STRATIGRAPHIC ANALYSIS AND REGIONAL CORRELATION OF OLIGOCENE AND EARLY MIOCENE STRATA IN THE YUCCA MOUNTAIN AREA

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ABSTRACT

The U.S. Department of Energy has investigated Yucca Mountain, Nevada, as a potential geologic repository for disposal of high-level nuclear waste. Below Yucca Mountain, groundwater flows in fractured middle Miocene volcanic tuffs and transitions to sedimentary and alluvial deposits in the vicinity of Southern Fortymile Wash. A robust characterization of the groundwater flow system is an important element in assessing long-term performance of a potential repository. However, in the area of southern Fortymile Wash, there is an inherent uncertainty among the characteristics of groundwater flow from the volcanic aquifer to the alluvial aquifer because contacts and the transition zone between the volcanic tuffs and the alluvial deposits are poorly characterized and constrained. In the area of southern Fortymile Wash, volcanic tuffs thin out to their southern distal extent. They were deposited on thick premiddle Miocene sedimentary sequences, were interfingered with middle Miocene alluvial deposits, and were ultimately covered by postmiddle Miocene alluvial deposits. Uncertainty in the characteristics and location of the aquifer transition zone from tuff to alluvium has been reduced during the past decade with results from boreholes drilled by Nye County. This drilling program revealed the presence in the subsurface of thick premiddle Miocene sedimentary sequences that were correlated with outcrops of comparable sedimentary sequences to the west and east of Yucca Mountain. For understanding the overall tectonic framework of the region, it was also important to consider the pre- and early-Miocene stratigraphy of the sedimentary and volcaniclastic rocks in the region, because these rocks record or reflect local and regional tectonic and volcanic events prior to the middle Miocene volcanic events that formed Yucca Mountain.

The objective of this report is to capture and summarize the U.S. Nuclear Regulatory Commission and Center for Nuclear Waste Regulatory Analyses staffs understanding of regional geologic characteristics of sedimentary basins downgradient of Yucca Mountain and their contribution to the groundwater flow systems and the long-term repository performance. This report considered a wide east-west study area of about 200 km [124 mi], with emphasis on the correlation of the Oligocene and Miocene strata of Fortymile Wash and the Nevada Test Site to the east with the Titus Canyon and equivalent strata in the Funeral and Grapevine Mountains to the west.

In the seven stratigraphic sections measured in the Funeral and Grapevine Mountains, 15 lithofacies were defined. These 15 lithofacies are interpreted to represent alluvial, lacustrine, palustrine, and volcanic depositional environments that reflect active faulting and basin subsidence in an extensional deformation regime. The 15 lithofacies are grouped into 4 lithofacies associations (LAs) representing common depositional processes and environments.

LA 1, dominantly composed of conglomerates and breccia, is attributed to Oligocene proximal alluvial fan development associated with faulting and graben formation activities.
LA 2, stratigraphically above LA 1, is composed mostly of conglomerates, distinct from those of LA 1, and of stratified sandstone. LA 2 represents braided fluvial network environments that drained from south to north. LA 3 is composed of volcanic and volcaniclastic conglomerate and sandstone, massive ashflow deposits, and ashfall tuff deposits. LA 3, stratigraphically above LA 2, is interpreted to represent further attenuation of the crust within the extensional regime that allowed the wide basin to continue to expand and the continental crust to thin out to a point that produced local synchronous volcanism. LA 4 is composed of three freshwater calcareous biomicrite lithofacies dominated by the presence of oncoids, stromatolites, or gastropods with minor coarse sand to pebble intervals and fine-grained clastic sequences. LA 4 is interpreted as representing lacustrine and palustrine environments established throughout the periods of

deposition of LA 2 and LA 3. These sediments became interbedded within various alluvial-fan deposits of LA 2 and LA 3 in topographically low areas at the distal edges of alluvial-fan systems throughout the period of overall basin subsidence. New preliminary regional correlations of the stratigraphy of Oligocene to early Miocene sedimentary and volcaniclastic strata to the west of Yucca Mountain have been established with strata to the south and east of Yucca Mountain.

The studies in this report produced several significant results.

(1) During the Oligocene and early Miocene, thick sedimentary and volcaniclastic sequences were deposited over a wide area of Nevada and eastern California in an expanding, complex, continental sedimentary basin. New regional correlations have been drawn between these sequences of deposits.

(2) The Yucca Mountain tuffs were deposited in an area with complex paleogeography and topography resulting from the deposition of thick Oligocene to early Miocene sedimentary and volcaniclastic sequences in an expanding continental basin. This paleogeography influenced the geometry of the tuffs, especially near their southern distal ends in the southern part of Fortymile Wash. In turn, this setting resulted in a complex and uncertain zone of contacts and transitions between the tuffs and older and younger sedimentary strata. Thus, the interpretation of the tuffs as having a fairly regular layer geometry may be oversimplified.

(3) The geologic record suggests that active Oligocene to early Miocene alluvial fans and lacustrine depositional environment systems developed in the presence of significant topographic relief due to active faulting during deposition prior to the middle Miocene Yucca Mountain tuffs formation. In contrast with other regional geologic and tectonic interpretations, substantial extensional deformation of the region began by Oligocene time to accommodate the sedimentation of these thick Oligocene to early Miocene continental sedimentary and volcaniclastic sequences.

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The study incorporates work carried out by Ms. Michele Gutenkunst as part of her master's thesis at Purdue University (Gutenkunst, 2006). Ms. Gutenkunst worked at CNWRA as a summer intern and was supervised at Purdue University by Dr. Kenneth Ridgway, Professor of Earth Sciences. Professor Ridgway worked under a consulting contract to CNWRA.

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: Stratigraphic data, including measured stratigraphic sections were collected while Ms. Gutenkunst was employed as a summer student at CNWRA. These data meet quality assurance requirements described in the CNWRA Quality Assurance Manual. Sources of other data, including those data from sections of Ms. Gutenkunst's thesis, including thin section analyses and radiometric age dates, were obtained through her other research funds at Purdue University. The sources of these data should be consulted to determine the level of their quality. Documents published by U.S. Department of Energy (DOE) contractors and supporting organizations were generated under the quality assurance program DOE developed for the Yucca Mountain project.

ANALYSES AND CODES: Maps and related geographic information system (GIS) data were generated and plotted by the software ArcView GIS© Versions 3.1 and 3.2a (ESRI, 2000, 1998), which are commercially available software codes that are maintained in accordance with CNWRA Technical Operating Procedure TOP–018.

References

Gutenkunst, M.L. "Stratigraphic and Geochronologic Analysis of Eocene-Miocene Synextensional Strata in the Grapevine and Funeral Mountains of Southwestern Nevada and Southeastern California: Implications for Regional Correlation of 'Pre-Basin and Range Stratigraphy." Master's Thesis. Purdue University. West Lafayette, Indiana. 2006.

ESRI. "ArcView GIS©." Version 3.2a. Redlands, California: ESRI. 2000.

ESRI. "ArcView GIS©." Version 3.1. Redlands, California: ESRI. 1998.

1 INTRODUCTION

1.1 Purpose

The U.S. Department of Energy (DOE) investigated Yucca Mountain, Nevada, located in the southern part of the Great Basin (Figure 1-1), as a potential geologic repository for permanent disposal of high-level nuclear waste. Risk-based performance assessment of this potential repository required consideration of potential pathways for radionuclide migration in the geosphere. The saturated zone beneath Yucca Mountain constitutes a potential groundwater flow pathway for radionuclide transport, but could also act as a potential natural barrier because radionuclide concentrations in groundwater can be substantially reduced by sorption onto mineral surfaces or by diffusion into the matrix of relatively impermeable rocks. Groundwater flow pathways originating from the water table beneath Yucca Mountain are conceptualized as flowing initially within fractured volcanic tuffs and transitioning to alluvial deposits in the vicinity of Southern Fortymile Wash prior to reaching the regulatory compliance boundary.

The alluvial aquifer system beneath Southern Fortymile Wash was of particular interest as a potential natural barrier because of the slower groundwater flow velocity and higher sorption capacity compared to that of the upstream volcanic tuff aquifers. Both DOE and the U.S. Nuclear Regulatory Commission (NRC) identified the retardation of radionuclides in the saturated alluvium as important to isolating high-level waste (e.g., Bechtel SAIC Company, LLC, 2004; NRC, 2004). Accordingly, reducing uncertainty on the characteristics of the groundwater flow system and the total distance that flow paths from beneath Yucca Mountain travel in alluvial deposits prior to reaching the compliance location is relevant and important to consider in the overall performance assessment of that potential repository.

Uncertainty in the location of the interface where the saturated zone transitions from tuff to alluvium, south of Yucca Mountain, has been reduced during the past decade as a result of information obtained from numerous boreholes drilled by Nye County (e.g., Bechtel SAIC Company, LLC, 2003). In addition to the depth-to-water measurements and hydraulic test data obtained from the Nye County boreholes, sedimentary rock samples and, in some wells, intact core samples have been obtained. These sedimentary rock and core samples, when considered in light of surface-based geophysical measurements and sedimentary rock samples obtained from outcrops, provided useful additional insight into the sedimentary and erosional sequences that produced the complex hydrostratigraphy of the alluvial basins in the Yucca Mountain region. Southern Fortymile Wash basin is one of those basins, closest to and downgradient of Yucca Mountain.

In addition to hydrostratigraphic information, the geologic and stratigraphic data and interpretations discussed in this report support evaluations of the DOE seismotectonic and volcanic hazard assessments. Development of seismic and volcanic hazard assessments is based in part on interpretations of the geologic record, including the nature and timing of tectonic forces that controlled development of the fault and volcano systems in the Great Basin. It was therefore important to establish knowledge on the pre- and early Miocene stratigraphy of the sedimentary and igneous formations in the region, because the rocks of these formations record or reflect local and regional tectonic and volcanic events prior to the late Miocene volcanic events that formed the strata in Yucca Mountain. In the overall tectonic framework of the region, it is important to assess deformation that occurred prior to and after the emplacement of the Yucca Mountain volcanic tuffs. For example, staff used these sedimentary and volcanic strata to quantify fault displacements to constrain palinspastic and topographic

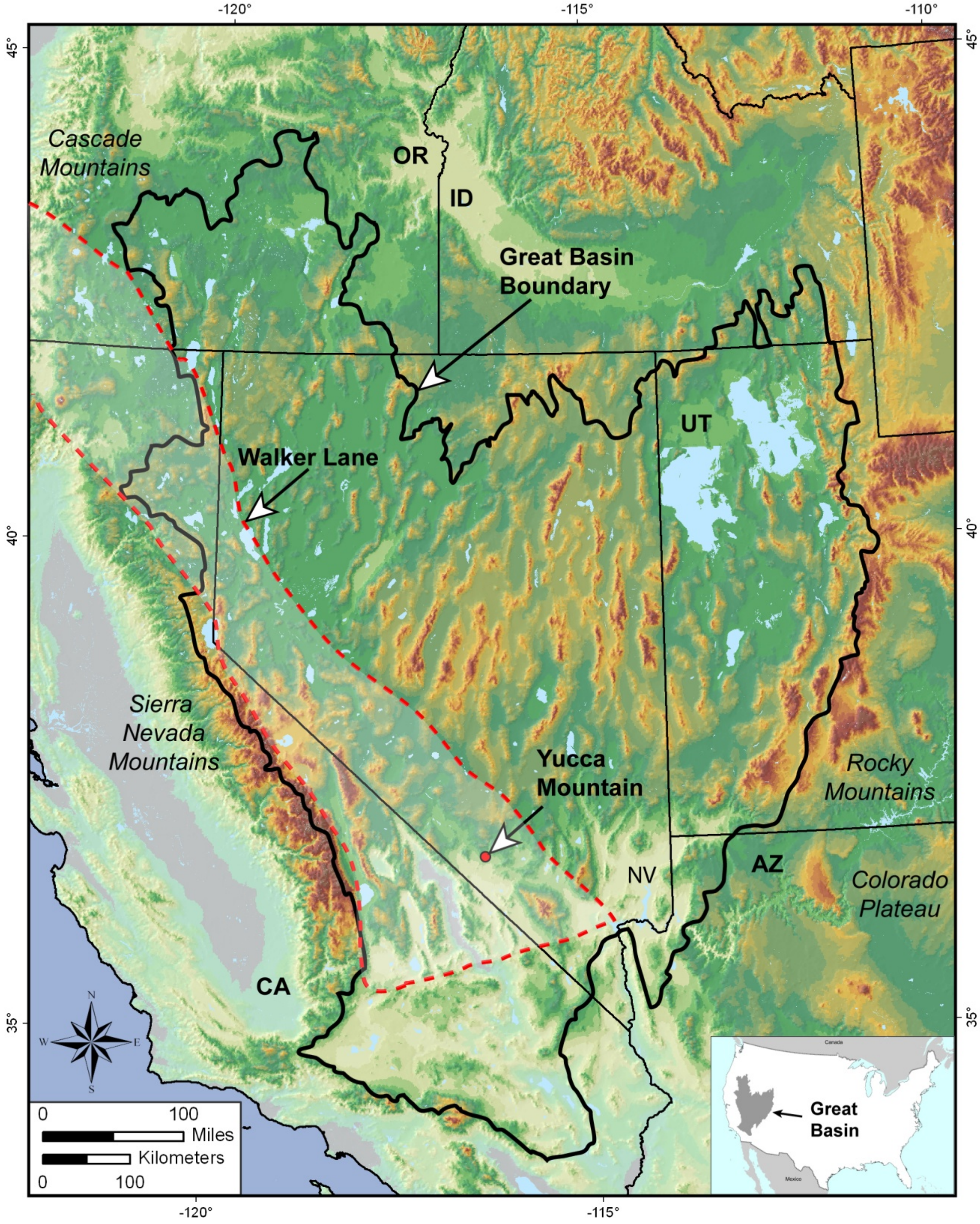

Figure 1-1. Physiographic Provinces of the Western United States

reconstructions of the region prior to the onset of late Miocene volcanism that laid down the Yucca Mountain volcanic tuffs.

The purpose of this report is to capture and summarize the NRC and Center for Nuclear Waste Regulatory Analyses (CNWRA®) staffs understanding and knowledge of regional and site geologic characteristics of the stratigraphic and structural framework of valley-fill sedimentary strata downgradient of the proposed Yucca Mountain repository. This knowledge was used to assess DOE conclusions regarding the nature of the valley-fill sedimentary aquifer and its role in repository performance. The information also was used to assess the overall tectonic setting and application of tectonic and stratigraphic information to seismic and volcanic hazard assessments. Thus, this report, similar to McKague, et al. (2010), captures NRC and CNWRAstaff knowledge on pre-repository host horizon emplacement geology and the focus needed to better assess the contribution of the natural system in a repository performance.

1.2 Background

Yucca Mountain lies within the Walker Lane Belt near the western edge of the Basin and Range physiographic province (Stewart, et al., 1968; Stewart, 1998). It is also located within the Great Basin of the southwestern United States, a region of interior drainage bounded on the west by the Sierra Nevada and the Cascade Range and on the east by the middle Rocky Mountains and the Colorado Plateau (Figure 1-1). The Basin and Range physiography is characterized by subparallel, north-trending mountain ranges that separate elongate and internally drained alluvial valleys. The valleys and ridges are the result of block-faulting related to Cenozoic (last 65 Ma[1]) extensional tectonics of western North America (Burchfiel, 1965; Stewart, 1988).

The ridge of exposed rocks forming Yucca Mountain includes several structural blocks that were tilted to the east on west-dipping high-angle normal faults (Day, et al., 1998). Two sedimentary basins flank Yucca Mountain: Crater Flat to the west and Jackass Flats to the east (Figure 1-2). Fortymile Wash, located in the western part of Jackass Flats and adjacent to Yucca Mountain to the east, is a desert wash characterized by ephemeral flows (Ressler, et al., 2000). The Amargosa Desert is a sedimentary basin located to the south of Yucca Mountain (Figure 1-2).

The general stratigraphy of the Yucca Mountain region consists of thick accumulations of Cenozoic sedimentary and volcanic strata deposited on multiply deformed Paleozoic and Precambrian rocks (older than 245 million years). Mesozoic rocks (245–65 million years old) are not present, reflecting the active convergent tectonics that characterized the Cordillera at that time in addition to exhumation and erosion of the ranges that followed during extensional deformation during the Cenozoic (last 65 million years).

[1]The symbol Ma stands for megaannum, which is equal to 1 million years.

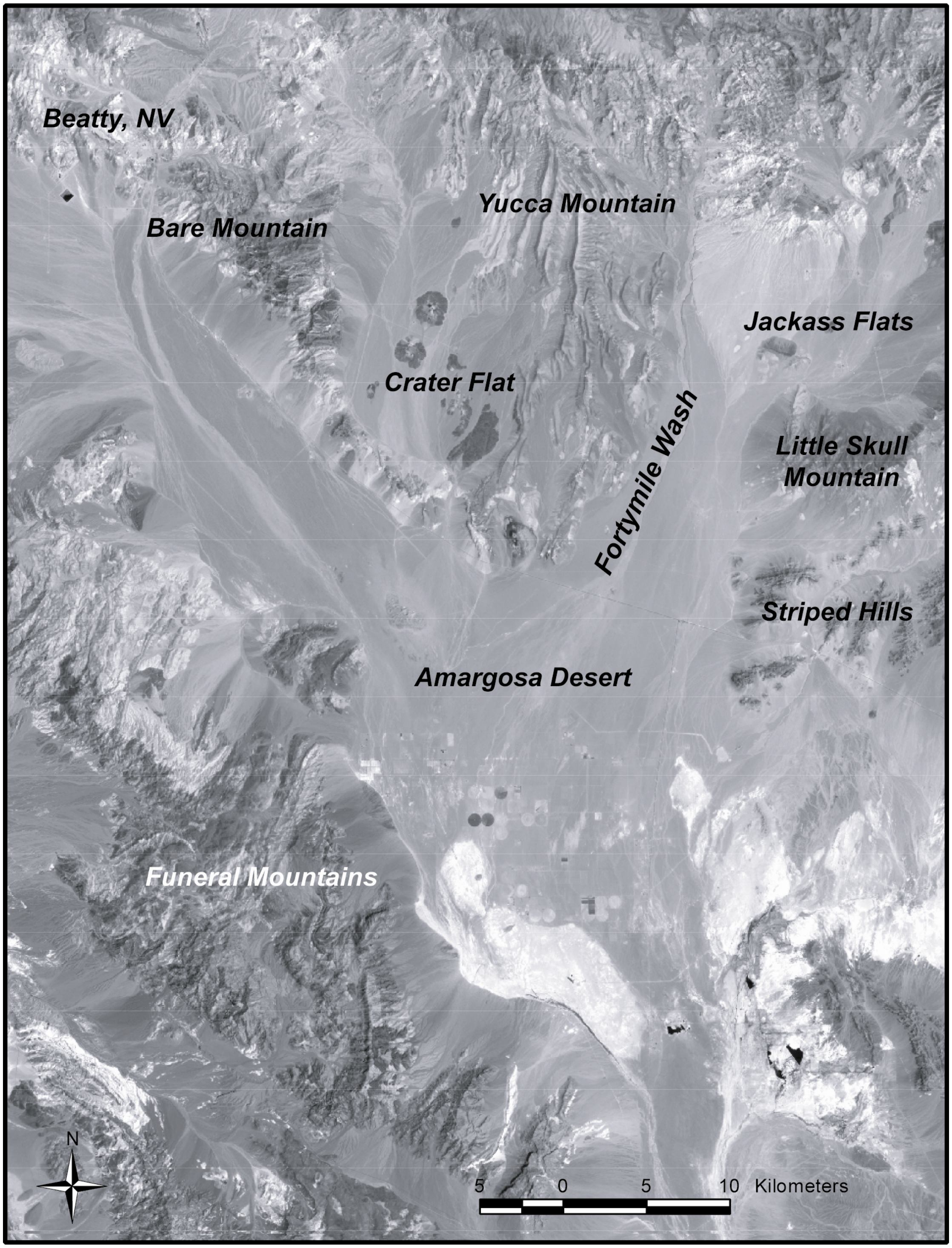

Figure 1-2. General Location of Yucca Mountain, Nevada

Yucca Mountain comprises a substantial accumulation of nonwelded to densely welded volcanic tuff, approximately 1,830 m [6,000 ft] thick. These tuffs were erupted from a series of middle to late Miocene (15–9 Ma) calderas that collectively form what has been defined as the Southwestern Nevada Volcanic Field [see Sawyer, et al. (1994) for the most recent regional stratigraphy of the Miocene volcanic rocks in the Yucca Mountain region]. The thick accumulation of middle to late Miocene volcanic tuffs masks many of the older geologic formations at Yucca Mountain. These older rocks are exposed elsewhere in the region, including Precambrian and Paleozoic sedimentary and metasedimentary strata at Bare Mountain, the Funeral Mountains, and the Striped Hills. Faulted Miocene volcanic rocks and younger rocks indicate that extensional deformation at Yucca Mountain has been active since approximately 14 Ma. In other parts of the Basin and Range, older syndeformational Tertiary strata suggest active extensional deformation began as early as about 40 Ma (e.g., Axen, et al., 1993). This suggested older extensional deformation phase raises the question as to whether the sedimentary rocks deposited in the various basins of the region prior to the Yucca Mountain volcanic tuffs also were laid down during an extensional deformation period and could reflect such deformation.

The Paleozoic carbonate strata and the late Miocene and younger volcanic strata of the Yucca Mountain area have been the focus of numerous investigations, the results of which have implications for the regional groundwater flow. By contrast, the Oligocene to early Miocene rocks, which consist of up to 2 km [1.2 mi] of sedimentary strata with minor volcanic rocks, were relatively unstudied. The potential importance of these strata to the regional hydrostratigraphy was largely unrecognized until a thick section was penetrated in the Nye County well NC–EWDP–2DB. Recognition of those strata led to the study by Murray, et al. (2002, 2003), who investigated equivalent strata exposed on the Nevada Test Site. That work targeted correlation of well cuttings from three Nye County wells in Fortymile Wash with outcrop-derived stratigraphic sections to the southwest, in the Funeral Mountains, and to the northeast, on the Nevada Test Site. Murray, et al. (2002, 2003) noted that the Cottonwood, Grapevine, and Funeral Mountains and the southern portion of the Nevada Test Site contain abundant continental deposits of Oligocene and lower Miocene strata, including strata originally mapped as the Horse Spring Formation and the Rocks of Pavits Spring.[2] Within the study area, the Horse Spring Formation consists of white to gray gastropod-rich, freshwater limestone, and fluvial conglomerate (Barnes, et al., 1982). Interbedded white to gray airfall tuff is common near the base of the unit, and minor amounts of sandstone and siltstone are also present (Barnes, et al., 1982). The Titus Canyon Formation is an Oligocene unit mapped in the Funeral Mountains that is time equivalent to the Horse Spring Formation. It consists of green tuffaceous sandstone and red conglomerate containing pebbles to boulders of quartzite and limestone. The Rocks of Pavits Spring (Barnes, et al., 1982) consist of gray tuffaceous sandstone, varicolored sandstone, conglomerate, minor ashfall tuff, and limestone.

