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Earth-Science Reviews 73 (2005) 245–270

EARTH-SCIENCE REVIEWS

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Upper Neogene stratigraphy and tectonics of Death Valley — a review

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Abstract

New tephrochronologic, soil-stratigraphic and radiometric-dating studies over the last 10 years have generated a robust numerical stratigraphy for Upper Neogene sedimentary deposits throughout Death Valley. Critical to this improved stratigraphy are correlated or radiometrically-dated tephra beds and tuffs that range in age from >3.58 Ma to <1.1 ka. These tephra beds and tuffs establish relations among the Upper Pliocene to Middle Pleistocene sedimentary deposits at Furnace Creek basin, Nova basin, Ubehebe–Lake Rogers basin, Copper Canyon, Artists Drive, Kit Fox Hills, and Confidence Hills. New geologic formations have been described in the Confidence Hills and at Mormon Point. This new geochronology also establishes maximum and minimum ages for Quaternary alluvial fans and Lake Manly deposits. Facies associated with the tephra beds show that ~3.3 Ma the Furnace Creek basin was a northwest–southeast-trending lake flanked by alluvial fans. This paleolake extended from the Furnace Creek to Ubehebe. Based on the new stratigraphy, the Death Valley fault system can be divided into four main fault zones: the dextral, Quaternary-age Northern Death Valley fault zone; the dextral, pre-Quaternary Furnace Creek fault zone; the oblique–normal Black Mountains fault zone; and the dextral Southern Death Valley fault zone. Post −3.3 Ma geometric, structural, and kinematic changes in the Black Mountains and Towne Pass fault zones led to the break up of Furnace Creek basin and uplift of the Copper Canyon and Nova basins. Internal kinematics of northern Death Valley are interpreted as either rotation of blocks or normal slip along the northeast–southwest-trending Towne Pass and Tin Mountain fault zones within the Eastern California shear zone.
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Keywords: Neogene; stratigraphy; tectonics; tephrochronology

1. Introduction

For most of the 20th century, the Upper Neogene (Pliocene through Quaternary) stratigraphy of Death Valley was relatively straightforward and unrefined. The first geologists working in Death Valley estab-

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0012-8252/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.earscirev.2005.07.004

lished a very useful relative-age stratigraphy for the Upper Neogene that consisted of seven main geologic units (Fig. 1): (1) Furnace Creek Formation; (2) Nova Formation; (3) Funeral Formation (or QTg1); (4) Quaternary gravel 2 (Qg2); (5) Qg3; (6) Qg4; and (7) Lake Manly deposits (Noble, 1934; Noble and Wright, 1954; Drewes, 1963; Hunt and Mabey, 1966; Denny, 1967; Hooke, 1972).

Recently, several independent, but coordinated, studies have reinforced and expanded this stratigraphic framework utilizing a variety of geochronologic techniques (Holm et al., 1994; Snow and Lux, 1999; Knott et al., 1999b; Klinger, 2001b; Klinger and Sarna-Wojcicki, 2001; Machette et al., 2001c; Sarna-Wojcicki et al., 2001). This has resulted in defining new geologic units and helps elucidate the complex tectonic history of the Death Valley pull-apart basin, which has long been a fundamental proving ground for extensional tectonics (Burchfiel and Stewart, 1966; Wright and Troxel, 1967; Wright et al., 1974; Wright, 1976; Wernicke, 1992).

The purpose of this paper is to review the recent refinements to the Upper Neogene stratigraphy of Death Valley. Although an abbreviated review of the stratigraphy is presented in Knott (1999), new research (Knott et al., 1999b; Klinger, 2001b; Klinger and Sarna-Wojcicki, 2001; Machette et al., 2001c; Sarna-Wojcicki et al., 2001) necessitates a more extensive update. In addition, in the past 10 yr, theories regarding the Late Cenozoic tectonic framework of Death Valley have evolved as the region is considered within the broader tectonic framework of the Eastern California shear zone (Knott et al., 1999b; Klinger and Sarna-Wojcicki, 2001; Lee et al., 2001).

2. Upper Neogene stratigraphy

Our understanding of the Upper Neogene stratigraphy of Death Valley has evolved greatly in the past decade (Fig. 1). Geologic units such as the Furnace Creek, Funeral and Nova Formations—all initially

