertical relief is locally 200 m. Estimates of fault slip rates range from 0.15 mm/yr to as much as 11.5 mm/yr during the Holocene, depending on which segment of the fault is being measured. A late Holocene slip rate of 3 to 5 mm/yr is estimated for one segment of the Death Valley fault (Anderson, L.W., Klinger et al. 1996). This is located at a locality where an alluvial fan surface with an estimated age of about 2 to 4 ka has been displaced vertically 10.5 m. These rates are notably larger than those estimated for the late Tertiary - middle Pleistocene time interval, suggesting a significant increase in fault activity during more recent times. Based on evidence suggesting that three or more surface rupturing events occurred on the Death Valley fault during the late Holocene (<2 ka), the maximum recurrence interval between events is about 650 year. The average recurrence interval for large ground-rupturing events during the Holocene appears to be between 500 and 1,300 years (Anderson, L.W., Klinger et al. 1996).

Death Valley-Furnace Creek fault systems–The combined Death Valley-Furnace Creek fault systems (including the southern Death Valley fault) extends along the east side of Death Valley as a nearly continuous series of normal and right-lateral faults for a distance of about 205 km. Closest distance to the potential repository is 50 km. Considered as a single feature, the estimated values for maximum moment magnitude and peak acceleration are greater than the values estimated for each separate fault system (Pezzopane 1996). As indicated in the descriptions of both the Death Valley and Furnace Creek faults, these features comprise the longest and most active fault system in the Yucca Mountain region.

Death Valley-Furnace Creek-Fish Lake Valley fault systems–The above statements apply to this combination of fault systems as well. At its closest approach, the system lies 50 km west of Yucca Mountain. With the addition of the right-lateral, oblique-slip Fish Lake Valley fault continues for another 83 km north-northwest from the northern end of the Furnace Creek fault.

Drill Hole Wash fault–The Drill Hole Wash fault is shown by W.C. Day and others (USGS, written communication to USGS YMPB staff, Preliminary Site Geologic Map, October 1996; Day et al. 1996b) to extend northwest along Drill Hole and Teacup Washes on the northeast side of the repository block. It is entirely concealed by surficial deposits except for a short distance where it crosses a spur of bedrock near the confluence of the two drainages. Although buried, data from drillholes in Drill Hole Wash and from the Exploratory Studies Facility excavation indicate the presence of two separate, but interconnected faults that offset the Tertiary volcanic rocks (Spengler and Rosenbaum 1980). The length of the fault is about 4 km, and the principal displacement is oblique-slip with a right-lateral sense of offset. Surficial sediments which range in age from mid-Pleistocene to early Holocene, cover most of the fault trace without scarps or other evidence of disruption or displacement.

Dune Wash fault–The Dune Wash fault trends south and southeast along the east side of the potential repository site for a distance of 3 km. It can be mapped in exposures of bedrock as a west-dipping normal fault with down-to-the-west displacement of 50 to 100 m in Tertiary volcanic rocks toward the north end (W.C. Day et al., USGS, written communication to YMPB staff, Preliminary Site Geologic Map, October 1996; Scott, R.B. and Bonk 1984). Evidence of Quaternary movement has not been detected in surficial deposits that conceal the fault toward the south.

East Pintwater Range fault–The East Pintwater Range fault is located along the east side of the Pintwater Range, about 81 km east of the potential repository site, and trends generally north in a 58-km long zone of discontinuous normal faults with down-to-the-east displacements. At one locality, scarps are shown on depositional or erosional surfaces that are possibly early to middle Pleistocene in age (Dohrenwend, Menges et al. 1991). Other faults are visible as weakly to moderately expressed lineaments and scarps on surfaces of Quaternary deposits (Reheis 1992).

Eleana Range fault–The Eleana Range fault lies about 37 km northeast of the potential repository site. It is a 13-km long northeast-trending normal fault with displacement down to the east. Over much of its length, the Eleana Range fault is considered to form the contact between Quaternary alluvium and bedrock (Paleozoic and Proterozoic), and scarps are mapped on alluvial surfaces at several localities (Swadley and Hoover 1990; Dohrenwend, Schell et al. 1992). The youngest surfaces on which scarps have been mapped are late Pleistocene, but most are early Pleistocene (> 740 ka) and Pliocene in age.

Emigrant Valley North fault–The Emigrant Valley North fault includes numerous short, subparallel normal faults in Emigrant Valley, 60 km northeast of the potential repository. The faults are in a northeast-trending zone that extends for about 28 km; displacements are mostly down to the northwest with possibly some strike-slip movement. Aerial photograph interpretations indicate fault scarps on late Quaternary alluvial fan deposits and possibly on pluvial lake deposits (Reheis 1992).

Fatigue Wash fault–The 17-km long Fatigue Wash fault is a north-trending, down-to-the-west, normal-to-normal-oblique slip fault located about 3.5 km west of the potential repository area. Average dip of the fault plane is 73°E west, and the displacement of Tertiary volcanic bedrock is shown in places to be about 72 m by R.B. Scott and Bonk (1984). Logging of a trench across the central portion of Fatigue Wash fault in Crater Flat and studies of scarp profiles along the fault trace by Coe, Oswald et al. (1995, 1996) provide evidence for 3 to 6 paleoearthquakes (5 preferred) since the early to middle Pleistocene. Four of the 5 preferred events occurred after 730 ka, and the two most recent events probably occurred between 20 and 70 ka. The age of the most recent displacement event, which resulted in 0 to 30 cm of vertical offset of the youngest soil layer, is constrained between 9 ka and 75 ka (20 to 60 ka preferred). The next youngest event, with a displacement of about 25 cm, is constrained between 15 and 100 ka in age (65 to 75 ka preferred). Earlier events include one dated as >180 ka (displacement ~ 105 cm) and the oldest dated at > 450 ka (displacement ~ 54 cm). Estimates of the average recurrence interval ranges from 120 to 250 ka. The Quaternary slip rate computed from 2.1 cumulative vertical offset of mid-Pleistocene units in the trench is 0.002 ± 0.001, whereas slip rates derived from scarp data to the north is 0.009 ± 0.006 mm/yr.

Furnace Creek fault zone–The Furnace Creek fault zone, a main component of the Death Valley-Furnace Creek-Fish Lake Valley fault system, is a northwest-striking, right-lateral strike-slip fault that is nearly coincident with the axis of Northern Death Valley for a distance of about 145 km. The nearest point of the fault to the Yucca Mountain site is 50 km. Style of faulting is primarily right lateral, and total displacement is on the order of tens of kilometers. Evidence for late Pleistocene to Holocene surface ruptures is common along the fault traces, with displacements as young as 0.2 to 2 ka and several <10 ka. Recent studies (Klinger and Piety 1996; Anderson, L.W., Klinger et al. 1996) found evidence for at least three late Holocene ground-rupturing events. Measurements of right-lateral offsets indicate that the average displacement for the last event, the timing of which could not be specifically determined, was about 4.7 m, although average single displacements are 2.5 to 3.5 m. Relationships observed at two different localities along the fault indicate: a short-term slip rate of 6 to 13 mm/yr based on a 248 to 330-m displacement of an alluvial fan estimated to have been deposited 25 to 40 ka; and a long-term slip rate of 8 to 10 mm/yr based on a 6 to 8-km right-lateral offset of an alluvial fan deposit that overlies a tephra bed correlated with the Bishop as with an age of 760 ka. The recurrence interval for large ground-rupturing events on the Furnace Creek fault zone during the late Quaternary appears to be about 600 to 800 year; the maximum surface rupture length is estimated to be about 105 km (Klinger and Piety 1996; Anderson, L.W., Klinger et al. 1996).

Ghost Dance fault–The Ghost Dance fault is the main fault in the central part of the potential repository area. It can be mapped for approximately 3 km along a zone of numerous fault splays that both parallel the main north-trending trace of the zone, and locally branch laterally off the main fault. A similar branching pattern is postulated vertically, such that the fault zone narrows with depth

(W.C. Day et al., USGS, written communication to YMPB staff, Preliminary Site Geologic Map October 1996). Spengler, Braun et al. (1993) interpreted the fault as a complex zone that varies in width from a few meters to as much as 213 m, with individual faults commonly spaced 15 to 46 m apart. Based on more recent mapping, Day et al. (1996b) subdivide the fault into three sections on the basis of offset and brecciation, with the width of the zone varying from 2 to 150m. Cumulative down-to-the-west displacement of bedrock within the zone ranges from as much as 6 m at its northern end to 15 to 20 in the central portion (Day et al. 1996b). No offset or fracturing of late Pleistocene or Holocene deposits has been detected in numerous trenches excavated across the fault, with the exception of a single fracture of uncertain origin developed in dense carbonate and opaline silica with U-series ages of 10 to 83 ka draped over bedrock on a strand of the fault in one trench (Taylor, E.M., Menges et al. 1996; Taylor, E.M., Whitney et al. 1996). The Ghost Dance fault bifurcates, with one branch connecting southwestward with the Abandoned Wash fault, a north-trending, west-dipping normal fault that also displaces bedrock but no Quaternary deposits (see below; Scott, R.B. and Bonk 1994; Day et al. 1996b). The other branch trends southeast, but does not appear to connect with the Dune Wash fault (W.C. Day et al., USGS, written communication to YMPB staff, Preliminary Site Geologic Map, October 1996; Day et al. 1996b).

Ghost Dance-Abandoned Wash faults–The Abandoned Wash fault is a down-to-the-west normal fault that displaces Tertiary bedrock. The fault trends southwest from the south end of the Ghost Dance fault for about 2 km. The Ghost Dance and Abandoned Wash faults have a combined length of about 5 km and could rupture as a single feature. However, there is no evidence for Quaternary activity on either of these faults (Taylor, E.M., Menges et al. 1996; Taylor, E.M., Whitney et al. 1996).

Grapevine fault–The Grapevine fault, located some 58 km west of Yucca Mountain, is a 20-km long, northwest-trending normal fault with down-to-the-southwest displacement and little or no strike-slip displacement. Vertical displacement of Tertiary rocks may be several thousand meters. Displacement occurred primarily during the late Pliocene and early Pleistocene, but there has been recurrent movement throughout the Quaternary as is indicated by alluvium being faulted in some places; some fault displacements took place as late as Holocene time. Alluvium has been deposited against fault scarps elsewhere.

Grapevine Mountains fault–The Grapevine Mountains fault includes two main normal faults and some subsidiary faults along the northwestern end of the Grapevine Mountains, about 67 km northwest of Yucca Mountain. The faults, with down-to-the-west displacements for the most part, trend generally northeast for a distance of 31 km. Parts of both of the main faults are shown as juxtaposing Quaternary alluvium against bedrock (Dohrenwend, Schell et al. 1992). Sections of one fault are interpreted as forming scarps on surfaces with ages of early to middle Pleistocene and possibly late Pleistocene.

Hunter Mountain-Panamint Valley faults–The Hunter Mountain fault, which lies 95 km west-southwest of Yucca Mountain, is an 85-km long northwest-striking fault along which both right-lateral and dip-slip displacements have occurred; latest movement took place in Holocene time. When treated separately, the Hunter Mountain fault does not constitute a relevant seismic source (Table 3.10-10; Subsection 3.10.8.1; Pezzopane 1996). If considered as a northwest continuation of the Panamint Valley fault (see description in a later subsection), however, the combined 185-km long feature can be classified as a relevant seismic source according to the criteria being used to identify such features for ground motion hazard analysis.

Indian Springs Valley fault–The Indian Springs Valley fault, on the west side of Indian Springs Valley, consists of subparallel faults in a 28-km long north-to-northwest-trending zone. The area lies 67 km east of Yucca Mountain. The Indian Springs Valley fault, with down to the east displacements, is variously expressed as fault contacts between Quaternary alluvium and bedrock and as weakly to moderately expressed lineaments and scarps on surfaces of Quaternary and Tertiary deposits (Dohrenwend, Menges et al. 1991).

Iron Ridge fault–The Iron Ridge fault extends south from near the south edge of the potential repository for a distance of about 9 km; it forms a southeastward splay of the Solitario Canyon fault to the west and continues southward towards and perhaps joining with the Stagecoach Road fault. This north-trending feature forms the bedrock-alluvial contact for half its total length, and prominent scarps between bedrock and colluvium are locally visible (Simonds et al. 1995). Displacement is primarily dip-slip, down to the west, and average dip is about 70° west. In at least one locality there is evidence of multiple faulting events in late Quaternary time (Simonds et al. 1995). Paleoseismic interpretations at one trench site suggest one possible small (0-10 cm) event of probable Holocene age, and a number of poorly resolved mid-Quaternary events with per-event displacements of about 70 to 100 cm (Ramelli et al. 1996). Timing constraints are insufficient to allow estimation of recurrence intervals or slip rates, but soil stratigraphic relationships do not suggest unique correlation of events with either the Solitario Canyon or Stagecoach Road faults.

Kawich Range fault zone–The Kawich Range fault zone is mapped as numerous subparallel northeast- to northwest-trending normal faults (down-to-the-west displacements) on the west side of the Kawich Range, about 57 km north of the potential repository (Ekren et al. 1971; Cornwall 1972; Reheis 1992). Over its 84-km length, most Kawich Range faults are shown as being in bedrock or as forming the bedrock-alluvium contact. More recent work suggests that scarps on alluvium are small (<2.6 m surface offset), discontinuous, span only 3.6 to 7.4 km of the fault zone, and are probably latest Pleistocene in age (Anderson, R.E., Bucknam et al. 1995). Although evidence of recurrent late Quaternary movement is equivocal, field relations suggest long recurrence intervals and low slip rates.

Kawich Valley fault zone–The Kawich Valley fault zone includes a cluster of faults near the middle of the north end of Kawich Valley and scattered faults along the west side of the valley. The faults trend generally north for a distance of about 43 km; the zone is located 61 km north of the Yucca Mountain site. The fault is expressed primarily as weakly developed lineaments and east-facing scarps on Quaternary deposits or erosion surfaces.

Keane Wonder fault zone–The Keane Wonder fault zone is an anastomosing group of northwest-trending fault strands and topographic lineaments mapped along the southwestern flank of the Funeral Mountains in Death Valley for a distance of about 25 km (Reheis and Noller 1991; Anderson, R.E., Bucknam et al. 1995). At its nearest point, the Keane Wonder fault zone lies 43 km southwest of Yucca Mountain. The style of faulting is primarily normal, with down-to-the-southwest displacement. No evidence of faulting in late Quaternary deposits and only equivocal evidence of isolated faulting in middle Pleistocene or older deposits was found along the main range-front fault zone. However, there is clear evidence of recurrent faulting in late Quaternary deposits on a 2-km-long fault splay near the southern end of Keane Wonder fault zone (Anderson, R.E., Bucknam et al. 1995). The youngest faulted fan surface at this locality is offset 1.8 m, and older fan deposits have been offset as much as 8-10 m. The most recent movement is estimated to have occurred 4 to 8 ka, and the ages of earlier movements are estimated to be 70 to 730 ka. Quaternary activity on this splay is more likely related to faulting on the nearby Death Valley-Furnace Creek fault system than to movement on the main strand of Keane Wonder fault zone (Anderson, R.E., Bucknam et al. 1995).

Mercury Ridge faults–The Mercury Ridge faults includes two northeast-trending faults that bound Mercury Ridge about 48 km east-southeast of the site area; the maximum length of the largest fault is 10 km. Fault relations indicate both dip-slip and strike-slip components of movement. The two faults have been variously mapped as forming the bedrock-alluvium contact, or as being concealed by Quaternary and Tertiary alluvium (Barnes, Ekren et al. 1982; Dohrenwend, Menges et al. 1991).

Midway Valley fault–The Midway Valley fault is a concealed fault within Midway Valley, about 3 km east of the potential repository, that was shown on structure sections by R.B. Scott and Bonk (1984) and later detected by gravity and magnetic surveys by Ponce (1993). These surveys suggest down-to-the-west Tertiary bedrock displacements of 40 to 60 m, but no surface displacement of the overlying early and middle Quaternary deposits has been observed either during surficial deposit mapping or in trenches in Midway Valley (Keefer and Whitney 1996). The length of the buried fault can only be estimated; the geophysical profiles show a structure at least 1 km long, and it may be as much as 5 km in total length.

Mine Mountain fault zone–The Mine Mountain fault zone, a major feature within the Spotted Range-Mine Mountain structural zone, extends along the south flank of Mine Mountain as two northeast-striking subparallel faults that are separated by as much as 200 m. Depending upon how various segments are connected, the length of the zone may be as much as 27 km; the closest distance of its projected trace to the potential repository is about 14 km. No exposure of the main fault plane has been found, so its dip is unknown. Recent mapping has shown that the Tiva Canyon Tuff is offset a distance of 1.2 km in a left-lateral sense across the fault zone at Mine Mountain, and that the Mine Mountain fault zone was active sometime during the period 7 to 10 Ma (D.W. O'Leary, USGS, written communication, Draft Milestone Report, Cane Springs and Rock Valley fault zone 1995). Fault activity may have continued at a much diminished rate into the Pleistocene epoch, but clear evidence of Pleistocene faulting has been found only at one locality at the northeast corner of Shoshone Mountain. The absolute age of this displacement has not been determined, but soil and caliche development suggests that it is older than about 50 ky.

Oak Spring Butte faults–The Oak Spring Butte faults, located along the eastern side of the Belted Range about 52 km northeast of Yucca Mountain, includes a series of generally north-trending normal faults in a zone 21 km long. Displacements are normal, with both-down-to-the-east offsets on east-dipping splays and down-to-the-west offsets on west-dipping splays. The youngest fault in the Oak Spring Butte faults is visible as a scarp on depositional or erosional surfaces interpreted to be of late Pleistocene age (Dohrenwend, Schell et al. 1992). Short sections of other faults are shown as weakly to moderately expressed lineaments or scarps on Tertiary deposits or as fault contacts between Quaternary alluvium and bedrock (Rogers, C.L. and Noble 1969; Reheis 1992; Dohrenwend, Schell et al. 1992).

Oasis Valley fault zone–The Oasis Valley fault zone is a cluster of north-trending normal faults 20 km long located in Oasis Valley some 24 km northwest of Yucca Mountain. Dip-slip displacements are both down to the east and down to the west. No clear evidence of late Quaternary movement has been found along any of the faults of the Oasis Valley fault zone (Anderson, R.E., Bucknam et al. 1995). However, a 2.5-km long section of one prominent strand is marked by a distinct air photo lineament that may reflect minor early Pleistocene displacement.

Pagany Wash–The Pagany Wash is one of the northwest-trending right-lateral strike-slip faults that have been mapped across the northeastern part of the site area (Scott, R.B. and Bonk 1984; Day et al. 1996b). It is developed in Tertiary volcanic rocks throughout much of its 4-km length, with a few short segments exposed in bedrock where it forms small scarps, but a 1-km segment is buried by surficial deposits of middle Pleistocene age toward the northwest end of the wash (W.C. Day et al., USGS, written communication to YMPB staff, Preliminary Site Geologic Map, October 1996) The fault terminates against the Solitario Canyon fault to the northwest and a north-striking fault associated with the Bow Ridge fault to the southeast. A trench excavated across Pagany Wash exposes the fault as a tightly cemented shear zone in bedrock beneath a bedrock regolith and colluvial units that are not displaced, indicating a lack of late Quaternary activity (Simonds et al. 1995; S. Pezzopane, USGS, written communication to himself, 1995).

Pahrump–The Pahrump fault zone is a northwest-striking, steeply west-dipping, right-lateral, oblique slip fault zone that lies 70 km southeast of the Yucca Mountain site. It extends for about 70 km along the east side of Stewart Valley and into central Pahrump Valley, although compelling evidence of late Quaternary deformation is present only along about 18.5-km long section. Right-lateral displacement of Paleozoic rocks is estimated to be greater than 16 to 19 km, and a minimum vertical displacement is estimated to be about 300 (Stewart 1988). The sense of Quaternary slip is similarly assumed to be primarily right lateral, but the amount of lateral displacement is unknown. The age of the most recent activity is Quaternary, evidenced by a few scarps of limited length and small surface offsets of surficial deposits (Anderson, R.E., Crone et al. 1995). The youngest movement is represented by the development of scarps ranging from 0.7 to 2.0 m in height, and by surface offsets up to 0.7 m. Though poorly constrained, these displacements may be early to middle Holocene in age (Anderson, R.E., Crone et al. 1995). The limited expression of Quaternary activity suggests that the Quaternary slip rate on the Pahrump fault zone is low, on the order of 0.009 to 0.02 mm/yr, depending on whether sediments with 15 m scarps are early Pleistocene or Tertiary in age.

Pahute Mesa faults–A number of faults have been mapped on Pahute Mesa north of Yucca Mountain. Lengths range from 0.5 to 4 km, with the longest series of overlapping fault traces in a zone measuring about 9 km in length. Nearest fault to the potential repository is at a distance of 48 km. The faults have diverse east to northwest trends and are generally shown to have dip-slip movement although there is some evidence to suggest a right-lateral strike-slip component. Based on air photo interpretations, weak to prominent lineaments or scarps have been delineated on surfaces of both Quaternary and Tertiary deposits (Reheis 1992).

Paintbrush Canyon fault–The Paintbrush Canyon fault, 4 km east of the potential repository, continues from about 10 km north of Yucca Wash to perhaps as far south as the north end of the Stagecoach Road fault, in which case it may have an overall length of about 28 km (Simonds et al. 1995). Estimates of the amount of Tertiary bedrock displacement range from 250 to 500 m down to the west (Lipman and McKay 1965; Scott, R.B. and Bonk 1984); average dip on the fault plane is about 71° west, and measurements on slickenside indicate that net displacement is dip slip to left oblique (Simonds et al. 1995). Paleoseismic studies reveal multiple faulting events along the Paintbrush Canyon fault during the Quaternary (most recent event as young as early Holocene to latest Pleistocene). Fault relationships are well exposed on the west side of Busted Butte in eolian sand deposits that record the last 600 to 700 thousand years of Pleistocene depositional and faulting history (Menges, Wesling et al. 1994; Menges and Whitney 1996b). Six to seven faulting events can be identified, with the oldest event occurring above sand with silicic ash correlated with the Bishop ash, three to four occurring after formation of a soil dated at about 400 ka., and the youngest occurring probably within a time period of 35 to 75 ka (50-60 ka preferred) (Paces, Menges et al. 1994; Menges and Whitney 1996b). Three to four faulting events are recorded in Quaternary deposits exposed in a trench excavation at the southeastern edge of Midway Valley (Menges and Whitney 1996b). The age of the oldest event at this locality has not been uniquely determined, but the most recent event displaced a unit dated at 38 ± 6 ka; this unit in turn is overlain by an unfaulted unit dated at 6 ± 1 ka (Menges and Whitney 1996b). Tighter timing constraints establish a 9 to 17 ka age for the most recent event on the fault in a trench at the northwestern base of Alice Ridge; there is evidence for at least three or more older events at this site (Menges and Whitney 1996b). The amount of the late Quaternary cumulative slip displayed in the Midway Valley trench excavation is 1.7 to 2.7 m, and at the Busted Butte exposures, total Quaternary displacement is 4.8 to 7.8 m. Total cumulative displacements are less (>1.45 to 1.7 m) at Alice Ridge. Single displacements vary widely both at and among sites, with preferred dip-slip ranges of 44 to 167 cm for Busted Butte, 40 to 98 cm for Midway Valley, and 6 to 39 cm for Alice Ridge. The combined age and displacement data indicate average recurrence intervals of 20 to 50 ky and a slip rate of 0.007 to 0.03 (preferred 0.015) mm/yr for the Midway Valley trench locality, preferred recurrence intervals of 50 to 120 ky and a slip rate of 0.001 to 0.01 (preferred 0.007) mm/yr for the Busted Butte locality, and preferred recurrence intervals of 80 to 100 ky and 0.001-0.004 (preferred 0.002) mm/yr for the Alice Ridge site (Menges and Whitney 1996b).

Paintbrush Canyon-Stagecoach Road faults–The combined length of these two faults is about 33 km. Each displays a history of recurrent Quaternary activity and, if they were to behave seismically as a single feature, the potential rupture could cause larger moment magnitudes and peak accelerations than ruptures that might occur on only one of the faults (see Table 3.10-10; Subsection 3.10.8.1; Pezzopane 1996).

Panamint Valley fault–The Panamint Valley fault is a 100-km long, generally north-striking fault that bounds the east side of the Panamint Range, about 95 km south-southwest of Yucca Mountain. The sense of displacement is predominantly dip slip with significant right-lateral components on some sections of the zone. Most of the Panamint Valley fault displays abundant evidence of late Quaternary or Holocene activity, with scarps as much as 6 to 61 m high formed probably during multiple faulting events (Smith, R.S.U. 1979). Some scarps occur along the range front, and others cross alluvial fans. Dip-slip displacements on the most recent event at the southern end of the fault is 0.4 to 1.2 m on the range-front fault (Zhang et al. 1990). At different localities, right-lateral displacements of topographic ridges with a maximum age of 17 ± 4 ka were measured as 24 ± 4 m, 27 ± 4 m, and 37 ± 4 m. Scarps from older events in some places show right-lateral displacements of 6 to 7 m for possibly two events and 11 ± 2 m for three to four events. Based on a displacement of 37 ± 4 m for a ridge dated as 17 ± 4 ka, a minimum Holocene-latest Pleistocene right-lateral slip rate is estimated to be 2.4 ± 0.8 mm/yr (Zhang et al. 1990). The average recurrence interval is estimated to range from 700 to 2,500 year (Smith, R.S.U. 1979).

Plutonium Valley-North Halfpint Range fault–The Plutonium Valley-North Halfpint Range fault is located along the western side of the Halfpint Range at its junction with Plutonium Valley and Yucca Flat. Various strands of this north-northwest-trending fault zone can be traced for a total distance of about 26 km; it lies 46 km east-northeast of the site area. Displacements are primarily dip-slip, with both down-to-the-east and down-to-the-west offsets. Short segments of the Plutonium Valley-North Halfpint Range fault are shown as weakly expressed lineaments and scarps on surfaces of both Quaternary and Tertiary deposits (Reheis 1992). Other sections are shown either as forming a fault contact between bedrock and Quaternary alluvium or as being concealed by the alluvium (Cornwall 1972).

Rock Valley fault–The Rock Valley fault system, located about 27 km southeast of Yucca Mountain, comprises at least three major east-northeast-striking left-lateral fault strands and numerous other complex interconnecting faults for a length of about 65 km within Rock Valley. Recent studies show that the fault zone has been episodically active since late Oligocene time, and the total displacement (largely left-lateral slip) is less than 4 km (D.W. O'Leary, USGS, written communication, Draft Milestone Report, Cane Springs and Rock Valley fault zone 1995). Quaternary displacements are distributed across three distinct strands where the fault occupies the main central part of Rock Valley. Most of the vertical displacement apparently has occurred prior to the last 10 Ma, although a seismic reflection profile in Rock Valley shows a subdued largely buried half-graben structure (Coe, Yount, et al. 1996). Quaternary fault scarps are preserved, particularly in the prominent central and northern part of the fault zone where scarp heights range from less than 1.0 to 2.5 m. Relations exposed in the western part of Rock Valley show the development of a 3-km wide graben having a scarp relief of nearly 2 m developed on the northern and central fault strands. A trench across the central strand in the graben structure reveals two faulting events; the most recent event occurred within the past 38 ky and is associated with 30 cm of vertical displacement, which, adding a probable left lateral component at a 22° rake, yields a possible 85 cm of net total displacement (Yount et al. 1987). More recent trenching investigations indicate at least three events on the southern and five events on the northern strands (Coe, Yount, et al. 1996). The most recent event is late Holocene in age on the southern strand, based on small displacement (0 to 10 cm of vertical and unknown lateral components) of units less than 2.5 ka in age. The lateral and vertical components for cumulative net slip associated with the five events on the northern strand are 14.2 and 1.2 m, respectively, based on the total offset of a channel thalweg across the fault. The recurrence intervals between the most recent and penultimate events is short, 5 to 10 ky, but the most recent event is present on only the southern strand and timing data is not available for older events. A recurrence rate on the order of 10^4 may be more representative of the overall fault zone. Poorly constrained late Quaternary slip rates are estimated as 0.05 to 0.02 mm/yr on the northern and central strands, and <0.002 mm/yr on the southern strand. Repeated, clustered, low-level (M_L 4.0) earthquakes within Rock Valley and vicinity indicate that faults within the zone remain seismically active (see Subsection 3.10.4.2). An M 3.5 earthquake occurred along the zone on September 7, 1995; the hypocenter was at a depth of

4 km and movement was strike-slip (K.D. Smith, University Nevada Reno, written communication to S. Pezzopane, USGS, 1995).

Rocket Wash-Beatty Wash fault–The Rocket Wash-Beatty Wash fault trends generally north for a distance of approximately 17 km. It is located about 19 km northwest of the potential repository site. The zone consists of a series of north-trending fault strands, with both down-to-the-east and down-to-the-west displacements of 10 to 30 m in Miocene volcanic rocks. Geomorphic and geologic relationships indicate that most or all displacement on this fault zone occurred in the late Miocene. There is no field evidence for offset or disruption of Quaternary deposits along the fault trace (Anderson, R.E., Bucknam et al. 1995).

Sarcobatus Flat fault zone–The Sarcobatus Flat fault zone lies along the western margin of Pahute Mesa and northeast of Sarcobatus Flat, located about 52 km northwest of the site area. The north-northwest-trending zone contains a series of relatively short faults (maximum length 12 km) with generally down-to-the-west displacements of Tertiary rocks, and can be traced for a total distance of about 51 km. Only one scarp about 100 m long with about 0.6 m of relief has been observed in alluvium, but there is no clear evidence that it represents a fault scarp. Several short inconspicuous lineaments in Quaternary deposits are recognizable on aerial photographs, but none of the lineaments examined in the field show surface offsets (Reheis 1992; Anderson, R.E., Bucknam et al. 1995).

Sever Wash fault–The northwest-trending, right-lateral strike-slip Sever Wash fault is mapped for a distance of about 4 km in the northern part of the site area (Scott, R.B. and Bonk 1984). The near-vertical main trace of the fault is exposed in Tertiary volcanic rocks on the southern flank of Sever Wash with evidence in the form of slickensides and Reidel shears for right-lateral stike-slip movements (W.C. Day et al., USGS, written communication to YMPB staff, Preliminary Site Geologic Map, October 1996; Day et al. 1996b). Parts of the fault are concealed by alluvium of Holocene age along the floor of the wash, and these deposits do not show evidence of having been disturbed by faulting (Simonds et al. 1995).

Solitario Canyon fault–The main trace of the Solitario Canyon fault extends southward from Yucca Wash for at least 18 km, and lies very near the western boundary of the potential repository (Simonds et al. 1995). Bedrock displacements vary from 61 m down-to-the-east at the northern end to more than 500 m down-to-the-west at the southern end (Scott, R.B. and Bonk 1984). Average dip of the fault plane is 72° west; slickensides indicate a component of left-lateral slip. A Quaternary fault scarp of mixed tectonic and erosional origin along the Solitario Canyon fault at the bedrock-surficial deposit contact can be traced fairly continuously for at least 14 km. Evidence from trenching suggests that four to six mid to late Quaternary surface-displacement events occurred, with an estimated cumulative dip slip of 2.2 ± 0.4 m (Ramelli et al. 1996). Single displacements are variable; estimates range from 10 to 120 cm. The most recent possible event is considered to be 15 to 60 ka (25 ka preferred) in age, and the ages of all of the four main events are probably less than 150 to 250 ka. The average recurrence interval for late Quaternary surface faulting is estimated to be within the range of 35 to 100 ka, with preferred values of 50 to 70 ka. Preliminary estimates of average slip rate range from 0.01 to 0.02 mm/yr; the preferred rate is 0.01 mm/yr (Ramelli et al. 1996). Basaltic ash is present at four trench sites along Solitario Canyon fault. The age of events associated with the ash is estimated to have occurred between 60 and 100 ka (preferred age of 75 ± 10 ka), based on preliminary uranium-series ages and tentative geochemical correlations of the ash with likely source eruptions at the Lathrop Wells cone (F. Perry, Los Alamos National Laboratory, written communication to S. Pezzopane, USGS, 1996).

South Ridge faults–The South Ridge faults are represented by two main faults, one of which can be traced nearly continuously for about 19 km. The faults, trending east to northeast with variable dip-slip to strike-slip displacements, are 50 km east-southeast of Yucca Mountain. One of the faults has been mapped as the contact between bedrock and Quaternary alluvium, and sections of other faults are shown either as being prominent to weakly expressed lineaments or scarps on Tertiary deposit surfaces or as being concealed by Quaternary and Tertiary alluvium (Barnes, Ekren et al. 1982; Dohrenwend, Menges et al. 1991; Reheis 1992).

Spotted Range faults–The Spotted Range faults are located primarily along the western side of Spotted Range, approximately 59 km east-southeast of the potential repository site area. Several north- to northeast-striking normal faults with down-to-the-west displacements are included over a length of 30 km. Individual faults juxtapose Quaternary alluvium against bedrock or occur as scarps on Quaternary and Tertiary surfaces (Dohrenwend, Menges et al. 1991; Reheis 1992).

Stagecoach Road fault–The Stagecoach Road fault is a north- to northeast-trending normal fault on the southeastern corner of Yucca Mountain, about 10 km south of the potential repository (Scott, R.B. 1992). It can be traced in mid-Pleistocene alluvium for approximately 4 km south of Stagecoach Road before becoming concealed beneath Holocene surficial deposits; total length of the fault may be as much as 9 km. The Stagecoach Road fault has variously been connected northward with the Iron Ridge fault or northeastward with the Paintbrush Canyon fault (Simonds et al. 1995). The amount of bedrock displacement is estimated to be 400 to 600 m down to the west (Scott, R.B. 1990); average dip is 73° west. Trench excavations display evidence for 3 to 7 faulting events during late Quaternary time (about 10 to 110 ka), with the age of the most recent event estimated to be early Holocene to latest Pleistocene (6 to 15 ka) (Menges and Whitney 1996b; Menges, Oswald et al. 1998). Alluvium of late Quaternary age is displaced 1.0 to 2.3 m, and slickenside measurements show that movement was predominantly dip-slip. Estimates of net single displacements vary from 14 to 99 cm, with preferred values of 40 to 67 cm. The age relations indicate average recurrence intervals of 5 to 50 ky (preferred range of 10 to 30 ky). Fault slip rates range from 0.006 to 0.07 mm/yr; preferred values are 0.03 to 0.05 mm/yr (Menges and Whitney 1996b; Menges, Oswald et al. 1998). A tuff with a K-Ar age of 8.5 ± 3 Ma has been vertically displaced about 100 m across the fault, which yields a long-term slip rate of 0.009 to 0.018 mm/yr.

Sundance fault–The Sundance fault was first identified by Spengler, Braun et al. (1994) as a series of near-vertical northwest-trending faults that intersect the Ghost Dance fault in the northern part of the repository block. More detailed mapping indicates that the total length of the fault is 750 m, and that it cannot be traced across the Ghost Dance fault (Potter, Dickerson, Day 1995; Day et al. 1996b). Cumulative down-to-the-northeast displacement of the Tiva Canyon Tuff bedrock does not exceed 11 m in surface exposures; slickensides observed in the Exploratory Studies Facility suggest a component of strike-slip movement. The fault is developed entirely in bedrock, but there is no evidence to indicate that any of the faulting activity occurred during the Quaternary.

Tolicha Peak fault zone–The Tolicha Peak fault zone is comprised of several individual north-northwest-trending faults that are located about 42 km northwest of Yucca Mountain. The combined length of the faults is approximately 22 km. Displacements are primarily shown as down to the southwest, but at some localities movement was apparently down to the northeast and at one place right-lateral, oblique slip is indicated (Reheis 1992). Moderately expressed to prominent lineaments and scarps have been mapped by photointerpretation on Quaternary surfaces (Reheis 1992). However, R.E. Anderson, Bucknam et al. (1995) found no unequivocal evidence of faulting in Quaternary deposits along any of the mapped areas in the field, and found little evidence to support the presence of a through going fault in this area.

Wahmonie fault–The Wahmonie fault trends generally northeast within the 30 to 60-km wide Spotted Range-Mine Mountain structural zone of northeast-trending, left-lateral faults that have experienced relatively small amounts of displacement. The length of Wahmonie fault is approximately 15 km, and its closest distance to the potential repository site is 22 km. The youngest displacement is considered to be Pleistocene, based on the presence of scarps or lineaments in deposits dated as 270 to 740 ka, and concealment of the fault trace beneath Holocene deposits (Swadley and Huckins 1990). At the southwest end of the fault zone, displacement is down to the northwest, but at the northeast end it is down to the southeast; total amount of displacement is not known.

West Pintwater Range fault–The West Pintwater Range fault is a west-dipping normal fault that trends generally north along the west flank of the Pintwater Range. The fault, located about 76 km east of Yucca Mountain, is discontinuous over a length of about 82 km. Displacements, generally down to the west, are reflected as prominent lineaments and scarps on Quaternary (primarily) and Tertiary deposits as young as early to middle and (or) late Pleistocene. At its northern end, the fault is mapped as the contact between bedrock and Holocene to Pliocene alluvium and colluvium (Ekren, Orkild et al. 1977; Dohrenwend, Menges et al. 1991).

West Specter Range fault–The West Specter Range fault bounds the western flank of a south-trending arm of the Specter Range, about 33 km southeast of Yucca Mountain. It trends generally north for a distance of about 9 km; displacement is dip-slip, predominantly down-to-the-west, with possibly a minor lateral component. Approximately 40 percent of the West Specter Range fault is characterized by scarps on Quaternary materials; about 35 percent is marked by tonal or vegetational lineaments or drainage alignments that may be associated with surface rupturing; and the remainder is concealed beneath unfaulted deposits (Anderson, R.E., Bucknam et al. 1995). The youngest movement is interpreted to be latest Pleistocene or Holocene along the northern section of the fault. The total surface offset represented by scarps on alluvium range from 0.3 to 0.5 m on the youngest faulted alluvium (about 15 ka) to as much as 1.4 m on older faulted alluvium (>128 ka). R.E. Anderson, Bucknam et al. 1995) estimate that the West Specter Range fault has a poorly constrained recurrence interval of at least 113 ky and a slip rate of <0.004 mm/yr between 15 and 128 ka.

West Spring Mountain fault–The West Spring Mountain fault is a 60-km long, north-northwest-striking, west-dipping normal fault that bounds the southwest side of the northern Spring Mountains. The fault is about 53 km southeast of the potential site. The main fault probably dips to the west at a high angle and has predominantly normal slip, but scarps along the southern extension show a left-stepping pattern that suggest possible right-lateral, oblique-normal slip. The West Spring Mountain fault forms scarps on surface deposits of Pleistocene age; the youngest surface-faulting event probably occurred during the latest Pleistocene or early Holocene and caused about 1.8 to 2.0 m of surface offset on the central section of the fault (Anderson, R.E., Bucknam et al. 1995). The 11-km long central section contains the largest scarps along the West Spring Mountain fault, indicating either larger displacement events than normal and (or) more frequent events than elsewhere along the fault. Scarps as large as 13.4 m (9.4 m of surface offset) on middle Pleistocene fan alluvium along the central section are considered to record average recurrence intervals of more than 28 ky and long-term slip rates of less than 0.07 mm/yr.

Windy Wash fault–The Windy Wash fault is a north-northeast-trending, west-dipping, normal-oblique slip fault on the east side of Windy Wash. The fault, located about 4.5 km west of the potential repository site, can be traced discontinuously from the southern rim of the Claim Canyon caldera to the southeastern edge of Crater Flat, a distance of about 25 km (Simonds et al. 1995). The amount of down-to-the-west Tertiary bedrock displacement is interpreted to be less than 500 m (Scott, R.B. 1990). Average dip of the fault is 63° to the west; slickenside measurements indicate mostly dip-slip displacement, with slight components of both right- and left-lateral slip. Evidence for Quaternary displacement along the northern and southern parts of the Windy Wash fault is limited to fault scarps in alluvium and fractures in the hanging walls of fault-line scarps. Trenches across scarps in alluvium along the central part contain evidence of 5 to 8 events in the past 400 ka (Whitney, Shroba et al. 1986; Whitney, Simonds et al. 1996). The most recent event displaced a late Holocene vesicular silty sand deposit by <10cm that underlies the modern desert pavement. Vertical displacements for the other events range from 8 to 100 cm, with preferred values of 12 to 88 cm. Middle gravels exposed in one trench across the central fault segment are displaced about 3.7 m down to the west. Recurrence intervals are estimated to vary from 40 to 57 ka, and average slip rates are computed as 0.0105 to 0.0092 mm/yr (Whitney, Simonds et al. 1996). This is somewhat lower than the 0.27 mm/yr long-term slip rate computed from 101 m of net offset of a basalt flow with 3.7 Ma K-Ar dates (Whitney, Menges et al. 1996).

Yucca fault–The Yucca fault is a north-trending, east-dipping fault that is estimated to be about 32 km long; it is located within Yucca Flat, about 40 km northeast of Yucca Mountain. Dips of 75°E to 80°E near the surface appear to flatten to 55° to 65° with depth. Vertical displacement of Tertiary volcanic rocks is 200 m, but the lateral component of movement (apparently right-lateral) may be equal to or greater than this amount. Quaternary activity is clearly indicated by scarps on Quaternary deposits (scarp heights are as much as 15.3 m) and by faulting of Quaternary deposits (Fernald et al. 1968; Swadley and Hoover 1990; Dohrenwend, Schell et al. 1992). Stratigraphic units ranging in age from about 160 to 800 ka are displaced along much of the length of the fault, and the youngest event may be late Pleistocene in age. In places, the Yucca fault is concealed by small deposits of Holocene alluvium.

Yucca Lake fault–The Yucca Lake fault is a generally northwest-trending normal fault, with displacement down to the northeast. Total length is about 17 km, and it lies about 36 km northeast of the Yucca Mountain site. As mapped by Cornwall (1972), the fault displaces Quaternary alluvium along a 13-km section, but data on the faulting characteristics or amount and age of displacement are lacking.

Yucca Wash fault–The Yucca Wash fault was inferred by R.B. Scott and Bonk (1984) to extend northwest beneath Quaternary alluvium in Yucca Wash for a distance of about 9 km based primarily on abrupt changes in the amount and style of deformation in rocks to either side of the drainage. The fault, postulated as right-lateral in character, is nowhere exposed, and the surficial deposits that mantle the floor of the wash are nowhere disturbed. Recent mapping and ground magnetic surveys have shown that north- to north-northwest-striking faults are the dominant structures in the wash and that many faults on the north side of Yucca Wash can be projected continuously south across the drainage into Midway Valley based on correlations of surface expressions of faults and geophysical anomalies (W.C. Day et al. USGS, written communication to YMPB staff, Preliminary Site Geologic Map, October 1996; Ponce and Langenheim 1994; Dickerson 1996). These relations indicate a northwest-trending strike-slip fault is not present along Yucca Wash.

3.10.7 Relevant Earthquake Sources

Pezzopane (1996) evaluated the relevance of faults in the Yucca Mountain region to the seismic hazard assessment for the potential repository. This was subsequently updated in the Deterministic Seismic Hazard Analysis (Subsection 3.10.10). The objectives were to provide a preliminary evaluation of whether known and suspected Quaternary faults within the region are subject to displacement and to evaluate whether maximum earthquakes on these faults could produce an 84th percentile peak horizontal acceleration at the potential repository site that equals or exceeds 10 percent of gravity (0.1 g) (NRC 1992). Results of this study were made available to the expert panel evaluating seismic sources for their consideration in characterizing inputs to the probabilistic seismic hazard analyses (Subsection 3.10.9). The remainder of this subsection is from Pezzopane (1996), unless otherwise referenced.

Ninety-four known or suspected individual faults and six fault combinations (assumed compound rupture on two or more faults) were identified for consideration as potential independent earthquake sources within the region (within 285 km of the Yucca Mountain site; Table 3.10-11). This evaluation was based on compilations of regional and local faults by Piety (1996) and Simonds et al. (1995). The evidence for Quaternary displacement together with estimates of maximum fault length were tabulated for each fault. Empirical relations were used with maximum fault lengths to calculate maximum earthquakes (Subsection 3.10.6.8). Ground motions were calculated using the maximum magnitudes and minimum fault-to-site distances with the average of five attenuation relations to identify those faults capable of generating median and 84th percentile values of peak horizontal acceleration of 0.1 g or greater on rock sites at the ground surface at Yucca Mountain. The evaluation did not consider time-dependent data such as fault slip rates or earthquake recurrence rates. It thus provides an evaluation of the potential level of peak acceleration an estimated maximum earthquake on each fault would produce at the site independent of time. The evaluations resulted in the identification of 67 faults or fault combinations that are classified as either relevant or potentially relevant earthquake sources. Relevant earthquake sources are defined as those documented with Quaternary displacement for which the maximum magnitude earthquake can produce a peak horizontal acceleration (84th percentile) of 0.1 g or greater at the site. Potentially relevant earthquake sources are similarly defined with the only difference being that Quaternary displacement is suspected, but not documented.

Brief descriptions of the faults classified as relevant or potentially relevant are given in Subsection 3.10.6.8. The descriptions, which incorporate much of the information from Piety (1996) and Simonds et al. (1995), as well as the results of recent paleoseismic studies of faults within and near the potential repository (Whitney and Taylor 1996), summarize the documented evidence for Quaternary fault activity, such as slip rate data, and supplement the data presented in this subsection.

Thirty-two Quaternary faults or fault combinations were identified as relevant seismic sources. Five more faults, which have only suspected Quaternary activity, were considered relevant because the faults may be structurally related to historical seismicity or other Quaternary faults or both, resulting in a total of 37 relevant fault sources all within 100 km of Yucca Mountain (Figure 3.10-16). Thirty potentially relevant faults were also identified (Figure 3.10-16). Some of the suspected Quaternary faults at Yucca Mountain are only a few kilometers long and are structurally bounded by longer, more prominent Quaternary faults. On the basis of their limited potential rupture dimensions, these local faults are unlikely to be individual seismogenic sources; yet, some of the short, intra-block faults are relevant to fault displacement hazard assessments because they could slip during nearby earthquakes on the bounding Quaternary faults. All but 6 of the 67 relevant and potentially relevant faults and fault combinations are located within 60 km of Yucca Mountain. More than half of the 37 relevant faults and most of the 30 potentially relevant sources have only limited paleoseismic data with which to assess Quaternary activity, slip rates, and recurrence intervals for use in probabilistic hazard assessments.

3.10.8 Estimation of Vibratory Ground Motion

The vibratory ground motions adopted for the seismic design of the potential repository should incorporate the effects of the seismic sources, propagation path, and local site geology specific to the Yucca Mountain region and site to the extent possible. Ideally, recorded ground motions from earthquakes in the Yucca Mountain region or Basin and Range Province would be used to develop attenuation relations for application at Yucca Mountain, but such data are small in amount and are not sufficient to adequately constrain any empirical models. The few data recorded in the Yucca Mountain region and Basin and Range Province and the geophysical and seismological properties derived for the region do nevertheless provide valuable information for estimating ground motions at the repository site.

Ground motions could be estimated from the empirical attenuation relations used for sites in the western United States but these are based primarily on strong motion records from reverse and strike-slip earthquakes in California. The style-of-faulting factors incorporated in some recent attenuation relations distinguish between reverse and strike-slip mechanisms. Normal faulting events are usually grouped with strike-slip events because the few normal faulting recordings have not shown larger ground motions than predicted for strike-slip events. Thus characterizing ground motions at Yucca Mountain using attenuation relations involves resolving whether (and to what extent) existing western United States attenuation models are applicable to the Basin and Range Province in general, and to Yucca Mountain in particular. The seismological questions asked must include whether differences in the factors which influence ground motions in the Yucca Mountain region and in the western United States would lead to significant differences in ground motion estimates for the two regions. These factors include seismic source properties, regional crustal properties, and shallow geologic site properties at the repository. Generally, comparisons must be made between Yucca Mountain factors and 'average' factors inherent in the western United States strong motion database.

Four ground motion studies have been completed recently that address these issues. The first, conducted by the USGS, was an empirical analysis of worldwide ground motion data from extensional regimes (Spudich et al. 1996). The expansion beyond the Basin and Range Province was necessary to build up a large enough database to yield statistically significant results. The second study comprised numerical modeling of selected scenario earthquake near Yucca Mountain in which ground motions were estimated using seismological models of the source, path, and site effects (Schneider et al. 1996). The numerical modeling allowed the region-specific crustal structure and site-specific rock properties to be incorporated in the ground motion estimates. The third study, conducted by the University of Nevada, Reno used weak motion recordings to characterize the near-surface attenuation at Yucca Mountain (Su et al. 1996). The last study is a ground motion characterization performed as part of the Probabilistic Seismic Hazard Analyses Project (Subsection 3.10.9) and is the most comprehensive of the four (USGS 1998). It incorporated results from the other three studies and resulted in ground motion attenuation relations specific to Yucca Mountain. The results of these four studies are described in the following sections.

3.10.8.1 Key Seismologic Parameters

Several key seismologic parameters are integral to the four ground motion studies discussed subsequently, particularly the various modeling studies. Insofar as they form the input to the various models, the parameters, and often their uncertainties, must be accurately quantified. The following discussion presents the current understanding of several of these parameters. The values assigned to the parameters used in each study are included in their primary references.

Path Q and Geometrical Spreading–The attenuation properties for the southern Great Basin (including Yucca Mountain) vary widely depending upon the data set and the analysis method. Several studies have made observations of the ground-motion attenuation rate with distance, which includes the combined effects of geometrical spreading and the damping parameter Q. In a study of Modified Mercalli intensities for the 1952 Kern County earthquake, Evernden (1975) concluded that there was a slightly lower ground motion decay rate toward the southern Great Basin than in Southern California. On the other hand, Chavez and Priestley (1985) found slightly greater attenuation in the southern Great Basin than in Southern California from an evaluation of the M_L scale. And in a most recent study, R.B. Herrmann (Schneider et al. 1996) showed comparable rates of decay in normalized geometrical spreading curves from the southern Great Basin and New Madrid.

Considering Q alone, and taking $Q(f) = Q_o f^\eta$ (f is frequency), various investigators have found significant differences in Q_o and η (Schneider et al. 1996). Values of Q_o at 1 Hz have been computed that vary between about 140 and over 750 with η ranging from 0.04 to 1.05.

Some factors contributing to these differences include the influences of:

- Assumptions about geometrical spreading and scattering
- Other source, path, and site effects
- Widely varying frequency bands, source-receiver distances, and regions of coverage
- Scattering versus anelastic Q

- Vertical versus horizontal component records and
- Earthquake versus explosion sources

Although the apparent differences in Q can be quite large, it is likely that a significant portion of these differences has origins in one or more of these factors.

For ground motion estimation at Yucca Mountain, uncertainty in Q has a relatively small impact on ground motion variability due to the dominance of close-in sources as suggested by the seismic hazards analysis of the Exploratory Studies Facility (Wong et al. 1996). However, the uncertainty is a factor at very high frequencies, for very low Q values, and for long travel paths (for example, at least 50 to 100 km).

Two-D Crustal Structure–Many underground nuclear explosions have been recorded at Yucca Mountain and in the surrounding region. Some of this data has been analyzed by Walck and Phillips (1990). The data constitute 1829 recordings from 109 events; of the recordings, 429 are from Yucca Mountain including 128 downhole recordings.

Based on these data, Walck and Philips (1990) developed 2-D velocity profiles from Pahute Mesa to Yucca Mountain and from Yucca Flat to Yucca Mountain. The 2-D structure is more prominent from Yucca Flat to Yucca Mountain than from Pahute Mesa to Yucca Mountain. For very shallow sources, such as underground nuclear explosions, this structure can have a significant effect on the ground motion. However, the effect on ground motions from earthquake sources at typical seismogenic depths (5 to 15 km) compared to the near-surface explosion sources has not been evaluated.

Site Kappa–Recordings of regional earthquakes at Yucca Mountain have been used to evaluate the near-surface attenuation (or spectral decay) parameter kappa at twelve sites by Su et al. (1996). Their data set comprises broadband digital recordings of twenty aftershocks of the 1992 Little Skull Mountain earthquake. These aftershocks occurred southeast of Yucca Mountain at distances of about 15 to 30 km, focal depths of 9 to 12 km and magnitude range M_L 2.6 to 4.5. The recording sites are located generally east and southeast of Yucca Mountain within about 40 km. Thus the results represent an estimate of kappa only for paths between Yucca Mountain and sites about 30 km to the southeast.

The computational approach involves simultaneous least-squares fitting of kappa, seismic moment, and corner frequency to the S-wave spectra (Anderson, J.G. and Humphrey 1991). The equation forms assume that the source spectrum corresponds to a Brune pulse with the displacement spectrum falling off proportional to ω^{-2} and that geometric spreading is 1/R. All other differences between the source and site spectra, including all path and site effects, are mapped into kappa.

The values of site kappa vary between a minimum of 0.005 sec at a station on Paleozoic rock and a maximum of 0.03 sec for a station on soil over Tertiary rock. Kappa measured at a site on the Yucca Mountain crest is 0.023 sec and, on the flank, 0.014 sec. The median kappa for all sites is 0.015 sec with a median standard deviation of the computed kappas of about 0.003. The average kappa of two tuff sites is 0.018 sec. These values are lower than for typical California softrock (0.03 to 0.04 sec; Silva and Darragh 1995). Therefore, at low levels of shaking, there is less damping from the tuff than for California soft-rock conditions. This leads to larger high frequency ground motion on the tuff as compared to California soft-rock, assuming that all other parameters are the same.

