Preliminary Geologic Map of the Southern Funeral Mountains and Adjacent Ground-Water Discharge Sites, Inyo County, California, and Nye County, Nevada

By C.J. Fridrich, R.A. Thompson, J.L. Slate, M.E. Berry, and M.N. Machette

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Introduction

This map covers the southern part of the Funeral Mountains, and adjacent parts of four structural basins—Furnace Creek, Amargosa Valley, Opera House, and central Death Valley (fig. 1). It extends over three full 7.5-minute quadrangles, and parts of eleven others (fig. 1)—a total area of about 950 square kilometers. The boundaries of this map were drawn to include all of the known proximal hydrogeologic features that may affect the flow of ground water that discharges from the springs of the Furnace Creek wash area, in the west-central part of the map (figs. 2 and 3, and see map and tectonic map). These springs provide the major potable water supply for Death Valley National Park.

The hydrogeologic features covered by this map include (see figs. 2 and 3, geologic map, and tectonic map): (1) the springs of the Furnace Creek wash area, (2) an active seep and much larger Pleistocene ground-water discharge deposits in the northeastern part of the map, (3) the exposed extent of the Paleozoic rocks that constitute the Paleozoic carbonate aquifer, where saturated, (4) the exposed extent of the alluvial conglomerates that constitute the Funeral Formation aquifer, where saturated, and (5) the structural data needed to project fault surfaces and bedding to depth. The above data were used, along with measured formation thicknesses, to generate a structure contour map on the base of the Paleozoic carbonate and Funeral Formation aquifer system in the southern Funeral Mountains and adjacent Furnace Creek basin (fig. 3).

This structure contour map (fig. 3) has been used as the basis for a computer model of the ground-water flow that feeds the Furnace Creek springs (Bredehoeft and others, 2005, 2008). It has also been used as an input to the design of a drilling program, conducted by The Hydrodynamics Group, LLC, for Inyo County. This program is investigating interbasin flow under the southern Funeral Mountains. Understanding interbasin flow is key to assessing the potential that radionuclides from the proposed high-level nuclear waste repository at Yucca Mountain, Nevada, could leak into and through, the Paleozoic carbonate aquifer, to discharge from the Furnace Creek springs, about 50 km southeast of the proposed repository.

The southern Funeral Mountains lie in the Death Valley region of the Basin and Range province. Basin-and-range tectonism, involving large-scale tectonic denudation along detachment faults, occurred later in the Death Valley region than throughout most of the remainder of the Basin and Range province (see fig. 4 of Dickinson, 2002, where Death Valley region = Walker Lane + ECSZ—Eastern California Shear Zone). Two areas of syn-basin-range tectonic denudation lie within the map area. First, the southeasternmost part of the Funeral Mountains metamorphic core complex is within the northwestern part of the map (see tectonic map). Second, the Furnace Creek basin (see fig. 1 and tectonic map), in the southern and western parts of the map, is part of a large supradetachment basin formed on the tectonically denuded lower plate of the Amargosa detachment fault. The Opera House basin, in the southeastern part of the map (fig. 1), is another supradetachment basin, and its master detachment fault projects under the southern Funeral Mountains. Strong extension, involving detachment faulting, has been a key feature in the formation of the geology and hydrogeology of the southern Funeral Mountains, and is reflected in the complex bedrock structure in much of the map area.

The Paleozoic carbonate rocks exposed in the southern Funeral Mountains (fig. 2) lie along part of the southwest termination of a vast carbonate aquifer system that covers most of southeastern Nevada, along with adjacent parts of western Utah and southeastern California (Bredehoeft and others, 2005, 2008; and references therein). This regional aquifer ends southwestward in the map area at the Furnace Creek fault, because the carbonate rocks have been tectonically removed from the area of the Furnace Creek basin, on the southwestern side of this fault. The Funeral Formation (QTf) aquifer locally extends the aquifer system beyond this termination, within the Furnace Creek basin; thus only one of the springs of the Furnace Creek wash area emanates directly from the carbonate aquifer. The rest are localized along topographically low points along the southwestward termination of the Funeral Formation (fig. 3). The chemistry of all of the Furnace Creek springs indicates they are fed mainly from the carbonate aquifer, by interbasin flow under the southern Funeral Mountains. Only about ten

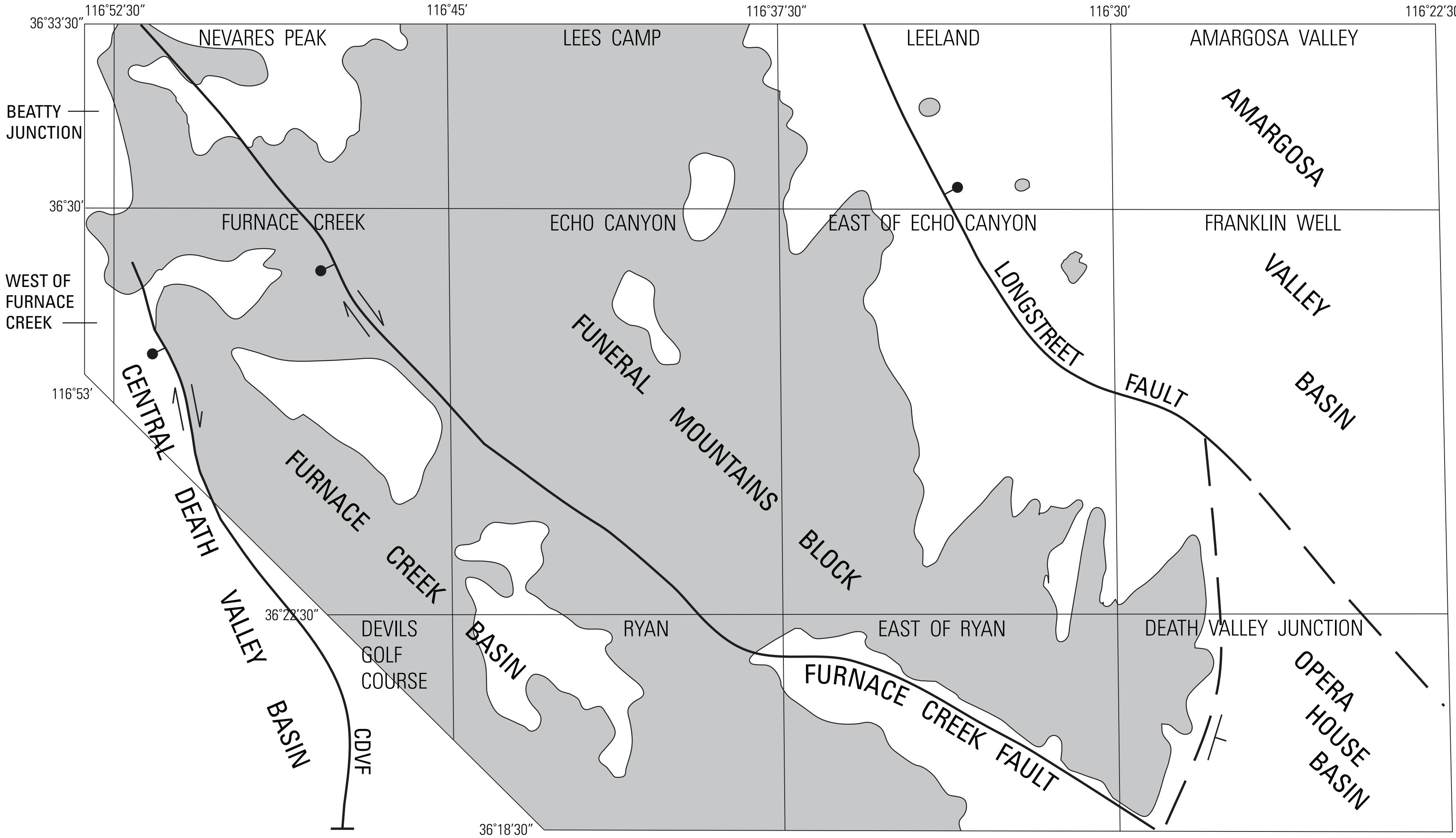

Figure 1. Index map showing the outline of the map area, bedrock area (shaded), 7.5-minute quadrangle outlines, principal faults, and the Funeral Mountains block and surrounding basins. Not shown is the northern limit of the Black Mountains, which forms the southwest margin of the Furnace Creek basin, immediately to the north of the diagonal map boundary. CDVF, Central Death Valley fault.