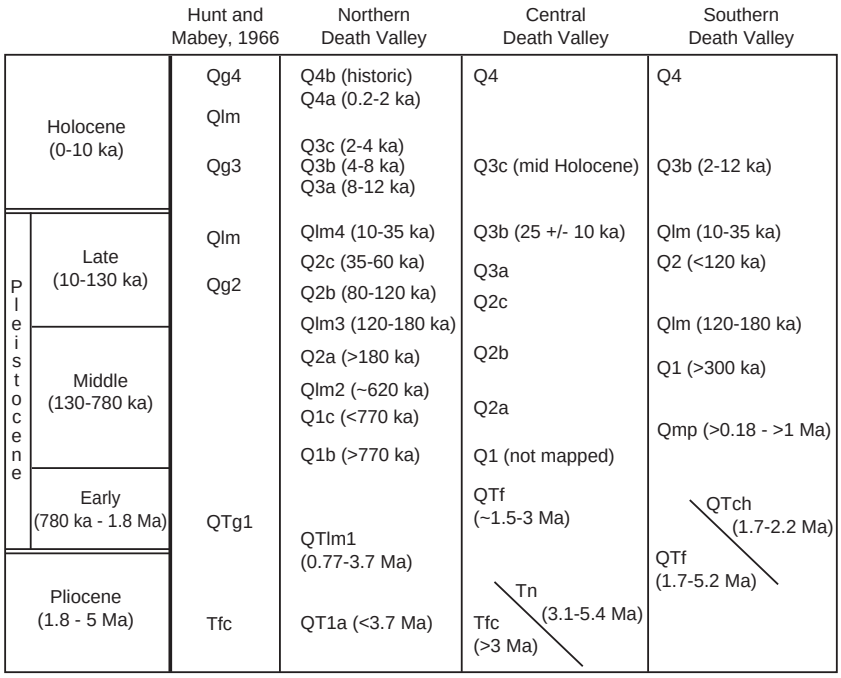


Fig. 1. Chart comparing Late Neogene geologic formations and map units of Hunt and Mabey (1966) for central Death Valley to later studies of northern (after Klinger, 2001b), central (after Machette et al., 2001c), and southern Death Valley (after Knott et al., 1999a,b; Beratan et al., 1999; Klinger and Piety, 2001; Sarna-Wojcicki et al., 2001). Abbreviations for formations and map units are: Quaternary gravels (Qg2, Qg3 and Qg4 of Hunt and Mabey; Q1, Q2, Q3 and Q4 for other studies); Lake Manly (Qlm and QTlm); Mormon Point Formation (Qmp); Funeral Formation (QTf); Confidence Hills Formation (QTch); Furnace Creek Formation (Tfc); Nova Formation (Tn).

described at least 50 years ago (see Hunt and Mabey, 1966)—now have radiometric- or correlated-age control. Conversely, the Confidence Hills (Beratan et al., 1999; Beratan and Murray, 1992) and Mormon Point Formations (Knott et al., 1999b) are newly described and the Ubehebe–Lake Rogers and Furnace Creek depocenters (Fig. 2) are the subject of several new studies (Klinger and Sarna-Wojcicki, 2001; Liddicoat, 2001; Machette et al., 2001c). The ages of the classic Quaternary alluvial-fan deposits, whose ages have long been problematic (McFadden et al., 1991), now have an incipient numeric-age framework (e.g., Nishiizumi et al., 1993) and are the subject of ongoing cosmogenic isotope investigations (Machette, pers. commun., 2003). In the following sections, a brief summary of each geologic formation or unit is provided followed by a description of the new age control and correlation to other deposits in Death Valley. The age control is mainly the result of the correlation of several key tuff and tephra marker beds summarized in Fig. 3.

2.1. Furnace Creek Formation

The Furnace Creek Formation, as defined by Noble (1934) and mapped in detail by McAllister (1973), consists of interbedded siltstones, sandstones, conglomerates and basalts in the Furnace Creek basin (Figs. 2 and 4). The Furnace Creek Formation and the overlying Funeral Formation mark the final depositional phases that began during the Late Miocene. The Furnace Creek basin is between the Black and Funeral Mountains. The Furnace Creek basin is bounded by the pre-Quaternary Furnace Creek and Grandview fault zones on the northwest and southwest, respectively (Wright et al., 1999). Hunt and Mabey (1966) and Wright and Troxel (1993) extended the Furnace Creek Formation northwest to include fine-grained deposits near the Kit Fox Hills (Fig. 2); however, the correlation between the Furnace Creek and Kit Fox Hills areas is lithostratigraphic and thus tentative.

Early studies of diatom and plant-fossil assemblages indicated a Pliocene age for the Furnace Creek Formation (Hunt and Mabey, 1966). The first radiometric age control for the Furnace Creek Formation was a 4.0 Ma K/Ar (whole-rock) age from a basalt flow in the overlying Funeral Formation (McAllister, 1973). These data supported a Pliocene age for the underlying upper part of the Furnace Creek Formation.

More recently, Machette et al. (2001c) found the 3.1–3.35 Ma Mesquite Spring tuffs in the upper Furnace Creek Formation near the southern margin of the Furnace Creek basin (Fig. 3). The Mesquite Spring tuffs are important marker beds in Late Neogene sediments of Death Valley. Originally thought to be a single tuff (Snow and White, 1990), Knott et al. (1999b) showed that there are at least two biotite phenocryst tuffs with similar glass shard composition. The stratigraphic, paleomagnetic and geochronologic data indicate that the lower and upper Mesquite Spring tuffs have ages of 3.1 and 3.35 Ma, respectively (Snow and White, 1990; Holm et al., 1994; Knott et al., 1999b; Knott and Sarna-Wojcicki, 2001a).