Although these results pertain to conditions in the Yucca Mountain region, the values obtained are limited by the data set available for interpretation. The data are deficient in large magnitude earthquakes (M_w 6.5 and larger); the smaller magnitudes limit the strains which develop in the media and consequently limit any potential nonlinear site effects. The data are also limited in the range of source-to-site recording distances and geometries. Variations in properties due to deeper structure, which would be sampled by earthquakes at longer distances, and due to any azimuthal differences in structure cannot be evaluated.

Local Seismic Velocity Structure–Of the many geotechnical and geophysical studies completed at the repository site, only very recent studies have reliably measured in situ velocities (Majer et al. 1996a). Most geophysical surveys were not conducted to measure near-surface values and the results are not reliable within the uppermost several hundred meters. Furthermore, the few geotechnical investigations yielding dynamic properties are not consistent with in situ velocity measures (Majer et al. 1996b). Only the Vertical Seismic Profile logging performed by Majer et al. (1996a) and Balch and Erdemir (1996) provides a reliable measure of the velocity profiles at six borings at Yucca Mountain. The results of these investigations are specifically applicable only at low strain. At strains of engineering interest, the shape of the strain-dependence must be assumed.

Vertical Seismic Profile surveys have been performed in six boreholes (G-2, G-4, NRG-6, SD-12, WT-2, by Majer et al. 1996b; UZ#16 by Balch and Erdemir 1996; Figure 3.10-17). These all lie on or outside the current repository boundary. The borings neither directly sample the repository block nor sample materials completely surrounding the block. Inferences made about repository conditions are therefore less reliable than if this were not the case.

Testing in boreholes G-4 and SD-12 used a hammer source which adequately samples shallow strata. Testing in the remaining boreholes and other testing in SD-12 used a vibroseis source. The deepest depth sampled was about 2,200 feet in borehole G-2. The Vertical Seismic Profiling field measurements were processed under Majer's direction to obtain P- and S-wave interval velocities (Majer et al. 1996b; Daley, Lawrence Berkeley National Laboratories, verbal communication in meeting, to A. Becker, Woodward-Clyde, 1997). The S-wave velocities from all borehole tests are shown in Figure 3.10-18.

Velocities in several thermal-mechanical layers were computed from these data (Table 3.10-12). Data on lithostratigraphic unit thicknesses from CRWMS M&O (1997e) were used to relate velocities in the six boreholes tested to the thermal-mechanical layers present in the upper 2000 feet. The average thicknesses of these layers under Yucca Mountain were evaluated from data from 67 borings (all borings) reported in CRWMS M&O (1997e).

Johnson, Majer, and Daley (University of California Berkeley and Lawrence Berkeley National Laboratories, verbal communication in meeting, to A. Becker, Woodward-Clyde, 1998) used the interval velocities to infer a representative velocity profile to a depth of about 1,000 feet (Table 3.10-13). The S-wave profile is shown in Figure 3.10-19 together with the thermal-mechanical layer velocities. The extreme upper and lower bound limits on the velocities reflect the wide spread in the interpreted interval velocities.

Below these depths, the velocity structure can be inferred to depths of about 3 km from refraction survey data (Mooney and Schapper report on status of regional geophysics, USGS Bulletin, in press, 1994), assuming a constant Poisson's ratio of 0.25. Below 3 km, the only available information on the velocity structure is found in the profiles used in regional earthquake locations (Harmsen 1993a). This deeper structure is shown in Figure 3.10-20.

Earthquake Stress Drop–An evaluation of stress drops for earthquakes in extensional regimes was performed in support of the ground motion characterization effort in the Probabilistic Seismic Hazard Analyses Project (USGS 1998) (stress drop is the difference in stress across the fault before and after an earthquake). Stress drop affects high-frequency ground motions so that a value greater than is typical for western United States earthquakes will increase high frequency motions above what is given by western United States empirical attenuation relations.

For the Yucca Mountain Project, a data set composed of earthquake records from extensional tectonic regimes, including both normal and strike-slip mechanisms, was compiled by Spudich et al. (1996) (further discussed in Subsection 3.10.8.2). These data were supplemented with data from the 1995 Dinar, Turkey earthquake which were not available to Spudich et al. (1996). The final data set comprised 210 horizontal components from 140 sites in 24 earthquakes, a magnitude range of M_w 5.1 to 6.9, and distances from 0 to 102 km. The Fourier spectra of these data were fit to a Brune-type spectrum with ω^{-2} spectral roll-off. A two-step inversion process was adopted to decouple the inversions for kappa and for stress drop. Stress drops computed for each earthquake were weighted to yield a median value for each mechanism.

The median stress drop for normal faulting earthquakes was about 45 bars and the value for strike-slip earthquakes (in extensional regimes) was about 55 bars. In comparison, stress drops for western United States earthquakes are about 70 to 100 bars (e.g., Boore and Joyner 1997). These differences in stress drop contribute to lowered high frequency motions in extensional regimes compared to transpressional regimes such as coastal California. The differences in normal faulting stress drop compared with the western United States values account for about a 15 percent reduction of normal faulting ground motion relative to western United States motion. Within extensional regimes, the stress drop differences between mechanism result in ground motions in normal earthquakes about 85 percent of strike-slip mechanisms.

3.10.8.2 Strong Motion Attenuation in Extensional Regimes

Spudich et al. (1996) conducted an empirical study of strong ground motions recorded in extensional regimes to assess whether the attenuation was different from standard attenuation models for shallow crustal earthquakes in other tectonic regions particularly California. They also developed a new set of attenuation relations based solely on these extensional regime data.

The earthquakes used in their study were all located in extensional tectonic regimes. Because the number of events in the entire Basin and Range Province is limited, the database includes ground motion recorded worldwide. Earthquakes with normal dip-slip, oblique, and strike-slip mechanisms were evaluated together. A total of 373 recordings (253 horizontal and 120 vertical recordings) is included in the final database. These represent earthquakes between M_w 5.1 and 6.9 and distances up to about 100 km.

Extensional Data and Western United States Empirical Attenuation Relations–Several representative attenuation relations based on western United States data were compared to the extensional data by Spudich et al. (1996): Boore et al. (1993), Idriss (1991), Sadigh et al. (1993), Campbell (1989, 1990), Campbell and Bozorgnia (1994), and Sabetta and Pugliese (1996). These relations generally represent the state-of-the-art in ground motion attenuation studies at the time of the Spudich et al. (1996) study.

The mean residual, or bias, was computed for each attenuation relation and indicates whether that model systematically underpredicts or overpredicts the extensional strong motion data. In general, the computed residuals indicate that the standard western United States attenuation relations overpredict ground motions from extensional regimes by about 15 to 35 percent on average (Spudich et al. 1996). At Yucca Mountain, near-fault ground motion is important because the background earthquake at close distances controlled the probabilistic hazard in the Exploratory Studies Facility study. Therefore, the bias was computed for a subset of the extensional data including only sites at distances less than 20 km (Spudich et al. 1996). For this short distance range, the overprediction is somewhat greater than for the full data set, although the standard deviations of the residuals are also larger.

The standard errors of the western United States models were compared to the standard errors computed from the extensional regime database for all distances and for distances less than 20 km (Spudich et al. 1996). For all distances, the computed standard errors are consistent with the range of standard errors from the attenuation models. For distances less than 20 km, the computed standard errors are toward the lower end of the range of the attenuation model standard errors, but the uncertainty in the estimated standard error is much larger. The standard errors in the western United States attenuation models appear to be comparable and thus applicable to extensional regimes.

Spudich et al. (1996) also evaluated the distance and magnitude scaling inherent in the western United States relations against the extensional data. They found that the distance attenuation represented by the extensional data set is weaker than in the western United States attenuation models. No systematic difference was found in the magnitude scaling of events in the extensional database as compared to the western United States models.

Extensional Regime Attenuation Relation–Spudich et al. (1996) developed a new attenuation relation to estimate ground motions in extensional regimes. The model is based on a functional form developed by Boore et al. (1993):

$$\log Y = b_1 + b_2(M\text{-}6) + b_3(M\text{-}6)^2 + b_4R + b_5\log R + b_6\Gamma$$

where $R = (r_b^2 + h^2)^{1/2}$ and Γ is 0 for rock sites and 1 for soil sites.

The extensional regime data set is rather sparse in terms of the magnitudes represented and has little data from rock sites at distances less than 10 km. Consequently, in the regression analysis several model parameters were fixed to values determined by Boore et al. (1993). The fixed parameters include the magnitude scaling terms (b_2 and b_3) and the depth term (h). All other parameters were estimated and the resulting coefficients are listed in Table B1 of Spudich et al. (1996).

Comparisons of median predictions from this model with those from several western United States attenuation models illustrate their differences. Figure 3.10-21 compares median acceleration response spectra for a rock site on the foot wall of a dipping fault (57.5°) at a rupture distance of 10 km for M_w 5, 6, and 7 events. Figure 3.10-22 makes the same comparisons for a rock site on the hanging wall. In general, at short to moderate periods the Spudich et al. (1996) model predictions are less than, or lie at the lower limit, of the western United States values. At long periods, the Spudich et al. (1996) model is similar to the western United States models. Notably, however, the Spudich et al. (1996) model has a much larger standard deviation at long periods than is usual for the western United States relations.

A third comparison is made for a rock site 25 km from a M_w 6.6 strike-slip event (Figure 3.10-23). At this larger distance, the Spudich et al. (1996) model is lower than the average of the western United States models by about 30 to 40 percent.

3.10.8.3 Little Skull Mountain Earthquake Ground Motions

The June 29, 1992 M_L 5.6 Little Skull Mountain earthquake is the largest to have been recorded within 20 km of Yucca Mountain. Moreover, it is the only earthquake in the Yucca Mountain region (excluding aftershocks) for which significant recordings of strong motion are available.

Focal mechanisms and seismic moments have been derived by several investigators (K.D. Smith et al., *The 1992 Little Skull Mountain Earthquake Sequence, Southern Nevada Test Site*, U.S. Geological Survey Open File Report, in press; Meremonte et al. 1995; Romanowicz et al. 1993; Zhao and Helmberger 1994; Walter 1993; Harmsen 1994; Mayeda and Walter, 1996; Ritsema and Lay 1993). In general, the main shock mechanism and moment are very well constrained with a dip of 56° and rake angle indicating a normal mechanism. Based on aftershock locations, the rupture plane extended about 4 km along strike and 6 km down-dip with the hypocenter at the lower southwest corner of the rectangle. The main shock seismic moment was computed at about 3.7×10^{24} dyne-cm.

The stress drops of the main shock and two large aftershocks were estimated from a point source inversion of the Fourier amplitude spectra (Silva et al., draft, "Description and Validation of the Stochastic Ground Motion Model," Brookhaven National Laboratory, Upton, New York, 1996). The stress drop estimates are listed in Table 3.10-14 and are consistent with those of other Basin and Range Province earthquake sequences (Subsection 3.10.8.1).

The earthquake strong ground motion recordings provided a valuable opportunity for comparison with existing empirical attenuation relations. An analysis of residuals with respect to five attenuation relationships was performed by Abrahamson and Becker (1996, Chapter 10). In general the residuals indicate that for larger distances, the empirical relations tend to overpredict the observed ground motions for the Little Skull Mountain earthquake. The average level of all residuals tends to decrease with period. The underprediction of ground motion at high frequencies can be attributed to lower kappa at the site compared with typical western United States values.

As part of the Scenario Earthquake Modeling Project, the ground motions from the Little Skull Mountain earthquake also were modeled by six groups as part of a model evaluation and validation process. Detailed results of this study are provided by Schneider et al. (1996) and are summarized in the following subsection.

3.10.8.4 Scenario Earthquake Modeling Project

Due to the lack of near-fault strong motion data from earthquakes in the Yucca Mountain region and the Basin and Range Province, the USGS organized a project to estimate vibratory ground motion for several earthquake scenarios affecting Yucca Mountain (Schneider et al. 1996). Participants in the study used established numerical modeling methods to simulate ground motions that were appropriate to the specific conditions at Yucca Mountain. As part of the modeling exercise, both median ground motion and its variability were estimated for each faulting scenario.

Six earthquake scenarios were evaluated (Table 3.10-15) based on two geologic criteria: the postulated sources are likely to have generated significant earthquakes in the past, and they are considered likely to produce ground motions that would impact seismic hazard estimates at Yucca Mountain. The six scenarios include four normal faulting events (M_w 6.3 to 6.6) at source-to-site distances of 1 to 15 km and two strike-slip faulting events, M_w 6.7 and 7.0, at distances of 25 and 50 km, respectively.

Six modeling teams, each with a different preferred modeling approach, first validated their Yucca Mountain-specific models using records from the 1992 M_L 5.6 Little Skull Mountain earthquake. The teams were allowed to modify input parameters with the constraint that they be consistent with the observations and results of previous work. Slip distribution and other fault dynamics were unspecified and left to the modelers to define. Following the validation phase of the project, each team prepared ground motion estimates (median and uncertainty) for the six scenarios.

The six modeling approaches were:

- Specific barrier method (Chin and Aki, University of Southern California)
- Stochastic method with ω^2 sub-events (Silva, Pacific Engineering & Analysis)
- Stochastic slip functions method (Joyner, USGS)
- Composite fractal source method (Zeng and Anderson, University of Nevada, Reno)
- Broadband Green's function method (Somerville, Woodward-Clyde Federal Services)
- Empirical method using underground nuclear explosion sources (Bennett, S-Cubed)

In the six modeling methods, the seismic source is prescribed only by the rupture geometry, seismic moment, and hypocenter. The manner in which the seismic slip is distributed and released on the fault plane varies between methods. The methods also vary significantly in their assumptions of wave propagation, site response, and overall level of complexity, but all the methods accommodate the essential aspects of seismic energy being generated from a finite source and propagated along a path to a site at the earth's surface. Complete descriptions of each modeling method are provided in Schneider et al. (1996).

Taken together, the six modeling methods represent the state-of-the-art, and the differences in resulting predictions capture an important component of the uncertainty in ground motions in these scenario earthquakes that can be applied to the variability of other simulations.

Model Validation–In the validation phase of the project, the teams incorporated various Yucca Mountain source, path, and site parameters to calibrate their models to best fit ground motions from five sites that recorded the Little Skull Mountain earthquake. Most of the six methods had also been previously calibrated against recordings from recent earthquakes.

The computed 5 percent damped response spectra for each of the six modeling teams are plotted in Figure 3.10-24 along with an observed spectrum from the Little Skull Mountain earthquake. The comparisons are for the recording site (Lathrop Wells) nearest to the Little Skull Mountain main shock source.

The mean residual and standard deviation for all five sites were computed for each model. The average model bias for all groups is included in Figure 3.10-25. The models produced ground motion estimates which were comparatively unbiased for periods less than 1 second, indicating that they are applicable to estimating ground motions in the Basin and Range Province. However, the bias for periods greater than 1 second indicates that the numerical simulation models do not work well for this event at long periods.

The standard errors of the modeling misfits are plotted in Figure 3.10-26. This is the model uncertainty and represents the limitations of each model. This modeling uncertainty is part of the total uncertainty of numerical simulations discussed later in this subsection.

Computed Ground Motion–Using the Little Skull Mountain-calibrated models, the six teams proceeded to compute motions for the six faulting scenarios. Five of the teams whose models were numerical simulations (i.e., all excepting the empirical underground nuclear explosion model) ran multiple realizations of the source process and computed a mean spectrum for each scenario.

Nonlinear site response effects were incorporated in the scenario ground motions. Lacking information on the dynamic response of tuffs at Yucca Mountain, the nonlinear response of these materials was assumed to be similar to the response of tuffs from the Los Alamos National Laboratory which had been tested (Wong et al. 1995). The simulated ground motions were modified to account for the expected nonlinear response of the top 40 m of the tuff. For the nearby normal faulting event scenarios, the increase in damping from non-linear effects reduced the high frequency ground motion by about a factor of two as compared to the ground motions computed assuming linear site response. In the more distant strike-slip faulting scenarios, the ground motions were much lower so the expected non-linear response of the tuff is not significant.

The computed median spectral accelerations for the scenario events are shown in Figure 3.10-27. Ground motions computed for the normal faulting scenario events at close distances (Bow Ridge, Solitario Canyon, and Paintbrush Canyon faults) are large: 34 Hz spectral accelerations range from

0.5 to 1.0 g at distances of 1 to 3 km. The more distant normal faulting scenario earthquakes (Bare Mountain and Rock Valley faults) resulted in ground motions with 34 Hz spectral accelerations of from 0.2 to 0.3 g. The scenario event at farthest distance (Furnace Creek fault, a strike-slip scenario) produced the lowest high frequency motion (less than 0.1 g at 34 Hz); its long period motions are comparable to the Bare Mountain and Rock Valley fault events as a result of the larger magnitude of the Furnace Creek fault event.

Comparisons with Western United States Attenuation Relations–The model simulations were compared with several western United States empirical attenuation relations (Sadigh et al. 1993; Boore et al. 1994; I.M. Idriss, University of California, Davis, written communication to N.A. Abrahamson, Consultant, 1994; N.A. Abrahamson, Consultant, and W.J. Silva, Pacific Engineering and Analysis, written communication to J. Schneider, Woodward-Clyde, October, 1995). The simulated median ground motions for the four normal faulting events exceed the western United States predictions by about 60 percent at distances less than 5 km and by about 20 percent at 15 km. The differences are largest at high frequencies, attributable primarily to low damping (kappa effects) in the shallow rock at Yucca Mountain and to larger crustal amplification for the Basin and Range Province. At long periods, the difference is attributed to the larger crustal amplification and directivity effects.

For the more distant strike-slip faulting earthquakes, the simulated median ground motions are greater than the western United States attenuation predictions by about 30 percent at 25 km distance, also at the high frequencies. This increase is similarly attributed to low kappa and larger crustal amplification. At 50 km, the simulated longer period ground motions are consistent with western United States empirical attenuation predictions because the effect of kappa is not as significant.

The simulated higher ground motions at high frequencies are consistent with records from the 1992 Little Skull Mountain earthquake. The high frequency ground motions from this event were significantly larger than predicted by western United States empirical attenuation relations.

The variability of the simulated motions is also greater than that computed for western United States empirical attenuation relations. The standard error is about 0.15 natural log units larger than found for empirical attenuation relations.

Ground Motion Variability–The variability of the ground motion was estimated in the Scenario Earthquake Modeling Project including modeling, method, parametric, and geometric variability (Schneider et al. 1996). The total variability is the combination of these sources of uncertainty. (The uncertainties in the ground motion part of the Probabilistic Seismic Hazard Analyses Project were treated slightly differently; USGS 1998.) Two types of uncertainty are considered: aleatory, representing random variations and captured in the standard deviation, and epistemic, representing scientific uncertainty due to limited data. Epistemic uncertainty is inherent both in median estimates and their aleatory variability.

The model variability (aleatory) is estimated from comparisons of the model predictions with recordings from actual earthquakes. In the Scenario Earthquake Modeling Project, this was captured in the Little Skull Mountain validation exercise and other validations each investigator had performed. Method variability (epistemic) is the uncertainty in the median ground motion introduced by our inability to know which numerical model will provide estimates closest to the correct median. Parametric variability (aleatory) is caused by variations in ground motion for future earthquakes due to variations in source, path, and site parameters in those events. It is computed by varying these parameters (optimized in the validation exercise) in other simulations. Geometric variability (epistemic) results from our inability to know what the geometry of a source truly is. For example, for a single fault, it is the uncertainty in the dip of that fault. In the Scenario Project, this term was only included in the computation of the total uncertainty depending on the details of the individual simulations.

The uncertainty computed for all the simulations is included in Schneider et al. (1996). The four sources of uncertainty for the Paintbrush Canyon scenario event are shown here in Figure 3.10-28. In general, the total uncertainty increases with period and the greatest contribution to the total uncertainty is the modeling uncertainty.

3.10.8.5 Ground Motion Characterization Supporting the Probabilistic Seismic Hazard Analyses Project

The most comprehensive evaluation of ground motions at Yucca Mountain was performed in support of the probabilistic seismic hazards analyses (Subsection 3.10.9). The goal of the evaluation was to formulate attenuation models describing vibratory ground motion at the repository. Expert elicitation methods were followed to integrate the range of scientific interpretations. Seven experts participated in the characterization, each with recognized technical expertise. The experts impartially evaluated various proponent models of ground motion based on information presented in a series of workshops. The characterization is documented in USGS (1998).

The experts provided point estimates of ground motion for a suite of prescribed faulting cases and these point estimates were subsequently regressed to attenuation equations. The ground motions constituted response spectral values (horizontal and vertical components) for specified spectral periods. The 'point estimates' constituted an estimate of the median ground motion, its variability (aleatory variability), and the uncertainty in each (epistemic uncertainty). Each faulting case corresponded to a particular magnitude earthquake, fault geometry, and source-site distance. The cases were designed to sample the magnitude-distance-faulting space in sufficient detail to provide a robust regression.

The ground motion estimates, and thus also the resulting attenuation relations, were developed for a free-field "reference rock outcrop" whose geotechnical conditions are the same as at the depth of the buried repository, and not conditions at the ground surface (Subsection 3.10.9). A separate analysis was performed to modify the ground motions to include the response of the tuff overlying the repository (USGS 1998).

In the course of the ground motion workshops, the results of all know relevant studies were presented. Among other issues, these included discussions of several seismological parameters including stress drop, crustal structure, Q, and site effects including kappa, site response and material nonlinearity. Workshop presentations covered seismological records from the 1992 Little Skull Mountain main shock and aftershocks and the 1993 Rock Valley sequence. The experts were briefed on source focal mechanisms, event locations, and elements of the seismograms. The extensional regime data set and results (Spudich et al. 1996) and the scenario earthquake investigation (Schneider et al. 1996) were of direct relevance to the ground motion characterization. Ground motion estimation methods were also reviewed including empirical attenuation relations, numerical simulations, and hybrid empirical numerical schemes.

Proponent Models–The experts computed their point estimates not from further analyses of measured strong ground motion data, but rather from existing 'proponent' models. The proponent models fell in several classes: empirical attenuation relations, hybrid empirical, point source numerical simulations, finite-fault numerical simulations, and blast models. All ground motion modeling relations evaluated as part of this study are listed in Table 3.10-16.

Because no empirical attenuation models exist for the Yucca Mountain region or the Basin and Range Province, the empirical models used in this study resulted from regression analyses of strong motion records primarily from California earthquakes. Thus all empirical relations required adjustments so they would better fit conditions in the Yucca Mountain region. The hybrid empirical model is derived from these relations and implicitly includes conversion factors which must be separately applied to the empirical relations.

The blast models are based on empirical records from underground nuclear explosions at the Nevada Test Site (Schneider et al. 1996). Three blast models were assessed, each with a different approach to account for differences in earthquake sources and explosion sources.

The numerical simulations were tailored to Yucca Mountain conditions and required no adjustments. The point source models are the simplest numerical models and also the best understood (Silva et al., draft, "Description and Validation of the Stochastic Ground Motion Model," Brookhaven National Laboratory, Upton, New York, 1996). The finite-fault numerical simulations were derived from the six models evaluated in the Scenario Earthquake Modeling Project previously described (Subsection 3.10.8.4). Three model approaches were chosen by the experts for their analyses:

- Stochastic method with ω^2 sub-events (Silva, Pacific Engineering & Analysis)
- Composite fractal source method (Zeng and Anderson, University of Nevada Reno)
- Broadband Green's function method (Somerville, Woodward-Clyde Federal Services)

Details of these models, as applied to the ground motion characterization study, are included in USGS (1998).

Conversion Models–Depending on the nature of the data sets upon which they are based, the empirical relations often represented source, path, and site conditions different from those encountered at Yucca Mountain. Suites of conversion factors were consequently computed as part of the study. They were developed using the results of numerical finite fault simulations, stochastic point source simulations, and empirical attenuation relations. Complete summaries of the conversion factors are presented in USGS (1998). The factors included corrections for the following:

- Source: western United States transpressional seismic sources to Yucca Mountain extensional seismic sources

- Crust: western United States crust to Yucca Mountain crust

- Site: reference rock outcrop to Yucca Mountain surface conditions

Eight conversion models for source and four for combined crust and site effects were available for application. The experts selected the conversions they wished to apply to the various empirical relations. If an empirical model did not require a correction term, then none was applied. For example, the numerical simulations were computed for Yucca Mountain conditions so no crust or site correction was needed and none was applied.

Additionally, many of the proponent models did not include the full range of ground motion parameters required. For example, not all the empirical models included vertical ground motions. Thus scaling factors were also developed in the same manner as the conversion models. They include:

- Ratios of vertical motion to horizontal motion
- Ratios of peak velocity to peak spectral acceleration
- Ratios of peak velocity to 1 Hz spectral acceleration
- Component-to-component variability models
- Spectral acceleration interpolation models

The scaling factors were applied in a manner analogous to the conversion models.

Attenuation Relations–Each expert developed a set of point estimates for the several cases representing different faulting styles, event magnitudes, source geometries, and source-site distances. The estimates comprised median ground motion, its variability, and the uncertainty in both. The estimates were derived directly from the models, conversions factors, and adjustment factors described above and other judgments by the experts.

These estimates were then parameterized using attenuation relations. The forms of the attenuation relations used by each expert are provided in Table 3.10-17. The experts constrained the relations describing their estimates as much or as little as they chose. For example, each selected a distance measure for the regression. Some chose to constrain the degree of magnitude saturation at close distances. Some chose to regress hanging wall and foot wall point estimates together rather than separately. Regression coefficients a_i, b_i, c_i, and d_i are listed in USGS (1998).

During the course of the Probabilistic Seismic Hazard Analyses Project, two faulting cases were identified which could not be captured by the cases for which the experts were developing point estimates. These special cases were: multiple rupture scenario on parallel faults, and a low-angle detachment zone rupture scenario. The experts addressed these scenarios by providing rules for applying their attenuation equations in each specialized case. Their adjustment factors are provided in USGS (1998).

As an example of the process, the point estimates for horizontal spectral acceleration for a case representing normal faulting (hanging wall) in a M_w 6.5 earthquake at a distance of 4 km are shown in Figure 3.10-29. Figures showing all four ground motion estimates, for all cases, and for all experts are contained in USGS (1998). All median estimates developed by a single expert were regressed using the median motion equation form (Table 3.10-17), subject to any constraints imposed by that expert.

Ground motion estimates for any of the four ground motion parameters may be computed using the sets of coefficients. Figure 3.10-30 presents one such set of estimates, corresponding to the median horizontal peak ground acceleration in a M_w 6.5 normal faulting earthquake on the hanging wall.

Typically, the seven sets of attenuation relations predict median ground motion which differ by less than a factor of 1.5. The experts' horizontal aleatory estimates, their epistemic uncertainties in the median estimates, and their epistemic uncertainties in the aleatory estimates all vary by less than about 0.1 natural log units.

3.10.9 Probabilistic Seismic Hazard Analyses

In order to assess the seismic hazards of vibratory ground motions and fault displacement at Yucca Mountain, probabilistic seismic hazard analyses have been performed (USGS 1998). The objectives of the analyses are to provide quantitative hazard results to support a Viability Assessment of the potential repository's long-term performance with respect to waste containment and isolation and to form the basis for developing seismic design criteria for the License Application. The hazard results are in the form of annual exceedance probabilities for which various levels of fault displacement at selected locations in the Controlled Area and vibratory ground motion at a hypothetical rock outcrop at the ground surface are expected to be exceeded.

The probabilistic seismic hazard analyses consist of three primary activities:

- Identification, evaluation, and characterization of seismic sources which will contribute to the fault displacement and vibratory ground motion hazard at Yucca Mountain
- Evaluation and characterization of vibratory ground motion attenuation including earthquake source, wave propagation path, and rock site effects
- Probabilistic seismic hazard analyses for both fault displacement and vibratory ground motion

Both the preclosure and postclosure performance periods of the repository are being addressed in the study.

By necessity, evaluations of seismic source characteristics, earthquake ground motions, and fault displacement involve interpretations of data. These interpretations have associated uncertainties related to the ability of data to fully resolve various hypotheses and models. In the Probabilistic seismic hazard analyses, the input includes both estimates of the parametric variability, and uncertainty in the interpretations. To evaluate scientific uncertainty, seismic source characterizations have been made by six teams of three experts each, who together form a composite expertise in the seismicity, tectonics, and geology of the Yucca Mountain site and region. The ground motion assessments have been made by seven individual experts.

Interpretations for hazard assessment have been coordinated and facilitated through a series of workshops. Each workshop was designed to accomplish a specific step in the overall interpretation and to assure that the relevant data were fully considered and integrated into the evaluations.

In the following subsections, the probabilistic seismic hazard analyses methodology for both vibratory ground motions and fault displacement, the expert teams' seismic source characterization for analyses of vibratory ground motions and their fault displacement models, and the associated hazard results are presented. The ground motion characterization performed by the probabilistic seismic hazard analyses ground motion experts was presented in Subsection 3.10-8.

3.10.9.1 Probabilistic Seismic Hazard Analyses Methodology

The probabilistic seismic hazard analyses methodology for vibratory ground motions was first developed by Cornell (1968, 1971) and has become standard practice in evaluating seismic hazards. The use of the methodology results in calculated annual probabilities that various measures of vibratory ground motion (e.g., peak horizontal acceleration) will be exceeded at a site (Figure 3.10-31). The resulting "seismic hazard" curve represents the integration over all earthquake sources and magnitudes of the probability of future earthquake occurrence and given an occurrence, its effect at a site of interest. The methodology for evaluating fault displacement hazard probabilistically is very similar to that for vibratory ground motions.

The calculation of probabilistic ground motion hazard requires three basic inputs (Figure 3.10-31):

- Identification of relevant seismic sources and a characterization of their source geometry
- Rate of earthquake occurrence for each seismic source and its magnitude distribution
- Attenuation relationships which provide for the estimation of a specified ground motion parameter as a function of magnitude, source-to-site distance, local site conditions, and in some cases, seismic source characteristics

For evaluating fault displacement hazard, the ground motion attenuation relationships are replaced by relationships which describe the distribution, sense, and amounts of displacement with earthquake occurrence. Both primary and secondary fault displacement are addressed. The three basic inputs for assessing both vibratory ground motions and fault displacement hazards are the products from the previously described characterization activities.

The mathematical formulation used for probabilistic seismic hazard analyses typically assumes that the occurrence of damaging earthquakes can be represented as a Poisson process. Under this assumption, the probability that a ground motion parameter, Z, will exceed a specified value, z, in time period t is given by:

$$P(Z > z|t) = 1 - e^{-\bar{v}(z) \cdot t} \leq v(z) \cdot t \qquad \text{(Eq. 3.10-1)}$$

where $\nu(z)$ is the average frequency during time period at which the level of ground motion parameter z exceeds value z at the site from all earthquakes on all sources in the region. The inequality at the right of Equation (3.10-1) is valid regardless of the probability model for earthquake occurrence, and $\nu(z) \cdot t$ gives an accurate and slightly conservative estimate of $P(z>z)$ for probabilities of 0.1 or less, if $\nu(z)$ is the appropriate time-averaged value for the specific time period of interest.

The frequency of exceedance, $\nu(z)$, is a function of the frequency of earthquake occurrence, the randomness of size and location of future earthquakes, and the randomness in the level of ground motion they may produce at the site. It is computed by the expression:

$$\nu(z)=\sum_{n} \alpha_n (m^o) \int_{m^o}^{m^u} f(m) \left[\int_{0}^{\infty} f(r|m) \cdot P(Z > z|m,r) \cdot dr \right] \cdot dm \qquad \text{(Eq. 3.10-2)}$$

where α_n (m^o) is the frequency of earthquakes on source n above a minimum magnitude of engineering significance, m^o; $f(m)$ is the probability density of earthquake size between m^o and a maximum earthquake the source can produce, m^u; $f(r \mid m)$ is the probability density function for distance to an earthquake of magnitude m occurring on source n; and $P(Z>z \mid m,r)$ is the probability that, given the occurrence of an earthquake of magnitude m at distance r from the site, the peak ground motion will exceed level z.

An important aspect of the probabilistic seismic hazard calculations is the treatment of uncertainty. For the above inputs, there are uncertainties which are quantified by the experts and included in their models. These uncertainties are propagated throughout the probabilistic analyses using a logic tree methodology resulting in a suite of hazard curves typically showing the mean, median, and various fractile curves.

The probabilistic seismic hazard analyses methodology shown in Figure 3.10-31 is formulated to represent the randomness inherent in the natural phenomena of earthquake generation and seismic wave propagation. The randomness in a physical process has come to be called aleatory uncertainty (NRC 1997b). In all assessments of the effects of rare phenomena, one faces uncertainty in selecting the appropriate models and model parameters because the data are limited and/or there are alternative interpretations of the data. This uncertainty in knowledge has come to be called epistemic uncertainty (NRC 1997b). The seismic source expert panel placed a major emphasis on developing a quantitative description of the epistemic uncertainty.

The logic tree formulation for seismic hazard analysis involves setting out the logical sequence of assessments that must be made in order to perform the analysis and addressing the uncertainties for each step in the assessment. Thus, it provides a convenient approach for breaking a large, complex assessment into a sequence of smaller, simpler components that can be addressed more easily.

Figures 3.10-32 and 3.10-33 show examples of logic trees. It is composed of a series of nodes and branches. Each node represents a state of nature or an input parameter that must be characterized to perform the analysis. Each branch leading from a node represents one possible alternative interpretation being evaluated. In practice, a sufficient number of branches are placed at a given node to represent the evaluator's uncertainty in estimating the parameter.

Probabilities are assigned to each branch that represent the expert's evaluation that the branch represents the correct value or state of the input parameter. These probabilities are conditional on the assumption that all the branches leading to that node represent the true state of the preceding parameters. Because they are conditional probabilities for an assumed mutually exclusive and collectively exhaustive set of values, the sum of the conditional probabilities at each node is unity. The probabilities are often based on scientific expert judgment because the available data are often too limited to allow for objective statistical analysis, and because scientific evaluation is needed to weigh alternative interpretations of the available data. The logic tree simplifies these evaluations, because the uncertainty in each parameter is considered individually, conditional on assumed known states from prior evaluations. The nodes of the logic tree are sequenced to express conditional aspects or dependencies among the parameters and to provide a logical progression of evaluations from general to specific in characterizing the input parameters for probabilistic seismic hazard analyses.

3.10.9.2 Seismic Source Characterization for Vibratory Ground Motions

Two main types of seismic sources were characterized by the seismic source expert teams: fault sources and areal source zones. Fault sources are used to represent the occurrence of earthquakes along a known or suspected fault trace or traces. Uncertainty in the definition of fault sources is expressed by considering alternative rupture lengths, alternative fault dips, and possible linkages with other faults. In addition, an evaluation is made of the probability that a particular fault is active (Figure 3.10-33); that is, it produces earthquakes in the current tectonic regime.

Faults were represented in the probabilistic seismic hazard analyses by segmented planar features; the fault dip and the minimum and maximum depths of rupture on the fault plane were specified by the seismic source expert teams (Figure 3.10-33). Earthquake ruptures typically are considered to occur with equal likelihood at any point on the fault plane; the size of the rupture being specified by an empirical relationship between magnitude and rupture area.

Areal source zones represent regions of distributed seismicity that are not associated with specific known faults such as "background earthquakes", and therefore the events are considered to be occurring on unidentified faults or structures whose areal extent are best characterized by zones. Areal zones may also be used to model the occurrence of earthquakes at great distances from a site when the details of the individual faults are not significant to the hazard assessment. The boundaries of regional source zones delineate areas that have relatively uniform seismic potential in terms of earthquake occurrence and maximum earthquake magnitude (Figure 3.10-34). Uncertainty in defining areal zones typically was expressed by considering alternative zonations of the region surrounding the Yucca Mountain site.

Two alternative approaches were used by the seismic source expert teams to characterize the spatial distribution of future earthquakes within the areal zones. The first considers that there is equal likelihood of occurrence of earthquakes at all locations within the areal zone. The alternative interpretation was nonuniform spatial occurrence expressed by a nonuniform spatial density function for the areal zone based on the historical seismicity. This interpretation implies that future seismicity is more likely to occur near where it has in the past. This interpretation currently is being used to develop the national seismic hazard maps for the U.S. (Frankel 1995).

Assessment of Maximum Magnitude–The maximum magnitude (M_{max}) for a seismic source represents the largest earthquake that can be generated by that source, regardless of its frequency of occurrence. Thus, M_{max} defines the upper limit of the earthquake recurrence relationship for the source.

The approach used to evaluate M_{max} for a fault source was to estimate the maximum physical dimensions of rupture on the source and use relationships between rupture dimensions and earthquake magnitude. The types of empirical relationships available are magnitude versus surface or subsurface rupture length, rupture area, maximum surface displacement, average surface displacement, and slip rate. Some published empirical relationships include more than one parameter, such as rupture length and slip rate or the product of rupture length and displacement (e.g., Anderson, J.G., Wesnousky et al. 1996). Estimates of the rupture area and average slip on the fault can also be used to estimate the seismic moment of the M_{max} and the moment is then converted to M_w using an empirical relationship, such as the one developed by Hanks and Kanamori (1979). The probabilistic seismic hazard analyses was conducted using M_w as the magnitude measure and all estimates of M_{max} were converted to this scale.

The seismic source expert teams considered multiple sources of uncertainty in estimating M_{max} for faults. These included consideration of:

- The relative merit of alternative rupture characteristics for estimating magnitude (such as estimates based on rupture length versus estimates based on maximum displacement)
- The relative merit of alternative published empirical relationships
- Uncertainty in estimating the physical dimensions of the maximum rupture on a fault

The logic tree in Figure 3.10-35 illustrates an example approach used to express these uncertainties. Alternative fault widths are assessed by considering a range of permissible maximum depths of rupture and alternative fault dips. Alternative maximum rupture lengths are assessed based on evidence for lasting segmentation points and differences in fault behavior. Alternative empirical relationships are considered: magnitude versus rupture length or rupture area from D.L. Wells and Coppersmith (1994), or magnitude versus rupture length and slip rate (Anderson, J.G., Wesnousky, et al. 1996). If the J.G. Anderson, Wesnousky, et al. (1996) relationship is used, then a distribution of possible fault slip rates is assessed. The example logic tree (Figure 3.10-35) shows only some of the branches to illustrate the various evaluations. The complete logic tree leads to the discrete distribution for M_{max} shown at the bottom of Figure 3.10-35.

Different approaches may be used to evaluate the M_{max} for areal source zones. In cases where an areal source zone is used to model the occurrence of earthquakes at large distances from a site where the details of the individual fault sources are not significant to the hazard assessment, M_{max} represents the largest earthquake determined to occur on any of the faults within the source zone. In cases where areal source zones are used to model the occurrence of earthquakes on unknown faults (there may be fault sources within the areal source zone that are modeled explicitly as separate sources in the hazard), M_{max} for the areal zone is determined by the largest fault not explicitly considered within the zone, or the largest earthquake that is not associated with surface faulting. The size of this fault will depend on the level of detailed mapping of the region and the identification of fault sources. Guidance for this evaluation is provided by studies that examine the frequency at which earthquakes of various magnitudes rupture the surface (e.g., Wells, D.L. and Coppersmith 1993; dePolo 1994; Pezzopane and Dawson 1996). The data sets of dePolo (1994) and Pezzopane and Dawson (1996) are specific to the Basin and Range Province.

Assessment of Earthquake Recurrence–Earthquake recurrence relationships for a seismic source describe the frequency at which earthquakes of various magnitudes occur. They are determined by estimating the overall frequency of earthquakes on the source, $\alpha_n(m^\circ)$, and the relative frequency of earthquakes of various sizes defined by the probability density of earthquake size, $f(m)$, between m° (minimum magnitude) and m^u (maximum magnitude). Different approaches were used to determine the recurrence relationships for areal source zones and fault sources.

The earthquake recurrence relationships for areal zones were determined from the historical seismicity catalogue compiled for the Yucca Mountain region (Subsection 3.10.2.2). The catalog was analyzed to identify and remove explosions and dependent events (earthquakes that were aftershocks or foreshocks of larger earthquakes) to produce data sets of earthquakes that can be considered to correspond to a Poisson process. Several alternative methods for identifying dependent events were used to express the uncertainty in the process. The seismic source expert teams used the alternative catalogs to develop alternative recurrence relationships for their areal zones.

The distribution of earthquake sizes in each areal source zone was interpreted to follow the Gutenberg and Richter (1954) exponential recurrence model. Because each source has a defined M_{max}, the truncated exponential magnitude distribution (Cornell and Van Marke 1969) was used to define the recurrence relationships.

The recurrence parameters needed for each areal source zone are $\alpha(m^\circ)$ and b. The maximum likelihood procedure developed by Weichert (1980) was used to estimate these parameters from the recorded data. The likelihood function used in this study was modified from that presented by Weichert (1980) to allow for variable periods of complete reporting within the boundaries of the source as well as variable magnitude intervals.

Two approaches were used to estimate the earthquake recurrence relationships for faults. The first involved estimating the frequency of large-magnitude surface rupturing earthquakes either by the use of recurrence intervals or by dividing an estimate of the average slip per event by an estimate of the fault slip rate. The complete recurrence relationship for the fault is then specified by constraining a particular form of an earthquake recurrence model (magnitude distribution function) (Figure 3.10-36) to pass through the estimated frequency of large events. The second approach was to translate the estimated fault slip rate into seismic moment rate and then partition it into earthquakes of various magnitudes according to the recurrence model used. Both of these approaches constrain the earthquake recurrence relationship for the fault at the frequency of magnitudes near M_{max}. The frequency of smaller-magnitude earthquakes is then extrapolated from this frequency based on the form of the recurrence model used. Various recurrence models were considered by the seismic source expert teams including the characteristic earthquake (Youngs and Coppersmith 1985), exponential, truncated exponential, and the maximum moment (Wesnousky et al. 1983) (Figure 3.10-36).

Summary of Expert's Seismic Source Characterization Assessments–The following summarizes the range of interpretations made by the seismic source expert teams regarding key components of their seismic source characterization models. More detailed discussions are included in USGS (1998).

Regional Faults–Regional faults were treated similarly by the seismic source expert teams. They were defined by most teams as Quaternary faults within 100 km of Yucca Mountain but outside the local vicinity of the site that were judged to be capable of generating earthquakes of M_w 5 and greater. Paleoseismic data from Piety (1996) and Whitney (1996) was used by all the teams to identify and characterize potential regional fault sources. Other sources, such as Anderson, R.E., Bucknam, et al. (1995), Anderson, R.E., Crone et al. (1995), McKague et al. (1996), Keefer and Pezzopane (1996), and Pezzopane (1996) also were used to varying degrees by some of the teams. Some of the faults that McKague et al. (1996) identified as Type 1 faults were considered but not judged relevant to the hazard analysis and were not included by the teams because of their short lengths, distance from Yucca Mountain, and evidence that indicates that many of these faults either have no significant Quaternary displacement or are much shorter than previously thought.

The number of regional faults considered by the expert teams ranged from 11 to as many as 36 (e.g., Figure 3.10-37). This reflects, in part, the judgments of the teams regarding the activity of various faults as well as the decision by some teams to also include potentially active faults. All of these faults are described in Subsections 3.10.6, and 3.10.7. One team included only faults that were judged to be active with a probability of 1.0, whereas the teams also included faults that were judged to be active with probabilities of less that 1.0. All of the teams modeled the regional faults as simple, planar faults to maximum seismogenic depth with generalized dips depending on the style of faulting (often 90° for strike-slip faults, 60° or 65° for normal-slip faults). Alternative fault lengths were included for most of the faults by all of the teams.

A variety of empirical relations were used by the teams to estimate M_{max} as previously described for both the regional and local fault sources. Two general approaches were used to estimate recurrence rates for the regional and local fault sources: slip rates and recurrence intervals. The four recurrence models previously described were used by the teams.

Local Faults–Varying fault behavioral and structural models were employed by the expert teams to capture the full range of complex rupture patterns and fault interactions in the characterization of local faults. Figure 3.10-38 shows an example of fault locations for an independent versus coalesced local fault model. A planar fault block model was preferred by most teams, with linkages along strike or coalescence down dip considered by all teams. Some type of simultaneous rupture of multiple faults was included in all models (e.g., Figure 3.10-38b). In general, preferred models for multiple fault rupture included two to four coalescing fault systems. Several teams used detachment models to constrain the extent and geometry of local fault sources. A seismogenic detachment fault was considered but not strongly favored as a source of large earthquakes by the teams. An example of the M_{max} distribution for the local faults estimated by one of the seismic source expert teams is shown in Figure 3.10-39.

The possibility that right-lateral shear is being accommodated in the Yucca Mountain region by a buried strike-slip fault was considered by all expert teams. Most of the teams included some variation of a regional buried strike-slip fault source though with low probability.

Volcanic Sources–Seismicity related to volcanic processes particularly seismicity related to basaltic volcanoes and dike-injection was considered by all teams but explicitly modeled as distinct source zones by only two expert teams. Volcanic-related earthquakes were not modeled as a separate seismic source by the other four teams because the low magnitude and frequency of volcanic-related seismicity was assumed to be accounted for by earthquakes in the areal zones.

Areal Source Zones–Areal source zones were defined by the expert teams to account for background earthquakes that occur on potential buried faults or faults not explicitly included in their model. Some teams included alternative areal zone models in their characterization within a 100-km radius of the Yucca Mountain site. The teams also defined areal zones that extended beyond 100 km of the Yucca Mountain site. Several teams defined a site area or zone solely for assigning a lower M_{max} to the area where more detailed investigations have been conducted and the inventory of fault sources is more complete. An example of one team's alternative seismic source zones is shown in Figure 3.10-40.

All seismic source expert teams used the truncated exponential model to estimate earthquake recurrence rates within the areal source zones. In regard to processing the catalog, the declustering methods of Veneziano and van Dyck (1985) and Youngs et al. (1987) were generally used by the expert teams. Adjustments for underground nuclear explosions in relevant zones were also made. Varying treatments of the background seismicity were included: (1) uniform smoothing of seismicity was used solely or given significant weight by most teams, and (2) non-uniform smoothing using Gaussian kernels having different smoothing distances was included by several teams.

Calculated Recurrence–An example of calculated earthquake recurrence relationships for one of the expert teams is shown in Figure 3.10-41. Plot (a) shows the distribution of earthquake frequencies computed using the team's model for local fault sources. The team's local fault source model contains about one and one-half orders of magnitude uncertainty in the combined recurrence rate for the local sources. Plot (b) shows the distribution of earthquake frequencies for their regional faults. Occurrence rates were computed for those portions of the regional faults that lie within about 100 km of the Yucca Mountain site. The uncertainty in the recurrence rate for the regional faults significantly smaller than that for the local fault sources. It should be noted that for all of the expert team's characterizations, the predicted recurrence rates for regional faults are dominated by those estimated for the Death Valley and Furnace Creek faults. Also shown on plot (b) are the observed frequencies of historical earthquakes occurring within 100 km of the Yucca Mountain site. Most of the smaller earthquakes are not close to the regional faults. Plot (c) shows the computed recurrence for regional source zones for those portions of the regional source zones that lie within 100 km of the Yucca Mountain site. The uncertainty in the recurrence rate for the regional sources zones is also significantly smaller than that for the local fault sources. Also shown are the observed earthquake frequencies. The predicted earthquake frequencies for the regional zones are somewhat greater than the observed frequencies because they are based on larger source areas that include regions of higher seismicity rates that lie beyond the 100 km circle. Plot (d) shows the distribution of earthquake frequencies computed for all the seismic sources in this team's model for the region that lies within 100 km of the Yucca Mountain site compared to the observed earthquake frequencies. There is reasonable agreement between the observed and predicted rates for magnitudes of interest to the ground motion hazard assessment.

Figure 3.10-42 compares the combined distribution for earthquake recurrence from all seismic sources and the mean results for the six expert team characterizations. There is generally less than an order magnitude range in uncertainty in the estimation of regional seismicity rates. At smaller magnitudes, the range reflects the differences in how the teams characterize the regional source zones. The overprediction of the observed rate of M_w 4 to 5 earthquakes within 100 km of the site reflects the teams' general assessment that larger regions are needed to characterize the seismicity rates. At larger magnitudes, the assessments from the individual teams lie within the uncertainty in the occurrence rates of earthquakes based on the historical record. Because the ground motion hazard is influenced largely (at least for high spectral frequency ground motions) by nearby seismic sources, the larger uncertainty in recurrence rates for the local sources, as typified by one team's interpretations in Figure 3.10-41, has a significant effect on the uncertainty in the ground motion hazard.

3.10.9.3 Vibratory Ground Motion Hazard

Vibratory ground motion hazard was computed at a defined reference rock outcrop having the properties of rock at a depth of 300 m below the ground surface at Yucca Mountain–the waste emplacement depth. Ground motion was computed at this reference location as a control motion for later determination of seismic design bases motions for surface and potential waste-emplacement level locations.

Based on equally weighted inputs from the six seismic source expert teams and the seven ground motion experts, the probabilistic hazard for vibratory ground motion was calculated for horizontal and vertical peak acceleration, spectral accelerations at frequencies of 0.3, 0.5, 1, 2, 5, 10, and 20 Hz, and peak velocity and are expressed in terms of hazard curves. The hazard is also expressed in terms of uniform hazard spectra. Peak ground acceleration, 0.3, and 1.0 Hz spectral values, and peak velocity are summarized in Table 3.10-18 for the annual exceedance probabilities of 10^{-3} and 10^{-4}. The largest source of epistemic uncertainty in the hazard results is due to the epistemic uncertainty in the ground motion characterization.

Deaggregation of the mean hazard for an annual exceedance probability of 10^{-4} shows that at 5 to 10 Hz (or other high frequencies) ground motions are dominated by earthquakes of smaller than M_w 6.5 occurring at distances less than 15 km. Dominant events for low-frequency ground motions, such as at 1 to 2 Hz, display a bimodal distribution including large nearby events and M_w 7 and larger earthquakes beyond distances of 50 km. The latter contribution is due mainly to the relatively higher activity rates for the Death Valley and Furnace Creek faults.

Extensive evaluations of parametric sensitivities of the ground motion hazard were performed. The recurrence approach (either slip rates or recurrence intervals) and recurrence model (e.g., characteristic, exponential, or maximum moment) are the parameters that contribute the most to uncertainty in the ground motion hazard, at the design basis hazard: 10^{-3} and 10^{-4} per year. M_{max} has a small effect on uncertainty especially for 10 Hz, because a large fraction of the hazard at this frequency comes from more frequent moderate-magnitude events. Geometric fault parameters (e.g., rupture lengths, dips, maximum depths) are minor contributors to uncertainty. These parameters have a moderate effect on the locations of earthquakes and on M_{max}, but do not affect earthquake recurrence. Although the seismic source expert teams results vary somewhat, the dominant sources for seismic hazard at 10 Hz ground motions are the Paintbrush Canyon-Stagecoach Road and Solitario Canyon faults (or coalesced fault systems including these two faults), and the host areal seismic source zone. For 1 Hz ground motions, the dominant seismic sources are the Death Valley and Furnace Creek faults and the same three sources mentioned above. Multiple-rupture interpretations of the type with comparable seismic moment release on more than one fault (i.e., those requiring modification of the attenuation equations) make a small contribution to the total hazard. Buried strike-slip faults, volcanic seismicity, and seismogenic detachments contribute negligibly to the total hazard.

The major contributor to epistemic uncertainty in the ground motion hazard is the expert's epistemic uncertainty in ground motion amplitude (within expert epistemic uncertainty). Additional contributions to epistemic uncertainty arise from moderate differences among the seismic source expert teams and among the ground motion experts as well as expand from the uncertainties expressed by the seismic source logic trees.

3.10.9.4 Fault Displacement Characterization

Several original approaches to characterize the fault displacement potential were developed by the seismic source expert teams based primarily on empirical observations of the pattern of faulting at the site during past earthquakes determined from data collected during fault studies at Yucca Mountain. Empirical data were fit by statistical models to allow use by the experts.

The potential for fault displacement was categorized as either principal or distributed faulting. Principal faulting is the faulting along the main plane (or planes) of crustal weakness responsible for the release of seismic energy during the earthquake. Where the principal fault rupture extends to the surface, it may be represented by displacement along a single narrow trace or over a zone that is a few to many meters wide. Distributed faulting is defined as rupture that occurs on other faults in the vicinity of the principal rupture in response to the principal displacement. It is expected that distributed faulting will be discontinuous in nature and occur over a zone that may extend outward several tens of meters to many kilometers from the principal rupture. A fault that can produce principal rupture may also undergo distributed faulting in response to principal rupture on other faults.

Both principal and distributed faulting are important to the assessment of the fault displacement hazard at the Yucca Mountain site. Nine locations within the Controlled Area were identified to demonstrate the fault displacement methodology. Two of the nine sites each had four identified faulting conditions. These locations were chosen to represent the range of potential faulting conditions. Some of these locations lie on faults that may experience both principal faulting and distributed faulting. The other points are sites only of potential distributed faulting.

The basic formulation for the probabilistic evaluation of fault displacement hazard is analogous to that for the ground shaking hazard. The hazard is represented probabilistically by a displacement hazard curve that is analogous to ground motion hazard curves. Thus, the hazard curve is a plot of the frequency of exceeding a fault displacement value *d*, designated by $v(d)$. This frequency can be computed by the expression $V(d) = \lambda_{DE} \cdot P(D>d)$ where λ_{DE} is the frequency at which displacement events occur on a feature at the site of interest, and $P(D>d)$ is the conditional probability that the displacement in a single event will exceed value *d*.

The approaches developed by the seismic source expert teams for characterizing the frequency of displacement events, λ_{DE}, can be divided into two categories: the displacement approach and the earthquake approach. The displacement approach provides an estimate of the frequency of displacement events directly from observed feature-specific or point-specific data. The earthquake approach involves relating the frequency of slip events to the frequency of earthquakes on the various seismic sources defined by the seismic source characterization models for the ground motion assessment. Both approaches are used for assessing the fault displacement hazard for principal faulting and distributed faulting.

