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INTERPRETIVE GEOLOGIC CROSS SECTIONS FOR THE DEATH VALLEY REGIONAL FLOW SYSTEM AND SURROUNDING AREAS, NEVADA AND CALIFORNIA

By

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MISCELLANEOUS FIELD STUDIES MAP
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ABSTRACT

This report presents a network of 28 geologic cross sections that portray subsurface geologic relations within the Death Valley regional ground-water system, a ground-water basin that encompasses a 3° x 3° area (approximately 70,000 km^2) in southern Nevada and eastern California. The cross sections transect that part of the southern Great Basin that includes Death Valley, the Nevada Test Site, and the potential high-level nuclear waste underground repository at Yucca Mountain. The specific geometric relationships portrayed on the cross sections are discussed in the context of four general sub-regions that have stratigraphic similarities and general consistency of structural style: (1) the Nevada Test Site vicinity; (2) the Spring Mountains, Pahrump Valley and Amargosa Desert region; (3) the Death Valley region; and (4) the area east of the Nevada Test Site.

The subsurface geologic interpretations portrayed on the cross sections are based on an integration of existing geologic maps, measured stratigraphic sections, published cross sections, well data, and geophysical data and interpretations. The estimated top of pre-Cenozoic rocks in the cross sections is based on inversion of gravity data, but the deeper parts of the sections are based on geologic conceptual models and are more speculative.

The region transected by the cross sections includes part of the southern Basin and Range Province, the northwest-trending Walker Lane belt, the Death Valley region, and the northern Mojave Desert. The region is structurally complex, where a locally thick Tertiary volcanic and sedimentary section unconformably overlies previously deformed Proterozoic through Paleozoic rocks. All of these rocks have been deformed by complex Neogene extensional normal and strike-slip faults. These cross sections form a three-dimensional network that portrays the interpreted stratigraphic and structural relations in the region; the sections form part of the geologic framework that will be incorporated in a complex numerical model of ground-water flow in the Death Valley region.

INTRODUCTION

In the last two decades, Federal, State, and local government agencies have expended considerable effort in attempting to characterize regional ground-water flow in the Death Valley regional flow system, a closed ground-water basin in southern Nevada and eastern California that includes Death Valley, the Nevada Test Site, and the potential high-level nuclear waste underground repository at Yucca Mountain (fig. 1). Characterization of this ground-water basin is significant for several reasons, including: (1) the need for prediction of flow paths and travel times of radionuclides that could potentially be released into the accessible environment from the Nevada Test Site and the potential repository at Yucca Mountain; (2) water quality and quantity issues for Death Valley National Park; and (3) potential impacts to farming communities and endangered species habitat near discharge areas and wells in the flow system.

This report presents a series of deep, interpretive geologic cross sections that transect the area of the Death Valley ground-water flow system. The area of investigation covers approximately 70,000 km^2 (latitudes 35°30' to 37°45' N., longitudes 115° to 117°45' W.). The purpose of this network of cross sections is to provide the structural and stratigraphic framework of the region as a component of USGS numerical modeling of regional ground-water flow in the region. These sections are intended to serve as the fundamental basis for the construction of a three-dimensional digital hydrogeologic framework model that itself provides the primary geometric basis for subsequent numerical analysis of the regional ground-water flow system. Similar networks of cross sections have been developed (Grose, 1983; IT Corp., 1996) for recent three-dimensional numerical models of the regional ground-water flow system (IT Corp., 1996; D'Agnese and others, 1997). The grid of geologic sections that is contained in this report provides a basis for comparison with existing three-dimensional framework models (IT Corp., 1996; D'Agnese and others, 1997), and should guide future revisions of the three-dimensional geologic framework model linked to the ground-water flow and radionuclide transport models.

The locations of the individual cross sections are presented on a 1:1,500,000-scale index map (fig. 2) as well as on 1:750,000-scale maps of LANDSAT imagery (fig. 3), regional place names (fig. 4), regional geology (fig. 5; after Faunt and others, 1997), regional gravity data processed as depth to Paleozoic basement (fig. 6; after Blakely and others, 1999), and general tectonic features of the region (fig. 7; after Grose and Smith, 1989). The cross sections themselves are shown on sheets 2 and 3. The cross sections are portrayed at 1:250,000 scale, and are accompanied by 1:100,000-scale enlargements of certain areas requiring a larger scale to portray geologic detail. The explanatory text that follows discusses the specific geometric relationships portrayed on the cross sections in the context of four general sub-regions (fig. 1) that have stratigraphic similarities and general consistency of structural style: (1) the Nevada Test Site vicinity; (2) the Spring Mountains, Pahrump Valley, and Amargosa Desert region; (3) the Death Valley region; and (4) the area east of the Nevada Test Site. The region north of the Nevada Test Site has been discussed by Ekren and others (1971); published cross sections that portray this area (Grose, 1983; IT Corp., 1996) are not updated here.

METHODOLOGY

Cross sections were constructed using AutoCAD on an unscaled digital template. To aid the construction of the subsurface interpretation, the AutoCAD template portrayed data extracted from an Arc/Info Geographic Information System (GIS), such as profiles of topographic and geophysical surfaces,

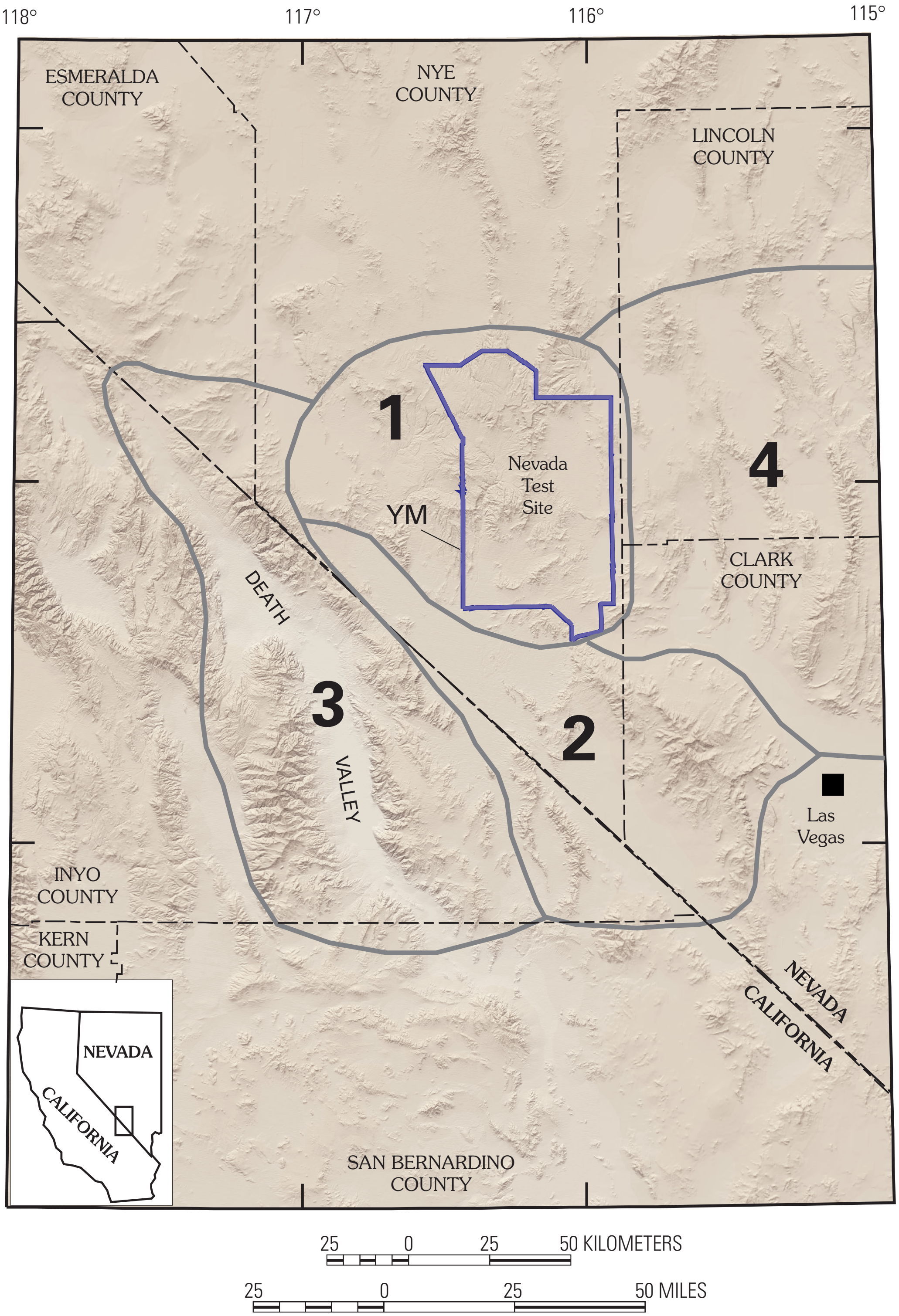

Figure 1. Map showing general geographic regions discussed in the text. Geographic regions are as follows: **1**, Nevada Test Site area; **2**, Spring Mountains, Pahrump Valley, and Amargosa Desert; **3**, Death Valley area; and **4**, east of the Nevada Test Site. YM, Yucca Mountain.

and the locations of existing geologic cross sections and cultural features. Data were extracted and added to the templates by intersecting a cross section trace with digital geologic map and surface data in Arc/Info. The data were converted from map to cross section view in AutoCAD where the templates were developed. Template data sets include the following:

(A) Topography. A topographic profile along the line of each section was created by intersecting a composited USGS 1° digital elevation model of the region (Turner and others, 1996).

(B) Locations of stratigraphic and fault contacts. A sequence of reference locations of geologic contacts, exposed faults, and faults interpreted on the basis of geophysical data was created by intersecting a digital geologic and tectonic compilation map for the Death Valley region and surrounding areas (Workman, Menges, Page, Taylor, Ekren, Rowley, Dixon, Thompson, and Wright, Geologic map of the Death Valley ground-water basin and surrounding areas, Nevada and California, work in progress).

(C) Tie points with previously constructed regional cross sections (Grose, 1983; IT Corp., 1996).

(D) Estimated thickness of Cenozoic deposits (fig. 6). Profiles were cut through modeled surfaces that estimate the thickness of Cenozoic deposits based on a computational inversion (Jachens and Moring, 1990) of gravity data (Saltus and Jachens, 1995; Blakely and others, 1998; Blakely and others, 1999). Prior to cutting profiles, the thickness data were subtracted from topography to convert it to a surface represented by altitude that could be represented on the sections.

Specific cross section locations were selected to be oriented perpendicular to Mesozoic or Neogene structural trends to maximize structural relief, and located in areas of maximum bedrock exposure. Certain sections were oriented parallel to ground-water flow directions (IT Corp., 1996; D'Agnese and others, 1997) in order to help portray geologic relations along the flow paths. A number of sections were located parallel to or coincident with previously published regional cross sections (Grose, 1983; Grose and Smith, 1989; IT Corp., 1996) in order to better compare geologic interpretations. The result of the criteria is an interlocking network of cross sections that crisscrosses the Death Valley regional flow system in all directions.

These geologic cross sections represent interpreted subsurface structural relationships. Interpretations are based on an integration of existing surface and subsurface geologic and geophysical data, combined with careful field checking of critical areas. The available data consist of appropriate geologic publications, maps, measured stratigraphic sections, published cross sections, well data, and geophysical data and interpretations. In general, the cross sections are tied to a new 1:250,000-scale regional geologic map compilation (Workman, Menges, Page, Taylor, Ekren, Rowley, Dixon, Thompson, and Wright, Geologic map of the Death Valley ground-water basin and surrounding areas, Nevada and California, work in progress), with more detailed structural information coming from many other reports published at larger map scales. Specific map data used in the cross section construction are presented in the explanatory text that follows.

The digital three-dimensional hydrogeologic framework model and flow model require a portrayal of geologic relations to a depth of at least 4 km below sea level. In some cases, cross sections were constructed to even greater depths for the purpose of resolving geometric relations between structural features in an internally consistent manner. Although these sections were created using all available surface and subsurface control, they are speculative below about 2 km below land surface; alternative configurations certainly are possible. These cross sections are not intended to resolve all outstanding scientific issues in the region. They are intended to be a synthesis of existing geologic interpretations in order to build a three-dimensional geometric framework in support of ground-water flow modeling. We acknowledge that there exists a great deal of geologic uncertainty related to the evolution of the southern Great Basin, and that these cross sections certainly do not resolve each and every issue. In many instances there is more than one published, viable geologic interpretation for an area. In the text that follows, data and fundamental assumptions used in creating the cross section interpretations are discussed, as is the justification for choosing one published interpretation of an area over another.

Several conceptual models were adopted throughout the construction of these cross sections to project geologic features to depth or beneath cover. The use of such concepts throughout the area of the Death Valley regional flow system yields a stylistic and interpretive consistency, but may also imbue these sections with certain interpretive prejudices. One conceptual model used throughout the cross sections is the interpretation that thrust faults in this region flatten with depth and generally have ramp-flat geometries, invoking a décollement style to the Paleozoic and early Mesozoic compressive tectonics (Armstrong, 1968; Burchfiel and others, 1974; Burchfiel, Wernicke and others, 1982). A caldera model with gently inwardly sloping topographic walls outboard of near-vertical ring faults defining the structural boundary of caldera subsidence (Lipman, 1984) was used for all calderas within the southwestern Nevada volcanic field. Listric geometry was assumed for normal faults with large offset (>1 km stratigraphic throw) that display significant rotation of hanging-wall rocks. Normal faults with less than about a kilometer of offset are assumed to be planar. Only the upper parts of the intrusions portrayed on these sections are shown; the shapes of the intrusions at depth are in general not defined.

STRATIGRAPHIC OVERVIEW

This section describes the sedimentary rocks of the Death Valley regional flow system and surrounding areas. Volcanic rocks of the two principal volcanic fields in the region, the southwestern Nevada volcanic field and the central Death Valley volcanic/plutonic field, are described in separate sections later in the report. These descriptions are an overview of the regional stratigraphy and are intended to complement, not replace, more detailed stratigraphic descriptions from geologic compilations of the region or parts of the region (Wahl and others, 1997; Slate and others, 2000; Workman, Menges, Page, Taylor, Ekren, Rowley, Dixon, Thompson, and Wright, Geologic map of the Death Valley ground-water basin and surrounding areas, Nevada and California, work in progress). Certain geologic units that are portrayed on the cross sections are not described here including granites, basalts, and older tuffs that originated from volcanic centers outside of the region. Detailed stratigraphic descriptions for these units appear in Workman, Menges, Page, Taylor, Ekren, Rowley, Dixon, Thompson, and Wright (Geologic map of the Death Valley ground-water basin and surrounding areas, Nevada and California, work in progress).