About 7.5 km to the southeast, Liddicoat (2001) interpreted paleomagnetic reversals within the upper part of the Furnace Creek Formation to be correlative with either between 3.04 and 3.33 Ma or 2.67 and 2.81 Ma. Either of these paleomagnetically-determined age ranges are consistent with the tephrostratigraphy of Machette et al. (2001c). All of these data indicate that the age of the upper part of the Furnace Creek Formation is <3.5 Ma.

Machette et al. (2001c) noted that the <3.5 Ma age for the upper part of the Furnace Creek Formation conflicts with the 4.0 Ma K/Ar age in the overlying Funeral Formation reported by McAllister (1973). One possible explanation for the age discrepancy is that 4.0 Ma age is flawed. Alternatively, if the K/Ar age is correct, then a number of hypotheses must be entertained to explain the various geologic relations. These include, but are not limited to, (1) post-Pliocene, northwest-down, slip on northeast–southwest-trending faults across the Furnace Creek basin (Wright et al., 1999) or (2) that the Funeral Formation containing the basalt is a proximal, coarse-grained facies of the Furnace Creek Formation to the northwest.

As a result, Machette et al. (2001c) placed the contact between the Furnace Creek Formation and overlying Funeral Formation at the facies transition where mudstones grade upward into conglomerates. These conglomerates contain Paleozoic clasts that Wright et al. (1999) interpret to record the progradation of alluvial fans due to uplift and denudation of the Funeral Mountains on the opposite side of the basin.