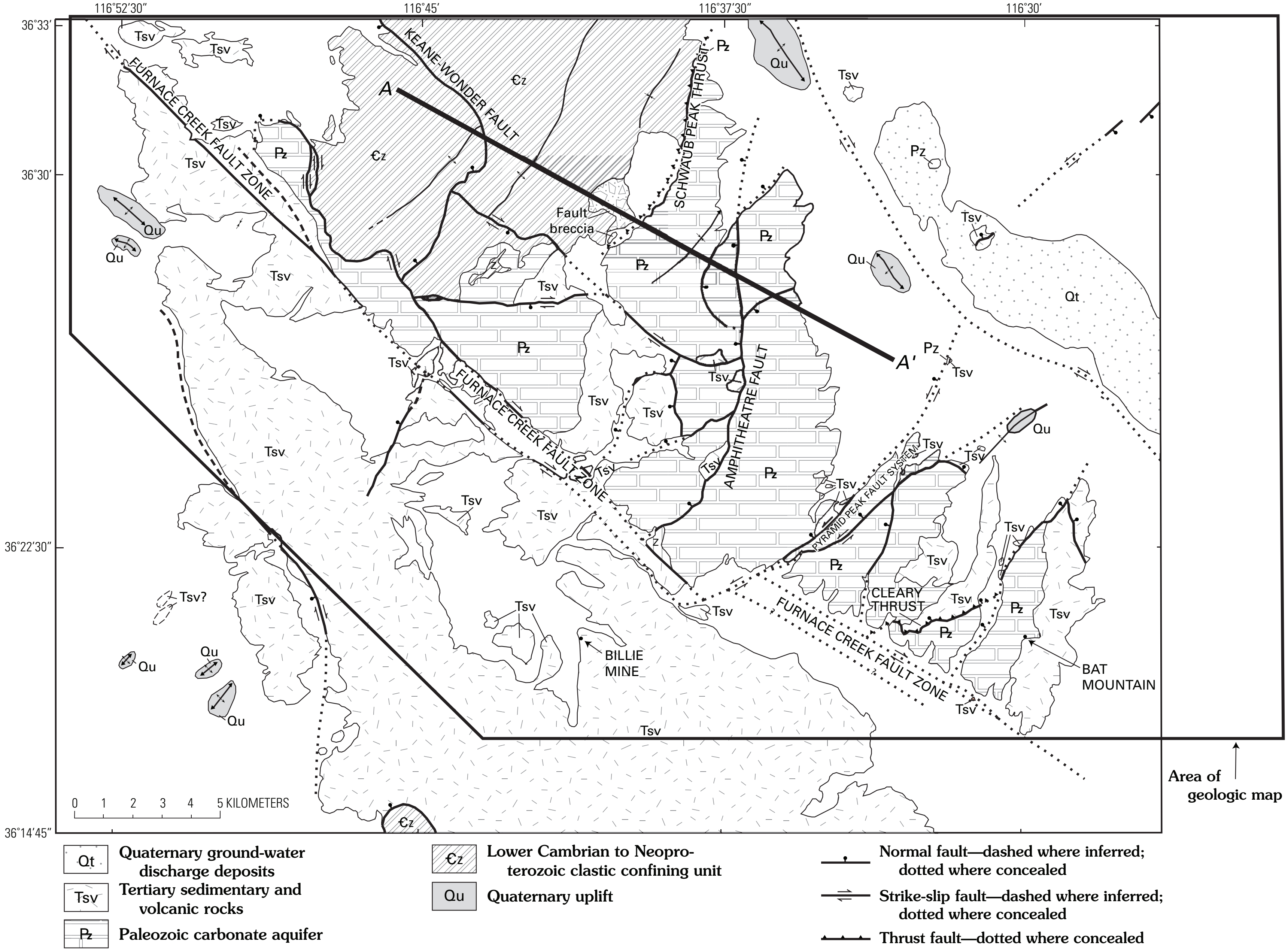

Figure 2. Simplified geologic map of the study area, showing the exposed distribution of the Paleozoic carbonate aquifer (Pz) and other major geologic features. Also shown are two locales mentioned in the text: Bat Mountain, the promontory at the southeast limit of the Funeral Mountains, and the Billie mine. *A-A'* is the line of section on hydrogeologic map (fig. 3)

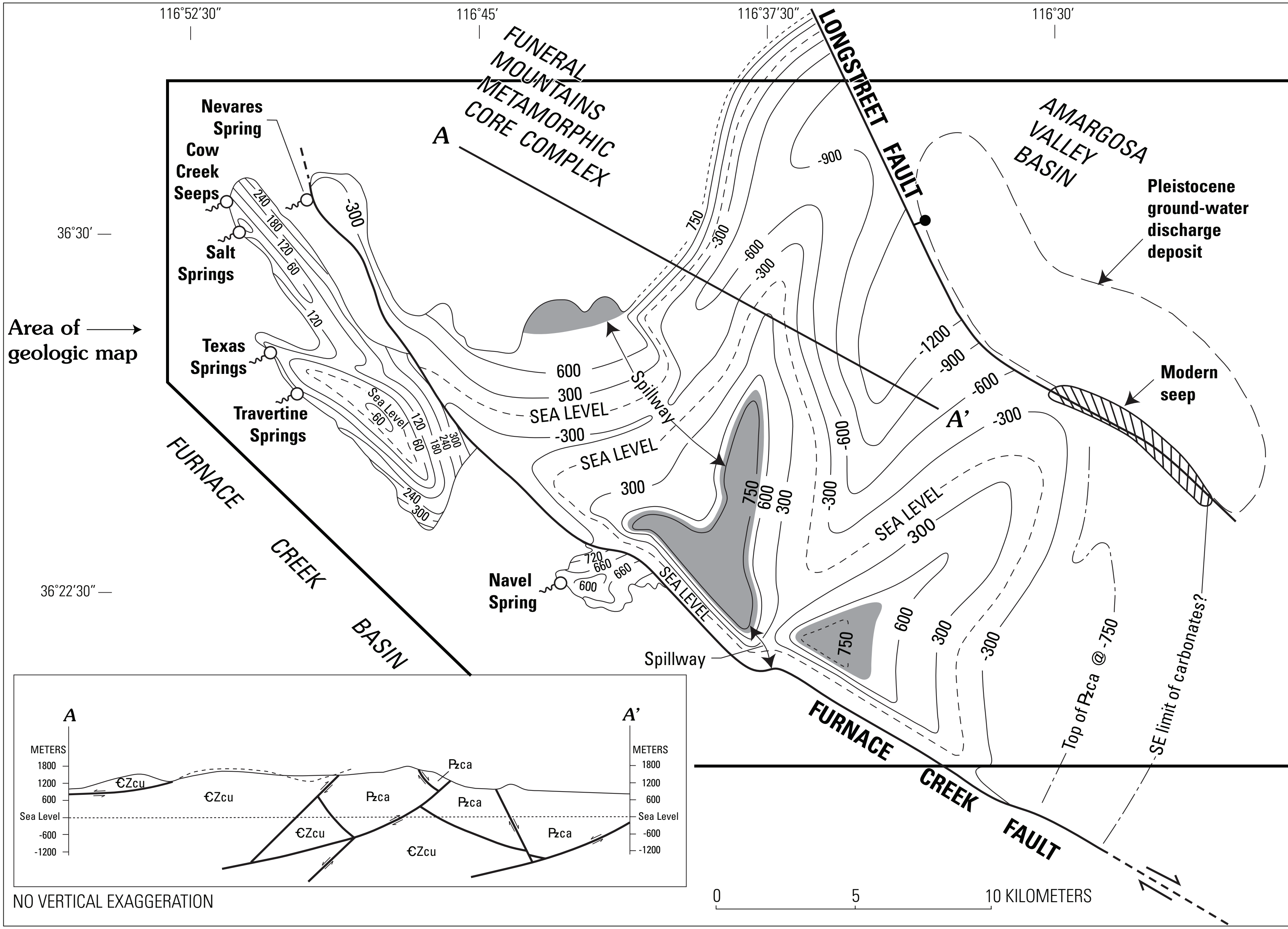

Figure 3. Hydrogeologic map showing the major springs of the Furnace Creek wash area, a modern seep and adjacent Pleistocene ground-water discharge mound in the northeast part of map, and a structure contour map drawn on the base of the Paleozoic carbonate aquifer (Pzca) within the Funeral Mountains block, and on the base of the Funeral Formation alluvial aquifer within the Furnace Creek basin. Shading in the Funeral Mountains block indicates areas in which the base of the Paleozoic carbonate aquifer (the top of €Zcu, the lower Cambrian to Neoproterozoic confining unit) is above the elevation that the water table has at the southwestern limit of the Amargosa Valley basin.

percent of the spring discharge is derived from local recharge to the carbonate aquifer rocks exposed in the southern Funeral Mountains (Bredehoeft and others, 2005, 2008).