The oldest sedimentary rocks of the region are Middle and Late Proterozoic carbonate and clastic rocks of the Pahrump Group (Heaman and Grotzinger, 1992) (including the Kingston Peak, Beck Spring, and Crystal Spring Formations) and the Late Proterozoic Noonday Dolomite. These rocks are as much as 5 km thick in an east-west-trending zone through southern Death Valley and the Kingston Range (fig. 4); they become thinner and eventually pinch out away from this basin (Stewart, 1972; Wright and others, 1974). This local trough has been interpreted as a failed rift (Wright and others, 1974). In the southern part of the region these rocks are deposited upon an older Proterozoic complex of gneiss and intrusive rocks (Xmi), whereas in the Panamint and Funeral Mountains these rocks are themselves metamorphosed to medium and high grades (ZYm) and intruded by granites (Labotka, 1980a, b). The Middle and Late Proterozoic carbonate and clastic rocks of the Pahrump Group and the Late Proterozoic Noonday Dolomite are lumped as unit ZYp on the cross sections. On cross section H-22, all Proterozoic rocks are shown as a single unit (ZYXm).

Late Proterozoic through Lower Cambrian rocks in the southern Great Basin form a wedge of mostly clastic sediments that thickens from less than 100 m east of Las Vegas, Nev., where basal strata are Lower Cambrian, to more than 5,000 m in the Inyo Mountains of California, where most of the sequence lies below basal Cambrian beds. These rocks are part of the clastic wedge of marine sedimentary rocks that was deposited along the passive margin within the Cordilleran miogeocline (Stewart, 1970, 1982). Rocks of this age have primary lateral facies changes across the region from quartzite and siltstone in eastern exposures to predominantly shale and carbonate in the west (Stewart, 1970). The westward increase in fine-grained clastic rocks and carbonate rocks in the clastic wedge is interpreted as recording a transition from shelf to slope-and-rise facies (Stewart, 1970). Throughout much of the central part of the Death Valley regional flow system, much of the clastic section consists of fine- to coarse-grained quartzite, siltstone, conglomeratic sandstone and minor amounts of carbonate rock. The section includes the Late Proterozoic Johnnie Formation (Zj) and Stirling Quartzite (Zs), the Late Proterozoic to Lower Cambrian Wood Canyon Formation (ЄZw), and the Lower Cambrian Zabriskie Quartzite (lumped with unit ЄZw). This clastic section is exposed through a broad area including the Spring Mountains, the Nevada Test Site, and the Death Valley area. In parts of the region, such as in the northern Funeral Mountains and in the Bullfrog Hills, these clastic rocks are metamorphosed to medium and high grades (ZYm). The Late Proterozoic Johnnie Formation and Stirling Quartzite are portrayed as a single, lumped unit (Zu) in the footwall of the Keystone thrust where these units are too thin to be shown separately; they are also lumped where these units are interpreted to occupy thrust duplexes at depth. Stewart (1970) defined a western region where laterally equivalent strata are thicker, finer grained, and more carbonate rich, consisting of siltstone, shale, limestone, dolomite, and fine-grained quartzite. Formations in this western region include the Wyman Formation, Reed Dolomite, Deep Spring Formation, Campito Formation, Poleta Formation, and Harkless Formation. Typical exposures of this western facies are found in the White and Inyo Mountains and Last Chance Range, Inyo County, Calif., and in Esmeralda County, Nev. Only two cross sections, H-1 and H-22, extend into this western region. However, formations representing the western facies are not shown; instead, the Late Proterozoic to Lower Cambrian section is lumped as a single unit, as discussed below.

Regional analyses of ground-water flow in the southern Great Basin have treated the Proterozoic to Lower Cambrian siliciclastic sequence as a single hydrogeologic unit. This interval, the lower clastic aquitard of Winograd and Thordarson (1975) and quartzite confining unit of Laczniak and others (1996) serves as hydrologic basement to the flow system. Where the Proterozoic to Lower Cambrian siliciclastic sequence is lumped on the cross sections, it is labeled LCCU (lower clastic confining unit).

A Middle Cambrian through Middle Devonian carbonate-dominated succession, about 4,500 m thick in this region, consists of dolomite, interbedded limestone, and thin but persistent shale, quartzite, and calcareous clastic units (Burchfiel, 1964). These rocks primarily represent a shelf facies, deposited along the passive continental margin; age-equivalent slope-facies carbonates are present west of the Death Valley region (Stewart, 1980). The lower part of this carbonate section (Lower and Middle Cambrian Carrara Formation, Middle and Upper Cambrian Bonanza King Formation, Upper Cambrian Nopah Formation, Lower and Middle Ordovician Pogonip Group) is exposed in most of the mountain ranges in the central and southern parts of the region. The mixed carbonate and clastic lithologies of the Lower and Middle Cambrian Carrara Formation represent the transition from the underlying Late Proterozoic through Lower Cambrian clastic sequence to the overlying carbonate succession (Palmer and Halley, 1979). The Middle and Upper Cambrian Bonanza King Formation was deposited conformably upon the Carrara Formation, and is a thick carbonate unit throughout the southern Great Basin. In contrast to the Proterozoic siliciclastic rocks, thickness variations of the Bonanza King Formation are subtle and not obviously related to a regional trend (Cornwall, 1972). The Upper Cambrian Nopah Formation lies above the Bonanza King Formation and consists largely of dolomite and limestone, with minor amounts of shale. The thickness of the Nopah is variable throughout the region, but is somewhat thicker in the northern and western parts than in the southern and eastern parts (Cornwall, 1972; Burchfiel, Hamill, and Wilhelms, 1982). All of these Cambrian carbonate strata are lumped together and labeled Ꞓnbc on the accompanying cross sections. The Ordovician section comprises the Pogonip Group, the Eureka Quartzite, and the Ely Springs Dolomite. All of the Ordovician-age formations are lumped together as Ordovician rocks, undivided (Ou) on the cross sections. The Ordovician strata in the vicinity of the Death Valley region contain a transition from a shelf facies in the east to a slope and basin facies in the west (Miller and Zilinsky, 1981; Burchfiel, 1964; Burchfiel, Hamill, and Wilhelms, 1982). The transition from shelf facies to slope facies is interpreted to have migrated southeastward during Silurian and Devonian time (Stevens and others, 1991).

In the southern Great Basin, Silurian to Lower Devonian strata are variously known as the Roberts Mountains Formation and the overlying Lone Mountain Dolomite (for example, at Bare Mountain), the Laketown Dolomite (for example, at the Nevada Test Site), and the Hidden Valley Dolomite (for example, in the Panamint Range). Devonian rocks include the Sevy Dolomite, the Simonson Dolomite, the Nevada Formation, the Devils Gate Limestone, and lateral equivalents such as the Lost Burro Formation in the Panamint Range (Langenhiem and Larson, 1973). All of these strata are lumped as Devonian and Silurian rocks, undivided (DSu) on the cross sections. Ordovician, Silurian, and Devonian age rocks pinch in beneath a major sub-Devonian unconformity (Miller and Zilinsky, 1981).

The lower to middle Paleozoic carbonate succession forms the major regional carbonate-rock aquifer that is involved in ground-water flow from central Nevada, through the Nevada Test Site and Yucca Mountain, and toward discharge sites in Ash Meadows and Death Valley to the south (Winograd and Thordarson, 1975; Bedinger and others, 1989; Dettinger and others, 1995). Regional analyses of ground-water flow in the southern Great Basin have treated the Middle Cambrian through Middle Devonian carbonate rocks as a single hydrogeologic unit; this lower carbonate aquifer (Winograd and Thordarson, 1975; Laczniak and others, 1996) serves as the principal Paleozoic aquifer in the flow system. Where this unit is lumped on the cross sections, it is labeled LCA (lower carbonate-rock aquifer).

Upper Devonian through Mississippian strata in the region are synorogenic clastic and carbonate rocks deposited in the foreland to the east of the Antler orogenic belt (Nilsen and Stewart, 1980; Poole, 1981). There are three distinct sedimentary assemblages within this sequence, a westernmost clastic-dominated facies, a central shale facies, and an eastern carbonate platform facies (Trexler and others, 1996). The Eleana Formation (MDe) is the westernmost clastic-dominated facies and is in the western and northern part of the region. It consists of as much as 2 km of siltstone, argillite, sandstone, conglomerate, and minor limestone deposited as turbidites and debris flows filling the Antler foredeep with material derived from the Antler allochthon (Poole and others, 1961; Trexler and others, 1996). The Eleana Formation grades laterally into a central shaly facies, the Mississippian Chainman Shale (Mc) to the east and south (Trexler and others, 1996). This unit is a monotonous, poorly exposed sequence of mudrock over 1,200 m thick and is interpreted to have been deposited in a muddy shelf environment (Trexler and others, 1996). To the southeast (in the Spotted Range and in the Indian Springs valley) the carbonate platform facies (Mu) of equivalent Mississippian age is less than 350 m thick and is composed primarily of limestone (Poole and others, 1961; Barnes and others, 1982) that was deposited on a carbonate bank (Trexler and others, 1996).

Pennsylvanian and Lower Permian carbonate rocks (ℙPu) are interpreted to have been deposited on a rapidly subsiding carbonate shelf on the western margin of the continent (Stewart, 1980). These rocks consist of limestone with interbeds of silty and sandy limestone (Stewart, 1980) and include the Lower Permian to Upper Mississippian Bird Spring Formation in the eastern part of the region, the Lower Permian to Middle Pennsylvanian Tippipah Limestone in the vicinity of the Nevada Test Site, and the Lower Permian to Middle Pennsylvanian Keeler Canyon Formation in the Last Chance Range and Cottonwood Mountains. Subsequent uplift ended deposition and locally removed as much as 1.8 km of section (Stone and Stevens, 1984). The Bird Spring Formation is nearly 2 km thick in the central Spring Mountains (Langenheim and Larson, 1973; Burchfiel and others, 1974). The Lower Permian Kaibab and Toroweap Formations (Pkt) are exposed in eastern Spring Mountains.

Mesozoic cratonic sedimentary rocks include the Middle(?) and Lower Triassic Moenkopi Formation and Upper Triassic Chinle Formation, lumped as unit ŦRcm, and the Lower Jurassic Aztec Sandstone (Ja). These units are exposed in the eastern and southern Spring Mountains. Mesozoic metasedimentary and metavolcanic rocks are present in the southern Panamint Range and Avawatz Mountains, but lie too far to the south to be portrayed on any of the cross sections in this report.

Tertiary strata of the region have been subdivided into three general categories based upon sequence stratigraphy (Snow and Lux, 1999): a pre-14 Ma early extensional sequence (included in Tso on the cross sections); a 14- to 6-Ma synextensional sequence that corresponds to the peak of volcanic activity in the southwestern Nevada and central Death Valley volcanic fields and to peak extension and deposition in the Furnace Creek basin (shown as Ts3 on the cross sections); and a post-6-Ma late extensional sequence (shown as Ts4 on the cross sections). Tertiary strata are labeled as Tsu where no age distinctions are made. Where the entire Quaternary-Tertiary section is combined on the cross sections due to lack of subsurface control, the label QTu is used.

Sedimentary strata deposited from 35 to 25 Ma (included in Tso) include the Titus Canyon Formation along the east side of the Funeral and Grapevine Mountains (Reynolds, 1974; Wright and Troxel, 1993), and older sedimentary rocks (informally called the "rocks of Winapi Wash") that occur in and near the Nevada Test Site (Slate and others, 2000). Sandstones in this interval are free of volcanic clasts. Sedimentary strata deposited between 25 Ma and 14 Ma (also included in Tso) include the Rocks of Pavits Spring in the vicinity of the Nevada Test Site (Slate and others, 2000) and unnamed units widely exposed in and around the Grapevine Mountains, Funeral Mountains and Bullfrog Hills. Sandstones are commonly tuffaceous; interbedded tuffs have been dated at 20–25 Ma (Cemen and others, 1999).

All of these Oligocene to Miocene Tertiary sedimentary units have variable thickness and facies, and their distribution is discontinuous, probably because they were deposited on the irregular pre-Tertiary erosional surface. In general, these older sedimentary units are pre-tectonic and pre-volcanic, predate the major extensional events of the Death Valley region, and show little or no relationship to present topography or structures.

The established earlier Tertiary fluvio-lacustrine depositional regime was interrupted and locally obliterated by the onset of regionally active extensional faulting and the establishment of major volcanic fields. Middle Miocene synextensional and synvolcanic sedimentary sections (Ts3) are predominantly between 14 and 6 Ma and include the Artist Drive Formation within the Furnace Creek basin and similar sedimentary sequences interpreted to underlie parts of the Amargosa Desert, Pahrump Valley, and Death Valley. Middle Miocene synextensional sediments consist of coarse, tuffaceous clastic rocks, locally derived megabreccias, and tuffaceous sandstone locally interbedded with volcanic rocks that range in composition from basalt through rhyolite. Geology and stratigraphic relations of sedimentary rocks of this age are discussed by Cemen and others (1985), Greene (1997), and Wright and others (1999).

Younger clastic sediments (Ts4) fill extensional basins throughout the region (Guth and others, 1988; Snow and Lux, 1999; Wright and others, 1999). Younger sedimentary units include the Funeral Formation of the Furnace Creek basin; these rocks are late extensional and have been deposited largely in restricted, intermontane basins that developed as extension progressed (Snow and Lux, 1999). Synextensional sedimentary rocks were deposited during this time only in the extreme western part of the region, such as in the Nova basin on the western side of the Panamint Mountains (Hodges and others, 1989).

STRUCTURAL OVERVIEW

The region transected by the cross sections includes parts of the southern Basin and Range Province, the northwest-trending Walker Lane belt, the Death Valley region, and the northern Mojave Desert. The region is structurally complex, where a locally thick Tertiary volcanic and sedimentary section unconformably overlies previously deformed Proterozoic through Paleozoic rocks. All of these rocks have been deformed by complex Neogene extensional normal and strike-slip faults.

The Paleozoic section throughout the region was affected by south- and southeast-directed shortening in the form of regional thrusts and more localized folds. This deformation is interpreted to be as old as Permian in the western part of the region (Snow, 1992) whereas frontal thrusts in the vicinity of Las Vegas affect Jurassic rocks and some of these thrusts may be as young as Early Cretaceous (Fleck, 1970; Fleck and Carr, 1990). The regional thrusts and folds, although subsequently dismembered by Neogene extension, have been correlated throughout the region on the basis of stratigraphic throw, sense of vergence, relative position, spacing and style (Burchfiel and others, 1983; Wernicke and others, 1988; Snow, 1992; Serpa and Pavlis, 1996). The major thrusts have stratigraphic offsets of several kilometers and horizontal displacements of as much as several tens of kilometers, based on offsets in regional facies trends (Fleck, 1970; Snow, 1992). The eastern, foreland part of this thrust belt includes Sevier-age thrusts that may correlate to thrusts in central Utah (Armstrong, 1968) and east-central Nevada (Taylor and others, 2000); correlations to the western parts of the belt are less certain.