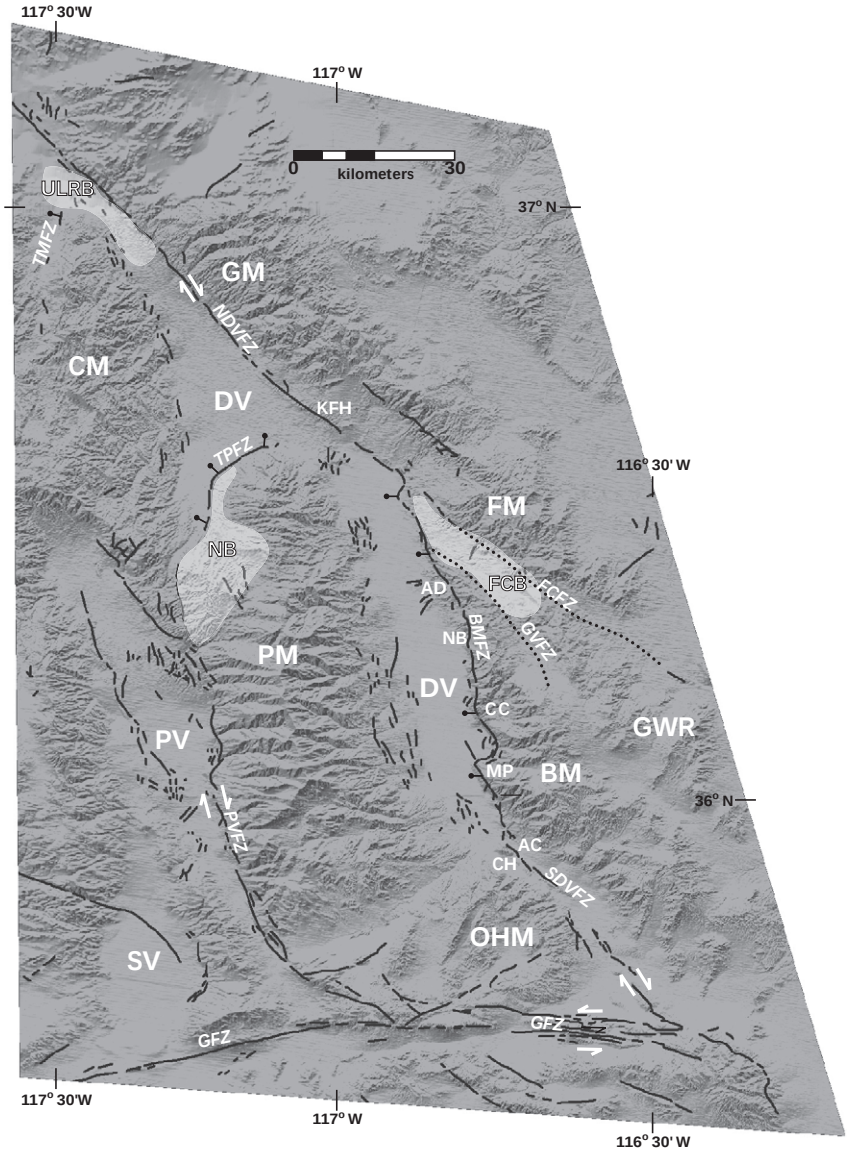


Fig. 2. Map showing major geographic features and Quaternary faults (black lines) of Death Valley. Arrows indicate motion on strike-slip faults; bar and ball indicates downthrown side of normal faults. Major geographic features are: Black Mountains (BM), Cottonwood Mountains (CM), Death Valley (DV), Funeral Mountains (FM), Grapevine Mountains (GM), Greenwater Range (GWR), Owlshead Mountain (OHM), Panamint Mountains (PM), Panamint Valley (PV), and Searles Valley (SV). Major fault zones are: the Black Mountains (BMFZ), Furnace Creek (FCFZ), Garlock (GFZ), Grandview (GVFZ), Northern Death Valley (NDVFZ), Panamint Valley (PVFZ), Southern Death Valley (SDVFZ), Tin Mountain (TMFZ), and Towne Pass (TPFZ). Locations of sedimentary deposits discussed in text are: Artists Drive (AD), Ashford Canyon (AC), Confidence Hills (CH), Copper Canyon (CC), Furnace Creek Basin (FCB), Kit Fox Hills (KFH), Mormon Point (MP), Natural Bridge (NB), Nova Basin (NB), and Ubehebe–Lake Rogers Basin (ULRB). Shaded relief base map derived from digital elevation model.

This interpretation places the Furnace Creek–Funeral contact slightly higher in the section, but still generally concordant with the interpretation of McAllister (1973). Machette et al. (2001c) have argued that this higher facies transition is a more appropriate upper contact for the Furnace Creek because of the associa-

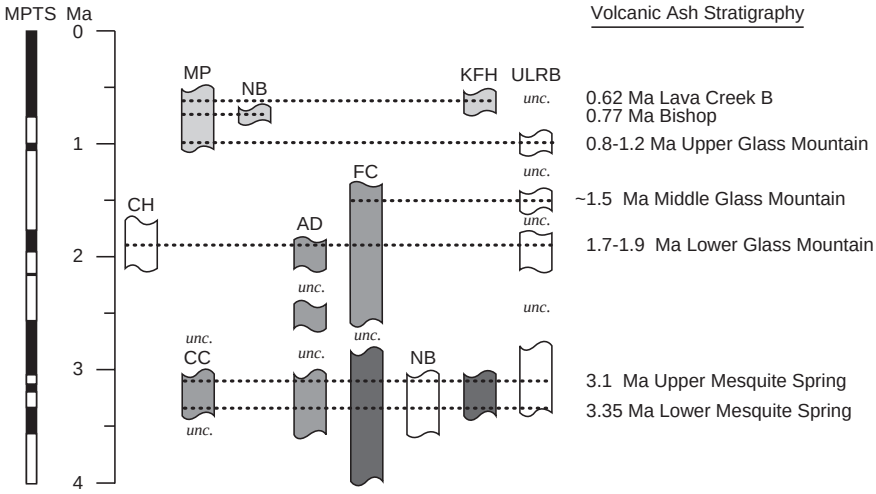


Fig. 3. Diagram showing correlation of Late Neogene deposits of Death Valley using selected volcanic ash and tuff marker beds. Locations shown on diagram are: Artists Drive (AD), Confidence Hills (CH), Copper Canyon (CC), Furnace Creek (FC), Kit Fox Hills (KFH), Mesquite Flat (MF), Mormon Point (MP), Natural Bridge (NB), Nova basin (NB), and Ubehebe–Lake Rogers (ULRB). Mormon Point Formation is light shade; Funeral Formation is intermediate shade; Furnace Creek Formation is dark shade. Unconformities (unc.) between stratigraphic sequences are shown as well. Discussion of other stratigraphic units is found in text. Magnetic Polarity Time Scale (MPTS) is shown at left. Black segments of MPTS are normal polarity and white segments are reversed polarity.

tion with the tectonic uplift of the Funeral Range. In contrast, the lower facies transition preferred by McAllister is indistinguishable from other facies changes in the section. Blair and Raynolds (1999) described similar facies in the upper Furnace Creek Formation adjacent to the northern margin of the Furnace Creek basin and Furnace Creek fault zone. These likely record uplift and progradational events; however, the lack of age control makes correlation to studies on the southern margin by Machette et al. (2001c) difficult.

Identification of a Mesquite Spring tuff in the Furnace Creek Formation allows correlation of the upper Furnace Creek with deposits at Copper Canyon, Artists Drive, and the Nova basin (Figs. 2 and 3).

2.2. Ubehebe–Lake Rogers deposits

The Ubehebe–Lake Rogers deposits are found in the Cottonwood Mountains and on the eastern Cottonwood Mountains piedmont southeast of the Tin Mountain fault zone (Fig. 2). This Miocene–Quaternary sedimentary sequence has only recently been described and the interpretation is rapidly evolving (Snow and White, 1990; Snow and Lux, 1999; Klinger and Sarna-Wojcicki, 2001). As a result, we believe that while the data collected to date are substantive, the formation designations for stratigraphic sequences remain tentative. Thus, we prefer Ubehebe–Lake Rogers deposits rather than describe these data under formal formational designations.