Methods and Approach

This study is built on previous bedrock maps (fig. 4) by McAllister (1970, 1971, 1973), Çemen (1983), and Wright and Troxel (1993). Whereas the previous maps cover nearly all of the bedrock (compare figs. 1 and 4), the quality of these maps is best in certain focus areas, and generally diminishes toward map boundaries. Throughout most of the map area, the bedrock mapping has been added to or corrected based on extensive field work, which was conducted by Fridrich (from 2001 to 2005), by Thompson (mainly from 1998 to 2002), and by Machette (2002). Field maps were compiled using a photogrammetric stereo plotter and modern airphotos. With few exceptions, the contacts on the present map are therefore located photogrammetrically, in combination with GPS measurements—tools that were unavailable to the previous mappers.

The present map compilation classifies the Cenozoic strata using a new regional tectono-stratigraphy (summarized below, and see fig. 5); whereas, in previous mapping, a number of different lithostratigraphic designations had been applied to these rocks. Several new $^{40}Ar/^{39}Ar$ dates were produced in the current study to constrain the new tectono-stratigraphy (see tectonic map and table 1). Several of these dates refute previous lithostratigraphic assignments for many of the Tertiary rocks exposed within the Funeral Mountains—see, for example, discussion of Artist Drive Formation under syn-basin-range sequence, below.

Additionally, a consistent level of geologic detail was developed throughout the current map, whereas the previous maps varied greatly in their geologic detail. In most cases, we added geologic detail; however, some prior published map data were omitted. For example, McAllister's two 1:24,000 scale geologic maps covering the Furnace Creek basin (1970, 1973; fig. 3) resemble outcrop maps. We generalized that extreme detail of outcrop geometry for the current map. Additionally, McAllister (1971) mapped upper and lower members of the Silurian and Devonian Hidden Valley Dolomite (DSh) in part of the study area. This formation is mapped as a single unit because we were unable to consistently extend the distinction throughout the rest of the map area.

Whereas we gathered numerous bedding attitudes, the majority of those on the map were compiled from the previous maps of McAllister (1970, 1971, 1973), Çemen (1983), and Wright and Troxel (1993). The previous maps were published at more expanded scales than the current map; hence, we were selective in compiling bedding attitudes. The interested reader is referred to those previous maps for the full data sets.

With the redrawing of the contacts, based on our new field work and photogrammetry, the locations of some of the compiled attitude measurements had to be shifted slightly to keep them within the rock units in which they were measured. Our photogrammetric and GPS results thus prove that some of the contacts and bedding-attitude measurements were inaccurately located on the previously published maps. We have done what we can to resolve this problem; however, it is inevitable that some of these compiled measurements still are imperfectly located. The resulting map shows, however, that bedding attitudes generally define consistent patterns over moderately large areas. Hence, the location accuracy of the compiled measurements, although imperfect, is more than adequate for our principal application of the map data, which was interpreting the three-dimensional geometry of the aquifer system (fig. 3).

With one exception, the formations of the Neoproterozoic through upper Paleozoic miogeoclinal stratigraphic sequence were subdivided on the current map following widely used, modern classification schemes, such as those applied by Monsen and others (1992). That exception involves the Neoproterozoic Stirling Quartzite, which is divided here into five informal members using the scheme of McAllister (1971) and Wright and Troxel (1993). This scheme differs slightly from that used by most other workers in the region (for example, Stewart, 1970, Monsen and others, 1992; Niemi, 2002).

The new map covers a far greater area of surficial deposits than do the previous maps, which focused on bedrock geology (compare figs. 1, 2, and 4). Moreover, we refined mapping of the surficial deposits to show more detail and to conform to current Quaternary stratigraphic classification schemes. The surficial geologic map of the Beatty 30′ × 60′ quadrangle, by Slate and Berry (1999), was modified to resolve minor edge-matching problems with new surficial deposits mapping south of latitude 36° 30′ N., in the Death Valley Junction 30′ × 60′ quadrangle, by the same authors (Slate and Berry, unpublished mapping).

A New Regional Cenozoic Tectono-Stratigraphy

The classification scheme for the Cenozoic rocks (fig. 5) was developed largely by Fridrich, based on fieldwork conducted throughout the Death Valley region, from 1992 to 2006. The Death Valley region is a large domain that is distinct relative to adjacent regions in its structural style and resulting topography. More importantly, the history of Cenozoic tectonism—and thus the tectono-stratigraphy—has an internally consistent pattern throughout this region, whereas both are distinctly different even short distances across the boundaries into adjacent regions.

The boundaries of the Death Valley region, as defined here, are similar to those of the south half of the Walker Lane belt, as defined by Stewart (1988). It extends from the southern Nevada Test Site southward to the Garlock fault and from the Spring Mountains (on the west side of Las Vegas,