The conditional probability of exceedance, $P(D>d)$, can be considered to contain two-parts: the variability of slip from event to event, and the variability of slip along strike during a single event. The teams developed several approaches for evaluating the distribution of slip at a location given a principal faulting event; others combine them into a single distribution function.

Principal faulting hazard was assessed for sites located on faults that the seismic source expert teams identified as being seismogenic. The preferred approach for estimating the frequency of displacement events is the use of slip rate divided by the average displacement per event. The slip rates were primarily based on the teams' seismic source characterization for the ground motion hazard assessment. The teams used a number of approaches to evaluate the conditional probability of exceedance. These are based on empirical distributions derived from Yucca Mountain trenching data normalized by various parameters, including the expected maximum displacement in the maximum event, the average displacement estimated from displacement data, and the average and maximum displacements estimated from the length of the feature.

To characterize the frequency of displacement events, the teams used the frequency of earthquakes developed for the ground motion hazard assessment multiplied by the conditional probability that an event produces surface rupture at the site of interest. The along-strike intersection probability was computed using the rupture length estimated from the magnitude of the event randomly located along the fault length. Most teams used an empirical model based on historical ruptures to compute the probability of surface rupture. The approach used by most of the teams to assess the conditional probability of exceedance was to define a distribution for the maximum displacement based either on the magnitude or the rupture length of the earthquake. This distribution is then convolved with a distribution for the ratio of the displacement to the maximum displacement to compute $P(D>d)$.

The majority of the seismic source expert teams considered the frequency of displacement events on features subject to only distributed faulting to be estimated by slip rate divided by the average displacement per event. The slip rates were based on the cumulative displacement and slip history. The teams used similar approaches for evaluating the conditional probability of exceedance to those used in the displacement approach for characterizing principal faulting hazard. The empirical distributions used are correlated with the scaling relationship used to estimate the average displacement per event.

The seismic source expert teams displayed the most variability in characterizing distributed faulting potential using the earthquake approach. The basic assessment of the frequency of earthquakes was derived from the seismic source characterization for ground motion hazard assessment defined by each team. The probability that an earthquake causes slip at the point of interest was assessed in a variety of ways. Most teams utilized the logistic regression model based on analyses of the pattern of historical ruptures. The widest variations in approaches were those for assessing the distribution for displacement per event on the distributed ruptures.

All of the teams considered the points on the Bow Ridge and Solitario Canyon faults as subject to principal faulting hazard. A few teams also considered some potential for principal faulting hazard at two locations on two intrablock faults. The teams varied widely in their assessments of the probability that distributed faulting could occur in future earthquakes at points that are located off of the block-bounding faults. These assessment were based on fault orientation, cumulative slip, and structural relationship. Four teams considered that the probability of displacement at a point in intact rock due to the occurrence of a future earthquake is essentially zero.

3.10.9.5 Fault Displacement Hazard

The probabilistic fault displacement hazard was calculated at nine demonstration sites within the Controlled Area. Two of the sites have four hypothetical conditions representative of the features encountered within the Exploratory Studies Facility. The integrated results provide a representation of fault displacement hazard and its uncertainty at the nine sites, based on the interpretations and parameters developed by the six seismic source expert teams. Separate results are obtained for each site in the form of summary hazard curves. Table 3.10-19 summarizes the mean displacement hazard results for the two design basis annual exceedance probabilities, 10^{-4} and 10^{-5}, at the nine demonstration sites.

With the exception of the block-bounding Bow Ridge and Solitario Canyon faults (sites 1 and 2, respectively), the mean displacements are 0.1 cm or less at 10^{-5} annual exceedance probability. At 10^{-5} probability, the mean displacements are 7.8 and 32 cm, respectively for these two faults. Thus sites not located on a block-bounding fault such as sites on the intrablock faults, other small faults, shear fractures, and intact rock are estimated to have displacements significantly less than 0.1 cm for periods up to 100,000 years.

The fault displacement hazard results display significant uncertainty. This uncertainty is indicative of the state of practice in probabilistic seismic hazard analysis for fault displacement, which is less mature than probabilistic analysis for ground motions. Nonetheless, the results obtained here are considered robust by virtue of the extensive efforts at expert elicitation and feedback, as well as the methodological developments, that were undertaken as part of this study. Sites with the highest fault displacement hazard show uncertainties comparable to those obtained in ground motion probabilistic seismic hazard analyses. Sites with low hazard show much higher uncertainties.

There is also a not unexpected correlation between the amount of geologic data available at a site and the uncertainty in the calculated hazard at that site. For sites where there are significant geologic data, the team-to-team uncertainty is less than one order of magnitude. For sites for which there are little or no data, the individual team curves span three orders of magnitude. The larger uncertainty at these sites is considered to be due to data uncertainty, i.e., less certain constraints on the team's fault displacement characterization models.

3.10.10 Deterministic Seismic Hazard Analysis of Potential Type I Faults at Yucca Mountain

A deterministic analysis of earthquake sources relevant to vibratory ground motion hazards at the Yucca Mountain site was conducted by the USGS using state-of-the-art techniques. The deterministic seismic hazard analysis was designed to meet a DOE commitment to the Nuclear Regulatory Commission to conduct deterministic analyses of Type I faults (see below) within 5 km of the Controlled Area boundary of the site as a supplement to the probabilistic seismic hazard analyses (Subsection 3.10.9), which actually provides the seismic hazard input to repository design. The general methodology of the deterministic seismic hazard analyses consists of identification and characterization of Quaternary faults as independent seismic sources for maximum earthquakes (i.e., the largest possible earthquake that can reasonably be expected to occur in association with a fault in the present tectonic regime). Source characterization includes estimation of deterministic maximum magnitudes from fault parameters such as rupture dimensions and single-event displacements. Critical ground motion parameters such as horizontal spectral response and peak horizontal acceleration are then calculated using ground motion attenuation equations. This deterministic analysis differs from the probabilistic methodology discussed in Section 3.10.9 primarily in that (a) it does not include time-dependent data such ages of faulting events, fault slip rates and recurrence intervals that are relevant to frequency of earthquake occurrence; and (b) it uses conservative, but reasonable, single-value data as input that do not explicitly incorporate uncertainty.

A reevaluation of Type I faults in the Yucca Mountain area, based on the definition of Type I faults in NUREG 1451 (NRC 1992) is currently underway using the above approach. These are faults which are of sufficient length and location to potentially affect repository design and performance, and are potentially subject to displacement, based on either direct evidence for Quaternary displacement, or one or more of the following indirect criteria:

- Association with seismicity
- Structural relations with other potential Type I faults
- Favorable orientation with respect to the contemporary stress field

Candidate Type I faults are identified depending on whether they meet at least one of the subject-to-displacement criteria. Candidate Type I faults are then classified as potential Type I faults if they meet the additional criterion for faults relevant to vibratory ground motion hazard at the site, in that they are capable of generating an 84th-percentile peak horizontal acceleration that equals or exceeds 0.1 g at the Controlled Area boundary. This definition of potential Type I faults approximately corresponds with the potentially relevant and relevant fault definition of Pezzopane (1996), as adapted from NUREG 1451 (NRC 1992) and summarized in Subsection 3.10.7.

3.10.10.1 Methods

Compilation of Fault Characteristics–A list of 118 seismic sources was developed from several published compilations of known and suspected Quaternary faults within approximately 100-km radius of Yucca Mountain (Pezzopane 1996; Piety 1996; McKague et al. 1996). Thirty-eight of these are local sources located inside or within 5 km of the Controlled Area boundary; they consist of 32 individual faults and 6 fault rupture combinations that are possible sources of distributed ruptures (Figures. 3.10-43 and 3.10-44). The latter distributed rupture sources are modified from the specific rupture scenarios described in Subsection 3.10.6.3, based on reevaluation of timing and geologic constraints for faulting events summarized in Table 3.10-8. Data were compiled for each source from published and unpublished literature sources, as described and tabulated in detail in a deterministic seismic hazard analyses report submitted to DOE by the USGS (C.M. Menges, USGS, written communication to I. Wong, WCFS, 1997). The compilation includes the following fault characteristics:

- The shortest horizontal distance between the nearest point on the surface trace of the fault and both a point in the center of the Yucca Mountain potential repository (YMPR) and the Controlled Area boundary (CAB)
- Documentation of Quaternary displacements
- Maximum fault lengths, used as a proxy for surface rupture length without segmentation (see Subsection 3.10.6.5), as measured along the mapped fault trace
- Where paleoseismic data are available (for 30 percent of faults), estimates of single-event displacements (Subsection 3.10.6.4), including the maximum (single largest measurement on the fault) and average (mean of measurements at all trench sites) displacements
- Fault geometry at seismogenic depth, including fault dips (estimated generically for various fault types from regional seismicity and geophysical data) and dip direction (based on surface outcrop)
- Sense of fault slip, determined from surface displacement patterns and slip indicators

A 15-km seismogenic depth was assigned to all faults based on local and regional seismicity catalogs.

Calculation of Maximum–A suite of four to seven maximum magnitudes (M_w) were calculated for each fault depending on the type of available data. Six values were computed from the series of log-linear regression equations developed by D.L. Wells and Coppersmith (1994) from empirical data on all slip-types of historical earthquakes (Subsection 3.10.6.7); these equations relate M_w to surface rupture length (here approximated by maximum fault length), average and maximum displacements per event, and three estimates of fault rupture area (the product of fault length and down-dip width; the latter derived from seismogenic depth and three estimates of fault dip). An additional M_w was converted with the regression of Hanks and Kanamori (1979) from direct estimates of the seismic moment, defined as the product of rupture area, average displacement, and the shear modulus. The arithmetic mean of these computed M_w estimates defines the deterministic maximum magnitude assigned to each fault or fault combination.

Calculation of Ground Motions–The vibratory ground motion hazard was evaluated for each source by calculating horizontal acceleration response spectra and peak horizontal acceleration. Acceleration response spectra are the primary measure of the deterministic seismic hazard, whereas peak horizontal acceleration is used primarily for determining whether the maximum earthquake of the fault meets the 0.1g criteria for potential Type I faults as defined earlier. The median (50th), 84th-, and 16th- percentile of both ground motion parameters are derived from the average of attenuation equations developed specifically for the Probabilistic Seismic Hazard Analyses Project (USGS 1998; Subsection 3.10.8.5). These calculations use the mean M_w and minimum distance to the Yucca Mountain potential repository (for response spectra) and Controlled Area boundary (for peak horizontal acceleration), as well as other input parameters (strike-slip versus normal faulting, hanging wall versus footwall position on normal faults, and single versus multiple rupture fault). The 7-function average developed by the Probabilistic Seismic Hazard Analyses Project ground motion experts represents a significant improvement from the attenuation equations used in previous studies (Pezzopane 1996; McKague et al. 1996) because the Probabilistic Seismic Hazard Analyses Project relations emphasize data from extensional tectonic regimes similar to the Yucca Mountain area, including region- and site-specific attenuation effects, and explicitly incorporate additional source and site parameters such as fault type and multiple faults.

Identification of Candidate and Potential Type I Faults–Each seismic source was classified initially as a candidate Type I fault on the basis of data, such as evidence for Quaternary displacements, source-to-site distance, fault length, historical seismicity, mapped fault patterns, and general fault orientation, that address the subject-to-displacement criteria in NUREG-1451 (NRC 1992). Candidate Type I faults were then classified as potential Type I faults relevant to ground motion hazard on the basis of whether the average of the 84th-percentile peak horizontal acceleration calculated from the Probabilistic Seismic Hazard Analyses Project attenuation relations exceeds the 0.1g criteria, as shown by sources plotted below and the right of the attenuation isopleth of the 7-function average in the magnitude-distance plot of Figure 3.10-45.

3.10.10.2 Deterministic Magnitudes-Ground Motions and Revised Potential Type I Faults

The deterministic maximum magnitudes calculated for the local seismic sources range from M_w 5.7 (e.g., Ghost Dance fault) to M_w 6.8 (the Paintbrush Canyon-Stagecoach Road-Bow Ridge fault combination) (Figure 3.10-45, Table 3.10-20). The largest magnitudes in the range of M_w 6.6 to 6.8 are associated with either the three largest block-bounding faults (the Solitario, Paintbrush Canyon, and Windy Wash faults), or fault combinations on the east and west side of the mountain that involve these faults. Most of the small magnitude deterministic earthquakes are related to either short isolated Quaternary faults (e.g., the Black Cone, Lathrop Wells, and East Busted Butte faults) or short bedrock faults with no direct stratigraphic or geomorphic evidence for Quaternary displacements (the Boomerang Point and Simonds faults). Even if active, the latter faults probably do not extend to large seismogenic depths, based on their short lengths and proximity to the large principal block-bounding faults, and thus, are unlikely to act as independent seismic sources (Table 3.10-20b). All sources with magnitudes greater than M_w 6.3 are associated with 21 faults or fault combinations identified as credible seismic sources (i.e., a probability of Quaternary activity >0) by the seismic source expert teams from the Probabilistic Seismic Hazard Analyses Project sources (Table 3.10-20a). The mean and median values of the distribution of maximum magnitudes calculated for these sources in the deterministic seismic hazard analyses and the probabilistic seismic hazard analyses have small differences, averaging < 0.1 magnitude units. The deterministic magnitude estimates of the remaining 17 faults that were not included as independent seismic sources by the Probabilistic Seismic Hazard Analyses Project expert teams are small, ranging from M_w 5.7 to 6.25, which were accounted for in the probabilistic analysis by a background earthquake.

Horizontal response spectra computed for the 38 local sources and three selected regional faults are summarized in Figure 3.10-46 and Table 3.10-20. These data indicate four controlling deterministic earthquakes that are associated with four rupture scenarios involving mainly multiple parallel and colinear rupture combinations along three principal Quaternary block-bounding faults in the site area: Solitario Canyon, Paintbrush Canyon, and Windy Wash faults and their subordinates. The single most significant scenario is the three-fault multiple rupture of Solitaria Canyon-Fatigue Wash-Windy Wash. The four controlling earthquake scenarios are predicted to produce peak horizontal spectral accelerations at approximately 10 Hz equal to or exceeding 1.0 g at the median and equal or exceed 2.0 g at the 84th-percentile. The next most important deterministic earthquakes with slightly lower peak spectral accelerations are associated with the large Quaternary block-bounding faults modeled as independent sources. Seismic sources identified by the Probabilistic Seismic Hazard Analyses Project expert teams could produce median horizontal 10 Hz spectral accelerations from 0.17 to 1.13 g (Table 3.10.20a), whereas similar ground motions for sources not characterized by expert teams are equal to or less than approximately 0.6 g (Table 3.10-20b). All of these local deterministic earthquakes are rare events, in that they are associated with faults with recurrence intervals greater than 10^4 years and slip rates $\leq$ 0.03 mm/yr (Subsections 3.10.6.2 and 3.10.6.6).

Regional deterministic sources are predicted to produce median horizontal spectral accelerations no greater than 0.5 g and 84th-percentile values not exceeding 0.9 g. Eighteen regional sources are capable of exceeding median peak horizontal accelerations of 0.1 g, and seven are capable of exceeding median values of 0.2 g. Roughly half of the regional faults are predicted to produce 84th-fractile horizontal acceleration spectra that exceed 0.1 g across the frequency range from slightly below 1 Hz to approximately 50 Hz.

Of the 118 local and regional seismic sources considered in this study, 111 sources meet either the broad Quaternary displacement and or structural-tectonic criterion for candidate Type I faults described in NUREG 1451 (see above; NRC 1992). However, only 53 faults meet the criterion for potential Type I faults, in that they are considered both subject to displacement and have the potential to produce peak horizontal accelerations that equal or exceed 0.1 g at the 84th percentile, using the deterministic mean maximum magnitudes, minimum horizontal distances, and the mean of the values derived from the average of the seven attenuation equations developed by the Probabilistic Seismic Hazard Analyses Project ground motion experts. This includes all of the local sources (32 individual faults and 6 fault rupture combinations) characterized within 5 km of the controlled area boundary. Of the 32 faults, 21 lack evidence of Quaternary displacement and may not be independent sources of earthquakes, mainly because they seem to be too short to penetrate to large seismogenic depths. Fifteen of the 80 regional faults are potential Type I faults relevant to ground shaking hazard. Ten of these faults have documented Quaternary displacements; activity on the remaining five is probably older than Quaternary, and thus, they may not be earthquake sources.

The results of this deterministic analysis differ from previous studies of Type I relevant faults in the Yucca Mountain area presented in McKague et al. (1996) and Pezzopane (1996) (Subsection 3.10.7). The number of local potential Type I faults in the site area is larger in the deterministic seismic hazard analyses because the analysis includes all mutually exclusive candidate Type I faults identified in both previous studies, as well as several other faults and particularly fault combinations not included in either. All of the local sources are potential Type I sources, sensu strictu, because of their very close proximity to the site, irrespective of maximum magnitude size. However, a number of the sources (65 percent) of the individual faults are considered to be unlikely seismogenic sources because of lack of evidence for Quaternary activity, fault dimensions, and structural setting. The number of regional potential Type I faults is significantly less, primarily because this analysis uses attenuation equations developed specifically for the Yucca Mountain site by the Probabilistic Seismic Hazard Analyses Project ground motion experts. These relations predict that the ground motion effects at the site of far-field sources are markedly reduced, relative to the attenuation equations used in the previous studies.

3.11 NATURAL RESOURCES

3.11.1 Introduction

As will be presented in this section, no known significant resource potential has been determined for the site area (see Tables 3.11-1a through 3.11-1e). The probability of economic accumulation of any known or unknown resources is considered to be unlikely. Groundwater is present at the site. However, water resources will be addressed following the completion of a water resources assessment report.

3.11.1.1 Objectives

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). Nevada leads the nation in the production of gold, silver, mercury, and barite (Nevada Bureau of Mines and Geology 1997). Gold is Nevada's leading commodity in terms of value (Nevada Bureau of Mines and Geology 1997). Brucite, magnesite, clays, gemstones, gypsum, iron ore, lead, sand, gravel, and crushed stone are some of the commodities that also were, or are, produced in Nevada. Because Yucca Mountain in Nye County, Nevada is a potential site for a permanent repository for high-level radioactive waste, the potential for disturbance of the site by human activities in search of natural resources must be considered. The first step in such an analysis is to determine the geologic potential for natural resources.

The purpose of this subsection of the Site Description is to identify and evaluate the natural resources within the geologic setting of the site and to assess the potential for natural resources within the Yucca Mountain Conceptual Controlled Area (see Figure 3.11-1 for a delineation of the controlled area). This subsection on natural resources includes a brief description of the resources (including metallic minerals, industrial rocks and minerals, hydrocarbons [petroleum, natural gas, oil shale, tar sands, and coal], and geothermal energy) currently known in the region or that could reasonably be postulated to be present at the site or "which would be marketable given credible projected changes in economic or technological factors" (10 CFR 60.21(c)(13)).

3.11.1.2 Regulations and Regulatory Guidance

The NRC promulgated its regulations for licensing a geologic repository in 10 CFR 60, *Disposal of High-Level Radioactive Wastes in Geologic Repositories;* Licensing Procedures. These regulations require that a Safety Analysis Report in an eventual License Application include:

> An identification and evaluation of the natural resources of the geologic setting, including estimates as to undiscovered deposits, the exploitation of which could affect the ability of the geologic repository to isolate radioactive wastes. Undiscovered deposits of resources characteristic of the area shall be estimated by reasonable inference based on geological and geophysical evidence. This evaluation of resources, including undiscovered deposits, shall be conducted for the site and for areas of similar size that are representative of and are within the geologic setting. For natural resources with current markets the resources shall be assessed, with estimates provided of both gross and net value. The estimate of net

value shall take into account current development, extraction, and marketing costs. For natural resources without current markets, but which would be marketable given credible projected changes in economic or technological factors, the resources shall be described by physical factors including tonnage or other amount, grade, and quality (10 CFR 60.21(c)(13)).

The regulations also require a discussion of the presence of potentially adverse conditions, and if present, the extent to which they detract from waste isolation. These conditions must be investigated outside the controlled area if they have the potential to affect isolation within the controlled area (10 CFR 60.21(c)(1)(i)](B)). The potentially adverse conditions related to natural resources are described in the NRC's siting criteria at 10 CFR 60.122:

(17) The presence of naturally occurring materials, whether identified or undiscovered, within the site, in such forms that:

(i) Economic extraction is currently feasible or potentially feasible during the foreseeable future; or

(ii) Such materials have greater gross value or net value than the average for other areas of similar size that are representative of and located within the geologic setting.

(18) Evidence for subsurface mining for resources within the site.

(19) Evidence of drilling for any purpose within the site.

The NRC has provided further regulatory guidance in their *Format and Content for the License Application for the High-Level Waste Repository* (NRC 1990) and in the *License Application Review Plan* (NRC 1994). This guidance and 10 CFR 60 are likely to be superseded when a Yucca Mountain site-specific regulation is promulgated by the NRC.

3.11.1.3 Previous Project Studies

Numerous investigations have been supported by the DOE in pursuing the assessment of natural resources at Yucca Mountain and the Southern Great Basin. These include an early mineral resources assessment (Bell and Larson 1982), an environmental assessment (DOE 1986), the Site Characterization Plan (DOE 1988b), an early investigation by Castor (1989), a mineral withdrawal evaluation of the Yucca Mountain Addition (Castor, Feldman et al. 1990), a regional compilation (Bergquist and McKee 1991) and a summary of the status for early site suitability (Younker et al. 1992).

The Yucca Mountain project has supported numerous natural resources investigations; most were carried out under the natural resources study plan (USGS 1992). Isotope geochemistry studies were carried out by the USGS to indicate whether there was a potential presence of economic resource deposits (Neymark et al. 1995; Marshall, Keyser et al. 1995; Peterman, Widmann et al. 1994). Preliminary petroleum investigations were reported by the USGS (Grow, Barker et al. 1994; J.A. Grow et al., *Seismic Reflection Evidence for Low-Angle Extensional Faulting in the Vicinity of the Grant Canyon Oil Field, Southern Railroad Valley, Nevada,* U.S.

Geological Survey Open File Report, draft, MOL.19980223.0227). Some preliminary natural resources information was included in the License Application Annotated Outline (YMP 1995c).

Reports on the various commodities were prepared from 1994 through 1997. The commodity reports included geothermal resources (CRWMS M&O 1996a), industrial rocks and minerals (Castor and Lock 1995), metallic and mined energy resources (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review), and hydrocarbon resources (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). The natural resources subsection of the Site Description draws heavily from the final commodity reports.

Information on the geology (Section 3), mineralogy and petrology (Section 6 and Subsection 3.5), geochemistry (Section 6), structures (Subsections 3.2 and 3.6), geophysics (Subsections 3.6 and 3.11.2.6.6), hydrology (Section 6), and remote sensing data (Subsection 3.11.2.6.7) has been gathered for the Yucca Mountain Conceptual Controlled Area and in mining districts and mineralized areas within the vicinity of Yucca Mountain.

3.11.1.4 Assumptions, Methods, and Procedures

The basic assumption used in this assessment is that resources throughout the Great Basin, including the Yucca Mountain study area, are defined on the basis of geological, geophysical, structural, and geochemical attributes, and that these attributes can be measured and compared. It is also assumed that natural resources within the study area occur within the same geologic environments as those in other parts of the Great Basin. The final assumption is that natural resource development is based on established engineering and economic principals and that the present conditions provide a valid projection for the foreseeable future (CRWMS M&O 1996a).

The assessment methods represent a broad cross-section of generally accepted views within the scientific community and of established industry practices regarding geologic, geochemical, geophysical, hydrologic, remote sensing, and drilling surveys (CRWMS M&O 1996a; Castor and Lock 1995; S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review; D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Methods used in the various resource investigations are discussed in the Subsections covering each commodity.

The following geologic indicators of natural resources are considered in resource assessments: anomalous amounts of minerals or elements that are characteristic of mineralized systems; favorable geologic structures and host rocks for potential ore; evidence of thermal waters; and favorable source material generation sites, reservoirs, and traps for hydrocarbons. Nearby discoveries and commercial developments, competitive interests, and market demand also are considered in evaluating land for potential natural resource development.

3.11.1.5 Quality Assurance Procedures Used

Data compilation for the natural resources commodity reports was conducted under an established M&O Quality Assurance Program (CRWMS M&O 1995c; Castor and Lock 1995; S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review; D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). The activities, including preparation and completion of the resource assessment reports, were evaluated under QAP-2-0, (*Conduct of Activities*), and determined to be quality affecting because the information in the report will be used for site characterization and license application. The issue of inadvertent human intrusion due to the potential presence of energy or mineral resources relates to waste isolation. NRC's regulations (10 CFR Part 60.21 and 60.122(b)(17-18)) discourage siting a repository if such resources are determined to be present.

The natural resource commodity reports cited above and their conclusions are primarily based on the interpretation of existing data, which is data developed prior to the implementation of a Quality Assurance Program under 10 CFR 60 Subpart G and on publications by investigators outside the OCRWM program. These data are largely peer-reviewed (reviewed and revised to conform to established practices, principals, and journal standards) and all may be traced to the primary source.

All of the natural resource commodity reports cited above were prepared under an approved plan prepared in accordance with the *Quality Assurance Requirements and Description* (DOE 1997). Much of the data included in this report were collected under such a program. Some of the geochemical analyses collected under the most recent metallic resources inventory (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) were collected and analyzed under an approved quality assurance program. Some geochemical data have been determined to be qualified data through a technical assessment carried out under the *Quality Assurance Requirements and Description*. Much of the project literature used in the preparation of this report was prepared under an approved QA program and so noted in the references cited.

3.11.2 Metallic Mineral Resources

3.11.2.1 Introduction

3.11.2.1.1 Purpose

The purpose of this subsection is to provide an assessment of the potential for deposits of metallic mineral commodities in the Yucca Mountain Conceptual Controlled Area and in metal mining districts of the Southern Great Basin on the basis of geologic, petrologic, geochemical, structural, geophysical, and remote sensing data. These data consist of previously published information and data collected by a variety of sources.

The Southern Great Basin contains valuable or potentially valuable metallic mineral deposits, including deposits with past or current production of gold, silver, mercury, base metals, and uranium. The presence of these deposits in the region and the identification of geologic features including veins and normal faults at Yucca Mountain that are similar to those in mineralized areas, have led some writers to propose that the Yucca Mountain Conceptual Controlled Area may have potential for metallic mineral deposits (Johnson, C. and Hummel 1991; Weiss, Noble, Larson 1996). Because gold and silver have been the most significant commodities produced in the Southern Great Basin in terms of total dollar value, this report gives most emphasis to determinations of potential for these metallic commodities.

3.11.2.1.2 Previous Work

Several authors (L.T. Larson et al., *Task 3 Progress Report for January, 1987 - June, 1988*, 3-1 to 3-28, unpublished report, Center for Neotectonic Studies, Mackay School of Mines, University of Nevada-Reno; Weiss, Larson, Noble 1993; Weiss, Noble, Larson 1995) have speculated that the rocks that make up Yucca Mountain may have been favorable for epithermal deposits due to:

- The existence of economic precious-metal mineralization in rocks of the Southwestern Nevada volcanic field to the west of the Yucca Mountain Conceptual Controlled Area
- The presence of vein and alteration mineral assemblages
- Structural deformation by faulting
- Elevated trace element contents in rocks of the Yucca Mountain Conceptual Controlled Area

In addition, because of mineral exploration and development in the region, as well as mineralogical, geochemical, and structural features at or near the potential repository site, Johnson and Hummel (1991) and Weiss, Noble, and Larson (1996) proposed that exploration and human intrusion related to mining will affect the site in the future.

Previous reports of features indicative of past hydrothermal activity in the immediate vicinity of the potential repository site are mainly based on petrographic and lithologic studies of samples from drillholes in Yucca Mountain. Silicification, propylitization (chlorite + albite + carbonate + illite alteration), argillization, and feldspar mineral alteration types were reported for some drilled intervals (e.g., Caporuscio et al. 1982; Maldonado and Koether 1983; Weiss, Larson, Noble 1993); such alteration types are commonly present in areas that contain volcanic-hosted epithermal precious metal deposits (Bonham 1988). Paleotemperatures of 200 to 300°C were estimated to have been attained during rock alteration at depths greater than about 1,500 m at Yucca Mountain on the basis of clay mineral species (Bish 1989) and fluid inclusion data (Bish and Aronson 1993). Fluid inclusion studies have shown that this temperature range includes the temperatures of epithermal fluids responsible for the deposition of epithermal precious metal deposits (Roedder 1984).

Vein mineral assemblages that include quartz, fluorite, barite, and pyrite were reported in drill core from Yucca Mountain (e.g., Bish et al. 1996; Caporuscio et al. 1982; Scott, R.B. and Castellanos 1984; Weiss, Noble, Larson 1996). These assemblages suggest that the veins were formed by hydrothermal fluids. Similar vein assemblages are commonly present in epithermal precious metal deposits (Bonham 1988) not known to be present at Yucca Mountain.

However, calcite ± silica veins that crop out or are found at shallow depths at Yucca Mountain have been deposited by downward movement of groundwater. On the basis of isotopic studies, Quade and Cerling (1990) and Stuckless, Peterman, Muhs (1991) proposed a surficial origin for calcite veins at Yucca Mountain (see Subsection 3.4.3.4 for greater detail.

In addition to vein minerals that are interpreted as a result of hydrothermal activity, pyrite was identified in core and cuttings from several drillholes in Yucca Mountain (e.g., Spengler, Byers, Warner 1981; Caporuscio et al. 1982; Maldonado and Koether 1983; Scott, R.B. and Castellanos 1984; Carr, M.D. et al. 1986). Pyrite is the most abundant sulfide mineral in the earth's crust, occurring in many environments, including hydrothermally altered rock (Deer et al. 1966). It is associated with many types of metal deposits, including volcanic rock-hosted precious metal deposits (Heald et al. 1987). According to Weiss, Noble, Larson (1996) and Weiss, Noble et al. (1993), pyrite at Yucca Mountain is an indicator of sulfidization that provides evidence for hydrothermal activity and "indicates the passage of fluids potentially capable of forming precious metal mineralization." However, Castor, Tingley, Bonham (1992) proposed that most of the pyrite in Tertiary volcanic rocks at Yucca Mountain was of ejectile origin and came from a previously formed hydrothermal system that probably was not located under Yucca Mountain.

Personnel of the Nevada Bureau of Mines and Geology have been investigating aspects of potential for economic mineral deposits at Yucca Mountain since 1989, when the DOE funded a mineral analysis of the Yucca Mountain Addition, an area which comprises about 30 percent of the proposed repository site. This resulted in a Nevada Bureau of Mines and Geology Open-File Report (Castor, Feldman, Tingley 1990). In 1991, Nevada Bureau of Mines and Geology began a study, as part of the proposed Bureau of Land Management (BLM) withdrawal of land, to examine core and cuttings from Yucca Mountain drillholes for evidence of hydrothermal activity and mineralization, logging portions of six drillholes. The results of drill core and cuttings logging, preliminary petrographic work, and chemical analyses were presented in Nevada Bureau of Mines and Geology Open-File Reports by Castor, Tingley, Bonham (1992, 1993).

Other studies that bear on mineral potential in the Yucca Mountain Conceptual Controlled Area include isotopic and geochemical studies by the USGS (Neymark et al. 1995; Marshall et al. 1996) and reports on past fumarolic activity underground at Yucca Mountain (Levy, Norman, Chipera 1996; Peterman, Spengler et al. 1996a). The use of fumarolic in this section refers to trace metal enrichment associated with degassing and vapor phase alteration of tuffs. This has been interpreted as "fumarolic" and/or hot springs mineralization related to the cooling of the Topopah Spring ashflow tuff.

3.11.2.2 Methods of Study

3.11.2.2.1 Literature Search

S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) compiled data on metallic and mined energy commodity deposits in the Southern Great Basin and elsewhere in the world using the Georef digital database and materials available at the University of Nevada library. Published information on geology, geophysics, geochemistry, drillhole lithology, petrography, and geochemistry in the Yucca Mountain Conceptual Controlled Area and nearby also were assembled.

3.11.2.2.2 Field Work

S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) sampled a broad area of the Southern Great Basin and analyzed 1,355 samples for major and trace elements, including 102 control samples and 48 replicate samples (Table 3.11-2). Not all samples obtained were analyzed chemically. Unanalyzed samples, about 50 in number, included samples obtained for petrologic and (or) mineral analysis only and cuttings samples deemed superfluous following acquisition. S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) discusses the quality assurance programs and procedures followed during sample preparation and analysis.

S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) used a "biased" sampling method. The bias was toward the most mineralized areas and therefore is a conservative (high) indication of metallic mineral resources. This method of sample collection is generally performed during the first stage of mineral exploration work to identify chemically or mineralogically anomalous target areas prior to more systematic or "grid" rock sampling. The conservative sampling method, which was used for selection of both surface and underground samples for this project, entails the collection of samples that appear to be mineralized or altered or that occur along structural features, such as faults, that are likely to host mineralization or alteration. Rock from veins, limonitized or hematized rock, silicified rock, clay-altered rock, and rock that appeared to contain evidence for any sort of mineralization or alteration was selectively sampled. Surface samples from the Yucca Mountain Conceptual Controlled Area were collected from faults or areas of breccia mapped by Scott, R.B. and Bonk (1984) and from any such features that were not previously mapped but were noted during field traverses by project geologists. During "biased" sampling, the field geologist collects specimens that have the highest likelihood of providing evidence for mineralization – the geologist is actively "prospecting" for the most mineralized samples available. Therefore, "biased" samples are not representative of the majority of the rock exposed at the sample site. Some sites in the Yucca Mountain Conceptual Controlled Area that yielded surface samples with elevated amounts of metallic commodity or pathfinder elements were revisited and further samples were collected.

The metal mining districts and mineralized areas outside the Yucca Mountain Conceptual Controlled Area that were examined and sampled by S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) are the Bullfrog, Bare Mountain, Tram Ridge-Thompson Mine, Northern Yucca Mountain, Calico Hills, Wahmonie, and Mine Mountain (Figure 3.11-1). The Bullfrog district, the most productive metal mining district in the Yucca Mountain region, was sampled most extensively because it was considered to represent the most likely model for potential economic metal deposits in the Yucca Mountain Conceptual Controlled Area as noted below (Subsection 3.11.2.6.2).

3.11.2.2.3 Sample Analysis

The sequence of analyses and reanalyses of geochemical samples in the metallic resources investigation is complex (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). In 1995, major oxide analyses by fusion Inductively Coupled Plasma Emission Spectrometry (ICP-ES) and trace element analyses by fusion Inductively Coupled Plasma Mass Spectrometry (ICP-MS) were performed on 800 samples by ACTLABS, a division of Activation Laboratories Ltd., Ancaster, Ontario, Canada.

In early 1996, NBMG personnel decided that further analyses of projected samples by ACTLABS using ICP-ES and ICP-MS techniques would not be utilized, but that Instrumental Neutron Activation Analysis (INAA) analyses by ACTLABS would be useful.

After April 1996, ACTLABS reran all 800 samples for: As, Co, Cr, Sb, Th, and W by INAA; Ag, Bi, Cu, Mo, Ni, Pb, and Zn by ICP-ES (aqua regia digestion); and Tl by ICP-MS (aqua regia digestion). These rerun analyses were generally determined by NBMG personnel to be acceptable on the basis of the reproducibility of analyses of control samples (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

3.11.2.2.4 Statistical Analysis of Geochemical Data

S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) contains an extensive discussion and tabulation of geostatistical analysis of geochemical data. Simple statistical analyses were performed on geochemical analysis of samples from the Yucca Mountain Conceptual Controlled Area and several mining districts in the Yucca Mountain region. Tables of results contain element detection limits and the high, low, mean, median, standard deviation, and skewness values for each element in each of the districts examined. The tables contain correlation coefficients for elements in samples from the areas studied. Correlation coefficients are a relatively simple and straightforward statistical method that is commonly used in exploration to discriminate sets of geochemical data (e.g., Miller, W.R. et al. 1992; Stolz et al. 1994; Van Moort et al. 1995). Correlation coefficient (r) values vary from +1, through 0, to -1. Correlation coefficient values quantify adequacy of fit to a linear regression curve (values of ±1 correspond to a perfect fit, and those of 0 to no linear fit), and signs indicate if the correlation is positive or negative. The significance of each coefficient was determined using a table for testing the null hypothesis $r = 0$ (Snedecor and Cochran 1967, p. 557). As the number of data pairs increases, the correlation coefficient will be significant at progressively lower values.

Statistical analysis using correlation coefficients may not be valid for data with non-normal distributions. However, frequency distributions of analytical results for most of the elements are log-normal, and analysis by the correlation coefficient method used (the Pearson method) is valid for these distributions. One disadvantage with the correlation coefficient method of statistical analysis is that a single analytical pair with very poor fit to the linear regression curve may reduce an otherwise strong correlation or strengthen a weak correlation; however, generally, this does not appear to be a problem for the geochemical data examined (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

3.11.2.2.5 Petrographic and Mineralogic Work

S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) examined thin sections prepared from selected project samples under a polarizing petrographic microscope using standard petrographic techniques (Nesse 1986). Additional work was done using reflected light microscopy. In addition, petrographic work on some samples was supported with examinations using a scanning electron microscope equipped with a KEVEX energy-dispersive X-ray microanalytical system.

X-ray diffraction analyses by S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) followed traditional methods (Hutchison 1974) on most of the samples that were examined in thin section and a few samples that were not examined petrographically. The X-ray diffraction analyses of powders prepared from hand samples used traditional methods (Hutchison 1974) with more modern computer-automated scan production and analysis.

3.11.2.2.6 Remote Sensing

A remote sensing study of the Yucca Mountain region was conducted by S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) using four Landsat Thematic Mapper subscenes that were integrated into a single large scene including south-central Nevada and eastern California. All seven thematic mapper bands were used. This digital data file was then subsampled into a Yucca Mountain master scene (corresponding approximately to the area of Figure 3.11-2) that was examined to determine if alteration areas and structural zones could be defined in known mining districts and mineralized areas.

The master Yucca Mountain region scene was georeferenced by S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada.* Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) using a series of points (primarily road junctions) that could be identified on the imagery and on various 1:100,000-scale maps of the area. Next, a series of ratio images were developed for the master scene. The ratio images included, but were not limited to, thematic mapper band 3 divided by thematic mapper band 1 which produced bright tones for iron-stained areas and thematic mapper band 5 divided by thematic mapper band 7 which produced bright tones for altered rock containing hydroxyl ion-bearing minerals including clays. A series of Principal Component Analysis and unsupervised classification images also were prepared. Various thematic mapper, ratio and principal component bands were examined to determine the best combination to identify known mining sites, structural features, and mineralized and altered areas. Previous remote sensing research (Gillespie 1980; Abrams, Ashley et al. 1977; Abrams, Sadowski, Prost 1984; Abrams and Brown 1984; Lepley et al. 1984; Sabins 1987; and Lillesand and Kiefer 1994) was used to provide information on likely combinations.

A false color composite combination of the thematic mapper 5/7 (as red), thematic mapper 3/1 (as green) and a third band (as blue) proved the most useful in delineating the altered versus unaltered areas in the scene. Three 1:100,000 scale subscenes (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada,* Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Plates 3-5) were produced using thematic mapper band 6 (thermal infrared) as the third or blue band. Using the thematic mapper band 6 allowed for the separation of unaltered volcanic and metasedimentary rocks from altered rocks (light colored) or light colored tuffs. The use of thematic mapper band 6 also helped to highlight the iron-stained and altered areas delineated by the ratios by reinforcing their color presentation. Each subscene was analyzed for alteration areas, structures, and indicators of hydrothermal activity and mineralization, particularly in the Yucca Mountain Conceptual Controlled Area and its immediate vicinity.

3.11.2.3 Metal Mining and Prospecting History

Portions of the Yucca Mountain region are crossed by the Emigrant Trail of 1849, later a branch of the old Mormon Trail used in the 1850s and 1860s by travelers from Salt Lake City to San Bernardino, California. Although some of the early users of the trail probably did some surficial prospecting along the way, Brigham Young did not encourage the pursuit of gold and silver by his followers, and little has been recorded of their exploration activities. The trail passed close by mineralized areas at Groom, Oak Spring, Tippipah Spring, Kane (Cane) Springs, Wahmonie, and the Amargosa Desert before crossing Death Valley and continuing on to San Bernardino. Most of these areas in the vicinity of the Yucca Mountain region probably sustained minor surface prospecting by early travelers along the route (Quade, Tingley et al. 1984).

More intense prospecting and mining in areas peripheral to the Yucca Mountain region followed the discovery of the Comstock Lode in 1859, which prompted waves of prospecting activity across the state of Nevada in the 1860s. This activity resulted in mineral discoveries in many areas surrounding the Yucca Mountain region: Groom district in 1864, Pahranagat in 1865, Tem Piute in 1865, and the southeastern district in about 1870. South of the study area, prospecting activity was reported in the Johnnie and Sterling areas as early as 1869 and at Chloride Cliff just over the California line in 1873 (Paher 1970).

Prospecting activity north and west of the Yucca Mountain study area increased following the discovery of the rich silver deposits at Tonopah in 1900 and gold at Goldfield in 1902. This intensive exploration resulted in precious metal discoveries and the development of mining camps in the Cactus Range as early as 1901, in the Bullfrog Hills in 1904, at Wellington, Trappmans, and Wilsons camps in 1904; at Tolicha (Quartz Mountain) and Gold Crater in 1905; at Transvaal and Lee (California) in 1906; and at Jamestown in 1907 to 1908.

Mining continued through the 1920s in the Bullfrog and Johnnie districts for gold and in the Bare Mountain district for fluorite. The flourishing silver mines at Tonopah also boosted the health of the industry in the area during this period. Small-scale prospecting and mining continued sporadically in camps scattered throughout the desert around the Yucca Mountain Conceptual Controlled Area. There was a brief surge in small-scale prospecting activity throughout the region in the early 1930s when the mining camp of Clarkdale was developed and minor production resumed from older mining camps including Tolicha in the Pahute Mesa area.

Prospecting and mining was unrestricted in this part of Southern Nevada and adjacent areas of Southeastern California until 1942, when the closure of the Nellis Bombing Range lands halted activity in that portion of the Yucca Mountain region. However, outside the Range, mining and prospecting activity continued, and exploration for disseminated gold deposits increased with the elevated gold price in the late 1970s and early 1980s. This favorable economic situation resulted in the reopening of several gold mines in the Bullfrog-Pioneer area including the Tramp, Stewart-Kelly, Sidewinder, Mayflower, Oasis, Mother Lode, and other mines, which enjoyed a brief period of gold production activity in the early 1980s. Some of the older mines including the Gold Bar, Montgomery-Shoshone, and Sterling have had varying amounts of production in recent years. New discoveries in the Bullfrog area near the Montgomery-Shoshone Mine led to the development of the orebody that is now being mined at the Barrick Bullfrog Mine. In the Bare Mountain district, recent developments include the Daisy project orebodies, some of which occupy ground formerly mined for fluorspar, and the Mother Lode Mine near the historic Telluride Mine.

3.11.2.4 Metallic Mineralization in Southern Nevada/California

Many hundreds of mines are located within the Southern Great Basin physiographic province. Mines and mining districts or mineralized areas have been classified according to USGS model types (Sherlock et al. 1996). Metallic ore deposit models are discussed in Chapters 5 and 6 of Castor et al. (in review).

Economic mineralization occurs in the Southern Great Basin (Figure 3.11-1; S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Plate 1). Economic gold mineralization, the most attractive target for potential exploration, occurs in volcanic rocks of the Southwestern Nevada volcanic field, west of the Yucca Mountain site at Bullfrog and in Paleozoic sedimentary rocks associated with Tertiary dikes at Bare Mountain. Evidence of currently non-economic or previously economic mineralization occurs in the region in the Bare Mountain, Bullfrog, Calico Hills, Chloride Cliff, Clarkdale, Echo Canyon, Lee's Camp, Johnnie, Lee (Lee's Camp and Big Dune), Mine Mountain, Oak Spring, Tolicha, Transvaal, Wahmonie, White Rock Spring mining districts and in the Claim Canyon, Northern Yucca Mountain, Thirsty Canyon-Sleeping Butte, Tram Ridge-Thompson Mine areas.

3.11.2.5 Mining and Prospecting in the Yucca Mountain Conceptual Controlled Area

There is no evidence of any mining activity in the Yucca Mountain Conceptual Controlled Area. All drilling and excavation was conducted by the DOE in support of site characterization. However, in June 1987, a block of 10 lode mining claims (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review; Yucca 1-10) were staked by A. J. Perchetti of Tonopah, Nevada (Castor, Feldman et al. 1990) along the crest of Yucca Mountain west of the Nevada Test Site and south of the Nellis Air Force Range. Following negotiations with DOE, Perchetti quit-claimed his mining rights. An area of about 4,000 acres that included these claims was temporarily withdrawn from mineral entry by the BLM. During surface traverses conducted as part of the metallic mineral assessment and previous work prior to the withdrawal no mine workings or prospect pits were identified within the Yucca Mountain Conceptual Controlled Area (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review; Castor, Feldman et al. 1990).

In an area on BLM land south of the Conceptual Controlled Area, west of the Nevada Test Site, and just north of U.S. Route 95 there are 35 additional, unpatented mining claims that are still active. Subsection 1.1 provides additional information on these claims.

3.11.2.6 Metallic Mineral Assessment of the Yucca Mountain Conceptual Controlled Area

3.11.2.6.1 Identified Metallic Resources in the Yucca Mountain Conceptual Controlled Area

On the basis of chemical analyses of samples collected in the Yucca Mountain Conceptual Controlled Area by S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review), no ore-grade resources of metallic commodities have been identified. Table 3.11-3 gives the highest values for metallic commodities measured on samples from the Yucca Mountain Conceptual Controlled Area during this study. Because of the presence of active gold and silver mines in the Southern Great Basin and elsewhere in Nevada, the value of measured amounts of these metals is of interest and will be discussed below.

The highest gold content measured in any sample from the Yucca Mountain Conceptual Controlled Area during this study is 175 ppb, or 0.0051 troy ounces per short ton (0.0051 opt), by ACTLABS in sample p1/4856.7. This sample was obtained from borehole UE-25 p#1, the only borehole at the site drilled through the Tertiary volcanics into the underlying Paleozoic rocks (see Subsection 3.11.2.6.8.8). Analyses by other labs reported lower gold contents for this sample (see Appendix 2 of S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*. Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review), which is a select sample of arsenian pyrite-bearing dolomite from a depth of over 1,400 m (see the description below in Subsection 3.11.2.6.6.5). Silver content of this sample was measured at 2.26 ppm, or about 0.066 opt, by USML. The combined value of gold and silver in this sample, at a gold price of about $370 per troy ounce and a silver price of about $4.80 per troy ounce, is $2.21 per short ton. If the values of other metals that are elevated in this sample are added (antimony, copper, mercury, molybdenum, and zinc, see S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Appendix 2), the value would still be less than $3.50 per ton at 1996 year-end prices. Also, the cost effectiveness of these minerals would be high. Extraction prices would have to be included to get a complete picture of how uneconomic these resources are.

At present, the lowest gold content of ore mined in Nevada is about 0.02 opt, and this ore has a value of $7.40 per short ton (assuming 1996 year-end gold price and no silver credit). At this time, production of this low value mineralized rock is only possible if it can be mined by open-pit methods and treated by low-cost heap leaching. Neither of these techniques is feasible for sulfide-bearing rock at depths greater than a few tens of meters. In addition, it is unlikely that large amounts of similar sub-ore grade rock can be proven by further sampling in drillhole p1, because the samples that were chosen for this study represent some of the richest sulfide occurrences in the hole.

The highest silver content measured in any sample from the Yucca Mountain Conceptual Controlled Area during this study is 4.03 ppm, or about 0.1 opt, in sample SD9/255.0 by Nevada Bureau of Mines and Geology. Replicate analyses for this sample by USML and Nevada Bureau of Mines and Geology yielded lower silver contents, and gold content of this sample is negligible (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Appendix 2). The value of the silver in a ton of this rock (at $4.82 per troy ounce) is about $0.57, far below currently mineable values. Sample SD9/255.0 is of lapilli tuff that was obtained from a stratigraphic location suggesting that it is related to fumarolic trace element enrichment (see S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Section 5.7.2), which has been found to be present in only small areas in the Yucca Mountain Conceptual Controlled Area; therefore, it is unlikely that large amounts of similar rock are present. In addition, there is little likelihood of depth extension for such stratabound occurrences.

The highest valued sample collected from the surface in the Yucca Mountain Conceptual Controlled Area is Yucca Mountain potential repository 0366, which has a high tin content (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Table 5.1) along with slightly elevated antimony, bismuth, lead, and zinc. At year-end 1996 metal prices, the tin in this sample is worth about $241.15 per short ton. If large amounts of similar rock were to be found in the Yucca Mountain Conceptual Controlled Area, it could constitute a valuable resource; however, on the basis of field examination, the amount of this type of rock in the Yucca Mountain Conceptual Controlled Area appears to be minor (see S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Sections 5.7.2 and 6.2.10). The rock sample with anomalous tin content was obtained from a one-rock float sample. Systematic additional sampling and analysis are underway to verify this assertion.

3.11.2.6.2 Evaluation of the Yucca Mountain Conceptual Controlled Area for Undiscovered Metallic Mineral Deposits

The evaluation of the Yucca Mountain site as a potential target for exploitation of economic metallic deposits relies on a comparison of the geology of the Yucca Mountain Conceptual Controlled Area to models of mineral deposition, along with geophysical, and geochemical analysis of the area.

3.11.2.6.3 Models of Potential Metallic Mineral in the Yucca Mountain Conceptual Controlled Area

Advances in geochemistry, geophysics, and geologic concepts, including the development of plate tectonic theory, led to the development of a large number of new or revised mineral deposit models during the period 1960 to 1990. Fluid inclusion techniques were increasingly employed during this period to determine the chemistry, pressure, and temperature of the fluids that deposited minerals in hydrothermal ore deposits. Gangue minerals have been almost universally employed in fluid inclusion studies because of the difficulty of studying inclusions in sulfide minerals, most of which are opaque, or nearly so. Stable isotope studies of fluid inclusions in epithermal deposits and in quartz-sericite-pyrite alteration of porphyry systems led to the conclusion that the fluids that deposited metals were derived from hydrothermally altered meteoric water and rock-water interaction experiments indicated that the metals could have been leached from deposit host rocks by this circulating meteoric water. This conclusion led to genetic models based upon the derivation of metals in epithermal deposits by leaching of upper crustal rocks by hydrothermally altered meteoric water (Dickson et al. 1979; Ellis, A.J. and Mahon 1967; Ilchik and Barton 1995). Other workers have suggested other sources for metals in some ore deposits, including extraction from upper crustal rocks by sea water, terrestrial brines, and contribution from metamorphic waters evolved deep in the crust (Evans, A.M. 1980; Lehrman 1986).

Geologic studies of porphyry and epithermal ore deposits by a number of authors (Sillitoe 1973; Sillitoe and Bonham 1984) reinforced the concepts of earlier workers including Lindgren (1933), Graton, and Spurr that these deposits were genetically related to magmas. Some investigators believe the magma is the source of the metal. Hedenquist and Lowenstern (1994) summarized the results of isotope, fluid inclusion, and geologic studies on the relation between magmas and ore deposits and concluded that magmas are a primary source of most of the metals in porphyry and epithermal ore deposits.

Mineral deposit models covering most metallic mineral deposits have been published by the USGS in two bulletins (Cox and Singer 1986; Bliss 1992). Sillitoe and Bonham (1984) and Bonham (1986; 1988) have published descriptive and genetic models relating to volcanic and porphyry-hosted ore deposits. Castor and Weiss (1992) discussed the epithermal precious metal deposit types present in the Southwestern Nevada volcanic field. Hedenquist and Lowenstern (1994), in an article on the role of magmas in the formation of hydrothermal ore deposits, discussed the models applicable to porphyry-related and volcanic-hosted hydrothermal ore deposits.

Site-specific drilling data (Subsection 3.5) indicates that the Yucca Mountain Conceptual Controlled Area contains a thick sequence of Tertiary volcanic rocks that overlie pre-Tertiary basement composed of Paleozoic carbonate sedimentary rocks. Ore deposit models applicable to the Yucca Mountain Conceptual Controlled Area must take into account both the rock types present in the area, the geochemistry and mineralogy of samples collected, and the types of alteration that may be related to metallic mineral deposits.

Hydrothermal ore deposits and prospects in the Southern Great Basin belong to several deposit classes.

- Epithermal volcanic rock-hosted precious metal deposits, examples occur in the Bare Mountain, Bullfrog, Clarkdale, and Tolicha districts
- Sediment-hosted gold prospects in the Bare Mountain district
- Hot-spring mercury deposits in the Transvaal, Tram Ridge-Thompson Mine, and Calico Hills districts
- Polymetallic vein deposits in the Bare Mountain, Mine Mountain, Lee, Echo Canyon-Lees' Camp, and Johnnie districts
- A porphyry-related copper-molybdenum prospect in the Oak Spring district
- Skarn tungsten prospects in the Oak Spring district
- Volcanic-rock hosted uranium occurrences in the Bullfrog district

In addition to the regional deposits, the Yucca Mountain Conceptual Controlled Area has been shown to contain fumarolic concentrations of trace elements. The only model for metallic deposits thought to have formed in this type of an environment is the Rhyolite-hosted tin model of Reed, B.L. et al. (1986), and local tin enrichment in a probable fumarolic setting in the Yucca Mountain Conceptual Controlled Area (Subsection 3.11.2.6.2) indicates that this model should be considered.