Snow and White (1990) defined the Ubehebe basin deposits as a sequence of interbedded conglomerates, tuffs, mudstones and basalts ranging in age from 3.17 ± 0.09 to 23.87 ± 0.23 Ma. Snow and Lux (1999) interpreted the gently dipping (<20°) conglomerate, marl and sandstone beds overlying the 3.7 ± 0.2 Ma Basalt of Ubehebe Hills as Nova Formation. This correlation to the Nova Formation is based largely on the presence of the 3.1–3.35 Ma Mesquite Spring tuff in both the Nova Formation and the sediments above the 3.7 Ma Basalt of Ubehebe Hills.

Snow and Lux (1999) noted that the Mesquite Spring tuff grades to the northeast into a tuffaceous (altered) marl as the surrounding facies grade from conglomerate to mudstone. Snow and Lux (1999) interpreted these relations to show that a playa lake, bound on the southwest by alluvial fans existed along Death Valley Wash ~3.2 Ma. To the east, between Death Valley Wash and the Northern Death Valley

Fig. 4. Oblique aerial view looking southeast at the north-dipping Furnace Creek Formation in the Furnace Creek basin. The light colored beds in the right center are lacustrine mudstones with breccias and conglomerates comprising the ridge in the foreground. In the lower right is the Furnace Creek alluvial fan with a dashed line along the trend of the Black Mountains fault zone. The arrow indicates the location of the 3.1–3.35 Ma Mesquite Springs tuff in the upper part of the Furnace Creek Formation.

fault zone, ~3.2 Ma breccia/conglomerates are interpreted as proximal alluvial-fan deposits (Klinger and Sarna-Wojcicki, 2001). Thus, the ~3.2 Ma playa lake inferred by Snow and Lux (1999) would have been narrowly constrained to the area of the present Death Valley Wash with flanking alluvial-fan deposits to the east and west.

One of the best exposures of the upper Ubehebe basin beds is in Death Valley Wash (Fig. 5) where Klinger (2001a,b) dated and correlated several tephra beds. Here, the 3.7 Ma Basalt of Ubehebe Hills is overlain by a Mesquite Spring tuff. This tuff is interbedded with mudstones that grade upward to conglomerates (Klinger and Sarna-Wojcicki, 2001). Intercalated with the conglomerates and separated by unconformities are tuffs from the lower (1.7–2.0 Ma), middle (~1.5) and upper (0.76–1.2 Ma) Glass Mountain tephra groups, all suggesting that the basin persisted well into the Early Quaternary (Klinger and Sarna-Wojcicki, 2001).

The 1.7–1.9 Ma lower Glass Mountain tuffs are interbedded with fine-grained sediments, which Klinger and Sarna-Wojcicki (2001) designated as Qlm1 (Fig. 1) or an early phase of Lake Manly. The Qlm1 deposits of Klinger and Sarna-Wojcicki (2001) are overlain in angular unconformity by breccia/conglomerates that contain 0.8–1.2 Ma upper Glass Mountain ash beds.

Overlying the gently dipping upper Ubehebe basin sediments are the flat-lying mudstones and evaporites of Lake Rogers. Klinger and Sarna-Wojcicki (2001) defined the Lake Rogers basin as a Quaternary-age structural depression located northwest of the Tin Mountain fault zone and west of the Northern Death Valley fault zone. These flat-lying sediments overlie the Ubehebe basin deposits in angular unconformity. Clements (1952) found mammoth fossils in the mudstones and sparse evaporite beds and interpreted the age as Quaternary.

Based on tephrochronology, the upper Ubehebe basin deposits are correlative with those from the upper part of the Nova Formation; the upper part of the Furnace Creek Formation; the upper part of the Funeral Formation at Copper Canyon; and the lower part of the Funeral Formation at Artists Drive. Identification of the lower Glass Mountain tephra beds indicates that the upper Ubehebe basin deposits are temporally correlative with the Funeral Formation in the Furnace Creek basin, the upper Funeral Formation at Artists Drive and the Confidence Hills Formation. The presence of upper Glass Mountain tephra beds indicates a correlation with the Mormon Point Formation.

Based on the presence of the Mesquite Springs tuff, Snow and Lux (1999) correlated the upper Ubehebe basin deposits with the Nova Formation. However, unlike the Nova Formation, deposition in the Ubehebe basin persisted into the Quaternary. It is obvious that the upper part of the Ubehebe basin

Fig. 5. View to the north of the Ubehebe–Lake Rogers basin deposits. Dark bed in the canyon wall at right is the 3.7 Ma Basalt of Ubehebe Hills, which marks the base of the upper part of the Ubehebe basin deposits. In the center are the Quaternary-age, flat-lying Lake Rogers deposits.

deposits are significantly younger from the Nova Formation. Also, the fine-grained facies of the upper part of the Ubehebe basin deposits are more similar to the upper part of the Furnace Creek Formation. We believe that these discrepancies make the correlation to the Nova Formation tentative. The presence of unconformities within the upper part of the Ubehebe basin deposits (Klinger and Sarna-Wojcicki, 2001) suggests that the depositional and tectonic history of this area is not sufficiently resolved and may warrant a new formation.