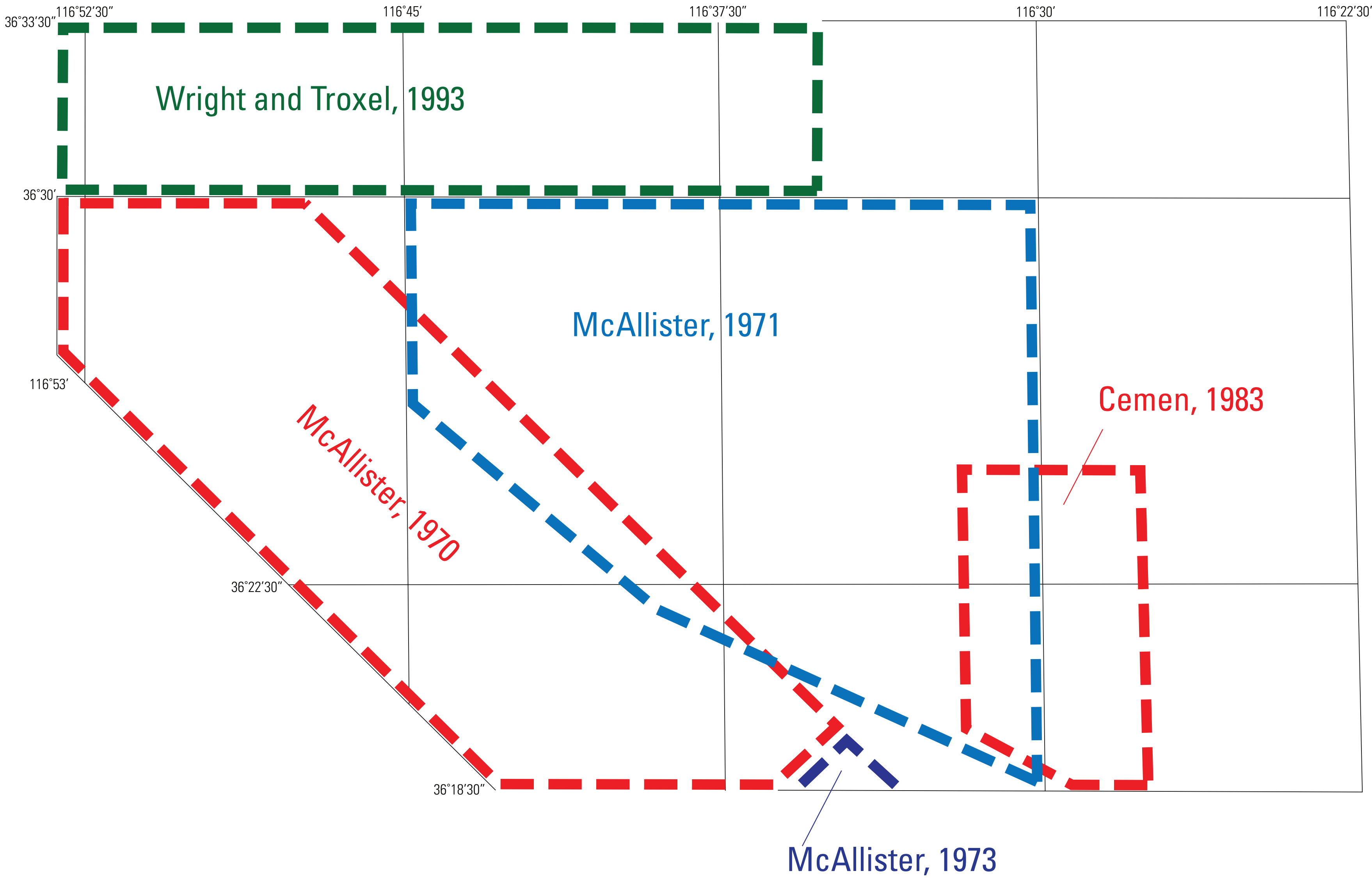

Figure 4. Map showing the approximate limits of previously published maps within the study area of the current map.

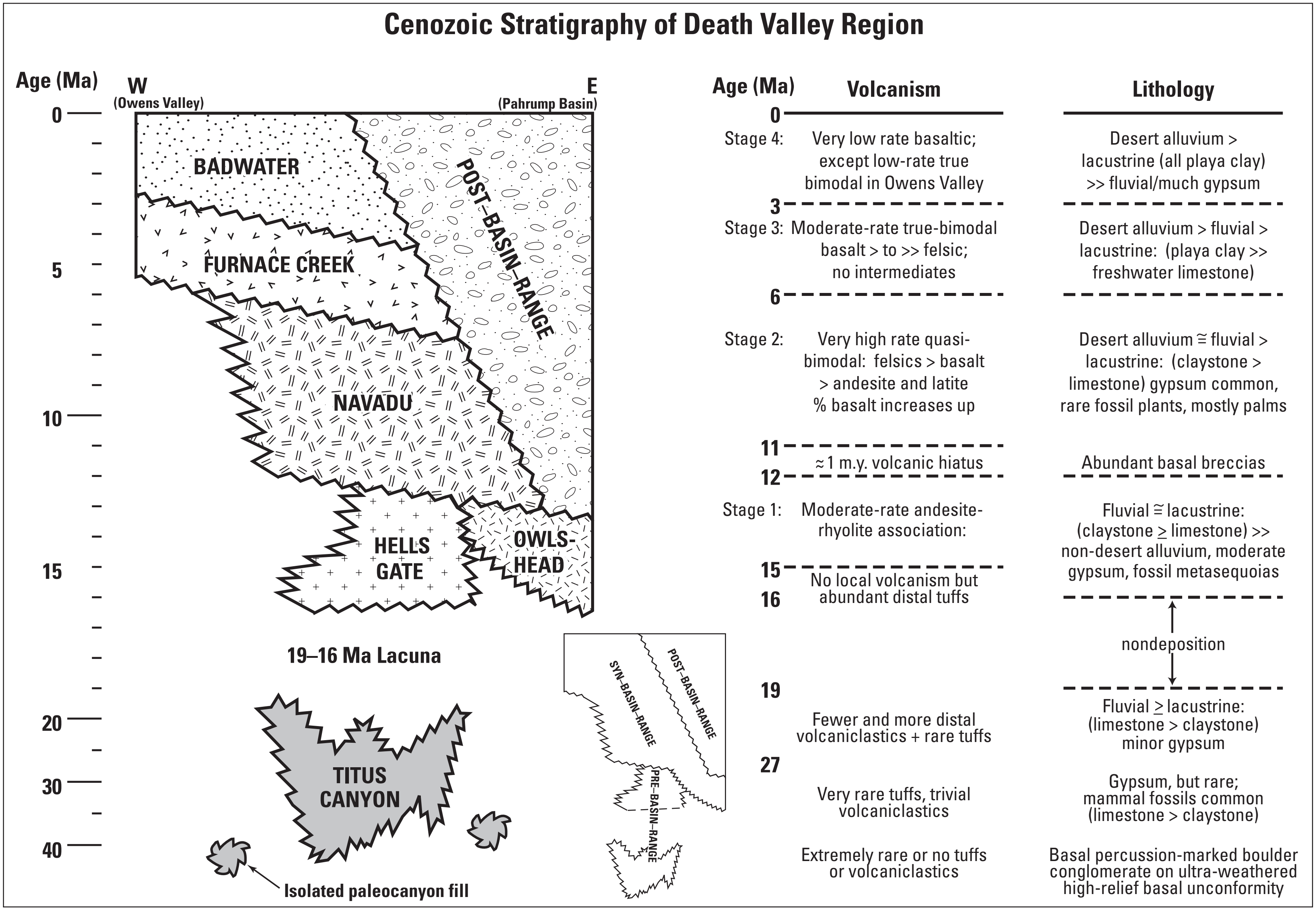

Figure 5. East-west and chronologic schematic diagram depicting the Cenozoic stratigraphy of the Death Valley region, showing the seven tectono-stratigraphic assemblages. Inset map (bottom, center) shows how these assemblages compose the pre-basin-range, syn-basin-range, and post-basin-range sequences. Two columns on the right summarize major volcanic and lithologic changes that occurred during deposition of Cenozoic strata. In map area, Hells Gate assemblage is not present, and post-basin-range sequence is represented only by the surficial deposits in all locales except the central Death Valley basin, which is limited to a narrow strip at the western limit of the map (see fig. 1).

Nev.) westward to the eastern front of the Sierra Nevada. Stewart showed that this region has a structural grain that reflects strike-slip strain that is greater in magnitude, or different in sense, than that in the surrounding regions.

The Cenozoic rocks are divided into three sequences: pre-basin-range, syn-basin-range, and post-basin-range (inset, fig. 5). The pre-basin-range and syn-basin-range sequences are further divided into two and four assemblages, respectively, and the post-basin-range sequence consists of a single assemblage (left side, fig. 5). The seven assemblages in this scheme are allostratigraphic units. The assemblages are separated by regionally extensive unconformities or disconformities (fig. 5), across which profound, abrupt changes in clast provenance and lithology (that is, depositional environment) are found. On a regional basis, and across most basins, these unconformities decrease in age to the north and west, reflecting migratory changes in tectonic patterns. Across these regionally extensive unconformities, radical changes are present in the distributions of basin-fill strata and in the patterns of facies changes within them. These changes record the creation of new basins and the major faults that bounded them, and the coincident total or partial abandonment of older basins and their master faults.

The changes in basin and fault geometries that occurred across the regional unconformities indicate that these widespread stratigraphic boundaries record regional-scale changes in the stress regime, coincident with rapid migrations in the focus of tectonism. The classification system used here for the Cenozoic rocks is thus a tectono-stratigraphy. It is partly a revision and extension of a tectono-stratigraphy proposed by Snow and Lux (1999) for the north-central part of the Death Valley region. However, this new tectono-stratigraphy is much broader in extent, and is based on new fieldwork and radiometric dating throughout the Death Valley region.