The Spring Mountains are a high-standing, relatively unextended block that preserves most of the geometry of the Sevier thrust belt. In contrast, the Montgomery Mountains and Resting Spring and Nopah Ranges to the west of the Spring Mountains expose thrust faults in extended and rotated blocks. Exposures of thrusts at various structural levels in the ranges provide insight into the possible original subsurface geometry. Several lines of evidence allow the suggestion that many of the thrusts have a décollement style, where thrusts have ramp-flat geometric style and are detached at a common stratigraphic level. Such evidence includes: (1) thrusts in the western and northwestern parts of the region consistently carry one or more members of the Late Proterozoic to Lower Cambrian clastic sequence (the Johnnie Formation, Stirling Quartzite, and Wood Canyon Formation), but no older units, in their hanging walls, (2) stratigraphically confined zones of lenticular fabric and slickensided surfaces suggestive of bedding-parallel shear are observed in both the Wood Canyon and Johnnie Formations, (3) map relations on the western flank of the Resting Spring Range (Burchfiel, Hamill, and Wilhelms, 1982, 1983) portray a number of thrusts flattening downward to the Johnnie Formation near the base of the Proterozoic clastic sequence, and (4) the large expanse of gently dipping Cambrian carbonate rocks in the upper plate of the Montgomery thrust to the east and northeast of Ash Meadows implies the presence of a hanging-wall flat. A number of the cross sections portray two distinct sub-regional bedding-parallel décollement intervals within the Late Proterozoic to Lower Cambrian clastic sequence, one within the Wood Canyon Formation and one within the Johnnie Formation. It is possible, however, that the Late Proterozoic to Lower Cambrian clastic sequence is a broad zone of distributed shear strain. Structurally high exposure of the Late Proterozoic to Lower Cambrian clastic sequence, including exposures in the Papoose Range, the Desert Range, the northwestern end of the Spring Mountains, and the northern end of the Resting Spring Range, are portrayed on the cross sections to be the result of syn-thrusting uplift above thrust duplexes that involve this part of the stratigraphic section at depth.

The easternmost thrusts, such as the Keystone thrust in the Spring Mountains, have a regionally extensive hanging-wall flat along a detachment horizon within the Middle and Upper Cambrian carbonates of the Bonanza King Formation (Burchfiel and others, 1974; Burchfiel, Wernicke, and others, 1982). Structurally higher thrusts to the west, such as the Wheeler Pass thrust in the Spring Mountains and the Gass Peak thrust in the Sheep Range (fig. 7), are detached within the Late Proterozoic to Lower Cambrian Wood Canyon Formation or the Late Proterozoic Stirling Quartzite. To the west of these two thrust traces, upper plate exposures in the Desert Range and the northwestern Spring Mountains contain lower units including much of the Late Proterozoic Johnnie Formation. This suggests a regional hanging-wall ramp from the Late Proterozoic siliciclastic sequence to the Cambrian carbonates, probably controlled by the regional stratigraphic pinch out of the Late Proterozoic and Lower Cambrian clastic sequence against the paleocontinental platform. This configuration results in older formations at the base of the structurally higher thrusts closer to the hinterland, and younger formations at the base of thrust sheets for the structurally lower thrust faults closer to the foreland.

Tertiary deformation of the region is characterized by a variety of structural patterns that overlap in space and time and include: (1) Basin and Range extension; (2) local extreme extension along detachment faults that currently have gentle dips; (3) development of discrete strike-slip faults and transtensional basins within the Walker Lane belt; and (4) Cenozoic volcanism that both preceded and temporally overlapped with regional extension, creating huge caldera complexes and depositing voluminous material into evolving basins.

The northwest-trending Walker Lane belt (Stewart, 1988) transects the area of the Death Valley ground-water flow system roughly parallel to the Nevada-California border. On a regional scale, the Walker Lane belt is dominated by strike-slip faults, but structures within the belt are discontinuous and appear to complexly interact with one another in accommodating an overall mixed right-shear and extensional strain field. The part of the Walker Lane belt that transects the area of the Death Valley ground-water flow system contains several large right-lateral faults with northwest orientations, such as the Stewart Valley–Pahrump fault zone and the Las Vegas Valley shear zone (fig. 7). The belt also contains a number of coeval structures of different orientation, including east-northeast-trending left-lateral strike-slip faults, such as the Rock Valley fault zone, the Cane Spring and the Mine Mountain faults (fig. 7), and north- to northeast-trending normal faults such as the Gravity fault, the Bare Mountain fault, and the faults at Yucca Mountain. The large strike-slip faults are generally buried beneath Tertiary sediments, although the traces of the faults are often defined by Quaternary fault scarps (Anderson and others, 1995; Piety, 1996). Gravity data (Blakely and others, 1998, 1999) portray a structurally complex pre-Tertiary surface adjacent to these faults consisting of steep-sided local depressions and ridges that must be fault bounded and probably represent local compression and extension within the overall strike-slip environment (Wright, 1989).

In the western part of the region, the Walker Lane belt also includes the detachment faults and metamorphic core complexes of the Death Valley region that have accommodated large-magnitude northwest-directed horizontal extension. The ranges bounding Death Valley (including the Panamint Mountains, the Funeral Mountains, and the Black Mountains) preserve major detachment faults that juxtapose lower plate mid-crustal medium- and high-grade metamorphic rocks against unmetamorphosed upper plate rocks across mylonite zones (Hamilton, 1988). The ranges are separated by major strike-slip faults, such as the Furnace Creek–Death Valley fault system. Both strike-slip faults and the extensional detachments appear to have evolved coevally and are the result of northwest-directed extension (Wright, 1989). On the cross sections, the detachments are shown to terminate or merge into the bounding strike-slip faults such that the strike-slip faults act as transfers between regions extending at different rates, or at different times. In this scenario the crust is broken along major strike-slip faults and major structural blocks slide past one another; at the same time each block is being internally extended along major detachment faults (Wright, 1989). Regardless of whether slip on the detachments originated at low angles or the faults formed at higher angles and subsequently flattened (Hamilton, 1988; Wernicke, 1992), the faults currently are domical in nature. On the cross sections they are shown as steepening from subhorizontal across the range top to moderate dips in the subsurface.

North and east of the Walker Lane belt, late Cenozoic extensional deformation was dominated by movement along north- to northeast-striking normal faults related to development of the characteristic basin and range structure and associated topography of the southern Great Basin (Stewart, 1980). The magnitude of late Cenozoic extensional deformation varied spatially in this region, with more-extended tracts alternating with less-extended domains (Wernicke and others, 1984; Guth, 1981; Wernicke, 1992). Left-lateral slip along east- to northeast-trending transverse fault zones, such as the Pahranagat shear zone (fig. 7) (Jayko, 1990), may have served to transfer extensional strain between individual extensional domains (Wernicke and others, 1984).

The two main volcanic centers in the region are the southwestern Nevada volcanic field, in the vicinity of the Nevada Test Site, and the central Death Valley volcanic field. The southwestern Nevada volcanic field is characterized by a thick sequence of regionally distributed welded tuffs that were derived from a central complex of nested calderas (Byers, Carr, Orkild, and others, 1976; Sawyer and others, 1994). In comparison, the central Death Valley volcanic field is composed of a series of lava flows and nonwelded tuffs that were derived from localized volcanic centers rather than climactic caldera-forming eruptions (Wright and others, 1991). Volcanic centers and Tertiary volcanic rocks that occur to the north of the Nevada Test Site are discussed by Ekren and others (1971, 1977).

CROSS SECTIONS IN THE VICINITY OF THE NEVADA TEST SITE

The area included in this section contains the Nevada Test Site and areas adjacent to it (fig. 1), including Pahute Mesa in the north; Bare Mountain, Crater Flat, Yucca Mountain, Timber Mountain, and Oasis Valley in the west; the Striped Hills, Specter Range, Rock Valley, and Jackass Flats in the south; and Mercury Valley, the Spotted Range, Frenchman Flat, and Yucca Flat in the east (fig. 4). This area includes the nuclear testing areas on the Nevada Test Site as well as the site of the potential high-level nuclear waste repository at Yucca Mountain on the western border of the Test Site. Parts or all of the following cross sections show the geology in this part of the Death Valley ground-water flow system: (from north to south) H-1, H-2, H-3, H-4, H-24, H-5, H-6, H-17, and (from west to east) H-25, H-28, and H-19.

Geologic map data used to construct these cross sections include geologic maps of the Nevada Test Site (Frizzell and Shulters, 1990; Wahl and others, 1997; Slate and others, 2000), the Timber Mountain caldera area, (Byers, Carr, Christiansen, and others, 1976), Pahute Mesa (Orkild and others, 1969), Rainier Mesa (Sargent and Orkild, 1973), and Jackass Flats (Maldonado, 1985). Many of these maps compile and revise geologic map data from systematic 1:24,000-scale geologic mapping of quadrangles in and near the Nevada Test Site by the U.S. Geological Survey in the 1950's and 1960's. Many of these 7.5-minute geologic quadrangle maps were consulted for detailed structural data; see Frizzell and Shulters (1990) for an index and individual citations for these maps. Additional geologic maps used include those of Bare Mountain (Monsen and others, 1992), Yucca Mountain (Day, Dickerson, and others, 1998), and Crater Flat (Faulds and others, 1994). There is a considerable amount of subsurface geologic data available from boreholes on the Nevada Test Site, but many of these penetrate only a part of the Tertiary section. Data from boreholes that penetrate the Paleozoic section are included in Carr and others (1986), Carr (1982), Carr and Parrish (1985), and Cole (1997). Tertiary stratigraphic nomenclature is from Sawyer and others (1994). Tertiary stratigraphic unit thickness data are from Byers, Carr, Orkild, and others (1976) for Timber Mountain Group and Paintbrush Group rocks, and from Carr and others (1986) for Crater Flat Group and older volcanic rocks. Caldera structures are modified from Byers, Carr, Christiansen, and others (1976) based on information in Christiansen and others (1977), Lipman (1984), Dickerson and Drake (1998), and Wahl and others (1997). The thickness and structural setting of the Proterozoic and Paleozoic units in the vicinity of the Nevada Test Site are primarily based on the work of Cole (1997) and Cole and Cashman (1999) and references cited therein.

Geophysical data used to constrain cross section interpretations include gravity and magnetic data from the vicinity of the Nevada Test Site (Bath and Jahren, 1984; McCafferty and Grauch, 1997; Grauch and others, 1999; Blakely and others, 2000) and gravity models of the thickness of Tertiary strata (Blakely and others, 1999; Hildenbrand and others, 1999; Grauch and others, 1999). Also consulted during cross section construction were interpretations of seismic reflection data across Crater Flat and Yucca Mountain (Brocher and others, 1998) and in the vicinity of Mid Valley (McArthur and Burkhard, 1986).

PRE-TERTIARY STRUCTURE OF THE NEVADA TEST SITE AREA

The pre-Tertiary structure of the Proterozoic and Paleozoic rocks in the Nevada Test Site area is inferred to be controlled by a dominantly southeast-vergent (foreland-vergent) thrust system (Caskey and Schweikert, 1992; Trexler and others, 1996; Cole and Cashman, 1999) involving Proterozoic through Mississippian rocks. Previous interpretations of the thrust faults in the vicinity of the Nevada Test Site interpreted all major thrust exposures as a single folded east-vergent thrust, called the CP thrust (Barnes and Poole, 1968). More recent work, based on detailed structural observations and regional considerations (Caskey and Schweickert, 1992; Trexler and others, 1996; Cole and Cashman, 1999), has interpreted the Belted Range, Specter Range, and Spotted Range thrusts as separate foreland-vergent (west- and south-vergent) structures and redefined the CP thrust as a hinterland-vergent (north- and east-vergent) structure. Within the Nevada Test Site and immediately surrounding region, the strike of the principal thrusts swings from north-northeasterly near

Yucca Flat in the northeastern part of the Nevada Test Site to easterly in the western and southern parts of the Nevada Test Site (fig. 7) (Snow, 1992; Cole and Cashman, 1999). The Belted Range, Specter Range, and CP thrusts all carry the Late Proterozoic and Lower Cambrian Wood Canyon Formation in their upper plates. Consequently, all of these thrusts are interpreted on the geologic sections to root into a regional thrust detachment at this stratigraphic level or lower.

The Belted Range thrust is the most northwesterly thrust structure identified in the vicinity of the Nevada Test Site and is almost completely buried beneath Tertiary volcanic rocks. Upper plate rocks of the Late Proterozoic to Lower Cambrian Wood Canyon Formation are exposed at the surface at Gold Meadows (fig. 4) and were penetrated immediately beneath the Tertiary volcanic cover in nearby wells on Rainier Mesa (Cole and Cashman, 1999). Lower plate rocks of the Upper Devonian and Mississippian Eleana Formation are exposed in outcrops only 4 km to the east along the west side of Yucca Flat. Caskey and Schweickert (1992) estimated more than 25 km of displacement across the Belted Range thrust. Sections H-2 and H-3 portray the inferred relations beneath volcanic cover; the Belted Range thrust is portrayed as having a simple hanging-wall flat based on surface exposures of rocks in the hanging wall, the Wood Canyon Formation, that dip 30°–45° to the west (Cole and Cashman, 1999). Lower plate rocks are portrayed as a footwall ramp, based on the presence of a complex footwall duplex, discussed below. The Belted Range thrust system strikes southwestward from Rainier Mesa and has been interpreted to correlate with the Meiklejohn Peak thrust at Bare Mountain (fig. 4), an east-west striking thrust fault that places Lower Cambrian Zabriskie Quartzite and younger strata above the Upper Devonian and Mississippian Eleana Formation (Monsen and others, 1992; Caskey and Schweickert, 1992; Cole and Cashman, 1999). In the west-central part of the Nevada Test Site, the Belted Range thrust system would lie buried beneath volcanic rocks to the north of exposures of Chainman Shale and Eleana Formation in the Calico Hills. Below the Belted Range thrust a stack of imbricate slices places Silurian and Devonian carbonate rocks and the Upper Devonian and Mississippian Eleana Formation over the Upper Mississippian Chainman Shale within a complex footwall duplex in the Eleana Range (Cole and Cashman, 1999). The duplex stack extends about 7 km outboard (east) of the main Belted Range thrust; it includes structures at the Calico Hills (shown at the north end of section H-27), Mine Mountain (section H-3), the Eleana Range (shown on section H-2), and near the northern border of the Nevada Test Site (section H-1).