2.3. Funeral Formation

Since being described in the Furnace Creek area by Thayer in 1897, the Funeral Formation has been mapped throughout the Black Mountains of central and southern Death Valley (see Hunt and Mabey, 1966). Funeral Formation outcrops range from broad expanses to small isolated outcrops. In general, the Funeral Formation consists of tilted and uplifted alluvial-fan conglomerates containing sparse intercalated basalts. The basalts are most prominently exposed in the upper reaches of the present Furnace Creek drainage basin (Fig. 2). The most extensive deposits of the Funeral Formation are found in the Furnace Creek basin (Fig. 2); Artists Drive and Copper Canyon; (Drewes, 1963; Hunt and Mabey, 1966; McAllister, 1970; McAllister, 1973; Wright and Troxel, 1984); and Kit Fox Hills (Wright and Troxel, 1993).

Both Noble (1934) and Hunt and Mabey (1966) hypothesized that the discontinuous outcrops prohibited correlation of the Funeral Formation from place to place. In addition, they both noted that there was no evidence that the Funeral Formation deposits were contemporaneous.

McAllister (1970, 1973) published the most comprehensive map and descriptions of the Funeral Formation. He also provided the initial numeric age control using a K/Ar date of 4.0 Ma on a basalt flow near the southeastern margin of the Furnace Creek basin. However, as described above, the basalt's age is not supported by ~3 Ma tephrochronologic and paleomagnetic ages in the underlying Furnace Creek Formation (Liddicoat, 2001; Machette et al., 2001c; Sarna-Wojcicki et al., 2001). The correlation of lower Glass Mountain (1.7–1.9 Ma) and middle Glass Mountain (~1.5 Ma) tephra beds within the Funeral Formation several kilometers northeast of the

Furnace Creek type locality supports the younger age for the Funeral Formation (Sarna-Wojcicki et al., 2001).

Knott et al. (1999a,b) mapped the Funeral Formation in the Artists Drive block, which is located west of the Black Mountains across the Black Mountains fault zone. Near the basal unconformity, Knott et al. (1999a) found two tuffs above and below the 3.28 Ma Nomlaki Tuff that have identical glass shard compositions. They named these tuffs the lower and upper Mesquite Spring tuffs because of their similarity to the Mesquite Spring tuff of Snow and White (1990). Based on the exposures and data from the Artists Drive locality, the ages of the lower and upper Mesquite Springs tuffs are interpreted to be 3.1 and 3.35 Ma (Knott and Sarna-Wojcicki, 2001a,b).

Below the 3.35 Ma lower Mesquite Spring tuff at Artists Drive is the lower Nomlaki Tuff. The lower Nomlaki tuff has a shard composition general similar to the Nomlaki Tuff, but outcrop data clearly shows this is not the Nomlaki Tuff (Knott et al., 1999b). Knott and Sarna-Wojcicki (2001a,b) used paleomagnetic and stratigraphic data to infer the age of the lower Nomlaki tuff to be >3.58 Ma (Fig. 6). Also below the lower Mesquite Spring tuff at Artists Drive is the tuff of Curry Canyon (Knott and Sarna-Wojcicki, 2001b). The age of this tuff is estimated to be between 3.35 and 3.58 Ma. The tuff of Curry Canyon is also found in the upper part of the Furnace Creek Formation (Machette et al., 2001c).

The upper part of the Funeral Formation at Artists Drive also contains a lower Glass Mountain ash bed. The lower Glass Mountain family of ash beds are important stratigraphic markers in Death Valley. This family of ash beds have an age range of 1.7–1.9 Ma (Sarna-Wojcicki et al., 2001). The reversed paleomagnetic polarity of the lower Glass Mountain ash bed at Artists Drive narrows the age of that ash bed to 1.8–1.9 Ma (Knott, 1998).

The tephrochronology shows that the lower part of the Funeral Formation at Artists Drive is time equivalent to the upper part of the Furnace Creek Formation. The upper part of the Funeral Formation at Artists Drive, however, is time equivalent to the Furnace Creek Formation in the Furnace Creek basin.

A Mesquite Spring tuff is also found in the upper part of the Funeral Formation at Copper Canyon (Knott et al., 1999b). This Mesquite Spring tuff has a biotite $^{40}Ar/^{39}Ar$ age of 3.1 ± 0.2 Ma (Holm et al., 1994), and thus could be either the upper or lower Mesquite Spring tuff.