Pre-Basin-Range Sequence

The pre-basin-range sequence of the Death Valley region was deposited during the initial, late Eocene to early Miocene (≥40 to ≈19 Ma) stage of extension. Tectonism in this stage formed broad shallow basins that trapped sediments, but did not form basin-range topography. The age of the base of the pre-basin-range sequence varies greatly throughout the region, at least partly because this sequence buried a moderately high-relief paleotopographic surface. The base of the pre-basin-range sequence is as old as late Eocene (≥40 Ma) to the northwest of the map area, in the southern Grapevine Mountains; but, in the map area, it is evidently Oligocene (≈30 Ma) in age. Fluvial conglomerates are abundant in the pre-basin-range sequence, and the provenance of pebbles and larger clasts indicates derivation from sources that are now separated from the map area by numerous ranges and closed basins—obstacles that no river could cross, and that must therefore have formed later.

Bedding in the pre-basin-range strata is generally conformable with that in underlying Paleozoic and Neoproterozoic sedimentary rocks, except in the vicinities of contractional structures in which the Paleozoic and older rocks were tilted during late Paleozoic through Mesozoic compressional tectonism. The general conformability of the pre-basin-range strata, as well as the scarcity of fanning dips and internal unconformities within them, indicate minimal extension-related tilting during pre-basin-range extension. In contrast, all younger (syn-basin-range and post-basin-range) strata are strongly disconformable to the underlying Paleozoic and Neoproterozoic rocks, and fanning dips and internal unconformities are abundant in the syn-basin-range sequence.

A lacuna—an interval of evident nondeposition, reflected in missing section—is present throughout the Death Valley region in the interval from ≈19 to ≈16 Ma (fig. 5). In the western part of the region, this lacuna separates two distinct assemblages of the pre-basin-range sequence—Titus Canyon and Hells Gate assemblages (fig. 5). In the east part of the region, the pre-basin-range sequence is largely absent but, where present, the ≈19- to ≈16-Ma lacuna separates it from the overlying syn-basin-range sequence (fig. 5). The map area falls within the eastern part of the region, in which the Hells Gate assemblage of the pre-basin-range sequence (fig. 5) is absent.

Syn-Basin-Range Sequence

Each of four assemblages of syn-basin-range strata (Owlshead, Navadu, Furnace Creek, and Badwater; fig. 5) were deposited in a specific stage of basin-range tectonism. Moreover, each of these four tectonic stages corresponds closely with a stage of volcanic activity in the region, each of which was distinct in terms of eruptive rates and magma compositions (see volcanism column, fig. 5). The unconformities that separate the four syn-basin-range assemblages are diachronous; they are generally younger by ≈1 to 2 m.y. to the northwest across the region. The upper and lower bounds of the four volcanic stages also show some evidence of westward younging, but less so than the tectonic stages; hence the correspondence of the two is imperfect. For example, two widespread tuffs, one at the end of each of the Furnace Creek and Owlshead stages of volcanism (volcanic stages 3 and 1; fig. 5), have ages (≈3.2 and ≈12.2 Ma) such that they prove the diachronous nature of the tectono-stratigraphic boundaries. These tuffs can be found either in the basalmost part of one of the tectono-stratigraphic assemblages, or in the uppermost part of the preceding assemblage, in different parts of the Death Valley region. But, otherwise, the distinct volcanic strata found within each of the tectono-stratigraphic assemblages are key to distinguishing them, and also provide a mechanism of quantitative discrimination by radiometric dating (see tectonic map and table 1).

In that part of the map area that lies between the Furnace Creek fault and the central Death Valley fault (CDVF; that is, in the Furnace Creek basin; fig. 1), the Owlshead, Navadu, Furnace Creek, and Badwater assemblages (fig. 5) correspond to the rocks of the Billie mine (Tos), and the Artist Drive, Furnace Creek, and Funeral Formations (QTf), respectively. The last three of these formations were defined in the original mapping of the basin by McAllister (1970). McAllister (1970) included the rocks of the Billie mine (Tos, south-central part of map) in the Artist Drive Formation, and considered these rocks to be equivalent to his lower sedimentary member of the Artist Drive Formation (Tnl) on the southwest flank of the basin.

Whereas the Artist Drive Formation contains lavas and tephras of the ≈11- to ≈6-Ma (volcanic stage 2 or Navadu tectonic stage; fig. 5) units of the central Death Valley volcanic field, the strata exposed at the Billie mine contains tephras derived from the ≈12.1- to ≈14.5-Ma (volcanic stage 1 or Owlshead tectonic stage; fig. 5) Owlshead volcanic field. Thus, radiometric dates disprove McAllister's correlation of the rocks of the Billie mine (Tos) with the lower sedimentary member of the Artist Drive Formation (Tnl). Moreover, on a regional basis, the strata containing the Owlshead- and Navadu-stage volcanic units are virtually everywhere separated by a clear formation boundary—an angular unconformity across which there is a profound and abrupt change in lithology and provenance.

Clasts of the local metamorphic rocks—those exposed in the lower plates of detachment faults in the Death Valley region—are notably absent from sediments of the pre-basin-range sequence, but are present even in some of the oldest syn-basin-range deposits. The timing of appearance of these clasts in the sedimentary record closely matches the radiometrically determined uplift ages for the local metamorphic core complexes from which they were derived (Holm and others, 1992; Hoisch and Simpson, 1993; Applegate and Hodges, 1995; Hoisch and others, 1997). The abundance and especially the maximum grade of locally derived metamorphic clasts in the syn-basin-range strata increases rapidly upsection. This is consistent with radiometrically determined uplift rates for the local metamorphic core complexes, which indicate that these rocks were rapidly uplifted and exposed by tectonic denudation, rather than by erosion, which operates at least an order of magnitude more slowly.

Post-Basin-Range Sequence

The base of the post-basin-range sequence is defined as the horizon at which significant faulting and related tilting is buried upsection throughout the vast majority of a basin. The base of this sequence is estimated to be ≈6- to 7-Ma in the Amargosa Desert and Opera House basins, and ≈2 Ma in the Furnace Creek basin (fig. 1). The post-basin-range sequence is absent, by definition, in the central Death Valley basin (fig. 1), because this basin is still actively subsiding. Hence, latest Pliocene to Holocene sediments in this basin are part of the syn-basin-range Badwater assemblage.

The post-basin-range sequence of the Death Valley region is not post-tectonic. Instead, the final stage of tectonism is feeble and ongoing, it postdates the formation of basin-and-range topography in any given place, and it has resulted only in very localized tilting of strata. Post-basin-range tectonism largely consists of horizontal offsets on a small number of large-scale strike-slip faults, and block-faulting along very widely spaced high-angle normal faults. For both, the tectonic rates indicated are very low compared to those of earlier syn-basin-range tectonism in the same basins. Post-basin-range strata are typically thin, even in basins in which the base is relatively old, indicating that deposition rates decline to very low levels once basin-range tectonism ends.

Description of Map Units

Surficial Deposits

Quaternary and Tertiary—On this map, surficial deposits are excluded from the tectono-stratigraphic classification scheme used for all of the other Cenozoic rocks. In a thin strip along the westernmost part of the map area, the surficial deposits are technically part of the syn-basin-range Badwater assemblage. Even where they are, as yet, untilted and unfaulted, these deposits are syntectonic because they were deposited in the actively subsiding central Death Valley basin (fig. 1) during the ongoing Badwater tectonic stage. In contrast, the coeval and older surficial deposits throughout the rest of the map are part of the post-basin-range sequence because they were deposited in basins in which basin-range tectonism had already ceased.