Models proposed in the Natural Resource Assessment Study Plan and other models considered important by personnel involved in the present study are presented in S.B Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of

Energy, in review). Table 3.11-2a summarizes the characteristics and applicable of the various models to Yucca Mountain.

3.11.2.6.4 Commodities and Deposit Types Not Considered

The geology of the Yucca Mountain Conceptual Controlled Area precludes the occurrence of many types of ore deposits and the commodities that they contain from consideration in an assessment of metallic mineral potential. Examples include whole groups of deposit types, including deposits related to mafic and ultramafic rocks, eliminating commodities including chromium, nickel, and platinum group elements. Deposits related to alkaline igneous rocks and carbonatites, which are not known to occur in the Yucca Mountain Conceptual Controlled Area, have also not been considered, eliminating commodities including niobium and the rare earth elements. Deposit types that occur in clastic sedimentary rocks, including quartz pebble conglomerate gold-uranium and sedimentary rock-hosted copper have likewise been eliminated because the necessary geologic environment is not known to occur in the Yucca Mountain Conceptual Controlled Area.

3.11.2.6.5 Comparison of the Geology of the Yucca Mountain Conceptual Controlled Area with Mineralized Areas in the Region

The presence of currently economic precious-metal mineralization in the Bare Mountain and Bullfrog districts to the west of the Yucca Mountain Conceptual Controlled Area, along with past production and known mineralization in other districts in the Southern Great Basin as outlined above (Subsection 3.11.2.5,) has led to speculation that the potential Yucca Mountain repository site may be favorable for precious-metal deposits (e.g., L.T. Larson et al., *Task 3 Progress Report for January, 1987 - June, 1988*, 3-1 to 3-28, unpublished report, Center for Neotectonic Studies, Mackay School of Mines, University of Nevada-Reno; Johnson, C. and Hummel 1991). Weiss, Noble, Larson (1996) noted that Yucca Mountain is not attractive for present-day mineral exploration when compared to the nearby Bare Mountain, Calico Hills, and Wahmonie areas, but stated that similarities in stratigraphy, structure, some vein and alteration mineral assemblages, and geochemistry between the Yucca Mountain Conceptual Controlled Area and some mineralized areas are evidence that precious-metal deposits could be present in the Yucca Mountain Conceptual Controlled Area (Weiss, Noble, Larson 1995, 1996). An evaluation of such comparisons will be presented below to help assess the potential for future inadvertent human intrusions and to assess the presence of potentially adverse conditions (see Subsection 3.11.1).

3.11.2.6.5.1 Stratigraphy

Regional Stratigraphy is discussed in Subsection 3.2. Stratigraphy of the Yucca Mountain Site vicinity is discussed in Subsection 3.5. See Tables 3.2-1, 3.2-2, 3.2-3 and Figure 3.5-1 for regional and site stratigraphic columns. The stratigraphic section in the Yucca Mountain Conceptual Controlled Area includes stratigraphic units that contain economic mineralization elsewhere. In the Bare Mountain Mining district, metallic resources have been mined at several locations in Paleozoic carbonate units, including the Lone Mountain Dolomite and the Roberts Mountains Formation which are present below 1,200 m in borehole UE-25 p#1 at the Yucca Mountain site. These units host historically active mercury deposits in the Telluride Mine area.

However, most of the precious metal production from the district has originated from the older Wood Canyon and Bonanza King Formations at the Sterling Mine, and probably from the Miocene rocks of Joshua Hollow and cross-cutting igneous rocks at the Mother Lode Mine (Figure 3.11-1). New mining at Rayrock's Secret Pass Mine is exploiting deposits in the Bullfrog Tuff and the Cambrian Nopah Formation.

In the Bullfrog district, gold-silver mineralization occurs in the Lithic Ridge Tuff at the Original Bullfrog Mine. Paintbrush and Timber Mountain Group ashflows contain most of the mineralization at the Bullfrog Mine, although as noted by Eng et al. (1996), rocks as low in the section as flows beneath the Lithic Ridge Tuff are mineralized. Other deposits in the district have mined gold-silver ore in the Bullfrog and Topopah Spring Tuffs (Gold Bar Mine), the Tiva Canyon and Rainier Mesa Tuffs (Bonanza Mountain pit), and the Rainier Mesa and Ammonia Tanks Tuffs (Montgomery-Shoshone Mine) (Figure 3.11-1).

In addition, other areas in the Southern Great Basin that have been withdrawn from mineral exploration contain prospective mineralization in units that occur in the Yucca Mountain Conceptual Controlled Area. These include gold-silver ore in the Clarkdale district, which contains gold-silver ore in the Rainier Mesa Tuff and younger conglomerate, and the Calico Hills district, which contains mercury mineralization in rocks of the Calico Hills Formation and the Topopah Spring Tuff.

Weiss, Noble, Larson (1996) noted that areas of hydrothermal activity in the region range in age between 12.9 Ma in the Wahmonie district and 7.5 Ma in the Clarkdale district.

Based on the summary discussions above of potential host rocks and timing of hydrothermal activity, it appears that economic metal mineralization that occurs in mining districts elsewhere in the region, is possible in the Yucca Mountain Conceptual Controlled Area. Furthermore, on the basis that mineralization elsewhere in the region predates rock types exposed and present at shallow depths in the Yucca Mountain Conceptual Controlled Area, evaluation of data from drillholes in the Yucca Mountain Conceptual Controlled Area is necessary to determine metallic mineral potential. This evaluation was conducted and the results are summarized below.

3.11.2.6.5.2 Structure

Subsections 3.2 and 3.6 describe geologic structure in the region and site vicinity. The geologic structure is dominated by steeply west-dipping, north-striking normal faults that are accompanied by a secondary set of steeply dipping, northwest-striking faults with probable right-slip displacement. Because faulting is considered to be an important controlling feature for many metallic mineral deposits, especially epithermal deposits, S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) compared the structure in the Yucca Mountain Conceptual Controlled Area with that of regional metal mining districts.

Castor, Feldman, Tingley (1990) argued that the pattern of faulting in the southwest part of the Yucca Mountain Conceptual Controlled Area was substantially different from that in precious-metal mining districts in the region. Rose diagrams of fault orientations in the southwest part of the Yucca Mountain Conceptual Controlled Area are tightly grouped around a near north-south orientation and the circular variance is low (between 0.18 and 0.34), whereas in the Wahmonie, Calico Hills, Northern Bare Mountain, and Southern Bullfrog districts fault orientation is considerably more variable (circular variance ranged between 0.61 and 0.80). These data indicate that faults exposed at the surface in the Yucca Mountain Conceptual Controlled Area are generally subparallel and, therefore, that fault intersections, which are commonly important mineralization controls, are relatively rare in the Yucca Mountain area (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

The patterns of faulting at the surface in the Yucca Mountain Conceptual Controlled Area may not reflect fault patterns in the deep subsurface. Geophysical data suggest that deep hidden structures may be present in the Yucca Mountain Conceptual Controlled Area. A map of the top of the Paleozoic carbonate rocks as calculated from regional gravity by D. Ponce (CRWMS M&O 1996a) shows a pronounced depression under the western half of the Yucca Mountain Conceptual Controlled Area that may be a fault-bounded north-south graben that cannot be explained by surface faulting. A second interpretation of the gravity data (Subsection 3.8; CRWMS M&O 1997e) shows an east-west, north-facing scarp in the Paleozoic-Tertiary surface located approximately in the center of the Yucca Mountain Conceptual Controlled Area that has no surface expression (see Figures 3.8-15 and 3.8-16). Similar buried features could host mineralized epithermal vein systems that do not extend to the surface due to burial by younger volcanic deposits. The ages of regional mineralization (some may be older than Paintbrush Group rocks as noted in the above subsection) also suggest that older mineralization could be buried by younger deposits.

Gold-silver mineralization in the Bullfrog district is generally hosted by flat-lying faults (as at the Original Bullfrog Mine) to shallowly or moderately dipping faults (as at the Bullfrog Mine, see S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Plates 8-10). However, in places in the Bullfrog district, mineralization is in high-angle features as at the Montgomery-Shoshone and Bonanza deposits. Low-angle structures in the Bullfrog district are probably the result of extreme extension, possibly in excess of 100 percent as proposed by Maldonado (1990). If this type of extreme extension is necessary as ground preparation for the formation of large amounts of epithermal precious-metal ore including that at the Bullfrog Mine, then the Yucca Mountain Conceptual Controlled Area is probably a poor candidate for similar extensive mineralization, because flat and shallowly dipping faults do not appear to be present (Subsection 3.8; CRWMS M&O 1996a, 1997e) and extension was undoubtedly less extensive at Yucca Mountain than in mining districts to the west.

3.11.2.6.5.3 Alteration

Early work on alteration in the Yucca Mountain Conceptual Controlled Area was reported by Caporuscio et al. (1982) who described detailed petrography of samples from boreholes G2 and b1 and noted textural relationships between a number of alteration products, including secondary zeolite and feldspar minerals. Broxton, Bish, Warren (1987) subdivided alteration mineral assemblages at Yucca Mountain into four zones (I through IV, in order of increasing depth) that were considered to have resulted from open-system geochemical reactions. These zones are identified on the basis of the presence or absence of volcanic glass and presence of various secondary minerals. The alteration zones vary systematically with depth, rather than occurring as localized products of specific hydrothermal incursions. They become thinner and occur at stratigraphically higher levels from south to north in Yucca Mountain, a phenomenon that is thought to have been a response to a thermal pulse related to high-level magmatic activity in the Timber Mountain-Oasis Valley caldera complex to the north (Broxton, Bish, Warren 1987).

Bish (1989) estimated paleotemperatures as high as 300°C for rock alteration at depths greater than about 1,500 m beneath Yucca Mountain on the basis of clay mineral species. Bish also showed that paleogeothermal gradients were highest in the north part of the Yucca Mountain Conceptual Controlled Area; paleotemperatures in excess of 100°C were postulated below depths of 1,000 m in borehole G2, but paleotemperatures higher than 75°C were not thought to have been attained in borehole G3 (which is ca. 1,533 m deep). Bish and Chipera (1989) proposed that secondary feldspar and other minerals indicated a fossil hydrothermal system at depths of approximately 1,100 m or more at Yucca Mountain, and noted that this alteration was shallowest in borehole G2. However, Weiss, Noble et al. (1993) reported discovery of secondary potash feldspar in tuff from hole a1 that suggests relatively high-temperature activity at a higher level than predicted by the above work. On the basis of clay mineralogy and fluid inclusion data, Bish and Aronson (1993) proposed that mineral alteration in Yucca Mountain was caused by a combination of low temperature diagenetic reactions and convective hydrothermal outflow connected with the Timber Mountain caldera complex at 11-10 Ma. Weiss, Noble, Larson (1996) provided a map showing areas of hydrothermal alteration in part of the Southwestern Nevada volcanic field, including an area that is essentially delineated by the locations of deep drillholes in the Yucca Mountain Conceptual Controlled Area.

Age-dating of clay and zeolite minerals from drillholes in the Yucca Mountain Conceptual Controlled Area by K-Ar and $^{40}Ar/^{39}Ar$ has been attempted, but the results are somewhat ambiguous. K-Ar alteration ages on illite/smectite on samples from depths of about 350 to 525 m in boreholes G1 and G2 suggest that the alteration took place as much as 0.8 my before and (or) 2.8 my after eruption of ashflow tuffs of the Timber Mountain Group; thus leading to speculation that at least part of the alteration took place in response to Timber Mountain magmatism (Bish and Aronson 1993). Zeolite $^{40}Ar/^{39}Ar$ ages on samples from Yucca Mountain range between 3.5 ± 0.2 Ma and 13.3 ± 1.5 Ma (Woldegabriel 1993). This extreme range indicates problems with dating minerals that are known to exchange cations, including potassium and loss of argon. Dates obtained on the deepest zeolite samples most closely approach the age range of illite/smectite minerals (Woldegabriel 1993).

S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) contains a detailed discussion of alteration in the Yucca Mountain Conceptual Controlled Area. This discussion is based on systematic X-ray diffraction analyses of clay minerals, X-ray diffraction and petrographic analyses of zeolite minerals, similar analyses for feldspars including the use of scanning electron microscopes and energy-dispersive X-ray spectra. Analyses also identified calcite, chlorite and pyrite. In summary, Weiss, Noble, Larson (1996) proposed that pyrite in pyritic Tram and Lithic Ridge Tuffs was deposited by hydrothermal activity in place and related it to the clay- and zeolite-mineral alteration in Yucca Mountain, which they believe to be hydrothermal alteration. However, S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) believe that the pyrite predated this alteration (see Subsection 3.11.2.6.8.7). This type of alteration is typical of thick vertically-zoned tuffaceous sequences, and many workers have referred to similar alteration as "diagenetic" alteration (Walton 1975; Broxton, Bish, Warren 1987; Hoover, D.L. 1968). The question of what to call this alteration is semantic. On the basis of clay mineralogy, Bish (1989) proposed alteration temperatures as high as 300°C at a depth of about 1,800 m in borehole G2, but still referred to the alteration as "diagenetic." In borehole G3, the highest temperature proposed by Bish was about 70°C at a depth of about 1,800 m where the main alteration phases are analcite and smectite. At the level of the pyritic Tram Tuff in borehole G3 (about 1100 m), Bish estimates an alteration temperature of < 70°C. Although the alteration in hole G3 can be called "hydrothermal" because it was caused by warm water, no record could be found of analcite-smectite alteration related to economic hydrothermal metallic mineralization.

Alteration in the Yucca Mountain Conceptual Controlled Area has been discussed by Weiss, Noble, Larson (1996) who equate this alteration with that in areas that contain epithermal precious-metal mineralization including in the Bullfrog Mining district. This comparison is based on clay mineral and zeolite alteration, along with deeper alkali-feldspar alteration in Yucca Mountain Conceptual Controlled Area drillholes. These are clearly altered rocks, and, as noted above, at least some of the alteration took place as a result of thermal waters. Whether the alteration process should be called "hydrothermal" or "diagenetic" is debatable, but S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) do not believe that the Yucca Mountain Conceptual Controlled Area rocks should be portrayed as altered rocks in the same sense as those in mining districts of the region. Alkali feldspar alteration similar to that below 1,200 m in borehole G2 is associated with ore in the Bullfrog district, but it is accompanied by sericite and strong propylitic alteration. Mineralization in the Wahmonie district is in a large area of clay alteration and limonitization which is much more pervasive and extensive than at Yucca Mountain. Alteration minerals in the Bare Mountain and Mine Mountain districts include alunite, which has not been found at Yucca Mountain. In addition, it is curious that Weiss, Noble, Larson (1996) did not call attention to areas on the Nevada Test Site that include Pahute Mesa, Yucca Flat, and Skull Mountain, where USGS drilling indicated alteration to clay, zeolite, silica, and alkali feldspar minerals (Moncure 1980).

3.11.2.6.6 Geophysics

During the last 30 years, a large number of regional and local geophysical surveys have been completed in Nevada in support of exploration for mineral deposits. Some of this work has been completed by the USGS and the Nevada Bureau of Mines and Geology, often in cooperative efforts, and the data have been made available to the general public. In the Southern Great Basin, research and weapons testing at the Nevada Test Site provided justification for additional geophysical studies, primarily using gravity, magnetic, and seismic techniques, and until recently, these data were generally less available to the public. A new phase of detailed and extensive geophysical studies has been under way since the mid-1970s in support of potential repository siting and the site characterization program. This extensive data set is available to the public, mainly as open-file reports. These data and their interpretations have been reviewed in the present effort to evaluate the mineral potential of the Yucca Mountain Conceptual Controlled Area (Table 3.11-4).

Because substantial geophysical work has been conducted in the Yucca Mountain area and the surrounding region, an extensive database is available for review (Agnew 1994; Oliver et al. 1995). Surface and borehole geophysical studies conducted over the period from 1979 to 1996 at Yucca Mountain have been synthesized and summarized in *Synthesis of Borehole and Surface Geophysical Studies at Yucca Mountain, Nevada and Vicinity* (CRWMS M&O 1996d; Majer et al. 1996b). Most of the data were collected in support of near-surface to basement geological studies, especially identification of fault and fracture zones. As noted by Langenheim, Hoover, Oliver (1991), the survey work and interpretations were not designed for mineral exploration and resource evaluation. Thus, the sequence and types of surveys, and survey specifications, are generally different from those designed by industry as a cost-effective mineral exploration program. S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) used the existing database and interpretations already completed by other scientists to indicate implications for metallic mineral resource potential and to examine the limits to which the existing geophysical data can be used to test for this potential.

Oliver (1987) provided a brief background for geophysical studies relating to the nuclear waste isolation program prior to the selection of the Yucca Mountain area as the first site for detailed geologic and engineering characterization. Wynn and Roseboom (1987) described the role of geophysics in identifying and characterizing potential repository sites and identified important characteristics of the various candidate rock types, including saturated and unsaturated zones in volcanic tuff. They described the principal geophysical methods, their main applications, and addressed the issues of resolution, detectability and physical properties. The paper provides an excellent background for an evaluation of mineral potential based on the data available.

3.11.2.6.6.1 Metallic Mineral Exploration Strategy

A typical metallic mineral exploration program would use existing gravity, magnetic, seismic, and electrical resistivity data to extend the known geology and evaluate the thickness of Tertiary volcanics and other cover material (i.e., Quaternary alluvium and lake beds, slope wash; Paterson and Reeves 1985; Blakeley and Jachens 1991). Other information available from these data may relate to the presence and type of faulting, type of magnetic "basement" rocks, and location of possible intrusive rocks (Wright, P.M. et al. 1985; Corbett, J.D. 1991; Ponce 1991). Detailed aeromagnetic surveys and selective detailed gravity surveys might then be completed to better define targets related to concealed intrusives. Airborne electromagnetic surveys may be undertaken to detect conductive vein mineralization (including alteration minerals) or silicified (resistive) or altered (generally conductive) rocks related to precious metals mineralization (Pierce and Hoover 1991). A variety of ground surveys, using electrical resistivity/induced polarization (IP), and electromagnetic techniques may then be completed to refine targets and recommend drill test locations (Ward et al. 1981; Hoover, D.B., Grauch et al. 1991; Corbett, J.D.

1991). A state-of-the-art exploration strategy (Ward et al. 1981) would provide for qualitative and quantitative interpretation (numerical modeling) perhaps followed by physical property studies and more detailed geophysics following the initial drilling.

3.11.2.6.6.1.1 Magnetic

The Yucca Mountain area, the Nevada Test Site, and surrounding regions are adequately covered by a series of aeromagnetic surveys of sufficient detail and quality to assist in a metallic mineral assessment of the Yucca Mountain Conceptual Controlled Area. The surveys have been properly adjusted and merged, using state-of-the-art techniques, to form regional surveys of the Nevada Test Site, the Beatty 1:100,000 Quadrangle, and the state of Nevada. These regional surveys provide the basis for identifying regional trends which may relate to major geological structures which control or are associated with economic mineralization. Positive magnetic anomalies that may arise from pre-Tertiary crystalline or intrusive rock at shallow depths within Walker Lane structural blocks include areas of mineralized rocks in the Calico Hills and Wahmonie districts, which appear to be part of a northwest-striking zone that extends into the mineralized areas of Northern Yucca Mountain and Tram Ridge-Thompson Mine. This trend projects along the northeast boundary of the Yucca Mountain Conceptual Controlled Area (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.5). Positive magnetic anomalies in the Calico Hills and at Wahmonie probably arise from intrusive sources and the alteration of pyrite to magnetite as a result of heating pre-Tertiary argillites overlying the intrusives. The Oak Spring district also overlaps an intense positive aeromagnetic anomaly that reflects the presence of the Climax stock. Weak magnetic anomalies related to intrusive activity may be present in the Bullfrog district, but the northwesterly zone of intense anomalies trends to the north of this important precious-metal district. Low magnetic intensity is observed over Crater Flat and the south part of the Yucca Mountain Conceptual Controlled Area, and the Mine Mountain and Bare Mountain districts do not correspond with regionally significant anomalies (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.5). A 280 nT anomaly near the northwest part of the Yucca Mountain Conceptual Controlled Area might be caused by a buried intrusive within the volcanic section, but this feature has not been numerically modeled.

3.11.2.6.6.1.2 Gravity

Gravity data, both detailed and regional, are also of adequate quality and coverage to aid in the evaluation of metallic mineral potential in the Yucca Mountain Conceptual Controlled Area, although these data are only indirect indications of mineral potential. Gravity trends are present, but, similar to the magnetic data, they are discontinuous at Crater Flat and weak at Yucca Mountain. The interpretation of gravity data, even with good control on the density of geologic units, is subject to considerable ambiguity. One interpretation of the Paleozoic-Tertiary contact based on gravity data is discussed regarding the potential for hydrocarbon accumulation (see Subsection 3.11.4.7.4). The USGS has used seismic refraction data to reduce the ambiguity of gravity interpretations in the Crater Flat-Yucca Mountain area, especially with respect to depth to pre-Tertiary rocks. An integrated interpretation of gravity and seismic refraction data by

Ackermann et al. (1988) indicates that depths to pre-Tertiary bedrock exceed 1,300 m beneath most of the Yucca Mountain Conceptual Controlled Area, and this has been corroborated by later interpretation of gravity data (see Subsection 3.8: CRWMS M&O 1996a). Recent interpretations of seismic reflection data suggest Paleozoic rocks may lie even deeper (1,800 to 2,100 m) beneath most of the Yucca Mountain Conceptual Controlled Area (Brocher, Hart et al. 1996). Low-density Cenozoic volcanics and alluvium probably exceed 1.5 km in thickness, as inferred from gravity, seismic reflection, and seismic refraction data, and drilling results. The exact nature of the Crater Flat feature is still open to debate although numerical models indicate the geometry of the basin could arise from a graben- like structural feature rather than a caldera (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). This interpretation is supported by the integrated 3-D model (see Subsection 3.8) and alternative interpretations discussed in Subsection 3.2.2.1.

3.11.2.6.6.1.3 Seismic

Teleseismic and magnetotelluric data do not contribute significant information regarding the mineral potential within the Yucca Mountain Conceptual Controlled Area. Electrical resistivity and electromagnetic methods (time domain electromagnetic very low frequency) cover only a limited part of the Yucca Mountain Conceptual Controlled Area, and these surveys address structures, stratigraphy, and alteration within the (near-surface) volcanic tuffs. Combined with the inferred depth to pre-Tertiary rock, the low resistivities at depth suggest poor current penetration to pre-Tertiary rock depths for mineral exploration methods (including induced polarization) presently favored by the mineral exploration industry. The widely spaced electrodes required for deep exploration, and resistivity and chargeability variability within the volcanic tuffs, suggest that the use of electrical methods to explore to depths in excess of 1,000 m would likely be unsuccessful within the Yucca Mountain Conceptual Controlled Area. Dipole-dipole resistivity/induced polarization (IP) surveys at Wahmonie, more than 25 km east of the Yucca Mountain Conceptual Controlled Area, suggest a broad area of buried disseminated sulfide mineralization that is associated with a magnetic anomaly and low resistivities (indicated by Schlumberger VES) that indicate the presence of alteration and mineralization (Hoover, D.B., Chornack et al. 1982). Magnetic and gravity trends extend from the Wahmonie area toward the Yucca Mountain Conceptual Controlled Area, but based on gravity studies and available drill sampling, sulfide mineralization in pre-Tertiary rocks (if present) would occur at depths in excess of 1,000 m. Sulfide enrichment at these depths probably could not be detected or resolved by present day electrical exploration methods, even at great care and cost.

3.11.2.6.6.1.4 Others

The geophysical data and interpretations reviewed by S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) do not directly indicate the presence of metallic (or other) mineral potential within the Yucca Mountain Conceptual Controlled Area. On the basis of geochemical studies there is some possibility of mineralization in pre-Tertiary rocks. The depth to this rock and low- to moderate electrical resistivities in overlying volcanic tuffs make it doubtful that with any confidence electrical methods would be able to resolve the presence of mineralized rocks at depth. Electrical methods do indicate low electrical resistivities associated with fracture zones and alteration zones within the Tertiary tuffs but where these have been evaluated geochemically there is no direct indication of the presence of significant metallic minerals. Limited induced polarization measurements indicate some weak polarization zones within the volcanic tuffs but above-background polarization could arise from clay and zeolite minerals as well as from rocks containing sulfide minerals. Interpretation of numerically modeled IP and resistivity data suggests sulfide (pyrite) concentrations could be as great as 0.5 w% if the IP responses observed were entirely due to sulfides.

S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) indicate that one area of possible exploration interest within or adjacent to the Yucca Mountain Conceptual Controlled Area is the source area of a magnetic anomaly which occurs along the northwest margin of the Yucca Mountain Conceptual Controlled Area (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.5). There is some possibility that the source is an intrusive body lying at depths of 400 to 1,000 m within the volcanic tuffs. This source area could be tested for the presence of sulfide mineralization to depths of ca. 600 m with state-of-the-art resistivity/IP, but the effort could be inconclusive for mineralized rocks at greater depths.

3.11.2.6.7 Remote Sensing

Remote sensing in the Southern Great Basin using thematic mapper imaging indicates that evidence of alteration is confined to bedded tuff units in part of the Yucca Mountain Conceptual Controlled Area whereas it crosses lithologic units in nearby mining districts and areas of mineralized rocks (Castor, Feldman, Tingley 1990). S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*. Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) contains an extensive discussion of remote sensing studies conducted as part of Yucca Mountain site characterization studies.

As noted by Castor, Feldman, Tingley (1990) remote sensing evidence of clay mineral alteration is present at Yucca Mountain and generally corresponds to exposures of bedded tuff between the Topopah Spring and Tiva Canyon Tuffs. This alteration can be seen as narrow red color anomalies, particularly along the west side of Solitario Canyon (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Plates 4 and 5). Evidence for combined clay mineral and iron oxide concentrations noted by Castor, Feldman, Tingley (1990) in these bedded tuffs is not visibly shown on the thematic mapper band 6 images. Thematic mapper imaging in the Yucca Mountain Conceptual Controlled Area shows little evidence of hydrothermal alteration (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Plates 4 and 5).

Along the northeast border of the Yucca Mountain Conceptual Controlled Area is a weak yellow thematic mapper false color area that appears to be an extension of the northeast-trending thematic mapper color lineament across Yucca Wash. Surface examination of outcrops in this area did not disclose either mineralized rocks or veins; the area appears to be underlain mainly by light-colored bedded tuffs. Minor clay alteration may be present but most of the bedded tuff is glassy and appears unaltered. Small areas of red to yellow color shown to the northwest along the Yucca Mountain Conceptual Controlled Area border appear to correspond to exposures of bedded tuff and zeolitized rocks of the Calico Hills Formation.

3.11.2.6.8 Geochemistry

3.11.2.6.8.1 Trace Element Frequency Distributions

Histograms of analytical data for selected elements in samples obtained from the Yucca Mountain Conceptual Controlled Area and from mining districts and mineralized areas in the Southern Great Basin are shown in Figures 5.6 to 5.12 in S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). These histograms may be used as graphic comparisons of geochemical patterns between the areas. For histogram preparation, analytical data for samples from the Northern Yucca Mountain, Claim Canyon, and Tram Ridge-Thompson Mine areas were combined because the trace element chemistry for these three adjacent areas is similar. In addition, samples from drillhole UE-25 p#1 (mainly Paleozoic rock) are separated from those from the rest of the Yucca Mountain Conceptual Controlled Area (all Tertiary volcanic rock). In all histograms, the values on the horizontal axis represent the highest value for that category (i.e., the frequency bar shown above 1 ppm on the horizontal axis represents samples with 0.1 to 1 ppm).

Histograms for gold (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.6) show that all mineralized areas, with the exception of the Northern Yucca Mountain + Claim Canyon + Tram Ridge-Thompson Mine areas and the Calico Hills district, have higher gold values than Tertiary rock samples from the Yucca Mountain Conceptual Controlled Area. The few Calico Hills district samples containing elevated values of gold are from veins in Paleozoic rocks in the Northern part of the district. As expected, histograms for the Bare Mountain and Bullfrog districts, which include samples from active gold mines, have the highest percentage of samples containing more than 0.1 ppm gold. In addition, the histograms representing these areas show nearly perfect log-normal frequency distributions. The histogram for the Wahmonie district shows a bimodal distribution for gold but this may be due to the low number of samples. The histogram for samples from borehole p1 clearly have more elevated gold values than those from the rest of the Yucca Mountain Conceptual Controlled Area.

Histograms for silver (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.7) show high values relative to Yucca Mountain Conceptual Controlled Area Tertiary rock samples for all mineralized areas except the northern Yucca Mountain + Claim Canyon + Tram Ridge-Thompson Mine areas.

However, some samples from borehole p1 contain elevated values of silver, indicating a higher content of silver compared with gold (compare S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.6 and 5.7). Samples from the Mine Mountain district are the richest in silver, followed by samples from the Wahmonie district. These two districts are characterized by silver-dominated precious-metal mineralized rocks, whereas the mineralized rocks in the Bare Mountain district are is clearly dominated by gold.

Arsenic content histograms (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.8) show strong similarities between the Bare Mountain and Mine Mountain districts. Arsenic distribution patterns between Yucca Mountain Conceptual Controlled Area Tertiary rocks, Northern Yucca Mountain + Claim Canyon + Tram Ridge-Thompson Mine samples, and samples from the Calico Hills are similar and arsenic contents are mostly at background levels. High arsenic contents (100 to 1,000 ppm) in the Calico Hills set are in vein samples from the northern part of the district. Even samples from the Bullfrog district, which contains low arsenic for a district with economic precious-metal mineralization, contains elevated arsenic relative to Yucca Mountain Conceptual Controlled Area Tertiary rocks. By comparison, samples from borehole p1 show a pattern of arsenic enrichment that is second only to that in the Mine Mountain and Bare Mountain districts.

Antimony histograms (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.9) are similar to arsenic histograms for mineralized areas and the Yucca Mountain Conceptual Controlled Area. The Bare Mountain and Mine Mountain districts show the most antimony enrichment. Yucca Mountain Conceptual Controlled Area Tertiary rocks, samples from the Northern Yucca Mountain + Claim Canyon + Tram Ridge-Thompson Mine areas, and samples from the Calico Hills show the least antimony enrichment. High antimony (100 to 1,000 ppm) in the Calico Hills set are in vein samples from the northern part of the district. Samples from the Bullfrog district show similar antimony distribution to Yucca Mountain Conceptual Controlled Area Tertiary rocks. Samples from borehole p1 are clearly enriched in antimony in comparison to samples obtained elsewhere in the Yucca Mountain Conceptual Controlled Area.

Mercury content histograms (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.10) exhibit strong similarities between Bullfrog district and Yucca Mountain Tertiary rock samples and contain relatively low values of mercury, and Wahmonie district samples are only slightly more enriched in mercury. As expected, the highest mercury contents are in samples from the Mine Mountain district, which contains evidence of past mercury production. The Bare Mountain district, Calico Hills district, the Northern Yucca Mountain + Claim Canyon + Tram Ridge-Thompson Mine areas, and borehole p1 in the Yucca Mountain Conceptual Controlled Area have slightly elevated levels of mercury.

Molybdenum content histograms for Yucca Mountain Tertiary volcanic rock samples and Northern Yucca Mountain + Claim Canyon + Tram Ridge-Thompson Mine area samples (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.11) show strong similarities in both distribution and content. Samples from the Calico Hills, Bullfrog, and Wahmonie districts have slightly higher molybdenum contents, with relatively high molybdenum in the Calico Hills set contributed by Paleozoic rock-hosted vein samples from the northern part of the district. Rock samples from Bare Mountain contain the highest amounts of molybdenum. The Mine Mountain district and borehole p1 in the Yucca Mountain Conceptual Controlled Area contain lower molybdenum contents than Bare Mountain, but have a relatively high percentage of samples containing between 10 and 100 ppm molybdenum.

Lead content histograms (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.12) show that samples from most Yucca Mountain mineralized areas and the Yucca Mountain Conceptual Controlled Area contain little lead. The Bullfrog district and Wahmonie district sets are slightly enriched, containing relatively high percentages of samples with lead in the 10 to 100 ppm range. Mine Mountain district samples show extreme enrichment, with more than half of the samples containing 1,000 to 10,000 ppm lead. In addition, the Mine Mountain district lead histogram shows a clear bimodal frequency distribution pattern, suggesting that it contains two distinct populations of mineralized rock.

3.11.2.6.8.2 Statistical Analyses

Simple statistical analyses of the geochemical data show some important patterns for samples from the Yucca Mountain Conceptual Controlled Area and mining districts and mineralized areas in the region. Because of overall consistency (see Subsection 3.11.2.2.3), USML analyses were used for elements where data from more than one laboratory were available. Standard statistical variables (mean, median, standard deviation, skewness, minimum, and maximum) are shown in Table 5.4 of S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). Correlation coefficients are shown in Tables 5.5 to 5.15 of S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

For the areas investigated by S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review), correlation coefficients show that normally expected correlations, particularly those between light rare earth elements, are positive at high confidence levels. For some areas, positive correlation between light rare earth elements and other lithophile elements including thorium and hafnium is also present. Such correlations are not applicable to assessment for precious- or base-metals, and are not discussed below.

3.11.2.6.8.2.1 Yucca Mountain Conceptual Controlled Area

S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) used results from 396 samples collected from the surface and from the Exploratory Studies Facility within the Yucca Mountain Conceptual Controlled Area in statistical calculations. For this group of samples, median values are low for silver, arsenic, gold, mercury, antimony, and base metals. Correlation coefficients between elements (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Table 5.5) do not show strong groupings of correlated elements; however, antimony and arsenic display strong correlation ($r = 0.93$). In addition, the elements bismuth, cadmium, gallium, lead, thallium, and zinc show strong mutual correlations ($>r = 0.50$, which is very high for a large sample set), undoubtedly due to their presence in fumarolic occurrences (see Subsection 3.11.2.6.8.5). Gold is weakly correlated with calcium and mercury, probably due to slight elevation in calcrete (Subsection 3.11.2.6.8.4). Silver and gold show weak correlation ($r = 0.19$), and there is no correlation between the precious metals and the pathfinder elements antimony and arsenic.

S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) separated drillhole data from the Yucca Mountain Conceptual Controlled Area into two populations for statistical evaluation. Twelve samples from borehole p1, which include Paleozoic rock samples, were grouped separately. All other drill samples, which consist entirely of Tertiary rocks, were placed in a second group. The larger drillhole data set consists of 401 samples. Correlation coefficients between elements in this data set (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Table 5.6) are generally similar to those seen in the Yucca Mountain Conceptual Controlled Area surface and Exploratory Studies Facility samples, with relatively strong arsenic and antimony correlation, low silver and gold correlation ($r = -0.03$), and weak correlation between the precious metals and arsenic and antimony. Relatively strong mutual correlation between barium, bismuth, lead, tellurium, and tin is probably due to their presence in fumarolic occurrences. By contrast, samples from borehole p1 show very strong mutual correlations ($r = 0.90$) between gold, silver, arsenic, antimony, mercury, and thallium (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Table 5.7). Molybdenum and bismuth correlate strongly with each other and show moderate correlations with precious metals. Copper, selenium, and antimony also show strong mutual correlation.

The large difference in sample populations between the two groups of drillhole samples prevents close comparison of the two. There also may be a problem with cuttings samples included in the borehole p1 group because drill logs indicate that there may be metallic contamination from drilling.

3.11.2.6.8.2.2 Bare Mountain District

Sampling in the Bare Mountain district provided 48 samples for statistical evaluation. Within this group, median values for gold, arsenic, antimony and mercury are higher compared to the other groups in the study. Correlation coefficients for the district as a whole (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Table 5.8) show moderately strong mutual correlations ($r > 0.75$) between gold, arsenic, and lead. Silver and gold correlate moderately ($r = 0.79$). There is also strong mutual correlation ($r > 0.98$) between copper, cadmium, beryllium, cobalt, and zinc, and molybdenum and bismuth also correlate strongly. Antimony and mercury, although present in elevated amounts in some samples compared to other samples in this study (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Table 4.1) do not correlate well with each other or any of the elements noted above.

When correlation coefficients for samples from the adjacent Sterling and Diamond Queen Mines are considered alone, a much stronger pattern of mutual correlations between precious metals and pathfinder elements can be seen (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Table 5.9). Gold and silver are highly correlative ($r = 0.95$), and there is mutual correlation between gold, silver, arsenic, copper, lead, and selenium ($r > 0.75$). Tellurium is also strongly correlated with the precious metals, and thallium is moderately correlated with them in this data set.

3.11.2.6.8.2.3 Bullfrog District

S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) examined a data set consisting of 246 samples from the Bullfrog district. These are mainly core and rock samples from the Bullfrog Mine, with some outlying samples. With the exception of gold, median values for most metallic elements are low for this data set compared to the other district samples for this study. The median gold content is about 100 times the median gold content of samples from the Yucca Mountain Conceptual Controlled Area. Surprisingly, there is only moderate correlation between gold and silver in the Bullfrog district as a whole ($r = 0.36$), and gold correlates most strongly with beryllium ($r = 0.43$). There is strong mutual positive correlation in this data set between silver, bismuth, cadmium, copper, antimony, and lead (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Table 5.10).

The patterns noted above for the Bullfrog district change dramatically when a single sample (YMR 0495) from the Original Bullfrog Mine is removed. This sample is extremely high in silver (1,598 ppm) compared to the other samples analyzed in this study and also has distinctively high bismuth, cadmium, copper, lead, and antimony for the district (see Castor et al., in review, Appendix 2). As shown in S.B. Castor et al. (*Assessment of Metallic and Mined*

Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Table 5.11), when this sample is removed the silver-gold correlation increases substantially (r = 0.75), and the strong correlations between silver and several elements noted above disappears.

3.11.2.6.8.2.4 Calico Hills

The Calico Hills data set used by S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada,* Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) consists of 51 samples. Maximum values for many metallic elements including silver, gold, copper, mercury, lead, antimony, and zinc (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada,* Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Table 5.4) are moderately high to high in samples from this district compared to other samples in this study. However, except for mercury, the higher values are restricted to veins in Paleozoic rock from the north part of the district (see Subsection 3.11.2.5.3.1 above). Strong mutual correlations (r ^{3} 0.80, see S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada,* Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Table 5.12) occur between gold, arsenic, cadmium, copper, lead, molybdenum, tin, tellurium, and zinc, but these undoubtedly represent the veins in Paleozoic rock noted above. Mercury, which is commonly elevated in altered volcanic rock in the southern part of the district, does not correlate at high confidence levels with other elements; it is most correlative with selenium (r = 0.53).

3.11.2.6.8.2.5 Mine Mountain District

Only 20 samples were available for statistical evaluation from the Mine Mountain district. Median values for arsenic, gold, antimony, mercury, copper, cadmium, lead, tellurium, and zinc are high to moderately high compared to other samples in this study (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada,* Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Table 5.4). Median gold at Mine Mountain is approximately six times higher than that in surface samples from the Yucca Mountain Conceptual Controlled Area, while mercury, lead, and antimony are 300 to 400 times the Yucca Mountain Conceptual Controlled Area median values. Minor amounts of mercury were mined in the Mine Mountain district, and the element is strongly mutually correlative with tellurium and thallium. Although there are some strongly correlative element pairs including silver with antimony and molybdenum with selenium within the Mine Mountain sample group, correlation coefficients (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada,* Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Table 5.13) show a general lack of strong mutual correlation between metals. The mineralized rocks in the Mine Mountain district are typified by high base metals, and in this regard the general lack of mutual correlation between base metals themselves (and most other metals) is suggestive of complex metal zoning or of more than one episode of metallization. Silver and gold are only weakly correlative at Mine Mountain (r = 0.51, not significant at the 99 percent confidence level). The distinct lack of correlation between gold and pathfinder elements including arsenic and mercury in the mineralized sedimentary rocks at Mine Mountain suggests that this district is geochemically unlike those that contain Carlin-type gold deposits (for example, Bare Mountain).

3.11.2.6.8.2.6 Northern Yucca Mountain, Claim Canyon, and Tram Ridge-Thompson Mine Areas

Taken together, 23 samples were collected from these three areas. The samples from the three areas have similar geochemical signatures, and resemble those from the southern part of the Calico Hills district, in that in many samples mercury is the only elevated element. Gold and silver contents, which are universally low, show no correlation ($r = -0.01$). Arsenic and antimony are mutually correlative, but show no correlation with precious metals, and gold does not correlate well with any of the metals shown in Table 5.14 of S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

3.11.2.6.8.2.7 Wahmonie District

Seventeen samples were collected from the Wahmonie mining district. The median gold value for this sample set is only slightly enriched compared to other samples from this study, but is five times the median value for surface samples in the Yucca Mountain Conceptual Controlled Area. Silver contents in Wahmonie district samples are locally high compared to other samples from this study, and gold correlates perfectly with silver ($r = 1.00$). Correlation coefficients (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Table 5.15) display strong mutual correlation ($r > 0.99$) between silver, gold, and tellurium, and less strong correlations between the precious metals and copper and the precious metals and cadmium. Arsenic shows essentially no correlation with the precious metals, and antimony is not correlative with gold or silver above the 95 percent confidence level.

3.11.2.6.8.2.8 Geochemical Variation with Depth in the Yucca Mountain Conceptual Controlled Area

The variation of gold, silver, and precious metal pathfinder elements with depth in Yucca Mountain is shown in Figures 5.13 through 5.17 of S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). Except for two samples of Paleozoic sedimentary rock, gold is present in concentrations of less than 10 ppb in drillhole samples and is under 4 ppb in all samples from depths of less than 800 m (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.13A). On the other hand, except for a few samples of Paleozoic rock, silver in excess of 0.3 ppm occurs only above 800 m in the Yucca Mountain Conceptual Controlled Area (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.13B). Silver is highest in samples from approximately the same stratigraphic level as the fumarolic accumulations of trace elements which vary in depth from less than 50 m to as much as 150 m, depending on the stratigraphic level of drillhole collars.

The important precious-metal pathfinder elements arsenic and antimony are at or near background levels above 700 m in drillhole samples (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.14). Below this level, concentrations of arsenic are highest in samples of Paleozoic rock. Antimony shows distinct enrichment between 800 and 900 m, where the element is enriched in manganese and(or) iron oxide bearing veins as discussed below (Subsection 3.11.2.6.6.3); arsenic also shows slight enrichment at about this level (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.14A).

Tin, bismuth, fluorine, and cerium are mainly enriched in samples from fumarolic occurrences (as discussed in Section 5.7.2 of S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). These samples were obtained from above 150 m in all boreholes (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figures 5.15 and 5.16). Tellurium is enriched in some of these samples (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.10A). Tellurium, along with selenium, is enriched in samples from depths of ca. 1,000 to 2,000 m (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) (Figure 5.17), which corresponds to the depth of the pyritic tuff (Section 5.7.4 of S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

On the basis of most pathfinder element data, potential, if any, for precious metal deposits in the Yucca Mountain Conceptual Controlled Area is at depths of 700 m or more as shown in Figures 5.14 through 5.17 of S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). This is based on the assumption that associated precious metal deposits, if they exist, are at or below the level of pathfinder element enrichment. As noted at Round Mountain by Tingley and Berger (1985) pathfinder halos generally extend above precious metal mineralized volcanic rock.

3.11.2.6.8.3 Specific Mineralogic, Lithologic, and Trace Element Associations in the Yucca Mountain Conceptual Controlled Area

Most samples that were collected from the Yucca Mountain Conceptual Controlled Area for the S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) study have trace element contents that are considered to be normal for the rock types that they represent. They have background concentrations of trace elements, and are not considered to show geochemical evidence for the presence of hydrothermal metallic mineral deposits. Other evidence may be present for these rocks including, alteration minerals or veins, that indicate that they were subjected to hydrothermal activity that could have led to the deposition of economic amounts of metallic commodities. This evidence does not necessarily indicate the presence of metal deposits, because, as noted by Hedenquist and Lowenstern (1994), "... the occurrence of ore deposits is uncommon compared to the widespread evidence for extinct hydrothermal activity, indicating that only a small proportion of hydrothermal systems form ore."

Because the Southern Great Basin contains several metallic mineral deposits that are, or have been, mined for gold, and because major gold deposits occur in volcanic rocks similar to those in the Yucca Mountain Conceptual Controlled Area, the results of gold analyses are of special interest. Exposed or very shallow gold deposits are indicated by ore-grade (>0.5 ppm) or near ore-grade gold analyses; however, there is little information on the level of gold content that is significant during exploration for "blind" gold deposits. Woodall (1988) extolled the modern development of sensitive analytical techniques that enable definition of "subtle but significant anomalies of as little as 5 to 20 ppb which may overlie economic gold deposits." The threshold for "anomalous" gold is dependent on host rock types in a prospective area and on the accuracy and repeatability of the analytical method used. According to work by Connors et al. (1993), who used a combined neutron activation and fire assay technique with a gold detection limit of 0.1 ppb and replicate agreement that was generally within 0.1 ppb, glassy silicic volcanic rocks collected from throughout the world range between <0.1 ppb and 4.5 ppb gold. Within this collection, peralkaline rhyolites have the highest gold contents, at 0.2 to 4.5 ppb, and subalkalic rhyolites the lowest, at <0.1 to 0.8 ppb. On the basis of minor amounts of data, peraluminous rhyolites contain even less gold, at <0.1 to 0.5 ppb. However, as noted by Connors et al. this work does not address possible variations in gold content in volcanic rocks due to devitrification, vapor-phase alteration, and groundwater movement. On the basis of gold measurement in peraluminous rhyolite flows from Northeastern Nevada using the same analytical method as that used by Connors et al. (1993). J.G. Price et al. (1992) showed that gold content varied from <0.1 to 0.4 ppb in hydrated vitrophyre, but was present in amounts as high as 2.5 ppb in devitrified rhyolite with vapor-phase quartz in cavities. These rhyolitic rocks, in the Toana Range, Elko County, show no evidence of hydrothermal alteration and there are no known mineralized areas associated with them (Lapointe, D.D. et al. 1991).

On the basis of the variation of gold analyses for control sample Con-2 (Section 1.4.3 and Appendix 4 of S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) USML gold analyses were found to be the most reliable of those obtained for this study. Maximum variation for Con-2 gold analyses by

USML was found to be 2 ppb. If the maximum gold content of rhyolitic rocks is about 2.5 ppb and maximum variation for gold analyses by USML is 2 ppb, then samples with gold contents in excess of 4.5 ppb might be considered anomalous. For the purpose of this assessment, samples that contain 5 ppb or more of gold are considered to be significant. This level of gold content does not constitute gold ore; it must be multiplied by 100 to equal the lowest grade of hard-rock gold ore that is currently mined (about 0.5 ppm or 0.02 ounces per short ton). However, from the standpoint of an exploration geologist, the discovery of rock with more than 5 ppb gold might be significant because it could indicate vertical or lateral leakage from a deposit of higher grade. For most exploration geologists, 5 ppb gold in the absence of elevated amounts of other elements, e.g. arsenic or evidence of hydrothermal alteration would be of little interest, and few explorationists would be willing to delineate borehole targets on the basis of surface samples with 5 ppb gold alone. The selection of 5 ppb as the threshold for anomalously high gold for this study is therefore considered to be conservative.

Only a few samples collected from the Yucca Mountain Conceptual Controlled Area during the Castor et al. (in review) study or earlier studies (Castor, Feldman, Tingley 1990; Castor, Tingley, Bonham 1993) were found to contain gold in higher amounts than 5 ppb. This is true despite the "biased" or conservative sampling approach used; an approach designed to collect rocks with the most likelihood of containing gold or other valuable metals deposited during hydrothermal activity (as discussed above in Subsection 3.11.2.2.2). The highest gold contents in any rocks collected from the Yucca Mountain Conceptual Controlled Area were measured in pyrite-bearing samples of the Silurian Lone Mountain Dolomite from depths greater than 1470 m in drillhole UE-25 p#1 which is discussed in more detail below (Subsection 3.11.2.6.8.8).

Some of the economic gold deposits in the Southern Great Basin contain silver in amounts comparable to, or in excess of, gold; in all of the mining districts in the region, regardless of the ratio of silver-to-gold, silver is correlative with gold (Tables 5.8, 5.9, 5.10, 5.11, 5.13, 5.15 in S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). Examples of deposits with silver contents roughly comparable to gold include most of the deposits in the Bullfrog Mining district and deposits in the north part of the Bare Mountain Mining district. In the Mine Mountain and Wahmonie mining districts to the east of Yucca Mountain, the amount of silver far exceeds the amount of gold. In these districts, the potential for economic development probably lies with silver ore, as in the recently productive Candelaria district about 200 km northwest of the Southern Great Basin. However, because silver is of considerably less value (silver currently sells for about $5 per ounce in comparison to $350 for an ounce of gold), silver deposits without gold or other metal credits must contain about 2 ounces of silver per ton of ore (ca. 70 ppm) to be economic at current prices. The presence or absence of silver in rocks at Yucca Mountain, particularly where associated with gold, is important to the consideration of metallic mineral potential. It is only economic if silver and gold are together and higher concentrations.

Silver measured in samples from the Yucca Mountain Conceptual Controlled Area by S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) ranges up to 4 ppm, which is anomalous in view of an average abundance of about 0.1 ppm or less in igneous rocks (Levinson 1974). However, samples with elevated silver from the Yucca Mountain Conceptual Controlled Area do not contain elevated gold or other metals suggestive of hydrothermal metallization.

Some trace elements that are typically found in gold ore (the so-called "pathfinder elements") are of interest in the metallic assessment of the Yucca Mountain Conceptual Controlled Area. The presence of anomalously high gold pathfinder element contents do not, in themselves, indicate that gold is present in economic or even anomalous amounts. However, to an exploration geologist their presence is an indication that the rocks that contain them should be examined more closely. Antimony, arsenic, bismuth, mercury, molybdenum, tellurium, thallium, and the base metals (copper, lead, and zinc) are the most commonly used gold pathfinder elements. Anomalously high amounts of these elements occur in some samples from Yucca Mountain. Table 5.4 in S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) gives the high, mean, median, low, and standard deviation for gold, silver, and pathfinder elements in samples from Yucca Mountain in comparison with those values for mining districts and mineralized areas in the Southern Great Basin.

Elevated amounts of trace elements important to the evaluation of metallic mineral potential occur in specific environments in the Yucca Mountain Conceptual Controlled Area. These environments are discussed below.

3.11.2.6.8.4 Mercury and Gold in Surface Calcrete, Silica, and Fault Gouge

Slightly elevated values of mercury occur in some samples of calcrete and silicified breccia at or near the surface in the Yucca Mountain Conceptual Controlled Area. The highest mercury content measured in samples from the Yucca Mountain Conceptual Controlled Area for this study is about 200 ppb in calcrete (Table 3.11-5, samples YMR 0395 and YMR 0447; S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). In addition, gold in excess of 5 ppb (as measured by USML) in surface samples from the Yucca Mountain Conceptual Controlled Area is generally in calcrete that is also weakly enriched in mercury (Table 3.11-4, S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). As much as 9 ppb of gold in calcrete from Yucca Mountain has been noted previously (Castor, Feldman, Tingley 1990). A few samples of silicified fault breccia with minor calcite are slightly enriched in mercury, but contain low gold (Table 3.11-4; samples YMR 0207, 0810 and 0811, S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). The highest gold content in any surface samples from the Yucca Mountain Conceptual Controlled Area is 11 to 12 ppb (measured in replicate) in a sample of smectite-bearing fault gouge that also contains slightly elevated mercury (sample YMR 0319). Surface samples from the Yucca Mountain Conceptual Controlled Area that are slightly enriched in gold generally do not contain elevated amounts of gold pathfinder elements other than mercury. An exception is sample YMR 0444, which is calcrete with slightly elevated thallium (2.65 ppm) and arsenic (13.8 ppm). In addition, many calcrete samples with or without elevated gold or mercury have arsenic contents in excess of 10 ppm, which is distinctly higher than the median arsenic content of Yucca Mountain Conceptual Controlled Area samples (about 3.2 ppm).

Calcrete in the Yucca Mountain Conceptual Controlled Area is present as veins and as breccia matrix.. It consists mostly of fine-grained light brown to white calcite with associated brown to white opaline silica. The calcrete veins commonly consist of thin discontinuous laminae. Many calcrete veins are located along major faults, and some are young enough to crosscut alluvium. Calcrete vein material along the Solitario Canyon fault is up to 1 m thick, forms the hanging wall of the fault, and cuts overlying alluvium. It consists of friable white calcite and well indurated white to light brown silica. Calcrete veins in Trench 14 locality west of the northern Exploratory Studies Facility portal consist of anastomosing and cross-cutting veins of variably lithified calcite and opal. Calcrete breccia is also commonly found along faults, it contains calcite and opal cement identical to that in the veins. The origin of calcite-silica deposits in Trench 14 is discussed in Subsection 3.4.3.4.

Calcrete is also present in crudely bedded deposits that are generally found on the gentle eastern slopes of Yucca Mountain. It is particularly well developed on Whaleback Ridge. The bedding is generally parallel to the slope upon which the calcrete occurs. Generally, but not always, bedded calcrete is less indurated than vein calcrete. Bedded calcrete locally contains opaline silica similar to that in calcrete veins and breccia.

Yucca Mountain calcrete generally contains tiny rounded granules of dark brown material and fine angular detritus. Some samples contain spherical or ovoid carbonate masses as much as a millimeter or more in diameter that are interpreted as filled root cavities or worm burrows. Cavities in the calcrete contain finely acicular carbonate, but most of the carbonate is micritic. The silica is locally seen to replace the calcite. It is mainly opal-CT on the basis of X-ray diffraction analysis (Castor, Feldman, Tingley 1990).