The hinterland-vergent CP thrust lies to the east and southeast of the Belted Range thrust (Cole, 1997; Caskey and Schweikert, 1992; Trexler and others, 1996; Cole and Cashman, 1999). The CP thrust is considered to be a back thrust that evolved nearly contemporaneously with the Belted Range thrust (Caskey and Schweikert, 1992). In the CP Hills, the CP thrust locally places Proterozoic and Cambrian rocks above a Mississippian and Pennsylvanian section (Caskey and Schweikert, 1992), but elsewhere the thrust is more commonly marked by a variety of imbricate faults and north- and west-vergent folds not necessarily accompanied by a well-defined thrust fault (Cole and Cashman, 1999). The CP thrust is inferred in the subsurface in western Yucca Flat from drill hole data where Cambrian and Ordovician rocks overlie Mississippian rocks (Cole, 1997; Cole and Cashman, 1999). In cross sections H-3 and H-2, the thrust is inferred to root back to the level of regional detachment, within the Proterozoic clastic section deep beneath the Halfpint Range east of Yucca Flat. Beneath Yucca Flat, the thrust is inferred to ramp steeply upsection in the hanging wall, so that in western Yucca Flat and the vicinity of the CP Hills the Lower Cambrian section (upper Wood Canyon Formation through Bonanza King Formation) lies above the deformed Devonian through Mississippian rocks of the footwall. The inferred steep thrust ramp is portrayed as having originated near the present location of the Carpetbag fault and is presently being truncated by it (sections H-3 and H-2).

The CP thrust is inferred to roughly parallel the Belted Range thrust and swing southwest from Yucca Flat and the CP Hills toward the possibly equivalent north-vergent Panama thrust at Bare Mountain (fig. 7) (Monsen and others, 1992; Caskey and Schweikert, 1992; Snow, 1992). The presence of this thrust southeast of the Calico Hills is inferred based upon hinterland-vergent folds in the Calico Hills that may be in the footwall of the CP thrust (Cole and Cashman, 1999). Beneath Yucca Mountain, the Silurian carbonate rocks penetrated by drill hole UE-25p#1 (Carr and others, 1986) are interpreted to be in the footwall of the CP thrust (section H-25). In sections H-25, H-27, and H-28, the CP thrust is shown somewhat diagrammatically as a north-vergent 30° ramp with Late Proterozoic and Lower Cambrian Wood Canyon Formation in the hanging wall.

The Specter Range thrust is a southeast-vergent thrust exposed in the Specter Range just south of the southern border of the Nevada Test Site (Burchfiel, 1965; Sargent and Stewart, 1971). The thrust fault places Late Proterozoic Stirling Quartzite and Late Proterozoic to Lower Cambrian Wood Canyon Formation in the hanging wall over folded Ordovician, Devonian, and Silurian strata in the footwall (Burchfiel, 1965) (shown on sections H-24, H-28, and H-27). Folding observed in the Ordovician and Silurian age rocks in the footwall of the Specter Range thrust is interpreted to be the result of a fault propagation fold at depth in the Specter Range (section H-28). The Specter Range thrust fault climbs upsection and loses stratigraphic throw to the northeast, where it appears to die out beneath Mercury Valley (Cole and Cashman, 1999). To the southwest, the existence of this thrust in the subsurface beneath the Tertiary cover of the northern Amargosa Desert is suggested by the presence of (1) Middle and Upper Cambrian Bonanza King

Formation, characteristic of the Specter Range thrust hanging wall, in the Skeleton Hills, and (2) Devonian carbonate rocks, characteristic of the Specter Range thrust footwall, in the Fairbanks Hills due south of the Skeleton Hills (sections H-27 and H-26). The Specter Range thrust has been correlated across the Amargosa Desert with the Schwaub Peak thrust in the Funeral Mountains (Snow, 1992).

In the vicinity of the Striped Hills in lower Rock Valley, the upper plate of the Specter Range thrust is inferred to include imbricate thrusts that are stacked and back-rotated to produce the vertical to overturned attitudes of the Proterozoic through Cambrian rocks exposed in the Striped Hills (Potter and others, 1999). The imbricate ramp geometry displayed on cross sections H-27, H-28, and H-17 contrasts with previous interpretations of the Striped Hills as the overturned limb of a north-vergent anticline (Snow, 1992; Caskey and Schweikert, 1992). The ramp-dominated thrust geometry is projected west in the subsurface of the Amargosa Desert on the south end of section H-25, to account for overturned Ordovician strata encountered in the Felderhoff Federal #25-1 well (Carr and others, 1995), 4.5 km to the east of section H-25. The imbricate stack is also inferred to project to the northeast, where 60°–70° north-dipping Cambrian rocks in Rock Valley (Sargent and Stewart, 1971) may be the result of two stacked thrust ramps (section H-28). The imbricate stack either dies out farther to the northeast or is truncated by the Rock Valley fault. The steep dips in the Striped Hills were achieved in pre-Oligocene time, as documented by a profound angular unconformity between Cambrian and Tertiary rocks in Rock Valley (Sargent and Stewart, 1971). Hence, the steep dips in the Striped Hills cannot be attributed to Neogene movement on the Rock Valley fault, and are most likely the result of earlier compressive deformation (Potter and others, 1999).

The Spotted Range thrust places Cambrian Bonanza King Formation over Upper Devonian and Mississippian strata; footwall rocks display tight to isoclinal folds that are overturned to the southeast (Barnes and others, 1982; Cole and Cashman, 1999). The upper plate of the thrust forms the core of the Spotted Range syncline in the Spotted Range just southeast of the Nevada Test Site; the syncline and infolded thrust contact can be traced along strike to the northeast in the Ranger Mountains east of the Nevada Test Site. Although it is exposed directly across Mercury Valley from the Specter Range thrust, the Specter Range thrust is interpreted to be a separate structure (Cole and Cashman, 1999). Caskey and Schweickert (1992) suggested that the Spotted Range thrust may have more than 25 km of offset and represents an eroded, eastern outlier (klippe) of the Belted Range thrust. Cross sections H-5, H-4, and H-3 portray the Spotted Range thrust and adopt the interpretation of Cole and Cashman (1999) who do not specifically define a root zone for the thrust.

GEOLOGY OF THE SOUTHWESTERN NEVADA VOLCANIC FIELD (SWNVF)

Volcanic rocks and their associated caldera collapse structures of the southwestern Nevada volcanic field (SWNVF) dominate the northwestern and west-central parts of the Nevada Test Site. Volcanism associated with the SWNVF occurred episodically between about 15 and 9 Ma (Byers, Carr, Orkild, and others, 1976; Sawyer and others, 1994). Eruption of voluminous, extensive ash-flow-tuff sheets resulted in the collapse of six known calderas, two of which overlapped to form the Silent Canyon caldera complex and three of them overlapped or were nested to form the Timber Mountain caldera complex and the Claim Canyon caldera (fig. 7). The sources of many of the older ash-flow tuffs remain uncertain because associated calderas have been buried or destroyed by younger calderas. Volumetrically subordinate, but related, silicic lava flows and minor pyroclastic flows were erupted from the calderas and from isolated volcanic vents within the field (Sawyer and others, 1994).

The Silent Canyon caldera complex underlies Pahute Mesa in the northern part of the Nevada Test Site, and includes the Grouse Canyon caldera and the Area 20 caldera (Sawyer and others, 1994). Both calderas are completely buried by younger rocks, mostly by ash-flow tuffs erupted from the adjoining Timber Mountain caldera complex, and were initially identified by gravity studies (Healey, 1968; Orkild and others, 1968). The Grouse Canyon caldera was formed by the eruption of the 13.7-Ma Grouse Canyon Tuff (Sawyer and Sargent, 1989; Ferguson and others, 1994; Sawyer and others, 1994); post-caldera lavas of the Belted Range Group erupted from the same area subsequent to collapse of the caldera. The Area 20 caldera is suggested to have formed by the eruption of the Bullfrog Tuff (Byers, Carr, Orkild, and others, 1976; Sawyer and others, 1994). The caldera complex gives rise to one of the largest gravity lows in Nevada (Saltus and Jachens, 1995), presumably because it is filled with a very thick section of low-density volcanic rocks within one or more calderas (Mankinen and others, 1999). Younger Tertiary volcanic rocks that bury the Silent Canyon caldera complex are gently dipping and disturbed by relatively minor normal faults (Orkild and others, 1969)—evidence that this caldera complex did not resurge. A number of deep exploratory drill holes have defined the subsurface distributions and elevations of the volcanic units within the complex (Sawyer and Sargent, 1989; Ferguson and others, 1994). These data have been used to construct a three-dimensional geologic framework model for the Silent Canyon caldera complex (McKee and others, 1999). The elevation of contacts for the Tertiary units within the Silent Canyon caldera complex in sections H-16 and H-1 are consistent with the McKee and others (1999) model. The configuration of the pre-Tertiary surface beneath the Silent Canyon caldera complex follows the work of

Mankinen and others (1999) and Hildenbrand and others (1999).

Volcanic activity within the SWNVF peaked volumetrically with the eruption of Paintbrush Group and Timber Mountain Group ash-flow tuffs, which formed the Timber Mountain caldera complex and the Claim Canyon caldera just to the south (Byers, Carr, Orkild, and others, 1976; Byers, Carr, Christiansen, and others 1976; Christiansen and others, 1965, 1977; Sawyer and others, 1994). The Claim Canyon caldera (Christiansen and Lipman, 1965; Byers, Carr, Orkild, and others, 1976; Byers, Carr, Christiansen, and others, 1976) is a remnant of a large caldera that formed as a result of the eruption of the Tiva Canyon Tuff (12.7 Ma) and possibly the Topopah Spring Tuff (12.8 Ma), both formations of the Paintbrush Group. The Timber Mountain caldera complex destroyed most of the Claim Canyon caldera; only the southern, primarily structural margin of the Claim Canyon complex is exposed (Christiansen and Lipman, 1965). Most of the caldera has been resurgently domed (Sawyer and others, 1994). The Timber Mountain caldera complex consists of the Rainier Mesa caldera, which formed as a result of the eruption of the 11.6-Ma Rainier Mesa Tuff and the Ammonia Tanks caldera, which formed as a result of eruption of the 11.45-Ma Ammonia Tanks Tuff (Sawyer and others, 1994). The caldera complex is centered on Timber Mountain, which formed as a result of the resurgence of the Ammonia Tanks caldera (Carr and Quinlivan, 1968). Topographic and structural margins for these two calderas (Slate and others, 2000) are primarily based upon recent interpretations of geophysical data (Grauch and others, 1999; Hildenbrand and others, 1999; Mankinen and others, 1999; Ponce, 2000; Ponce and others, 2000). The Timber Mountain caldera complex and Claim Canyon caldera are shown on cross sections H-2, H-3, H-16, and H-25. Depiction of the Timber Mountain caldera complex generally follows that of Byers, Carr, Christiansen, and others (1976) with modifications that reflect work on caldera collapse geometry as presented in Lipman (1984). Caldera margin ring faults are portrayed as steeply dipping, following the observations of Lipman (1984). The resurgent doming of the Ammonia Tanks caldera along the reactivated ring fracture is from Christiansen and others (1977). A resurgent intrusion is inferred to underlie the caldera complex at a depth of approximately 4 km based on inferred thickness of the intracaldera Tertiary volcanic rocks (Byers, Carr, Christiansen, and others, 1976) and on geophysical modeling of a gravity high under Timber Mountain (Kane and others, 1981; Grauch and others, 1999). The Black Mountain caldera (fig. 7), located northwest of the Timber Mountain caldera complex, is the source of the 9.4-Ma tuffs of the Thirsty Canyon Group (Noble and others, 1984; Sawyer and others, 1994). The Black Mountain caldera is interpreted on cross section H-1 as a simple collapse caldera with a resurgent dome within it.

GEOLOGY OF THE EASTERN NEVADA TEST SITE

The eastern half of the Nevada Test Site is dominated by the Tertiary extensional basins of Yucca Flat and Frenchman Flat and by a series of northeast-striking, left-lateral strike-slip faults. The two general fault types, the north-south-striking faults of the extensional basins and the strike-slip faults, appear to represent in a general way the interplay between basin-range extension and deformation associated with the Walker Lane belt (Carr, 1984). Normal faults radial to the caldera complexes of the southwestern Nevada volcanic field are evidence of local, caldera-related modifications to the stress field as well (Minor, 1995). In general, Paleozoic carbonate rocks underlie most of this region. The Paleozoic carbonate rocks are truncated to the west by the Belted Range thrust, and to the northeast by the core of the Halfpint anticline (Hinrichs, 1968), but are otherwise continuous through the eastern half of the Nevada Test Site, although disrupted locally by thrusts and cut by Tertiary normal and strike-slip faults.

Yucca Flat is the main extensional basin of the eastern Nevada Test Site, and is in most general terms a simple half-graben dominated by north-striking, east-dipping, down-to-the-east normal faults such as the Jangle-Halfpint, the Yucca, and the Carpetbag faults (Dockery, 1984; Carr, 1984). The structure of Yucca Flat is shown on sections H-1, H-2, H-3, and H-4; H-19 is a longitudinal section along the axis of the basin. The structure of eastern Yucca Flat is relatively well known based on outcrop control in the Halfpint Range and borehole intercepts in the basin. The Paleozoic carbonate section is as thick as 4.7 km thick and generally dips 15°–30° to the west and southwest in the hanging wall of the Carpetbag–Yucca Flat fault system, beneath eastern and northeastern Yucca Flat. From drilling, the carbonate section is known to be continuous under the main Yucca Flat testing areas (Cole and others, 1997; Cole and Cashman, 1999). The configuration of the Paleozoic rocks on cross sections H-3, H-2, and H-19 is also consistent with an interpreted subcrop map of Paleozoic units present at the pre-Tertiary unconformity as based on drill hole intercepts (Cole, 1997). The stratigraphic and structural relations of the Tertiary volcanic rocks in Yucca Flat are generalized from published 1:12,000-scale cross sections (IT Corp., 1996) that were constructed based on abundant borehole control and seismic data. The Tertiary basin fill consists predominantly of a thick alluvial section underlain by generally west-dipping outflow sheets from the southwestern Nevada volcanic field. Gravity models of the Yucca Flat basin (fig. 6) define a Tertiary-Quaternary basin as much as 2.5 km deep to the east of the Carpetbag fault, a mid-basin high to the west of the Carpetbag fault, and a shallower basin to the west of the high (Phelps and others, 1999; Ferguson and others, 1988) (section H-2). The Yucca Flat basin is deepest at its southern end where it abuts the dividing ridge with

Frenchman Flat to the south (fig. 6) (Dockery, 1984). Yucca Flat is enclosed at its northern end where the Proterozoic rocks in the core of the Halfpint anticline converge with the Belted Range structure (Hinrichs, 1968) (section H-1). The Climax stock, shown on cross section H-1 as a narrow, steep-sided feature, intrudes the Paleozoic carbonate section at the northern end of Yucca Flat (Houser and Poole, 1960). A second stock, the Gold Meadows stock, is exposed on Rainier Mesa (Grauch and others, 1999) (section H-1).

Frenchman Flat is a roughly circular extensional basin that lies to the south of Yucca Flat and shares much of the same stratigraphic and structural setting as well as sharing a history of nuclear testing. On the basis of gravity data, this basin is overall much deeper than Yucca Flat (fig. 6) (Grauch and others, 1999). Interference between north-striking normal faults and northeast-striking strike-slip faults is inferred to result in a local pull-apart, shown on sections H-19 and H-5.