Qayy **Alluvial deposits in annually active channels (Holocene)**—Sand,silt, and lesser gravel, intermixed and interbedded; unconsolidated, poorly to moderately well sorted, poorly to well bedded, locally crossbedded

Qay **Alluvial deposits in recently active channels (Holocene and Pleistocene)**—Gravel, sand, and silt; intermixed and interbedded; unconsolidated, poorly to moderately well sorted, poorly to well bedded, locally crossbedded. Clasts are commonly angular to subrounded; locally well rounded

Qp **Playa sediments (Holocene and Pleistocene)**—Silt, fine sand,clay, and evaporates; intermixed and interbedded; polygonal desiccation cracks common

Qc **Colluvial deposits (Holocene to Pleistocene)**—Angular to subangular granule- to boulder-size clasts with variable amounts of sand, silt, and clay as matrix. Generally unsorted and nonbedded or poorly bedded; matrix probably partly of eolian origin, locally cemented by carbonate. Forms talus deposits and thin mantles of debris along flanks and bases of steep slopes; deposited by rainwash, sheetwash, creep, and mass wasting

Qm **Marl (Holocene and Pleistocene)**—Calcareous siltstone, pale yellowish brown, yellowish-gray or grayish-orange; weathers white to very light gray; silty to sandy; soft, plastic when wet. Consists of calcite, various clay minerals, quartz and opaline silica, silt, and sand-size rock fragments. Includes several thin chalk beds as much as 1 m thick and discontinuous beds of small, irregular limestone nodules. Locally contains sparse to common pencil-size calcareous cylinders that probably are calcified plant stems. Unit is thought to represent deposits and precipitates formed in areas of ground-water discharge, including paludal environments. Reported ages are Pleistocene (90 ka to 15 ka; Paces and others, 1997)

Qls **Landslide deposits (Holocene and Pleistocene)**—Breccia formed in recent landsliding; landslide geomorphology is pristine to weakly dissected

Qayo **Alluvial deposits in recent low terraces (Holocene)**—Gravel, sand, and silt; intermixed and interbedded; unconsolidated to weakly consolidated, poorly to moderately well sorted, poorly to well bedded, locally crossbedded. Clasts are angular to subrounded; locally well rounded. Surface has faint bar-and-swale topography with cobbles marking former bars that are slightly higher than pebbly swales, or is planar with slightly to locally moderately packed pavement. Pavement clasts are weakly to moderately varnished. Soil typically has cambic B horizon and stage I carbonate horizon. Thickness of unit generally ranges from less than a meter to 10 m, but may be as much as 20 m adjacent to tectonically active mountain fronts

Qai **Alluvial deposits in mid-level terraces (Pleistocene)**—Gravel, sand, and silt; intermixed and interbedded, weakly to moderately well consolidated. Clasts are unsorted to moderately well sorted, poorly to well bedded, angular to rounded. Surface is planar with moderately packed to densely packed pavement; pavement clasts are moderately to well varnished. In places, thin eolian sand deposits mantle the surface. Soil development varies from a cambic B horizon and a stage I to II carbonate horizon to an argillic B horizon and an approximately 1-m-thick stage III to IV carbonate horizon. Thickness of unit less than 1 m to 10 m

Qao **Alluvial deposits in high terraces (Pleistocene)**—Gravel, sand, and silt; intermixed and interbedded, light gray, moderately well consolidated. Clasts are unsorted to moderately well sorted, nonbedded to well bedded, angular to rounded; matrix is sandy to silty. Surface is planar with densely packed pavement; pavement clasts are well varnished making this unit medium to dark colored on most surface. In places, thin eolian sand deposits mantle surface. Soil development varies from a well-developed cambic B horizon and a stage II carbonate horizon to an argillic B horizon and an approximately 1-m-thick, stage III to IV carbonate horizon. Thickness of unit less than 1 m to 10 m

QTa **Old alluvial deposits (Pleistocene and late Pliocene)**—Gravel, sand, and silt; intermixed and interbedded, light brownish gray to light gray. Clasts are angular to subrounded, generally poorly sorted, poorly bedded, and moderately to well cemented with carbonate. Surface is eroded and dissected; commonly forms rounded ridges or ballenas. Where preserved, pavement is generally moderately to densely packed and includes tabular fragments cemented by pedogenic carbonate and opaline silica; varnish on pavement clasts is variable but commonly strongly developed. Soils typically consist of a stage III to IV carbonate horizon as much as 2 m thick; argillic horizons, where present, postdate much of the erosion. Thickness of unit may exceed 40 m

QTx **Landslide deposits (Pleistocene and late Pliocene)**—Rock-avalanche breccias exposed as tongues extending from Bat Mountain (at southeastern limit of Funeral Mountains; fig. 1 and map) onto alluvial apron to east; composed of clasts derived primarily from Kelley's Well Limestone (Tok) and red sandstone member (Ttr) of Titus Canyon assemblage; also includes erosionally dissected landslide masses exposed in Furnace Creek valley; maximum exposed thickness of ≈15 m

Syn-Basin-Range Sequence

Consists of Badwater, Furnace Creek, Navadu, and Owlshead assemblages (fig. 5).

Badwater assemblage (early Quaternary? to Pliocene)—Includes Funeral Formation (QTf) and ≈4.5 Ma Funeral basalt (Tby) in map area. Similar age basalts are found in upper part of Furnace Creek assemblage to south of map area; thus, inclusion of Funeral basalt in Badwater assemblage is local

QTf **Funeral Formation (early Quaternary? to Pliocene)**—Alluvial conglomerates with angular to subangular clasts to ≈1 m; moderately to poorly consolidated; clasts derived from Paleozoic and Neoproterozoic rocks exposed in adjacent southern Funeral Mountains; strongly fanning dips present in basal 10 to 30 m; maximum exposed thickness of ≈200 m. Maximum measured subsurface thickness, encountered in Inyo-Travertine #2, (Fridrich, unpub. data, 2007) of 305 m, in center of Texas Spring anticline. In this most basinal location, formation has thin interbeds of playa siltstones in middle and lower part and, in all but top 70 m of unit, similar siltstone has infiltrated to form a dense matrix around alluvial clasts, such that only uppermost, silt-free 70 m of formation has significant permeability. Base of formation is ≈4.5 Ma in south-central part of map area, decreasing to <3 Ma to northwest (see tectonic map and table 1; based on $^{40}Ar/^{39}Ar$ dates by Miggins (unpub. data) and Knott and others, in press)

Tby **Basalt (Pliocene)**—Olivine basalt lava flows and related local scoria deposits, phenocryst-poor, locally interfingers with lowermost part of Funeral Formation (QTf) in south-central part of map; superimposed stippled pattern applied in oxidized vent areas; maximum exposed thickness of ≈175 m

Furnace Creek assemblage (upper Pliocene to upper Miocene)

Furnace Creek Formation (upper Pliocene to upper Miocene)—Maximum exposed thickness of approximately 2.2 km; consists of:

Tft **Travertine (Pliocene)**—Travertine, fine- to medium-bedded, with interbeds of siltstone and pebble conglomerate; classified by McAllister (1970) as base of Funeral Formation (QTf); however, profound abrupt lithologic change at top and strongly fanning dips in immediately overlying, basal part of Funeral Formation alluvial deposits (QTf) indicate these travertines are better considered as part of Furnace Creek Formation

Tf **Playa and playa margin rocks of Furnace Creek basin (Pliocene)**—Interbedded playa claystones, siltstones, sandstones; with minor thin limestone and marl interbeds; includes minor beds that are pebbly or sparsely gypsum-bearing; moderately to well consolidated, thin- to medium-bedded, pale yellowish tan to light ochre-brown

Tfu **Upper claystone (Pliocene)**—Claystone, pale yellow with pumiceous tuff at base

Tfcu **Upper and middle conglomerates (Pliocene)**—Conglomerate beds found throughout middle and upper part of Furnace Creek Formation; composed mainly of clasts either of Artist Drive Formation lithologies from Black Mountains, or of Paleozoic and Neoproterozoic sedimentary lithologies from Funeral Mountains. In both cases, supporting matrix is typically a dirty and typically bentonitic sandstone and can be many different bold colors, such as greens, yellows, reds, and browns

Tfg **Gypsum-rich member (Pliocene)**—Claystone with abundant gypsum; locally contains minor borate deposits

Tfrx **Rock-avalanche breccias (upper Pliocene to upper Miocene)**—Megabreccias and much lesser mesobreccias composed of clasts of various Paleozoic rock formations exposed along southwest range-front of southern Funeral Mountains; transitional to Giant block breccias (Tflx)

Tflx **Giant block breccias (upper Pliocene to upper Miocene)**—Genetically related to rock-avalanche breccias (Tfrx) but composed of clasts that are large enough to map and identify at 1:50,000 scale; rock formations from which giant blocks were derived shown in parentheses; thick internal lines denote contacts between giant blocks