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[2]The United States Geologic Survey (USGS) no longer uses the Horse Spring Formation nomenclature for recent studies related to Yucca Mountain because it concedes that an apparent age discrepancy with the type section of the Horse Spring Formation in the Lake Mead region (Bechtel SAIC Company, LLC, 2003) invalidates the correlation. Instead, USGS refers to all rocks older than the 14 Ma Tram Ridge Group as “Pre-volcanic sedimentary rocks” with the map designation of “Tge” (Wahl, et al., 1997; Spengler, et al., 2007). The former stratigraphic nomenclature that includes the Horse Spring Formation and Rocks of Pavits Spring is retained in this report, however, because (i) with the exception of the digital map in Wahl, et al. (1997), USGS has not yet provided official guidance on its use; (ii) none of the primary data source USGS geologic maps have been updated to reflect the change in terminology; and (iii) stratigraphic correlations developed in Murray, et al. (2002, 2003) and Gutenkunst (2006) suggest that correlation of the Horse Springs Formation strata near Yucca Mountain to the Lake Mead type section remains valid.

1.3 Scope

Murray, et al. (2002, 2003) assessed the sedimentary strata between Miocene volcanic strata and Paleozoic limestone in the Nye County wells and thereby helped defined the subsurface stratigraphy of the Fortymile Wash and Amargosa basin. Three important aspects of that work were (i) development of detailed stratigraphic profiles or stratigraphic sections of exposed Oligocene and lower Miocene strata in the Yucca Mountain region; (ii) an examination of the cuttings from the Nye County wells and correlation of the well stratigraphy to outcrop data from the Horse Spring Formation and Rocks of Pavits Spring of the Funeral Mountains and the Nevada Test Site; and (iii) construction of two interpretative cross sections, one through the Nye County wells along U.S. Highway 95 and the other across the Nevada Test Site from the Funeral Mountains to the Spotted Range, including Fortymile Wash.

This report considers a wide east-west study area of about 200 km [124 mi], with emphasis on the correlation of the pre-Basin and Range Oligocene and Miocene strata of Fortymile Wash and the Nevada Test Site to the east with the Titus Canyon and equivalent strata in the Funeral and Grapevine Mountains to the west. The Horse Spring Formation and equivalent strata mapped as the Titus Canyon Formation in the Funeral Mountains range in age from Eocene to Miocene (38 to 16 Ma) based on vertebrate fossils and Ar-40/Ar-39 radiometric ages (Stock and Bode, 1935; Reynolds, 1974). Two tuff beds in the Titus Canyon Formation yield Ar-40/Ar-39 isochron Oligocene age of 34.3 and 30.0 Ma (Saylor and Hodges, 1991). The oldest airfall tuff in the Horse Spring Formation produced a K-40/Ar-39 Oligocene age of 30.2 Ma (Marvin, et al., 1970).

This report gives results of investigation of the geology of exposures of Oligocene to early Miocene strata in the Grapevine and Funeral Mountains located west of Yucca Mountain and uses the results to draw correlations with Oligocene to early Miocene strata to the south and east of Yucca Mountain.

2 LITHOSTRATIGRAPHIC DESCRIPTION AND INTERPRETATION

Seven stratigraphic sections of Oligocene and Miocene strata were measured in the Grapevine and Funeral Mountains of California and Nevada. They are listed next from northwest to southeast; their locations are shown on Figure 2-1.

(1) Leadfield

(2) Titus Canyon 1a

(3) Daylight Pass

(4) State Line

(5) Keane Spring

(6) Turtle Canyon

(7) Yellow Ridge

Within these stratigraphic sections, 15 lithofacies were defined according to their grain size, lithology and sorting, the presence or lack of sedimentary structures and macrofauna, and other physical characteristics. This section presents summarized lithologic descriptions and depositional interpretations for the 15 lithofacies that also are summarized in Table 2-1. A key for these and subsequent measured stratigraphic sections is presented in Figure 2-7. More detailed lithostratigraphic descriptions are found in Gutenkunst (2006). Based on their depositional processes and environments, these 15 lithofacies have been grouped into four lithofacies associations (LAs).

2.1 Lithofacies

Lithofacies 1: Clast-Supported Quartzite Conglomerate

The clast-supported conglomerate of Lithofacies 1 consists of well rounded to subrounded, moderately sorted quartzite clasts ranging from pebble to boulder in grain size (Figure 2-2a). Some quartzite clasts are up to 6 m [20 ft] in diameter. These massively bedded, clast-supported conglomerates are characterized by large, polished quartzite clasts in a medium to very coarse-grained red sandstone matrix. The largest clasts are typically found near the base of this lithofacies, near the Paleozoic-Tertiary contact. Many of the clasts are fractured with observable offsets varying from a few millimeters to 50 cm [20 in] (Figure 2-2b). Percussion marks are also seen on many of the boulder and cobble quartzite clasts (Figure 2-2c). Medium to fine-grained horizontally laminated red sandstone beds are found intermittently interbedded within the boulder conglomerate (Figures 2-2d). These laterally discontinuous beds {~1–2 m, [3.3–6.6 ft]} range in thickness from 5–30 cm [2–12 in] and are moderately sorted. Lithofacies 1 is best observed in the central Funeral Mountains and recorded by the Turtle Canyon measured stratigraphic section (Figure 2-3). Lithofacies 1 is also observed in the Leadfield (Figure 2-4), Titus Canyon 1a (Figure 2-5), and Yellow Ridge (Figure 2-6) measured stratigraphic sections at or near the base of the section.

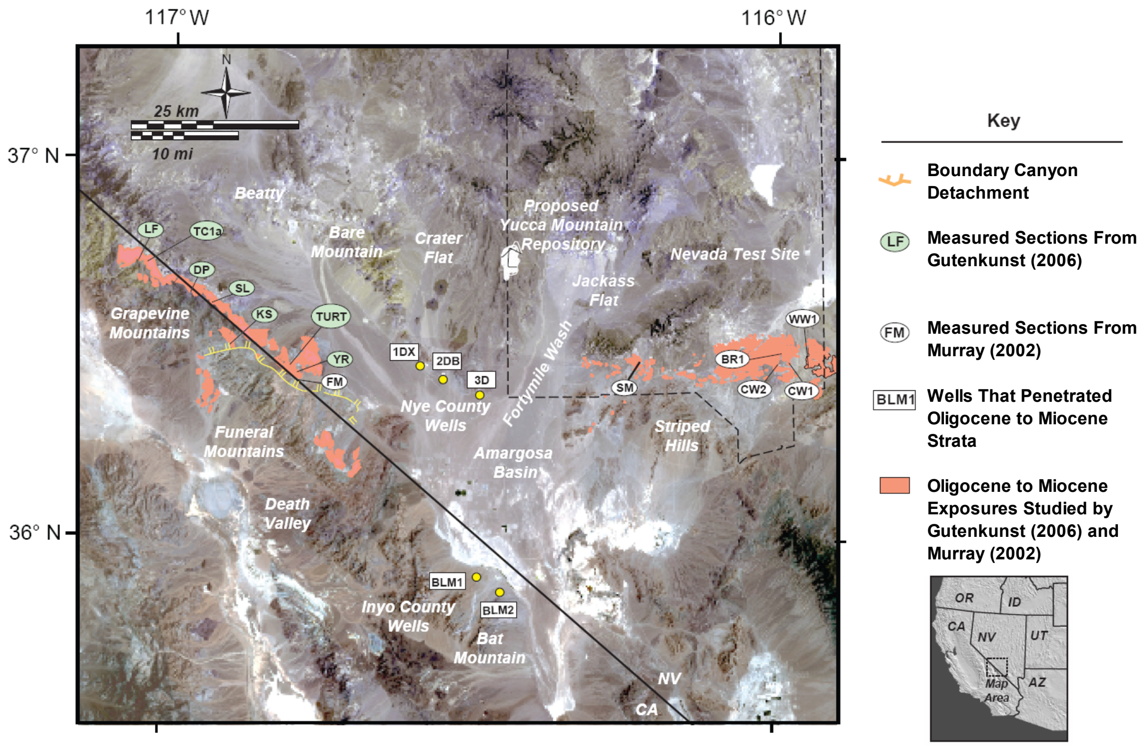


Figure 2-1. Satellite Image of the Study Area with Locations of the Stratigraphic Sections

Table 2-1. Summary of Lithofacies*

Lithofacies	Description	Transport Process	Depositional Environment
Lithofacies 1 Clast-supported quartzite conglomerate	Massive clast-supported boulder to cobble conglomerate with sandstone matrix; moderately sorted fractured and rounded quartzite clasts; rare interbedded horizontally laminated sandstone	Streamflow/traction currents	Braided stream
Lithofacies 2 Monolithologic carbonate breccia	Gray monolithologic breccia; poorly sorted granule to large boulder carbonate clasts in a carbonaceous matrix	Sediment gravity flow	Alluvial fan-rock avalanche (megabreccia)
Lithofacies 3 Coarse, poorly sorted conglomerate	Poorly to moderately sorted pebble to cobble conglomerate supported by a sandy matrix; primarily subangular carbonate clasts; rare interbedded horizontally laminated sandstone	Sediment gravity flow	Alluvial fan-debris flow
Lithofacies 4 Clast-supported conglomerate	Moderately to well-sorted clast-supported pebble to cobble conglomerate with sandy matrix; quartzite and chert clasts commonly fractured; massive, normal grading in 20 cm-12 m thick beds; rare horizontal stratification, imbrication	Streamflow/ traction currents	Proximal Scott-type braided stream-gravel dominated
Lithofacies 5 Clast-supported chert conglomerate	Well-sorted clast-supported conglomerate interbedded with pebble-rich sandstone; composed primarily of chert pebbles or cobbles; 1-1.5 m fining-up packages topped by horizontal or trough cross-stratified sandstone; imbrication	Streamflow/traction currents	Distal Donjek-type braided stream-mixed bedload

Table 2-1. Summary of Lithofacies* (continued)			
Lithofacies	**Description**	**Transport Process**	**Depositional Environment**
Lithofacies 6 Moderately to well-sorted sandstone	Fine to very coarse white quartz-rich sandstone; moderately to well-sorted; horizontal, planar, and trough cross-stratification; beds 1-200 cm often with normal grading	Streamflow/traction currents	Sandy braided river-South Saskatchewan type
Lithofacies 7 Oncoid-rich biomicrite	Biomicrite with mud to silt size grains; beds range in thickness 10-200 cm and are laterally discontinuous; contains spheroidal/ellipsoidal oncoids 1-8 cm in diameter; minor coarse sand to pebble intervals with fragmented oncoids.	Biogenic precipitation of carbonate-minor traction currents	Higher-energy lacustrine
Lithofacies 8 Stromatolite-rich biomicrite	Biomicrite with mud to silt size grains; overall laterally discontinuous 10-150 cm beds but can be traced up to 300 m; contains laterally linked and stacked stromatoloid hemispheroids; minor coarsening up sequences	Biogenic precipitation of carbonate	Low-energy lacustrine
Lithofacies 9 Gastropod-rich biomicrite	Mud size grains dominate biomicrite; thinly laminated limestone beds 5 cm-1m thick contain gastropods ~3 mm in diameter	Biogenic precipitation of carbonate	Low-energy lacustrine
Lithofacies 10 Carbonaceous fine-grained sequence	Fine-grained packages up to 10 m thick of interbedded 3-150 cm beds of sandstone, siltstone, marlstone, and limestone; transitional contacts vertically and laterally between units; grain size ranges from fine-grained sandstone to mudstone	Streamflow-pedogenic alteration	Distal alluvial fan; pedogenic alteration, palustrine environment
Lithofacies 11 Volcaniclastic sandstone and conglomerate couplet	Volcaniclastic couplet of pebble to cobble matrix-supported conglomerate (5-500 cm thick beds) and interbedded medium-very coarse tuffaceous sandstone (5-30 cm thick beds); massive, horizontal stratification, or reverse grading; poorly to moderately sorted	Fluid gravity flow-inconfined flow	mid-alluvial fan-sheetflood
Lithofacies 12 Fine-grained volcaniclastic sandstone	Fine to very coarse volcaniclastic sandstone; well-sorted; horizontally stratified or massive 2-200 cm thick beds; rare trough cross-stratification and convolute bedding; interbedded with minor conglomerate, siltstone, and mudstone	Streamflow	Braided stream, distal portion of alluvial fan
Lithofacies 13 Massive volcaniclastic sandstone	Medium to coarse-grained massive tuffaceous sandstone; 2-12 m beds are moderately sorted with sparse pebble conglomeratic intervals; minor volcanic breccia	Sediment gravity flow-traction currents	Hyperconcentrated flood-flow
Lithofacies 14 Massive tuff	White fine to medium-grained massive tuff; generally discontinuous and thin (~10 cm) but can very thick (34 m) and continuous over large distances	Suspension fallout	Airfall-pyroclastic eruption
Lithofacies 15 Interbedded sandstone and mudstone	Fine-grained horizontally stratified sandstone interbedded with siltstone and mudstone demonstrating horizontal, wavy, and ripple lamination; bioturbation	Fluid gravity flow	Distal alluvial fan-sheetflood, lacustrine
*Gutenkunst, M.L. "Stratigraphic and Geochronologic Analysis of Eocene-Miocene Synextensional Strata in the Grapevine and Funeral Mountains of Southwestern Nevada and Southeastern California: Implications for Regional Correlation of 'Pre-Basin and Range' Stratigraphy." Master's thesis. Purdue University. West Lafayette, Indiana. 2006.			

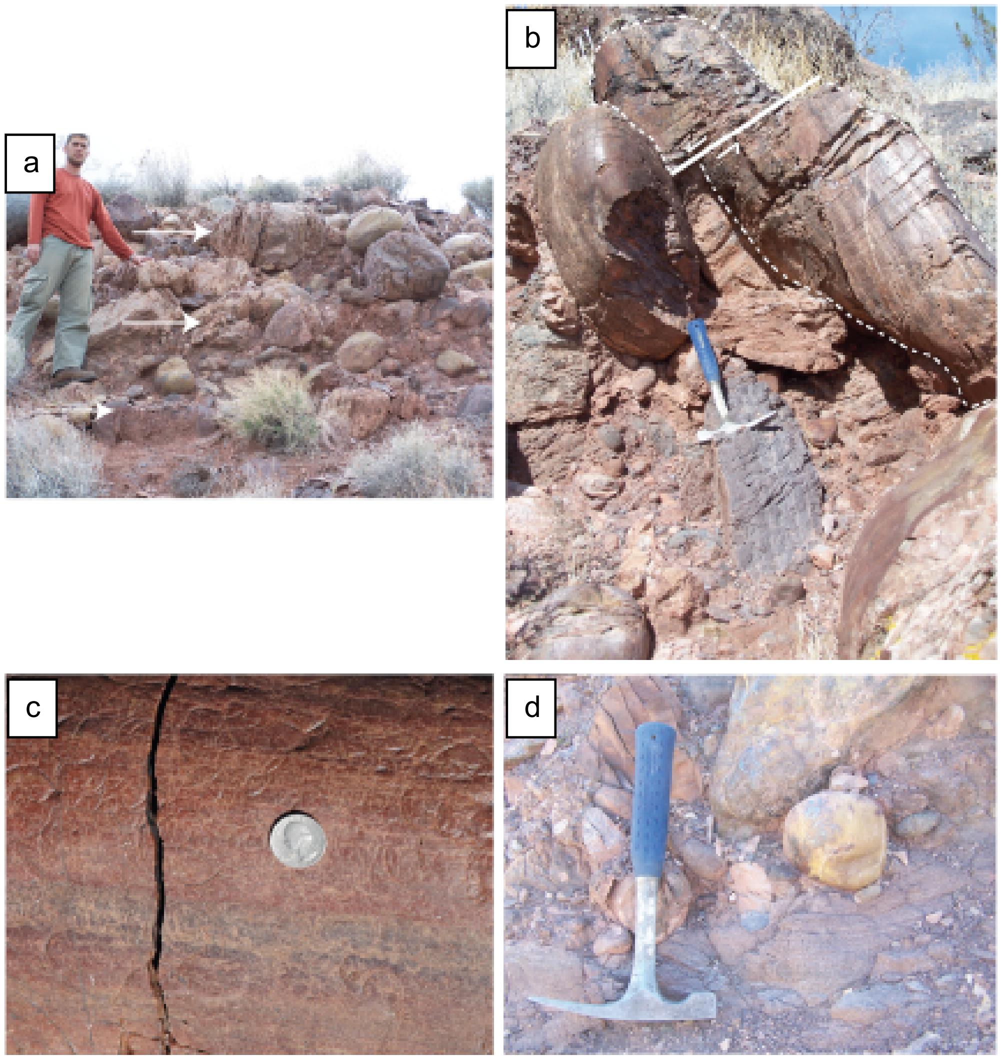


Figure 2-2. Photographs of Lithofacies 1, Clast-Supported Quartzite Conglomerate

Lithofacies 2: Monolithologic Carbonate Breccia

Lithofacies 2 consists of monolithologic, poorly sorted breccia. The fractured breccia is dark gray to light gray or tan in color and is composed of angular to rounded carbonate clasts (Figures 2-8a,b). Localized areas within the breccia display both crackle and jigsaw brecciation (Yarnold and Lombard, 1989). Many of the clasts are large, coherent limestone blocks that often contain original, relict bedding and lamination distinctive of the Bonanza King Formation (Hunt and Mabey, 1966, Figure 2-8c). The limestone blocks have been observed to be more than 100 m [328 ft] in width in the West Fork region of Titus Canyon, whereas entire outcrops of Lithofacies 2 can be hundreds of meters in width (Reynolds, 1969). The carbonate matrix appears to consist of the same limestone and dolomitic material as the clasts (Reynolds, 1969). The 10 to 17 m [33 to 56 ft] interval of the Titus Canyon 1a measured stratigraphic section best records this lithofacies (Figure 2-5). This lithofacies is also seen in the Leadfield measured section (Figure 2-4) and is found in the southern Grapevine Mountains near the Daylight Pass measured section.

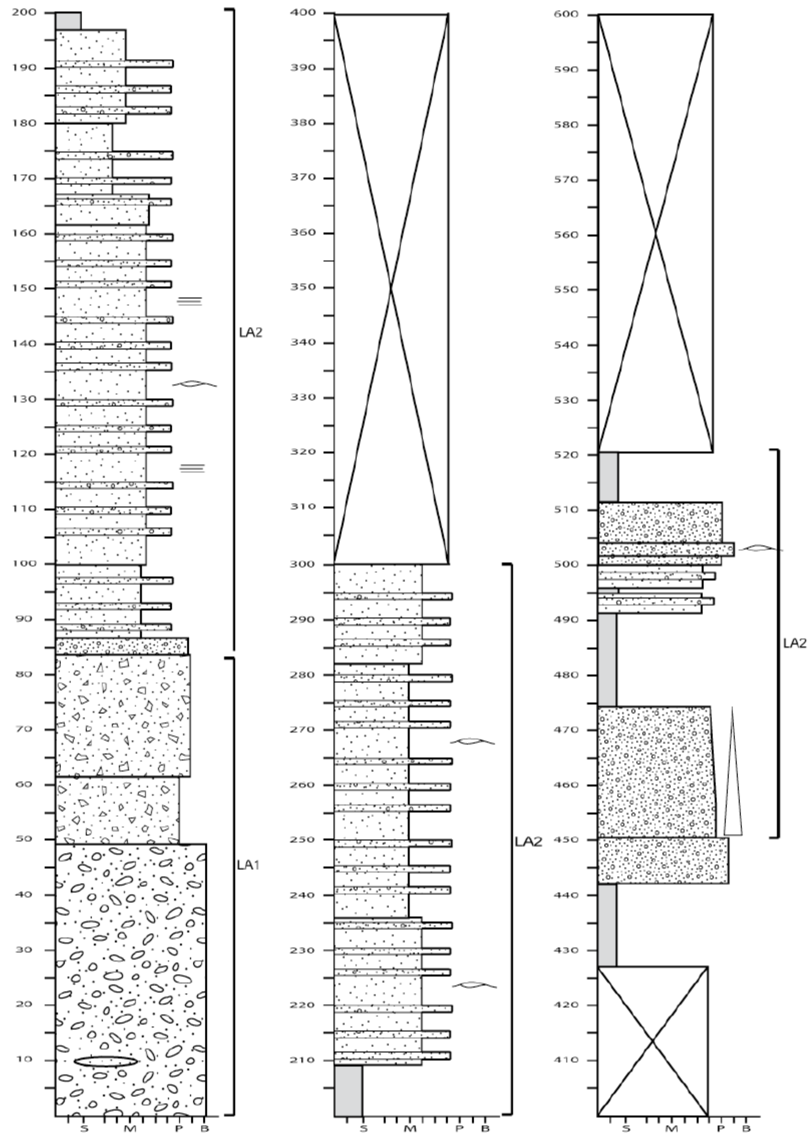


Figure 2-3. Turtle Canyon Stratigraphic Section

Lithofacies 3: Coarse Poorly Sorted Conglomerate

Lithofacies 3 is a poorly to moderately sorted conglomerate that is primarily clast supported with localized areas that are matrix supported (Figure 2-9a). Generally, Lithofacies 3 is observed to be composed of massive pebble conglomerate beds with minor cobble conglomerate intervals (Figure 2-9a-b). Local areas of inverse grading are noted (Figure 2-9c). Bedding thicknesses are hard to determine due to the massive nature of the beds; where definable beds are observed, they are approximately 50 cm [20 in] to 15 m [49 ft] thick. Locally, interbedded with the conglomerate are moderately sorted medium to fine-grained horizontally stratified and laminated sand beds that are 5–30 cm [2–12 in] thick within laterally discontinuous beds (Figure 2-9c). This lithofacies is particularly well exposed in the 30 to 40 m [98 to 131 ft] interval of the Yellow Ridge measured stratigraphic section (Figure 2-6) and also seen in the Turtle Canyon (Figure 2-3) and Keane Spring sections (Figure 2-10). This lithofacies is common throughout the study area.