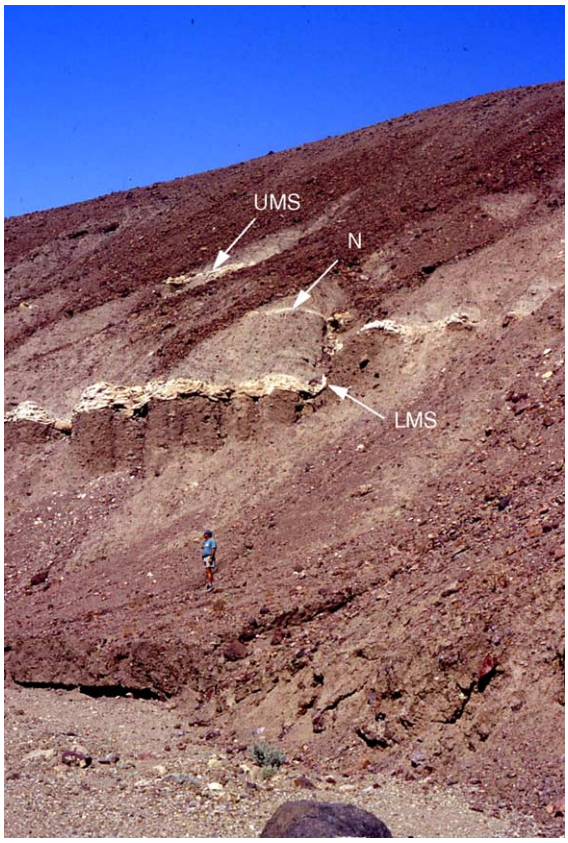


Fig. 6. Funeral Formation breccias and conglomerates interbedded with the 3.35 Ma lower Mesquite Spring tuff (LMS), 3.28 Ma Nomlaki Tuff (N), and ~3.1 Ma upper Mesquite Spring tuff (UMS) in Hunt Canyon at Artists Drive. LMS is approximately 1 m thick.

Topping (1993) obtained a zircon fission-track age of 5.2 Ma for a tuff within the Funeral Formation of the southern Black Mountains. This age makes these breccias and conglomerates the oldest deposits mapped as Funeral Formation yet dated. The 5.2 Ma age makes this southern outcrop of Funeral Formation time equivalent to the middle part of the Furnace Creek Formation at its type locality and the lower Nova Formation.

Wright and Troxel (1993) mapped poorly sorted conglomerates in the Kit Fox Hills northeast of Furnace Creek as belonging to the Funeral Formation. Underlying the Funeral Formation just 2 km

northwest, Knott and Sarna-Wojcicki (2001a,b) found a Mesquite Spring tuff interbedded with mudstones. If the interpretation of Machette et al. (2001c) is extended to the Kit Fox Hills, then the mudstones underlying the Funeral Formation would be temporally and lithologically equivalent to the upper Furnace Creek Formation.

Wright and Troxel (1984) also mapped the Funeral Formation near Ashford Canyon in the southern Black Mountains northeast of the Confidence Hills (Fig. 2). The Funeral Formation here is comprised of uplifted and tilted alluvial-fan conglomerates. Wright and Troxel (1984) inferred that a basalt flow exposed at the base of the section is the same as the 1.7 Ma basalt (K/Ar) that forms Shoreline Butte in the northern Confidence Hills (Fig. 2). The 1.7 Ma age is consistent with the correlation of 1.7–1.9 Ma lower Glass Mountain tephra beds in the overlying conglomerates (Knott, 1998). This section of Funeral Formation is contemporaneous with the Funeral Formation in the Furnace Creek basin (Sarna-Wojcicki et al., 2001); the upper part of the Funeral Formation at Artists Drive (Knott et al., 1999b); the Confidence Hills Formation (Sarna-Wojcicki et al., 2001); and the upper part of the Ubehebe–Lake Rogers deposits (Klinger, 2001a). Given its location only a few kilometers from the Confidence Hills, this deposit is probably more likely and appropriately part of the Confidence Hills Formation; however, this is based on limited data and should be confirmed by additional studies.

The more recent tephrochronologic studies have enabled correlation of the Funeral Formation from place to place throughout the Black Mountains. In addition, the tephrochronology allows correlation of the Funeral Formation to other deposits in Death Valley. The tephrochronology also has shown that the age of the Funeral Formation is time transgressive (Fig. 3).

2.4. Nova Formation

The Nova Formation was originally mapped northwest of the Panamint Mountains (Hunt and Mabey, 1966). The Nova Formation is composed of conglomerates, breccias and intercalated basalt flows. According to Hunt and Mabey (1966), the base of the Nova Formation (Fig. 1) in Death Valley is not exposed, but is in fault contact with the low-angle Emigrant Canyon fault. To the north and west, the Nova Formation is uplifted by the high-angle Towne Pass fault (Fig. 1). The age of the Nova Formation ranges from 5.4 ± 0.4 Ma (whole rock K/Ar Hodges et al., 1989) to 3.35 ± 0.13 Ma (Snow and Lux, 1999).