The southern part of the Nevada Test Site is dominated by a family of left-lateral faults collectively referred to as the "Spotted Range–Mine Mountain shear zone" by Carr (1984). These faults, including the Rock Valley, Cane Spring, and Mine Mountain faults (fig. 7), generally strike north-northeast, have demonstrated left-lateral offset of a few kilometers, and have variable sense and amount of dip displacement along their traces (Frizzell and Shulters, 1990). Some of these faults (especially the Rock Valley fault) continue to be active seismically (Piety, 1996). Faults of the Spotted Range–Mine Mountain shear zone are shown on sections H-27, H-28, H-6, H-4, H-5, and H-19. This family of strike-slip faults has associated north-striking normal faults that link the strike-slip faults and form local pull-apart basins between them. The normal faults and strike-slip faults create complex map patterns to the west of Frenchman Flat (Frizzell and Shulters, 1990; Maldonado, 1985) (sections H-5 and H-4).

The Wahmonie volcanic center lies southeast of the Calico Hills and east of Jackass Flats (sections H-5 and H-17). The Wahmonie Formation consists of andesitic lava flows and pyroclastic deposits that thin away from the Wahmonie volcanic center (Sawyer and others, 1994). Intrusive rocks are interpreted to be present beneath the volcanic center at shallow depths, based upon limited surface exposures and upon geophysical data (Ponce, 1984). Gravity and magnetic data (Grauch and others, 1999) suggest that these intrusive rocks are separate from an intrusion inferred to exist beneath the Calico Hills to the northwest.

GEOLOGY OF YUCCA MOUNTAIN AND THE CRATER FLAT BASIN

South and southeast of the Timber Mountain–Claim Canyon caldera complex, two large normal faults, the Bare Mountain fault and the Gravity fault (fig. 7), bound the asymmetric graben of the Crater Flat basin (Fridrich, 1999b), which includes topographic Crater Flat and Yucca Mountain to the east. These two faults project southward and define a 20- to 25-km-wide north-striking trough underlying the Amargosa Desert area (fig. 6) (Blakely and others, 1998).

The east-dipping Bare Mountain fault bounds the western flank of the basin. Cross sections H-24, H-5, and H-4 depict the Bare Mountain fault dipping between 45°–60° based on measured dip of the fault plane in outcrop (Monsen and others, 1992) and seismic reflection data in southern Crater Flat (Brocher and others, 1998). Seismic reflection data imply a 4-km-thick west-tilted Tertiary section in the immediate hanging wall of the fault in the Crater Flat basin. North of U.S. Highway 95, the Bare Mountain fault is characterized by a steep gravity gradient where the dense Precambrian and Paleozoic section is at or near the surface (Brocher and others, 1998; McCafferty and Grauch, 1997; Grauch and others, 1999). The interpreted southern extension of the Bare Mountain fault appears on regional gravity maps (Snyder and Carr, 1982; McCafferty and Grauch, 1997; Blakely and others, 1999) as a more gentle, but still persistent, east-sloping gradient that diminishes in magnitude to the south. Here the Bare Mountain fault is interpreted to either lose displacement or become progressively more deeply buried (see cross sections H-7 and H-17), although it is possible that the southward-diminishing anomaly is caused by a southward splaying of the fault into a series of small steps.

The west-dipping Gravity fault bounds the eastern side of the Crater Flat basin (Winograd and Thordarson, 1975), to the west of the Striped and Skeleton Hills. The fault is everywhere buried beneath Tertiary and Quaternary basin fill of Jackass Flats and the Amargosa Desert. The Gravity fault is evident on regional gravity maps (Snyder and Carr, 1982; McCafferty and Grauch, 1997; Blakely and others, 1999; Grauch and others, 1999) as a north-trending, west-sloping gradient bounding relatively low gravity values on the west. Cross sections H-24, H-6, and H-7 portray the Gravity fault as having a total displacement of about 1 km across several fault splays, based on regional seismic reflection data (Brocher and others, 1993) and drill hole data (Carr and others, 1995). The geophysical signature of the Gravity fault attenuates to the north (Grauch and others, 1999), which may indicate that the fault dies out to the north (as shown on section H-5), or that its displacement is partitioned onto a number of buried splays beneath Jackass Flats.

Within the Crater Flat basin, the Neogene fault patterns are dominated by closely spaced, north- to northeast-striking, west-dipping normal faults, between which the volcanic units were tilted gently to the east (Scott and Bonk, 1984; Day, Dickerson, and others, 1998). The block-bounding faults are spaced 1–4 km apart, and have chiefly west-side-down throws of as much as hundreds of meters. Principal among these are the Paintbrush Canyon fault, the Solitario Canyon fault, the Windy Wash fault, and the Crater Flat fault (see sections H-24, H-5, and H-4). The dips on exposed west-dipping fault planes range from moderate (40°–50°) to steep (75°–85°) (Scott and Bonk, 1984; Day, Dickerson, and others, 1998; Day, Potter, and others 1998). Southwest-plunging slickenside lineations and mullions on fault planes indicate that fault motion was left oblique, with the strike-slip component subordinate to the dip-slip component in most cases (Scott and Bonk, 1984; O'Neill and others, 1992; Simonds and others, 1995; Day, Dickerson, and others, 1998; Day, Potter, and others 1998). On cross sections H-24, H-5, and H-4, the faults are interpreted to terminate at the Bare Mountain fault at depth.

Cross sections across Crater Flat do not portray a proposed source caldera for the Bullfrog Tuff beneath Crater Flat (Carr and others, 1986; Carr, 1988). A seismic reflection profile across Crater Flat (Brocher and others, 1998) shows no evidence of a buried caldera in Crater Flat; the proposed caldera was contested on geologic grounds (Scott, 1990) and is inconsistent with an inferred source for the Bullfrog Tuff in the Area 20 caldera (Sawyer and others, 1994). Cross sections across the Crater Flat basin in general portray a "basin-and-range" style of faulting and do not portray the volcanic rocks of Yucca Mountain underlain by a shallow extensional detachment, as suggested by Hamilton (1988) and Scott (1990). New geologic mapping in the Yucca Mountain region does not support the presence of a detachment at the Paleozoic-Tertiary contact (C. Potter, USGS, written commun., 1999). Brocher and others (1998) also argued against the presence of such a detachment, on the basis of seismic reflection data.

A buried northeast-striking fault is interpreted beneath southern and central Yucca Mountain and the Calico Hills, from regional gravity data. There is a steep northeast-trending gravity gradient that tracks a 20-mgal northwest-side-down step in the isostatic residual gravity (fig. 6, near the label of cross section H-25) (McCafferty and Grauch, 1997; Grauch and others, 1999). Interpretations shown on cross sections H-6, H-5, and H-27 follow previous workers (Spengler and Fox, 1989; Fridrich and others, 1994) in interpreting this steep gravity gradient as a fault that offsets the basal Tertiary unconformity and the older Tertiary units, being subsequently buried by Crater Flat Group and younger rocks. Beneath Yucca Mountain, the comparatively thin section of pre-Crater Flat Group volcanic rocks penetrated by drill hole UE-25p#1 (Carr and others, 1986) has been interpreted as evidence for a structurally controlled topographic high (Fridrich and others, 1994).

To the east of Yucca Mountain, the southern part of the Calico Hills exposes folded and thrusted Devonian and Mississippian rocks unconformably overlain by Miocene volcanic rocks. This part of the Calico Hills forms a broad Neogene dome, inferred to be related to an intrusion at depth (Maldonado and others, 1979) as shown on cross sections H-27, H-28, and H-4. The presence of such an intrusion is indicated by the presence of hydrothermally altered rocks in outcrop and supported by metamorphism of carbonate rocks in the exploratory drill hole UE25a-3 (Maldonado and others, 1979). Scattered small exposures of approximately 10-Ma rhyolite plugs are present in the southern Calico Hills, but cross sections H-27, H-28, and H-4 portray the main intrusive body at a depth of about 3 km, to be consistent with depth estimates for the magnetic source (Oliver and others, 1995; Grauch and others, 1999).

GEOLOGY OF BARE MOUNTAIN AND OASIS VALLEY

West of the Crater Flat basin are Proterozoic and Paleozoic rocks in the uplifted block of Bare Mountain. The Bare Mountain block is bounded on the east side by the Bare Mountain normal fault and on the west by the Carrara strike-slip fault (Stamatakos and others, 1997). The structure of this mountain is the result of complex overprinting of Mesozoic compressive and Tertiary extensional events (Monsen and others, 1992; Fridrich, 1999b). The largest extensional structure within the block is the Gold Ace fault, a north-striking, gently east-dipping normal fault that separates high-grade metamorphic rocks of northwestern Bare Mountain from the low-grade metamorphic rocks in the rest of the mountain (Fridrich, 1999b). Maximum uplift of the lower plate of the Gold Ace fault is 18 km (Hoisch and others, 1997). The Bare Mountain fault is interpreted as a hanging-wall splay of the Gold Ace fault; the two faults are portrayed as merging at depth on sections H-4, H-24, H-5, and H-6. The Gold Ace fault projects out into the southern part of the northern Amargosa Valley, where it is buried by Quaternary deposits.

The Fluorspar Canyon detachment fault lies on the north side of Bare Mountain and is inferred to be continuous with the Bullfrog Hills detachment northwest of Bare Mountain. This detachment surface separates nonmetamorphosed Tertiary volcanic strata in the upper plate from the metamorphosed Proterozoic and Paleozoic rocks of the lower plate at Bare Mountain (Fridrich, 1999b; Monsen and others, 1992). In the southern Bullfrog Hills, complexly faulted upper plate volcanic rocks are disrupted by listric normal faults that sole into the detachment zone, which consists of lenses of nonmetamorphosed Paleozoic strata bounded above and below by gently dipping faults (upper and lower detachment faults of Maldonado and Hausback, 1990; Maldonado, 1990b), all of which overlie a lower plate of amphibolite-grade metamorphic rocks (Hoisch and others, 1997). The Fluorspar Canyon–Bullfrog Hills detachment system is portrayed on cross section H-4. Both the hanging wall and the footwall of the Gold Ace fault are in the footwall of the Fluorspar Canyon detachment. The Fluorspar Canyon–Bullfrog Hills detachment system lies to the north and northwest of Bare Mountain, and projects in the subsurface beneath Oasis Valley. Additionally, the Gold Ace fault, which is older and lies beneath the Fluorspar Canyon detachment, must also project for some distance to the north. We portray the Fluorspar Canyon–Bullfrog Hills detachment system as a near-surface detachment fault and the Gold Ace fault as a deeper fault that projects into Oasis Valley (Fridrich, Minor, Ryder, and others, 1999). These structural relations are portrayed on cross sections H-4, H-16, and H-3.

The Oasis Valley basin is an area of alluvium and Tertiary volcanic rocks that lies north of Bare Mountain and west of the Timber Mountain caldera complex. Geophysical data suggest that the basin is filled with a thick sequence of low-density Tertiary volcanic rocks (Grauch and others, 1999). The basin is interpreted to be a half graben that is bounded on its west side by a large, east-dipping normal fault called the Hogback fault (Fridrich, Minor, Ryder, and others, 1999; Grauch and others, 1999) (section H-3). The Hogback fault is inferred to have formed near the eastern termination of the Fluorspar Canyon–Bullfrog Hills detachment system and represents large magnitude uplift of the footwall rocks following tectonic denudation (Fridrich, Minor, and Mankinen, 1999). A second major structure within the basin is the Thirsty Canyon lineament (fig. 7), a buried feature defined by a series of northeast-trending gravity and aeromagnetic anomalies that extend from the northwestern corner of the Nevada Test Site southwestward into Oasis Valley (Grauch and others, 1999). The Thirsty Canyon Lineament coincides with the inferred boundaries of the Silent Canyon and Timber Mountain caldera complexes and is interpreted as a pre-existing fault zone that served to localize the western sides of these two caldera complexes (Grauch and others, 1999) (sections H-2 and H-1).

CROSS SECTIONS IN THE VICINITY OF THE SPRING MOUNTAINS, PAHRUMP VALLEY, AND THE AMARGOSA DESERT

The region south and east of the Nevada Test Site includes the Tertiary basins of the Amargosa Desert and Pahrump Valley, and the mountain ranges that surround these basins, including the southern end of the Funeral Mountains, the Specter Range, the Montgomery Mountains, the Nopah Range, the Resting Spring Range, and the Spring Mountains (figs. 1 and 4). Parts or all of the following cross sections show the geology in this part of the regional flow model: (from north to south) H-4, H-24, H-5, H-6, H-17, H-7, H-8, H-19, H-9, H-10, H-11, and H-12, and (from west to east) H-22, H-26, H-27, and H-28.

Geologic map data used to construct these cross sections include geologic maps of the Funeral Mountains (Wright and Troxel, 1993), Bare Mountain (Monsen and others, 1992), the Striped Hills and Specter Range (Burchfiel, 1965; Sargent and Stewart, 1971; Sargent and others, 1970), the Spring Mountains (Burchfiel and others, 1974), and the Montgomery Mountains and Nopah and Resting Spring Ranges (Burchfiel, Hamill, and Wilhelms, 1982, 1983). Previously constructed regional cross sections of this area (Burchfiel and others, 1974; Wright and others, 1981; Grose, 1983; Grose and Smith, 1989) were consulted during construction of the sections included here. A limited amount of subsurface geologic data on the Paleozoic section is available from two boreholes in the northern Amargosa Desert (Carr and others, 1995).

Geophysical data used to constrain cross section interpretations include gravity and magnetic data from the region (McCafferty and Grauch, 1997; Grauch and others, 1999; Blakely and others, 2000) and gravity models of the thickness of Tertiary strata (fig. 6) (Blakely and others, 1998, 1999; Grauch and others, 1999). Also consulted during cross section construction were interpretations of seismic reflection data in the northern part of the Amargosa Desert (Brocher and others, 1993).

PRE-TERTIARY STRUCTURE

The Spring Mountains preserve two major, regionally extensive thrust faults, the Keystone thrust to the east and the Wheeler Pass thrust to the west (Burchfiel and others, 1974). The principal feature of the Keystone thrust is a hanging-wall flat with detachment occurring at the level of the Middle and Upper Cambrian Bonanza King Formation (sections H-24 and H-9). A structurally lower thrust is locally present beneath the Keystone thrust (Burchfiel and others, 1974). To the west, the Keystone allochthon is deformed into a ramp syncline that preserves Pennsylvanian and Lower Permian Bird Spring Formation in its axis (sections H-11, H-10, and H-9). The syncline is disrupted by a number of minor thrusts including the Mack Canyon, Lee Canyon, and Deer Creek thrusts (Burchfiel and others, 1974). The Wheeler Pass thrust places the Late Proterozoic to Lower Cambrian clastic sequence in its upper plate over the Pennsylvanian and Lower Permian Bird Spring Formation in its foot wall (section H-24). Farther to the northwest in the Spring Mountains, the structurally higher Kwichup Spring thrust also carries the Proterozoic section in its hanging wall; this thrust has been substantially modified by later extension (Abolins, 1999). Structurally high Proterozoic rocks in the northwestern Spring Mountains are interpreted to be the result of thrust duplexing of the Proterozoic rocks. This duplex may correlate with a similarly interpreted structure in the Pintwater Range (Caskey and Schweikert, 1992).