Tfc **Basal conglomerate (upper Miocene)**—Conglomerate beds found at base of Furnace Creek Formation; contains well-rounded to subrounded pebble- to small boulder-size clasts of Paleozoic sedimentary lithologies and Hunter Mountain Quartz Monzonite from the northern Panamint Range (on the west side of the central Death Valley basin), mixed with clasts of Artist Drive Formation lithologies from Black Mountains, in a sandstone matrix

Greenwater Volcanics (upper Pliocene to upper Miocene)—Interfingers laterally with Furnace Creek Formation; consists of:

Tfb **Basalt**—Sparsely vesicular lava flows and much lesser scoria, with sparse olivine and plagioclase phenocrysts; charcoal gray

Tfp **Pyroclastic deposits**—Felsic nonwelded ash-fall tuffs, mainly dacitic and biotite-rich, light gray; probably correlative with petrographically similar lava flows and agglutinated ash-fall tuffs found to south and southeast of map area, including the dacite of Brown's Peak

Navadu assemblage (upper to middle Miocene; ≈6.5 Ma to ≈12 Ma)

Tnix **Fault Breccia (Miocene)**—Brecciated Paleozoic rocks exposed along strands of Furnace Creek fault; assigned to Navadu assemblage because Navadu tectonic stage was principal interval of movement on this fault; actual interval in which these breccias formed may be broader

Artist Drive Formation (Miocene)—Name applied by McAllister (1970) to Navadu strata exposed on southwestern margin of Furnace Creek basin (at north end of Black Mountains). Maximum exposed thickness of ≈1.6 km. Divided into three informal members, lowermost of which is subdivided into a sedimentary part and a mafic volcanic part, which partly interfinger with each other. Coeval basin-fill strata (Artist Drive equivalent) were deposited in half-grabens within Funeral Mountains, and within locally wide Furnace Creek fault zone on southwest flank of these mountains

Tnu **Upper member**—Upper, sedimentary part consists of fluvial conglomerates grading down into sandstones and then into interbedded claystones and freshwater limestone. Lower volcanic part consists of felsic tuffs of upper part of Shoshone Volcanics (Wright and others, 1991) and lesser, interbedded basalt flows at base. Equivalent to McAllister's (1970) upper sedimentary and upper pyroclastic members, combined

Tnm **Middle member**—Upper, sedimentary part consists of sandstones grading down into interbedded lacustrine claystones and freshwater limestone. Lower, volcanic part consists mainly of felsic lavas and tuffs of lower part of Shoshone Volcanics. Equivalent to McAllister's (1970) middle sedimentary and lower pyroclastic members, combined

Lower member—subdivided into:

Tnl **Sedimentary part**—Pebbly sandstone and interbedded, locally gypsiferous claystone. Equivalent to McAllister's (1970) lower sedimentary member

Tab **Volcanic part**—Basalt and andesite lavas and possible related intrusives; andesite is correlative with ≈11 Ma Sheephead Andesite (Wright and others, 1991), a widespread unit exposed to south, southeast and southwest of map area, which has abundant large laths of plagioclase in radiating clumps; basalt has a moderate abundance of plagioclase and olivine phenocrysts. Equivalent to McAllister's (1970) basaltic rocks of Artist Drive Formation

Artist Drive equivalent (Miocene)—Navadu strata exposed within Funeral Mountains, and along southwest flank; mapped by McAllister (1970, 1971, 1973) as part of Furnace Creek Formation; however, tuffs in these deposits petrographically resemble ≈8- to ≈10-Ma Shoshone Volcanics, and $^{40}Ar/^{39}Ar$ dates determined in this study support that (see tectonic map and table 1); divided into four map units:

Tng **Alluvial deposits**—Alluvial conglomerates that were deposited in small basins formed on downthrown sides of major Miocene normal faults in southern Funeral Mountains; composed of clasts derived from various Paleozoic rock formations

Tnp **Playa deposits**—Claystones, commonly gypsum-bearing, and lesser siltstones and sandstones, typically moderately consolidated and pale yellow in color, with rare interbedded off-white to pink tuffs that resemble the ≈8- to ≈10-Ma Shoshone Volcanics

Tnrx **Rock-avalanche breccias**—Megabreccias and much lesser mesobreccias composed of clasts of various Paleozoic rock formations exposed in the southern Funeral Mountains; transitional to giant-block landslide breccias (Tnlx)

Tnlx **Giant-block breccias**—Genetically related to rock- avalanche breccias (Tnrx) but composed of clasts that are large enough to show at 1:50,000 scale; rock formations from which giant blocks were derived shown in parentheses; thicker internal lines denote contacts between giant blocks, whereas thinner internal lines denote formation contacts within giant blocks. Given the very large size of these blocks and the close proximity to source, process of origin of this unit may be better described as gravity sliding than as rock avalanching

Owlshead assemblage (Miocene)—Composed of rocks of Billie mine, to south of Furnace Creek fault, and of three lithologic map units of Bat Mountain Formation, to north of this fault, at southeast limit of Funeral Mountains

Tos **Rocks of Billie mine (Miocene)**—Orange sandstone, well consolidated, commonly with well-rounded pebbles mainly of quartzite, black chert, and Hunter Mountain Quartz Monzonite; fines upward: fluvial at base and at least partly lacustrine in upper part; includes thin interbedded ash-flow and ash-fall tuffs in lower part that have yielded dates of 12.7 and 13.7 (K-Ar, Wright and others, 1999) and 13.4 Ma ($^{40}Ar/^{39}Ar$, sanidine, this study); maximum exposed thickness of perhaps 150 m

Bat Mountain Formation (Miocene)

Toss **Sandstone member**—Volcaniclastic arkosic sandstone with minor thin conglomerate and mudstone interbeds, dominantly ochre colored; commonly crossbedded indicating a braided stream environment of deposition; contains sparse pebbles derived from various Paleozoic rock formations of southern Funeral Mountains and vicinity; a waterlaid tuff exposed at top was dated at ≈13.5 Ma ($^{40}Ar/^{39}Ar$, sanidine); maximum exposed thickness of ≈300 m

Tog **Conglomerate member**—Pebble to boulder (dominantly cobble) alluvial conglomerate, mainly clast supported, with a poorly sorted matrix of dirty sandstone; clasts are typically subangular and consist of various Paleozoic lithologies derived from southern Funeral Mountains and vicinity; also contains much lesser clasts of Kelley's Well Limestone (Tok) and Red Sandstone member of Titus Canyon assemblage (Ttr)—only in basal ≈50 m of unit; interfingers at base with Kelley's Well Limestone and at top with sandstone member; overall color as observed from a distance is medium reddish brown; maximum exposed thickness of ≈300 m

Tok **Kelley's Well Limestone (Miocene)**—Massive to thick-bedded, micritic cream-white freshwater limestone with local biostromes of finely laminated algal limestone and rare lenses of interbedded conglomerate resembling overlying cobble conglomerate member of Bat Mountain Formation (Tog). Unit contains numerous small rootless slump faults that strike roughly north-south, that sole into bedding downsection and are progressively buried upsection; maximum exposed thickness of ≈100 m

Pre-Basin-Range Sequence

Titus Canyon assemblage (Oligocene to early Miocene)—A group of correlative rock formations, which include Titus Canyon (Wright and Troxel, 1993), Ubehebe (Snow and Lux, 1999), and Amargosa Valley Formations (Çemen and others, 1999). All three of these formation names have been used in the Funeral Mountains by these different authors. Three informal members designated below (units Ttr, Ttl, and Ttg) are taken from Çemen and others (1999). Çemen also designated an upper member of Amargosa Valley Formation. Rocks mapped as that member (see fig. 2; p. 68 Çemen and others, 1999) are included here in red sandstone member, based on lithology and new $^{40}Ar/^{39}Ar$ dating conducted in this study.