Silicified breccia occurs along some faults in the Yucca Mountain Conceptual Controlled Area, and is particularly well developed along faults on the east side of Solitario Canyon. The breccia contains clasts of variably silicified ashflow tuff set in a light-colored silica matrix that commonly contains minor late crystalline calcite. Based on X-ray diffraction analysis, the silica consists mainly of opal-CT, cristobalite, and tridymite (Castor, Feldman, Tingley 1990), but may also include late white chalcedony.

Gouge is rarely found along faults at the surface in the Yucca Mountain Conceptual Controlled Area. Although faults may appear to contain clay, the fracture filling is mainly composed of pulverized rock.

It is difficult to explain the slightly elevated gold values observed in calcrete relative to other surface samples from Yucca Mountain. If the calcrete is pedogenic, as proposed by Quade and Cerling (1990), Stuckless, Peterman, Muhs (1991) (see Subsection 3.4.3.4 for an extensive discussion), and the National Research Council (1992), the gold must have been deposited by pedogenic processes. The source of pedogenic carbonate in the calcrete would almost certainly be windblown carbonate particles and the gold itself may have originally been included in these particles, possibly blown in from the Bare Mountain area to the west (which contains both gold deposits and Paleozoic carbonate rocks). Mercury and arsenic are associated with the Bare

Mountain deposits, but so are other elements, including antimony and molybdenum, that do not appear to be enriched in the calcrete. The presence of slightly elevated mercury and arsenic in the calcrete may be due to organic fixing of these elements in the carbonate, rather than to windblown introduction. The challenge of trying to identify the source of the gold in these veins is academic, owing to the extremely low gold contents.

Sample YMR 0319 (Table 3.11-5; Castor, Garside et al. 1997) was collected from a N 7°W, vertical or steeply west-dipping structure that has been mapped as the northern extension of the Solitario Canyon fault (Scott, R.B. and Bonk 1984; Day et al. 1996a). The fault is well exposed in trench SCF-15, excavated for paleoseismic studies. YMR 0319 is a chip sample taken across a 0.5 m thick zone of mottled red, green, and yellow gouge consisting dominantly of pulverized bedded tuff with clasts of welded ashflow tuff. The 11 ppb gold analysis from this sample was performed by USML, and reanalysis by USML yielded 12 ppb gold. NBMGAL analysis of the same sample yielded <2 ppb gold. Analysis by USML of a sample of red silicified breccia that occurs along the west side of the same fault yielded 0.4 ppb gold. Aside from a slightly elevated level of mercury, YMR 0319 does not contain elevated gold pathfinder elements.

3.11.2.6.8.5 Trace Elements in Fumarolic Deposits, Paintbrush Tuff

Rock with elevated levels of barium, bismuth, fluorine, lead, thallium, tin, and zinc occurs in a specific stratigraphic interval in the Paintbrush Group in and near the Yucca Mountain Conceptual Controlled Area. These occurrences are scattered widely on the surface and include a locality in the Exploratory Studies Facility that is particularly enriched in bismuth, fluorine, thallium, and base metals. The rock is distinguished by the presence of hematite and limonite staining and clay alteration, commonly in association with opaline silica. All of the occurrences are located stratigraphically in or above the uppermost part of the welded portion of the Topopah Spring Tuff and below white to light brown bedded tuffs related to the Pah Canyon Tuff. Host rocks are typically coarse lapilli-fall tuff, bedded tuff, and nonwelded ashflow tuff. In addition, an interval of pale red, clay-altered, bedded tuff about 1 m thick in drillhole GU3 that occurs at the same stratigraphic level as the surface and Exploratory Studies Facility occurrences is enriched in the same suite of elements, as are samples from about the same horizon in boreholes SD-7, SD-9, and SD-12. In addition to the elements listed above, samples from these occurrences may also have elevated levels of antimony, arsenic, silver, tellurium, and uranium, but do not contain elevated levels of gold. Table 5.17 in S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) lists samples and reports analyses for selected elements.

Light brown to orange, coarse, vitric, lapilli tuff is commonly present beneath or near these occurrences, and the occurrences commonly include a thin bed of pink, clay-altered, hematitic tuff and wholly to partially silicified tuff in various shades of red and gray in the vicinity of the brown to orange lapilli tuff. Vein-like, stratiform, and irregular masses of distinctive red, silicified bedded tuff have been found at several locations in the Yucca Mountain Conceptual Controlled Area (sample locations YMR 0123, 0248, 0400, 0462, and 0474 [see S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Plate 2 for locations of samples] Figure 3.11-2). The silicified rock, which in places occurs along faults is associated with clay-altered and hematite-stained tuff, but altered and hematized rock at these locales is restricted to small areas, generally less than 10 m in diameter. Partially calcitized tuff is present at some of the occurrences.

Common minerals identified in samples from these trace metal accumulations in and near the Yucca Mountain Conceptual Controlled Area include cristobalite, opal-CT, chalcedonic quartz, hematite (both red earthy and black specular varieties), smectite clay (montmorillonite and possibly nontronite), calcite, and adularia. The silicified rock generally contains unaltered phenocrysts of plagioclase, potash feldspar, clinopyroxene, and oxidized biotite, along with spherulites and fragments of ashflow tuff, in a matrix of isotropic to nearly isotropic silica that replaced the glassy portion of the rock (Castor, Feldman, Tingley 1990). Barite is generally present in trace amounts, but is common in some samples. It is relatively abundant in drill sample GU3/408.0, which contains 1.4 percent barium (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Table 5.17). In sample GU3/408.2 fine crystals of barite occur with adularia in cavities (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.18). Fluorite was identified in one sample that contains 0.9 percent fluorine (Exploratory Studies Facility sample SPC 00509201). Specular hematite with cassiterite occurs abundantly in another sample (YMR 0366). The cassiterite occurs as fine crystals as much as 0.1 mm in diameter that are finely intergrown with books of hematite (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.19). Gahnite ($ZnAl_2O_4$) was identified in a surface sample (YMR 0371, S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.20). An unnamed black manganese oxide with bismuth + lead ± titanium was found in samples from the Exploratory Studies Facility (SPC 00509204) and in sample GU3/408.2.

Occurrences of glassy rock containing high values of silver contents are present in the same general stratigraphic interval that contains elevated bismuth and other metals. Drill sample SD9/255.0, which contains the most silver of any sample in the Yucca Mountain Conceptual Controlled Area at 2.5 to 3.4 ppm (several silver analyses were performed for this sample), consists of light brown, glassy lapilli tuff with minor clay that occurs stratigraphically just above welded Topopah Spring Tuff cap rock. Along with silver, this sample is enriched in barium, but does not contain other trace elements, e.g., bismuth, that characterize trace element accumulations at this stratigraphic level. In addition, other silver enriched vitric tuff samples were noted higher in the section between the Topopah Spring and Tiva Canyon Tuffs (samples SD9/92.4 and UZ14/92.2 both contain more than 1.5 ppm silver, Appendix 2). During previous work, a surface sample of slightly clay-altered, glassy, reworked tuff impregnated with calcite containing approximately 0.5 ppm silver was noted at about the same stratigraphic level by Castor, Feldman, Tingley (1990). These examples of glassy tuff with elevated values of silver do not have elevated gold contents and generally do not contain pathfinder elements above background levels.

Some occurrences of rock at Yucca Mountain containing high values of bismuth and base metals were recorded in Castor, Feldman, Tingley (1990) and Castor, Tingley, Bonham (1993), and although the restricted stratigraphic location was noted, a specific origin was not proposed. On the basis of the geochemistry and geology of the Exploratory Studies Facility occurrence, Levy et al. (1996) and Peterman, Spengler et al. (1996a) proposed a fumarolic origin. This hypothesis is probably correct because it explains the restriction of the geochemically anomalous rock to a specific stratigraphic horizon.

The Exploratory Studies Facility occurrence was described by Barr et al. (1996) as a zone of intense fumarolic alteration that was formed by interactive processes of vapor-phase crystallization and oxidation with associated alteration. Levy et al. (1996) noted that the presence of cristobalite and smectite are consistent, respectively with cooling of the Topopah Spring Tuff and localized hydrothermal effects related to this cooling. Levy et al. (1996) speculated that structural disruption accompanied and followed the fumarolic alteration and that the altered material was subaerially exposed. Peterman, Spengler et al. (1996a) proposed that the Exploratory Studies Facility occurrence was a mound-like feature within which intense water-rock interaction occurred that yielded localized alteration, and noted that precious-metal enrichment was lacking.

Because of its high tin content, the area of sample YMR 0366 is of particular interest. This area, which is about 1500 m south from the collars of drillholes G3 and GU3, contains bedded tuff in contact with underlying crystal-rich welded cap rock of the Topopah Spring Tuff—units Tpbt and Tptr, respectively, (Day et al. 1996b) and is cut by a series of high-angle, west-side down, normal faults with north-northwest to north-northeast strikes (Day et al. 1996b). Other samples taken from this area, which is approximately 200 m long but only a few meters wide (Figure 3.11-2), also have locally elevated values of tin along with antimony arsenic, barium, bismuth, fluorine, lead, thallium, and zinc (samples YMR 0111 to 0115, YMR 365, YMR 400, and YMR 802, in Table 5.17 of S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada,* Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). Sample YMR 0366 is pale pink to red silicified tuff that is cut by irregular stock work veins of specular hematite up to 3 cm thick. On the basis of surface outcrops it is not representative of large volumes of rock, and lies in an area about 20 m in diameter that is underlain by silicified, calcified, and clay-altered bedded tuff that mainly consists of nonwelded to partially welded ashflow tuff and lapilli fall tuff. To the north of this altered area the bedded tuff sequence contains light brown vitric lapilli fall tuff (sample YMR 0113) with local seams of pale red arsenic-rich hematized tuff (YMR 0115) and veins or layers of brown to red opaline silica (YMR 0114). Sample YMR 0400, about 100 m north-northeast of YMR 0366, is red silicified tuff that contains high values of tin, bismuth, lead, and zinc. Some of the silicified and hematized samples were collected along or near moderately to steeply west-dipping faults, but others originate from conformable seams in the bedded tuff sequence.

On the basis of the work of S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada,* Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review), the widespread occurrence of similar alteration and geochemistry that is restricted stratigraphically at or just above the top of the Topopah Spring Tuff is considered to represent extensive fumarolic alteration and mineralization immediately following the deposition of this ashflow sheet. This fumarolic activity was probably similar to processes that have been described by Keith (1984) who noted enrichment of antimony, arsenic, boron, bismuth, tin, thallium, base metals, and other trace elements in association with fumarolically deposited iron oxide and hydroxide, opal, cristobalite, aluminum fluoride hydroxy hydrate, gypsum, and fluorite on a recent, largely dacitic, ashflow deposit in the Valley of Ten Thousand Smokes, Alaska. Papike et al. (1991) further identified alunite and smectite in altered vent rock from this locality and described processes of elemental migration and deposition during fumarolic activity and subsequent weathering. In addition, the formation of fumarolic mounds and ridges on the Bishop Tuff was described by Sheridan (1970). He proposed that they were formed by vapor-phase alteration around vents in nonwelded vitric tuff atop the welded portion of the ash flow during its devitrification, and that this alteration caused induration and subsequent preservation of vent area tuff relative to surrounding material. More recently, Stimac et al. (1996) described trace element minerals deposited by vapor phase activity in the Bandelier Tuff of New Mexico, including phases that contain lead, bismuth, silver, tin, and barium.

The presence of locally high tin values and the notable occurrence of specular hematite with cassiterite in sample YMR 0366 (see above), suggest that deposition related to fumarolic activity at the top of the Topopah Spring Tuff was somewhat akin to vapor-borne tin deposition in rhyolite lavas in New Mexico, Mexico, and elsewhere (Duffield et al. 1990). In addition, a trace element suite somewhat like that of the Topopah Spring Tuff occurrences, but including gold and molybdenum, was noted by Kavalieris (1994) in uneconomic concentrations associated with formation of a lava dome of intermediate composition in Java.

The fumarolic occurrences at Yucca Mountain contain trace elements that must have been removed from the cooling Topopah Spring Tuff and deposited as sublimates in fumarolic mounds. These deposits could subsequently have been redistributed by surficial weathering processes prior to their preservation by burial beneath tuffaceous deposits related to the extrusion of later units of the Paintbrush Group. The particular trace element suite in these deposits would have been determined by various factors including the primary metal budgets in the Topopah Spring Tuff, the ability of evolved fluids to extract and transport the metals, depositional processes and products, and weathering processes. It is reasonable that fumarolic metal components mainly derived from the rhyolitic basal and middle parts of the Paintbrush Tuff should be different from components described in fumaroles related to volcanism of intermediate composition, for example those reported by Keith (1984) and Kavalieris (1994). The lack of trace metal accumulations in lower level vapor-phase altered portions of the unit, which contains cavities lined with silica phases, calcite, minor specular hematite, and traces of amber colored amphibole(?), indicates that the trace element components were mainly retained until fluids reached the surface or the relatively porous tuff units above the welded cap rock of the Topopah Spring Tuff.

3.11.2.6.8.6 Veins in Tertiary Volcanic Rocks in the Subsurface

At Yucca Mountain mineral filled fractures have been generally referred to as veins, but are also commonly called "fracture coatings" or "fracture fillings." Because veins are defined as epigenetic mineral fillings of various kinds of fractures (including faults) this is the genetic term that will be used. Use of the term "vein" does not indicate that the feature has any economic potential. Some of the mineral accumulations associated with the fumarolic depositional environment discussed above (Subsection 3.11.2.6.8.5) are veins and these will not be further considered here.

Veins intersected by drilling in Yucca Mountain have more varied mineral assemblages and textures than the veins exposed at the surface. S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review), identified veins in drillhole samples from depths ranging between 47 and 1,806 m beneath Yucca Mountain. Although veins are relatively abundant over large drill intervals in the logged boreholes, other large intervals contain no veins. Vein mineral assemblages show some systematic variation with depth. In general order of increasing depth, the most common mineral assemblages found in veins from drill core at Yucca Mountain are:

- Calcite + cristobalite ± fluorite ± tridymite (may include elongated lithophysal cavities with vapor phase minerals)
- Calcite or quartz, or both, ± tridymite ± fluorite ± clay minerals ± zeolite minerals ± barite ± manganese and iron oxide minerals
- Quartz + analcite ± calcite ± fluorite
- Calcite + barite + quartz
- Calcite + albite + quartz

Vein carbonate from drill samples generally occurs as white calcite in relatively coarse crystal aggregates even at shallow depths and as coarse bladed druses greater at depths. Veins similar to surface calcrete veins that contain calcite ± opal-CT were not found in drill core. Vein samples from depths of more than 1645 m in borehole G2 contain carbonate minerals other than calcite; kutnahorite ($CaMn\{CO_3\}_2$) and dolomite have both been reported (Castor, Tingley, Bonham 1992).

S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) report that silica in veins from drillhole samples includes tridymite, cristobalite, and quartz. Samples from shallow depths generally contain cristobalite and tridymite. Vein samples from borehole G2 between depths of 933 m (3,062 feet) and 936 m (3,073 feet) contain opal-CT with chalcedony. In borehole GU3, cristobalite and tridymite, may occur in elongated lithophysal cavities rather than true veins, and generally give way to quartz below about 300 m.

In drill samples vein quartz ranges in texture from chalcedonic to finely granular and fine to medium comb quartz. Vein paragenesis commonly consists of early chalcedony, followed by fine comb quartz, with relatively coarse late carbonate. In core from depths greater than 5,000 feet (1,524 m) in borehole G2, drusy quartz fillings are present which contain crystals more than 1 cm long. Drusy quartz has also been intersected in other drillholes, generally at depths in excess of 1,000 m, including an occurrence with pyrite and limestone fragments in cuttings taken from below 1,220 m (4,000 feet) in borehole UE-25 p#1 (see Subsection 3.11.2.6.8.7).

The zeolite minerals analcite, clinoptilolite, and mordenite occur in veins at Yucca Mountain. Analcite is found in drill core from relatively restricted depths. In several samples by it was detected by X-ray diffraction, but in other samples it was identified by optical microscope because it occurs as well-formed trapezohedrons more than 1 mm in diameter (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.21). The analcite occurs in quartz ± calcite ± fluorite veins. It both predates and postdates quartz deposition, and predates calcite deposition. At Yucca Mountain the depth of analcite-bearing veins increases from north to south, in terms of both stratigraphic level and distance from the surface. In the most northerly borehole (G2) analcite occurs in veins cutting the Prow Pass and Bullfrog Tuffs at 962 to 1,051 m depths, in borehole b1 it occurs in veins cutting the Tram Tuff at 1,080 to 1,170 m (3,543 to 3,829 feet) depths, and in borehole G3 it has been identified in the Lithic Ridge Tuff at depths of 1,310 to 1,530m+ (4,297 to 5,020+ feet). These locations are roughly equivalent to the upper part of alteration zone III of Broxton, Bish, and Warren (1987), which is characterized by the presence of analcite after pyroclasts and in the matrix.

Clinoptilolite is a common alteration and vein mineral in alteration zone II of Broxton, Bish, and Warren (1987). Reddish-brown clinoptilolite and white mordenite were found in chalcedony veins cutting intermediate flow rock beneath the Tram Tuff in boreholes G1 at 1,148 m (3,765 feet) and similar veins were noted in borehole H1 below 1,200 m; both occurrences are below alteration Zone II. The clinoptilolite occurs along the walls of the veins but is clearly a vein mineral, while the mordenite is a very late stage mineral filling central cavities in the veins. White, finely acicular mordenite was found in several places, including small amounts at about 880 m (2,890 feet) in borehole G2.

Fluorite occurs in borehole samples from Yucca Mountain in different forms in veins depending on the depth of occurrence. At shallow levels (300 to 400 m) in drillhole GU3, light gray to green or purple fluorite occurs in thin irregular veins with or without silica minerals and calcite (Castor, Tingely, Bonham 1992). In hand specimen, this fluorite appears to occur as botryoidal crusts. In the Exploratory Studies Facility, irregular veins of similar purple fluorite were found in a small part of the Main Drift (sample SPC-00510784, Figure 3.11-2). Under magnification the fluorite occurs as fine rounded cubes or octahedrons and cubes that appear to have been rounded by partial dissolution (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.22). At levels deeper than 900 m in boreholes G2, G3, and b1, white to green fluorite in macroscopically anhedral masses occurs in veins along with calcite ± quartz ± analcite (Castor, Tingley, Bonham 1992). Under the scanning electron microscopy, this fluorite is seen to occur as rounded masses with sharp, finely crystalline surfaces (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.21). According to Castor, Tingley, Bonham (1992) at depths of about 1,685 to 1,705 m (5,530 to 5,595 feet) in borehole UE-25 p#1 white to gray fluorite occurs as cubes up to 2 mm in diameter in chip samples that also contain pyrite and drusy quartz from.

Barite has been found in several vein samples from two drillholes at Yucca Mountain. In borehole G2 barite was reported in samples from depths of 1,535 to 1,720 m (Castor, Tingley, Bonham 1992) and also from depths of about ca. 1,280 m (4,200 feet) and ca. 1,735 m (5,696 feet) (Caporuscio et al. 1982). In a sample from about 1,200 m depth in borehole b1 a vein of white barite up to 5 mm thick cuts an earlier quartz-calcite vein (Castor, Tingley, Bonham 1992). Barite was also identified in a vein containing clinoptilolite, silica, manganese oxide, iron oxide, and traces of pyrite at about 1,125 m depth in borehole G1 (sample G1/3,764.9). All barite vein occurrences are within alteration zones III and IV of Broxton, Bish, and Warren (1987).

Manganese oxide minerals occur in calcite ± quartz veins in alteration Zones I and II of Broxton, Bish, and Warren (1987). S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) noted manganese oxide-bearing veins in most of the core holes they logged, however none were found at depths greater than 1,050 m. These veins are best developed in borehole G2 at a depth between 825 and 970 m, where manganese oxide ± carbonate ± quartz veins with orientations of 0 to 70° to the core axis are common. Lithiophorite and cryptomelane with minor pyrolusite were identified by X-ray diffraction powder patterns and scanning electron microscope analyses in quartz + calcite veins between depths of 860 m and 920 m in borehole G2. The lithiophorite occurs with finely drusy quartz and acicular cryptomelane and minor apatite in cavities in the veins as roughly equant grains 20 to 100 microns in diameter. Lithiophorite was reported previously from a dozen different intervals between depths of about 250 m and 500 m from five Yucca Mountain drill boreholes (Carlos et al. 1991). The manganese minerals hollandite and todorokite have been reported in fractures between depths of approximately 600 and 900 m in drill borehole G4 (Arney-Carlos et al. 1990). Manganese oxide occurs in quartz ± calcite veins at 875 to 980 m in borehole b1 and at 605 to 660 m and 940 to 950 m in borehole G3. Todorokite was also reported from depths of approximately 975 m in borehole b1 by Caporuscio et al. (1982); manganese oxide veins in this borehole occur mainly between 920 and 1,000 m.

S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) identified hollandite, pyrolusite, and lithiophorite (?) by petrographic microscope in a manganese oxide + quartz vein from borehole G2 (sample G2/2741.6). On the basis of its scanning electron microscope/energy-dispersive spectrum, the hollandite contains major manganese, barium, and oxygen, with variable amounts of potassium, strontium, and possible arsenic. Lithiophorite (?) is the most common manganese mineral, occurring as fine granular to book-like grains as much as 30μ across (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.23). It could not be positively identified because lithium is not detectable by scanning electron microscope/energy-dispersive spectrum. On the basis of scanning electron microscope/energy-dispersive spectrum spectra, some of the hollandite contains minor arsenic.

Veins contain hematite and limonite commonly accompanied by manganese oxide minerals in many samples from boreholes in the Yucca Mountain Conceptual Controlled Area. However, iron oxide and hydroxide in veins extend to deeper levels than manganese oxide. Irregular hematite veinlets were found in association with carbonate veins as deep as 1,530 m in borehole G3. In borehole G2, hematite occurs along with manganese oxide in the deeper parts of the manganese oxide vein interval described above, and hematite dominated the veins (between approximately 990 m and 1,050 m. A zone of hematite-carbonate veins, hematitic stockwork veining, and hematitic hydrothermal breccia occurs at depths between 820 and 910 m in boreholes c1, c2, and c3, which were drilled within an area of approximately 100 m diameter. Iron oxide veins are also relatively common between 800 and 1,000 m in borehole b1, and between 600 and 900 m in boreholes GU3 and G3.

In the Yucca Mountain Conceptual Controlled Area veins containing pyrite are found only at depths in excess of 1,000 m. Examples have been noted in samples from boreholes G1, G2, H1, and UE-25 p#1. In borehole G1, traces of pyrite were found in a silica-zeolite vein from a depth of approximately 1,125 m. Shallowly to moderately dipping chalcedony veins up to 4 mm thick that contain finely disseminated pyrite occur at 1,054 to 1,058 m in depth in borehole G2. Tiny veinlets of pyrite + quartz + chlorite occur in propylitically altered intermediate flow rock between 1,587 and 1,609 m in borehole G2. Chips taken from a depth between 1,128 and 1,162 m in borehole H1 contain quartz + zeolite veins with trace amounts of pyrite cutting zeolitically altered intermediate flow rock. Vein pyrite was also identified in ashflow tuff and Paleozoic rock below 1,100 m in borehole UE-25 p#1. The shallowest occurrence of pyrite in the Yucca Mountain Conceptual Controlled Area was reported in a drusy quartz vein from a depth of 994 m (3,260.6 feet) in borehole G2 by Weiss, Noble, Larson (1996); however, macroscopic, optical petrographic, and scanning electron microscope by S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) examination did not reveal pyrite in this vein, which contains manganese oxide minerals, iron-titanium oxide, fine-grained quartz and clay, and late drusy analcite (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.24).

Most vein-bearing samples from Yucca Mountain Conceptual Controlled Area drillholes do not contain elevated amounts of trace elements except for locally high barium and fluoride, although fluorite-bearing veins from 1,310 to 1,347 m in borehole G3 have slightly elevated arsenic and antimony (see samples G3/4,297.3 and G3/4,315.3, Appendix 2 of S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). Manganese oxide- and iron oxide-bearing veins are exceptions to this general rule. Samples containing manganese oxide-bearing veins from boreholes G2, G3, G4, and a1/b1 contain elevated values of antimony and slightly elevated values of arsenic, plus a few contain elevated values of thallium. None contain elevated levels of silver or gold. Vein samples from borehole G2 have the highest antimony and arsenic contents; Castor, Tingley, Bonham (1993) reported as much as 80 ppm arsenic and 23 ppm antimony in these samples. Samples obtained from borehole G2 by S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in* *the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) contain as much as 47.4 ppm antimony (sample G2/2,704.2) and 45.3 ppm arsenic (sample G2/2,926.2). The highest value of thallium reported for manganese oxide-bearing veins is about 8 ppm (sample a1/2,182.0).

Samples that contain iron-oxide-bearing veins also have elevated levels of antimony and arsenic; examples have come from boreholes G1, G2, G3, b1, and SD7, with the highest antimony value at 18.4 ppm (sample b1/2623.0) and the highest arsenic value at 55.9 ppm (sample G3/5,020.4).

According to Weiss, Noble, Larson (1996), samples containing hematite-silica veins from boreholes c1, c2, and c3 contain as much as 77.4 ppm arsenic, 15.1 ppm antimony, 207 ppm molybdenum, and 2.0 ppm bismuth. Samples of hematitic veins and breccia collected by S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) from the same locations were also found to contain elevated levels of antimony (as much as 7.96 ppm, sample c2/2,783.0), and arsenic (as much as 41.7 ppm, sample c3/2,902.0). The elevated values of molybdenum and bismuth reported by Weiss, Noble, Larson (1996) in samples from boreholes c2 and c3 were not verified by S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review); however, slightly elevated bismuth was detected in hematitic breccia from nearby borehole b1 (1.47 ppm, sample b1/2,371.3).

3.11.2.6.8.7 Pyritic Tuff

Most of the pyrite known to be present in the Yucca Mountain Conceptual Controlled Area lies in the basal part of a single rhyolite ashflow subunit. This occurrence has been discussed previously by Castor, Tingley, Bonham (1994) and most of the following discussion is from that paper. Pyrite is relatively abundant in nonwelded lithic-rich ashflow tuff in the lower part of the Tram Tuff from boreholes G1, G3, H1, H4, and b1 (Figure 3.11-2) at depths below about 1,000 m. Sparse pyrite occurs in bedded tuff beneath the Tram Tuff in boreholes G3 and b1, but pyrite is lacking in correlative bedded tuff from borehole G1. The basal nonwelded lithic-rich part of the Lithic Ridge Tuff in borehole G3 also contains minor pyrite.

According to Weiss, Noble, Larson (1996), pyrite is absent in the Tram Tuff in borehole H1; however, based on drill samples examined for this study it is clearly present and concentrated in lithic fragments in both core and cuttings from the basal Tram Tuff between depths of 997 and 1,104 m. In addition, Weiss, Noble, Larson (1996) noted pyrite in "tuffs of the Crater Flat Group, probably within the Bullfrog Tuff" in drill borehole H4. However, examination of cuttings from borehole H4 by S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) did not disclose pyrite in the Bullfrog Tuff (intersected at depths of 693 to 806 m), whereas abundant pyrite was found to be present in cuttings from 1,018 to 1,162 m. The writers agree with Whitfield et al. (1984) that this interval is in the lower part of the Tram Tuff (Whitfield et al. did note contamination of cuttings in this interval with distinctive chips of Bullfrog Tuff from up hole [also noted during this study] and this may be the source of the confusion by S.I. Weiss et al. (*Multiple Episodes of*

Hydrothermal Activity and Epithermal Mineralization in the Southwestern Nevada Volcanic Field and their Interrelation with Magmatic Activity, Volcanism and Regional Extension, University of Nevada, Reno, in review).

Pyrite mainly occurs in lithic fragments in the Tram Tuff (as noted by Spengler, Byers, Warner 1981, in a log of borehole G1). It also occurs as small, commonly rounded grains in the tuff matrix, but is not present in pumice fragments (Castor, Tingley, Bonham 1994). Quartz + calcite veins cut part of the pyritic interval in borehole b1, but these veins do not carry pyrite. Veins are rare or absent in the pyritic ashflow tuff in boreholes G1 and G3.

In general, the pyrite shows little or no evidence of oxidation, although a few grains rimmed by limonite occur in the tuff matrix and limonitic halos surround pyritic lithic fragments in some intervals. The upper 4 m of pyritic Tram Tuff in borehole G3 includes pyritic fragments with white rinds from which the sulfide seems to have been leached.

Most of the pyritic lithic fragments are of mafic to intermediate volcanic or subvolcanic rocks that range from unaltered to variably silicified, argillized, or propylitized. Pilotaxitic texture is common in these fragments, which contain plagioclase ± biotite ± amphibole ± pyroxene phenocrysts. Rare lithic fragments of pyritized ashflow tuff contain phenocrysts of quartz and potash feldspar. Most mafic phenocrysts in the pyritic lithic fragments are altered, but some biotite is unaltered. In many lithic fragments, pyrite partially replaces mafic phenocrysts. Outside the lithic fragments, biotite phenocrysts are the only mafic mineral. Here they are generally unaltered and do not contain pyrite. Primary titanomagnetite is present in lithic fragments and in the matrix of pyritic ashflow tuff. Pyrite partially replaces titanomagnetite in some lithic fragments, but matrix titanomagnetite is not pyritized. In pyritic fragments, plagioclase ranges from unaltered bytownite-labradorite to thoroughly argillized pseudomorphs. In the matrix, plagioclase is mainly oligoclase and andesine and is generally unaltered.

In the lithic fragments pyrite occurs in veinlets and as disseminated grains ranging from irregular anhedra to perfect cubes. It is commonly associated with quartz veinlets and in some fragments also occurs lining chalcedony- and calcite-filled cavities (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.25). Most of the pyrite is very fine grained, but masses up to 2 mm in diameter are present. Pyrite veinlets do not cut the matrix and are terminated at contacts between lithic fragments and the matrix (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.26).

On the basis of modal analyses, pyrite comprises 0.4 to 2.8 percent and titanomagnetite <0.1 to 0.8 percent by volume of pyritic ashflow tuff in the Tram Member. Lithic fragments make up 20 percent or more, by volume, of this rock, and it has been estimated least 50 percent of these fragments contain pyrite (Castor, Tingley, Bonham 1994). Therefore, pyrite-bearing fragments comprise at least 10 percent by volume of the pyritic portion of the Tram Member. Pyritic bedded tuff beneath the Tram Member generally contains only traces of pyrite, but more than 1 percent pyrite was found at 1,189 m in borehole b1 in a 10 cm thick bed of fine, well-sorted tuff.

The thickness of pyritic ashflow tuff in the Tram Tuff varies between about 60 m in borehole G3 and 165 m in borehole b1. In boreholes b1 and G3 pyrite occurs in the upper 28 m of the bedded tuff unit beneath the Tram Tuff. Although Castor, Tingley, Bonham (1994) reported no pyrite in the Tram Tuff from borehole G2, reexamination of the core showed that trace amounts of pyrite are present in lithic fragments although the tuff is partly oxidized. Pyrite occurs in the basal 45 m of the Lithic Ridge Tuff in borehole G3, mostly in lithic fragments similar to those in the Tram Member.

S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) concluded that most of the pyrite in the Tram Tuff, and therefore most of the pyrite in the Yucca Mountain Conceptual Controlled Area, was introduced as ejecta, rather than by in situ hydrothermal activity. The pyrite veins, chalcedony, silicification, and alteration of phenocrysts in lithic fragments, but not in the enclosing tuff, argue for this origin. Pyrite grains in the matrix, which are much less abundant than in the lithic fragments, are thought to represent pulverized ejecta.

Sulfidization following ashflow deposition is thought to be an untenable explanation for the origin of pyritic tuff at Yucca Mountain because biotite and titanomagnetite, which are partially replaced by pyrite in the lithic fragments, are not pyritized in the tuff matrix. Sulfidization of ferrous minerals has been demonstrated for roll-type uranium deposits in Texas and Wyoming. In these deposits, partial to complete replacement of ferrous minerals by sulfide seems to be ubiquitous. For example, essentially all of the titanomagnetite grains in reduced rock at the Benavides uranium deposit, Texas, have been affected by iron disulfide replacement (Reynolds and Goldhaber 1978).

The Tram Tuff is exposed in Beatty Wash (Carr, W.J., Byers, Orkild 1986), Northern Yucca Mountain, and Northern Bare Mountain (Monsen et al. 1990) west and northwest of the proposed repository site. Neither pyrite nor evidence of oxidized pyrite has been reported during examinations of these exposures; however, these exposures of Tram Tuff are neither as thick or as lithic-rich as that intersected by drillholes beneath the Yucca Mountain Conceptual Controlled Area. The Tram Tuff (undifferentiated) has been identified in only eleven borings at the Yucca Mountain site (CRWMS M&O 1997e, Plate 41). Based on outcrop and subsurface data, this unit thins rapidly to the north from borings in the vicinity of Drill Hole Wash and becomes thicker toward the south and borehole USW G-3. W.J. Carr, Byers, Orkild (1986) speculated that the Prospect Pass caldera was the source of the Tram Tuff.

The pyritic ashflow tuff in the Tram Tuff is thickest in boreholes b1, G1, and H1, thinner in borehole G3 to the south, and is not well represented in borehole G2. It is not possible, using these data, to determine a source direction for the pyritic tuff based on thickness distribution.

S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) believe that pyritic ejecta in the Tram and Lithic Ridge Tuffs originate from a hydrothermal deposit that formed prior to their eruption. The presence of chalcedony and lack of hydrothermal alteration in some pyritic lithic fragments indicate that this deposit was the result of epithermal activity. Initial dismantling of the sulfide deposit began during the eruption of the Lithic Ridge Tuff at approximately 14 Ma, followed by considerably more destruction during eruption of the Tram Tuff at approximately 13.5 Ma.

Weiss, Noble, Larson (1996) have objected to this interpretation, regarding pyrite in the Tram Tuff and elsewhere in the subsurface of the Yucca Mountain Conceptual Controlled Area to be the result of in situ sulfidization during hydrothermal activity. According to Weiss, Noble, Larson pyrite cannot survive a major ashflow eruption because "subalkaline silicic magmas typically erupt at temperatures between about 700 and 900+°C." However, the temperatures reported by Weiss, Noble, Larson are magmatic temperatures, not eruptive temperatures.

Preservation of pyrite in ashflow tuff indicates relatively low temperatures during eruption, deposition, and cooling. The pyritic portions of the Tram and Lithic Ridge Tuffs are nonwelded, which suggests relatively low depositional temperatures (Eichelberger and Koch 1979). According to Warren, Sawyer et al. (1989), magmatic temperatures of the basal high-silica rhyolitic portions of ashflow tuffs of the Paintbrush and Timber Mountain Tuffs were about 660°C prior to eruption. On the basis of its phenocryst assemblage (quartz makes up a large proportion of phenocrysts compared to other units in the Southern Great Basin, and either a pyroxene or an amphibole or both is lacking [Byers, Carr, Orkild et al. 1976]), the basal part of the Tram Tuff is a high-silica rhyolite (the presence of large amounts of intermediate lithic fragments and the absence of glass make chemical determinations difficult). Marti et al. (1991) computed temperature changes caused by 12 to 14 percent lithic fragments (by volume) in a mixture of 800°C gases and other (presumably juvenile) ejecta for three different arrays of lithic fragment size and original lithic temperatures. On the basis of this work, they predicted temperature decreases of as much as 300°C in 100 seconds or less. This work did not consider further cooling of the mixtures by processes including expansion of the gas phase, convective heat transport and radiative transfer. Marti et al. (1991) also did not consider the effects of larger amounts of lithic material, which would logically lead to even larger temperature decreases. Assuming an original magmatic temperature of around 700°C, and subtraction of 300°C from the modeling of Marti et al. (1991) an eruptive temperature of about 400°C is indicated. The combined effects of the incorporation of relatively cool lithic ejecta, the adiabatic expansion of magmatic gas during eruption, and the incorporation of atmospheric gas would lower eruptive and depositional temperatures of the lithic-rich tuff including the basal Tram to temperatures of 400°C or even lower.

Although pyrite can be oxidized in air at temperatures below 500°C, this is a relatively slow process. Schorr and Everhart (1969) noted partial oxidation of pyrite at temperatures as low as 370°C. However, according to Archibald and Harris (1949), pyrite oxidation in air is slow below 450°C. Jorgensen and Moyle (1981) reported that oxidation of pyrite grains less than 75 microns in diameter in air as determined by thermogravimetric and differential thermal analyses is too slow for measurement at temperatures below 420°C. They also found that oxidation is only partially complete at 435°C after 20 hours, and is incomplete after 100 minutes at 470°C. In practical application, the temperature used to roast pyrite in air has been given as 500 to 600°C (Rosenqvist 1974).

Pyrite is restricted to the lower parts of the Tram and Lithic Ridge Tuffs. If the pyrite deposit was in the roof of the magma chamber from which both ashflow units were erupted, pyritic fragments that fell into the chamber may have sunk a short distance before eruption, subsequently being ejected with early ash flows of each unit. However, juvenile rinds do not occur on pyritized fragments suggesting that they were not immersed in magma, and the lack of alteration in some fragments indicates that they were not subjected to magmatic temperatures for significant amounts of time. In this regard, the model of Eichelberger and Koch (1979) for the incorporation of large amounts of lithic fragments in ashflow tuff (i.e., rapid enlargement of the surface vent area during eruption) appears to be a factor.

The eruption of both ashflow units from a single vent area that included a pyritic deposit extending from thoroughly altered rock at depth to nearly unaltered near-surface rock seems most plausible. Eruption of the lower part of both units from a vent area containing pyritized rock, followed by eruption of the upper part of the units from different non-pyritized vent areas is possible, but unlikely. Pyritic ejecta in the upper part of each ashflow unit could have been oxidized during devitrification and vapor phase activity, or oxidation may have taken place following cooling, with pyritic fragments in the lower parts of each unit remaining unoxidized by virtue of location beneath the water table, which probably moved up section following each addition to the volcanic sequence.

No other example of pyritic ejecta in ashflow tuff is reported in the literature, but there is no reason why the Yucca Mountain occurrence should be unique. Incorporation and survival of pyritic ejecta has been noted in airfall tephra from modern phreatic eruptions in the French West Indies, and at Mount Baker, Washington (Heiken and Wohletz 1985).

The eruption that produced pyritic tuff at Yucca Mountain expelled a large amount of pyritic rock. On the basis of intersections in boreholes G1, G3, H1, H4, and b1, ashflow tuff in the Tram Tuff with significant pyrite contents has an average thickness of about 100 m over an area of at least 5 km^2 - a volume of 5×10^8 m^3. If this tuff contains 10 percent pyritic lithic fragments by volume, it includes 5×10^7 m^3 or 130 million metric tons of pyrite-bearing rock (at a conservative density of 2.6 t/m^3). This is a minimum tonnage that does not include pulverized ejecta in the ashflow matrix, pyritic ejecta in the bedded tuff and Lithic Ridge Tuff, or extensions of pyritic tuff outside the area proscribed by the drillholes listed above. This amount of pyritized rock is comparable to that found in many ore deposits. Low trace metal contents and the apparent lack of sulfides other than pyrite in the pyritic tuff suggest that the original deposit was essentially barren of base and precious metals, although trace element contents are likely to be reduced by dilution in the tuff.

Exposed areas of hydrothermal activity in the Southern Great Basin are too young to have been incorporated in the Tram and Lithic Ridge Tuffs. The oldest known volcanic-hosted hydrothermal activity in the region produced gold, mercury, and fluorite mineralization in approximately 14 Ma felsic volcanics at Bare Mountain, and silver veins in 13.2 Ma or younger intermediate to felsic volcanic rocks at Wahmonie. Both areas contain altered volcanic rock with pyrite (Castor and Weiss 1992), but hydrothermal minerals in both areas are 12.9 Ma or younger (Jackson, Jr., M.R. 1988).

Castor, Tingley, Bonham (1994) made the following statements regarding trace element contents of the pyritic tuff. Bismuth, mercury, molybdenum, selenium, and tellurium are locally concentrated in pyritic Tram Tuff and are more enriched in some samples made up of single pyritic lithics. Although lithic-rich Tram Tuff in borehole G2 contains little or no sulfide, it also contains elevated levels of bismuth, tellurium, and selenium. In addition, pyritic bedded tuff directly under the Tram Tuff in borehole b1 contains elevated arsenic, molybdenum, lead, thallium, and bismuth contents. Arsenic and antimony are generally at low levels in pyritic Tram Tuff and Lithic Ridge Tuff, but are at relatively high levels in parts of these units that do not contain pyrite. Slightly elevated silver contents, as much as 0.337 ppm, were found in pyritic Tram Tuff, and particularly in pyritic lithic fragments. In borehole G3, silver contents are low, but are slightly elevated in pyrite-bearing portions of the same unit and in the Lithic Ridge Tuff.

Analysis of samples collected by S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) has substantially verified the work of Castor, Tingley, Bonham (1993). Many samples of pyritic tuff have elevated selenium contents, and some contain slightly elevated levels of lead, mercury, molybdenum, and tellurium (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Table 5.18). Elevated arsenic and copper are rare. Silver is very slightly elevated, if at all, and gold is less than 4 ppb in all samples. Sample G3/3700.1, which consists of a single large pyritic clast, contains 16.5 ppm Se, the highest of any sample from the Yucca Mountain Conceptual Controlled Area, as well as 3.23 ppm tellurium, 186 ppm copper, and 1.22 ppm bismuth.

3.11.2.6.8.8 Gold and Gold Pathfinders in Paleozoic Carbonate Rock

Paleozoic rock was penetrated by only one drillhole in the Yucca Mountain Conceptual Controlled Area (borehole UE-25 p#1) at a depth of about 425 m (1,240 feet), and some of this rock contains direct geochemical and mineralogic evidence for an episode of precious-metal mineralization. Castor, Tingley, Bonham (1993) noted the presence of pyrite and drusy quartz chips associated with carbonate rock in cuttings from this borehole between depths of 1,204 and 1,244 m, pyrite and fluorite along with brownish gray to white carbonate rock chips from 1,686 to 1,704 m, and carbonate chips with traces of pyrite from 1,704 to 1,707 m. Castor, Tingley, Bonham (1993) listed chemical analyses for samples from these intervals and reported that chip samples from depths of more than 1,200 feet contain relatively high levels of antimony, arsenic, fluorine, and silver, and that samples from below 1,600 feet have elevated antimony, bismuth, copper, fluorine, gold, lead, mercury, molybdenum, silver, selenium, thallium, and zinc. Although gold contents were only minimally elevated (4 to 10 ppb), Castor, Tingley, Bonham (1993) noted that this trace element assemblage is similar to that associated with gold deposits in the Bare Mountain Mining district. Table 3.11-6 shows selected analyses by S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) of samples from below 1,100 feet in borehole UE-25 p#1.

S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) have substantiated, and enlarged somewhat upon, the work of Castor, Tingley, Bonham (1993) by examining both core and cuttings from borehole UE-25 p#1. The drillhole was spot cored and several intervals of this core were examined including two short intervals in Tertiary ashflow tuff approximately 190 and 40 m above the Paleozoic contact. The lower of these consists of sheared and calcitized tuff that contains pyrite along irregular veins. Samples of this tuff contain slightly elevated values of barium, fluorine, and mercury ± antimony, arsenic, and zinc, however gold and silver are at background levels at a depth of approximately 1,195 feet (Table 3.11-6, samples p#1/3920.8 and p#1/3922.3; S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

The Tertiary-pre-Tertiary contact was not cored, but cuttings containing both tuff and Paleozoic carbonate were taken between depths of approximately 1,200 and 1,250 feet, and samples from this interval contain slightly elevated levels of antimony, arsenic, mercury, and zinc. The contact was identified as a high-angle fault at 1,238 feet using television logging (Carr, M.D. et al. 1986). See Subsection 3.8.4.2 for additional discussions regarding this contract. A considerable amount of core was drilled below the contact, beginning at a depth of about 1,275 feet in Silurian Lone Mountain Dolomite that contains minor amounts of pyrite between depths of 1,325 and 1,490 feet. The pyrite occurs with calcite in veins, locally disseminated in breccia, and along stylolite fractures (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figure 5.27). Samples of pyrite-bearing rock from this interval contain consistently elevated values of gold, silver, antimony, arsenic, mercury, selenium and zinc. The highest gold measured in this rock, at 142 ppb by USML and 175 ppb by Nevada Bureau of Mines and Geology NBMG (well below ore grade, but easily the highest gold content in any sample from the Yucca Mountain Conceptual Controlled Area), is associated with moderately elevated values of silver, arsenic, mercury, molybdenum, antimony, selenium, thallium, and zinc (Table 3.11-6, sample p#1/4856.7, Table 3.11-5, S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). The location of these samples at depths greater than 1,240 feet indicates that gold could not be mined economically at the Yucca Mountain site. Little pyrite was noted in core from borehole UE-25 p#1 below 1,490 m, but as noted previously, cuttings from approximately 1,680 to 1,700 m in depth that contain pyrite ± fluorite, contain elevated trace metal contents; cuttings obtained for this study (sample p#1/5,540) contain slightly elevated levels of molybdenum, lead, and antimony. Core and cuttings from below about 1,700 m in borehole UE-25 p#1 contain only local traces of pyrite and have low gold pathfinder contents.

Scanning electron microscope examination of sample p#1/4,856.7 shows that pyrite in both breccia and stylolitic fractures contains as much as 4 wt% arsenic. The pyrite in the breccia occurs in euhedral to rounded grains up to 30-μ in diameter, and is associated with fine-grained dolomite and sparse sphalerite. The stylolitic fractures contain similar pyrite, as well as calcite and traces of sphalerite and apatite (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Figures 5.27 and 5.28). Unlike pyrite associated with gold at the Sterling Mine in the Bare Mountain mining district, the pyrite in this sample does not have arsenic-rich rims. Instead, the highest arsenic contents are generally, but not always in the cores of pyrite grains. Metallic gold was not noted in this sample.

The origin of the pyrite in the stylolitic fractures is not clear. Styolites are considered to form by dissolution in carbonate rocks. In general, material in styolites is thought to accumulate as insoluble minerals during dissolution, and include clay, iron oxide, and carbon compounds that build up during this dissolution. Although the sulfide may have accumulated in this way, it was probably introduced following styolite formation by hydrothermal activity, which also introduced the gold and other trace metals.

Three types of evidence suggest that gold enrichment in borehole p1 is similar to gold mineralization at the Sterling Mine. These include the presence of gold in Paleozoic carbonate rock that is partly silicified and clay altered, similar trace element suites, and the presence of arsenic-bearing pyrite. Stylolitic fractures that carry sulfide have not been reported at the Sterling Mine, but could easily have been missed.

3.11.2.6.9 Uranium at Yucca Mountain

There is no mention in the literature of uranium prospects on Yucca Mountain (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). However, Yucca Mountain is covered by silicic volcanic rocks, predominantly ashflow tuffs. These have moderate to elevated amounts of uranium (compared to a crustal abundance of about 2.7 ppm) (Levinson 1974; S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). The anomalous uranium is confirmed by state-wide aerial radiometric maps of equivalent uranium (Duval and Pitkin 1988). The crystallized portions of such volcanic rocks have been shown in many areas to have only 20 to 70 percent of their uranium relative to portions which have nonhydrated or hydrated glass (Rosholt et al. 1971), and the majority of these rocks on Yucca Mountain are primarily crystallized or vapor-phase altered. The thorium:uranium ratio of glassy silicic to intermediate-composition volcanic rocks has been shown to vary in the range of 3:1 to 5:1 (Rosholt et al. 1971; Austin and D'Andrea 1978).

The values of uranium and thorium in unaltered silicic pyroclastic volcanic rocks collected during the mined energy resources study are generally consistent with the above pattern (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). Ten samples (YMR 0027, 0213, 0311, 0322, 0324, 0349, 0359, 0459, 0485, and 0840) (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Appendix 5-1) of ashflow tuffs without visible veining or hydrothermal alteration that were collected from surface outcrops on Yucca Mountain average 4.33 ppm uranium, 18.8 ppm thorium, and have an average thorium:uranium ratio of 4.3:1. Similar values have been reported for the tuffs by other workers (Broxton, Warren, Byers 1986; Schuraytz et al. 1986). The majority of rock samples from the surface of Yucca Mountain were collected to evaluate veined, silicified, or otherwise altered rock. The uranium contents and thorium: uranium ratios from those samples are highly variable and have a considerable range. However, most samples do not have thorium:uranium ratios above 5:1 or 6:1, suggesting that significant amounts of uranium have not been preferentially removed, either during crystallization or as a result of interaction with groundwater. The thorium:uranium ratios of Yucca Mountain surface samples do range downward to very low numbers. These probably reflect rock samples which consist in part of secondary mineral matter such as opal, calcrete, or chalcedony. Uranium is likely to have been concentrated in these minerals while thorium did not move from original sites in the rock (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

Silicic volcanic rocks of the Southwestern Nevada volcanic field include both peralkaline and metaluminous units (Sawyer, D.A. et al. 1994). Peralkaline volcanic rocks are commonly enriched in incompatible elements, including uranium, and hydrothermal disseminated and vein-type uranium deposits may form in caldera environments, especially those of peralkaline affinity. The outflow ashflow tuffs of Yucca Mountain are not peralkaline (Sawyer, D.A. et al. 1994), and may thus be somewhat less likely to host concentrations of uranium (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

During the National Uranium Resource Evaluation studies of the 1970s and early 1980s, only five geochemical stream sediment samples were collected in dry stream washes that drain the west flank of Yucca Mountain (Cook 1980). Most of Yucca Mountain and the adjacent Nevada Test Site to the east were not sampled for that study. The samples that were collected do not contain elevated amounts of uranium; most contain <4 ppm uranium, and one sample contains between 5.8 and 7.5 ppm. One of the samples having <4 ppm uranium, from northwest of Black Cone in north-central Crater Flat has a high log U/Th value (>-0.08). It is not certain if this sample was collected from a wash which drains Yucca Mountain or Bare Mountain. In any event, the sample may represent a slight local concentration of uranium in stream sediments. The reasons for such accumulations are unknown, and although they occur more frequently in stream washes which drain areas of uranium mineralization, many do not and are unexplained. Such samples, without other evidence of uranium mineralization in the bedrock of the drainage area, do not indicate prospect for uranium deposit (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

During the National Uranium Resource Evaluation program, the Yucca Mountain area was surveyed by airborne radiometric methods as part of a survey of the Death Valley 1 x 2° Quadrangle (Geodata International Inc. 1980a). On the basis of visual examination of the survey data, there are no radioactive anomalies in the flight-line profiles over Yucca Mountain that would suggest significant concentration of uranium (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). A uranium resource evaluation of the Death Valley 1 by 2° Quadrangle (Berridge 1982) found that Tertiary volcanic rocks in the vicinity of Yucca Mountain (as well as many other areas in the quadrangle) were not favorable for volcanogenic uranium deposits. An area in the vicinity of Beatty, where uranium occurrences and mines with small production are found, was considered favorable. The study by Berridge (1982) included only the west margin of Yucca Mountain.

From examination of the geochemical data from Yucca Mountain surface and drillhole samples (and comparison with other areas) the following conclusions can be drawn (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review):

- The average uranium content of fresh (not altered) ashflow tuff from surface samples (samples YMR 0027, 0213, 0311, 0322, 0324, 0349, 0359, 0459, and 0485) is 4.33 ppm (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). The highest value in these unaltered samples is 6.5 ppm (see Appendix 1 of S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). Thorium from these samples averages 18.8 ppm; the average thorium:uranium ratio is 4.3:1. These values are about average for rhyolitic rocks in the Southern Great Basin and elsewhere in Nevada on the basis of comparison of state-wide aerial gamma-ray data (Duval and Pitkin 1988) with the occurrence of such rocks in Nevada (Stewart and Carlson 1978).

- Surface samples from Yucca Mountain have, on average, more elevated uranium values than do drillhole samples (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). The average uranium content of all Yucca Mountain surface samples is 7.87 ppm; the lowest reported analysis is 4.5 ppm, and a number have values in the 10 to 25 ppm range, with a high of 63 ppm (sample YMR 0460, Appendix 2). On the other hand, drillhole samples average 3.91 ppm uranium and none contain more than 15 ppm (Appendix 5-2). This is due to minor localized concentrations by organics, peroxide coatings, silica and calcite on the detrital grains of the surface sample.

- Elevated uranium values in surface samples from Yucca Mountain are predominantly from rocks that have veinlets, coatings or breccia cement of silica, especially opal or chalcedony (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). Many opal and chalcedony veins and coatings are fluorescent in short-wave ultraviolet light. This fluorescence is commonly associated with elevated uranium content as the activator producing the fluorescence (Castor, Henry, Shevenell 1996). Thin opal veinlets and coatings in the shallow subsurface are known from other studies to contain uranium in amounts up to 280 ppm; this opal is interpreted to result from deposition in open cavities from percolating groundwater in the unsaturated zone over long periods of time (Paces, Neymark et al. 1996).