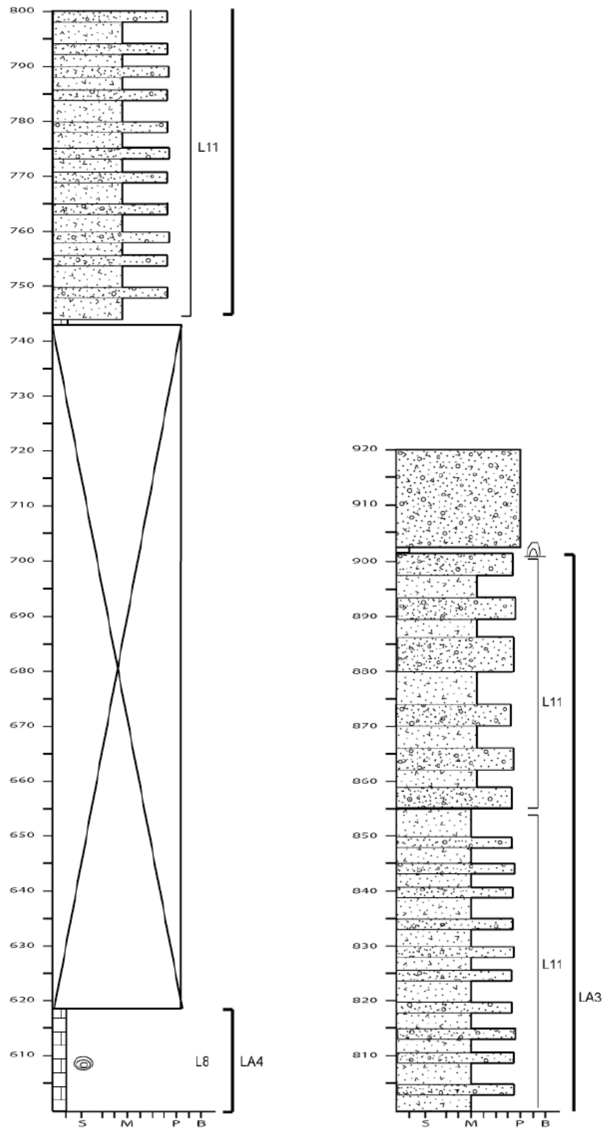


Figure 2-3. Turtle Canyon Stratigraphic Section (continued)

Lithofacies 4: Clast-Supported Conglomerate

Lithofacies 4 consists of a moderately to well sorted, pebble to cobble conglomerate (Figure 2-11a,b). This conglomerate is clast supported (Figure 2-11a–e) with localized areas that approach matrix supported with a large sandstone component (Figure 2-11b). It is dominantly composed of quartzite and chert clasts but also contains carbonate, sedimentary, plutonic, and volcanic clasts that can display consistent fracture patterns or deformation (Figure 2-11a,b,d). The clasts are subrounded to rounded, with a matrix composed primarily of medium to coarse-grained sandstone. Sharp, erosive bases are seen at the base of many of the beds (Figure 2-11c), and scour and fill structures are locally observed (Figure 2-11d). Overall, Lithofacies 4 is crudely bedded in 20-cm [8-in] to 12-m [39-ft] intervals with fairly continuous sheet like geometries (Figure 2-11c). Single beds can be traced more than 100 m [328 ft] in some cases. Whereas other beds display a wedge like geometry extending only tens of meters. Locally, normal grading is present, with conglomerate fining upward to medium or

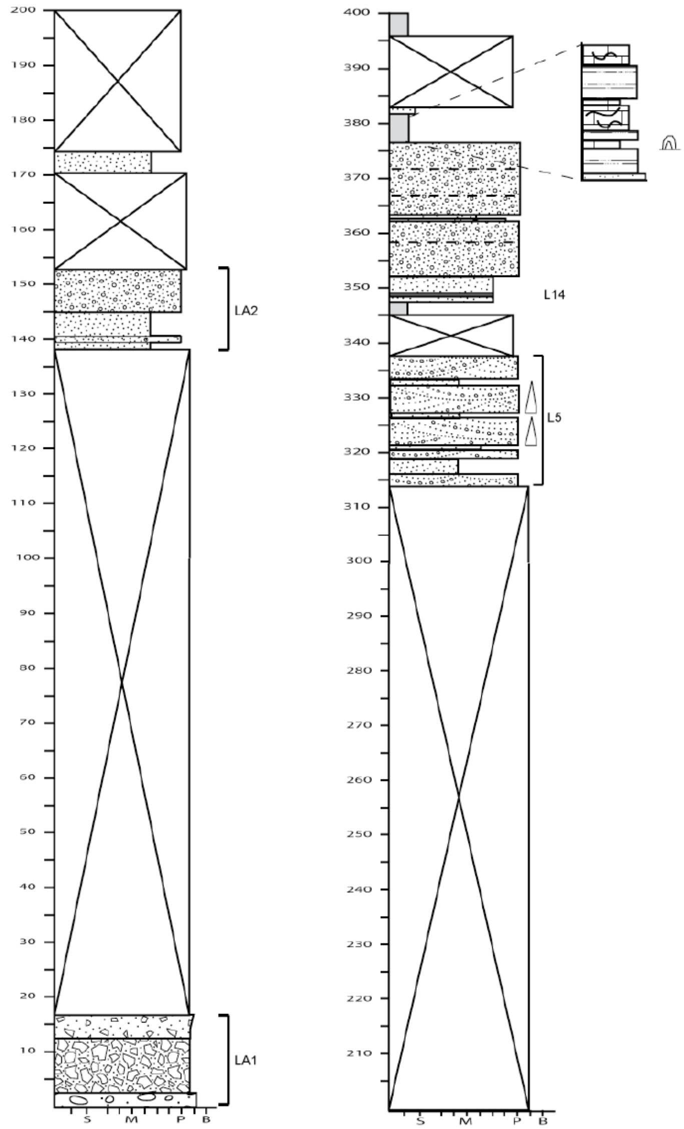


Figure 2-4. Leadfield Stratigraphic Section

coarse sandstone in packages ranging in thickness from 0.75 to 2 m [2.5 to 6.6 ft]. Crude horizontal stratification can be seen, as well as clast imbrication within some of the conglomerate outcrops (Figure 2-11e). A characteristic representation of Lithofacies 4 is seen in the 300 to 320 m [984 to 1,049 ft] interval of the Keane Spring measured stratigraphic section (Figure 2-10). This lithofacies also is seen in the Leadfield (Figure 2-4), Turtle Canyon (Figure 2-3), Titus Canyon 1a (Figure 2-5), Yellow Ridge (Figure 2-6), Daylight Pass (Figure 2-12), and State Line sections (Figure 2-13).

Lithofacies 5: Clast-Supported Chert Conglomerate

Lithofacies 5 is characterized by well-sorted, clast-supported pebble to cobble conglomerate dominated by chert clasts (Figure 2-14a). The conglomerates often contain crude horizontal stratification within fairly extensive beds that range in thickness between 10 cm [4 in] and 1.5 m [5 ft] (Figure 2-14b). Localized areas contain clast imbrication, which typically appears within

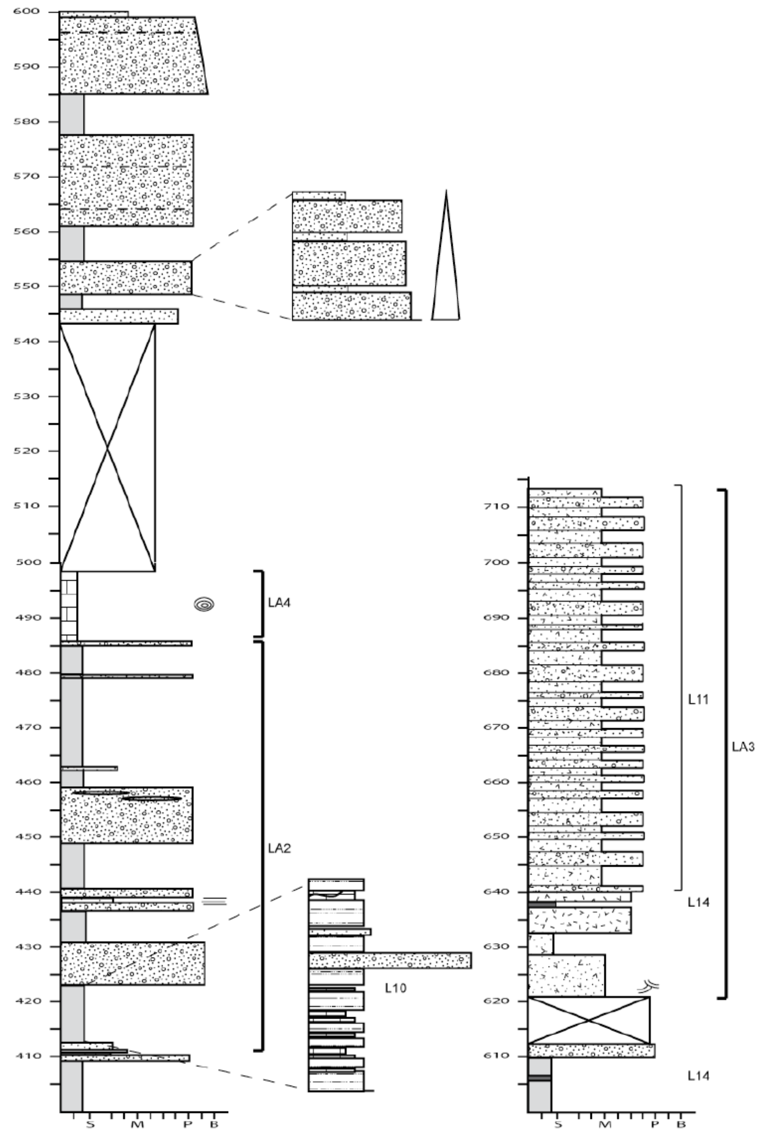


Figure 2-4. Leadfield Stratigraphic Section (continued)

the basal half of the conglomerate beds (Figure 2-14a). Normal graded 1 to 1.5-m [3 to 5-ft]-thick sequences with pebble to cobble conglomerate fining up to medium-grained sandstone are common but not always clearly expressed (Figure 2-14b). These units are generally observed as subparallel lenticular packages that extend tens of meters. The beds within Lithofacies 5 are often marked by erosive contacts (Figure 2-14c). Clasts are primarily the basal half of the conglomerate beds (Figure 2-14a). Normal graded 1 to 1.5-m less than 10 cm [4 in] in diameter and are generally black and green chert, but quartzite, sedimentary, and rare carbonate and plutonic clasts are also seen within Lithofacies 5 (Figure 2-14a). Interbedded 10 to 50-cm [4 to 20-in]-thick moderately to well-sorted, medium-grained sandstone units are common (Figure 2-14b,c) with some co-assessing up sequence of conglomerate beds (Figure 2-14d). The 314 to 338-m [1,030 to 1,109-ft] portion of the Leadfield measured stratigraphic section best demonstrates the characteristics of Lithofacies 5 (Figure 2-4). This lithofacies is also found in the Yellow Ridge measured section (Figure 2-6).

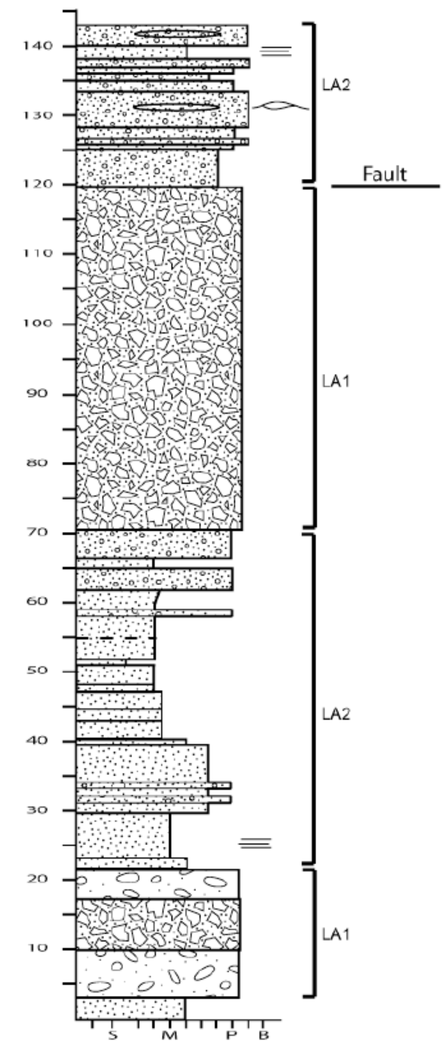


Figure 2-5. Titus Canyon 1a Stratigraphic Section

Lithofacies 6: Moderately to Well-Sorted Sandstone

Moderately to well-sorted, fine to very coarse, red and white sandstones comprise Lithofacies 6 (Figure 2-15a). These sandstones contain horizontal stratification (Figure 2-15a) as well as planar (Figure 2-15b) and trough cross stratification (Figure 2-15c). Ripple lamination is also observed within the fine-grained sandstones (Figure 2-15d). Commonly, the sandstone unit is interbedded with granule to pebble conglomerate, and together, these units are often found horizontally stratified and fill broad 4 to 20-m [13 to 66-ft]-long troughs that coalesce laterally with one another (Figure 2-15a,e). Other sandstone and conglomerate beds appear to be fairly continuous and sheetlike as well as aggradational (Figure 2-15e). Bedding packages are 1–200 cm [0.4–79 in] thick and often fine upwards from a granule to cobble conglomerate lag up to a fine- to medium-grained sandstone (Figure 2-15f). Outsized pebble to cobble clasts can be found in many of these packages, which are best exposed in the central Funeral Mountains within the Turtle Canyon and Yellow Ridge measured stratigraphic sections where Lithofacies 6

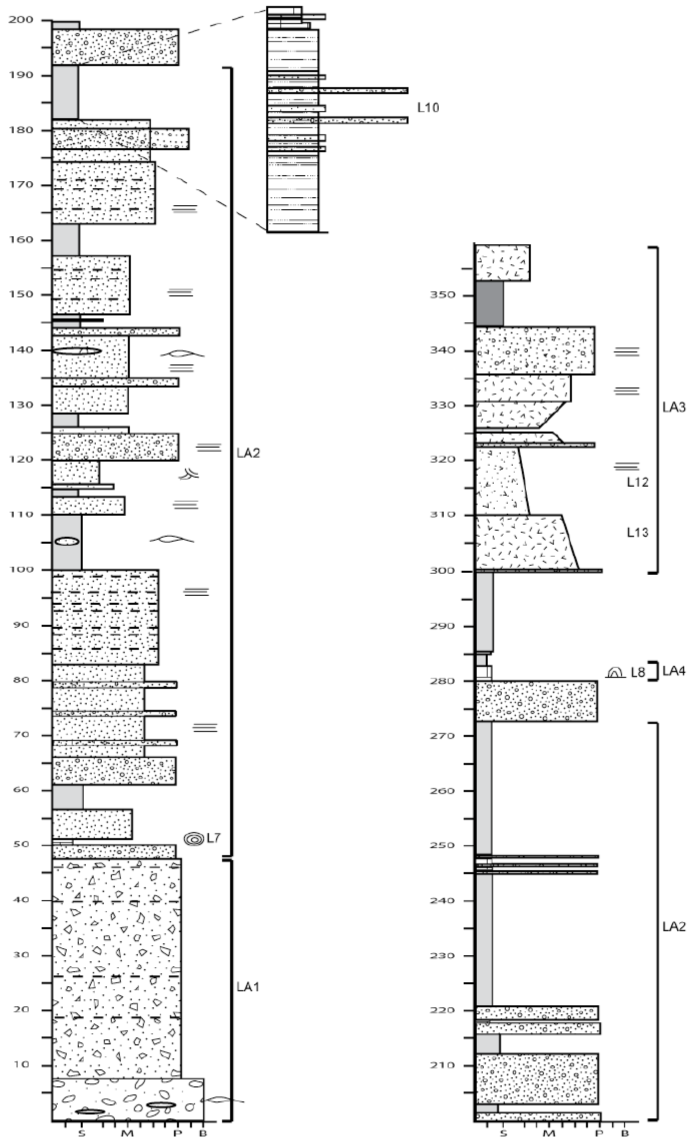


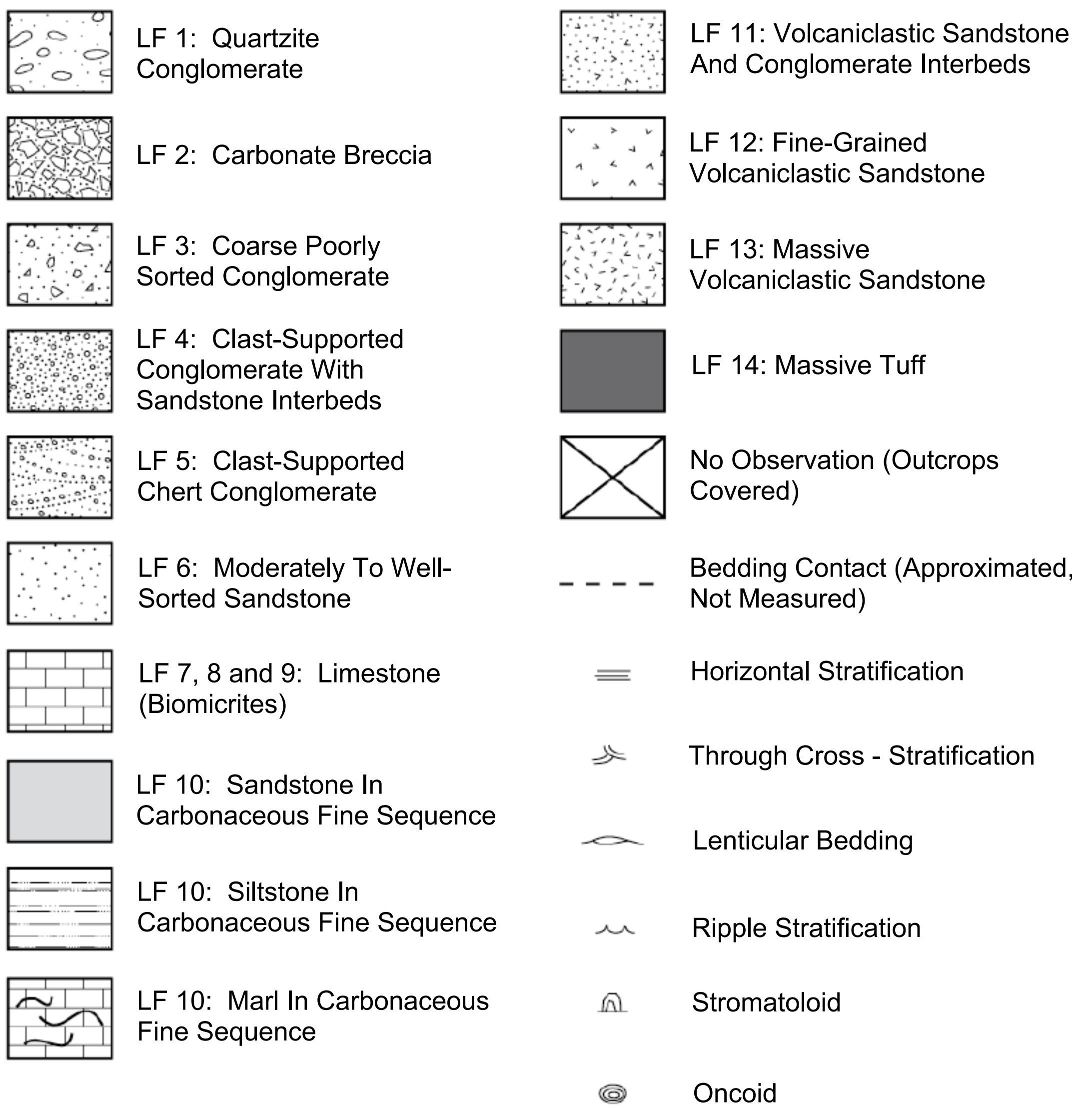
Figure 2-6. Yellow Ridge Stratigraphic Section

is found in thick intervals, particularly in the 83 to 105 m and 162 to 167-m [272 to 546-ft] intervals of the Turtle Canyon measured stratigraphic section (Figure 2-3) and 66 to 100-m [216 to 328-ft] interval of the Yellow Ridge section (Figure 2-6).