The Montgomery Mountains are continuous with the northwestern Spring Mountains and extend southwestward to bound the northern and northwestern margins of Pahrump Valley. The Montgomery thrust is the major thrust exposed in the range; it is a southeast-vergent fault that places the Late Proterozoic Stirling Quartzite on top of the Upper Ordovician Ely Springs Dolomite in the northeastern Montgomery Mountains (Burchfiel, Hamill, and Wilhelms, 1982, 1983). Based upon consistent 30°–35° dips of strata in the hanging wall, the Montgomery thrust appears to have a hanging-wall flat geometry; a southeast-overturned syncline is present in the foot wall (Burchfiel, Hamill, and Wilhelms, 1982) (sections H-9, H-27, and H-28). The thrust loses stratigraphic offset in the southwestern Montgomery Mountains where Late Proterozoic to Lower Cambrian Wood Canyon

Formation overlies Middle and Upper Cambrian Bonanza King Formation (Burchfiel and others, 1983). Continuous exposures of the Bonanza King Formation to the northwest towards Devil's Hole imply that the Montgomery allochthon overlies an extensive hanging-wall flat (sections H-27 and H-28).

Wernicke and others (1988) and Snow and Wernicke (1989) correlated the Montgomery thrust with the Wheeler Pass thrust, a correlation that requires 13–15 km of right-lateral offset on the Grapevine fault (Burchfiel and others, 1983). Burchfiel and others (1983) inferred that the Montgomery thrust dies out into folds to the northeast in the Spring Mountains, noting that the Grapevine fault preserves evidence for dip-slip movement only. We follow the work of Abolins (1999), who inferred that the Montgomery thrust lies structurally above the Wheeler Pass thrust and is correlative to the Kwichup Spring thrust in the northern Spring Mountains. Both of these thrust faults contain Wood Canyon Formation, Stirling Quartzite, and Johnnie Formation in the upper plate and are approximately on strike with one another (if normal fault movement is taken into account). Similar facies of the Johnnie Formation are present in the upper plate of both faults (Abolins, 1999). Furthermore, facies relations in Upper Mississippian strata (Stevens and others, 1991) indicate that the Montgomery thrust does not correlate with the Wheeler thrust but with a structurally higher thrust, such as the Kwichup Spring thrust.

In the central Resting Spring Range, several imbricate thrust faults are exposed that dip moderately eastward, climb up section to the south and east, and carry the Late Proterozoic to Lower Cambrian clastic section over the Lower Cambrian carbonates (sections H-12, H-10, and H-11). All of the imbricate thrust faults in the central Resting Spring Range sole into the structurally lowest Resting thrust (Burchfiel and others, 1983) and the Late Proterozoic Johnnie Formation is the oldest unit involved in the thrusting (Burchfiel and others, 1983). This suggests that the northernmost exposures of the Resting thrust are near the level of regional décollement. Just east of the Resting Spring Range, two thrust faults are exposed at the northern end of the Nopah Range. The structurally lower Shaw thrust places Middle and Upper Cambrian Bonanza King Formation over a southeast-overturned footwall syncline that contains Pennsylvanian and Lower Permian Bird Spring Formation in its core. The structurally higher Chicago Pass thrust carries Late Proterozoic Stirling Quartzite and Late Proterozoic to Lower Cambrian Wood Canyon Formation in its hanging wall over the Shaw thrust plate. Correlation of the Shaw thrust in the Nopah Range with the Resting thrust in the Resting Spring Range (Burchfiel and others, 1983) requires that the Resting thrust ramp upsection in both its footwall and hanging wall (section H-11).

The Clery thrust and the Schwaub Peak thrust are exposed in the Funeral Mountains west of the Amargosa Desert. The Schwaub Peak thrust has been correlated with the Specter Range thrust, which is exposed to the northeast in the Specter Range on the basis of similarities in stratigraphic throw, footwall structural style (Snow, 1992), and facies relationships within the footwall Upper Mississippian carbonates (Stevens and others, 1991). Both the Specter Range and Schwaub Peak thrusts place Stirling Quartzite and Wood Canyon Formation over folded Ordovician, Devonian, and Silurian strata (compare sections H-7 and H-2). A south-vergent fold in the footwall Ordovician and Silurian rocks of the Specter Range thrust fault (Burchfiel, 1965) is portrayed on sections H-28, H-27, and H-26 as a result of a blind thrust and fault-propagation-fold structure beneath the Specter Range thrust.

The pre-Tertiary structural geometry portrayed on the cross sections may be summarized by reviewing the regional thrust plate topology used during section construction (fig. 8). The farthest west and structurally highest allochthon in the region lies above the Grapevine thrust and the correlative Meiklejohn thrust at Bare Mountain and the Belted Range thrust in the vicinity of the Nevada Test Site (Snow, 1992). Below this plate lies the Schwaub Peak/Specter Range plate (Snow, 1992). The Schwaub Peak/Specter Range allochthon includes the interpreted Striped Hills imbricate thrust ramp sequence (Potter and others, 1999). This imbricate stack is interpreted to die out along strike to the west, becoming a fold in the upper plate of the Schwaub Peak thrust. The Clery/Montgomery/Kwichup Spring plate (Stevens and others, 1991; Snow, 1992) forms the footwall to the Schwaub Peak/Specter Range plate in the Specter Range and Montgomery Mountains. Beneath the Clery/Montgomery/Kwichup Spring plate lies the Baxter/Chicago Pass/Wheeler plate, which forms the northern Resting Spring Range, the southern Montgomery Mountains, and the western Spring Mountains (Burchfiel and others, 1983; Snow, 1992). The structurally lowest rocks in the Resting Spring Range form the footwall of the Resting Spring/Shaw plate, and is called the "Amargosa unit" by Burchfiel and others (1983). The "Amargosa unit" forms a small part of the Resting Spring Range and most of the Nopah Range, and correlates with the Keystone plate. The Amargosa unit comprises the complete succession of stratigraphic units from the Pennsylvanian and Lower Permian Bird Spring Formation in the northern Nopah Range to the Late Proterozoic Noonday Dolomite in the southern Nopah Range. Many meters of bedding-parallel sheared rock in the lower third of the Johnnie Formation in the southern Nopah Range suggest that the Keystone allochthon is floored by a regional décollement near the base of the Proterozoic clastic sequence in the Nopah and southern Resting Spring Range (sections H-11 and H-12).

TERTIARY EXTENSION WEST OF THE SPRING MOUNTAINS

To the west of the Spring Mountains, Tertiary extension has destroyed the once-contiguous thrust

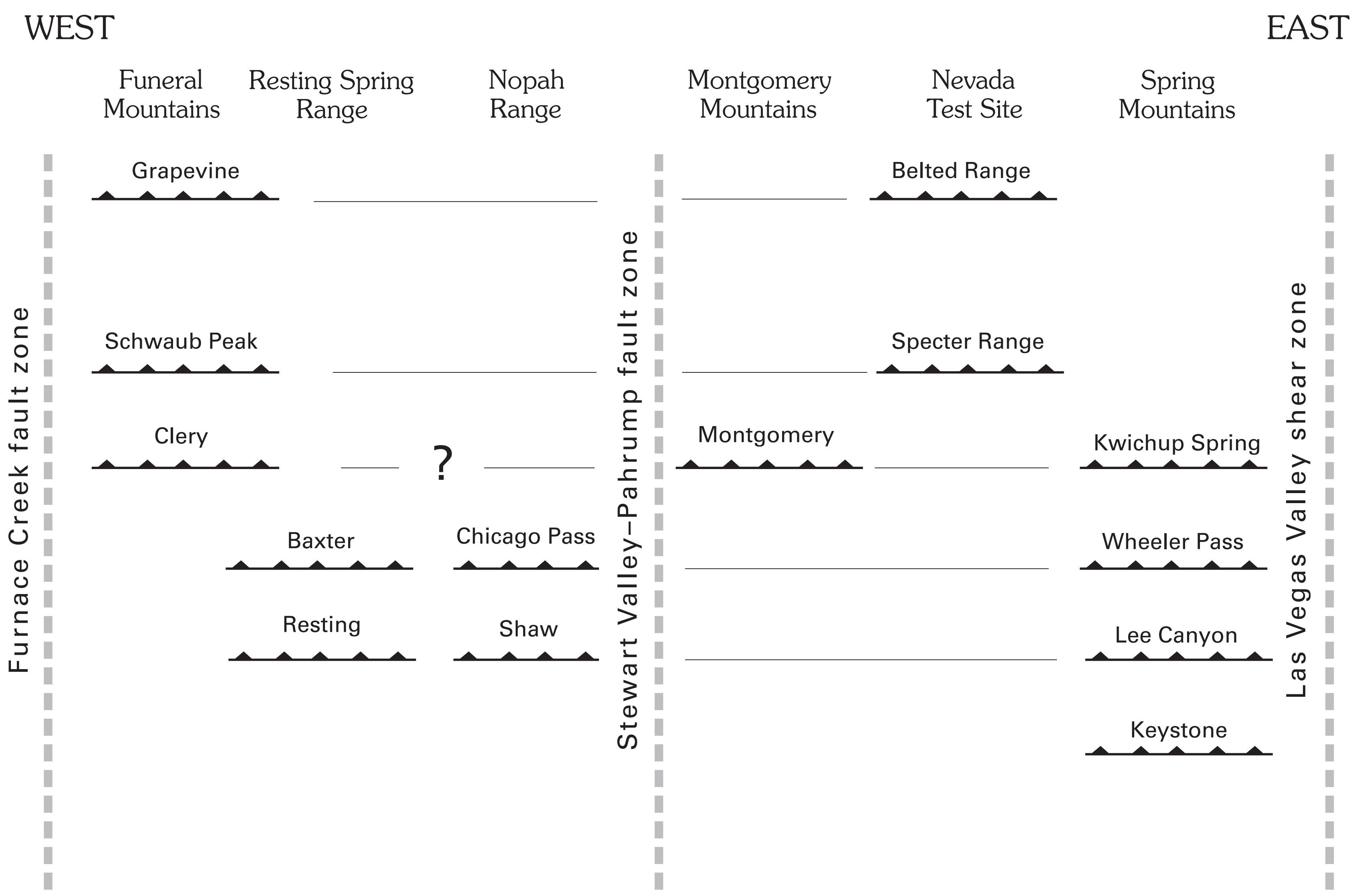

Figure 8. Correlation diagram of thrust faults in the vicinity of the Spring Mountains, Pahrump Valley, and Amargosa Desert.

belt; most of the mountain ranges preserve the Proterozoic and Paleozoic section in 30°–50° east-tilted range blocks (Wright and others, 1981; Wright and Troxel, 1973). These ranges are interpreted to be bounded by west-dipping normal faults, however the magnitude of Tertiary extension and the projection of these range-bounding faults at depth are controversial. Deep seismic reflection profiles were interpreted (Serpa and others, 1988) to suggest that the frontal faults of the Nopah and Resting Spring Ranges were gently listric and flattened into a mid-crustal detachment zone at a depth of about 15 km. However, regional estimates of extension based upon correlation of thrust faults puts the Nopah and Resting Spring Ranges within a zone of extreme crustal extension, implying that these ranges are thin slivers of crust that detached above a migrating flexure in highly thinned crust (Holm and others, 1992; Wernicke, 1992). Cross sections H-10, H-11, and H-12 adopt the style of Serpa and others (1988) in portraying these faults as being listric and extending to greater than 10 km depth before flattening into a crustal detachment.

The Grapevine fault (GVF, fig. 7) is the range front fault on the western side of the Spring Mountains, where it places the Bonanza King Formation in the hanging wall against the Johnnie Formation in the footwall (Burchfiel, Hamill, and Wilhelms, 1982, 1983) (section H-8). Kinematic indicators on the fault (Burchfiel and others, 1983) and stratigraphic facies data on either side of the fault (Abolins, 1999) indicate that the fault has predominantly normal, dip-slip offset.

A gently dipping normal fault, the Point of Rocks detachment fault is exposed at the extreme northwest end of the Spring Mountains, just south of U.S. Highway 95 (PRD, fig. 7). This fault places Cambrian Bonanza King and Nopah Formations on Late Proterozoic Stirling Quartzite and Johnnie Formation (Burchfiel, 1965; Abolins, 1999); about 2,000 m of stratigraphic section are missing where the fault is exposed. Isolated exposures of the detachment present to the southwest of Point of Rocks indicate that at least locally the fault is gently dipping (sections H-24 and H-7). We interpret the Point of Rocks fault as displacing strata down to the north-northwest off of the Spring Mountains. At depth, the Point of Rocks detachment fault is interpreted to cut down section in the hanging wall and to merge with or excise an earlier thrust fault (Abolins, 1999) (section H-24). The Point of Rocks fault may trend southward towards the Montgomery Mountains, separating isolated exposures of Cambrian carbonate rock from nearly continuous exposures of Late Proterozoic Johnnie Formation in the Montgomery Mountains (Burchfiel and others, 1983). Such a fault trace would require that this southern part of the fault dip more steeply and have oblique-slip displacement down-to-the-northwest (sections H-7 and H-19). The inferred southern part of the Point of Rocks detachment fault may be traced to a mapped steeply dipping normal fault in the Montgomery Mountains that places rocks as young as the Middle and Upper Cambrian Bonanza King Formation against Late Proterozoic Stirling Quartzite (Burchfiel and others, 1983). The northeast end of the Point of Rocks detachment is not exposed; it may connect with the western part of the Las Vegas Valley shear zone.