Ttc **Amargosa Valley Formation, undivided**—Undivided unit only used for scattered small exposures where lithologic subdivision is impractical at 1:50,000 scale; elsewhere subdivided into:

Ttr **Red sandstone member**—Pebbly sandstone and much lesser interbedded thin marl and pebble to small-cobble conglomerate; medium red to much lesser grayish green or, rarely, ochre colored; pebbles moderately to well rounded and derived mainly from Paleozoic and Neoproterozoic lithologies of southwestern Great Basin—chiefly quartzites and black cherts, along with rare pebbles of Mesozoic granite, mainly Hunter Mountain Quartz Monzonite; sand is arkosic, typically rich in biotite flakes, and mainly volcaniclastic; tuff at top in section exposed ≈2 km northwest of Bat Mountain was dated in this study at ≈22 Ma ($^{40}Ar/^{39}Ar$, sanidine; D.P. Miggins, USGS, Denver, unpub. data, 2008); tuff filling a paleochannel at top of section exposed on southern Bat Mountain was dated at ≈19.5 Ma (K-Ar, biotite; Çemen, 1983); maximum exposed thickness of ≈300 m

Ttl **Limestone member**—Freshwater limestones and marls interbedded with equally or more abundant tuffaceous siltstones, sandstones, and minor tuffs; moderately well consolidated except for claystones, which are mostly poorly consolidated. Tuff near base was dated at 24.7 Ma (K-Ar; Çemen, 1983), but was petrographically identified in this study as ≈27 Ma Monotony Tuff; tuffs near top are dated at ≈22.5 Ma (Ar/Ar; K-Ar) and 23.5 Ma (K-Ar) and resemble ≈21 to ≈24 Ma tuff members of Pahranagat Formation. Unit includes interbedded fluvial conglomerates in small isolated exposures ≈10 to 16 km northwest of Bat Mountain; maximum exposed thickness of ≈120 m

Ttg **Conglomerate member**—Alluvial conglomerate, moderately consolidated, consisting of subangular clasts to ≈1 m, derived from locally subcropping Paleozoic rock formations, in a matrix composed of lateric red clay and lesser sand that is volcaniclastic near top of unit; thickness highly variable, maximum of ≈225 m

Pre-Tertiary Units

Mzx **Fault breccia (Mesozoic)**—Composed of brecciated Wood CanyonFormation (Ꞓwu, Zwm, and Zwl); found immediately to west of, and apparently spatially and genetically related to Schwaub Peak thrust, which is generally considered to be of Mesozoic age

Mp **Perdido Formation (Mississippian)**—Medium to dark gray limestone with interbedded lesser siltstone and sandstone; top eroded; maximum preserved thickness of ≈155 m

Mt **Tin Mountain Limestone (Mississippian)**—Limestone, mainly dark to light gray; commonly crinoidal or cherty, with some thin minor pale red argillaceous beds; estimated maximum thickness of ≈100 m

Dl **Lost Burro Formation (Devonian)**—Consists of three parts: upper 340 m is medium gray mixed dolomite and limestone overlain by light gray limestone, which is sandy at very top; middle 300 m is light gray dolomite with some widely spaced dark gray beds; basal 80 m is light gray dolomite interbedded with dark-brown weathering siltstone, sandstones, and chert beds

DSh **Hidden Valley Dolomite (Devonian and Silurian)**—Lower part is dark gray cherty dolomite;upper part is light gray, slightly argillaceous dolomite. Above color distinction is locally modified by alteration and may not be consistent across map area. Thickness varies from 265 m in southeast part of map to 440 m in northwest part

Oes **Ely Springs Dolomite (Ordovician)**—Dolomite and limy dolomite, containing abundant dark gray chert layers and nodules 5 to 20 cm thick; dark gray grading to medium gray at top; maximum thickness of ≈150 m

Oe **Eureka Quartzite (Ordovician)**—Ledge-forming, white to pink orthoquartzite, grading down into a light to medium red dolomitic sandstone at base; estimated maximum thickness of ≈120 m

Op **Pogonip Group, undivided (Ordovician)**—Estimated maximum thickness of ≈670 m; consists of:

Opa **Antelope Valley Limestone**— Limestone and silty limestone; Medium gray; finely to coarsely crystalline and predominantly nodular, massive to laminated beds

Opn **Ninemile Formation**—Siltstone and shale, light to moderate brown or reddish brown, and typically finely interlaminated with olive black to dark medium gray silty limestone or dolomite

Opg **Goodwin Limestone**—Limestone and lesser silty limestone, ledge-forming, medium to dark gray

Nopah Formation (Cambrian)—Consists of three members: a thin basal shale member, and two carbonate members that are locally mapped together as a combined unit; estimated maximum thickness of ≈520 m

Ꞓnc **Smoky and Halfpint Members, undivided**

Ꞓns **Smoky Member**—Dolomite, cliff-forming, very light gray to medium gray, in indistinct medium to thick beds

Ꞓnh **Halfpint Member**—Dolomite with locally abundant black chert nodules and layers; medium to dark gray; thin to thick bedded, finely to coarsely crystalline, bedding generally very indistinct

Ꞓnd **Dunderberg Shale Member—**Fissile shale, greenish brown with subordinate interbeds of medium gray to pale brown, thinly bedded limestone

Bonanza King Formation (Cambrian)—Light to dark gray limestone and dolomite with much lesser orange brown silty layers; estimated maximum thickness of ≈1100 m; divided into:

Ꞓbb **Banded Mountain Member**—Combined unit consisting of thefollowing two units:

Ꞓbbu **Upper part**—Dolomite and limestone, cliff forming, fine to medium crystalline, thickly bedded; composed of three color bands of approximately equal thickness, from base to top: light gray, dark gray and medium gray.

Ꞓbbl **Lower part**—Dolomite and limestone, distinctively striped in alternating light- to dark-gray beds ranging from 0.5 to 6 m thick.

Ꞓbp **Papoose Lake Member**—Mostly dark gray dolomite and limestone intercalated with sparse but distinctive yellowish orange silty and sandy intervals.

Ꞓc **Carrara Formation (Cambrian)**—Heterogeneous unit of shale or slate and lesser micaceous siltstone intercalated with three prominent beds of dark greenish-gray limestone and silty limestone; estimated maximum thickness of ≈490 m

Єz **Zabriskie Quartzite (Cambrian)**—Orthoquartzite, cliff forming, dark to medium purplish red, fine to medium grained, thick bedded and commonly cross-stratified; estimated maximum thickness of ≈250 m

Wood Canyon Formation, undivided (Cambrian and Neoproterozoic)—Thick sequence of argillites (weakly metamorphosed siltstone) with interbeds of sandstone and dolomite. Estimated maximum thickness of intact formation is ≈1200 m; consisting of:

Єwu **Upper member (Cambrian)**—Sequence of interbedded quartzite and siltstone with numerous orange dolomite beds which are most abundant at and near base and are commonly oolitic

Zwm **Middle member (Neoproterozoic)**—Fining-upward sequence consisting mainly of siltstone, but with abundant interbedded thin sandstone beds in lower part, and a pebbly arkosic sandstone at base; sandstones are pale greenish gray; siltstones are medium to dark greenish brown

Zwl **Lower member (Neoproterozoic)**—Siltstone and very fine grained micaceous quartzite, thin to thickly bedded, dark to medium brown or greenish gray section is divided into four sections of roughly equal thickness by three prominent beds of interbedded orange dolomite, each ≈15 m thick

Stirling Quartzite (Neoproterozoic)—Estimated maximum thickness of ≈1500 m; consisting of:

Zse **E member**—Orthoquartzite, fine grained, medium to thick bedded, white to pale yellowish brown or pale red

Zsd **D member**—Fine- to medium-grained feldspathic sandstone,with numerous siltstone interbeds in lower part of unit, decreasing in abundance upward

Zsc **C member**—Dolomite, fine to medium grained, massive to thin bedded, typically pale orange

Zsb **B member**—Fine-grained arkosic sandstone, micaceous siltstone, and thin beds of carbonate rocks

Zsa **A member**—Impure sandstone, mostly fine to coarse grained, commonly arkosic and bearing characteristic jasperoid grains and small pebbles; includes abundant beds of quartz-pebble conglomerate near base and a thin orange dolomite marker bed in upper part

Zju **Johnnie Formation (Neoproterozoic)**—Shale and lesser carbonate rocks; only uppermost ≈100 m of formation exposed in map area

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