Lithofacies 7: Oncoid-Rich Biomicrite

Lithofacies 7 is a freshwater limestone and oncoid-bearing biomicrite. Oncoids are small {<10 cm [4 in]}, concentrically laminated calcareous structures of various shapes, formed by blue-green algae. The oncoids range in size from less than a centimeter to 8 cm [3 in] with irregular spheroidal to ellipsoidal shapes (Figure 2-16a). Smooth, concentrically stacked laminae surround granular sand or pebble nuclei (Figures 2-3a, 2-16b,c). Some of the nuclei have an elongated shape, and others are composed of reworked oncoid fragments (Figure 2-16a,b). Disruptions in the laminae are observed and are evidence of burrowing

Lithofacies (LF) and Other Lithologic Symbols



Definition of Axes:

X axis = Grain Size: Silt (S), Medium-Grained Sandstone (M), Pebble (P), Cobble (C), Boulder (B)

Figure 2-7. Key for Lithologic Symbols and Axes of the Seven Stratigraphic Sections

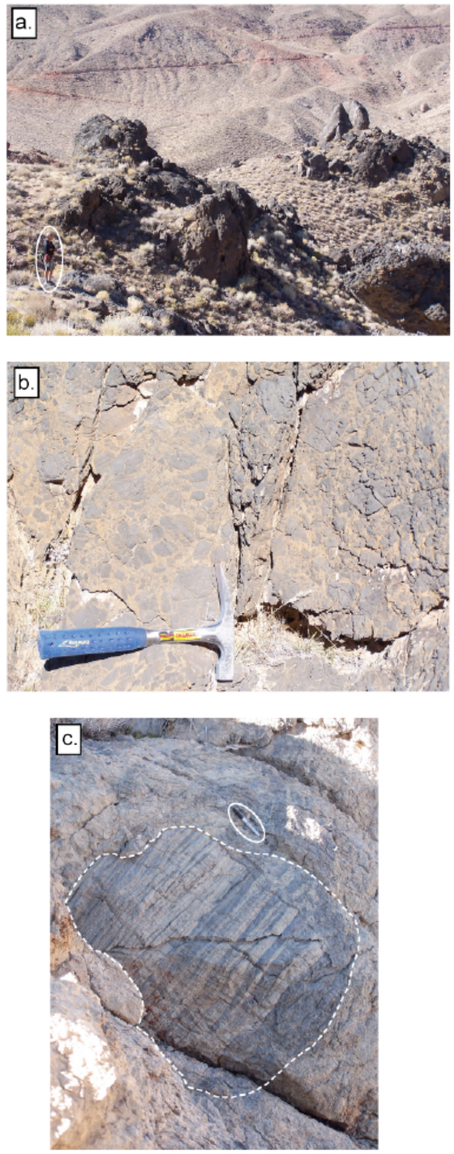


Figure 2-8. Photographs of Lithofacies 2, Monolithologic Carbonate Breccia

(Figure 2-16c). Often, the oncolites are intact; however, fragmented oncoids are also observed within the biomicrite and are also often associated with coarse sandstone to pebble intervals (Figure 2-16d,e,f). Oncolitic beds range in thickness from 10 cm [4 in] to 2.5 m [8 ft] and can be traced for tens of meters but overall are laterally discontinuous. This lithofacies is best exposed in the Leadfield measured stratigraphic section (Figure 2-4) from 486 to 497 m [1,594 to 1,631 ft] but is also seen in the Turtle Canyon section {600–617 m [1,968–2,024 ft]} and Yellow Ridge section {50–52 m [164–171 ft]} (Figures 2-3, 2-6).

Lithofacies 8: Stromatolite-Rich Biomicrite

Lithofacies 8 consists of freshwater micritic limestone that contains stromatolites (stromatolites are similar to oncoids but are typically much larger and massive, often subspherical or tabular).

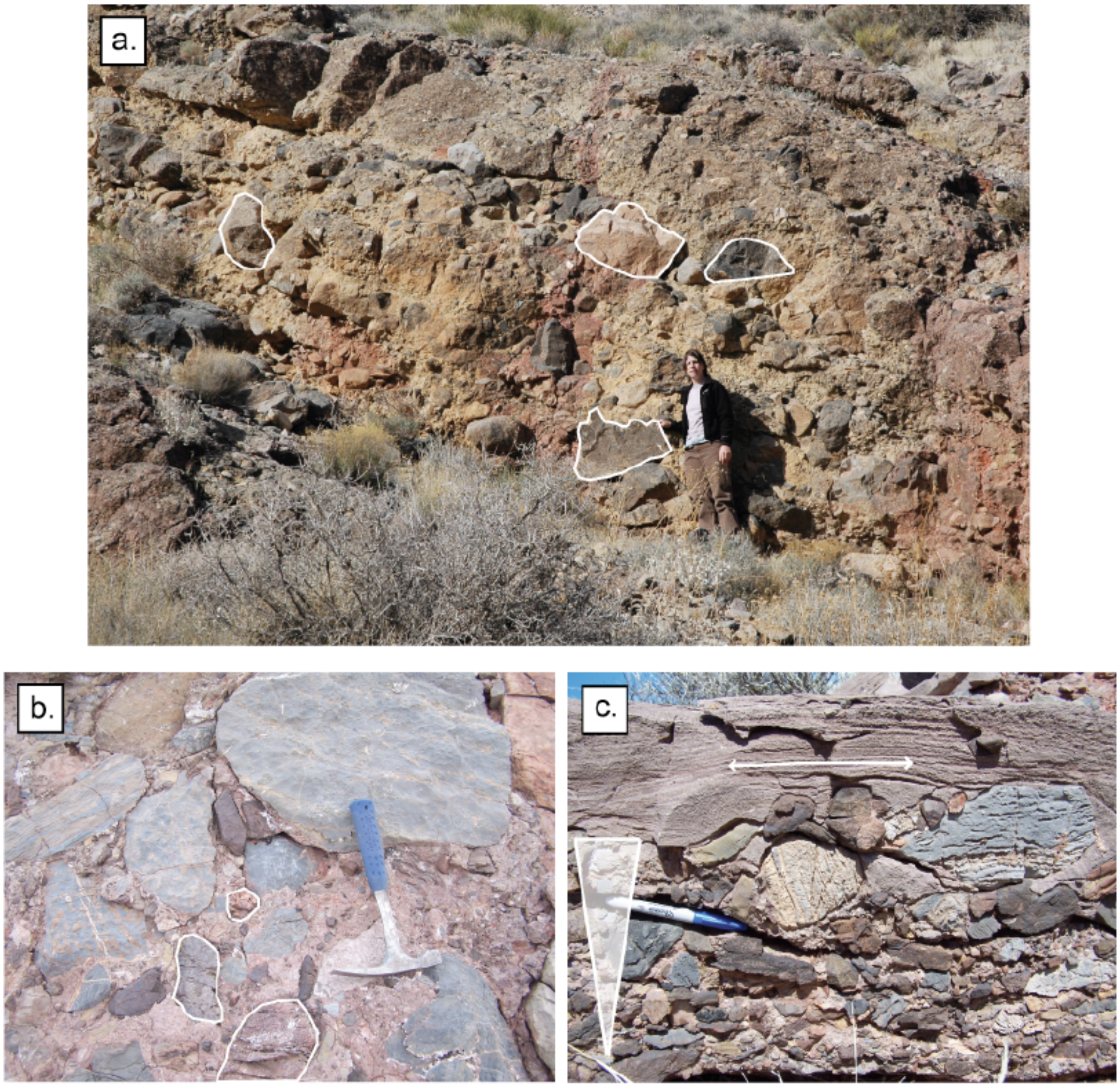


Figure 2-9. Photographs of Lithofacies 3, Coarse Poorly-Sorted Conglomerate

Limestone beds range in thickness from 7 cm [2.8 in] to 1.5 m [5 ft] that, at times, display minor upward coarsening sequences capped by siltstones (Figure 2-17a). Tan to brown limestone

beds are generally discontinuous; however, some beds can be traced for up to ~300 m [984 ft] with varying thicknesses but are generally discontinuous. Algal lamination is observed within the micrite with local areas of well-developed, laterally linked and stacked hemispheroid packages that range in thickness from 5 to 20 cm [2 to 8 in] (Figure 2-17b,c). Lithofacies 8 is best expressed in the southern portion of the central Funeral Mountains mapping area but is also recorded in the 280 to 283-m [919 to 928-ft] interval of the Yellow Ridge measured stratigraphic section (Figure 2-6) as well as the 145 to 147-m [476 to 482-ft] interval of the Daylight Pass section (Figure 2-12).

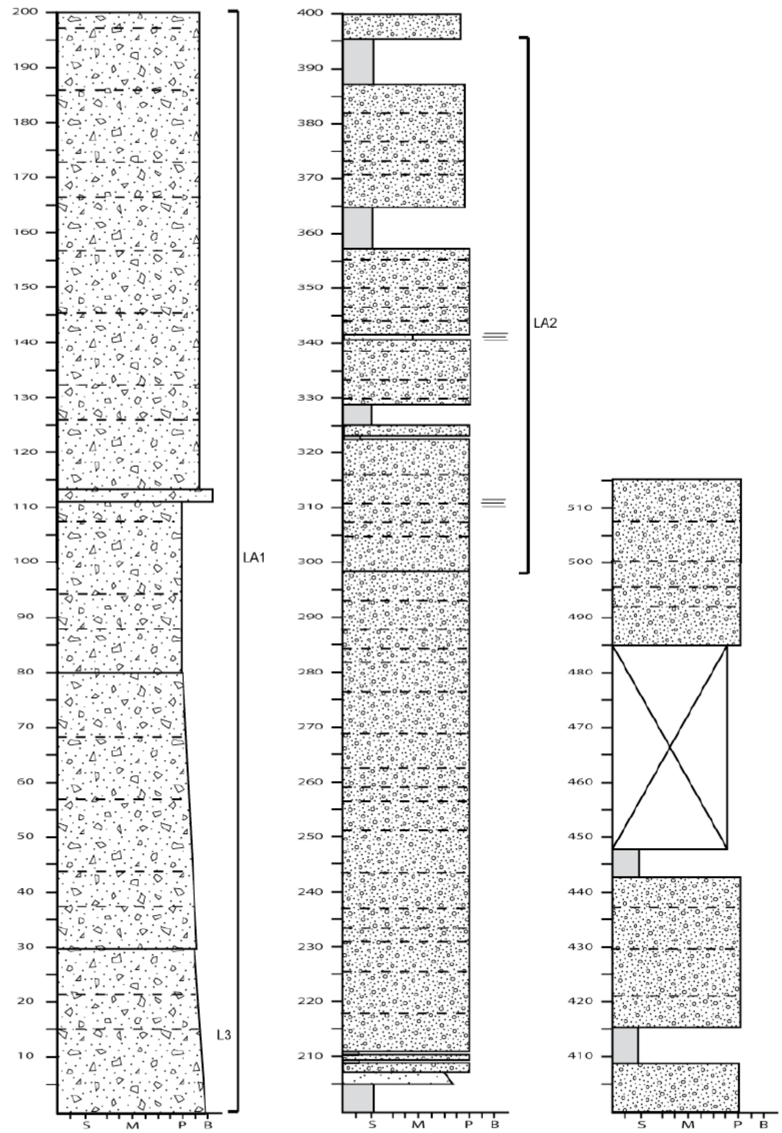


Figure 2-10. Keane Spring Stratigraphic Section

Lithofacies 9: Gastropod-Rich Biomicrite

Fine-grained white to tan freshwater limestone beds are included in the gastropod-rich biomicrite facies. These laminated limestones are fairly tabular with beds that range in thickness from 3 cm [1.2 in] to 1 m [3.3 ft] and are often interbedded with the stromatolitic beds of Lithofacies 8 (Figure 2-18a,b). The gastropod fossils that are observed in the limestone beds have relatively small diameters ranging from ~3 to 6 mm [0.1 to 0.2 in] (Figure 2-18c). Lithofacies 9 is most common in the central Funeral Mountains mapping area but is also seen in isolated areas within the Grapevine Mountains.

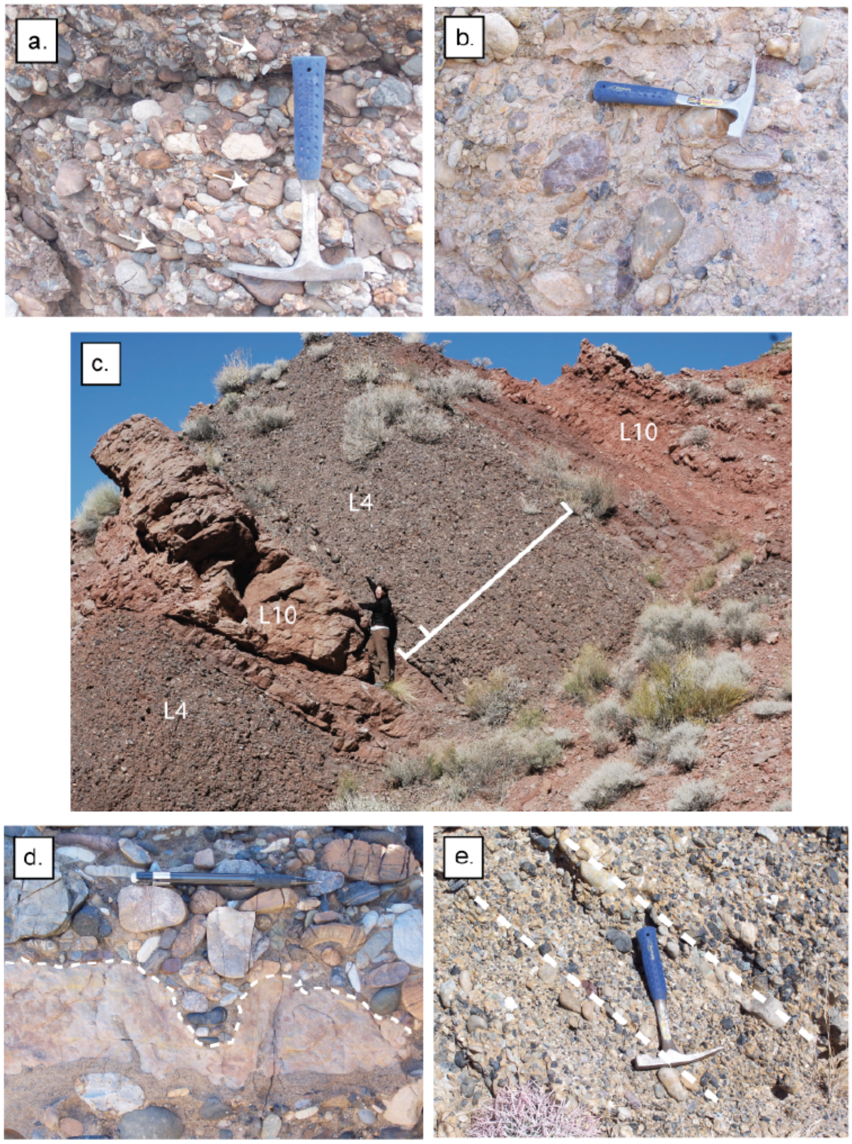


Figure 2-11. Photographs of Lithofacies 4, Clast-Supported Conglomerate

Lithofacies 10: Carbonaceous Fine-Grained Sequence

Interbedded sandstone, siltstone, marlstone, and freshwater limestone define Lithofacies 10; these units have gradual transitions between one another both vertically and laterally (Figure 2-19a,b). Individual beds can be laterally discontinuous over relatively short distances (Figure 2-19a), but packages of Lithofacies 10 can be traced over distances of more than 100 m [328 ft]. Beds range from 3 cm [1.2 in] to 1.5 m [5 ft] in thickness and most have often a mottled appearance. Calcareous siltstone beds are the dominant lithology in Lithofacies 10. These beds have an overall nodular and blocky appearance with calcrete nodules that often have a distinctive red color (Figure 2-19c). White to gray oxidation rings (Figure 2-19d) and minor amounts of bioturbation can be seen within the siltstone beds that overall fine upward into

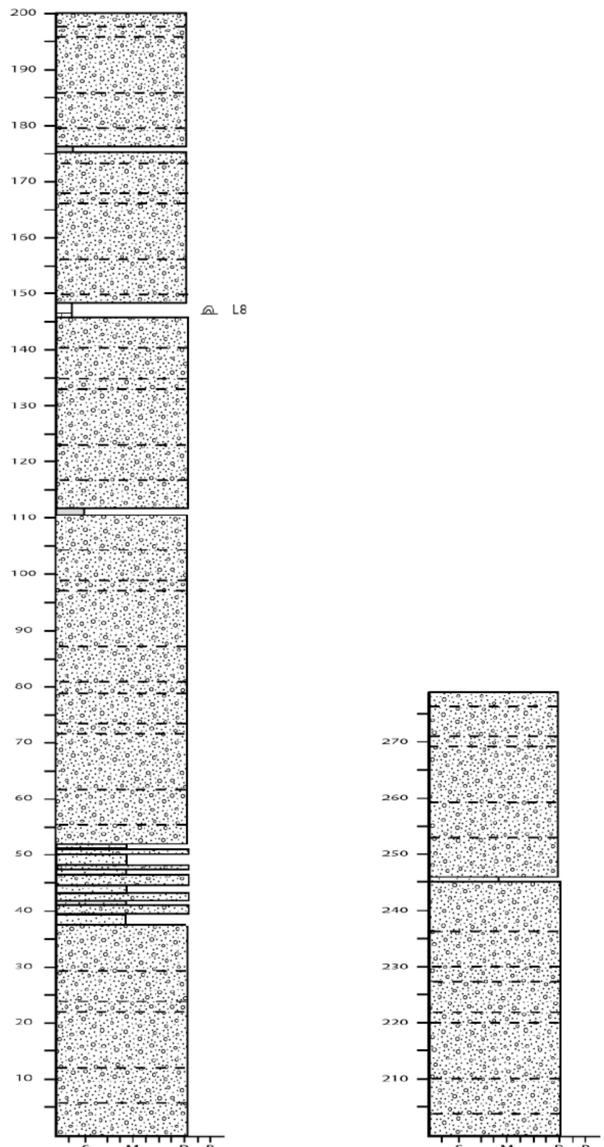


Figure 2-12. Daylight Pass Stratigraphic Section

claystone with silty localized areas near the top of the bed. Irregular tubes, often approximately perpendicular to bedding, are seen within the siltstones and are often filled with calcite (Figure 2-19e). Sandstone, marlstone, and limestone are also found within Lithofacies 10. The red fine-grained sandstones are usually massive and devoid of structure but can show horizontal lamination and minor ripple lamination. The sandstone beds range in thickness from 2 to 50 cm [0.8 to 20 in] but average bed thickness is ~10 cm [4 in] (Figure 2-19a). Mottled colors of white, pink, gray, and purple are observed in marlstones (muddy limestones) that are dominated by clay size particles and range in thickness from 10 cm [4 in] to 1.5 m [5 ft] (Figure 2-19f). The limestones in Lithofacies 10 are white to tan in color and vary from micrite to sparite. The limestones are generally massive and 10–20 cm [4–8 in], thick and at times, poorly developed algal laminae can be noted (Figure 2-19g). Lithofacies 10 is found throughout the field area, commonly interbedded with Lithofacies 4 and 6 in all of the measured sections

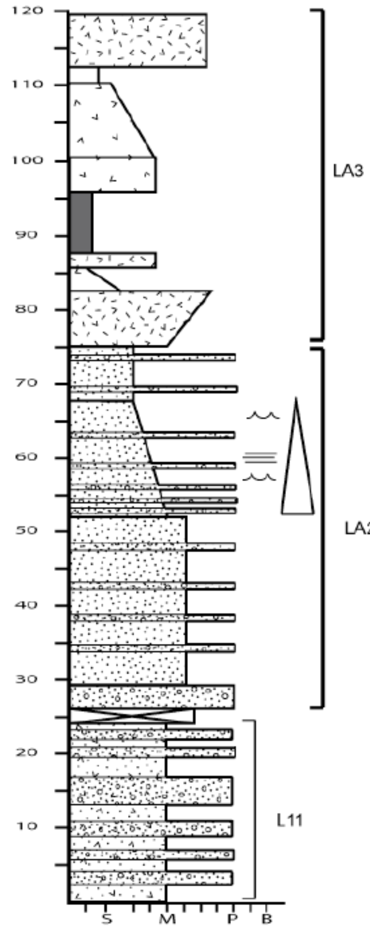


Figure 2-13. State Line Stratigraphic Section

(Figure 2-19h,i). The 376 to 383-m [1,234 to 1,257-ft] interval of the Leadfield measured section best expresses all the lithologic units of this lithofacies (Figure 2-4).

Lithofacies 11: Volcaniclastic Sandstone and Conglomerate Couplet

Lithofacies 11 consists of green, moderately to well-sorted, clast-supported, pebble-cobble conglomerate alternating with medium to very coarse-grained, green to white tuffaceous sandstone (Figure 2-20a). Average thickness of these sandstone and conglomerate couplets is ~50–70 cm [20–28 in]. The individual sandstone beds of the couplet range in thickness from 5 to 30 cm [2 to 12 in], whereas the conglomerate beds can range anywhere between 5 cm [2 in] and 5 m [16 ft] thick, generally averaging thicknesses no greater than 40 cm [16 in] (Figure 2-20a–c). Boulder-sized clast can be observed within pebble conglomerate beds (Figure 2-20d). Horizontal stratification is seen at times within both the conglomerate and sandstone beds of the couplet, although the units are often massive. The beds of Lithofacies 11 are fairly tabular and can be traced laterally for more than 100 m [328 ft] (Figure 2-20a). This lithofacies can be observed in the Grapevine Mountains and central Funeral Mountains.

In the Leadfield measured stratigraphic section, it is best exposed in the 643 to 712-m [2,110 to 2,336-ft] interval (Figure 2-4).

Figure 2-14. Photographs of Lithofacies 5, Clast-supported Chert Conglomerate

Lithofacies 12: Fine-Grained Volcaniclastic Sandstone

Lithofacies 12 is dominated by green to yellow, fine to very coarse-grained tuffaceous sandstone, with minor amounts of red sandstone and small outsized pebble clasts (Figure 2-21a). The well-sorted sandstone beds are 2 cm [0.8 in] to 2 m [6.6 ft] thick and display horizontal stratification or massive, with rare small-scale trough cross stratification and convolute bedding (Figure 2-21b,c,e). Beds have erosional bases and are laterally discontinuous distance 10–20 m [33–66 ft]. The basal portion of Lithofacies 12 contains interbeds of minor conglomeratic intervals. These conglomerates are generally only 5 cm [2 in] thick but can be as thick as 50 cm [20 in]. Fine-grained units of purple to black, horizontally laminated siltstone and mudstone, 2–50 cm [0.8–20 in] thick, are also found within this unit (Figure 2-21d). Characteristic intervals of this lithofacies can be seen from 622–632 m [2,041–2,073 ft] in the Leadfield measured stratigraphic section (Figure 2-4).