- Uranium values are uniformly low in samples from the Calico Hills hydrothermally altered area. Acid leaching there may have removed uranium from most of the rocks sampled in this study. Areas of acid leached volcanic rocks are probably unlikely areas for uranium concentration (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

- It is not unusual to find a few elevated uranium values in hydrothermally altered rocks or vein material from volcanic-hosted epithermal mineral deposits. For example, a limited number of samples from the Bullfrog district (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Appendix 5-1) have elevated uranium, and this has been noted at mining districts in the Nellis Air Force Range (Mellan Mountain district; Tingley et al. 1996). Occurrences of sparse uranium minerals or of anomalous amounts of uranium or radioactivity are not uncommon in Nevada's mining districts (Garside 1973). It is likely that such sporadic uranium concentrations are related to redistribution by hydrothermal fluids in these districts, especially in those hosted by volcanic rocks that may have uranium available in amounts that could be moved and concentrated. In the majority of cases, these anomalous uranium concentrations from Nevada's precious- and base-metal mining districts are not known to form ore bodies (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

3.11.2.7 Conclusions

The Tram Ridge-Thompson Mine mineralized area is in a large area of hydrothermally altered rock as shown by remote sensing imagery (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review, Plate 4) and by field work (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). The alteration mineralogy and trace element chemistry is similar to that in the Southern Calico Hills. The youngest rocks affected by alteration appear to be rocks of the Rainier Mesa Tuff and alunite from the area has been dated at 11.6 ± 0.4 Ma and 12.9±0.5 Ma (McKee and Bergquist 1993, as cited in Mattson 1994).

Geophysical work supports the presence of a large buried igneous intrusion in the Wahmonie district (Ponce 1981; Hoover, D.B. et al. 1982), and a west-northwest-trending zone of positive aeromagnetic anomalies extends from Wahmonie, through the Calico Hills, near Claim Canyon, to a site just west of the Northern Yucca Mountain area. These anomalies may be due in part to buried intrusions similar to that at Wahmonie, although they are likely due in part to extensive exposures of the Topopah Spring Tuff. This general pattern is also indicated by gravity highs in the Wahmonie and Calico Hills areas, although the gravity data suggests off-set east-west anomalies to the west of the Calico Hills.

The youngest stratigraphic units affected by the hydrothermal activity in this postulated zone of buried intrusive activity are rocks of the Paintbrush Group. In the Yucca Mountain Conceptual Controlled Area, Paintbrush Group rocks, whether exposed or intersected by drilling, are not hydrothermally altered or mineralized (except for local fumarolic activity). In addition, glassy rhyolitic flow rocks in the Calico Hills Formation intersected in borehole WT-16 in Yucca Wash are unaltered, whereas the same rocks in the Southern Calico Hills nearby are locally to pervasively clay-altered and silicified. It therefore appears that the post Paintbrush alteration and mineralization that is present within a few kilometers of the Yucca Mountain Conceptual Controlled Area in the Calico Hills and in Claim Canyon does not extend into the Yucca Mountain Conceptual Controlled Area.

Hydrothermal alteration and slightly elevated pathfinder element anomalies are present below the level of the Calico Hills Tuff in the Yucca Mountain Conceptual Controlled Area, particularly in borehole G2. On the basis of drill core and cuttings examined (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review; Caporuscio et al. 1982; Castor, Tingley, Bonham 1992; and Castor, Tingley, Bonham 1993), samples from drillhole G2 show the most compelling evidence for hydrothermal activity in Tertiary volcanic rocks in the Yucca Mountain Conceptual Controlled Area that cannot be explained as the result of local minor fumarolic activity (as in the Paintbrush Group) or of inclusion of previously altered and mineralized material (as in the pyritic Tram Tuff). The evidence for hydrothermal activity in borehole G2 consists of pyrite and other minerals (e.g., barite) in veins as well as the presence of propylitic and alkali feldspar alteration at depths in excess of 1,600 m. In addition, hematite and manganese oxide veins in borehole G2 contain elevated amounts of the pathfinder elements arsenic and antimony at depths as shallow as 700 m. Minor amounts of similarly veined rock with slightly elevated levels of antimony were sampled by drillholes to the south of G2, including boreholes a1, c1, c2, and c3, but this is relatively rare, as is alteration of probable hydrothermal origin.

The presence of pre-Paintbrush Group hydrothermal activity in the Northern Yucca Mountain area has been suggested by Weiss, Noble, Larson (1996) as an important factor in the evaluation of the Yucca Mountain Conceptual Controlled Area for epithermal precious-metal deposits. The implication of these occurrences is that Paintbrush Group rocks in the Yucca Mountain Conceptual Controlled Area may overlie, and thus mask, areas of mineralized rocks in the Crater Flat Group and older rocks. However, the trace element chemistry of samples from the Northern Yucca Mountain area do not include elevated precious metal contents, and while such occurrences demonstrate that local hydrothermal activity took place during Crater Flat Group magmatism, they do not provide direct evidence for an episode of precious-metal mineralization at that time.

3.11.2.8 Summary

Data necessary for the assessment of the Yucca Mountain Conceptual Controlled Area for deposits of metallic mineral and mined energy resources (uranium) were collected and analyzed by S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). Because of the presence of current and past metallic mineral production in the Southern Great Basin, mainly gold and gold-silver deposits, in geologic settings that are somewhat similar to that of the Yucca Mountain Conceptual Controlled

Area, there has been some speculation of favorability for similar deposits in the Yucca Mountain Conceptual Controlled Area.

On the basis of extensive sampling and geochemical analysis by S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review) and previous work, the Yucca Mountain Conceptual Controlled Area contains no identified metallic mineral or uranium resources. In addition, on the basis of detailed study of the geology, geochemistry, mineralogy, mineral alteration, geophysical data, and remote sensing, the Yucca Mountain Conceptual Controlled Area 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.

Surface and Exploratory Studies Facility examination revealed only minor amounts of local mineralized rock and mineral alteration, and metal commodity concentrations were generally found to be low. The highest metallic commodity values in the Yucca Mountain Conceptual Controlled Area occur in scattered occurrences of mineralized rock and alteration that are considered to be of fumarolic origin. These occurrences are of minimal size and have little potential for depth extension. A select float sample containing about 3 percent tin was collected from one occurrence in the south part of the Yucca Mountain Conceptual Controlled Area; however, examination of the occurrence revealed that only very minor amounts of similar rock were present. A fumarolic occurrence identified by USGS and other workers in the Exploratory Studies Facility was found to contain elevated (from a geochemical interest only, not economically mineable) base metal and bismuth contents, but these are well below economic concentrations.

The maximum gold content in a surface sample from the Yucca Mountain Conceptual Controlled Area is 11 ppb, far below economic concentrations of 680 ppb or more. This sample is of fault gouge from the north part of the Yucca Mountain Conceptual Controlled Area. The gold content is slightly elevated, but, taken by itself, does not indicate potential for gold deposits. In addition, several other surface samples were found to contain more than 5 ppb gold, but these are samples of calcrete that is thought by most workers to be of pedogenic, rather than hydrothermal, origin. Pathfinder elements for precious metal exploration were generally low in surface and Exploratory Studies Facility samples other than those from fumarolic occurrences, although mercury was slightly elevated in some calcrete samples.

Examinations of core and cuttings from 25 drillholes in and near the Yucca Mountain Conceptual Controlled Area were performed during this study. Following this examination, 454 core and cuttings samples were obtained for chemical analysis and other study. None of these samples were found to contain economic concentrations of metallic commodities, rather did they contain anomalous values.

Gold contents in drill samples of Tertiary volcanic rock are very low, with the highest value at 4 ppb. Silver contents were generally low, although as much as 4 ppm silver was found in rocks associated with fumarolic alteration similar to that sampled on the surface and in the Exploratory Studies Facility. Pathfinder elements for precious metal exploration, including arsenic and antimony, are also generally low in drillhole samples. However, slightly elevated contents at depths in excess of 700 m are associated with manganese and iron oxide veins that could be related to hydrothermal activity. Veins of several other types cut Tertiary volcanic rocks beneath Yucca Mountain. Although these veins contain minerals that are associated with metallic mineral deposits elsewhere, including barite and fluorite, they have low precious metal, base metal, and pathfinder element contents at Yucca Mountain.

Pyrite, a mineral that commonly occurs in association with metallic ore deposits, occurs at depths of more than 1,000 m under the Yucca Mountain Conceptual Controlled Area, and has been pointed to by other workers as evidence of metallization. However, on the basis of work by S.B. Castor et al. (*Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review), and prior studies, most of the pyrite in volcanic rock beneath Yucca Mountain is considered to have been introduced as ejectal material in ashflow tuff and is not considered to be evidence of hydrothermal activity in place. The pyrite is associated with elevated amounts of selenium and other precious metal pathfinder elements, but it is not associated with elevated values of gold or silver.

On the basis of geochemical and mineralogical analyses of all of the Yucca Mountain Conceptual Controlled Area samples, and comparison with similar analyses of 414 surface, underground, and drillhole samples from mining districts and mineralized areas in the Southern Great Basin, the potential for economic metallic mineral deposits is considered to be low to nonexistent in the Yucca Mountain Conceptual Controlled Area. Simple statistical analysis indicate substantial differences between geochemical patterns for precious metals, base metals, and pathfinder elements between the Yucca Mountain Conceptual Controlled Area and metal mining districts in the region.

Comparisons were made with models of metallic mineral commodities that might reasonably be expected to occur in the Yucca Mountain Conceptual Controlled Area on the basis of geologic setting. These models included volcanic rock-hosted epithermal precious metal deposits, sedimentary rock-hosted gold deposits, hot-spring mercury deposits, polymetallic vein deposits, detachment-related polymetallic deposits, polymetallic replacement deposits, porphyry copper-molybdenum and calc-alkaline molybdenum deposits, skarn tungsten deposits, copper skarn deposits, zinc-lead skarn deposits, rhyolite-hosted tin deposits, epithermal manganese deposits, simple and disseminated antimony deposits, and placer gold deposits. There is little or no evidence to support economic levels of metallic mineralized rocks on the basis of any of these models.

Although potential for volcanic rock-hosted epithermal precious metal deposits at depth cannot be completely ruled out in the Yucca Mountain Conceptual Controlled Area, the indirect evidence for these deposits (mineral alteration and slightly elevated pathfinder element contents) is at depths of 700 m or more. In the unlikely event that a volcanic rock-hosted precious-metal deposit, similar to the Bullfrog Mine near Beatty, is present under the Yucca Mountain Conceptual Controlled Area, it probably could not be mined economically at these depths either now or in the foreseeable future.

Direct evidence for alteration and mineralizaton commonly associated with sedimentary rock-hosted gold deposits was found in drillhole UE-25 p#1 at depths in excess of 1,400 m. This evidence consists of pyrite-bearing veined and brecciated Paleozoic rock with as much as 175 ppb gold and elevated amounts of elements including arsenic and thallium that are typical of Carlin-type deposits. In addition, this rock contains arsenic-bearing pyrite, also typical of Carlin-type mineralization. Similar geochemistry and mineralogy is present at the Sterling Mine in the Bare Mountain district about 16 km west of the Yucca Mountain Conceptual Controlled Area. However, the potential for mining a similar deposit, if present at depths in excess of 1,200 m (the shallowest occurrence of Paleozoic rocks in the Yucca Mountain Conceptual Controlled Area based on geophysics and drilling evidence) is very low.

The potential for deposits of uranium resources is also considered to be very low in the Yucca Mountain Conceptual Controlled Area. Uranium contents are mostly at background levels in rocks of the Yucca Mountain Conceptual Controlled Area, and slightly elevated uranium contents (the highest is 65 ppm) are not believed to indicate potential for economic grades of mineralized rock (at least 1000 ppm).

3.11.3 Industrial Rocks and Minerals Resources

The Southern Great Basin contains many occurrences of valuable or potentially valuable industrial minerals (Castor and Lock 1995). The potential for industrial mineral resources in the Yucca Mountain Conceptual Controlled Area was assessed by Castor and Lock (1995) and the following discussion is summarized from their report.

3.11.3.1 Methodology for Industrial Minerals Assessment

Consideration of the industrial mineral potential within the Yucca Mountain Conceptual Controlled Area was mainly based on petrographic and lithologic studies of samples from drillholes at Yucca Mountain (Castor and Lock 1995). The potential for economic development of industrial minerals in the Yucca Mountain Conceptual Controlled Area was assessed by comparing available geologic information on potential mineral occurrences in the rocks of Yucca Mountain with available information on industrial mineral deposits in the surrounding region and elsewhere. Castor and Lock (1995) relied on the geologic description of the rock samples and did not perform additional field work for their study.

Published information on industrial minerals in the Yucca Mountain area was compiled and synthesized by Castor and Lock (1995) as part of their study. Castor and Lock (1995) conducted a literature search by area and commodity using materials available in the University of Nevada, Reno, Mines Library, and produced a 1:250,000 scale map (Figure 3.11-3) using published data as well as unpublished material from the NBMG files.

3.11.3.2 Industrial Rocks and Minerals Classifications (Models)

Industrial minerals include all those earth materials used by man except metallic ores, mineral fuels, water, and gems (Harben and Bates 1990). The term "nonmetallics" is not entirely synonymous with industrial minerals, because the end use of the mineral, rather than its composition, generally determines its category. Mineralogy, rather than concentration, is commonly the principal determinant of the end-use application of industrial minerals. Highly sophisticated processing is generally required to convert a crude, mine-run mineral or rock into a marketable product of value-added, specialty industrial minerals. Some industrial minerals are site specific because of unique physical or chemical characteristics that occur only at a specific deposit (Eyde and Wilt 1989).

Because of the wide diversity in chemical and physical properties, origin, and end-use application of industrial minerals, several schemes have been devised to classify industrial minerals (Eyde and Wilt 1989). Bates (1960) classified deposits with a high place value as industrial rocks and classified deposits with a high unit value as industrial mineral deposits. Harben and Bates (1990) revised the classification to emphasize geological associations and commodities; their major categories were igneous, sedimentary, surficially altered, and metamorphic, with specific commodities in subheadings under these categories. Kline (1970) classified industrial minerals into either chemical minerals or physical minerals based on their end-use applications.

Most descriptions of industrial minerals and rocks (U.S. Bureau of Mines 1985; Lefond 1983) use the commodity as a mineral name for the major categories and discuss various geological environments under those headings.

3.11.3.3 Industrial Minerals in the Great Basin

Most of the industrial mineral production in the region surrounding the Yucca Mountain Conceptual Controlled Area has originated from four mining districts: the Bare Mountain, Bullfrog, Ash Meadows, and Death Valley mining districts (Castor and Lock 1995). The first two had primarily precious metal production, whereas the Ash Meadows and Death Valley districts are solely industrial mineral districts (Castor and Lock 1995).

The industrial rocks and minerals production in the Bare Mountain and Bullfrog mining districts was generally not significant (Subsection 3.11.2; Castor and Lock 1995). Gold was mined in the Bare Mountain (Fluorine) district as early as 1861 and fluorspar (fluorite) deposits were discovered there in 1918. The Bare Mountain district has produced more fluorspar than any other district in Nevada. Most of the fluorspar came from the Daisy mine, which operated continuously between 1928 and 1989 (Castor 1988; Castor 1990). Before mining ceased, the Daisy mine was the last remaining producer of fluorspar in the Western United States. Other industrial mineral commodities listed for the Bare Mountain district are marble, kaolin, montmorillonite, silica, perlite, and volcanic cinder (Tingley 1984). Production of these commodities has been minor, with the exception of volcanic cinder mined from a deposit near Lathrop Wells (Castor and Lock 1995).

The Bullfrog district has had minor clay production since the 1950s (Cornwall 1972).

Clay is produced from the Ash Meadows district in California and Nevada, and small amounts of zeolite are also produced (Castor and Lock 1995). The Ash Meadows district covers a large sink and meadow area in the Amargosa Desert in Nevada and California. Clay was discovered in the district in 1917, and has been mined there fairly steadily since 1918 (Hosterman and Patterson 1992). Large-scale clay mining in Ash Meadows took place in the late 1920s and early 1930s, and was revived in the 1970s. Clay is mined from deposits in both California and Nevada, and processed in Nevada. The Ash Meadows district is now the site of most of Nevada's clay production. In addition, small amounts of zeolite are mined from the California side of the Ash Meadows district and processed in Nevada.

The Death Valley district, which is wholly within California, is one of the best known sources of borate minerals in the world and has also been important as a source of talc (Castor and Lock 1995). Production of borates from Death Valley began in 1881 to 1882. Borate production nearly ceased during the period 1928-1956 (Evans, J.R. et al. 1976). Modern production began in the 1970s when the Death Valley deposits became a major source of calcium borate; production continues to the present at the Billie Mine. Mining of talc deposits in the Death Valley area began about 1910, but production of significant amounts of the mineral from Death Valley did not take place until the 1940s (Evans, J.R. et al. 1976). With the exception of the Omega Mine, which is located south of the boundary of Figure 3.11-3, talc mines in the Death Valley district are inactive (Piniazkiewicz et al. 1994).

3.11.3.4 Industrial Rocks and Minerals at Yucca Mountain

Many of the industrial rock and mineral commodities that occur in the Great Basin do not occur in geologic settings similar to that at Yucca Mountain, they include alunite, basalt, feldspar, gypsum, kyanite, lithium, mica, pyrophyllite, quartz and quartzite, salt (salines and brines), sandstone, silica sand, sodium compounds (sodium carbonate and sulfate), sulfur, and wollastonite. Barite, clay minerals, fluorite, and zeolites, have been identified in samples from Yucca Mountain (e.g. Caporuscio et al. 1982; Scott, R.B. and Castellanos 1984; Bish 1989; Broxton, Bish, Warren 1987) and are further discussed in this subsection. Building stone, construction aggregate, limestone, pumice, silica, and vitrophyre/perlite are other possible commodities that can be encountered at Yucca Mountain and will also be discussed here.

3.11.3.4.1 Barite

3.11.3.4.1.1 Barite Occurrences at Yucca Mountain

Barite occurs sparingly in core from boreholes in the Yucca Mountain Conceptual Controlled Area (Castor and Lock 1995). Barite crystals were reported at depths of 1,737 m (5,696 feet) and 1,280 m (4,200 feet) by Caporuscio et al. (1982), 1,718 m (5,636 feet) and 1,200 m (3,938 feet) by Castor, Tingley, Bonham (1993), and 1,706 m (5,597 feet) by Castor and Lock (1995).

3.11.3.4.1.2 Economics of Barite Resources at Yucca Mountain

The geologic setting in the Yucca Mountain Conceptual Controlled Area is not favorable for bedded barite deposits in Paleozoic rock except at depths of more than 1,200 m (the depth of Paleozoic rocks in borehole UE-25 p#1), clearly excessive depths for open pit mining. Therefore, the potential for these types of barite deposits (from which all barite in Nevada is now produced) in the Yucca Mountain Conceptual Controlled Area is considered to be nil. Minor amounts of barite occur in some thin veins in volcanic rock at depths of 1,200 m or more in Yucca Mountain. However, the Yucca Mountain Conceptual Controlled Area is considered to have little or no potential for barite production because these barite occurrences are minor and at such great depths.

3.11.3.4.2 Building Stone

3.11.3.4.2.1 Building Stone Occurrences at Yucca Mountain

In the Yucca Mountain Conceptual Controlled Area, considerable amounts of Tertiary tuff are accessible at the surface for use as building stone (Castor and Lock 1995). Ashflow sheets of both the Timber Mountain Group and the Paintbrush Group crop out as prominent ridges. The Timber Mountain Group is the source of most of the building stone extracted by Nevada Neanderthal Stone near Beatty. Ashflow tuffs are uniform over large lateral distances. Exposures of the Rainier Mesa, Tiva Canyon, Yucca Mountain, Pah Canyon, and Topopah Spring Tuffs provide a considerable range of lithologic textures and colors.

The Topopah Spring Tuff on the whole, is reported to be porous and not indurated. These properties make the rock suitable for cutting and shaping, but do not enhance polishing. Densely welded or glassy types of tuff are less porous, are presumably of greater strength, and would take a better polish. The presence of lithophysae (hollow, bubble-like structures, see Subsection 3.5.2.1) in many of the tuff units could enhance the textural appeal of the stone. Where they are relatively sparse, their presence of lithophysae does not weaken the structural integrity of the stone. However, some units contain abundant, large lithophysae, and this type of stone may not be suitable for cutting without crumbling (Castor and Lock 1995).

In the Yucca Mountain Conceptual Controlled Area, several units within the Timber Mountain and Paintbrush Groups exhibit distinctive fracturing styles that may be detrimental to building and dimension stone (Castor and Lock 1995). The lower lithophysal and hackly zones of the Paintbrush Group have columnar jointing (Scott, R.B. and Bonk 1984) associated with more glassy compositions and associated with cooling effects during deposition. It is reported that the welded part of the zone is characterized by thin, shingle-like partings parallel to the foliation plane (Scott, R.B. and Bonk 1984). These authors also describe hackly fracturing and exfoliation in the rocks of several zones in the Paintbrush Group, suggesting that the rock may show detrimental weathering effects as a building or dimension stone. Clinkstone zones in the Paintbrush Group exhibit uniform texture, but conchoidal fracturing in this rock might be an unfavorable factor in its potential as building stone.

3.11.3.4.2.2 Economics of Building Stone Resources at Yucca Mountain

Large amounts of Tertiary age tuff are available in the Yucca Mountain Conceptual Controlled Area, and it is possible that some of this material could be used as building stone. The likelihood of extraction of this ashflow tuff for building stone is dependent on intangible factors including future demand for particular colors and textures of stone. The tuff in the Yucca Mountain Conceptual Controlled Area 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 other tuffs outside the Yucca Mountain Conceptual Controlled Area. As dimension stone that could be quarried and prepared in a tile or panel plant, this tuff does not appear to have features that would make it more valuable for dimension stone preparation than the Tertiary tuffs currently being quarried by Nevada Neanderthal Stone at sites that are closer to its Beatty cutting plant.

It is unlikely that underground excavation of the repository by tunneling and mining equipment would produce blocks of rock equivalent to quarry blocks that could be used in a fabrication plant because breakage of this material is not controlled in terms of size and shape. The development of infrastructure including access roads, electrical power, and water supply would provide no significant advantages to building stone over those currently available in areas closer to presently developed areas in the region.

3.11.3.4.3 Clay

3.11.3.4.3.1 Clay Occurrences at Yucca Mountain

Minor amounts of sepiolite have been identified in samples from Yucca Mountain (Vaniman, Bish, Broxton et al. 1984); this clay mineral is present in extremely small amounts and cannot be considered to be a potential industrial mineral commodity (Castor and Lock 1995).

Smectite group clays are ubiquitous in Yucca Mountain rocks (Bish 1989), however most rocks from Yucca Mountain contain smectite minerals in relatively small quantities.

Two zones of abundant smectite occur at depth in members of the Paintbrush Group (Bish and Vaniman 1985). The uppermost of these zones was identified in borehole USW G-2. The stratigraphic sequence that contains this clay, the ashflow tuffs and bedded tuffs between the Tonopah Spring and Tiva Canyon Tuffs, is also extensively exposed at the Yucca Mountain Conceptual Controlled Area (Scott, R.B. and Bonk 1984).

The lower zone of smectite enrichment in the Paintbrush Group does not crop out within the Yucca Mountain Conceptual Controlled Area (Scott, R.B. and Bonk 1984). In volcanic rock units that are stratigraphically below the Paintbrush Group, smectite was identified in amounts that ranged up to 50 percent at depths of 2,000 feet or more (Bish and Vaniman 1985).

A fracture lined with nearly pure white smectite was noted at a depth of 2,226 feet in drillhole USW GU-3, and clay mineral contents were elevated in drillholes near faults in the Yucca Mountain area (Bish and Vaniman 1985). Although fault-controlled clay deposits occur at the New Discovery mine in the Beatty area, no similar concentrations have been noted at or near the surface in the Yucca Mountain Conceptual Controlled Area (Castor and Lock 1995).

3.11.3.4.3.2 Economics of Clay Resources at Yucca Mountain

The potentially available amount of smectite in the outcropping exposures was evaluated by Castor and Lock (1995). The lower zone of smectite enrichment in the Paintbrush Group does not crop out (Scott, R.B. and Bonk 1984), and it is therefore unlikely that it has economic potential in the Yucca Mountain Conceptual Controlled Area (Castor and Lock 1995) and should be considered as a subeconomic occurrence rather than as a resource.

Although smectite clay is clearly present in the Yucca Mountain Conceptual Controlled Area, 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 is insufficient to compete with regional sources of clay (Castor and Lock 1995).

The value of clay minerals is dependent on commercial quality and marketability, which is determined by testing to establish parameters of brightness, swelling capacity, plastic viscosity, gel strength, and slakeability. Because mineable quantities are not present, testing to establish parameters needed for marketability was not done. In addition, it is not clear what processes would be necessary to produce marketable clay commodities from the Yucca Mountain resource. Therefore, it is unrealistic to assign any value to the clay resource at Yucca Mountain (Castor and Lock 1995).

3.11.3.4.4 Construction Aggregate

3.11.3.4.4.1 Construction Aggregate Occurrences at Yucca Mountain

The canyons and alluvial fans in the Yucca Mountain Conceptual Controlled Area contain minor amounts of high-quality construction sand and gravel in comparison to regional resources (Castor and Lock 1995). Most of the detritus in these sands and gravels is probably sound, durable welded ashflow tuff; however, some structurally inferior nonwelded and bedded tuff fragments are probably also present. Abundant welded ashflow tuff bedrock exposures in the Yucca Mountain Conceptual Controlled Area 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 both sand and gravel and bedrock deposits in the Yucca Mountain Conceptual Controlled Area less desirable.

3.11.3.4.4.2 Economics of Construction Aggregate at Yucca Mountain

Under present circumstances, the Yucca Mountain Conceptual Controlled Area has little or no potential for production of construction aggregate except for internal use by the DOE or its contractors during repository construction or other activities in the vicinity. Aggregate for Portland cement concrete probably will have to be transported to the site from outside the Yucca Mountain Conceptual Controlled Area. The Yucca Mountain Conceptual Controlled Area is more than 150 km from the Las Vegas metropolitan area on existing major paved roads, and (at 6 cents per ton-km) truck haulage costs would amount to $9.00 per short ton, about twice the average price for construction aggregate in Nevada. Furthermore, large amounts of sand and gravel and of bedrock that are usable for high-quality construction aggregate are present in areas that are much less distant from Las Vegas. However, the establishment of rail service into the Yucca Mountain Conceptual Controlled Area for haulage of materials to a high-level radioactive waste repository could have the effect of making large amounts of low-cost crushed rock available for use in the Las Vegas metropolitan area during construction of the repository. However, this would cease after closure of the repository. Large quantities of already extracted ashflow tuff made available during repository excavation at Yucca Mountain might be attractive for rail haulage into the Las Vegas metropolitan area. Therefore, the potential for crushed stone production from Yucca Mountain cannot be discounted.

3.11.3.4.5 Fluorite

3.11.3.4.5.1 Fluorite Occurrences and Resources at Yucca Mountain

Fluorite has been identified in small amounts in core and cuttings from the Yucca Mountain Conceptual Controlled Area (Castor and Lock 1995). Fluorine analyses for 189 samples of core and cuttings that were obtained from six drillholes in the Yucca Mountain Conceptual Controlled Area ranged between < 0.02 and 2.44 wt% (Castor, Tingley, Bonham 1993).

Fluorite-bearing veins in the volcanic section are thin and contain only small amounts of fluorine; no analyzed samples contain more than 2.44 wt% fluorite, which translates to about 1.2 wt% fluorspar (Castor and Lock 1995). No fluorite was identified during the surface appraisal of the Yucca Mountain Addition (Castor 1989), and although fracture-coating fluorite was found in core at depths as shallow as 318 m, thicker veins that carry fluorite (up to 1 cm thick) occur at depths at or below 970 m. None of these reported occurrences are of sufficient grade or tonnage to constitute an economic resource (Castor and Lock 1995).

3.11.3.4.5.2 Potential for Fluorite Resources at Yucca Mountain

Fluorite has been identified in samples from the subsurface in the Yucca Mountain Conceptual Controlled Area (Castor and Lock 1995). Fluorspar has been an important industrial mineral in the Bare Mountain Mining district in the Southern Great Basin, and the episode of fluorite mineralization at Bare Mountain is considered to be of Tertiary age. Furthermore, fluorspar has been mined from deposits in volcanic rocks in Nevada outside the Southern Great Basin. Therefore, the presence of economic fluorspar deposits in volcanic rocks in the Yucca Mountain Conceptual Controlled Area is possible. However, the likelihood of economic deposits is considered to be remote because fluorite-bearing veins in the volcanic section are thin and have low contents of fluorine. Vein fluorspar deposits of significant size, if any are present in volcanic rocks at Yucca Mountain, are likely to occur at substantial, and probably unmineable depths. Fluorspar potential in the Yucca Mountain Conceptual Controlled Area is considered to be low (Castor and Lock 1995).

3.11.3.4.6 Limestone

3.11.3.4.6.1 Limestone Occurrences at Yucca Mountain

Limestone or dolomite does not crop out in the Yucca Mountain Conceptual Controlled Area (Castor and Lock 1995). However, considerable thicknesses of dolomite were encountered in the base of a drillhole at depths of 4080 feet (Carr, M.D. et al. 1986) in the Silurian age Lone Mountain Dolomite and Roberts Mountain Formation. Rocks of the Lone Mountain Dolomite extend from a depth of 1,244 m (4,080 feet) to 1,668 m (5,470 feet) as a continuous sequence of generally light gray, aphanitic to medium crystalline dolomite, which is poorly bedded and often brecciated and contains sparry dolomite and secondary calcite as fillings in vugs and veins.

3.11.3.4.6.2 Economics of Limestone Resources at Yucca Mountain

Given its low unit value, economic extraction of limestone and dolomite is not possible at the depths at which it is known to occur in the Yucca Mountain Conceptual Controlled Area (Castor and Lock 1995). The Yucca Mountain Conceptual Controlled Area is considered to have no potential for production of limestone or dolomite (Castor and Lock 1995).

3.11.3.4.7 Pumice

3.11.3.4.7.1 Pumice Occurrences at Yucca Mountain

Pumice-rich tuff layers are exposed in the Yucca Mountain Conceptual Controlled Area in the bedded tuff sequence that separates the welded portions of the Tiva Canyon and Topopah Spring Tuffs of the Paintbrush Group. On the basis of lithologic descriptions of drill core (Spengler, Byers, Warner 1981; Maldonado and Koether 1983; Scott, R.B. and Castellanos 1984; Spengler and Chornack 1984; Spengler, Muller, Livermore 1979) and descriptions by Diehl, S.F. and Chornack (1988), this interval contains interbedded airfall tuff, reworked tuff, and nonwelded ashflow tuff in which some layers contain up to 90 percent pumice fragments. To the north of drillholes H-6 and H-4 (Figure 3.11-2), welded tuffs of the Pah Canyon and Yucca Mountain Members occur within this sequence, separating it into three bedded tuff sequences. The bedded tuff sequence, or sequences, range in thickness from about 18 m in drillhole G-2, to 15 m in drillhole GU-3 (Diehl, S.F. and Chornack 1988).

3.11.3.4.7.2 Economics of Pumice Resources at Yucca Mountain

Although the Paintbrush bedded tuffs include pumice-rich layers, they are generally considered to have low potential for pumice or pumicite production because they are on the whole moderately to well indurated, commonly contain 10 percent or more lithic fragments, and are variably altered to clay (Castor and Lock 1995). During field examinations of the southwestern part of the Yucca Mountain Conceptual Controlled Area (Caster, Feldman, Tingley 1990) the bedded tuff sequence was not found to contain any layers of unconsolidated fragments of glassy lump pumice suitable for high value pumice products. However, it is possible that the bedded tuffs in the Paintbrush Group may include thin beds of fine-grained glassy pumicite of sufficient quality for use as pozzolan or fine abrasive. A 30 cm thick bed of white to light-gray, well-sorted, poorly indurated airfall tuff was noted in outcrop by Diehl and Chornack (1988, p. 90) and may be an example of this type of material.

The potential for pumice or pumicite production from the Yucca Mountain Conceptual Controlled Area is considered to be low (Caster and Lock 1995). No occurrences of economic pumice or pumicite are known, 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 available for sale 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.

3.11.3.4.8 Silica

3.11.3.4.8.1 Silica Occurrences at Yucca Mountain

No large masses of silica have been noted in the Yucca Mountain Conceptual Controlled Area (Castor and Lock 1995). Only minor amounts of white to bluish-gray chalcedonic silica and macrocrystalline and drusy quartz were seen in thin veins in drill core (Castor, Tingley, Bonham 1992). Surface exposures of resistant silicified breccia, which mostly occurs along faults, are present in the south part of the Yucca Mountain Conceptual Controlled Area. This breccia, which forms zones up to 6 m wide, is heterogeneous and consists of clasts of ashflow tuff set in mixtures of opal-CT and calcite containing minor chalcedony (Castor 1989).

3.11.3.4.8.2 Economics of Silica Resources at Yucca Mountain

Neither the thin silica veins encountered in drillholes or the impure siliceous breccia found on the surface can be considered to have commercial significance as sources of silica (Castor and Lock 1995). Volumetrically significant deposits of high-grade silica are not known to occur in the Yucca Mountain Conceptual Controlled Area and it is not considered to have any potential for silica production.

3.11.3.4.9 Vitrophyre/Perlite

3.11.3.4.9.1 Vitrophyre/Perlite Occurrences at Yucca Mountain

No exposures or drillhole intercepts of glassy silicic domes, flows, or intrusions have been recorded in the Yucca Mountain Conceptual Controlled Area, although these rocks are present a few km to the north in the rhyolite of Fortymile Canyon (Scott, R.B. and Bonk 1984). However, the Yucca Mountain Conceptual Controlled Area contains some dense vitrophyric welded ashflow tuff layers that may contain expandable perlite (Castor and Lock 1995).

In the Yucca Mountain Conceptual Controlled Area, the Tiva Canyon Tuff of the Paintbrush Group includes vitric rock (Castor and Lock 1995). However, most of this is partly devitrified or consists of light-colored, nonwelded to moderately welded rock with variable amounts of clay alteration. Maldonado and Koether (1983) describe cuttings of quartz latitic cap rock of the Tiva Canyon Tuff from drillhole G-2 as a 13.7 m thick interval of densely welded, vitric ashflow tuff. No data were found on water content or loss of ignition of this material, but it contains 10 to 15 percent feldspar phenocrysts, which together with its relatively low silica content as a quartz latite, suggest that the welded tuff is not usable as commercial perlite. The Tiva Canyon Tuff cap rock is extensively exposed in the Yucca Mountain Conceptual Controlled Area (Scott, R.B. and Bonk 1984).

In the Yucca Mountain Conceptual Controlled Area, the Topopah Spring Tuff of the Paintbrush Group contains dense gray to black vitrophyre near its top and base. The upper vitrophyre, which is part of the quartz latitic cap rock of the member, is densely welded ashflow tuff that contains 10 to 20 percent phenocrysts of feldspar, biotite, and hornblende, and ranges between 1 and 4 m in thickness as measured in core from drillholes (Spengler, Byers, Warner 1981; Maldonado and Koether 1983; Scott, R.B. and Castellanos 1984; Spengler and Chornack 1984; Spengler, Muller, Livermore 1979). A search of the literature revealed no data on water content or loss on ignition for this unit (Castor and Lock 1995), but the vitrophyre-cap rock was described as perlitic in core (Spengler and Chornack 1984). Vitrophyre in the upper part of the Topopah Spring Tuff in hole USW G-2 ranges from vitric to devitrified over small irregular intervals (Caporuscio et al. 1982). The portion of the Topopah Spring Tuff that contains this thin vitrophyre unit is widely exposed in the Yucca Mountain Conceptual Controlled Area (Scott, R.B. and Bonk 1984).

Vitrophyre in the basal part of the Topopah Spring Tuff is thicker than that in the cap rock. On the basis of intercepts in drillholes, the Topopah vitrophyre ranges between 9 and 25 m thick, and averages about 15 m thick (Spengler, Byers, Warner 1981; Maldonado and Koether 1983; Scott, R.B. and Castellanos 1984; Spengler and Chornack 1984; Spengler, Muller, Livermore 1979; Drilling Support Division 1995a, 1995b). On the basis of loss on ignition measurements ranging between 3.34 and 3.66 wt% (reported in F.R. Singer et al., *Geochemistry of Borehole Samples from USWG-1 and USWG-3/GU-3, Yucca Mountain, Nevada*, U.S. Geological Survey, in press), the vitrophyre may contain sufficient amounts of structural water for use as commercial perlite (Castor and Lock 1995). The part of the Topopah Spring Tuff that contains this vitrophyre is not exposed in the Yucca Mountain Conceptual Controlled Area, but it does occur a few hundreds of meters to the northwest on the northeast slopes of Castellated Ridge (Scott, R.B. and Bonk 1984).

3.11.3.4.9.2 Economics of Perlite Resources at Yucca Mountain

Although the Yucca Mountain Conceptual Controlled Area does not contain glassy silicic volcanic rock in the form of domes or flows, which are the most likely sources for perlite, ashflow sheets in the Yucca Mountain Conceptual Controlled Area contain dense vitrophyre that may have potential as perlite.

The most likely source of perlite in the Yucca Mountain Conceptual Controlled Area is in the lower vitrophyre zone of the Topopah Spring Tuff of the Paintbrush Group because it is present in mineable thicknesses (Castor and Lock 1995). However, that unit is not exposed in the Yucca Mountain Conceptual Controlled Area. If testing results indicated that the unit might be suitable for the production of expanded perlite, it is unlikely that it would be mined because of the thick overburden.

Considering the large amount of domestic perlite resources, the potential for perlite mining from the Yucca Mountain Conceptual Controlled Area in the near or distant future is considered to be low (Castor and Lock 1995).

3.11.3.4.10 Zeolites

3.11.3.4.10.1 Zeolite Occurrences at Yucca Mountain

Clinoptilolite-heulandite group zeolites and mordenite are present in significant amounts in volcanic rocks of the Yucca Mountain Conceptual Controlled Area (Castor and Lock 1995). Considerable literature is available on these occurrences because sorption and retardation of radionuclides by zeolites may be a factor in repository performance assessment and design (Bish and Vaniman 1985). In addition, study of these minerals is important in understanding their potential reactivity in a repository environment. Age dates on zeolites have been used in attempts to date diagenetic or hydrothermal activity in the volcanic sequence at Yucca Mountain (WoldeGabriel et al. 1993). The zeolite erionite occurs in small amounts in a single stratigraphic horizon at Yucca Mountain, along with rare phillipsite, chabazite; and stilbite (Bish and Chipera 1991).

Quantitative data on zeolite mineral contents of borehole samples from Yucca Mountain are reported in Levy (1984a) and Bish and Vaniman (1985) and provide some idea of zeolite mineral potential (Castor and Lock 1995). Zeolite mineral deposits in the Western U.S. that are being mined, or that have been investigated for economic potential, contain about 50 percent or more zeolite. Therefore, borehole intervals identified as containing 50 percent or more clinoptilolite + mordenite have been compiled in order to estimate the size of the zeolite resource in the Yucca Mountain Conceptual Controlled Area (Castor and Lock 1995).

Samples with 50 percent or more zeolite come from strongly zeolitized zones in ashflow tuff and bedded tuff in several stratigraphic units (Castor and Lock 1995). The zeolitized tuff probably represents the overlap of an alteration zone defined by the presence of clinoptilolite and mordenite (diagenetic alteration zone II of Broxton, Bish, Warren 1987) with tuff that retained a large component of vitric material following the original cooling of the tuffs. The affected units include the basal part of the Topopah Spring Tuff of the Paintbrush Group, the tuff and lava of the Calico Hills, all three members of the Crater Flat Tuff, and bedded tuffs associated with these units.

3.11.3.4.10.2 Economic Resources of Zeolite at Yucca Mountain

A large subeconomic resource of zeolite is present at Yucca Mountain (Caster and Lock 1995), however, the stratigraphic units that contain this estimated resource do not crop out within the Yucca Mountain Conceptual Controlled Area (see Scott, R.B. and Bonk 1984). Although zeolitized rock may reach the surface along the northeast border of the Yucca Mountain Conceptual Controlled Area, the zeolite is covered by considerable thicknesses of tuff containing little or no zeolite (about 500 m in borehole USW G-2) a short distance to the south. Because zeolite deposits are mined by open-pit methods, the amount of overburden is an important factor, and the zeolite subeconomic resource in the Yucca Mountain Conceptual Controlled Area 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. For instance, nearby deposits in the Ash Meadows and Beatty areas (Figure 3.11-3) are of much higher grade and are more easily mineable. Many high-grade zeolite deposits in the Western United States have been evaluated by mining companies, oil companies, and chemical companies, and their commercial potential has been known to industry for years; however, hundreds of millions of tons of zeolite have no commercial value as the total domestic market is only 35,000 to 45,000 tons per year.

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

3.11.3.5 Industrial Rocks and Minerals Resources Conclusions

Deposits with past or current production in the region include borate minerals, building stone, clay, construction aggregate, fluorspar, silicate, and zeolites (Figure 3.11-3) (Castor and Lock 1995). Clay minerals, zeolites, fluorite, and barite have been identified in samples from drillholes at Yucca Mountain (Caporuscio et al. 1982; Scott, R.B. and Castellanos 1984; Bish 1989; Broxton, Bish, and Warren 1987). Alunite, basalt, feldspar, gypsum, kyanite, lithium, mica, pyrophyllite, quartz and quartzite, salt (salines and brines), sandstone, silica sand, sodium compounds (sodium carbonate and sulfate), sulfur, and wollastonite do not occur in geologic settings similar to that at Yucca Mountain. There is little or no estimated potential for barite, construction aggregate, fluorspar, limestone, pumice, silica, perlite, and zeolites in the Yucca Mountain Conceptual Controlled Area. Construction aggregate may be generated as the repository is built and may have internal use at that time or it may be marketable to ship it to local markets, such as Las Vegas if a rail line is built to connect the two locations, but it otherwise does not possess any economic advantage over other aggregate closer to end users outside the repository.

Some of the Tertiary age tuff could be used as building stone but it does not have any properties or features that would make it more marketable than other stones readily available closer to processing plants and end users. The potential for economic deposits of clay in the Yucca Mountain Conceptual Controlled Area is considered to be low to moderate (Castor and Lock 1995).

3.11.4 Hydrocarbon Resources

This subsection will discuss oil, natural gas, tar sands, oil shale, and coal resources. This subsection may be revised in the Working Draft License Application to address items such as additional alternate interpretations of the Tertiary volcanics/Paleozoic sediments contact based on additional geophysical data and interpretations available for incorporation into the site 3-D model.

The Great Basin represents the regional area of investigation since it is the tectonic-physiographic province within which the Yucca Mountain site is located. The area of investigation is shown on an index map of Nevada, Utah, California, and Arizona, showing Yucca Mountain, oil and gas fields, and wildcat wells (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press, Figure 1).

The components necessary for generation, migration, and preservation of hydrocarbons are source rocks, reservoir rocks, seals, traps, depth of burial, and heat source/geothermal gradient. These components characterize the habitat of hydrocarbons in the Great Basin and will be described in this subsection. This information can then be compared to the Yucca Mountain area to assess the potential for hydrocarbon resources there.

3.11.4.1 Previous Studies of Hydrocarbon Resources

Brief discussions on oil and gas potential are presented as part of general resource evaluations in Bell and Larson (1982) and Castor, Feldman, Tingley (1990). Papers by Aymard (1989), Chamberlain, R. (1991), Grow, Barker, Harris (1994), Trexler, J.H. et al. (1996), and Barker, C.E. (1994) have presented information aimed more directly at making an evaluation. The most recent work was done by Cashman and Trexler (1996) which contains a summary of state records of drilling and show reports for 24 wildcats drilled in Southern Nevada. The literature on the occurrence of petroleum in the Great Basin, especially Eastern Nevada, is abundant, well beyond its importance as a national resource (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Numerous papers on commercial and non-commercial occurrences are in Schalla and Johnson (1994) and other publications of the Nevada Petroleum Society.

3.11.4.2 Hydrocarbon Genetic Models

The essential components of a petroleum system are generation site (which includes the source rock, depth of burial, and geothermal gradient), reservoir rock, trap, and seal. If any of these components is missing the system is incomplete and an accumulation cannot develop. Multiple systems can coexist and the relationships of the components may be poorly understood, even in regions that have been extensively explored and developed. By summarizing the state of knowledge of these components in the Great Basin the habitat of oil in the Great Basin will be defined. This definition can then be applied to an assessment of the Yucca Mountain area (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press).

A typical petroleum system consists of a well-defined basin with source rocks buried to sufficient depth to reach generation conditions. A generation site is defined by the presence of a viable source rock in a thermal setting conducive to the generation of hydrocarbons. Hydrocarbons from the generation site can migrate into a wide range of reservoir rocks and accumulate in traps defined by structure or stratigraphy or both. Traps generally predate or are contemporaneous with the creation of a generation site. Trap seals are usually provided by impervious strata (stratigraphic seal) or unconformities (structural seal). Fault seals also can be present either in combination with stratigraphy by juxtaposition of reservoir and impervious strata or as a sealing element independent of stratigraphic conditions (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Pressure and hydrodynamic seals also can be present.

Development of geologic structure is fundamental to hydrocarbon accumulations through the creation of: generation sites from regional increases in thermal conditions; migration paths resulting from faulting and fracturing; and trap geometries resulting from faulting (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Hydrocarbon traps are also formed by the juxtaposition of impermeable lithologies above reservoir rocks. Geologic structures are abundant in the Great Basin. From middle Paleozoic through Cretaceous time the Great Basin region was the site of a series of compressional episodes. During Tertiary time extensional structures became predominant (Figure 3.11-4).

3.11.4.3 Exploration History in the Great Basin-Chronology of Activity and Evolution of Concepts

This subsection presents the exploration concepts that have been applied to the Great Basin region (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). This information comes from written documentation and inferences made from historical drilling activity and exploration projects.

Oil and gas exploration in the Great Basin prior to World War II was sporadic and records of activity are poor (Figure 3.11-5) (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Generally, exploration was motivated by promotions or surface evidence of hydrocarbons. There was no participation in exploration by major oil companies during this period. Marsh gas was developed for local markets near Farmington, Utah, in 1892, and near Fallon, Nevada, during the 1920s (Heylmun 1961; Garside, Hess et al. 1988, p. 8). The oil seep at Rozel Point has seen intermittent development beginning about 1896 (Boutwell 1904, p. 475). The location of a few wildcat wells in the region apparently was based on the theory of hydrocarbon accumulation in anticlines, but most drilling was to depths less than 2,000 feet. The most productive oil and gas venture of the period was the Catlin oil shale operation where 9,450 barrels of oil were produced by retort during 1917 to 1924 (Moore, S.W. et al. 1983, p. 8).

After the war, the region attracted the attention of major oil companies and prospects were more commonly based on scientific investigations (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). From 1946 through 1953 exploration was focused on surface structures or surface seeps. Results of this drilling were discouraging and exploration was waning when Shell brought in 1 Eagle Springs in Railroad Valley in early 1954. The Shell prospect was based on the theory that anticlinal traps in Paleozoic rocks in the ranges were breached; that valley fill sediments were necessary to provide a seal. The prospect was defined by gravity and seismic surveys and anticipated oil from Paleozoic source rocks with reservoirs in Paleozoic rocks (Peterson, J.A. 1994b). However, subsequent development showed that the oil was generated in Tertiary lacustrine strata, was mostly in Tertiary-age reservoir rocks, and the trap did not conform to the anticlinal structure that had been mapped with seismic data. The discovery at Eagle Springs triggered a migration of exploration from the ranges to the basins although the large anticlines that can be readily mapped in the areas of Paleozoic outcrop continued to attract occasional wildcats. During the late 1960s and early 1970s there was some success developing Eagle Springs Field but discouraging wildcat results and an industry slump combined to limit drilling in the region to less than 10 boreholes a year. However, more than 125 dry hole wildcats were drilled in the Great Basin between the discovery of Eagle Spring (1954) and Trap Spring (1976) fields, reflecting both the difficult nature of exploration in this province and lack of sizable economic hydrocarbon accumulations in the area.

In 1976, a consortium of companies led by Northwest Exploration, using an exploration model developed by Filon Exploration, discovered Trap Spring Field (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). The exploration model was an analog to conditions at Eagle Springs; a truncated fault-block trap, with early and middle Tertiary reservoirs charged with oil from early Tertiary source rocks

(Figure 3.11-6). The model stipulated that high-standing fault blocks on the flanks of the Neogene basins could be mapped using aerial photography and geophysical methods and that exploration targets were on the flanks of these high-standing blocks (Foster and Vincelette 1991, p. 405). The use of new geophysical techniques, especially common-depth point seismic reflection, greatly improved the quality of data recovered from these surveys. The discovery rekindled exploration in the region and in a short time most of the basins in East-Central Nevada were under lease.

Subsequent investigations by Northwest Exploration found the exploration model to be deficient in several aspects (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). The oil produced at Trap Spring was identified with source rocks of the Chainman Shale, the Trap Spring fault block did not have significant erosional truncation, and aerial photography proved to be unreliable as a tool to map high-standing fault blocks. The exploration model was modified to include any fault block with trap geometry in close proximity to the site of generation (French 1994b, p. 268). Also, exploration was no longer limited to those basins with early Tertiary source rocks like the Sheep Pass or Elko formations. In this manner the 'Railroad Valley' model evolved. In the years subsequent to the Trap Spring discovery 11 fields have been found using variations on this modal.

In 1975, the discovery of Pineview Field opened the Utah-Wyoming thrust belt (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). The large size and relative simplicity of traps in this province is appealing and because overthrust faults had been mapped in the Eastern Great Basin, exploration for these targets expanded into that region. The overthrust model is a variation on the anticline model of Eagle Spring exploration and has been discussed by numerous workers (Cameron and Chamberlain 1987; Chamberlain, R. 1991; Dobbs et al. 1993; Hulen, Pinnell et al. 1994; Moulton 1993; Roeder 1989), but no accumulations have been found that can be unambiguously linked to it.

Exploration technology also evolved during the post-Trap Spring period (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Improved gravity modeling techniques, soil-gas surveys, trace element surveys, magneto-telluric surveys, and 3-D seismic surveys have been used to define exploration targets and attempt to improve the success ratio. But the complexity of the geology of the region necessarily leads to ambiguity in the results of these exploration techniques and the incidence of success remains sporadic.

Prior to 1990 the nearest oil and gas exploration wildcat to Yucca Mountain was more than 80 km (50 miles) distant (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Since that time two exploration projects have resulted in drilling three new boreholes and one re-entry project (Figure 3.11-7). The scientific basis of the wildcat and re-entry attempt located 25 km (15 miles) northwest of Yucca Mountain is not known (the Coffer Hole). The borehole is within the limits of the Oasis Valley caldera and reached a total depth of 3,871 feet in the Timber Mountain Tuff (Grow, Barker, Harris 1994). Oil shows were reported at 1,430 to 1,480 feet, but have not been verified. The attempt to re-enter the hole was not successful and a twin location was announced in April, 1996. Two wildcats were drilled by Felderhoff 20 km (12 miles) southwest of Yucca Mountain in the Amargosa Desert (the Smith Wells) have been documented by Grow, Barker, Harris (1994) and

Carr, W.J., Grow, Keller (1995). The exploration project was designed to evaluate traps charged by oil from the Chainman Shale or Eleana Formation and used rancher's reports of surface shows as supporting evidence. The wildcat locations were based on a gravity survey (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Minor gas shows were recorded in Ordovician rocks in the 25-1 Federal borehole and in Tertiary sedimentary rocks at 5-1 Federal. A new wildcat location in the vicinity of the Felderhoff tests was announced in early 1997.

3.11.4.3.1 The Railroad Valley Model

The structural complexity of the Great Basin allows a variety of petroleum systems to be hypothesized (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Consequently, numerous exploration models have been developed in the pursuit of prospect evaluation. The focus of exploration in proven hydrocarbon provinces of the conterminous United States is usually on the definition of a reservoir, a trap and a seal. The question of hydrocarbon generation is not an issue in basins where production has been established.

But in the Eastern Great Basin, petroleum exploration models are source rock driven as explained below (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Several workers have demonstrated that the principal Mississippian source rocks of much of the region had not advanced to full maturity by Miocene time (Figure 3.11-8) (Poole and Claypool 1984; Inan and Davis 1994). This is verified by the conodont alteration index map prepared by Harris, Wardlaw et al. (1980). This map shows that outcrops of Mississippian source rocks are at a low state of maturity in a large area of the Eastern Great Basin, including areas where production of oil generated from those rocks has been established. If the source rocks are sub-mature in the vicinity of the petroleum accumulations then the accumulated oil must be the product of two cases:

- Localized pre-Basin-Range stratigraphic or tectonic burial and generation that has not been identified
- Burial and generation since the onset of the Basin-Range extension

A viable exploration model located in this region that includes the first case as the condition of oil generation must implicitly or explicitly demonstrate the location of the generation site. Because of Mesozoic-age deformation, exploration models that include the second case must account for modification of the distribution of Paleozoic-age source rocks in order to constrain the area of post-Basin-Range generation sites. The consequence of these circumstances is that exploration in the Great Basin is source-rock driven; definition of the area of generation precedes the definition of trap, reservoir and seal in importance. To formulate a viable exploration model it is important to locate generation sites in time and space. This aspect of exploration sets the region apart from other petroleum provinces in the lower United States (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press).

Definition of a Neogene-age generation site like Railroad Valley requires two elements:

- An understanding of the distribution of potential source rocks by means of a paleogeologic map
- Knowledge of the thermal regime that has the affected source rocks

A paleogeologic map of Railroad Valley shows that the Chainman Shale was present in a syncline at the time the basin formed and was incorporated into the fault blocks that comprise the center of the basin (Figure 3.11-9) (French 1989; Peterson, J.A. 1994a, p. 28). In addition, the fault blocks of the basin are overprinted on the syncline in such a way that the intra-block geometry of the Paleozoic rocks facilitates migration to fault-block traps (Figure 3.11-10).