STRIKE-SLIP FAULTS IN PAHRUMP VALLEY AND THE AMARGOSA DESERT

The Stewart Valley–Pahrump fault zone (Stewart and others, 1968; Stewart and Crowell, 1992; Burchfiel and others, 1983), also referred to as the State Line fault zone (Hewett, 1956), is a regionally extensive, right-lateral, strike-slip fault zone that is part of the Walker Lane belt. This system of faults roughly parallels the California-Nevada boundary through the Stewart Valley and the Pahrump Valley (fig. 7). The fault zone may be as long as 150 km (Blakely and others, 1998; Schweickert and Lahren, 1997), and is estimated to have between 20 and 30 km of right lateral offset based on offset of Proterozoic and Paleozoic rocks (Stewart and others, 1968), interpreted correlations of thrust sheets, and offsets in regional facies trends (Stevens and others, 1991). The faults are almost everywhere buried by Tertiary rocks; the zone is exposed in the southern Montgomery Mountains where it juxtaposes parts of the Late Proterozoic Johnnie Formation and Stirling Quartzite (Burchfiel and others, 1983). Gravity data show that the fault is associated with complex variations in the elevation of the Paleozoic-Tertiary contact (Blakely and others, 1998). In Pahrump Valley, the Stewart Valley–Pahrump fault zone forms a buried transpressional bedrock ridge separating two steep-sided, probably fault-bounded basins (fig. 6) (Blakely and others, 1998) (sections H-11 and H-12). The basins are interpreted to be transtensional basins associated with right steps in this fault system (Wright, 1989; Blakely and others, 1998). Interpretations of gravity and magnetic data suggest that the fault system projects northwestward across the Amargosa Desert roughly parallel to the Nevada-California border (Blakely and others, 1999), rather than turning northward into Crater Flat (Schweickert and Lahren, 1997). Northwest of Stewart Valley the Stewart Valley–Pahrump fault zone forms another northwest trending bedrock ridge that separates two northwest-trending basins (fig. 6) (Blakely and others, 1999) (sections H-8 and H-19).

In the northwestern arm of the Amargosa Desert, between the Funeral Mountains and Bare Mountain, strike-slip deformation is partitioned between several faults (Fridrich, 1999a) (sections H-4, H-5, and H-6). Faults interpreted in this area include the Porter Mine fault of Fridrich (1999a) along the eastern edge of the Funeral and Grapevine Mountains, and the Carrara fault, located along the western side of Bare Mountain (fig. 7) (Stamatakos and others, 1997). Strike-slip faults are inferred to separate the Funeral Mountains from the Bullfrog Hills based on juxtaposition of different facies of Tertiary volcanic rocks (Fridrich, 1999a). The Carrara fault is projected to lie beneath the Tertiary surficial deposits on the western side of Bare

Mountain, and is inferred to have about 3 km of right-lateral strike-slip displacement and a minimum of 300 m of vertical displacement (Stamatakos and others, 1997) (sections H-23, H-5, and H-6). Regional gravity data indicate that a shallow basin exists south of the Carrara fault, between southern Bare Mountain and the Funeral Mountains (fig. 6) (McCafferty and Grauch, 1997). A relatively minor fault with north-side down and possible strike-slip offset is inferred to exist at the north end of the Amargosa Desert, just north of U.S. Highway 95 and south of Crater Flat (sections H-25 and H-26). This fault is predicated on the abrupt truncation of Miocene tuffs along an escarpment north of the highway, an abrupt truncation of magnetic anomalies along this same trend (Maps A and B, McCafferty and Grauch, 1997), and an outcrop of Miocene Ammonia Tanks Tuff that appears displaced to the west on the south side of the fault relative to where this formation crops out north of the fault (Swadley and Carr, 1987).

CROSS SECTIONS IN THE VICINITY OF DEATH VALLEY

The region covered by these cross sections (fig. 1) contains Death Valley itself, Furnace Creek Wash and parts of the Amargosa Desert to the east of Death Valley, and surrounding mountain ranges. These mountain ranges include the Grapevine and Funeral Mountains, the Panamint Mountains, the Black Mountains, and the Resting Spring Range (fig. 4). Parts or all of the following cross sections show the geology in this part of the regional flow model: (listed generally from north to south) H-15, H-14, H-13, H-1, H-2, H-3, H-4, H-5, H-6, H-16, H-7, H-8, H-17, H-19, H-9, H-10, H-11, and H-12.

There is no single published map of the entire Death Valley region that could be used as a resource during cross section construction. Instead, structural data were obtained from several larger scale maps covering smaller parts of the region. The smallest scale geologic map data used to construct the cross sections include page-size fault maps and generalized geologic maps of southern and central Death Valley (Wright, 1974; Wright and others, 1991), the 1:96,000-scale map of Hunt and Mabey (1966), and compilation maps of Death Valley produced by the California Division of Mines and Geology (Streitz and Stinson, 1977; Jennings and others, 1963; Strand, 1967). More detailed geologic maps used during cross section construction include maps of the northern and central Funeral Mountains (Wright and Troxel, 1993), the southern Funeral Mountains and the Furnace Creek Wash area (McAllister, 1970, 1973, 1974; Cemen and Wright, 1990), the Black Mountains (Drewes, 1963; Wright and Troxel, 1984; Greene, 1997), the central Panamint Mountains (Albee and others, 1981), the northern Panamint Mountains (McKenna and Hodges, 1990; Wernicke and others, 1986, 1993; Hodges and others, 1989, 1990), the Last Chance Range (Wrucke and Corbett, 1990), the Bullfrog Hills (Maldonado, 1990a; Maldonado and Hausback, 1990; Conners and others, 1998), and the Dublin Hills (Chesterman, 1973). Limited subsurface geologic data are available from boreholes in the Furnace Creek Wash area (discussed in Wright and others, 1999). Previously constructed regional cross sections that portray the Death Valley area (Wright and others, 1981; Grose, 1983) were consulted during construction of the sections included here.

The general configuration of the pre-Tertiary surface is based upon published modeled inversions of regional gravity data (fig. 6) (Saltus and Jachens, 1995; Blakely and others, 1998, 1999); a local gravity survey was conducted near the Mormon Point turtleback (Keener and others, 1993). Sections H-7 and H-6 utilize interpretations of seismic reflection data collected in the northern part of the Amargosa Valley (Brocher and others, 1993). Sections H-12 and H-22 in southern Death Valley and the southern ends of the Resting Spring and Nopah Ranges incorporate interpretations based on seismic reflection data that have been collected by the Consortium for Continental Reflection Profiling (COCORP) (Geist and Brocher, 1987; Serpa and others, 1988; Serpa, 1990). Subsurface structural features affecting Tertiary rocks in the Amargosa Desert are based in part on interpretation of aeromagnetic data from that region (Blakely and others, 2000).

GRAPEVINE/FUNERAL MOUNTAINS BLOCK

The Grapevine and Funeral Mountains preserve the upper and lower plates, respectively, of the Boundary Canyon detachment (Wright and Troxel, 1993; Hamilton, 1988). In the Grapevine Mountains, the upper plate contains weakly metamorphosed Late Proterozoic through Paleozoic rocks that are complexly deformed (Reynolds, 1974) (see sections H-4 and H-5). The pre-Cenozoic Grapevine thrust and related folds are disrupted by Tertiary extensional structures (Reynolds, 1974). The Boundary Canyon detachment in the central Funeral Mountains (fig. 7) is a gently dipping (now domical) fault (sections H-6 and H-5) that juxtaposes amphibolite-grade metamorphic rocks of the lower plate against the unmetamorphosed rocks of the upper plate across a mylonitic zone only a few meters thick (Wright and Troxel, 1993; Hamilton, 1988). The detachment is a system of faults; additional major detachments disrupt the lower plate (Wright and Troxel, 1993). The amount of apparent uplift of the lower plate is at a maximum of about 30 km in footwall rocks immediately below the detachment (Hoisch and Simpson, 1993). Metamorphic grade drops off to the southeast and successively younger (and shallower) rocks are exposed. At the southeastern end of the Funeral Mountains, Late Proterozoic and Paleozoic rocks are again exposed and feature the pre-Cenozoic Schwaub Peak and Clery thrusts (sections H-7 and H-8).

The Funeral Mountains detachment is bounded, or merges laterally with, strike-slip faults on both flanks of the Funeral Mountains. On the southwestern flank of the Funeral Mountains, the northern Death Valley fault bounds the detachment (see sections H-7 and H-6). On the eastern flank of the Funeral Mountains, the Boundary Canyon detachment projects beneath the Amargosa Desert (sections H-16 and H-6). The northwestern end of the Amargosa Desert is portrayed as being a very shallow Tertiary basin that is floored by nearly flat-lying detachment faults. The Tertiary section above the detachments is interpreted as a 500-m- to 1-km-thick upper plate that consists of listric fault blocks composed primarily of steeply dipping, highly attenuated sedimentary and volcanic rocks, similar to exposures on the east flank of the Funeral and Grapevine Mountains (Wright and Troxel, 1993) and in the Bullfrog Hills (Maldonado, 1990b). The Funeral Mountains detachment is interpreted on sections H-16, H-22, and H-6 to be separated from the Bullfrog Hills detachment (Maldonado and Hausback, 1990; Maldonado, 1990b) by a strike-slip fault (the Porter Mine fault of Fridrich, 1999a), which is the northern extension of the Stewart Valley–Pahrump fault zone (fig. 7).

NORTHERN DEATH VALLEY AND GRAPEVINE CANYON AREA

The dominant structural element in northern Death Valley is the Death Valley strike-slip fault with as much as 70–80 km of right-lateral offset. Regional gravity data indicate that the northern Death Valley basin is less 500 m deep at the north end of the valley (fig. 6), adjacent to Grapevine Canyon (Blakely and others, 1999). Farther to the south, rhombic pull-apart structures associated with this fault create deep basins filled with Upper Tertiary and Quaternary deposits (Blakely and others, 1999).

Structure in the Paleozoic rocks is complex and includes the subsurface projection of the Grapevine thrust, which places Cambrian carbonates over middle Paleozoic carbonate rocks (Reynolds, 1974). North of Grapevine Canyon, the Paleozoic carbonate rocks form a broad anticlinal fold that is complexly deformed by low-angle normal faults, high-angle normal faults, and strike-slip fault splays associated with the Death Valley fault (Oakes, 1977) (sections H-14, H-13, and H-15). These rocks are extremely hydrothermally altered in the very northern part of the range. On the basis of hydrothermal alteration of the Paleozoic section, the presence of local rhyolite dikes, and scattered granite outcrops, the Paleozoic carbonate rocks in the northernmost part of the Grapevine Mountains have been interpreted as having been domed by a granitic intrusion at shallow depths (Oakes, 1977). To the northwest on Slate Ridge, the Proterozoic clastic rocks are intruded by Jurassic and Cretaceous age granites of the Sylvania pluton (section H-1). The transition from carbonate terrane of the northern Grapevine Mountains to the Proterozoic clastic of Slate Ridge is nowhere exposed.

The Tertiary volcanic stratigraphy for the area northeast of Grapevine Canyon is dominated by the Timber Mountain Group welded tuffs (Rainier Mesa Tuff and Ammonia Tanks Tuff), but locally Pliocene rhyolitic and basaltic rocks predominate. The Timber Mountain Group tuffs are about 250 m thick in the vicinity of Bonnie Claire Flat, northeast of Grapevine Canyon, based on outcrops of Ammonia Tanks Tuff near the basin center. Based on regional gravity models (Blakely and others, 1999), the total thickness of Cenozoic rocks appears to increase toward the northeast from around 250 m near the California-Nevada State line to just over 1 km in northwestern Sarcobatus Flat, and greater than 2 km in the main part of Sarcobatus Flat (fig. 6). As such, there may be a significant thickness of older volcanic rocks beneath the Timber Mountain Group rocks.

CENTRAL DEATH VALLEY VOLCANIC/PLUTONIC FIELD AND THE FURNACE CREEK BASIN

East of the Black Mountains, west of the Resting Spring Range, and south of the Furnace Creek Range is a synextensional basin occupied by an assemblage of Tertiary sedimentary, volcanic, and plutonic rocks that form the central Death Valley volcanic/plutonic field and the Furnace Creek basin (Wright and others, 1991, 1999). This region is bounded on the north and northeast by the Furnace Creek fault, on the east by normal faults that bound the western side of the Resting Spring Range, and on the south by the Sheephead fault and southern Death Valley fault (fig. 7) (Wright and others, 1991). The Furnace Creek–Death Valley fault is a major northwest-striking right-lateral strike-slip fault that is over 250 km long with as much as 68 km of right-lateral offset (Stewart and others, 1968; Snow and Wernicke, 1989). The fault separates more highly extended rocks to the south and west from less extended rocks of the southern Funeral Mountains and the Resting Spring Range (Wright and others, 1999). Lateral offset along the fault is interpreted to diminish to the southeast (Wright and Troxel, 1967). Near Eagle Mountain, the fault, or kinematically related faults, curve southward as gently dipping, north- to northeast-striking, down-to-the-west normal faults that bound the east side of the Furnace Creek basin. Detailed mapping (Burchfiel, Hamill, and Wilhelms, 1982) shows several large fault blocks rotated along listric normal faults just along the western side of the Resting Spring Range, approximately along strike with the Furnace Creek fault; these listric faults indicate shallow crustal extension to the west near the terminus of Furnace Creek fault (sections H-9 and H-26). Strata on Eagle Mountain west of the Resting Spring Range and south of the Furnace Creek fault are also rotated to the east as if into a listric normal fault. Besides the bounding structures, the entire synextensional basin is characterized by generally curved faults that trend northeast and are presumably listric (see section H-11). Also present are intrabasinal faults with right-lateral motion, such as the Grand View fault that lies between the Greenwater Range and the Black Mountains.

The Cenozoic intrusive and extrusive rocks in the Death Valley area are younger than 16 Ma and were emplaced during Tertiary extension. Volcanic rocks of the central Death Valley plutonic/volcanic field consist of predominantly silicic- to intermediate-composition lava flows and associated fallout tephra erupted from various centers within the 11.5- to 5.0-Ma time interval (Wright and others, 1991). Only one relatively widespread welded ash-flow tuff, the Rhodes Tuff, is recognized within the volcanic field (Wright and others, 1991); most of the volcanic units appear to be associated with local source areas (for example, H-11 shows the Brown Peak volcanic center) and have limited areal distribution (Wright and others, 1991). No volcanic rocks associated with the central Death Valley volcanic field are known in outcrop north of the Furnace Creek fault zone, however it is possible that some volcanic rocks are present in the subsurface. The general absence of strong magnetic anomalies in the vicinity of the Amargosa Desert between the southwestern Nevada volcanic field and the central Death Valley volcanic/plutonic field (Blakely and others, 2000) implies that strongly magnetic volcanic rocks from either field are thin or absent (Carr, 1990; Blakely and others, 2000). The volcanic section overlies either Tertiary granites or Precambrian metamorphic rocks. West of the Grandview fault, the Tertiary plutonic rocks include the Willow Creek gabbro-diorite pluton and the granite at Smith Mountain, which overlie the Death Valley turtlebacks (see sections H-11 and H-10). These plutons were apparently intruded at mid-crustal depths and uplifted with the lower plates of the turtlebacks during Tertiary extension (Asmerom and others, 1990; Holm and others, 1994). East of the Grandview fault, plutonic rocks include higher level Tertiary granite plutons of the central Death Valley–Kingston Range belt, which intrude the volcanic pile and most of the extensional faults (Wright and others, 1991) (see sections H-11 and H-12).