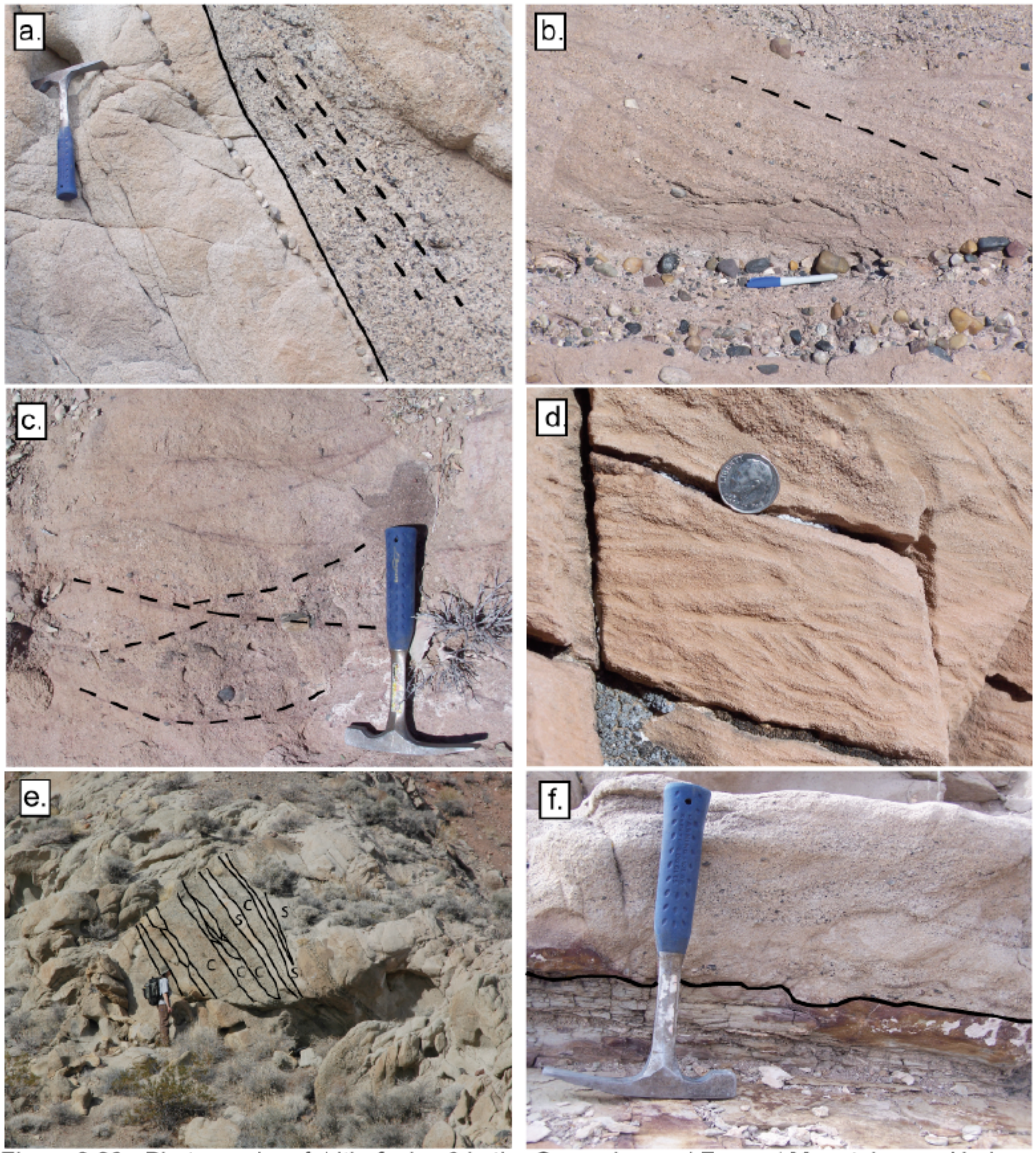


Figure 2-15. Photographs of Lithofacies 6, Moderately to Well-Sorted Sandstone

Lithofacies 13: Massive Volcaniclastic Sandstone

Lithofacies 13 consists of light shades of tan, yellow or red, medium to very coarse-grained sandstone (Figure 2-22a,b). This tuffaceous sandstone is typically moderately sorted and massive in nature (Figure 2-22b) with areas of minor horizontal stratification. Where discernable, discreet beds appear to range in thickness from 3 cm [1.2 in] to 12 m [39 ft], generally averaging thicknesses greater than 1 m [3.3 ft]. This lithofacies has a distinctive weathering pattern that creates large hollows or caves in outcrop (Figure 2-22c). Sparse, 2 to 10-cm [0.8 to 4-in]-thick pebble conglomeratic intervals that incorporate a high amount of volcanic clasts are found interbedded with the sandstone as well as minor volcanic breccia. This lithofacies is best expressed in the Yellow Ridge measured stratigraphic section from 352 m [1,155 ft] to the top of the section (Figure 2-6).

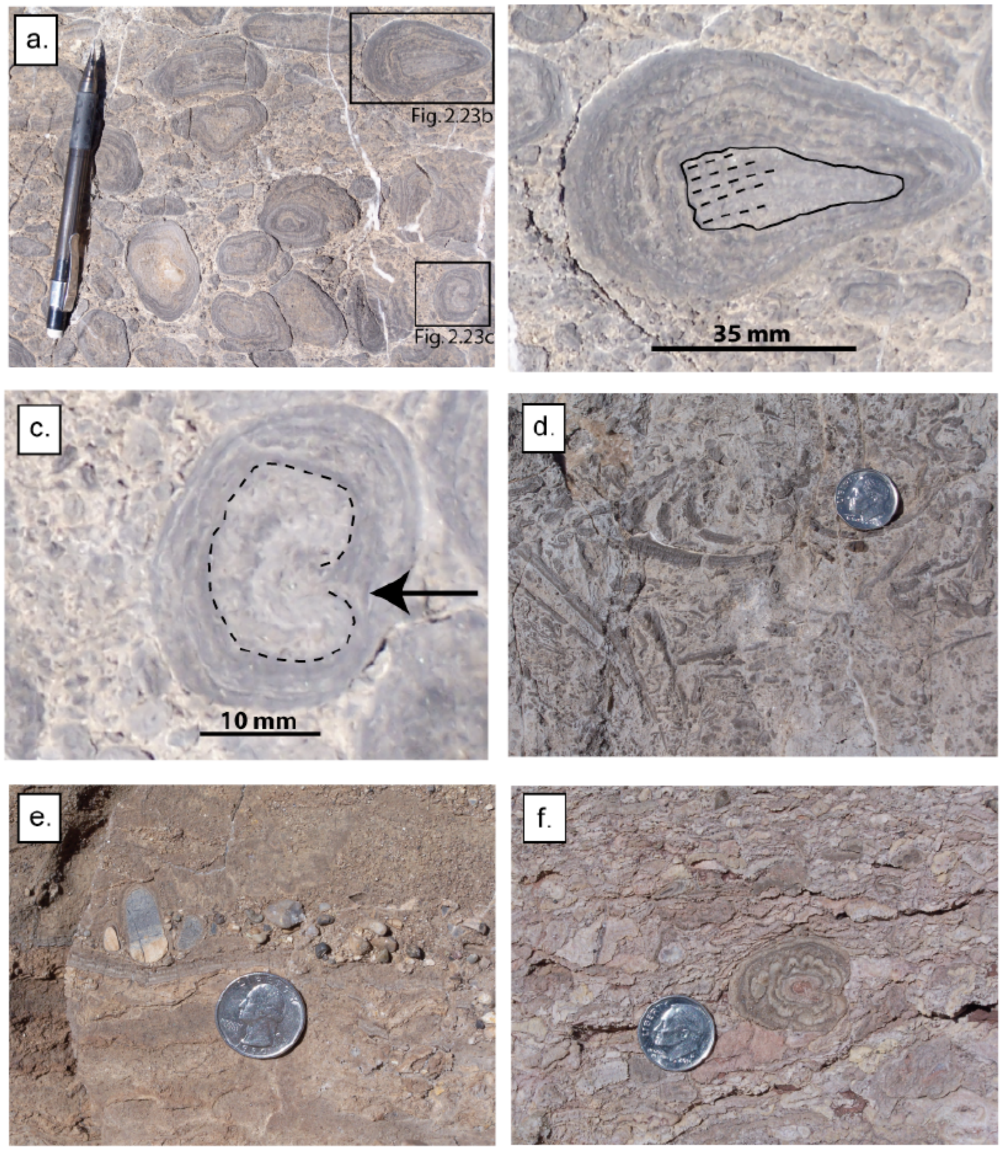


Figure 2-16. Photographs of Lithofacies 7, Oncoid-Rich Biomicrite

Lithofacies 14: Massive Tuff

The massive tuff of Lithofacies 14 consists of fine to medium-grained white tuff that is moderately to well sorted. Bedding thickness can be relatively thin {5 cm [2 in]} or thick {34 m [11 ft]} (Figure 2-23a,b,c). The tuff beds are generally ~10 cm [4 in] thick and laterally discontinuous over a distance of 10–20 m [33–66 ft]. In the Grapevine Mountains, the crystal tuff of Reynolds (1974), in Lithofacies 14, varies in thickness from 12–34 m [39–111 ft]. Due to its laterally continuous nature, it is used as a stratigraphic marker. Some of the tuff units demonstrate normal grading and are capped by tuffaceous mudstones. Pumice grains are noted in some of the tuff deposits as well as partial, inconsistent welding in places. This lithofacies is best represented by the Yellow Ridge measured stratigraphic section 342 to 353-m [1,122 to 1,158-ft] interval (Figure 2-6).

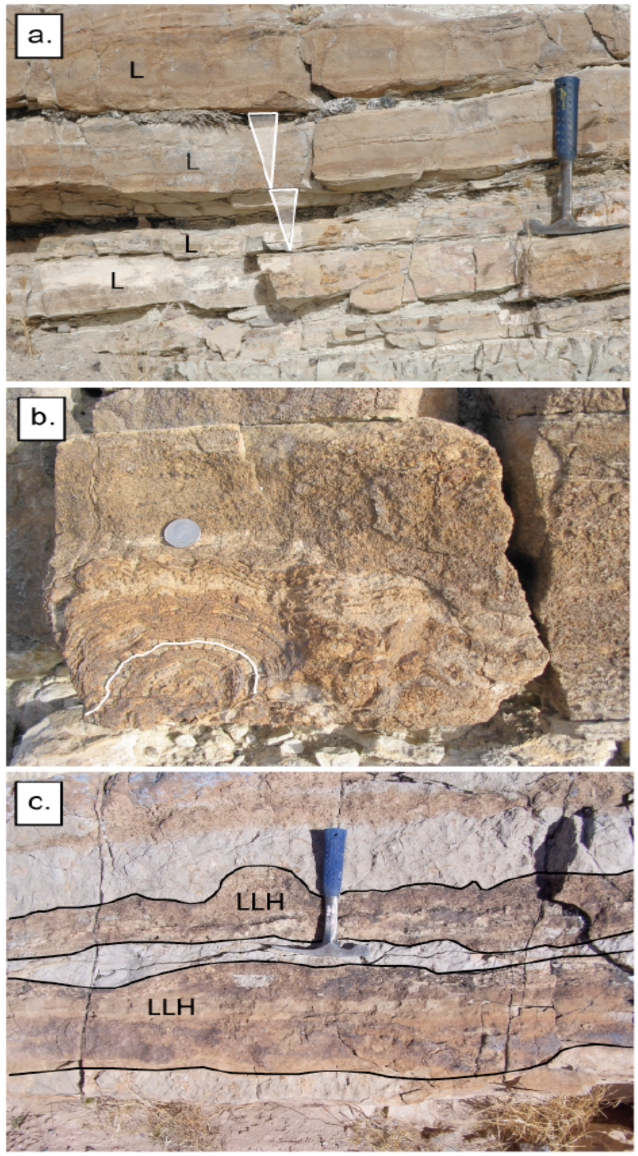


Figure 2-17. Photographs of Lithofacies 8, Stromatolite-Rich Biomicrite

Lithofacies 15: Interbedded Sandstone and Mudstone

Lithofacies 15 consists of interbedded finely bedded, well-sorted, horizontally stratified, lenticular fine-grained sandstone, siltstone, and mudstone (Figure 2-24a). The 0.5 to 3-cm [0.2 to 1-in]-thick mudstone and siltstone beds show horizontal and wavy lamination as well as mud-filled voids reminiscent of burrows (Figure 2-24b,c). While most of the beds are white to tan, various colors of red, purple, green, and yellow are also observed. Symmetric, ladderback ripples with rounded peaks are present (Figure 2-24d). Lithofacies 15 was not exposed in any of the seven measured stratigraphic sections but is well exposed in the southeastern portion of the mapping area within the central Funeral Mountains.

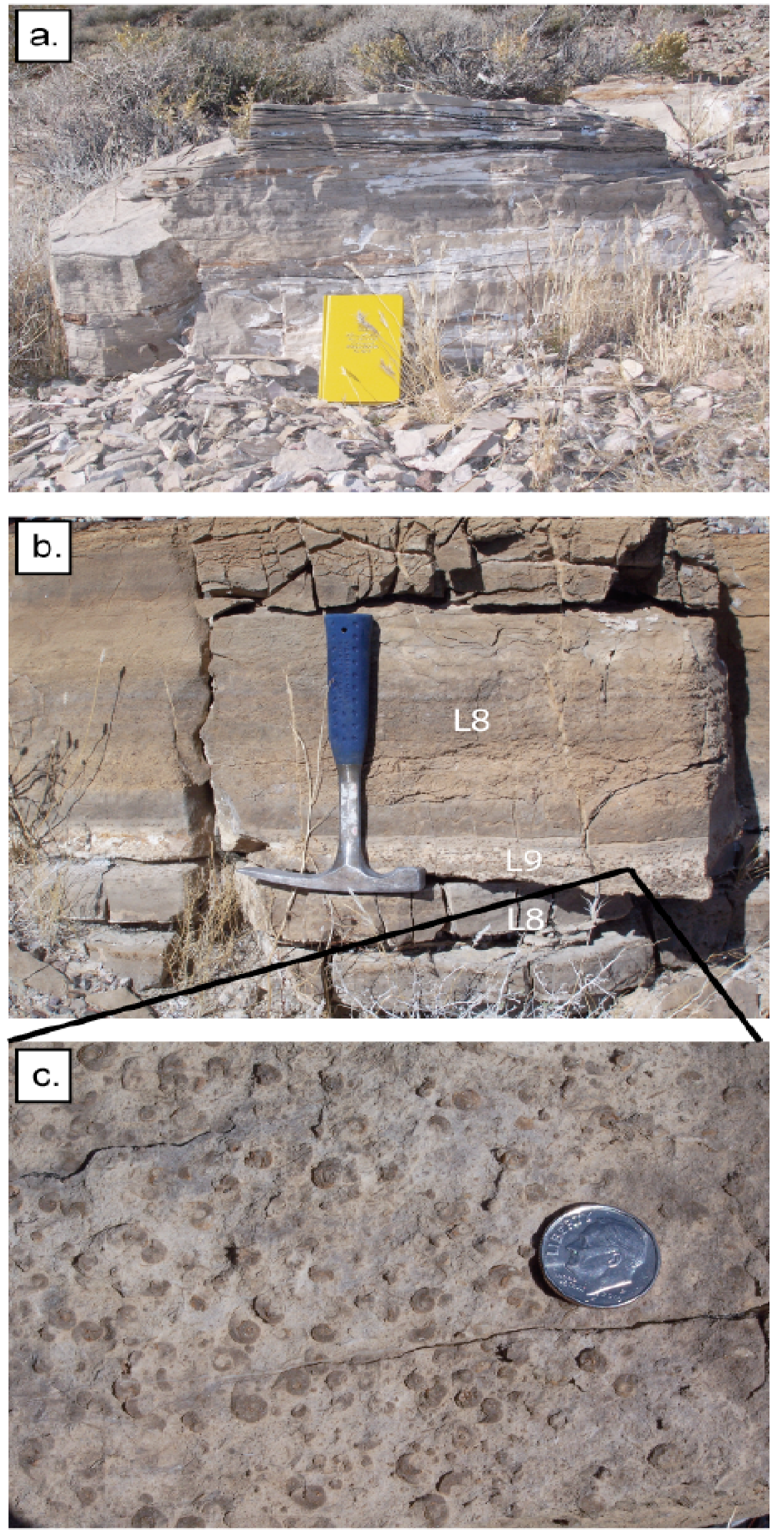


Figure 2-18. Photographs of Lithofacies 9, Gastropod-Rich Biomicrite

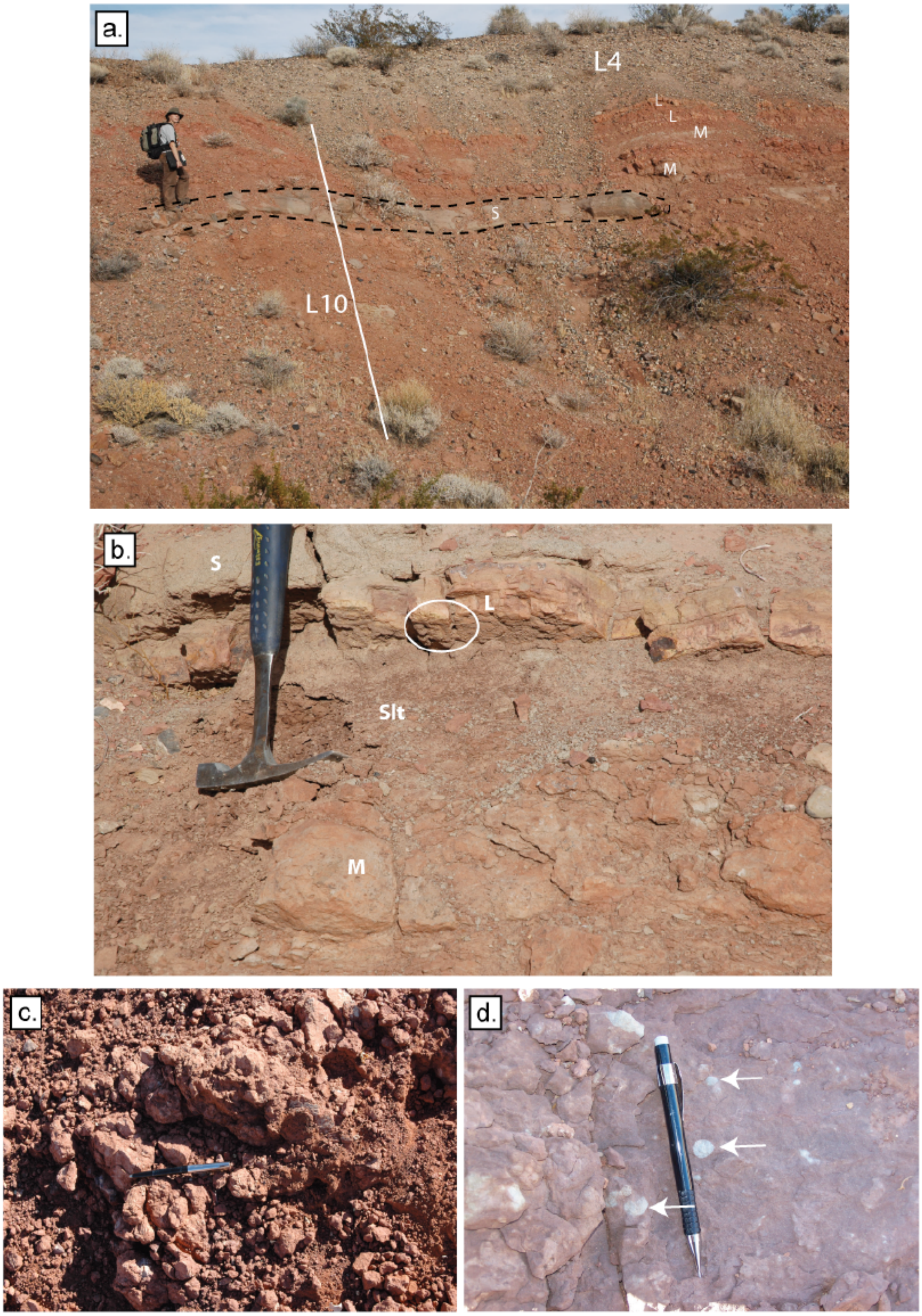


Figure 2-19. Photographs of Lithofacies 10, Carbonaceous Fine-Grained Sequence

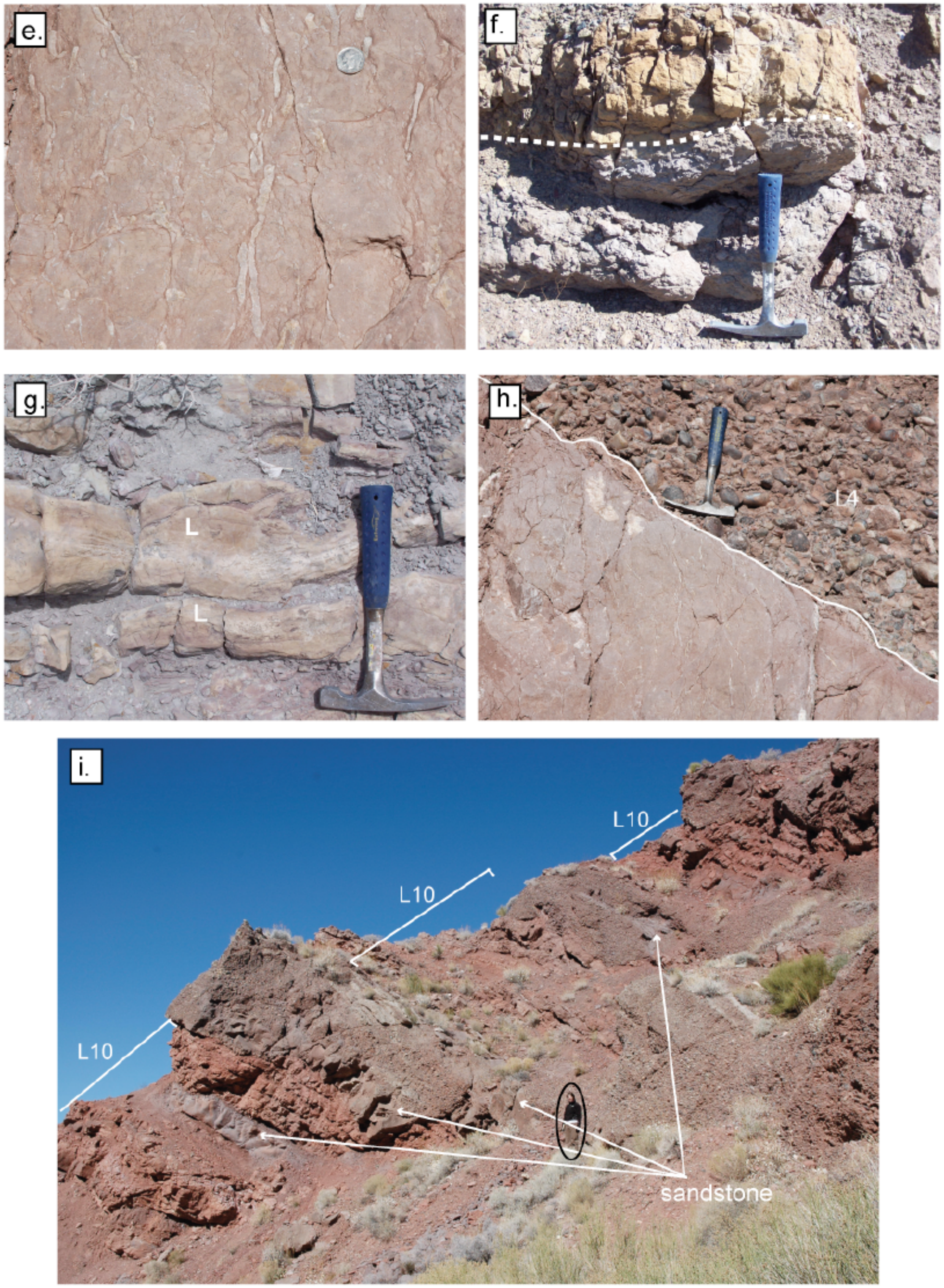


Figure 2-19. Photographs of Lithofacies 10, Carbonaceous Fine-Grained Sequence (continued)