The thermal setting in the central part of the Railroad Valley basin is probably influenced by the unconformity at the base of the syntectonic valley fill. French and Hulen (1993) presented evidence that the unconformity segregates groundwater flow and becomes a thermal blanket for subjacent strata. This has the effect of creating a thermocline and propagating higher temperatures below the unconformity in the basin than exists at an equivalent depth of burial in the adjacent ranges where the unconformity is not present (French 1994c, p. 110; Meissner 1995, p. 71). A structural mechanism that modifies the thermal regime of the basin has also been suggested by Lund et al. (1993, p. 958). Hulen, Goff et al. (1994) presented a hydrothermal model that elevates temperatures (possibly during the Neogene) and facilitates generation and migration in local settings. His hypothesis is appropriate for a basin setting, like the Grant Canyon-Bacon Flat area in Railroad Valley, and a range setting, like Yankee Mine (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press).

3.11.4.3.2 Exploration Results and Viability of Exploration Concepts

The exploration experience in the Great Basin shows that commercial accumulations are associated with Neogene-age generation and migration, and that this is most likely to occur in a Neogene-age basin that contains an adequate quantity of potential source rock (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). The age of deposition of the source rock is less important than the state of thermal maturity at the time of burial in the basin. Trap geometry is mostly a product of Neogene extension but may be controlled in part by structure inherited from earlier episodes of deformation. These conditions imply that the pre-Neogene paleogeologic map is an important exploration tool and that exploration based on a petroleum system model that does not incorporate Basin-Range extensional structure is speculative and must therefore be assigned a greater element of risk. The understanding of Great Basin petroleum systems as outlined above guides this evaluation of the Yucca Mountain area.

The results of exploration in the region clearly ascribe success to the fault-block model (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). But the prospects that employ this model are complex, exploration targets tend to have small areas, and the reserves attributable to them are difficult to assess. Whereas prospects based on overthrust or simple anticline models are less complex, the trap areas are large, and large potential reserves can be demonstrated. For these reasons, some prospect delineation in the region will continue to be made using the overthrust or anticline models in the foreseeable future.3.11.4.4 Source Rocks.

3.11.4.4 Source Rocks

3.11.4.4.1 Source Rocks of Great Basin Producing Areas

Numerous formations of the Eastern Great Basin have been studied for source rock potential (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). The formations on this list can be categorized as either proven or potential source rocks. Proven source rocks are those that can be associated with significant volumes of naturally occurring hydrocarbons. The definition of a significant volume is subjective. For purposes of exploration any volume of oil large enough for a definitive oil-type analysis is significant. Theoretically, a proven source rock might be at a state of advanced maturity and have no remaining potential. This possibility is important to keep in mind when evaluating areas where source rocks are over mature. Of the formations discussed below, the Chainman Shale and Sheep Pass Formation are the only ones associated with commercial production.

3.11.4.4.1.1 Proven Source Rocks, Great Basin

3.11.4.4.1.1.1 Chainman Shale

The Chainman Shale has been identified as the source rock for oil produced at Trap Spring, Grant Canyon, Bacon Flat, Kate Spring, Duckwater Creek, and Sans Spring fields in Railroad Valley; and Blackburn, and North Willow Creek fields in Pine Valley (Poole and Claypool 1984, p. 201; Herring 1994, p. 295; French and Kozlowski 1994, p. 275; Grabb 1994, p. 251; Hansen et al. 1994, p. 331). As of the end of 1996 these fields have produced about 39 million barrels. Using a typical recovery factor of 30 percent for these fields, then over 130 million barrels has been generated and accumulated from the Chainman. The average yield of the Chainman from 56 analyses of samples from 11 boreholes in the Railroad Valley area is about 7 mg/g (1.8 gal/ton). French (1994a, p. 176) documented that the lower part of the formation, which has pyrolysis yields in the range of 10 to 30 mg/g (2.6 to 8.0 gal/ton) contributes disproportionately to the generation capacity of the formation (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press).

3.11.4.4.1.1.2 Sheep Pass Formation

The Sheep Pass Formation is the source rock for oil produced at Currant and Eagle Springs fields in Railroad Valley (French 1983, p. 17; Poole and Claypool 1984, p. 202). Cumulative production from these fields through 1996 is 4.4 million barrels. An average recovery factor of 30 percent applied to this production, results in a minimum estimate of 15 million barrels generated and accumulated from the Sheep Pass. In 46 analyses from 7 boreholes, the average pyrolysis yield from the Sheep Pass Formation is 13.43 mg/g (4.7 gal/ton)

3.11.4.4.1.1.3 Other Formations

Other formations have been identified as the source rock for non-commercial oil production (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Pilot Shale is the source rock for the exhumed accumulation at Yankee Mine (Figure 1, Hulen and Wavrek 1997). The Elko Formation is the likely source for some of the oil recovered from wildcats drilled in Huntington Valley, 40 km (25 miles) southwest of Elko (Schalla 1994, p. 166). Also, the Elko Formation was developed for oil shale production during the early 1900's (Moore, S.W. et al. 1983, p. 8). An unnamed Tertiary lacustrine deposit is the probable source for oil encountered during drilling operations by a mining company in Buena Vista Valley (Schalla et al. 1994, p. 129). Miocene and Pliocene sediments have been identified as the probable source for oil produced at West Rozel Field, located 80 km (50 miles) northwest of Salt Lake City (Bortz et al. 1985, p. 275).

3.11.4.4.1.2 Potential Source Rocks, Great Basin

In addition to the proven source rocks, other formations have been a factor in motivating oil and gas exploration in the region, because of the perception that these formations have the potential to generate hydrocarbons (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). The perception is based on the results of source rock analyses. Although research of this type is often done on a proprietary basis, a large number of evaluations have become part of the public domain. The NBMG has assembled a database of source-rock analyses on borehole cuttings and cores from corporate, academic, and government sources. The most extensive tabulation is in Poole and Claypool (1984). Some of the formations that have been studied for source potential in the region are: Ordovician Kanosh Shale, Ordovician Vinini Formation, Devonian Woodruff Formation, Mississippian Webb Formation, and Cretaceous Newark Canyon Formation (Figure 3.11-11).

3.11.4.4.1.3 Chemical Analysis of Great Basin Source Rocks

The analyses presented in the French report (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press) are important as a base from which to judge the source rocks of Southern Nevada. The best gauge of source rock quality are the examples of the Chainman Shale and Sheep Pass Formation of the Railroad Valley area where substantial production has been found. The formations are present in that basin at a wide range of maturity levels, which allows a close comparison of a source rock in a pre-generation state with the results of a generation episode.

3.11.4.4.2 Source Rocks of Southern Nevada

Significant volumes of oil or gas have not been found in Southern Nevada or adjacent California and Arizona; therefore, there are no proven source rocks in this region. Potential source rocks also are scarce; most analyses reported to date indicate advanced maturity (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Thus, if viable source rocks exist they are in subcrop or have not yet been analyzed. The data collected show that the Eleana Formation, the Chainman Shale, and Joshua Hollow were once source rocks at the localities sampled but little generation capacity remains. In addition, various Tertiary rocks present in boreholes and excavated by mining operations have indications of source potential.

3.11.4.4.2.1 Eleana Formation

The Eleana Formation has been sampled for source potential at outcrops and in boreholes within and near the Nevada Test Site (Aymard 1989). These results show that the Eleana has total organic carbon content commensurate with a good source rock, ranging as high as 5 percent by weight. However, pyrolysis yields are low, generally less than 1 mg/g (0.25 gal/ton). Maturity indicators show that the Eleana is mature to overmature as a source rock.

3.11.4.4.2.2 Chainman Shale

Recent work has resulted in the identification of the Chainman Shale at outcrops previously mapped as the upper member of the Eleana. The formations are juxtaposed by thrust faults, with the Chainman present in the lower plate (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press; Trexler, J.H. et al. 1996, p. 1756). This work shows that boreholes UE 17e, UE 25a-3 (Figure 3.11-7), and several other boreholes penetrated the Chainman. The core and cuttings of the formation have been sampled for source rock quality. The total organic carbon content of the sample indicates fair to good source rocks are present, and the productivity index from pyrolysis is indicative of moderate maturity. But the Tmax index shows advanced maturity and the pyrolysis yields are small. Trexler, J.H. et al. (1996, p. 1757) interpret the generation capacity of the Chainman mostly spent and the remaining potential will yield gas and condensate.

3.11.4.4.2.3 Joshua Hollow and Other Tertiary Strata

At the north end of Bare Mountain, the rocks of Joshua Hollow are exposed in the wall of an open-pit mine (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press, Figure 4). The outcrop was sampled and analyzed by C.E. Barker (1994). Although the samples have moderately high total organic carbon content, pyrolysis yields are modest. A dike is present in the pit wall, and these samples may have been altered by a local thermal event. The rocks of Joshua Hollow are early Miocene in age and underlie the succession of Neogene volcanic formations of the region (Monsen et al. 1992).

These Tertiary sedimentary rocks predate most of the volcanic deposits in the Yucca Mountain area and occupy a stratigraphic position analogous to the Sheep Pass and Elko formations of east-central and Northeast Nevada (Figure 3.11-11). Potential source rocks could be present beneath the volcanic strata of the Crater Flat and Yucca Mountain areas if the rocks of Joshua Hollow and equivalents have sufficient lateral extent.

Boreholes in Area 8 of the Nevada Test Site, 50 km (30 miles) northeast of Yucca Mountain penetrated organic-rich beds that yield up to 36 mg/g (9.5 gal/ton) when pyrolyzed. These are lacustrine beds that overlie the volcanic strata and are part of the early alluvium that filled the basin of Yucca Flat. They are roughly analogous to the Miocene-Pliocene source rocks that have generated the oil produced at Rozel Point and West Rozel fields.

3.11.4.4.3 Source Rocks at Yucca Mountain

Oil or gas have not been found in Southern Nevada or adjacent California and Arizona; therefore, there are no proven source rocks in this region. Potential source rocks are scarce; most analyses reported to date indicate advanced maturity. If viable source rocks exist, they are in subcrop or have not yet been analyzed. The data collected so far show that the Roberts Mountains Formation, Eleana Formation, and the Chainman Shale were once source rocks at the localities sampled in the Nevada Test Site region, but little generation capacity remains. In addition, various Tertiary rocks present in boreholes and excavated by mining operations have indications of source potential.

3.11.4.4.3.1 Paleozoic Strata

The Roberts Mountains Formation was penetrated in borehole UE-25 p#1 (Figure 3.11-7). Two core samples of dark gray dolomite were analyzed for source rock potential. The total organic carbon content of these samples is above minimum for carbonate source rocks, but the pyrolysis yield was modest. The maturity of the formation is well advanced according to the conodont alteration index, but not overmature; whereas vitrinite reflectance and fluid inclusion data indicate an overmature source rock (Grow, Barker, Harris 1994, p. 1303; Barker, C.E. 1994, p. 13).

3.11.4.4.3.2 Tertiary Strata

Various Tertiary strata in the region contain enough organic matter to be considered potential source rocks (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). These Tertiary sedimentary rocks predate most of the volcanic deposits in the Yucca Mountain area and occupy a stratigraphic position analogous to the Sheep Pass and Elko formations of east-central and Northeast Nevada (Figure 3.11-11). Potential source rocks could be present beneath the volcanic strata of the Crater Flat and Yucca Mountain areas, if the rocks of Joshua Hollow and equivalents have sufficient lateral extent.

3.11.4.5 Reservoir Rocks

3.11.4.5.1 Reservoir Rocks of the Great Basin Producing Areas

Oil is produced from a wide range of reservoir rocks in the Eastern Great Basin, from Devonian dolomite to Tertiary debris slides (Figure 3.11-11) (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). In addition to the productive reservoirs, several formations with good reservoir characteristics have been targets of exploration but have yet to be found hosting an accumulation. The complexity of the geology of the region coupled with the paucity of exploratory boreholes precludes lateral extrapolation of reservoir quality over large areas. Consequently, reservoir quality must be evaluated on a local, case-by-case basis. This situation is mitigated somewhat by the pervasive fracturing that has accompanied the structural evolution of the region and has created fracture-enhanced reservoirs in strata that otherwise have poor reservoir qualities.

A few formations with notable reservoir quality are discussed by French (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). The formations French provides (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press) are not comprehensive, but are representative, and are provided to establish background for comparison with the Yucca Mountain area. It can be noted from the formations presented that the reservoirs of the Eastern Great Basin can consist of a variety of lithologies.

3.11.4.5.2 Reservoir Rocks in Southern Nevada

Some of the potential reservoir rocks of the Yucca Mountain area are described by French (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press) and shown in Figure 3.11-11. Petrophysical data on Paleozoic rocks is presented by French (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). The listed formations were identified based on descriptions in the literature, borehole evaluations, field observations, and similarity to proven reservoirs in the region. Formations judged to be targets of exploration in the area, but not present at Yucca Mountain proper are included in French's report (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). The list is not exhaustive; local conditions of stratigraphy and structure can combine to create good petroleum reservoirs in strata that would not otherwise be prospective. In general, more formations appear to have good reservoir characteristics in the Yucca Mountain area than the other producing areas of the Great Basin, but there is less lateral continuity of good reservoir strata in the Yucca Mountain area.

The Paleozoic stratigraphy of the Yucca Mountain area is generally similar to that of Railroad and Pine Valleys (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press; see Subsection 3.2.2 and Table 3.2-1 of this document). Correlative formations are noted by French (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Important differences include the greater degree of development of cavernous porosity in the Yucca Mountain area and the absence of persistent horizons of reservoir rock in Middle Devonian strata. Cavernous porosity is well-developed at outcrops of the Banded Mountain member of the Bonanza King Formation; the Antelope Valley Limestone; and the Devils Gate Formation in, and adjacent to, the south part of the Nevada Test Site. The cavernous porosity is associated with late fractures that may be related to the development of strike-slip faults in the area. Cavernous porosity is not as well developed in these formations a few miles to the north, in the central part of the Nevada Test Site. Also, beds of laterally continuous, good-quality reservoir rock in the Simonson Dolomite of Eastern Nevada and Western Utah, are not distinguishable in the Yucca Mountain area. The Nevada Formation is mapped instead of the Simonson and the lateral extent of reservoir rock within that formation is not known.

3.11.4.5.3 Reservoir Rocks of Yucca Mountain

Some of the potential reservoir rocks of the region surrounding Yucca Mountain are described by French (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press) and shown in Figure 3.11-11. Petrophysical data on Paleozoic rocks is presented by French (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press).

The nearest relevant analysis of Paleozoic rocks is from borehole UE-25 p#1 in the southeast part of the Yucca Mountain Conceptual Controlled Area (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press) (Figure 3.11-7). There, 560 m (1,845 feet) of Silurian rocks of the Lone Mountain Dolomite and Roberts Mountains Formation were penetrated. The upper 424 m (1,390 feet) of the interval is the Lone Mountain, which was extensively cored (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press, Figure 7). Core analyses show that porosity and permeability of the formation is poor to fair (Anderson, L.A. 1991, p. 32). But the core is broken by abundant fractures making analysis difficult and resulting in a negative bias in the data.

The Tertiary section of the Yucca Mountain area has the same basic stratigraphic components that are proven reservoirs in the producing areas of the region, but some important differences can be recognized (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). The basal Tertiary section of the Yucca Mountain area is a sequence of continental sedimentary rocks with minor volcanic constituents. The unit is listed by French (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press) as the rocks of Joshua Hollow and apparently contains potential source and reservoir strata. Because of lack of outcrop or borehole penetration, this section is poorly known in the Yucca Mountain area, although cavernous porosity was encountered in correlative strata at Felderhoff 51 Federal, about 20 km (12 miles) south of Yucca Mountain.

Overlying the rocks of Joshua Hollow is a sequence of volcanic rocks comprised mostly of ashflow tuffs, similar to conditions at Railroad Valley where there is production from these rocks (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Like Railroad Valley, the ashflow tuffs have a wide range of matrix porosity but matrix permeability is generally poor (CRWMS M&O 1996d). In general, individual ashflow units in the Railroad Valley area are thicker, with a greater degree of welding and better development of cooling joints than those in the Yucca Mountain area (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press, Figure 9). Debris slides that were deposited as a consequence of Basin-Range tectonics also are present in both areas. The slide mass exposed at the south end of Crater Flat has a greater degree of brecciation and more uniform morphology than the debris slides of Railroad Valley. This implies that the slide at Crater Flat was fluidized during emplacement to a greater extent. Although the breccia is cemented and there is little matrix porosity, many post-emplacement fractures are open and the units probably have good permeability (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press, Figure 10).

Several basalt flows were deposited in Crater Flat in latest Miocene and Pliocene time and are interbedded with syntectonic sedimentary deposits. The oldest of these is listed in Table 3 of French's report (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain*

Vicinity, Nye County, Nevada, in press). Beds of basalt of similar age and depositional setting produce hydrocarbons at Rozel Point and West Rozel fields in Western Utah.

3.11.4.6 Seals

3.11.4.6.1 Seals of Great Basin Producing Areas

Fault seals are another important component of Basin-Range accumulations and may occlude petroleum from traps in the mountain ranges (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Faults may have intrinsic sealing properties or they may be seals by circumstances of stratigraphic juxtaposition. Both situations exist in the fields of Eastern Nevada. Normal faults that seal by juxtaposition are documented in Blackburn, North Willow Creek, Tomera Ranch, Trap Spring, and Sans Spring. Faults that are seals independent of stratigraphic offset have been identified at Eagle Springs and Trap Spring fields (Figure 3.11-12). Along the tens of miles of range-front faults that define Pine and Railroad valleys there is only one site, Bruffey Seep in Pine Valley, where petroleum has leaked to the surface. This implies that these faults may be efficient seals regardless of the wide variety of stratigraphic juxtapositions that must exist along them and that they impede migration from Neogene generation sites in the basins to Mesozoic-age traps present in the ranges. Foster et al. (1987, p. 1006) indicated that calcite deposited by hot springs could be a factor in creating some sealing faults in the region, but the permeability of basin-bounding faults in the region has not been studied.

Sealing elements within the stratigraphy of the Great Basin are impermeable beds and unconformities (Figure 3.11-11) (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Fine-grained siliciclastic rocks in the Chainman Shale and Eleana Formation have low permeability and could act as seals for accumulations in subjacent Paleozoic strata. Unconformities that can be documented as hydrocarbon seals are the unconformity at the base of valley fill sediments, the unconformity at the base of Tertiary volcanic strata, and the unconformity at the base of the Tertiary stratigraphic section. Depending on the local Tertiary depositional history these unconformities may merge into one or two horizons or may not be present. Impermeable strata that are known to be seals include beds in the Humboldt and Indian Well formations and in the Salt Lake and Garrett Ranch groups. There are no unambiguous examples of sealing strata in the Paleozoic stratigraphic section.

Sealing horizons of the Great Basin may play a role in the thermal regimes in the region in addition to limiting accumulations and migration paths (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). French and Hulen (1993) presented evidence that the unconformity at the base of valley fill in Railroad Valley segregates groundwater flow and becomes a thermal blanket for subjacent strata. This has the effect of creating a thermocline and propagating higher temperatures below the unconformity in the basin than exists at an equivalent depth of burial in the adjacent ranges where the unconformity is not present.

3.11.4.6.1.1 Seal at Base of Valley Fill

The unconformity at the base of the valley fill of Railroad Valley was recognized as an important seal after the discovery of the Eagle Springs Field (Murray and Bortz 1967). It is informally referred to as Unconformity A and separates various lithologies of Neogene syntectonic basin fill above from pre-basin fill strata below. The unconformity is disconformable to angular and represents more of a lithostratigraphic boundary than a chronostratigraphic one. Subjacent strata in Railroad Valley ranges from Oligocene volcanic rocks to Devonian dolomite. In special circumstances like Kate Spring Field, where a debris slide at the base of the valley fill is in contact with subjacent Paleozoic bedrock, the unconformity is above the slide mass, separating it from the overlying valley fill sediments (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press).

The seal at the base of valley fill in the Railroad Valley area is very important (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). It has proven to be a very efficient barrier to liquid hydrocarbons. Over 305 km (1,000,000 ft) of valley fill has been drilled, with shows reported in less than 0.1 percent of that total. The unconformity is the seal for traps that account for 98 percent of the production in the basin. The seal appears to be effective despite conditions that imply the seal should be imperfect; it is the boundary between a wide variety of lithologies both above and below it. Also, as a barrier to fluid movement the unconformity may create a thermal blanket that facilitates the generation process. This condition is discussed in the Subsection on Petroleum Systems of the Great Basin.

The seal at the base of valley fill is less efficient at Pine Valley where shows are more common and production has been established in strata above the unconformity (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). At Three Bar Field, oil is produced from the Humboldt Formation, which comprises the lower part of the valley fill (Figure 3.11-11). This indicates that the seal in Pine Valley has partial permeability or that the seal has been breached in places in the basin. Because the oil produced from the Humboldt is similar to that produced nearby from below the unconformity it is likely that the seal is breached.

3.11.4.6.1.2 Seal at Base of Tertiary Strata

Another important seal in the region is the unconformity at the base of Tertiary strata (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). This seal can occur at both the base of Tertiary volcanic rocks and Tertiary sedimentary rocks. This horizon is the top seal for accumulations at Blackburn and North Willow Creek fields in Pine Valley, and for the oil produced from the Paleozoic strata at the 32-29 Spencer-Federal wildcat in Railroad Valley. At Pine Valley the unconformity is between underlying Mississippian and Devonian strata and overlying volcaniclastic sediments of the Indian Well Formation.

3.11.4.6.1.3 Other Seals

Various other components of the stratigraphic column have proven sealing properties (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). The Oligocene age Currant Tuff of the Garrett Ranch Group is the top seal of part of the accumulation at Trap Spring (Figure 3.11-12). Other seals are impervious beds in the Salt Lake Group at West Rozel Field, Humboldt Formation at Three Bar Field, Indian Well Formation at Tomera Ranch Field, and Chainman Shale at the Meridian 32-29 Spencer-Federal wildcat.

3.11.4.6.1.4 Seals of Yucca Mountain Area

Because production has not been established in the Southern Great Basin the identification of sealing elements within the stratigraphy at Yucca Mountain is problematical (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Bedded tuffs within the sequence of Tertiary volcanic strata could provide seals for accumulations in ashflow tuffs, similar to conditions at Trap Spring Field (French 1994b, p. 267). The unconformity at the base of the Tertiary section that seals some of the fields of Pine Valley is also present in the vicinity of Yucca Mountain and is important for potential accumulations in Paleozoic strata.

The most important sealing horizon in the Great Basin, the unconformity at the base of valley fill, is absent at Yucca Mountain (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). The 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 (Faulds et al. 1994). Because the basin of Crater Flat 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.

3.11.4.7 Traps in Great Basin Producing Areas

3.11.4.7.1 Description of Proven Great Basin Trap Types

Because the Great Basin has been affected by multiple structure-forming episodes, a large variety of trap geometries exist in the region (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). These have been classified according to structural origin and degree of modification by Basin-Range extension (French 1994c). Figure 3.11-13 shows the classification of traps and illustrates them schematically. Every commercial accumulation known in the region can be classified as a Basin-Range trap in a basin setting (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press, Figure 20). These traps are closest to generation sites in time and space and have the greatest probability of receiving a hydrocarbon charge. The proven traps of the Great Basin generally have thick oil columns and small areal extent which makes them difficult targets. They also have internal complexities that impedes efficient drainage and reduces the success ratio of development wells.

3.11.4.7.2 Description of Unproven Great Basin Trap Types

Traps located in the ranges of the province have long attracted exploration because of their size and structural simplicity (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). About 200 wildcats have been drilled to evaluate prospects located in the ranges. The results of this exploration has been dismal; shows of live oil have been sparse and drilling problems have been common. Traps either have not received a petroleum charge or have been breached and drained as at Yankee Mine (Hulen, Pinnell et al. 1994). Because of the timing of trap formation relative to hydrocarbon generation traps in the ranges are more remote in time or space or both to generation sites than are traps located in the basins (French 1994c, p. 112).

Figure 3.11-13 illustrates the difficulty of getting petroleum into a Mesozoic-age fold located in a range of Eastern Great Basin (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). At the time the fold develops it can only be charged by remigration of oil from an accumulation produced during the Permian-Triassic generation episode or by migration from a generation site created by local tectonic burial or thermal flux. Thrust faults associated with the folds in the region have mostly ramp geometry which limits the volume of source rock that can be incorporated into a generation site of tectonic burial. If Mesozoic generation and trap formation should coincide and accumulation form, it would have to remain intact during Neogene extension. A more plausible means of charging a Mesozoic-age fold trap is migration from a Neogene-age generation site. Except for the exhumed accumulation at Yankee Mine, however, evidence for this having occurred is sparse (Hulen and Wavrek 1997, p. 2).

3.11.4.7.3 Thrust-fold Traps of Mesozoic Age

The possibility of Mesozoic-age thrust-fold structural traps developed in Paleozoic strata in the vicinity of Yucca Mountain is alluded to in the section on generation sites (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Traps of this type are illustrated by Chamberlain, R. (1991) and discussed by Chamberlain, A.K. (1991) who speculated about the presence of billion-barrel fields in the Yucca Mountain area. The possibility that such traps exist is speculative. Extrapolation of the Belted Range Thrust fault through the Yucca Mountain area have been made by Caskey and Schweickert (1992, p. 1317), Snow (1992, p. 82), and Wernicke, Snow, Walker (1988, p. 257). But, giant thrust-related structural traps that are unmodified by Basin-Range extension (Class b., Figure 3.11-13) as envisioned by Chamberlain, A.K. (1991) do not exist.

The previous discussion on generation sites stipulates that a trap of this type could be charged by contemporaneous generation from tectonically buried Mississippian source rocks or by petroleum migrating from a Neogene generation site in Crater Flat (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). In the former circumstance the migration distance is short but an accumulation would have to remain intact during Basin-Range extension which resulted in creation of numerous normal faults in the area (Sawyer, Wahl et al. 1995). In the latter case generation postdates Basin-Range extension but the generation site is remote from the trap and migration would have to negotiate a complex system of normal faults. Thus the only Mesozoic-age thrust-fold trap that can exist in the Yucca Mountain area is one that has been modified in some way by Basin-Range faulting (Class e. or f., Figure 3.11-13).

In addition to structural complications, identification of top seal for these traps is problematic (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Chamberlain, A.K. (1991) and Chamberlain, R. (1991) do not discuss seals, but imply that an overthrust plate or impermeable beds of the Eleana are anticipated. R. Chamberlain's cross section also indicates the possibility of a seal at the base of the Tertiary section but lateral trap limits are still a function of impermeable strata in fold geometry.

No production in the Great Basin has been established from a trap of this type. The seep excavated at Yankee Mine is similar in that it is located in a range and the oil is hosted in folded Paleozoic strata. But the geometry of the trap there is not clear and no seal is present (Hulen, Pinnell et al. 1994).

3.11.4.7.4 Basin-Range Traps

Since mid-Miocene time, Basin-Range extensional tectonics has caused the development of numerous fault blocks with potential trap geometry at Yucca Mountain (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Traps of this type are tilted blocks bounded on at least one side by a normal fault. The bounding fault or faults must have sealing characteristics for a trap of this type to retain an accumulation. Because the time of fault-block formation overlapped the deposition of volcanic strata in the area, trap geometry of deeper horizons does not coincide with that of formations deposited during the late stages of deformation. For this reason traps in Paleozoic rocks are discussed separately from traps that include Tertiary volcanic formations.

Although fault-block traps described above have a similar morphology to productive traps in the Great Basin, they are significantly different in structural setting (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). The productive traps are situated in alluviated areas where Neogene syntectonic sediments are present overlying Paleozoic and middle and early Tertiary volcanic and sedimentary rocks on a sealing unconformity. The fault-block traps of Yucca Mountain are more closely analogous, for example, to fault blocks of the Pancake Range adjacent to Railroad Valley or to the Rozel Point area. No production has been established from 'emergent' fault-block traps, although it is possible that additional development at Rozel Point may prove profitable. The Yankee Mine seep probably represents a non-commercial accumulation. The combination of limited size, lack of proven top seal, and remoteness to generation sites impairs the viability of these structures as exploration targets. Evaluations of range fault-block traps have generally been an inadvertent consequence of testing Mesozoic-age thrust-fold structures. The fault-block traps nearest Yucca Mountain that are in a structural setting comparable to the productive traps of the region are those that comprise the basin of Crater Flat.

The fault-block geometry of the Paleozoic rocks that underlie Yucca Mountain is largely inferred from geophysical investigations. A single borehole, UE-25 p#1 on the east side of the mountain, penetrates the sub-Tertiary unconformity. Figures 3.8-16 and 3.11-14 are alternate interpretations of this unconformity. Whereas Figure 3.11-14 is an interpretation of the subsurface structure of Paleozoic rocks based on gravity data (Ponce and Oliver 1995, p. 38), Figure 3.8-15 is based on the 3-D geologic model and incorporates interpretations of various data (see Subsection 3.8). Borehole UE-25 p#1 tested one area of structural closure which can be interpreted as a horst based on the gravity data or one of a series of structural high points that could be considered as potential traps. This block is bounded on the north, east, and west sides by faults that juxtapose Tertiary formations with the Paleozoic strata. The south end of the block is off the mapped area but a few miles to the south the gravity low of Fortymile Wash truncates the gravity anomaly associated with the horst block indicating that the high-standing block of Paleozoic rocks is also limited in that direction (Ponce and Oliver 1995, p. 40). The UE-25 p#1 borehole was drilled into the north end of the horst block where over 560 m (1,800 feet) of Silurian dolomite was penetrated. No hydrocarbon shows were encountered which indicates that at least the north part of the horst does not contain hydrocarbons. A triangle-shaped fault-block bench west of the horst block underlies the west part of the site and also has trap geometry. The bench is bounded to the north and west by faults that place Tertiary strata against Paleozoic rocks. To the southeast the bench is bounded by the fault on the west side of the horst block and has displacement down to the west. The Paleozoic strata of the bench is in fault contact with the Paleozoic strata of the horst along this boundary. The integrity of the bench trap may be contingent on the intrinsic sealing properties of this fault contact which may juxtapose formations of similar lithology.

The following interpretation, from French (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press), may be supplemented in later revisions of this document by alternate interpretations based on further interpretation of information from other sections or newly developed information. The structure map used to identify trap geometries in the Tertiary volcanic rocks is contoured on the top of the Prow Pass Tuff of the Crater Flat Group (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). This horizon was chosen because it is subjacent to the Calico Hills Tuff, (which may behave as a seal), there is good control for the contour surface, and it does not crop out extensively in the area. The Prow Pass is in the unsaturated zone in the area of Figure 3.11-15 and the formation has been evaluated with boreholes in a number of fault blocks. But there are several ashflow tuffs below the Prow Pass that could be petroleum reservoirs and the structure of the Prow Pass is assumed to be representative of the structure of those formations also (Figure 3.11-11). The structure of the Prow Pass is defined by borehole and seismic data. It consists of a series of east-tilted fault blocks that are elongate in a north-south direction and bounded on the west by west-dipping normal faults. Structural culminations within individual blocks generally coincides with coincide maximum displacement on the bounding faults (Figure 3.11-15). Some of the larger traps are also indicated in Figure 3.11-14 by closure of contour lines. These were selected based on structural relief and minimum number of bounding faults. The trap limits as shown are rather arbitrary; variation in quality of fault seals will result in substantially different trap geometries. This geologic interpretation will be compared with the repository Viability Assessment (VA) design during fiscal year 1998.

3.11.4.8 Age of Petroleum-Influencing Structures in the Great Basin

Geologic structures are abundant in the Great Basin (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). From middle Paleozoic through Cretaceous time the Great Basin region was the site of a series of contractional episodes. During Tertiary time extensional structures became predominant. The following brief discussion describes the structural evolution of the region in terms of relevance to known oil and gas occurrences. Comparisons are drawn between the structure of producing areas and the Yucca Mountain vicinity.

3.11.4.8.1 Antler Structures

During the Antler orogeny of Devonian-Mississippian time the Roberts Mountains allochthon was emplaced in central Nevada (see Subsection 3.2.3.1 and Figure 3.2-14). The allochthon did not extend into the area of Railroad Valley but caused the development of a basin of deposition for the Chainman Shale, the major source rock of that area. Similar basin development occurred in the area of Pine Valley but there, late movement on the Roberts Mountains Thrust fault resulted in the allochthon overriding part of the Chainman Basin. A consequence of the late movement was the introduction of additional potential source rocks carried on the allochthon such as the Vinini and Woodruff formations (Carpenter et al. 1993, p. 14). The impact of the Antler orogeny in the area of Yucca Mountain was similar to that of Railroad Valley. The Roberts Mountains allochthon did not extend into the project area but a consequence of the episode was the development of a fore basin where potential source rocks of the Eleana Formation and Chainman Shale were deposited (Trexler, J.H., Cole, Cashman 1996).

3.11.4.8.2 Late Paleozoic-Mesozoic Compression

A number of contractional episodes are included in the late Paleozoic through Mesozoic time bracket (see Subsection 3.2.3.1; D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). This period includes the Pennsylvanian Humboldt orogeny, Permian-Triassic Sonoma orogeny, Jurassic Elko orogeny, and Jurassic-Cretaceous Sevier orogeny (Stewart 1980; Thorman et al. 1992).

Deformation in the Railroad Valley area during this time is mostly attributable to the Sevier orogeny and resulted in the creation of large-wavelength, low-amplitude folds with some thrust faults of ramp geometry (Subsection 3.2.3.1, Figures 3.2-15 and 3.2-16; D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Erosion of the folds modified the distribution of the Chainman Shale (Figure 3.11-16). Although trap geometries were created, generation was sporadic and these traps were not charged uniformly in the region (Poole, Claypool, Fouch 1983, p. 212; Barker and Peterson 1991, p. 39).

In the area of Pine Valley most deformation during this time can be attributed to the Humboldt and Sevier orogenies (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). The Humboldt orogeny is documented by an angular unconformity that formed in Late Pennsylvanian time. The Sevier orogeny had more significant impact, with the development of large folds and thrust faults similar to Railroad Valley (Carpenter et al. 1993, p. 23). As at Railroad Valley, the important affect of the Sevier deformation on the petroleum potential of the area was modification of the distribution of source rocks. In addition, new potential source rocks were deposited locally as part of the Newark Canyon Formation in a continental setting (Vandervoort and Schmitt 1990, p. 568). Trap geometries formed during the contractional episodes but entrapment of hydrocarbons probably did not occur until Neogene time (Flanigan 1994, p. 356).

The Paleozoic strata of the Yucca Mountain area also have been deformed by tectonism of this period (Caskey and Schweickert 1992). Most of the contractional structure is associated with the Sevier orogeny, but some thrust faults and folds are older and may be products of the Sonoma episode (Snow 1992). Overthrust faults are a more important component of the contractional structure in Southern Nevada, and have both ramp and flat geometry. This geometry has led to interpretations that associate the thrust faults in Southern Nevada with those of the Sevier thrust belt in central Utah (Stewart 1980). But Taylor, W.J. et al. (1996) have argued that the Southern Nevada thrust faults can be linked to those found in the area of Railroad and Pine valleys. In addition to modifying the distribution of Mississippian source rocks by erosion, deformation during this period has caused tectonic burial of some of the source-rock bearing strata probably causing the source potential to be spent at that time (Trexler, J.H. et al. 1996, p. 1756).

3.11.4.8.3 Tertiary Extensional Structures

During Tertiary time tectonism in the Great Basin was predominantly extensional (Figure 3.11-4. Several episodes occurred and are manifested in different ways: Paleogene depositional basins, middle Tertiary low-angle normal faults, and Neogene-age Basin-Range high-angle and low-angle normal faults and depositional basins (Fouch 1979; Axen et al. 1993; Stewart 1980, p. 110). Source rocks were deposited in Paleogene depositional basins as part of the Sheep Pass Formation in the vicinity of Railroad Valley and the Elko Formation in the vicinity of Pine Valley. Subsequent low-angle and high-angle normal faulting caused the development of the present basins that have incorporated parts of the older Tertiary depositional basins (Lund et al. 1993; Carpenter et al. 1993). The basins of Railroad and Pine valleys were also overprinted on fold and thrust fault structure of the previous contractional episodes. Paleozoic-age source rocks preserved in these folds have been incorporated into fault blocks that comprise the central part of the basins and are now under conditions of hydrocarbon generation (Figures 3.11-8 and 3.11-14). In the case of Railroad Valley the fold geometry of the Paleozoic strata in the basin fault blocks has facilitated migration from the generation site into fault-block traps. Also, in some cases, like Blackburn Field in Pine Valley, a Sevier-age fold has been incorporated into the trap geometry (French 1994c, p. 109; Carpenter et al. 1993, p. 30). In the Great Salt Lake area generation sites and fault-block traps also developed during Neogene extension. But there, the source rocks are part of the sequence that filled the new basins (Bortz 1987, p. 557).

3.11.4.9 Structural Comparison of Railroad Valley/Pine Valley to Yucca Mountain Area

Although the Tertiary structural history of the Yucca Mountain area is similar to the producing areas of the Great Basin the extensional setting of the Yucca Mountain area is significantly different (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). The most obvious difference is that the fields of the producing areas are situated in Neogene-age basins whereas the repository site is in a Neogene-age mountain block. Also, the degree of displacement on the normal faults that define the basins and ranges is much greater in the area of Pine and Railroad valleys (Jacherns and Moring 1990; D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press, Figure 15). Because of the timing of volcanism, volcanic rocks are an important component of basin fill in the Yucca Mountain area. This contrasts sharply with Railroad Valley where an important unconformity developed after the last major deposition of volcanic strata and before the onset of Basin-range extension. The extensional structural framework of the Yucca Mountain area has some similarity to the setting in the Great Salt Lake area. Displacement on normal faults in the vicinity of Rozel Point and West Rozel fields is relatively modest, source rocks are part of the basin-fill sequence, and fault-block traps have been formed by Neogene extension.

3.11.4.10 Timing and Generation (Maturity) in Southern Nevada

3.11.4.10.1 Distribution in Time

3.11.4.10.1.1 Pre-Neogene Episodes of Generation

Indices of thermal history show a complex pattern of maturity of the Mississippian source rocks in the Yucca Mountain area (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press, Figure 15) (Grow et al. 1994, p. 1308; Trexler, J.H. et al. 1996, p. 1756). Within a region of advanced maturity is an area in which source rocks of the Chainman Shale retain some generation capacity. This area trends northeast-southwest through the Nevada Test Site and can be projected into the area of Yucca Mountain. The pattern implies that multiple generation episodes are possible:

- One or more episodes that caused the source rocks to mature prior to the development of the present outcrop and subcrop configuration

- A Neogene episode involving source rocks that had remnant potential at the time modern generation sites formed

Two possibilities have been identified as Case 1 generation episodes. Barker, C.E. (1994) attributes older generation to stratigraphic burial during Permian and Triassic time, and supports this hypothesis with basin modeling. The models include the presence and subsequent erosion of about 1.5 km (5,000 feet) of Triassic strata. Trexler, J.H. et al. (1996) present the possibility that tectonic burial created generation sites in Mesozoic time. Both scenarios may have been factors in the evolution of mature Mississippian source rocks, but the two possibilities have substantially different implications for the location of generation sites relative to accumulation traps. This is discussed in greater detail in the subsection on the distribution of generation sites in space.

3.11.4.10.1.2 Neogene Episode of Generation

Case 2 is analogous to conditions described for producing areas of the Eastern Great Basin (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Tertiary source rocks and the Mississippian source rocks that held remnant generation capacity could be incorporated in generation sites of this episode. Because of earlier generation activity, the product of Mississippian source rocks in Neogene-age generation sites would be some oil and wet gas (Trexler, J.H. et al. 1996, p. 1758). Paleogene and early Neogene source beds, like those sampled at the Felderhoff 5-1 Federal wildcat, have had a moderate thermal history and could be generating hydrocarbons in the Yucca Mountain vicinity if buried adequately by subsequent Cenozoic strata. The young age and shallow stratigraphic burial of Neogene source rocks like those present at the base of basin fill at Yucca Flat would require unusual local thermal conditions for the development of a generation site.

3.11.4.10.2 Distribution in Space

3.11.4.10.2.1 Distribution of Generation Sites with Paleozoic Source Rocks

The spatial distribution of generation sites that involve Mississippian source rocks depends on the episode of generation under consideration (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Three episodes of generation imply the existence of three generation sites through time. The Permian-Triassic episode discussed by Barker, C.E. (1994) was a product of stratigraphic burial and therefore regional in scope. In this generation model the pattern of variable maturity illustrated by Grow et al. (1994) and French (*Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press, Figure 15) was caused by local variations in heat flow or depth of burial.

The Mesozoic episode of tectonic burial postulated by Trexler, J.H. et al. (1996) was limited to areas where the Mississippian source rocks were sufficiently buried under the upper plate of an overthrust fault (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Identification of these sites requires a paleogeologic interpretation to filter structural noise of subsequent tectonism. The work of Trexler, J.H. et al. (1996), Caskey and Schwieckert (1992), and Snow (1992), shows that source rocks of the Eleana Formation could have been buried in this manner by the Belted Range Thrust fault in an arcuate belt from the area of the Eleana Range south and west through the Yucca Mountain area to the vicinity of Bare Mountain. Some of the petroleum generated during this episode would have migrated into structural traps in the upper plate of the thrust fault that evolved during emplacement. The volume that could have been generated by this episode is related to structural configuration. The ramp geometry on the Belted Range Thrust shown by Frizzell and Shulters (1990) implies that a limited amount of Eleana was tectonically buried.

Neogene-age generation sites that involve Mississippian source rocks like those of Pine and Railroad Valleys are limited to those areas where rocks with sufficient remnant potential have been incorporated into thermally favorable settings (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). The basin that underlies Crater Flat could be in this category if burial is adequate and source rocks with potential are present. Geophysical data indicate that the basins that underlie the Amargosa Desert and Jackass Flats are less well developed and are unlikely to contain Mississippian source rocks buried deeply enough to be generating hydrocarbons (Healey, D.L. et al. 1987; Ponce and Oliver 1995, p. 43; Mooney and Schapper 1995, p. 103). At the north end of Yucca Mountain a magnetic anomaly has been attributed to the presence of magnetized Eleana Formation 2,100 m (7,000 ft) below the surface (Bath and Jahren 1984). The magnetization is a result of metamorphism caused by contact with an intrusive. About 10 km (6.5 miles) to the east, in the

Calico Hills, magnetized argillite of the Eleana is intruded by late Miocene rhyolite (Maldonado 1985). If the Eleana had source potential prior to the emplacement of the intrusive it is possible that fault-block traps of the Yucca Mountain area could have been charged by petroleum generated during the thermal episode that magnetized the formation. This possibility seems remote. Source-rock analyses of formation samples from borehole UE 25a-3, identified as Chainman Shale, indicate overmature source beds. However, there is little evidence of live or dead oil in the Eleana or adjacent beds in the Calico Hills as would be expected if the emplacement of the intrusive had caused significant generation.

3.11.4.10.2.2 Distribution of Generation Sites with Tertiary Source Rocks

Another generation site may have been created by burial of Tertiary-age source rocks in the basin of Crater Flat. Oligocene-Miocene age rocks of Joshua Hollow are present at the north end of Bare Mountain, where some beds have source potential (Barker, C.E. 1994; Monsen et al. 1992). These rocks are roughly correlative to the rocks of Pavits Spring of the vicinity of Mercury and the Horse Spring Formation identified at the 5-1 Federal wildcat and have been identified in the UE-25 p-#1 borehole on the east side of Yucca Mountain (Carr, M.D. et al. 1986, p. 28). O'Leary (1996, pp. 8-33) speculates that as much as 1,800 m (5,900 feet) is present in the Crater Flat basin. Overlying volcanic strata and basin fill could be up to 1,700 m (5,600 feet) thick. Depending on organic content, stratigraphic position, and heat flow, source beds in the Joshua Hollow could be generating hydrocarbons. Because of proximity in both time and space, traps of the Yucca Mountain area are more likely to be charged with hydrocarbons from this generation site than any other under consideration. The combination of Tertiary-age source rocks in a Neogene-age generation site generating petroleum to charge nearby traps is similar to the conditions that exist at Railroad Valley, where the Sheep Pass Formation is the source of oil produced at Eagle Springs Field, and at the Rozel Point area, where oil generated from the Salt Lake Group is produced.

3.11.4.11 Summary Comparison of Yucca Mountain to Great Basin Producing 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 (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Most of the variations indicate that there is little probability for the accumulation of hydrocarbons at the repository site.

Source rocks of Mississippian and Tertiary age have generated the oil that is commercially produced in the region (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Likewise, source beds have been identified in the Mississippian and Tertiary stratigraphy of the Yucca Mountain area. However, Mississippian-age source rocks are at an advanced state of maturity compared to counterparts in the area of Railroad and Pine valleys. 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 is no longer intact. Tertiary-age source rocks are present in the Yucca Mountain area but the state of knowledge about them is meager. They may be present in the basin of Crater Flat where they could be buried adequately for generation 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 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 ashflow tuffs, and late Tertiary debris slides and basalt are proven reservoirs in the region and have counterparts in the vicinity of the project (Figure 3.11-11). In addition, cavernous porosity is present in a wider range of stratigraphy around Yucca Mountain than exists in the producing areas.

Fault-block traps similar to those that produce elsewhere in the Great Basin are also present at Yucca Mountain. 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 adjacent to the west.

Some of the sealing elements documented at the producing fields are represented at Yucca Mountain. The unconformity at the base of the Tertiary section and bedded tuffs within the sequence of ashflow tuffs are two examples. But the principal seal of Railroad Valley, the unconformity at the base of the valley fill, is absent at Yucca Mountain because it is not buried by syntectonic deposits. In Crater Flat basin there is an unconformity at the base of syntectonic alluvium, but because the basin developed during the deposition of the Tertiary ashflow tuffs; the volcanic formations are part of the basin-fill stratigraphy. This contrasts sharply with Railroad Valley, where volcanic activity ceased before the basin began to develop.

Summary of Topics of Uncertainty and Impact on Assessment-The state of knowledge about the components of the petroleum systems that might exist in the Yucca Mountain area is good considering the complexity of the geology of the area and the frontier status of oil and gas exploration in Southern Nevada. Available information on reservoir rocks, sealing horizons, Paleozoic-age source rocks, and fault-block trap geometries has been summarized in this subsection. There is more uncertainty concerning Tertiary-age source rocks and thrust-fold structure of Paleozoic rocks in the Yucca Mountain vicinity. Also, the relevance of the seal at the unconformity at the base of valley fill to the development of generation sites in the region is not well understood. The principal impact of these factors of uncertainty is on the definition of generation sites in time and space and on the delineation of thrust-fold trap geometry of the Paleozoic strata of the Yucca Mountain area.

Source rocks have been identified in the rocks of Joshua Hollow and equivalent formations of the area. But the thickness and distribution of the source beds is not documented. If a depocenter for this sequence was present in the area of Crater Flat, as suggested by O'Leary (1996, pp. 8-33), it is possible that a generation site has developed in the center of this basin. The volume of hydrocarbons generated from this site would be contingent on the volume and quality of the source rocks incorporated into it.

Because of extensive cover by Tertiary volcanic strata the structural configuration of the Paleozoic rocks in the Yucca Mountain is poorly known. Consequently, the distribution of Mississippian-age source rocks must be inferred by extrapolation from scattered outcrops and geophysical data. This condition reduces confidence in identifying generation sites in time and space that involve these rocks. Also, delineation of thrust-fold trap geometry in Paleozoic strata under Yucca Mountain is highly speculative.

The importance of a basin-wide seal such as that present at the base of the valley fill in Railroad Valley is not well understood. D.E. French (1989), D.E. French and Hulen (1993), and Meissner (1995) presented evidence that a permeability barrier at that horizon acts as a thermal blanket, resulting in elevated temperatures subjacent to it. As a consequence the depth of burial required to attain temperatures necessary for generation of hydrocarbons is less than would be the case without the barrier. If this circumstance is important to the existence of generation sites in the region, and if no such barrier exists in the Yucca Mountain-Crater Flat area, then thermal/burial conditions outside those stipulated by the proven model are required to form a generation site.

The French model assumes temperatures are elevated beneath the thermal insulating blanket developed by valley fill deposited over the lower Tertiary and Paleozoic units of the Railroad Valley area. The majority of the deeper basin area at the top of the Paleozoic is within the hydrocarbon generation window in the Crater Flat Basin. What is not well known is the configuration and actual depth of the basin, but it appears to be sufficiently thick to allow for maturation of source beds, if such units exist in the lower Tertiary of the basin. The insulation effect is not required for generation. The insulation effect is a complex feature tied to variation in thermal conductivity and insulating qualities of rock units. This can vary basin to basin. Few basins of the world require the presence of a thermal blanket trapping heat in order to generate petroleum. What is required is a temperature gradient sufficient to reach maturation temperatures at basin depth. Similarly, regarding assurance of the presence of Paleozoic source units, particularly discussions regarding the Chainman or Mississippian section, well UE-25p #1 penetrates the lower Paleozoic section. Dips are to the north at 45 degrees in the well. Even in the lower Paleozoic at well UE-25p #1, the conodont color alteration index reported for samples taken from the Ordovician and Silurian are 3 CAI. That places the lower Paleozoic in the late oil window for areas in and adjacent to the site. Furthermore, it is possible that the Mississippian section is present to the north and within the oil window. So generative potential from the Paleozoic and the Tertiary exists in the broader site area. The 3 CAI material from UE-25p #1 is not included in the French summary information, and may not have been available to him for consideration, although the information has been known within the program for the past two years.

3.11.4.12 Description of Estimated Oil and Gas Resources

The geologic complexity of the Great Basin and limited amount of exploration in the region combines to impair the statistical validity of a risk-based assessment of hydrocarbon prospects. A technique to circumvent this situation is to evaluate the potential of a generation site so that the amount of petroleum in a system model can be assigned an order of magnitude. A method adapted from Mackenzie and Quigley (1988) is used here.

The generation site to be assessed is largely speculative, but is the petroleum system with the greatest likelihood of supplying hydrocarbons to traps in and near Yucca Mountain. The criteria of proximity in time and space of the generation site to traps is best satisfied by the model that involves burial and generation of the rocks of Joshua Hollow in the Crater Flat basin during

Miocene to Holocene time. Other models, such as the thrust-fold model alluded to by Chamberlain, R. (1991) may be valid and might demonstrate potential for greater generated volumes. But the remoteness of the generation sites of these models to the present array of potential traps severely discounts the prospective quality of these models. Table 5 in French (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press) presents the estimation of parameters and calculations used to determine the hydrocarbon potential in the Yucca Mountain area. The calculation is presented in stepwise fashion and discussion of the parameter estimations is presented for each step.

Using upper limit parameters it is difficult to assign significance to the petroleum potential of the Yucca Mountain area. The volume of 740,000 barrels is an unrisked resource. Many companies attach risk factors to exploration to reflect the statistical probability of success. The risk factor can have a wide range, but 10 to 20 percent chance of success is commonly used. This would establish an exploration target of 7,400 to 14,800 barrels. Although the values of the various resource-calculation parameters could be modified substantially and remain within the realm of possibility, exceptional circumstances, like an active hydrothermal system, seem to be required to make a viable exploration target at Yucca Mountain. The same technique was used to calculate a hydrocarbon resource, corresponding to Line 8, of 785 million barrels for Railroad Valley (French 1989).

Finally, the association of the basin setting with commercial accumulations in the region is obvious, but the significance is not clear. The lack of seeps or shows in the mountain blocks adjacent to basins with generation sites indicates that migration into the range fault blocks has not occurred. This may be the consequence of inadequate exploration or there may be undefined conditions that have imbued basin-bounded faults with sealing characteristics. Given the results of wildcats that have been drilled in mountain range blocks, the latter circumstance seem more likely. If this is the case, the hydrocarbon potential of the Yucca Mountain area is further diminished, and the probability of finding an accumulation is highly unlikely.

3.11.4.13 Tar Sands

3.11.4.13.1 Tar Sands Description and Models

Heavy crude oil and tar sands (bitumen) are petroleum-like liquids or semi-solids which occur naturally in porous media (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). Natural tar has a viscosity > 10,000 mPa s (equal to a centipoise). Water has a viscosity of 1 mPa s at room temperature. Tar sand deposits are defined as having hydrocarbons with an in situ viscosity of more than 10,000 mPa s at reservoir conditions. Because viscosity data are not often available, heavy oils having an API gravity (density) of 10° or less are commonly considered tars (Kuuskraa and Paque 1984). Heavy oil is petroleum crude oil that is characterized by high viscosity; it is often difficult to recover.

Tars have a density greater than 1,000 kg/m^3 (Khayan 1982). Tar is a naturally occurring petroleum product in tar sands, which are essentially sandy sedimentary rock containing tar or extra-heavy oil in large quantities (Tissot and Welte 1984). Such bitumens can occur in other porous rocks as well. They are, in most cases, the result of petroleum degradation in reservoirs. These hydrocarbon products are, thus, residual materials which occur in porous rocks where petroleum has entered by migration, accumulated, and subsequently become degraded. This latter phenomenon is commonly associated with the invasion of the reservoir by meteoric waters, and may include biodegradation, water washing, loss of volatiles, and oxidation. Very few tar sand occurrences (probably less than 1 percent of world reserves) are believed to be accumulations of immature, non-degraded heavy oils (Tissot and Welte 1984).

In some cases a small amount of heavy oil can be produced from tar sands, but most tar sands can only be produced by mining the reservoir rock or by using sophisticated subsurface methods of enhanced hydrocarbon recovery, such as steam-assisted gravity drainage (Tissot and Welte 1984).