To the north of the central Death Valley plutonic/volcanic field, the Furnace Creek basin is a synextensional sedimentary trough closely associated with the Furnace Creek fault zone. The principal sedimentary units within the Furnace Creek basin are the 14- to 6-Ma Artist Drive Formation, the 6- to 4-Ma Furnace Creek Formation, the Greenwater Volcanics that are intercalated with Furnace Creek Formation, and the Funeral Formation. Geology and stratigraphic relations within this basin are discussed by Cemen and others (1985), Greene (1997), and Wright and others (1999). The Billie Mine block (section H-19) is a structurally high block within the Furnace Creek basin (see section H-19). The Billie Mine block is interpreted to be a transpressional pop-up related to splays of the Grand View fault with as much as 1.6 km of structural relief (Greene, 1997; Wright and others, 1999).

Geophysical models predict a much thinner Tertiary sedimentary section within the Furnace Creek basin than would be inferred based upon the known thickness of the Tertiary units. A modeled thickness of the Cenozoic basin fill based on a mathematical inversion of gravity data (Blakely and others, 1998) predicts that the Furnace Creek basin is in many places only ½ km deep, and locally 1 km deep (fig. 6). However, the total stratigraphic thickness of the three principal Tertiary units within the basin is at least 2 km. Many of these sediments contain abundant Paleozoic carbonate rock clasts, and thus may be considerably denser than expected. Still, only part of the disparity between the modeled thickness and the stratal thickness can be accounted for by varying density-depth assumptions (Blakely and others, 1999). One possible solution, shown on section H-19, is that a wedge of structurally disrupted and attenuated Late Proterozoic and Paleozoic rocks underlies the Tertiary basin fill to the south of the Furnace Creek fault. Wright and others (1999) described the few bedrock exposures of Late Proterozoic and Paleozoic rocks within the basin. Paleozoic rocks penetrated by the workings of the Billie Mine are brecciated and structurally attenuated. Although not interpreted as strictly part of the Amargosa chaos (Wright and others, 1999), Paleozoic rocks beneath the basin must in a general way be "chaos-like", forming a disrupted and attenuated section that structurally overlies the ductilely deformed crystalline complex that is presumed to underlie the basin. The identity of these rocks on the cross sections is in general not defined—we infer that the "chaos-like" intervals could range from rotated, fault-bounded blocks as much as the size of Eagle Mountain, to complexly faulted brecciated rock. On cross sections H-19, H-9, and H-10, no attempt has been made to construct a full Paleozoic sequence south of the Furnace Creek fault, these units are labeled PzZx and are interpreted to have been thoroughly structurally disrupted and covered by synextensional Tertiary volcanic and sedimentary rocks. Sections that are farther south portray Tertiary intrusive rocks at depth.

THE BLACK MOUNTAINS

The crystalline core of the Black Mountains, to the east of Death Valley, lies beneath a major system of gently inclined normal faults, above which the Panamint Mountains west of the valley have moved. These major, low-angle detachment faults are expressed in three structural culminations, the Death Valley turtlebacks (BWT, CCT, and MPT on fig. 7). The origin of these features has been controversial (for example, see review paper by Hamilton, 1988) but they are generally considered to be analogous to metamorphic core complexes in that they are domical, consist of a core of gneiss that dips away from the domes, and are overlain by deformed but unmetamorphosed rocks that are separated from the gneissic core by mylonitized rocks beneath the detachment surface (Crittenden and others, 1980; Wernicke, 1992). The three turtlebacks are overlain by Tertiary sedimentary and volcanic rocks cut by abundant listric normal faults that flatten and merge with the detachment faults atop the turtlebacks (Greene, 1997) (see sections H-9 and H-11). Overlying the Middle Proterozoic gneissic basement that cores the turtlebacks is a mid-crustal dioritic pluton, the Willow Spring pluton (Asmerom and others, 1990; Holm and others, 1994) (see sections H-11 and H-10). This pluton is floored by the core complex itself and appears to have acted as a brittle cap above the ductilely deforming metamorphic rocks beneath (Holm and others, 1994). The fault surface of the Badwater turtleback is known to be a composite surface, consisting of low-angle and high-angle segments (Miller, 1991). On the cross sections, these fault surfaces are shown as gently domed and project gently to the east, north, and northwest beneath the Tertiary section. The cross sections show the gently dipping turtleback surface being truncated by an active range-front fault on the Death Valley side (Keener and others, 1993).

Associated with the turtlebacks is another famous Death Valley feature, the Amargosa chaos (Noble, 1941; Wright and Troxel, 1999). These intricately faulted rock units were understood to be related to a gently dipping structural feature that separated the basement rocks from the chaos and was termed the "Amargosa thrust". The chaos was known to include fault blocks of Late Proterozoic sedimentary rocks, Cambrian sedimentary rocks, and Tertiary volcanic, plutonic, and sedimentary rocks. Wright and Troxel (1984) were the first to recognize the chaos and the associated fault as being attenuated section above a major extensional detachment feature (section H-12).

THE PANAMINT MOUNTAINS

The Panamint Mountains bound the western side of central Death Valley, Calif. The mountains consist largely of Middle Proterozoic gneissic basement overlain by Late Proterozoic sedimentary rocks (Hunt and Mabey, 1966; Labotka and others, 1980; Albee and others, 1981). Paleozoic rocks are preserved on Tucki Mountain, at the north end of the range, where they form the upper plate of the Tucki Mountain detachment (Wernicke, and others, 1986; McKenna and Hodges, 1990). Upper Paleozoic and Mesozoic rocks are preserved in the southern part of the range where they occupy the footwall of an interpreted thrust fault (Wrucke and others, 1995). Tertiary volcanic rocks occur in the southern part of the range, and in fault-bound slices along the eastern flank of the range (McKenna and Hodges, 1990).

The central Panamint Mountains are dominated by a north-northwest-trending anticline cored by the metamorphic gneiss (Labotka and others, 1980; Albee and others, 1981; Labotka and Albee, 1990). The Mesozoic Hall Canyon and Skidoo plutons are sill-like, generally concordant with the metamorphic fabric, and intruded at approximately the Pahrump Group–Johnnie Formation contact (Hunt and Mabey, 1966) (see sections H-8 and H-16). The Proterozoic rocks have been broadly folded, cut by numerous north-striking, steeply dipping normal faults and intruded by the Miocene Little Chief stock (Albee and others, 1981; Labotka and Albee, 1990) (see sections H-11 and H-10).

Late extensional structures are at least partly responsible for the unroofing of the range. The range is bounded on the east, north, and west sides by diachronous extensional structures that as a whole have been termed the Tucki Mountain detachment system (Wernicke and others, 1986; McKenna and Hodges, 1990). This system of northwest-directed extensional structures has been best described at the northern end of the Panamint Mountains at Tucki Mountain (Wernicke and others, 1986; Hodges and others, 1987) but has been mapped southward along the east side of the range (McKenna and Hodges, 1990; Andrew, 2000) as the Harrisburg fault, although its total extent along the east side of the range is not well defined. Extensional detachments along the east and north sides of the range are domed and dip subparallel to the dip of the strata (for example, see sections H-8, H-19, and H-9). The west side of the range is bounded by an even younger detachment, the Emigrant fault (Hodges and others, 1987, 1989). This system of faults dips gently to the west, cuts the detachments that bound the east side of the range, and places Miocene and Pliocene sedimentary rocks and rock avalanche deposits against the Late Proterozoic section (Hodges and others, 1989; Cichanski, 2000) (see sections H-8, H-16, and H-19).

A major, gently west-dipping normal fault zone, called the East Panamint fault system, is intermittently exposed at the base of the Panamint Mountains. This fault zone has Middle Proterozoic gneissic basement in its footwall and the Late Proterozoic clastic section in its hanging wall (Hamilton, 1988). The fault zone also contains a complex assemblage of tectonized lenses of Paleozoic strata and tilted Tertiary Trail Canyon volcanic sequence (McKenna and Hodges, 1990) that serves to date major motion on this fault (see sections H-19 and H-9). Late Proterozoic clastic rocks are interpreted on the cross sections to be absent to the east of this fault. The cross sections that portray the configuration of the basement within Death Valley itself mostly show a tectonically denuded surface of Proterozoic gneissic basement unconformably overlain by Tertiary sections that contain Miocene syntectonic sedimentary rocks and possibly volcanic rocks equivalent to the Trail Canyon volcanic sequence (McKenna and Hodges, 1990) (see sections H-11, H-9, and H-19).

CROSS SECTIONS TO THE EAST OF THE NEVADA TEST SITE

The area east of the Nevada Test Site (fig. 1) extends from the Halfpint Range eastward to the Sheep Range and Pahranagat Valley area. The region includes the Spotted Range, the Pintwater Range, the Desert Range, the Sheep Range, and the Pahranagat Range, as well as large intervening valleys including Emigrant, Tikaboo, and Desert Valleys (fig. 4). Parts or all of the following cross sections show the geology in this part of the Death Valley ground-water basin: (from north to south) H-1, H-2, H-3, H-18, H-4, H-5, and H-7, and (from west to east) H-20, and H-21.

Geologic map data used to construct these cross sections include geologic maps of Lincoln County (Tschanz and Pampeyan, 1970) and Clark County (Longwell and others, 1965), as well as maps and published interpretations from the Indian Springs area (Guth, 1981, 1990) and the Pahranagat area (Jayko, 1990).

Geophysical data used to constrain cross section interpretations include gravity and magnetic data from the region (Kane and others, 1979; Healey and others, 1981; Saltus and Snyder, 1986; Saltus and Ponce, 1988) and gravity models of the thickness of Tertiary strata (Saltus and Jachens, 1995; Blakely and others, 1999).

The pre-Tertiary structure of this area is dominated by the Gass Peak thrust, a large, east-vergent thrust that places Late Proterozoic Stirling Quartzite and Late Proterozoic to Lower Cambrian Wood Canyon Formation over highly folded and locally overturned Pennsylvanian and Permian carbonate strata (Longwell and others, 1965; Guth, 1981) (sections H-2 and H-3). The thrust extends for at least 140 km along the eastern side of the Sheep Range and southward into the Las Vegas Range (Longwell and others, 1965; Guth, 1981). North of the Pahranagat shear zone, the thrust has been correlated with the Pahranagat and Mount Irish thrusts in the Pahranagat Range (Longwell and others, 1965; Taylor and others, 2000). The Gass Peak thrust is correlated with the Wheeler Pass thrust in the Spring Mountains on the basis of consistent structural level and footwall structural style (Longwell, 1974; Guth, 1981). Net horizontal displacement could exceed 30 km (Guth, 1981). In the Las Vegas Range, subhorizontal upper plate Cambrian and Ordovician strata imply a hanging-wall flat; the abrupt appearance of strata as young as Mississippian in the Sheep Range to the west suggests the presence of a hanging-wall ramp syncline (sections H-2, H-5, and H-7). A relatively minor, steeply west dipping thrust fault, called the Pintwater thrust, extends for about 25 km along the west side of the Pintwater Range and has about 1 km of stratigraphic separation (Longwell and others, 1965; Guth, 1990) (section H-5).

West of the Sheep Range, the Gass Peak thrust plate is folded into a regional, north-trending fold pair, the Pintwater anticline (Longwell and others, 1965) and the Spotted Range syncline (Barnes and others, 1982). The folds are traceable for about 100 km and have a combined width that spans four mountain ranges (the Sheep, Desert, Pintwater, and Spotted Ranges). Late Proterozoic Johnnie Formation is exposed at the core of the Pintwater anticline; structural relief of the fold pair may be as great as 7 km (Caskey and Schweickert, 1992). Guth (1990) inferred that the Pintwater anticline was primarily the result of isostatic uplift related to denudation of the upper plate above a major extensional detachment. However, gravity data do not appear to support the presence of structurally high crystalline basement beneath the Desert Range that would be required by models of the region that invoke extreme extension (Guth, 1990). Cross sections H-2, H-4, H-3, and H-5 portray a more moderate amount of extension and infer that the Pintwater structural high is primarily the result of a duplex within the Proterozoic clastic section at depth (Caskey and Schweikert, 1992).

The Las Vegas Valley shear zone (sections H-7 and H-8) is interpreted as a system of right-lateral strike-slip faults, based on displacement of thrust faults on either side of the shear zone (Longwell, 1974; Stewart and others, 1968) and evidence of oroflexural bending (Albers, 1967) related to dextral slip, as defined by arcuate trends in the strike of tilted beds and fold axes (Burchfiel, 1965; Guth, 1981; Wernicke and others, 1984). Right-lateral offset of correlative features across the Las Vegas Valley shear zone is estimated to be from 40 to 66 km (Longwell, 1974). This offset is accomplished by a combination of fault offset and folding, but the relative amount of displacement related to faulting and to bending varies along the structure. The correlative Gass Peak and Wheeler Pass thrusts are displaced 23 km by the fault, and bending north of the fault zone accounts for another 22 km of displacement (Burchfiel, 1965). Offset by strike-slip faulting decreases dramatically northwestward, becoming negligible in the Spotted Range–Specter Range area, where the shear zone is inferred to die out into a zone where all of the displacement is taken up by bending. Paleomagnetic studies indicate that the clockwise bending in ranges along the north side of the Las Vegas Valley shear zone represents a broad zone of shear accommodated by vertical axis rotation of blocks on the order of a few kilometers in lateral dimension (Nelson and Jones, 1987; Sonder and others, 1994). The right-lateral offset along the Las Vegas Valley shear zone has been interpreted as accommodating differential amounts of extension on either side of it (Wernicke and others, 1984; Wernicke, 1992).

North of the Las Vegas Valley shear zone, Tertiary extensional faults have overprinted the Mesozoic thrust belt (Guth, 1981, 1990; Wernicke and others, 1984). The extensional faults are part of the Sheep Range detachment, a system of down-to-the-west normal faults that are inferred to flatten and converge at depth into a deep detachment zone, based upon significant rotation of bedding in the eastern part of the region (Guth, 1981, 1990; Wernicke and others, 1984). These listric faults are portrayed on cross sections H-5 and H-3 where they are shown as disrupting the continuity of the Gass Peak allochthon. Tertiary sedimentary deposits filled syntectonic basins that formed with the major extensional faults of the Sheep Range detachment system (Guth and others, 1988). Gravity models portray most of these basins as being relatively shallow, having mostly less than a kilometer of Tertiary sediments (section H-5).

The Pahranagat shear zone is a northeast-trending system of left-lateral strike-slip faults at the northern end of the Sheep Range (Jayko, 1990) (section H-2). The fault zone is about 13 km wide, extends for at least 40 km along strike and consists, from south to north, of three principal faults: the Maynard Lake fault, the Buckhorn fault, and the Arrowhead Mine fault (Jayko, 1990). All of the faults in the Pahranagat shear zone dip steeply to the northwest and show oblique-slip as well as left-lateral strike-slip displacement. The faults end at the north end of

Desert Valley where they may link kinematically to the Sheep Range detachment (Wernicke and others, 1984); the faults cannot be traced through the Desert and Pintwater Ranges (Jayko, 1990).

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