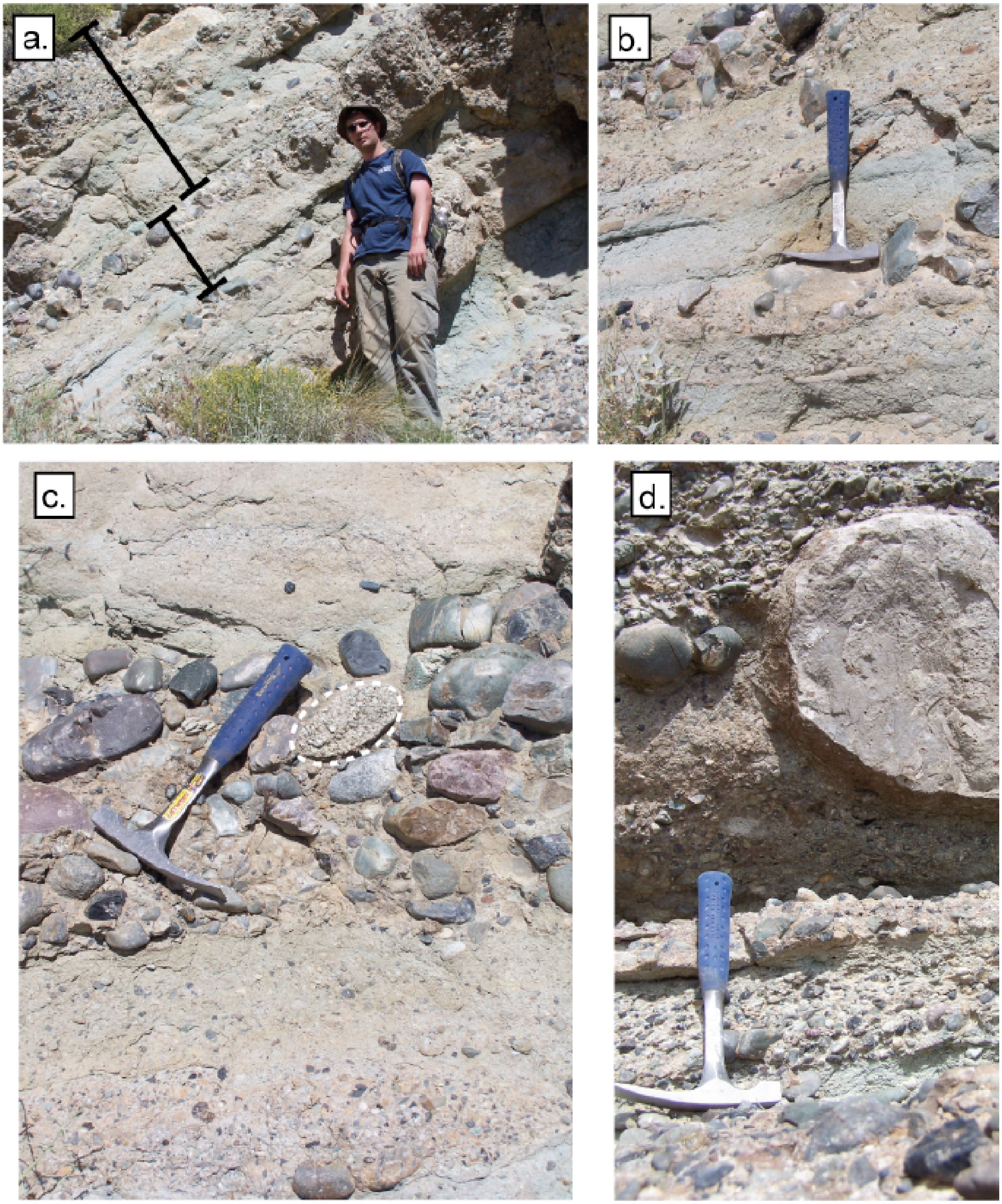


Figure 2-20. Photographs of Lithofacies 11, Volcaniclastic Sandstone and Conglomerate Couplet

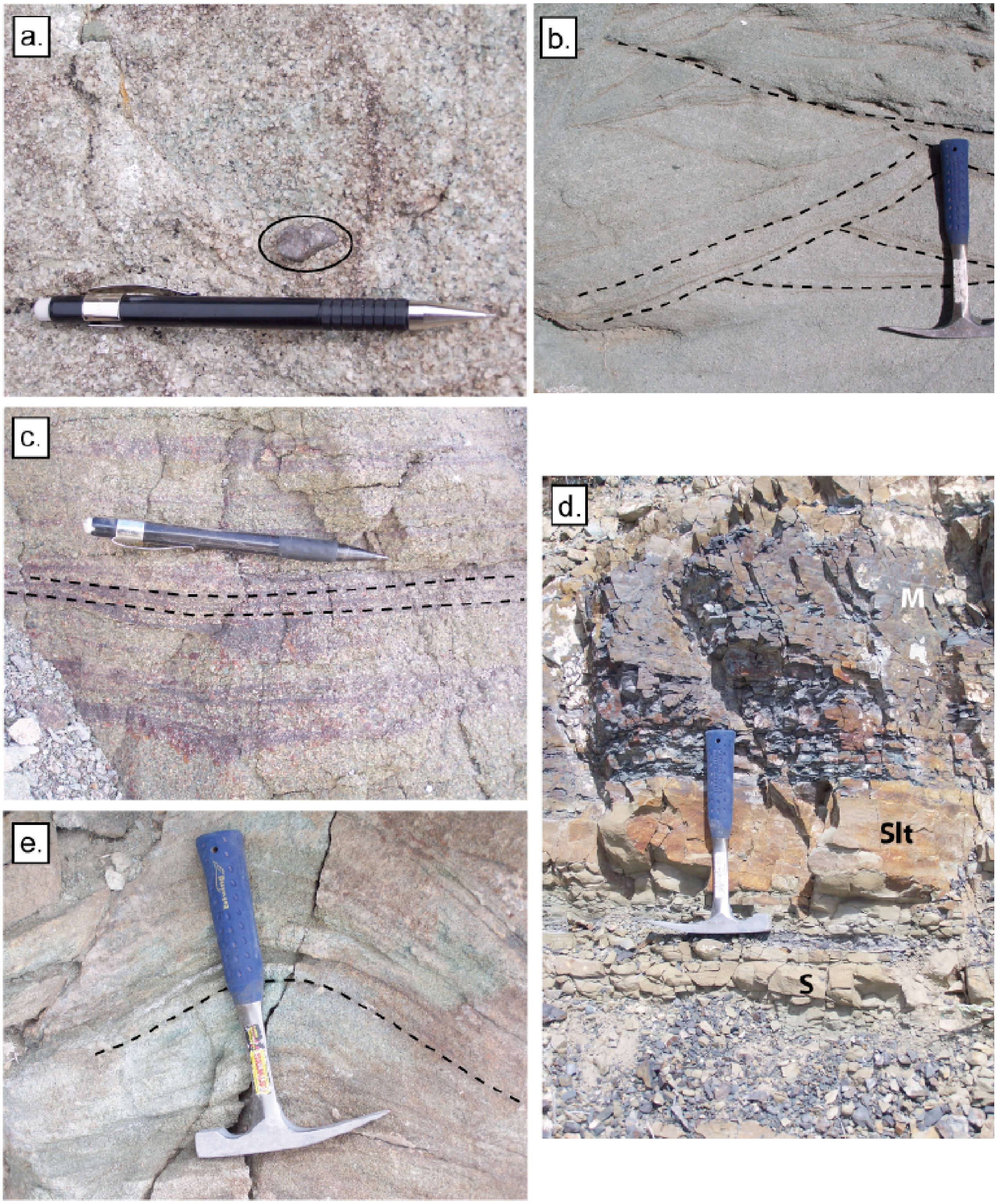


Figure 2-21. Photographs of Lithofacies 12, Interbedded Sandstone and Mudstone

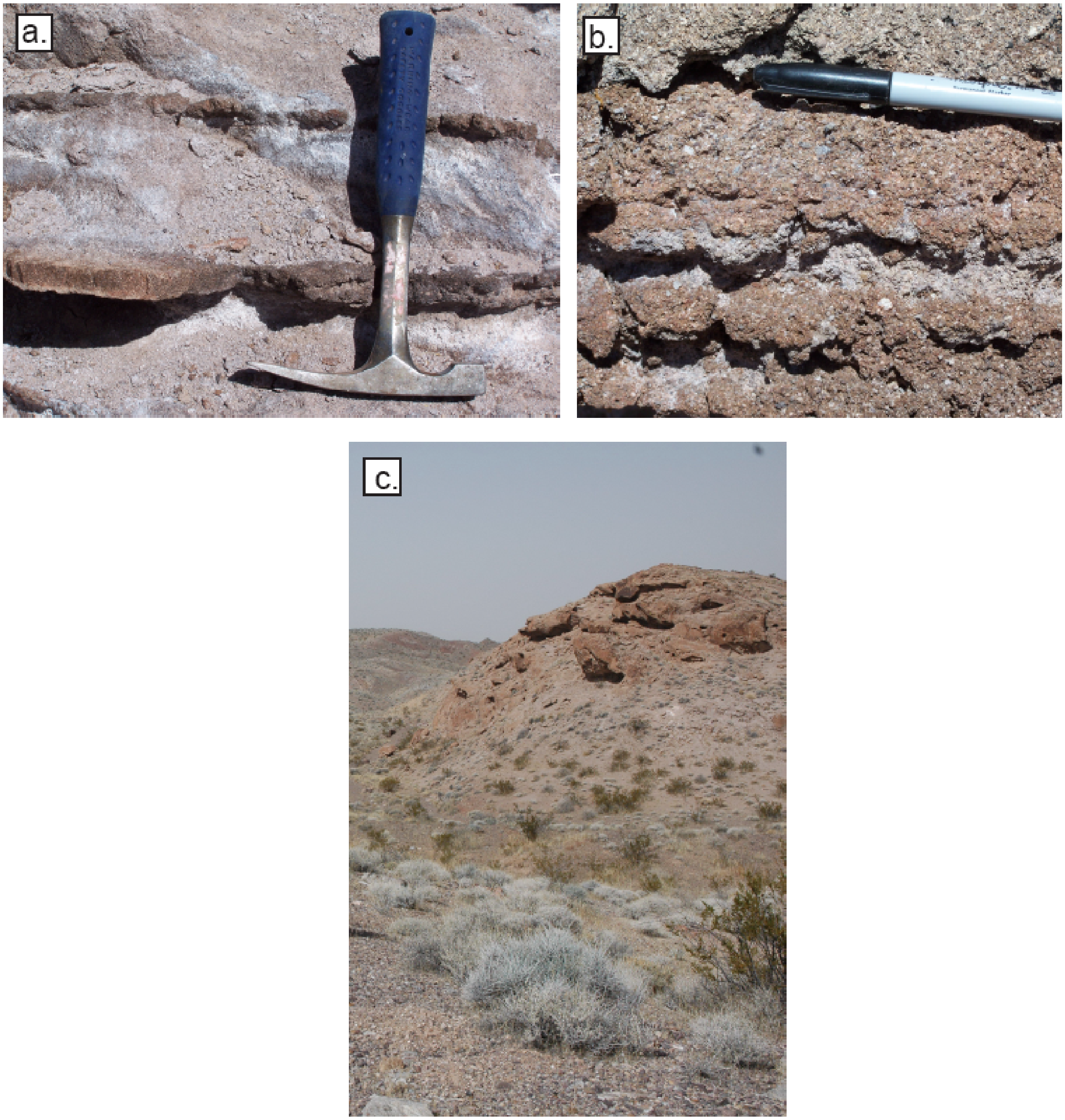


Figure 2-22. Photographs of Lithofacies 13, Massive Volcaniclastic Sandstone

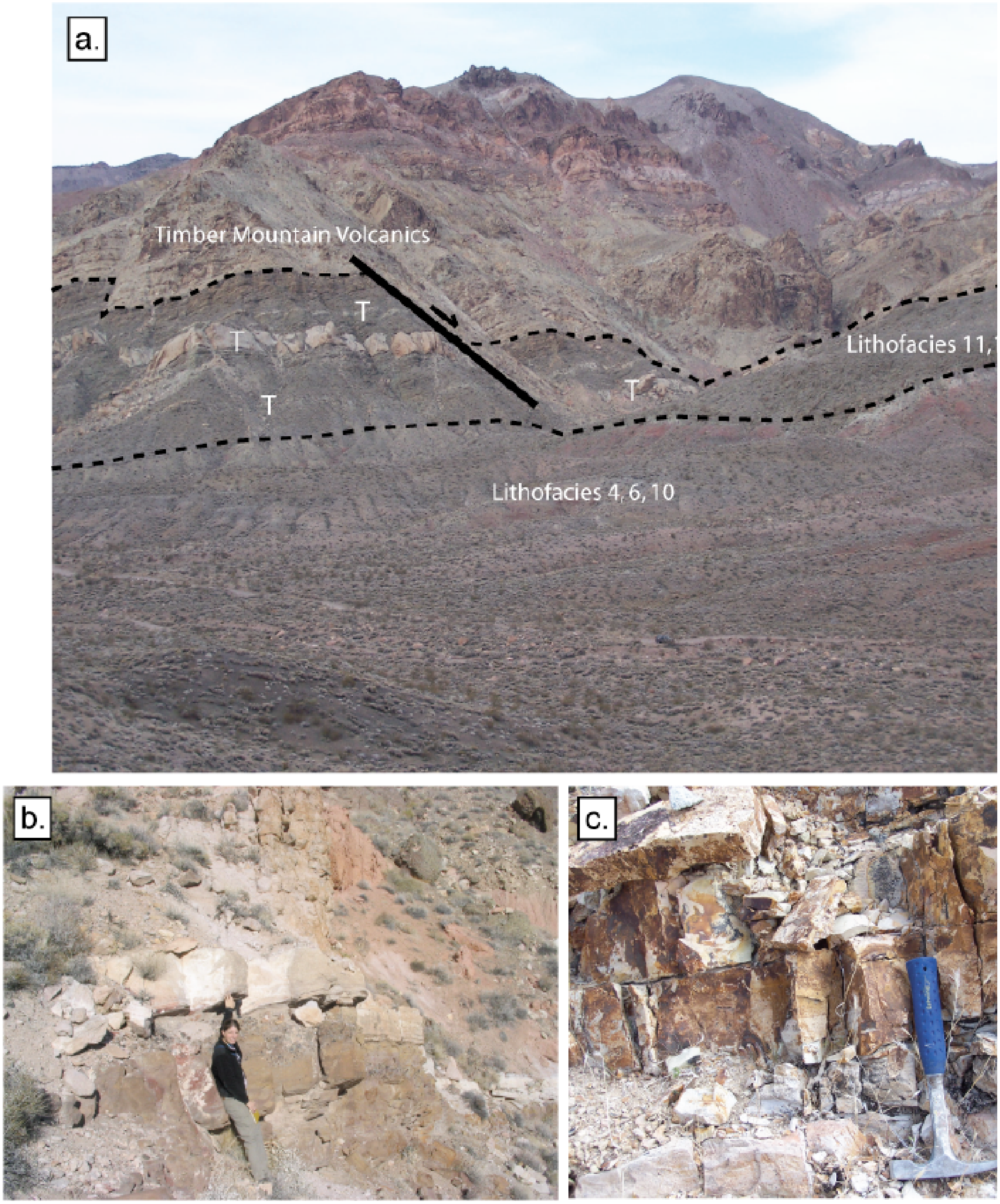


Figure 2-23. Photographs of Lithofacies 14, Massif Tuff

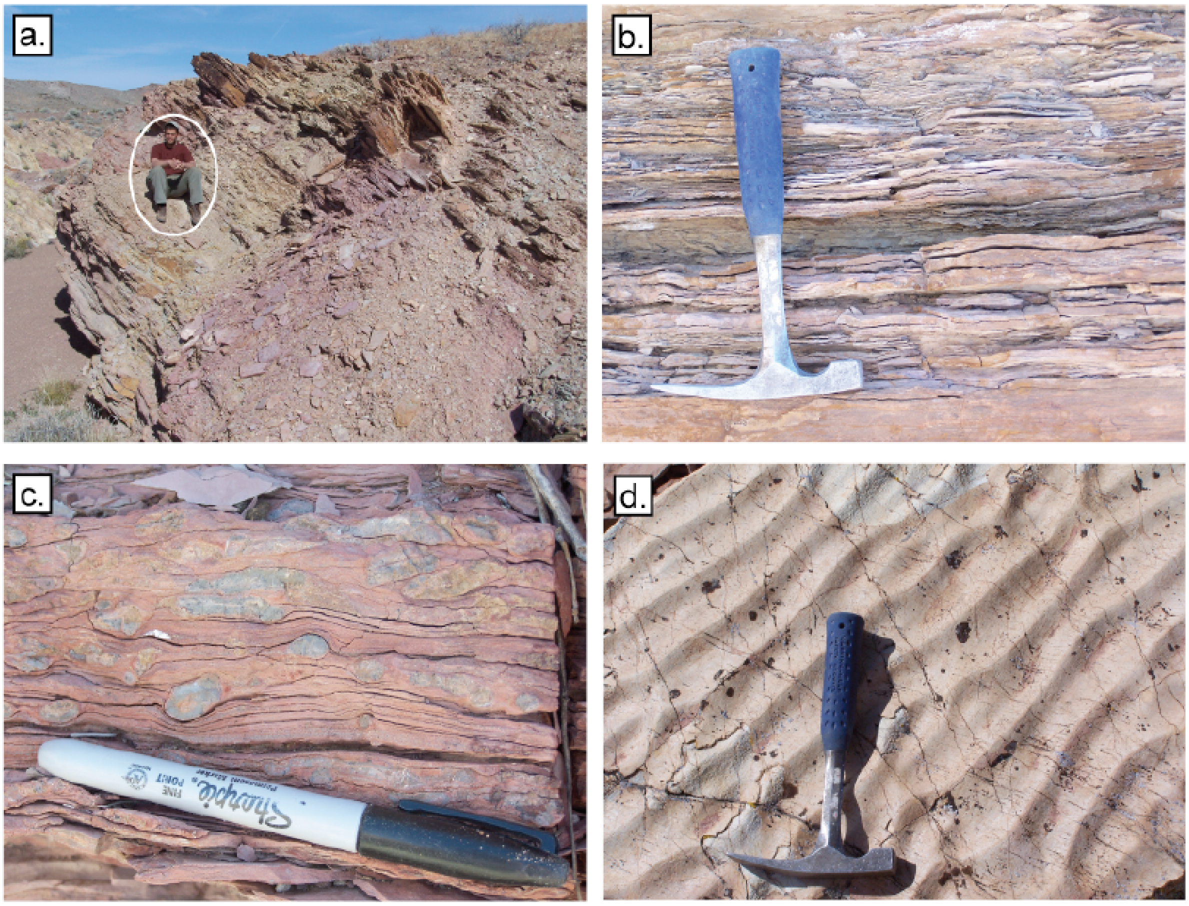


Figure 2-24. Photographs of Lithofacies 15, Interbedded Sandstone and Mudstone

2.2 Lithofacies Associations and Depositional Model

The 15 lithofacies described in the previous sections reflect alluvial, lacustrine, palustrine, and volcanic depositional environments. These lithofacies have been divided into four lithofacies associations (LAs) that represent common depositional processes and depositional environments.

LAs 1, 2, and 3 represent distinct depositional environments during different time intervals. LA 4 does not represent a unique time and stratigraphic interval, because it is found interbedded within LAs 2 and 3. The four LAs are summarized in Table 2-2 and discussed in detail next.