Bitumen (tar-sand) and heavy-oil deposits represent a significant energy resource in the United States. The total United States tar-sand resource has been estimated at about 57 billion barrels (Crysdale et al. 1992). United States heavy oil deposits are probably 80 to 100 billion barrels; about half in California (Crysdale et al. 1992). Few tar sands in the United States are currently being exploited, except for road-surfacing material. Unless economic conditions change, the future economic viability of such deposits is not promising. Tar sands are currently economical when mineable at the surface; deposits at depths of one or more kilometers are unlikely to be exploited in the foreseeable future.

3.11.4.13.2 Tar Sands in the Southern Great Basin

There are no known tar sands in the Southern Great Basin of Nevada (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). A variety of minor oil seeps and solid bitumen occurrences are known from Northern Nevada; data on these are summarized in Garside, Hess et al. (1988). The solid bitumen at these localities occurs as veins, generally less than a centimeter to a few tens of centimeters wide, in rocks ranging in age from Ordovician to Tertiary. The solid bitumen is believed to represent degraded, originally liquid, hydrocarbons that were either left behind along migration paths or are the product of arrested oil generation in or near organic-rich submature to mature source rocks.

3.11.4.13.3 Tar Sands in Southern Nevada

Barker, C.E. (1994) reported that small, generally microscopic, blebs of pyrobitumen were noted in thin sections of the Eleana Formation from drillholes in the Yucca Flat area and from the Oak Springs area north of Yucca Flat (approximately 50 km east of Yucca Mountain) (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). However, the Eleana Formation crops out in the Calico Hills east of Yucca Mountain and on Bare Mountain to the west of Yucca Mountain (Cornwall 1972), making it likely that it occurs deep in the subsurface below Yucca Mountain as well. Additionally, bitumen occurs in certain veins at the Bullfrog Mine. There are no other known solid bitumen localities from Southern Nevada (Garside, Hess et al. 1988); this lack may reflect the fact that petroleum source rocks are less common in this part of the state (Garside, Hess et al. 1988; Grow, Barker, Harris 1994), and thus there has been less opportunity for residual accumulations related to migration or generation. It is significant that the bitumen occurrences described above are never known to be present in rocks in more than very minor amounts (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

3.11.4.14 Oil Shale

3.11.4.14.1 Oil Shale Description and Models

Oil shale is commonly defined as an organic-rich shale that can yield substantial quantities of oil when subjected to destructive distillation (retorting or pyrolysis) at low confining pressure in a closed retort system (Yen 1976). The actual lithology of rocks referred to as oil shales is highly variable; some are true shales while others are marls or carbonate rocks (Tissot and Welte 1984). The only excluded lithology is sandstone, as rocks of this lithology are not normally deposited under conditions favorable for the accumulation and preservation of organic material (Tissot and Welte 1984). The organic material in oil shales is mainly kerogen, an insoluble solid material. Oil shales have also been defined as sedimentary rocks having an ash content of more than 33 percent and containing organic matter that cannot be extracted with ordinary solvents for petroleum but yield oil upon distillation (Thrush 1968). There is thus no oil and little extractable bitumen in oil shale, in contrast to tar sands. The kerogen in oil shales is not distinguished from that of petroleum source rocks; to some extent the pyrolysis which produces shale oil by destructive distillation of the rock is comparable to the burial heating of petroleum source rocks and subsequent generation of petroleum (Tissot and Welte 1984).

To be economic, oil shales must be considerably richer in kerogen than most petroleum source rocks (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). Shales may be considered potential source rocks for petroleum if they have 0.5 percent or more total organic carbon. However, oil shales must have at least 5 percent organic carbon to be suitable for economic retorting (Tissot and Welte 1984). Highly organic shales that have not been deeply buried (immature shales) are thus the most promising oil shales. Therefore, the equivalent of an oil shale, sufficiently buried, constitutes a petroleum source rock. However, the reverse (i.e., that the equivalent of a petroleum source rock, shallowly buried, constitutes an oil shale) is not necessarily true, due to the requirement of richness for economic retorting (Tissot and Welte 1984).

The kerogen in oil shales may be almost entirely algal remains or an admixture of amorphous organic matter and identifiable organic remains (Tissot and Welte 1984). The environment of deposition of oil shales is also variable, ranging from large lakes (like those of the Green River Formation of the Western United States) to shallow seas (for example, widespread black shales of several ages in Europe), deep marine basins (for example, the Vinini Formation of Nevada), and small lakes, bogs, and lagoons (where deposits may be associated with coal).

3.11.4.14.2 Oil Shale in the Southern Great Basin

Although oil shales were exploited in Nevada and elsewhere in the early 20th Century (Garside 1983), the availability of liquid hydrocarbons from drilled wells soon made such oil-shale plants uneconomic (Castor, Garside et al. 1997). Shortages of oil in the 1980s led to a reconsideration of the economic viability of oil from oil shales. However, there is little interest in oil shales as sources of oil in most of the world today. The future supply and demand for oil and natural gas are both likely to increase for some time, but there are considerable uncertainties with regard to the absolute amount of demand and alternate sources of energy. It does not appear possible to forecast the future development of oil shale, as major exploitation appears to be too far in the future. There is no evidence that any new developments will take place in oil shale exploitation in this decade.

Reports of oil shales in Nevada are limited to the northern half of the state (Garside 1983). Oil shales of Eocene age in the vicinity of Elko, Nevada were exploited for their oil in the early 20th Century; no other attempts to extract shale oil from deposits in Nevada are known. Northern Nevada oil shale localities are known from Early Cretaceous to earliest Oligocene lacustrine rocks (Elko, Sheep Pass, Newark Canyon Formations) as well as from Paleozoic marine dark shales (including the Ordovician eugeosynclinal Vinini and Woodruff Formations, and trough and platform deposits such as the Chainman Shale and Phosphoria Formation) (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

3.11.4.14.3 Oil Shales in Southern Nevada

Only Mississippian rocks have a depositional environment compatible with oil shales (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). These rocks have been described in surface outcrop and drillhole in the Yucca Mountain area by a number of workers (Mattson 1994, and references therein; Trexler, J.H. et al. 1996). The Chainman Shale is interpreted to have been deposited in a basin with restricted circulation which was probably anoxic at times. Rare shale samples having a total organic carbon of up to 5 percent are reported from the Chainman of the area; more typical samples are reported to have 1 to 2 percent total organic carbon (Trexler, J.H. et al. 1996). A generally contemporaneous unit, the Eleana Formation, was apparently deposited in a foredeep trough which was located further from the edge of the middle Paleozoic landmass than the Chainman of the marginal shelf basin (Trexler, J.H. et al. 1996). Most of the Eleana is probably less organic rich than the Chainman if Trexler, J.H. et al. (1996) are correct that the higher total organic carbon samples of Eleana reported by Barker, C.E. (1994) represent Chainman Shale. Although 5 percent total organic carbon approaches the values needed for a rock to be considered oil shale, these rocks have been heated such that as much as 80 percent of their original hydrocarbon content may have been lost (Trexler, J.H. et al. 1996).

3.11.4.14.4 Oil Shale at Yucca Mountain

Mississippian rocks may or may not be present at depth at Yucca Mountain (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). It is not certain if rocks of the Chainman Shale are present at depth under Yucca Mountain; the Eleana Formation may occur at depth, as it is known from both Bare Mountain to the west and the Calico Hills to the east (Trexler, J.H. et al. 1996). As discussed above, there is no evidence that either of these units contain appreciable amounts of oil shale. Even if oil shales are present, 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 below Yucca Mountain is 1,200 m (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review), which is uneconomical for extraction.

3.11.4.15 Coal

3.11.4.15.1 Coal Descriptions and Model

Coal is generally defined as a combustible sedimentary rock formed from plant remains in various stages of preservation by processes which involved the compaction of the material by burial (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). Commonly, for a rock to be considered coal, it must contain carbonaceous material formed from compaction and induration of plant remains in an amount greater than 50 percent by weight and 70 percent by volume.

3.11.4.15.2 Coal in the Southern Great Basin

There are no commercial deposits of coal in Nevada, and there has been no significant mining of coal in the last 75 years (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). However, because coal was valuable for mining and milling, and for steam railroad locomotives, it was actively sought in the state from the earliest mining activity to about the 1920s. Apparently, a reward was offered by the Central Pacific Railroad for the discovery of good quality coal near the railroad; this offer is probably one reason for the coal exploration effort in the middle and late 19th century. A number of coal beds were found during this period (Horton 1964; Garside, Papke et al. 1980), although most were thin or of poor quality, and many were steeply dipping (requiring underground mining). Coal was produced during this period because of necessity; however, the ability of railroads to deliver coal from areas such as Utah and Colorado made Nevada coal uneconomic. Early reports of many Nevada coal deposits were often quite glowing and generally overstated the quality, quantity, and production; this is similar to other promotional descriptions of mining properties of that era. Because of the active search for coal during Nevada's early days, there is a moderately extensive literature on Nevada coal during this period (Garside, Papke, Schilling 1980). It seems likely that most significant outcrops of coal of any quality were found and reported during that time (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

The presence of coal in Nevada is confined to certain Tertiary lacustrine units, mainly in the northern part of the state, and Mississippian clastic rocks in Eastern Nevada (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). The Chainman Shale and related rocks of Eastern Nevada and Western Utah has coal reported from several localities; most of these were discovered during the early mining development of the state. The coal at these localities is commonly thin (30 to 60 cm) and the rocks which surround it are, in many cases, folded or highly faulted. Significant coal resources are known from Cretaceous and early Tertiary rocks of the Rocky Mountain region east of Nevada. Such coal deposits are not known from Western Utah or Nevada; much of Nevada was probably undergoing erosion during this period. Cretaceous and early Tertiary rocks of Southern Nevada are primarily subaerial fluvial deposits (Stewart 1980); no coals are known from them. Tertiary coals in Nevada are commonly of low rank and high ash content (Garside, Papke et al. 1980); they are apparently Miocene or early Pliocene in age (Fouch 1979), and were deposited in lakes of relatively limited extent. There are no known outcrops of Neogene coal in Southern Nevada, although there may be coaly beds in some rock units of the area (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

3.11.4.15.3 Coal in Southern Nevada

There are no reports of coal from Southern Nevada in the vicinity of Yucca Mountain (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). Because coal was actively sought during early mining and mineral exploration, it seems unlikely that any coal beds of significance were missed; during this period prospectors had access to areas now excluded from mining and prospecting (the Nevada Test Site and the Nellis Air Force Range).

Based on present understanding of the environment of deposition of rock units known from the general vicinity of Yucca Mountain, the only pre-Tertiary unit that might have any coaly material in it is the Chainman Shale. Recent research suggests that Chainman Shale is present in the Calico Hills area east of Yucca Mountain (Cashman and Trexler 1994), where it is considered equivalent to unit J of the Mississippian Eleana Formation. The Chainman is dark gray to black, monotonous mudstone; Cashman and Trexler (1994) interpret it to have been deposited on a muddy continental margin. There are no features of the Chainman in the area of the Nevada Test Site that would suggest swamp conditions necessary for the deposition and formation of coal, and no coal is known from the unit in the vicinity (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

The area closest to Yucca Mountain where coal has been reported is about 10 km west southwest of the community of Crystal Springs in west central Lincoln County (Poole and Claypool 1984, pp. 195, 217). This locality is about 110 km northeast of Yucca Mountain. It is likely that similar coal occurrences were investigated during very early work in the Pahranagat Mining district, possibly in the vicinity of Mount Irish about 16 km to the north of the locality near Crystal Springs (see references in Garside, Papke et al. 1980). The name Coal Valley (located north of Mount Irish) is probably named for these coal prospects, although their exact location is unknown today, and they have not been further described or reported on for the past 130 years (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

The Eleana Formation has an age range similar to the Chainman, but is interpreted as a submarine fan deposit (Cashman and Trexler 1994); coals are not deposited in such deep marine environments.

The closest coal-mining area to Yucca Mountain is the Coaldale area of Western Esmeralda County, about 175 km northwest of Yucca Mountain (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). Coal beds there are 1 to 3 m thick, but contain many partings, and quality is reported to vary horizontally (Hance 1913). Faults and folds make following the coal beds underground difficult. Although there are a moderate number of workings in the area, it appears that little coal was produced. One railcar load was shipped to the Tonopah-Goldfield area for free distribution during the winter of 1911 to 1912, but the high ash content reportedly made it a poor domestic fuel (Hance 1913).

The only mention of coal in Tertiary rocks of Southern Nevada is that in Barker, C.E. (1994), who describes coaly material from Tertiary sedimentary rocks encountered in drillholes of Area 8 on the Nevada Test Site (about 60 km northeast of Yucca Mountain). The humic coals and carbonaceous mudstones, which were encountered at 300 to 600 m in the drillholes, have not been buried deeply, as indicated by the low level of compaction and overall low rank (Barker, C.E. 1994). The maximum total organic carbon reported is 26 percent; several samples have from less than 1 percent to a few percent total organic carbon. The low total organic carbon values (for coals) suggests that they are low-grade lignites, similar to other rather poor quality Nevada Tertiary coals (Garside, Papke et al. 1980).

3.11.4.15.4 Coal at Yucca Mountain

No coal or coal-bearing Tertiary sedimentary rocks have been encountered in drillholes on and adjacent to Yucca Mountain (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). In the Yucca Mountain area, rocks younger than about 15 Ma are almost entirely volcanic in character, consisting of Miocene ashflow tuffs, flows, and associated bedded pyroclastic rocks. No significant lacustrine units are known from them (Mattson 1994). Stratigraphic descriptions of Miocene lacustrine and fluviatile rocks older than these volcanic units, which are known from the general vicinity of

Yucca Mountain (including the Horse Spring Formation and rocks of Pavits Spring), are not reported to contain coal (Mattson 1994). As the Tertiary stratigraphic sequence is quite well known in this area (Subsections 3.2 and 3.5), it is unlikely that coals of any significance are present under Yucca Mountain, certainly in the Tertiary rocks.

Based on knowledge of other Chainman coals (Garside, Papke et al. 1980), any similar beds that might be in the subsurface under Yucca Mountain would almost certainly be thin, possibly steeply dipping or folded and faulted, and of poor quality. Additionally, the Chainman Shale, if present, must be at least as deep as the base of the Tertiary under Yucca Mountain at a depth of 1,200 m or more (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

3.11.4.16 Conclusions - Hydrocarbon Potential of the Yucca Mountain Area

- The basic elements of a viable petroleum system: generation site, reservoir rocks, trap geometry, and seals are present in the Yucca Mountain area, therefore, the petroleum potential is greater than zero (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press).

- Several petroleum system models are possible in the area, but the Railroad Valley model demonstrates the greatest likelihood of supplying traps in the Yucca Mountain area with hydrocarbons (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). Alternative models will be evaluated in the future to assess risk discounted volumes of potential.

- Several parameters of the Railroad Valley model are less that optimal. In particular, the area of the generation site and volume of source rock incorporated in it are limited compared to the productive basins in the region. Also, 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 (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press). The regional unconformity seal is absent in the area of Yucca Mountain proper, but penetrations of the section in Crater Flat are insufficient to conclude that seals of comparable quality do not exist in the area.

- The model indicates that there may be enough potential in the area to attract occasional exploration in the foreseeable future. Because of the limited potential of the hypothetical generation site in the Crater Flat Basin, exploration would most likely be focused on targets in close proximity to it (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press).

- Under the structural interpretation presented in this subsection, the most attractive exploration target for hydrocarbons in Paleozoic strata in the Yucca Mountain area has been at least partly evaluated by the UE-25 p#1 borehole. Potential traps that involve Tertiary rocks have been partly evaluated by various boreholes drilled to investigate the repository site (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press).

- Should exploration for oil and gas intrude the repository site it would most likely be an outgrowth of activity triggered by a discovery in the vicinity of Crater Flat or possibly the basin of the Amargosa Desert. The exploration targets would probably be Neogene-age fault-blocks traps containing oil or gas generated from early Miocene-age source rocks (D.E. French, *Assessment of Hydrocarbon Resources of the Yucca Mountain Vicinity, Nye County, Nevada*, in press).

Based on the information presented in detail in this subsection and summarized above, there is little likelihood that future generations would be attracted to the Yucca Mountain site as a favorable target for hydrocarbon exploration. There is a somewhat greater likelihood that there is enough potential to attract exploration in Crater Flat or other basin locations in the site vicinity. To date, however, no indications of hydrocarbon resources have been observed in site boreholes, including UE-25 p-#1 drilled into the Paleozoic section or in water wells drilled in Crater Flat.

3.11.4.17 Favorability for Tar Sands at Yucca Mountain

Because accumulations of tar sand and heavy oil are closely related to the migration and accumulation of petroleum, estimates of hypothetical or speculative occurrence must consider the potential for petroleum accumulation (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). The evaluation in this subsection is based on the present knowledge of similar accumulations, potential stratigraphic units that are likely to host such accumulations, the probable depths of such rocks, and thus, the economic viability of deposits which might be in them (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

It is extremely unlikely that tar sands are concealed at depth below Yucca Mountain but not exposed in rocks of the surrounding area (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). There is no evidence for the accumulation of such deposits in the region, and the area of Yucca Mountain is considered to have low potential for the accumulation and preservation of liquid petroleum as well (Grow, Barker, Harris 1994). In the unlikely event that tar sands were present at Yucca Mountain, they would most likely be found in the Paleozoic marine rocks which occur at depths of 1,200 m or more. Conventional recovery methods for tar sands require surface mining and processing of large volumes of rock. Mass mining underground at such depths is certainly not economically feasible now or in the foreseeable future. Techniques may be refined or developed in the future to produce some liquid hydrocarbons from certain subsurface tar-sand deposits, but they will not find economic application until very large surface deposits have been exploited and such exploitation has barely begun.

3.11.4.18 Favorability for Oil Shale at Yucca Mountain

There is no evidence that either of the Mississippian units (Eleana or Chainman) contain appreciable amounts of oil shale (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). Even if oil shales are present, 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 below Yucca Mountain is 1,200 m. Such speculative deposits would have to be mined by underground methods at those depths and that is unlikely until other more cost-effective energy sources (including rich surface oil shales in the United States) are near exhaustion in the distant future. Economic conditions in the U.S. have not yet warranted exploitation of rich oil shales such as those exposed at the surface in the Green River Formation of Wyoming. Thus, oil shales are unlikely in the Yucca Mountain Conceptual Controlled Area, and if any are present, exploitation is not economically feasible for the foreseeable future (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

3.11.4.19 Favorability for Coal at Yucca Mountain

No coal or coal-bearing Tertiary sedimentary rocks have been encountered in drillholes on and adjacent to Yucca Mountain (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). As the Tertiary stratigraphic sequence is quite well known in this area, it is unlikely that coals of any significance are present under Yucca Mountain, certainly in the Tertiary rocks.

There is not enough information to conclude with absolute certainty that no coal beds occur in the Chainman Shale that may be present under Yucca Mountain, although it is quite unlikely (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review). However, based on knowledge of other Chainman coals (Garside, Papke et al. 1980), any similar beds that might be in the subsurface under Yucca Mountain would almost certainly be thin, possibly steeply dipping or folded and faulted, and of poor quality. Additionally, the Chainman Shale, if present, must be at least as deep as the base of the Tertiary under Yucca Mountain at a depth of 1,200 m or more. Such coals are certainly not economic today and are not likely to be economic in the foreseeable future (S.B. Castor et al., *Assessment of Metallic and Mined Energy Resources in the Yucca Mountain Conceptual Controlled Area, Nye County, Nevada*, Deliverable UNR2M or SPT7CM4 to U.S. Department of Energy, in review).

3.11.5 Geothermal Resources

3.11.5.1 Geothermal Resource Definition, Classification, and Historical Development

The word geothermal pertains to the heat of the earth's interior. Geothermal energy is extracted from the earth's internal heat. That internal heat can be generated by several processes (including subsurface magma chambers and crustal thinning) that will be described later. Geothermal reservoirs are classified based on temperature, geochemistry, depth, volume, and permeability described below. In order to have a geothermal resource, there must be a continual source of heat and of fluid, 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 ultimate user. These points will be discussed in more detail in this subsection.

3.11.5.1.1 Temperature

Temperatures naturally increase with depth due to the heat from the earth's interior. This general increase in temperature with depth is called the geothermal gradient. This gradient differs from place to place depending on the heat flow in the region and the thermal conductivity of the rocks. The average geothermal gradient is approximately 25°C/km of depth.

One of the most widely used classification systems of geothermal reservoirs (Muffler 1979) divides thermal reservoirs into three regimes based on temperature and potential use. The three types are: low-temperature systems, less than 90°C, potentially available for use in space heating and agriculture; intermediate-temperature systems, 90 to 150°C, to provide heat for use in various industrial processes; and high-temperature systems, greater than 150°C, to provide steam used to generate electrical power.

3.11.5.1.2 Geochemistry

The principal geochemistry issues related to geothermal resource are dissolved constituents and stable isotopes.

3.11.5.1.2.1 Dissolved Constituents

Thermal fluids are typically classified on the basis of the major dissolved chemical constituents. Heated waters containing dissolved solids could corrode equipment, thus making the heated water uneconomical to use. The thermal fluid should not contain a high proportion of corrosive dissolved solids (White, Muffler et al. 1971; Trexler, D.T., Flynn, Kolnig et al. 1979). CRWMS M&O (1996a) describes the dissolved constituents found in geothermal waters. Silica is the only dissolved constituent mentioned here because it can be used to estimate the temperatures of deep geothermal reservoirs (Fournier 1981) as explained later in this subsection. Silica concentrations vary with temperature, pH, and availability of amorphous silica (Fournier and Rowe 1966).

3.11.5.1.2.2 Stable Isotopes

The stable isotopes of hydrogen and oxygen are effective natural tracers of thermal and hydrologic conditions (Craig, H. 1961, 1963). On the basis of the isotopic composition of hydrogen, H. Craig (1963) concluded that most geothermal fluids throughout the world were largely of meteoric origin Reaction of meteoric waters with hot silicate or carbonate rocks left the resulting thermal waters with their original isotopic composition of hydrogen because such rocks contain very little hydrogen relative to the amount in water. In contrast, the isotopic composition of oxygen was shifted to heavier values relative to values of local meteoric water. The shift occurs because most rocks contain relatively heavy oxygen, there is more oxygen in a given volume of rock than in the water in its pore space, and the isotopic fractionation between silicate minerals and water decreases with increasing temperature (e.g., Friedman and O'Neil 1977, Figure 16).

3.11.5.1.3 Depth, Volume, and Permeability

There are several factors other than temperature and geochemistry that determine the potential for a geothermal resource or the value of a reserve. These factors include depth, volume, and permeability. The depth of thermal water should be shallow enough to allow for economic recovery of the heat. The volume of available fluid should be large enough to provide a steady source of heat. The rock should have adequate permeability to sustain its water flow.

3.11.5.2 Methodology of Study

An assessment of the geothermal resources within a 50-mile radius of the Yucca Mountain Site was conducted by Flynn et al. (CRWMS M&O 1996a) to determine the potential for commercial development of geothermal resources within the study area. Subsection 3.11.5 relies heavily on Flynn's report. Flynn's assessment was based on a study plan prepared by the USGS in which the boundaries of the investigation were determined. The study was conducted in three stages. The first stage was a review of previous work on geothermal resources, including a literature search of available data on geology, hydrology, geophysics, and drilling. The studies were reviewed and compiled into a comprehensive bibliography. Regional and local geology, geochemistry, geophysics, and drillhole information were further compiled, evaluated, synthesized, and interpreted as part of the study in press.

The second stage included the collection of data sets. Geochemical data on springs and wells have been routinely collected throughout the study area for more than 50 years. The quantity of existing data (approximately 1,100 chemical analyses) was sufficient for the assessment by Flynn et al. (CRWMS M&O 1996a). Available data from the Yucca Mountain area were compared to similar data from developed and undeveloped geothermal areas in other parts of the Great Basin to assess the resource potential for geothermal development at Yucca Mountain.

Data were collected and digitized for use in a Geographic Information System (CRWMS M&O 1996a). A series of maps were produced depicting geology, geochemistry, volcanic centers, thermal springs, temperature gradient, heat flow, aeromagnetics, and Bouguer gravity. An extensive geochemical database of the springs and wells in the study area was also compiled and digitized. These data were displayed at a common scale and were overlain in various combinations to identify coincident anomalies such as the co-location of many thermal springs in Northern Nevada with well-defined fault zones (CRWMS M&O 1996a).

In the third stage, attributes of developed geothermal areas were compared with features of the Yucca Mountain area. The temperature, flow rate, and logistical requirements for successfully developed geothermal areas were numerically ranked and compared with attributes of the Yucca Mountain area (CRWMS M&O 1996a).

3.11.5.2.1 Assumptions

The geothermal resource assessment was based on methods established by the USGS (Godwin et al. 1971) and adopted by the geothermal industry. The industry is regulated by the U.S. Bureau of Land Management and various State agencies. The following geologic indicators were considered: late Tertiary or Quaternary volcanism; geysers, fumaroles, mud volcanoes, and thermal springs; and twice the normal subsurface temperature gradients in deep wells. Additional specific geologic indicators used included: siliceous sinter; elevated silica content of spring water; the Na/K ratio in spring water; abnormally high heat flow; porosity and permeability of reservoir rocks; and electrical, magnetic, gravity, airborne infrared, and other geophysical surveys. Nearby discoveries and commercial developments, as well as competitive interests, were also considered in the evaluation of land deemed valuable for geothermal energy development (CRWMS M&O 1996a).

The basic assumption used in this assessment was that geothermal resources throughout the Great Basin, including the Yucca Mountain study area, are defined on the basis of geophysical and geochemical attributes, including temperature, depth, and flow rate, which can be measured and compared. It was also assumed that geothermal resources within the study area occur within the same geologic environments as those in other parts of the Great Basin. It was further assumed that geothermal development is based on established engineering and economic principals and that the present conditions provide a valid projection for the foreseeable future (CRWMS M&O 1996a).

3.11.5.2.2 Methods of Analysis and Associated Uncertainties

Several methods were used to assess the potential for geothermal resources within the study area. These include chemical geothermometers, SiO_2 versus enthalpy diagrams geophysics, and various forms of remote sensing.

3.11.5.2.2.1 Chemical Geothermometers

A geothermometer is a feature (a mineral, chemical, etc.) of the rocks that forms within known thermal limits under particular conditions of pressure and composition and whose presence thus denotes a limit or a range for the temperature of the fluid surrounding the rock.

Geothermometer calculations must meet several prerequisites to reliably estimate subsurface temperatures (CRWMS M&O 1996a). The most important require that:

- Temperature-dependent reactions exist between water and rock in the reservoir.
- There is a sufficient abundance of reacting constituents.

- Chemical equilibration occurs in the reservoir.
- No change in water composition occurs at lower temperatures as waters flow toward the surface.
- No mixing occurs between reservoir waters and other waters at shallower depths (Fournier et al. 1974).

More reliable data are obtained using the chemical composition of the hottest fluid discharging in a spring group, because it is less likely to have been affected by dilution than the cooler springs. Because existing data were used in Flynn's assessment and because most waters represented by the Yucca Mountain data are relatively cool, the last two conditions above probably were not met in most cases (CRWMS M&O 1996a).

Various geothermometers are more reliable in certain temperature ranges. Most geothermometers are applicable to geothermal waters where equilibrated reservoir temperatures are $\geq$ 180°C (CRWMS M&O 1996a). Flynn (CRWMS M&O 1996a) summarized an evaluation of the various geothermometers including the Na/K geothermometer, the Na-K-Ca geothermometer, the chalcedony geothermometer, the Na-Li geothermometer, the K-Mg geothermometer, and the K-Na geothermometer.

Evaluation of the waters in the Southern Great Basin was conducted by consulting the chalcedony geothermometer temperatures (CRWMS M&O 1996a). Chalcedony geothermometer temperatures were used to categorize the waters as:

- Non-thermal waters ($T < 25$°C)
- Low-temperature waters ($25 \leq T < 90$°C)
- Intermediate-temperature waters ($90 \leq T < 150$°C)
- High-temperature waters ($T \geq 150$°C)

When no chalcedony geothermometer temperature could be calculated for a site, the Na-K-Ca geothermometer was consulted (CRWMS M&O 1996a).

3.11.5.2.2.2 SiO_2 versus Enthalpy Diagrams

Silica versus enthalpy diagrams were used to determine the pre-mixing or pre-boiling temperatures of thermal waters. In order to select springs for which the silica-enthalpy mixing model may be appropriate, the measured water temperatures should be at least 50°C less than the calculated silica and Na-K-Ca geothermometers and the silica (quartz or chalcedony) geothermometer temperature should be significantly less than the Na-K-Ca temperature, and only a small amount of conductive cooling can occur during upflow (Fournier 1991). It can not be determined if the last criteria is met at any of the sites, but the first two criteria can be readily evaluated. None of the potentially high-temperature waters satisfied the criteria, yet five low-temperature waters and four intermediate-temperature waters satisfied the first two criteria. None of these sites occur within the Yucca Mountain Conceptual Controlled Area.

3.11.5.2.2.3 Geophysics

Geophysics is part of a geothermal exploration package. Gravity, magnetic, and heat flow studies are important geophysical surveys for geothermal assessments (CRWMS M&O 1996a) because they are non-invasive methods for characterizing large areas. Seismic information can provide information about subsurface stratigraphy and geologic structure and the location of active tectonic processes. However, for the Great Basin, there is little data available that indicates either a positive or negative correlation between seismicity and geothermal activity even though the region is seismically active. Therefore, this correlation is not a typical component of a geothermal exploration package.

Gravity survey data are frequently used in geothermal exploration programs for defining large scale structures and fault offsets if there is sufficient density contrast between the geologic units. Important gravity information was obtained from Ponce and Oliver (1995), Healey and Miller (1979), Snyder and Carr (1982), and Saltus (1988). The Basin and Range west of longitude 109° W is dominated by an extensive gravity low (Eaton et al. 1978). This large area (1,000 by 1,300 km) coincides with a region of pronounced and broadly distributed crustal extension, high heat flow, repeated Cenozoic igneous activity, abundant hot springs, peripheral seismicity and Quaternary volcanism (Eaton et al. 1978). Magnetic surveys also may be used to indicate geothermal resource assessments in some cases. For example, in Northern Nevada, Mabey et al. (1978) identified a prominent, narrow, northwest-trending magnetic high known as the Cortez rift. This rift is 10 km west of the Beowawe geothermal which supports a 16 MWe dual flash geothermal power plant, and which is on the northeast-trending Malpais fault. Aeromagnetic data from Beowawe are influenced by the north-northwest trend of the Cortez rift. This rift is believed to be the result of a zone of diabase dike intrusions, 5 km wide, that penetrate the entire thickness of the crust. If this is the case, the proximity of this deeply penetrating structure to the Beowawe geothermal system indicates magnetic surveys can provide information about geothermal sites (CRWMS M&O 1996a).

Heat flow is defined as the product of the temperature gradient and thermal conductivity. Heat flow is reported in units of milliWatts per square meter. Sass et al. (1971) conducted a systematic analysis of temperature gradients and heat flow in Northern Nevada and divided the region into three heat flow provinces: a region of average heat flow (approximately 85 mWm^{-2}); a region of elevated heat flow, the Battle Mountain Heat Flow High; and, a region of below average heat flow designated the Eureka Heat Flow Low. Recent work shows that Yucca Mountain is part of the Eureka Low (Sass, Dudley, Lachenbruch et al. 1995, p. 159).

3.11.5.3 Historical Developments

The Geothermal Steam Act of 1970 established the framework for exploration and development of steam and hot water found on public lands by designating known geothermal resource areas.

The Geothermal Steam Act defines a known geothermal resource area as an area in which the geology, nearby discoveries, competitive interests, or other indications would, in the opinion of the Secretary of the Interior, engender a belief in men who are experienced in the subject matter that the prospects for extraction of geothermal steam or associated geothermal resources from an area are good enough to warrant expenditures of money for that purpose (Godwin et al. 1971).

The known geothermal resource areas, located largely on public land, were classified by the U.S. Department of the Interior on the basis of high-temperature-gradients, hot springs, fumaroles, and other geothermal surface indicators. No sites were identified in the vicinity of Yucca Mountain. Several sites were subsequently offered for lease according to the provisions of the Geothermal Steam Act, and many of these areas today support operating geothermal power plants and other applications.

In the late 1970s to early 1980s, a significant effort was focused on the development of high-temperature geothermal resources in Utah and Nevada. This project was known as the Industry Coupled Drilling Program and was jointly administered by the DOE and the geothermal industry. Large-scale drilling programs were completed at 10 sites in Nevada and two in Utah. Both of the Utah sites and 5 of the 10 Nevada sites presently support geothermal power plants. None of the sites selected were near Yucca Mountain (CRWMS M&O 1996a).

3.11.5.4 Conceptual Model of Geothermal Systems

Geothermal systems can be categorized by two models depending on the ultimate source of the geothermal water (CRWMS M&O 1996a). In the first model, thermal waters can be generated from the areas of deep-seated, regional, high heat flow that form a conductive system, which may drive hydrothermal convection (Renner et al. 1975). According to the second model, thermal waters can be related to igneous hydrothermal systems, where cooling, high-level, silicic or mafic magma bodies provide energy for hydrothermal convection (Smith, R.L. and Shaw 1975, 1978). For high-temperature geothermal systems, these two models probably overlap to some extent because a high, regional geothermal gradient alone could not sustain the temperatures found in most high-temperature regional geothermal systems for extended periods of time (Renner et al. 1975). Low-temperature systems may occur as a result of either model, but typically are associated with conduction-dominated systems considered to consist of either hot, dry rock or basin, aquifer systems.

The origin of geothermal fluids has been debated for more than a century (CRWMS M&O 1996a). Conceptual models describing fluid recharge to Great Basin geothermal systems include components of deep fault zones that penetrate regions with elevated thermal gradients (40 to 60 C/km) and provide permeable zones for the downward percolation of meteoric water and the upward migration of thermal fluids (Hose and Taylor 1974; Muffler 1979). Later refinements to these general concepts suggested that fluid recharge was associated with alluvial fans that are saturated with meteoric water and overlie range-bounding faults (Wollenberg et al. 1975).

Because geothermal fluids consist principally of meteoric waters, recharge models have inherently relied on stable isotopes as natural tracers (CRWMS M&O 1996a). As a result, two classes of geothermal fluid recharge models have been proposed for the Great Basin: high elevation recharge and paleo-recharge. Many geothermal springs in the Great Basin are not located sufficiently close to elevated recharge areas to depend solely on this mechanism, prompting some to propose that geothermal fluids entered the system during a cooler and wetter climate such as the Pleistocene (Welch et al. 1981; Mariner et al. 1983; Flynn and Buchanan 1990).

3.11.5.5 Geothermal Resources of the Great Basin

Part of the Basin and Range Physiographic Province is considered to be favorable for the occurrence of geothermal systems, because of a generally high heat flow and the extensional tectonic regime that provides the conduits for thermal water flow (Mariner et al. 1983). Normal faults provide near-surface conduits for the circulating waters and thus control the locations of most of the identified hydrothermal convective systems (Mariner et al. 1983).

Geothermal resources are widespread in the Great Basin (Trexler, D.T., Flynn et al. 1983; Reed, M.J. 1983), but are restricted to specific geologic environments that include three essential features: a heat source, circulating fluids, and an open and permeable fracture system that allows fluid flow in a reservoir rock (CRWMS M&O 1996a). Some geothermal systems also include a cap rock that restricts the fluids from flowing to the surface. Geothermal fluid surface temperatures in Northern Nevada range from 20 to 98°C, but subsurface temperatures approach 270°C in some locations.

The distribution of geothermal springs and wells is presented in Figure 3.11-17 (CRWMS M&O 1996a). The majority of high-temperature springs occur in Northern Nevada, along major faults that bound mountain ranges (Garside and Schilling 1979). In fact, Plate 1 of Garside and Schilling (1979) clearly demonstrates the absence of spring temperatures greater than 41°C south of latitude 38° 30' in Nevada.

Temperature gradient data in the study area have been collected for more than 30 years. Lachenbruch et al. (1987) reported that four, shallow-depth holes, located on the Nevada Test Side, in 1957 had temperature gradients ranging from 30 to 40°C/km, with a mean near 35°C/km. Heat flow measured in the saturated zone of five wells at Yucca Mountain yields a similar thermal gradient (Sass, Dudley, Lachenbruch et al. 1995). These authors note (pp. 159 and 167) that groundwater flow within open drillholes are around casing adds variability and uncertainty to heat flow measurements.

Edmiston (1982) showed that the high-temperature, commercially viable geothermal resources were located on the eastern and western margins of the Basin and Range province, as well as in the Battle Mountain heat flow high (Sass, Lachenbruch, Munroe et al. 1971). The interior portions of the province contain widespread low- to intermediate-temperature geothermal resources (Ward, S.H. 1983). Most of the geothermal power plant production wells produce a combination of water and steam, and are developed in the vicinity of known high-temperature geothermal springs. The location of other geothermal developments are intimately associated with Quaternary age silicic volcanism.

On the basis of isotopic data from several different but related sources, geothermal fluids discharging at the surface throughout the Great Basin were recharged during the Pleistocene period, 20 to 30 ka, by a combination of surface flow and leakage from pluvial lakes (Flynn and Buchanan 1990).

3.11.5.5.1 Structure

Many geothermal springs in the Great Basin are associated with, and developed within, fault zones (CRWMS M&O 1996a). These faults systems have resulted from regional extensional tectonics that have formed the Basin and Range Province (see Subsection 3.2.1). Under the extensional regime, the crust is cracked and thinned, providing avenues for the passage of deeply circulating groundwater.

The region around Yucca Mountain has abundant Quaternary faulting (Simmonds et al. 1995 and Figure 3.10-10); however, the water table is so deep at Yucca Mountain that thermal springs associated with faults would not be expected.

3.11.5.5.2 Geothermal Models

Research, exploration, and development programs conducted throughout the Great Basin have culminated in an extensive database that consists of geology, geophysics, geochemistry, and drillhole data (CRWMS M&O 1996a). Analysis of these data has provided several conceptual flow models of geothermal systems that assist in understanding and eventual development of the resource (Reed, M.J. 1983). The model discussed here is by Blackwell (1983). Various conceptual models that have been developed specifically for Basin and Range geothermal systems require that thermal energy is transferred both vertically and horizontally by deeply circulating meteoric waters. The depth of circulation varies from place to place depending on local heat flow. Heat flow in the Basin and Range is extremely complex, resulting from the superposition of more than 600 Ma of recurring tectonic and volcanic activity (Blackwell 1983). Disturbances in observed heat flow can be related to circulation of groundwater with broad anomalies such as those at and near Yucca Mountain, attributed to shallow circulation (Sass, Dudley, Lachenbruch et al. 1995).

Blackwell (1983) synthesized existing data from throughout the Basin and Range. Factoring in irregular spacing and complicated fluid flow patterns, Blackwell concluded that most of the heat flow in the Basin and Range can be accounted for with a simple conceptual model that assumes the presence of a thermal source at a temperature of 1,350°C at a depth between 10 and 20 km. Heat flow was shown to vary with time after emplacement of the heat source (112 mWm^{-2} after 5 Ma and 90 mWm^{-2} after 10 Ma); heat flow varied very little with position, except in the vicinity of range-bounding faults where heat flow variations were extreme (CRWMS M&O 1996a).

3.11.5.6 Geothermal Potential at Yucca Mountain

Geothermal indications for the Yucca Mountain area are summarized in Table 3.11-7. Some of these indications are discussed briefly below.

3.11.5.6.1 Discussion on Lack of a Heat Source

Magma bodies below larger calderas (>10 km diameter) cool slowly and may be heat sources for up to 2 Ma (Wohletz and Heiken 1992). Silicic volcanism located close enough to Yucca Mountain to have provided heat to the local hydrologic regime ended more than 11 Ma.

Calculations based on theoretical cooling models (Smith, R.L. and Shaw 1978) indicate that magma chambers associated with calderas of the central zone of the Southwestern Nevada Volcanic field would have completely crystallized and cooled to ambient temperature several million years ago. Additionally, Sass, Dudley, Lachenbruch et al. (1988) report that the heat flow at Yucca Mountain is controlled in part by fluid flow in the Paleozoic carbonate aquifer at depth; thus, heat flow data do not indicate any perturbations in the vicinity of the Southwestern Nevada Volcanic field that could be correlated with residual heat from these old magmatic systems.

The basalts of the Crater Flat area southwest of Yucca Mountain are not believed to contribute significant amounts of heat to be sources of heat for geothermal fluids (CRWMS M&O 1996a). The individual basaltic eruptions in the Yucca Mountain area are of small volume, and are apparently the products of mantle-derived magma that rose quickly through the crust with little or no contamination (Vaniman et al. 1982). Such isolated basaltic vents in a continental setting do not have high-level magma chambers and represent short-term events with little value as a heat source (Edwards, L.M. et al. 1982). Therefore, they are not believed to contribute significant amounts of heat to the upper crust. The dikes and pipes that feed such isolated, small volume centers do not provide sufficient long-term crustal heat to drive a geothermal system (Delaney 1987; Wohletz and Heiken 1992). Therefore, the basalts of the Crater Flat area southwest of Yucca Mountain are not likely sources of heat for geothermal fluids.

3.11.5.6.2 Heat Flow at the Nevada Test Site

Heat flow evaluations of the Nevada Test Site and Yucca Mountain have been completed in conjunction with thermal gradient studies (Sass, Lachenbruch, Mase et al. 1980; Sass and Lachenbruch 1982; Lachenbruch et al. 1987; Sass, Dudley, Lachenbruch et al. 1995; Sass, Lachenbruch, Dudley et al. 1988). Sass, Lachenbruch, Munroe et al. (1971) suggested that the thermal low in Southern Nevada results from capture of heat by water flow in the Paleozoic carbonate aquifer.

The thermal regime at Yucca Mountain has been "interpreted as a series of relatively shallow hydrologic perturbances both regional and local, superimposed on a normal (65 to 95 mWm^{-2}) Basin and Range heat flow" (Sass, Dudley, Lachenbruch et al. 1995, p. 159).

3.11.5.6.3 Hydrology and Heat Flow

Fridrich, Dudley et al. (1994) showed the relationship between the hydraulic gradient, gravity data, and heat flow. The contours of the potentiometric surface appear to parallel the gravity contours from the Yucca Mountain Conceptual Controlled Area to the northeast corner of the Nevada Test Site for a distance of about 40 km. Superimposed on their map is the outline of the heat flow low (Sass, Lachenbruch, Dudley, et al. 1988), which roughly overlies the two gradients (Figure 3.11-18). The heat flow low has been interpreted as an area of downward moving groundwater. Fridrich, Dudley et al. (1994) interpret the gravity low as a northeast-trending buried graben. The hydraulic gradient is interpreted as the drop in the potentiometric surface resulting from groundwater infiltration along a permeable basement fault contact into the underlying Paleozoic carbonate aquifer (Fridrich, Dudley et al. 1994). This interpretation, although not unequivocal, is consistent with the explanation for the low heat flow within the

Eureka Low directly beneath the potential repository site (Sass, Lachenbruch, Dudley et al. 1988). The only anomaly that therefore appears in an otherwise flat-lying potentiometric surface is related to groundwater downwelling. Active geothermal systems in the Great Basin are characterized by artesian (upwelling) conditions in the vicinity of faults and fractures, which is not observed in the Nevada Test Site or Yucca Mountain areas (CRWMS M&O 1996a).

"There is a 'bull's eye' of low heat flow (<40 mWm^2) a few kilometers in principle dimensions, centered on the potential repository" (Sass, Dudley, Lachenbruch et al. 1995).

3.11.5.6.4 Temperature Gradient Logs

Sass, Lachenbruch, Dudley et al. (1988) reported on temperature logs from 18 geologic and hydrologic test wells at Yucca Mountain.

These temperature and lithologic logs illustrate the nature of the geothermal resources, including the temperature, depth, and structural and stratigraphic controls (CRWMS M&O 1996a). The geothermal resources are deep (400 to 500 m), low-temperature (<60°C), and appear to be structurally controlled (restricted to fault zones).

3.11.5.6.5 Indirect Observations 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.

3.11.5.6.5.1 Thermal Springs and Spring Deposits

In the region surrounding Yucca Mountain, including the Amargosa Desert and the Nevada Test Site, springs have potential as low-temperature geothermal energy resources (Bell and Larson 1982). The closest warm springs to Yucca Mountain are those at Beatty, 20 km to the west (CRWMS M&O 1996a). Warm springs in the Amargosa Desert to the south are nearly 50 km away, although warm-water wells are recorded 20 km to the south. Owing to the deep water table, there are no warm springs in the immediate vicinity of Yucca Mountain (i.e., in the Yucca Mountain Conceptual Controlled Area).

The presence of sinter in a spring deposit is evidence for a hot-water system with present or past subsurface temperatures of more than 180°C (White, Muffler et al. 1971). Siliceous spring deposits (sinter) from high-temperature fluids of Quaternary age are not reported on geologic maps or in the hydrogeologic literature of the study area within 50 miles of Yucca Mountain (CRWMS M&O 1996a). The lack of such evidence suggests that no thermal fluids from high-temperature reservoirs have discharged to the surface in the study area recently enough to have been preserved.

Travertine deposits are commonly indicators of low-temperature geothermal reservoirs whose temperature is too low for siliceous sinter to be deposited. In Southern Nevada and adjacent California, many flowing springs associated with extensive areas of travertine are interpreted as discharging from a regional carbonate aquifer as the apparent result of interbasin flow (CRWMS

M&O 1996a). In general, springs associated with travertine throughout the world range in temperature from approximately 30 to 100°C (Wohletz and Heiken 1992).

Calcareous spring deposits (spring tufa and travertine) are known from Ash Meadows and Death Valley, south of Yucca Mountain (Winograd and Doty 1980). No sites are reported from the region north of Yucca Mountain; this is an area of recharge and relatively deep groundwater. A few of the smaller areas of calcareous spring deposits in Southern Crater Flat may have been deposited from small-volume springs or seeps that derive their waters from the valley fill aquifer. The springs that deposited the large areas of travertine likely resembled the large-flow springs in Ash Meadows and Death Valley today, and were probably moderately warm (~30° to 40°C). However, smaller flow springs that deposited some small areas of calcareous deposits were not necessarily anomalously warm (>10°C above ambient temperature). The spring deposits south of Yucca Mountain range in age from less than 10 ka to several hundred thousand years, and some sites have deposits of more than one age (Paces, Mahan et al. 1995).

In summary, available information on spring deposits in the vicinity of Yucca Mountain indicates that presently flowing or pre-existing springs at these sites were or are only moderately warm (probably 30 to 40°C). Sites of calcareous spring deposits closest to the Yucca Mountain Conceptual Controlled Area may represent extinct springs that were not anomalously warm (see climate section for paleontologic data relating to temperature). There is no indication from the spring deposit data that the area surrounding the Yucca Mountain site, including the Yucca Mountain Conceptual Controlled Area, has potential for anything but low-temperature geothermal resources (and those only at depth) (CRWMS M&O 1996a).

3.11.5.6.5.2 Indications from Stable Isotope Geochemistry

Where data were available, stable isotope analyses were evaluated at the sites to determine if there was any evidence for enrichment of ^{18}O, which would be evidence for high-temperature water-rock interactions within the reservoir. No high-temperature waters (>150°C based on their calculated chalcedony geothermometer temperatures) had associated stable isotope data. Data for 14 of the Yucca Mountain Conceptual Controlled Area wells have chalcedony temperatures in the low-temperature range. There is a slight displacement from the Nevada Meteoric Water Line (a line on a graph of deuterium versus ^{18}O that can indicate thermal waters) for groundwaters and pore waters at Yucca Mountain (see Subsection 5.3.4.2.4), but these are typical of waters in arid regions that incur some evaporation prior to recharge (Craig 1961; Dansgaard 1964). There was no evidence from stable isotope data of high-temperature isotopic exchange that is indicative of equilibrium temperatures >150°C within the Yucca Mountain Conceptual Controlled Area and the Yucca Mountain site has considerably less potential for a productive intermediate-temperature resource than many other areas within 50 miles of the site (CRWMS M&O 1996a).

3.11.5.6.5.3 Indications from Chemical Geothermometers

Chemical analyses from over 1,100 distinct sampling locations were compiled and evaluated to determine the geothermal potential of Yucca Mountain and the area within 50 miles of Yucca Mountain (CRWMS M&O 1996a). Flynn et al. (CRWMS M&O 1996a) showed the distribution of measured temperatures in springs and wells throughout the study area. It is clear from their diagram that the area is dominated by surface water temperatures <50°C and, in much of the area, temperatures are <25°C. Subsurface temperatures measured in wells do not show significant departure from the surface measurements; all of the elevated temperatures were recorded in deep wells. Because most waters sampled in the Yucca Mountain Conceptual Controlled Area are relatively cool, geothermometers require cautious interpretation. Based on chalcedony geothermometer values, all waters within 50 miles of Yucca Mountain were categorized by their potential to originate from a low-temperature (<90°C), intermediate-temperature (90° $\leq$T <150°C), or high-temperature ($\geq$150°C) resource. Flynn et al. (CRWMS M&O 1996a) showed the distribution of chalcedony geothermometers calculated for springs and wells throughout the study area. The data do not reveal any anomalous areas. Only two sites (U20C and DRI LG105) have data which may indicate a useful high-temperature resource at depth, and neither of these sites is located within the Yucca Mountain Conceptual Controlled Area. None of the locations where chalcedony temperatures are $\geq$90°C occur near Yucca Mountain. Therefore, the potential for the existence or discovery of a high-temperature geothermal resource at or within 50 miles of the Yucca Mountain site is minimal (CRWMS M&O 1996a).

Only one site within the Yucca Mountain Conceptual Controlled Area (USW WT-7) has similar Na-K-Ca and chalcedony geothermometer temperatures suggesting that the geothermometer temperatures are reliable (CRWMS M&O 1996a). The data indicate that the water originates from a very low-temperature resource (chalcedony = 31°C and Na-K-Ca = 35°C). Because other sites in the Yucca Mountain Conceptual Controlled Area belonging to the low-temperature category have chalcedony temperatures <125°C, the temperatures cannot be considered reliable, but are indicative of a relatively low-temperature resource. Hence, the majority of sample sites indicate a low-temperature or nonthermal resource occurs beneath Yucca Mountain and that the potential for this low-temperature resource at Yucca Mountain is no greater than in other parts of the Great Basin. In fact, because the water table is very deep beneath the potential repository site, the potential utility of such a resource is lower at Yucca Mountain than at many other Great Basin sites (CRWMS M&O 1996a).

3.11.5.7 Gravity Data Indications

The lack of active surface thermal features in the Yucca Mountain Conceptual Controlled Area, such as hot springs and fumaroles, makes the discussion of a detailed relationship between gravity and geothermal activity speculative at best (CRWMS M&O 1996a).

3.11.5.8 Economics of Geothermal Resources

The economic exploitation of geothermal resources depends on the co-location of a viable geothermal resource and a prospective market for the product (CRWMS M&O 1996a). Currently, all commercial geothermal electric power generation comes from two types of hydrothermal resources: vapor-dominated (steam) and liquid-dominated (hot water). The well with the highest measured temperature within 50 miles of Yucca Mountain is well UE-20f with a temperature of 121°C at a depth of 3,740 m, which is not much different from the geothermal gradient of the area. The depth exceeds even the deepest, high-temperature geothermal production wells in the Great Basin.

Geothermal power plants within the Great Basin (Figure 3.11-19) presently produce about 600 MWe at 15 locations (CRWMS M&O 1996a). None of which are within 50 miles of Yucca Mountain.

In addition to electric power production, geothermal energy is currently used for space heating and industrial processes throughout the region (Figure 3.11-20). Direct utilization technologies are those that use the thermal energy with no conversion to electricity (CRWMS M&O 1996a). The locations of the principal direct-use geothermal developments are shown in Figure 3.11-20. Examples of existing and potential operations within the Great Basin exploiting direct-use are presented in Flynn et al. (CRWMS M&O 1996a) and include year round gold mining, home heating, food dehydration, and aquaculture.

The temperature and depth of the commercial direct use projects in the Great Basin were compared to the temperature and depth data of five representative wells in the study area (CRWMS M&O 1996a, Figure 44). The data show that, with the exception of one project, all of the Yucca Mountain wells are considerably deeper than the commercial projects. The temperatures of the Yucca Mountain wells at depth are comparable with surface thermal waters used for recreation and aquaculture in other locations in Southern Nevada. However, the heated water is too deep to be economically used for those purposes. This simple comparison suggests that the fluids at Yucca Mountain are not commercially viable when compared with existing operations.

The absence of a positive geothermal anomaly and the extreme depth to low-temperature fluids essentially rules out geothermal exploration or development on a commercial scale in the Yucca Mountain area (CRWMS M&O 1996a).

Results of this study indicated that thermal fluids ranging in temperature from 40 to 57°C occur throughout the Yucca Mountain area at depths ranging from 400 to 500 m below the surface. Chemical analyses of fluids throughout the area, and in various lithologic formations, indicate that most waters are non-thermal in origin. Calculated chemical geothermometers were in general disagreement with measured temperatures and are used cautiously in this subsection. Geophysical data, including gravity, magnetics, seismic, and heat flow data failed to delineate any systematic structural evidence for a thermal anomaly. Hydrological data indicate that weakly 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 Southern Great Basin. Some surface geothermal manifestations were identified within a 50-mile radius of Yucca Mountain, but, based on the present level of development, small-scale recreational uses are the only likely applications (CRWMS M&O 1996a).

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NOTE: For each reference either a document accession number (NNA.19xxxxxx.xxxx) or a technical information center number (TIC xxxxxx) is provided. If a number is not currently available, it is noted by TBD (to be determined). All DTNs and TDIFs should be considered TBV (to be verified).

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