2.2.1 Lithofacies Association 1 (Lithofacies 1, 2, and 3)

LA 1 is dominantly composed of Lithofacies 1, a clast-supported quartzite conglomerate, and Lithofacies 3, a matrix-supported conglomerate (Table 2-2; Figure 2-25). LA 1 is seen at the base of the Oligocene–Miocene sedimentary section. Key exposures can be observed in the Leadfield section (Figure 2-4) from 0–16.5 m [0–54 ft] and the Turtle Canyon section from 0–76 m [0–249 ft] (Figure 2-3).The poorly sorted carbonaceous monolithologic breccia with large limestone clasts of Lithofacies 2 is primarily interbedded within Lithofacies 1 in the

Table 2-2. Summary of Lithofacies Associations*			
Lithofacies Association	**Lithofacies**	**Depositional Environment**	**Basinal Setting**
Lithofacies Association 1 (Lithofacies 1, 2, 3)	Moderately sorted clast-supported quartzite conglomerate, poorly sorted conglomerate, poorly sorted matrix-supported carbonate breccia	Fairly proximal alluvial fan- debris flows, rock avalanches, proximal braided stream	Initiation of extension recycles unconformity quartzite clast lag and exhumes Precambrian-Paleozoic carbonaceous strata left as topographic highs with the development of small grabens, fan
Lithofacies Association 2 (Lithofacies 4, 5, 6)	Moderately to well sorted clast-supported quartzite and chert conglomerates at times stratified, moderately to well sorted and stratified sandstones	Proximal and distal braided streams	Basin development continues as multiple braided stream systems develop, both proximal and distal
Lithofacies Association 3 (Lithofacies 11, 12, 13, 14)	Poorly to moderately sorted volcaniclastic sandstone and conglomerate couplet, fine-grained stratified tuffaceous sandstones, medium to coarse-grained massive tuffaceous sandstones, fine to medium-grained massive tuff	Distal alluvial fan-sheet flood. Braided stream of distal fan and pyroclastic eruption-ashflow, ashfall	Crust attenuation with continued basin extension creates local volcanism that is reworked by gravity and stream flow processes on an alluvial fan
Lithofacies Association 4 (Lithofacies 7, 8, 9, 10, 15)	Oncoid-rich, stromatolite-rich, and gastropod-rich biomicrites and interbedded sandstone, siltstone, and mudstone, marlstone, and limestones	Lacustrine/distal alluvial fan-sheet flood and palustrine systems	Continued basin expansion creating topographic lows for lacustrine and palustrine development
*Gutenkunst, M.L. "Stratigraphic and Geochronologic Analysis of Eocene-Miocene Synextensional Strata in the Grapevine and Funeral Mountains of Southwestern Nevada and Southeastern California: Implications for Regional Correlation of 'Pre-Basin and Range' Stratigraphy." Master's thesis. Purdue University. West Lafayette, Indiana. 2006.			

Grapevine Mountains (Figure 2-25). The deposits of Lithofacies 2 are found scattered along the Cambrian–Tertiary contact in the Grapevine Mountains and are composed of fragments of the Bonanza King Formation, which is consistently found at or near the contact with the Tertiary strata. Below the Cambrian–Tertiary contact, the low angle normal faults of Titus Canyon fault or Fall Canyon are observed and the outcrop appearance of the Lithofacies 2 megabreccias that are interbedded with the stratigraphy of LA 1 appear to be linked to the trace of these faults.

The deposition of LA 1 is attributed to proximal alluvial fan development during the Oligocene. Initial activity on a fault is recorded by the incorporation of the unconformity basal lag of well-rounded quartzite clasts and streamflow deposits of Lithofacies 1 into small grabens. As a fault scarp developed, potentially the Titus Canyon fault or Fall Canyon fault zone (Figure 2-26), sufficient relief was generated to trigger rock avalanches derived from the footwall. Continued fault activity and the exhumation and subsequent erosion of Precambrian and Paleozoic strata of the Death Valley region is recorded by the incorporation of angular clasts, primarily of carbonate strata, into Lithofacies 3. These deposits have been interpreted to represent fairly proximal alluvial fan deposits due to the large clast size, poor sorting, and angular clast shapes; all are indicative of short transport distances. The rounded quartzite clasts found within LA 1 are interpreted to be reworked and do not necessarily represent lengthy transport distances related to the large amount of time represented by the Paleozoic–Tertiary unconformity. This is particularly true for Lithofacies 3, which is composed of proximal alluvial fan deposits with angular to subangular carbonate clasts derived from the locally exposed passive margin strata and rounded to subrounded quartzite clasts. These subrounded clasts were most likely from previous deposits of Lithofacies 1.

2.2.2 Lithofacies Association 2 (Lithofacies 4, 5, and 6)

LA 2 is composed of the interbedded Lithofacies 4, 5, and 6 (Table 2-2). Lithofacies 4 and 5 are both clast-supported, moderately to well-sorted pebble to cobble conglomerates; both contain clasts of chert and quartzite, among other clasts, but Lithofacies 5 is dominated by chert. Lithofacies 6 is composed of moderately to well-sorted stratified sandstone. LA 2 is found stratigraphically above LA 1 and is best exposed in the Titus Canyon 1a measured stratigraphic section (Figure 2-5) from 120–143 m [394–469 ft], from 298–447 m [978–1,466 ft] in the Keane Spring section (Figure 2-10), and from 76–300 m [249–984 ft] in the Turtle Canyon section (Figure 2-3). LA 2 is commonly found interbedded with LA 4. This interbedded relationship is expressed by both fluvial-(Figure 2-27) and lacustrine-dominated systems (Figure 2-28). Deposition of LA 2 is attributed to braided fluvial networks that overall drained south to north. Gravel-dominated (Lithofacies 4), mixed bedload (Lithofacies 5), and sand-dominated (Lithofacies 6) braided systems are represented within LA 2. Similar thicknesses are observed for Lithofacies 4, which is most abundant in the northern portion of the study area, and Lithofacies 6, which is most abundant in the south. Lithofacies 5 is found in subordinate amounts throughout the study area. The internal structure within the lithofacies of LA 2 and bedding geometries, as well as the interfingering relationship with LA 4, supports a braided fluvial network interpretation.

2.2.3 Lithofacies Association 3 (Lithofacies 11, 12, 13, and 14)

LA 3 is composed of volcanic and volcaniclastic deposits. The volcaniclastic conglomerate and sandstone sheetflood deposits of Lithofacies 11, fine-grained volcaniclastic sandstones of Lithofacies 12, massive volcaniclastic sandstone of Lithofacies 13, and ashfall tuff deposits of Lithofacies 14 make up LA 3 (Figure 2-29; Table 2-2). Good examples of LA 3 can be found from 621–712 m [2,037–2,336 ft] in the Leadfield measured section (Figure 2-4) and from 301–358 m [987–1174 ft] in the Yellow Ridge section (Figure 2-6). The deposition of LA 3 is interpreted to result from further attenuation of the crust with synchronous volcanism. As the basin continued to expand, the crust may have thinned to a point that local volcanism occurred. The deposition of Lithofacies 11, 12, and 13 is attributed to the rapid sedimentation typically associated with volcanism. By incorporation of interbedded tuffs (Lithofacies 14), the amount of volcanic material increases in the upper parts of the Leadfield section and the Yellow Ridge section, where LA3 was observed and represents increasing volcanic activities. The sheetflood,

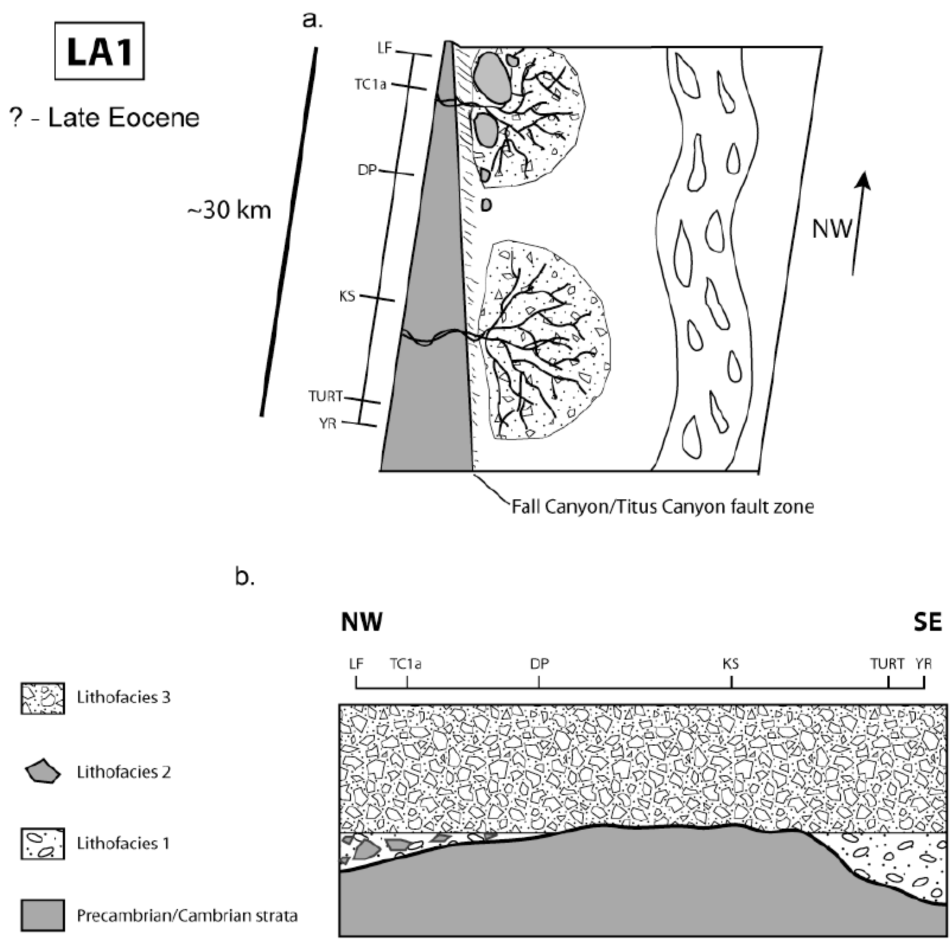


Figure 2-25. Map and Along Strike Cross-Sectional View of Lithofacies Association 1

fine grained braided stream, and hyperconcentrated flood flow deposits are representative of mid and distal alluvial fan deposits. Lithofacies 11 becomes more fine-grained from the northern to southern portion of the field area. This change in grain size over a relatively short distance supports the alluvial fan interpretation. Often, syneruptive deposition results in alluvial fan gravity and streamflow deposits of a tuffaceous nature. The tuff deposits of Lithofacies 14 and the minor volcanic breccia and volcanic clasts conglomerate incorporated within the massive sandstone of Lithofacies 13 document this volcanic activity directly.

2.2.4 Lithofacies Association 4 (Lithofacies 7, 8, 9, 10, and 15)

LA 4 deposits also interfinger with the distal alluvial fan deposits of LA 3 (Figure 2-29). LA 4 is best expressed in the 621 to 713-m [2,037 to 2,339-ft] interval of the Leadfield measured stratigraphic section (Figure 2-4), 75 to 120-m [246 to 394-ft] interval of the State Line measured section (Figure 2-13), and 300 to 359 m [984 to 1,178 ft] interval of the Yellow Ridge measured section (Figure 2-16).

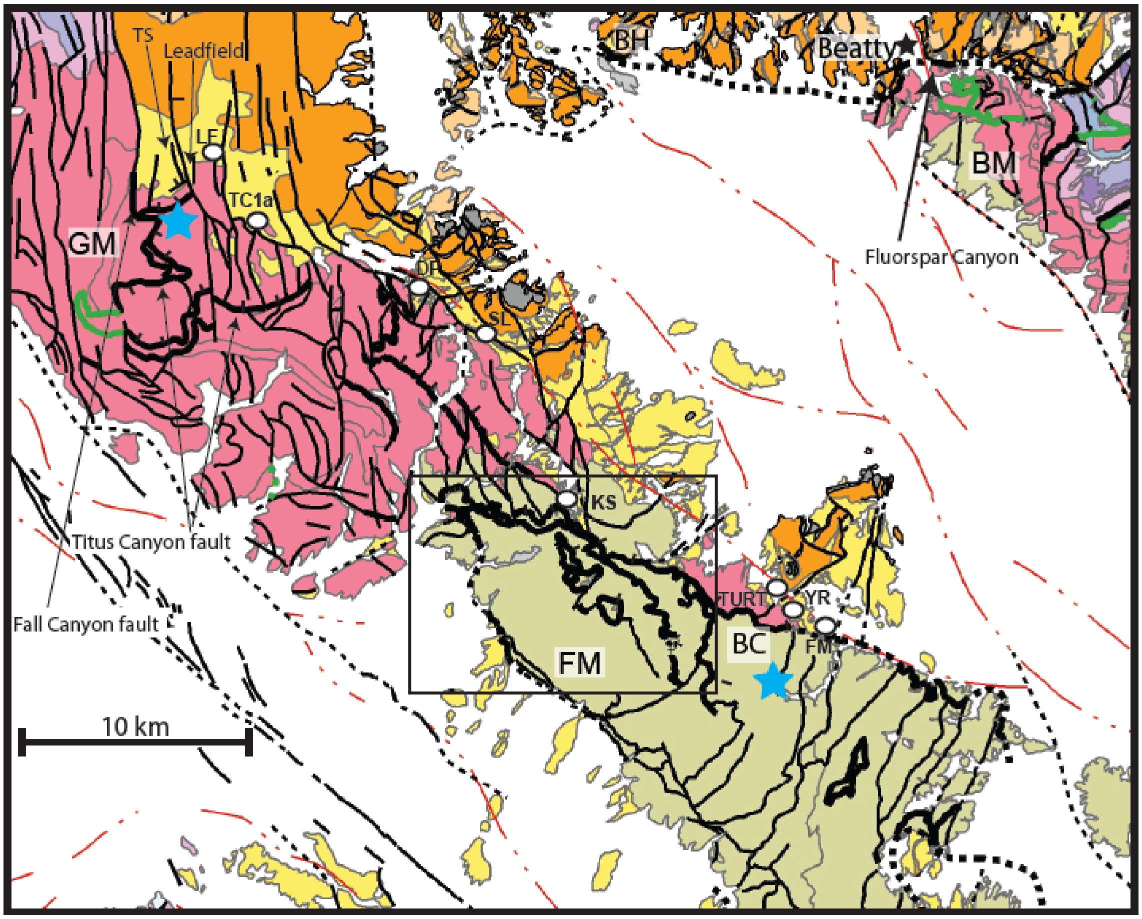


Figure 2-26. Geologic Map of the Funeral and Grapevine Mountains

Lithofacies 7, 8, 9, 10, and 15 make up LA 4. The three biomicrite lithofacies of Lithofacies 7, 8, and 9 are found within LA 4 and are defined by their oncoid, stromatoloid, or gastropod microfossils. These lithofacies also contain minor coarse sand to pebble intervals. The fine-grained calcareous sequence of Lithofacies 10 and the fine-grained clastic sequence of Lithofacies 15 are also associated with LA 4. LA 4 is found interstratified within LAs 2 and 3 (Figures 2-27, 2-28, 2-29) and is illustrated from 486–497 m [1,594–1,631 ft] in the Leadfield measured section (Figure 2-4) and 50–51 m [164–167 ft] in the Yellow Ridge section (Figure 2-6). The best exposures of LA 4 are found in the southern portion of the mapping area in the central Funeral Mountains (Figure 2-1).

The development of topographically low areas through basin subsidence allowed for the development of LA 4. These low areas are found at the distal edges of alluvial-fan systems and are represented by lacustrine and palustrine environments. The lacustrine environments include low energy environments that allow for the development of algal mats as well as wave-influenced, higher energy environments that allow for the development of oncoids. The interbedded nature of LA 4 with various alluvial-fan deposits of LAs 2 and 3 shows the constant disruption of the fine-grained sequences with interbedded sediment pulses, indicating continued development of the basin (Figures 2-27, 2-28, 2-29).

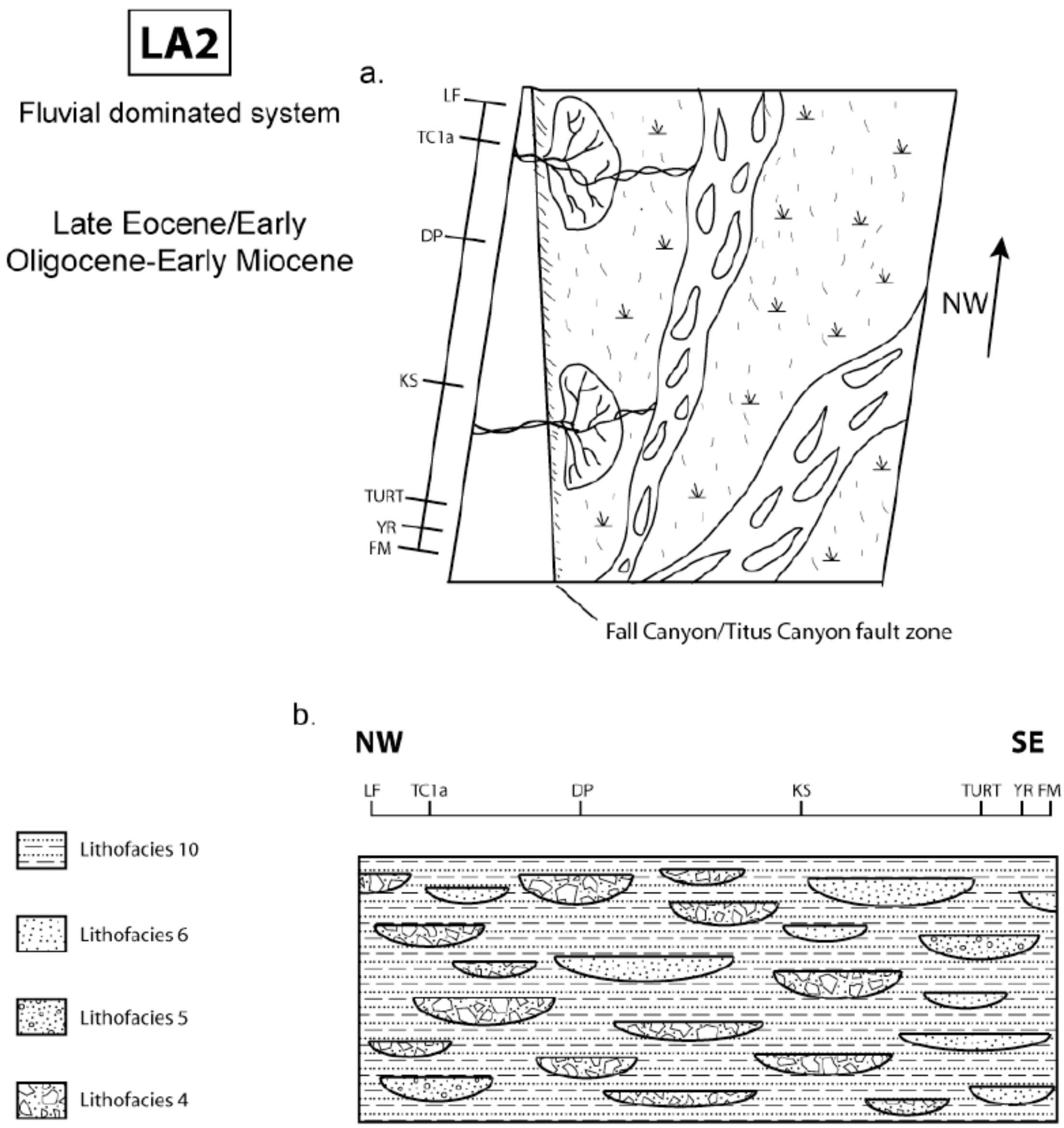


Figure 2-27. Map and Cross-Sectional View of Lithofacies Association 2

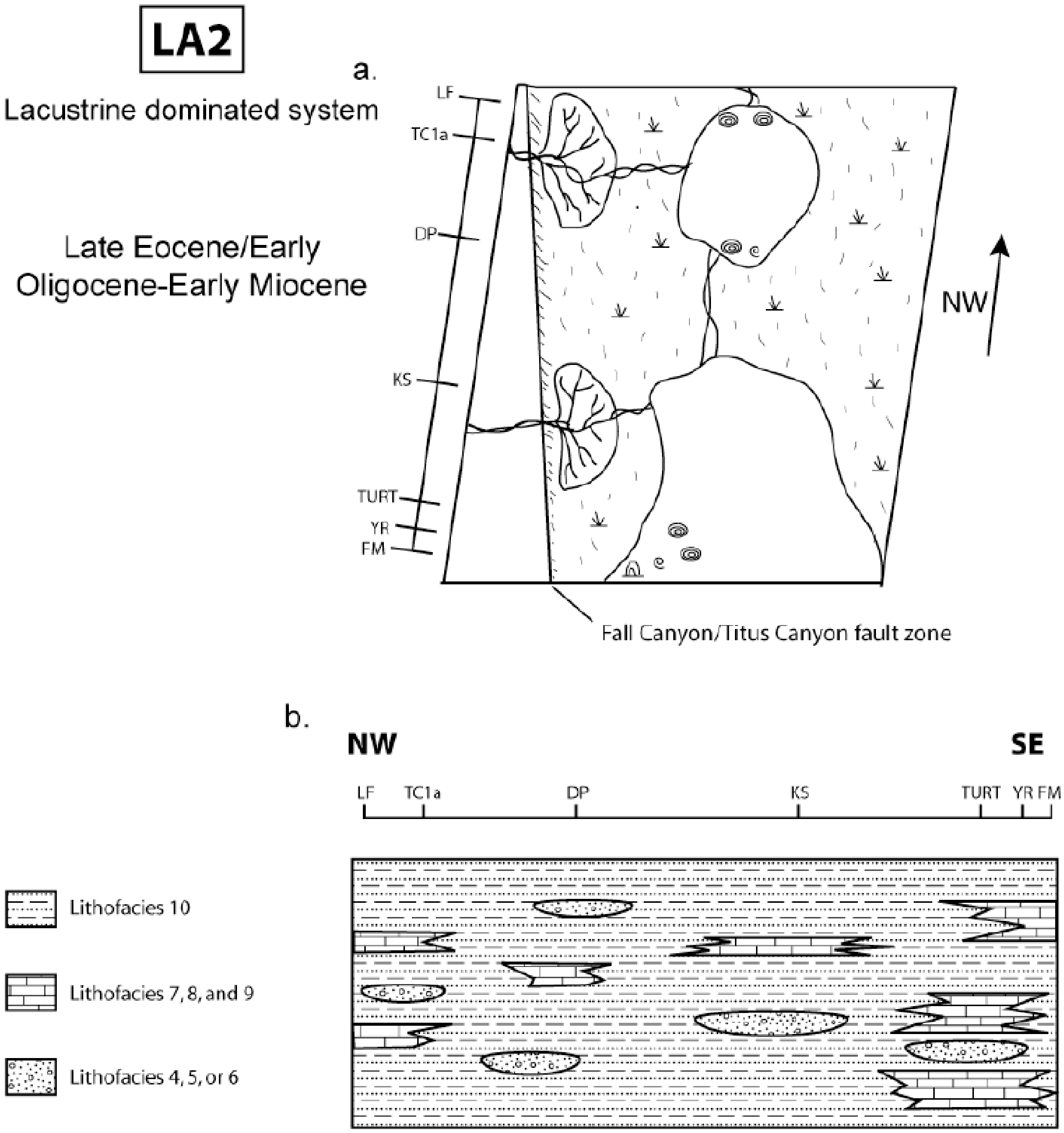


Figure 2-28. Map and Cross-Sectional View of Lacustrine Dominated System Lithofacies Association 2

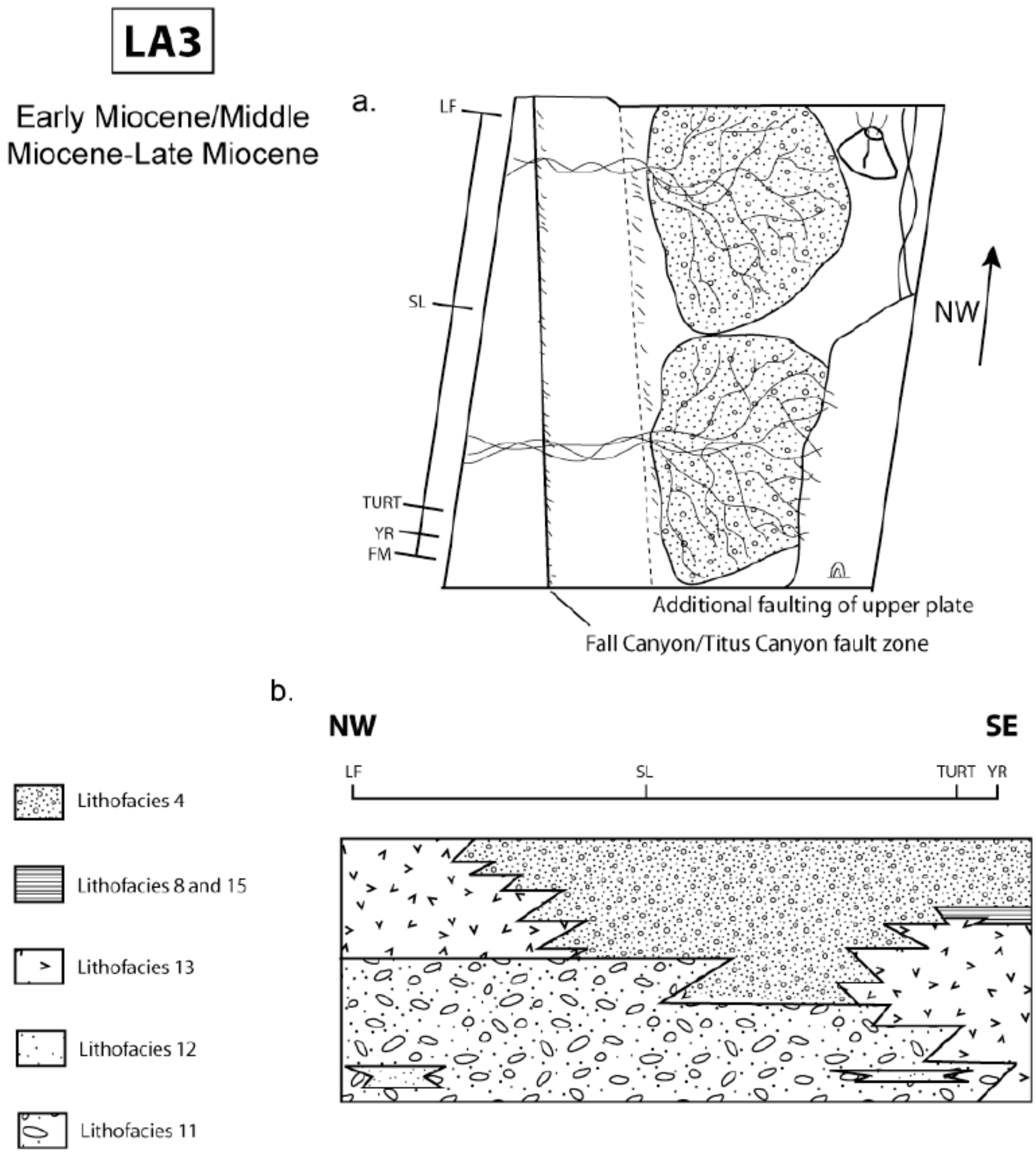


Figure 2-29. Map and Cross-Sectional View of Lithofacies Association 3

3 REGIONAL CORRELATIONS OF OLIGOCENE TO EARLY MIOCENE STRATA

The "pre-Basin and Range" Eocene–Miocene stratigraphic units are of specific interest in this study. Locally, these units can be found in the Grapevine and Funeral Mountains and on the Nevada Test Site and have been identified in the subsurface by several wells within the Amargosa Basin (Figure 2-1). Gutenkunst (2006) established new correlations of the stratigraphy of Oligocene to early Miocene sedimentary and volcanic strata studied in the Funeral and Grapevine Mountains to the west of Yucca Mountain with studies mainly from Murray, et al. (2002, 2003) to the east of Yucca Mountain and with numerous other studies. These correlations are summarized next.

The Titus Canyon Formation is the oldest of Death Valley's Cenozoic stratigraphy (Stock and Bode, 1935; Reynolds, 1969). The type section, as well as all previously reported age data for the Titus Canyon Formation, is found in outcrops of the Grapevine Mountains (Table 3-1, Figure 3-1). The oldest radiometric date for the Titus Canyon Formation is a 34.3 Ma Ar-40/Ar-39 biotite isochron age obtained from a tuff found interbedded with conglomerate in the bottom part of the type section for the Titus Canyon Formation (Saylor and Hodges, 1991). Titanothere, horse, hyracodont rhinoceros, artiodactyl, and rodent mammalian fossils were noted by Stock and Bode (1935) in the lower part of the Titus Canyon section and give a lower age limit of Late Eocene to Early Oligocene (~38–30 Ma), which agrees with the radiometric date of Saylor and Hodges (1991). Note that within the 636 m [2,087 ft] of the Titus Canyon type section (Reynolds, 1969), the 34.3 Ma tuff Saylor and Hodges (1991) collected was ~370 m [1,214 ft] above the base of the section and the mammalian fossils have not been observed in the basal part of the section. Therefore, the lower age limit of the Titus Canyon could potentially be older than Late Eocene-Early Oligocene (Figure 3-1).

The presence of volcanic material in the upper portion of the Titus Canyon section has provided further age constraints. Saylor and Hodges (1991) reported 34 Ma Ar-40/Ar-39 biotite isochron age of 30.0 Ma from a tuffaceous sandstone collected ~20 m [66 ft] below the disconformity between the variegated facies and green conglomerate facies Reynolds (1969) identified. A radiometric age of ~27 Ma was obtained from a tuff near the center of the section (Reynolds, 1974). Snow and Lux (1999) report a Ar-40/Ar-39 age of 15.52 + 0.21 Ma for the marker tuff within Reynolds' (1969) green conglomerate Saylor and Hodges (1991) obtained a final isochron age of 12.0 Ma approximately 100 m [328 ft] above the disconformity between the variegated facies and green conglomerate facies of Reynolds (1969) from a tuff interbedded within the green conglomerate facies, thus 12.0 Ma is the upper age limit of the Titus Canyon Formation. Snow and Lux (1999) question the 12.0 Ma date of Saylor and Hodges (1991) as they observed chloritic alteration at ages comparable to movement on the Boundary Canyon detachment within tuff samples they collected from the Funeral and Grapevine Mountains. They suggest that similar alteration has occurred within the sample for which the 12.0 Ma date was obtained and that it is not representative of the true age of the green conglomerate.

Table 3-1. Tertiary Stratigraphy of the Death Valley Region (Modified from Snow and Lux, 1999; Barnes, et al., 1982)

	Panamint Mountains		Cottonwood Mountains		Funeral Mountains		Grapevine Mountains		Test Site
	Stratigraphic Nomenclature	Snow and Lux (1999)	Stratigraphic Nomenclature	Snow and Lux (1999)	Stratigraphic Nomenclature	Snow and Lux (1999)	Stratigraphic Nomenclature	Snow and Lux (1999)	Stratigraphic Nomenclature
Pliocene	Nova Fm.	Nova Fm.	volcanics and marl	Nova Fm.					
Pliocene		Navadu Fm.		Navadu Fm.	Funeral Fm.	Funeral Fm.			
Miocene			middle conglomerate		Furnace Creek Fm.	Furnace Creek Fm.			
Miocene					Artist Drive Fm.	Artist Drive Fm.	ash flow tuffs	Test Site volcanics	Pavits Spring
Miocene			Ubehebe sandstone		Bat Mtn. Fm., Pavits Spring	Bat Mtn. Fm.	unnamed tuff sequence	Leadfield Fm.	
Miocene				Panuga Fm.	Kelly's Well Limestone	Panuga Fm.	green conglomerate	Panuga Fm.	
Miocene				Ubehebe Fm.	Amargosa Valley Fm., Horse Spring Fm.	Ubehebe Fm.	DV Buttes beds	Ubehebe Fm.	
Oligocene			lower conglomerate						Horse Spring Fm.
Oligocene					Titus Canyon Fm.		Titus Canyon Fm.	Titus Canyon Fm.	

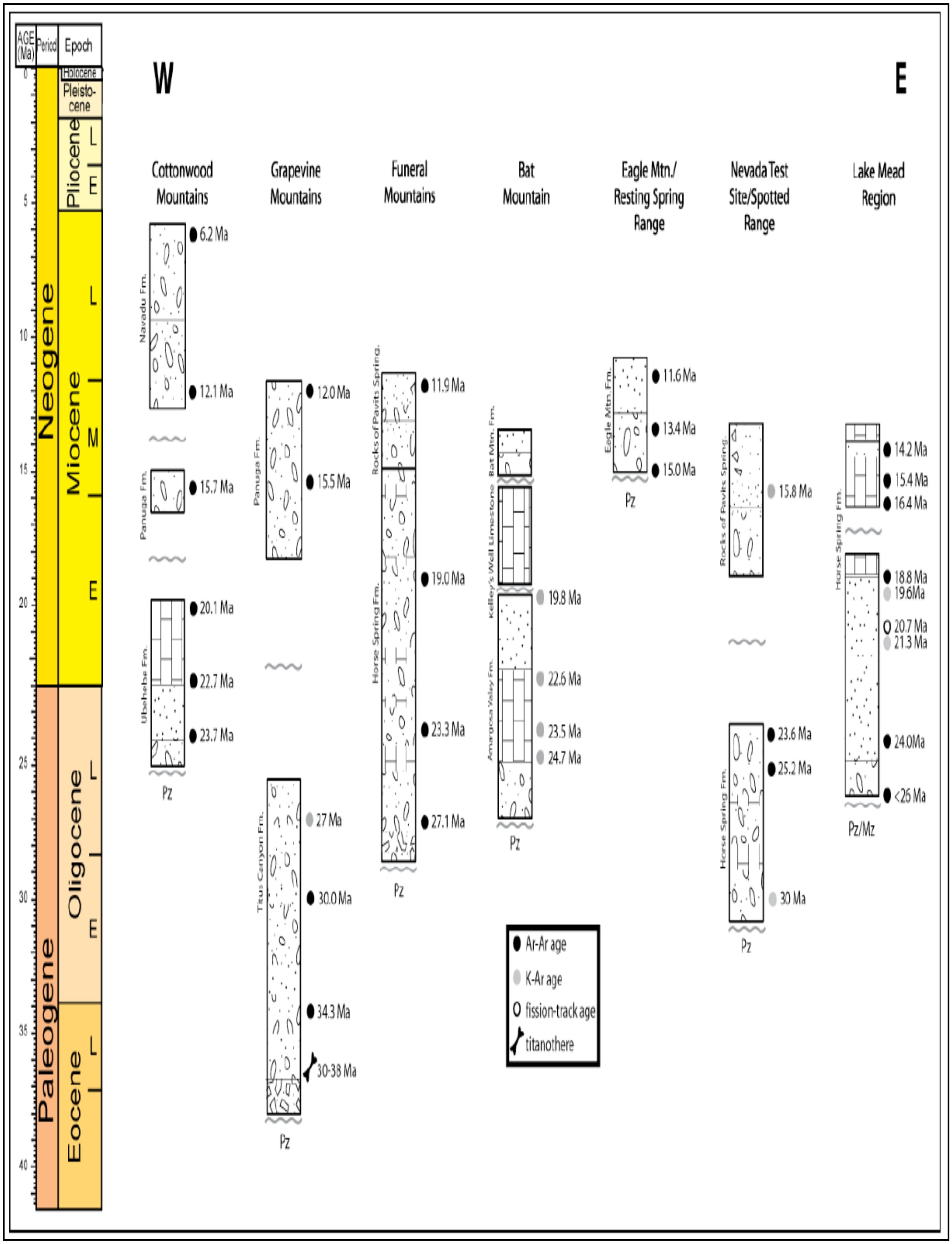


Figure 3-1. Regional Summary of Eocene-Miocene Stratigraphy

Overlying the Titus Canyon and Panuga Formations in the Grapevine Mountains are volcanic units of the southwestern Nevada volcanic field, including the Crater Flat Group, Paintbrush Group, and Timber Mountain Group, which range in age from ~15 Ma to 11.45 Ma (Sawyer, et al., 1994). These ages could further indicate that the 12.0 Ma age Saylor and Hodges (1991) obtained is too young and that the upper age limit of the “pre-Basin and Range” strata in the Grapevine Mountains is ~15.5 Ma. Not all of the Eocene to Miocene strata in the central and northern Funeral Mountains have been formally named. Mapping by Wright and Troxel (1993) has identified the Titus Canyon Formation as the lowest part of the Cenozoic stratigraphy in the Funeral Mountains. Wright and Troxel (1993) the overlying sedimentary units as Miocene sandstone, siltstone, conglomerate, and tuff (Tss) and Miocene tuffaceous sandstone and volcanic breccia (Tst). Murray, et al. (2002) studied these same stratigraphic units and interpreted them as the Horse Spring Formation based on correlation to similar strata Barnes, et al. (1982) mapped on the Nevada Test Site (Table 3-1). The USGS no longer utilizes this formation name due to an older apparent age than the type section in the Lake Mead region (Bechtel SAIC Company, LLC, 2003), but as seen in Figure 3-1, there is significant age overlap between the two areas. The Horse Spring Formation on the Nevada Test Site consists of gastropod-rich limestone, conglomerate with carbonate and quartzite clasts, sandstone, siltstone, and intermittent air-fall tuff (Barnes, et al., 1982; Hinrichs, 1968). The only age reported for these strata is a K/Ar biotite age of 30 +/- 0.9 Ma that was obtained from one of the basal tuffs on the Nevada Test Site (Barnes, et al., 1982; recalculated after Steiger and Jager, 1977; Dalrymple, 1979).

Approximately 150 km [94 mi] to the east, in the Muddy Mountains of the Lake Mead region, Bohannon (1984) described the type section for the Horse Spring Formation. This formation contains similar lithologies of conglomerate, sandstone, limestone, and tuff, but some of the strata are younger based on radiometric dates (Figure 3-1). Beard (1996) and Bohannon (1984) provided primary Ar-40/Ar-39 and K-40/Ar-39 age constraints for the strata in the Lake Mead region; these and range from <26–8.5 Ma. Additional dates are provided by many authors including Anderson, et al. (1972); Shafiqullah, et al. (1980); Carpenter, et al. (1989); Donatelle, et al. (2005); and Martin (2005) for the Oligocene–Miocene Horse Spring Formation.

In the Funeral Mountains as well as on the Nevada Test Site, the Rocks of Pavits Spring have been identified as overlying the Horse Spring Formation (Table 3-1; Barnes, et al., 1982; Murray, et al., 2002). Barnes, et al. (1982) describe the Rocks of Pavits Spring on the Nevada Test Site as containing conglomerate with quartzite and carbonate clasts, varicolored sandstone, volcaniclastic sandstone, and small amounts of ashfall tuff and limestone. In the central Funeral Mountains, Murray, et al. (2002) observed outcrops similar to the strata mapped and described by Barnes, et al. (1982) and correlated them. Wright and Troxel (1993) originally mapped these outcrops in the Funeral Mountains as their Tsa unit, described as Miocene arkosic sandstone, conglomerate, and subordinate siltstone. The Rocks of Pavits Spring have a maximum age of 18.3 Ma based on the inclusion of clasts from the radiometrically dated Hiko Tuff (Armstrong, 1970). Ash beds within the unit have been dated at 15.8 Ma (K-Ar), and intercalculated Nevada Test Site volcanics range in age from 13.5–13.1 Ma (Carr, et al., 1986). This study reveals that the upper age limit is represented by a Ar-40/Ar-39 dated 11.9 Ma tuff in the uppermost parts of the Rocks of Pavits Spring within the Funeral Mountains (Figure 3-1).

In addition to the Funeral and Grapevine Mountains and the Nevada Test Site, Eocene-Miocene strata are found at exposures across the central Basin and Range including the Cottonwood Mountains, Bat Mountain, Eagle Mountain/Resting Spring Range, and the Lake Mead region. A summary of geochronologic ages for these locations is presented in Figure 3-1. The Cottonwood Mountains to the west of Death Valley are the westernmost locality of pre-Basin

and Range strata in the examined region. Snow and Lux (1999) formally proposed Ubehebe, Panuga, and Navadu as formation names for these strata, which are found primarily in the northern reaches of the Cottonwood Mountains within the Ubehebe Basin (Table 3-1). These formations are described and summarized from measured sections and observations from work by Snow (1990) and Snow and White (1990). Pre-Basin and Range stratigraphy is also found at or near Bat Mountain, located at the southern tip of the Funeral Mountains. Cemen, et al. (1985) provided the most recent summary of these strata, known as the Amargosa Valley Formation, Kelley's Well Limestone, and the Bat Mountain Formation.

Niemi, et al. (2001) described and named a sedimentary sequence of Miocene stratigraphy found on the southern portion of Eagle Mountain and the eastern side of the Resting Spring Range. Their measured section located at the southeastern portion of Eagle Mountain is the type locality for the Eagle Mountain Formation. Bohannon (1984) studied the Oligocene and Miocene stratigraphy of the Lake Mead region in detail, and enhancements of his stratigraphy have been made by several geologists since that time, particularly by Beard (1996). The Oligocene–Miocene sedimentary strata of the Lake Mead region include the Horse Spring Formation, the red sandstone unit, and the Muddy Creek Formation (Figure 3-1).

4 SIGNIFICANCE OF RESULTS

These studies produced several significant results. These relate to (i) the extent and distribution of the Oligocene–Lower Miocene strata of Fortymile Wash and the Nevada Test Site to the east and of the Funeral and Grapevine Mountains to the west, (ii) the paleogeography that presided over the deposition of these strata, and (iii) the suggestion that the extension phase in the region started earlier in Oligocene time rather than in late Miocene time.

(i) Regional lithologic and geochronologic data show that thick sedimentary and volcaniclastic formations were deposited during the Oligocene to early Miocene over a wide area of Nevada and eastern California and support a strong case for correlation with Oligocene to early Miocene strata into the subsurface near Yucca Mountain. The regional geochronologic data and detailed descriptions of lithologic units exposed in the Grapevine and Funeral Mountains, as well as previous descriptions of similar units from the Nevada Test Site (Murray, et al., 2002, 2003), indicate the Oligocene to early Miocene strata extend at least from the Death Valley area to the west to the Lake Mead area to the east over a distance of more than 200 km [125 mi]. The lithostratigraphy documented here for these units, based on outcrop measured sections, provides a detailed look at the rock types that may affect groundwater flow from the Yucca Mountain area to the south into the Amargosa desert. Understanding the distribution of these strata in the subsurface is important for conceptualizing regional groundwater flow; the potential for these strata to act as pathways or barriers to groundwater flow should be included in any hydrostratigraphic framework model. Accounting for these strata in regional cross sections also is important for proper structural interpretations.

(ii) The clear evidence of active alluvial fans and lacustrine depositional environment in the Oligocene and early Miocene time implies the presence of significant topographic relief during deposition. Similar topography must have also existed during deposition of the middle and late Miocene tuffs that form Yucca Mountain. Within this context, the distribution of the tuffs likely has been influenced by the preexisting topography. In this type of complex setting, on-lapping and off-lapping stratigraphic relationship should be expected in the volcanic stratigraphy. Interpretation of the overlying tuff stratigraphy as possessing a regular geometry may be oversimplified, (especially near the base of the tuff sequence), given the complex and dynamic paleogeographic setting suggested in this report. This is particularly true in the more southern distal extent of some tuffs that are interbedded with sedimentary deposits in the subsurface in the southern Fortymile Wash and the Amargosa Desert areas.

(iii) The regional extent and thickness of the Oligocene to early Miocene strata documented over a wide part of Nevada and eastern California suggest that pre-Basin and Range extension resulted in a large and complex fairly continuous continental sedimentary basin. The present distribution of these strata suggests that the area has not undergone large magnitude extension nor large amounts of strike-slip displacement as required by some tectonic models (McKague, et al., 2010). These new interpretations also have implications for regional reconstructions of the Basin and Range in southeastern California and Nevada (e.g., Snow and Wernicke, 2000). Some of the most accepted reconstructions envision little extension in the study area until Late Miocene time. In contrast, the present results require that extension began by Oligocene time to form the accommodation space needed to deposit significant continental strata several kilometers thick.

In summary, during the Oligocene and early Miocene, thick sedimentary strata were deposited over a wide area of Nevada and eastern California in an expanding complex and fairly continuous continental sedimentary basin. The geologic record suggests that active Oligocene to early Miocene alluvial fans and lacustrine depositional environment systems developed in the presence of significant topographic relief due to active faulting during deposition prior to the middle and late Miocene Yucca Mountain tuffs deposition. Thus, in contrast to other interpretations, substantial tectonic extensional deformation of the region began by Oligocene time before the deposition of the Yucca Mountain tuffs to create space to accommodate these thick continental sedimentary sequences. The Yucca Mountains tuffs were deposited in a complex paleogeography and topography, which influenced the geometry of the tuffs, especially near their ends in the southern part of Fortymile Wash. Thus, the interpretation of the overlying tuffs as having an even and regular layer geometry may have been oversimplified. In turn, this setting produced an uncertain zone of contacts and transition between the tuffs and older and younger sedimentary strata. Because of their wide distribution and significant thicknesses in the subsurface, the sequences of Oligocene to early Miocene strata should be considered with greater importance in the regional stratigraphic and structural interpretations of the Fortymile Wash and Amargosa Desert basin.

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