The 3.35 Ma age is on a Mesquite Spring tuff found in the upper part of the Nova Formation (Fig. 7). The Mesquite Spring tuffs are found in the Ubehebe basin and in isolated outcrops in the Cottonwood Mountains (Snow and White, 1990; Snow and Lux, 1999). Based on the presence of the 3.1–3.35 Ma Mesquite Spring tuffs, Snow and Lux (1999) extended the Nova Formation to include the Cottonwood Mountain sediments. In the Cottonwood Mountains, the base of the Nova Formation is delineated by the 3.7 ± 0.2 Ma Basalt of Ubehebe Hills (Snow and Lux, 1999). As mentioned above, new research by Klinger and Sarna-Wojcicki (2001) indicate the Ubehebe basin deposits are significantly younger and lithologically different. For these reasons, we believe that the extension of the Nova Formation to the upper Ubehebe basin deposits is tentative at this time and requires additional research (see Section 2.2).

The Nomlaki Tuff is also found in the Nova Formation northwest of the Panamint Mountains (J. Tinsley, pers. commun., 1994). In addition, the Nomlaki Tuff is found in alluvial-fan deposits along the eastern Cottonwood Mountain piedmont, south of Ubehebe (Knott, 1998).

Based on the tephrochronology (Fig. 3), the upper part of the Nova Formation is temporally equivalent to the upper part of the Furnace Creek Formation of Machette et al. (2001c); the lower part of the Funeral Formation at Artists Drive; and the upper part of the Copper Canyon (Knott et al., 1999b). These correlations are different from Hunt and Mabey (1966) who equated the Nova Formation with the Funeral Formation based on lithology.

2.5. Confidence Hills Formation

In southern Death Valley, evaporite, mudstone and conglomerate beds are uplifted and exposed in the Confidence Hills adjacent the Southern Death Valley fault zone (Wright and Troxel, 1984). Troxel et al. (1986) identified three ash beds within these sediments, including the Huckleberry Ridge ash bed, which was erupted from the Yellowstone Caldera at

Fig. 7. Typical exposure of Nova Formation breccias and conglomerates interbedded with the 3.35 Ma lower Mesquite Spring tuff. Total thickness of tuff is about 6 m. The upper 5 m is tuffaceous debris flows.

about 2.07 Ma. Paleomagnetic data show that this sedimentary section ranges in age from <1.79 to >2.15 Ma (Pluhar et al., 1992). Based on these unique lithologies and temporal qualities, Beratan et al. (1999) named these playa and alluvial-fan deposits the Confidence Hills Formation.

Subsequent tephrochronologic studies of the Confidence Hills Formation have identified the Blind Springs Valley tuff (formerly the tuff of Taylor Canyon; 2.22 Ma); the tuff of Confidence Hills (1.95–2.09 Ma); the tuffs of Emigrant Pass (1.95–2.09 Ma); the lower Glass Mountain tuffs (1.79–1.95 Ma); and the Huckleberry Ridge ash bed (Sarna-Wojcicki et al., 2001).

The lower Glass Mountain tuffs are a key stratigraphic marker for correlation of the Confidence Hills Formation to other deposits in Death Valley (Fig. 3). The Confidence Hills Formation is temporally equivalent to the upper Funeral Formation at Artists Drive, the lower Funeral Formation at Furnace Creek and the upper Ubehebe–Lake Rogers deposits (Fig. 3). Based on the presence of a lower Glass Mountain tuff and proximity to the type locality, we have tentatively extended the Confidence Hills Formation to include tilted basalt flows and conglomerates across Death Valley at Ashford Canyon (Fig. 2). These deposits were previously mapped as Funeral Formation (see Section 2.3).

2.6. Mormon Point Formation

The Mormon Point Formation (formally described herein) consists of interbedded mudstones, conglomerates and tephra beds, which are well exposed in their type locality at Mormon Point (Knott et al., 1999b). Based on lithostratigraphy, Noble and Wright (1954) assigned a Quaternary age to these sediments. Subsequent studies show that the Mormon Point Formation contains the ~0.5 Ma Dibekulewe, 0.62 Ma Lava Creek B, 0.77 Ma Bishop and 0.8–1.2 Ma Upper Glass Mountain ash beds (Knott et al., 1999a,b; Hayman et al., 2003). The base of the Mormon Point Formation is in fault contact with Precambrian rock (Fig. 8). The fault is one of the low-angle normal faults often referred to as turtlebacks (Wright et al., 1974). The top is defined by an angular unconformity, on which 120–180 ka Lake Manly gravels are deposited.

The Mormon Point Formation is also found at Natural Bridge, just north of Badwater (Fig. 2). At Natural Bridge, coarse-grained breccias, interpreted to be alluvial-fan deposits, are interbedded with the 0.77

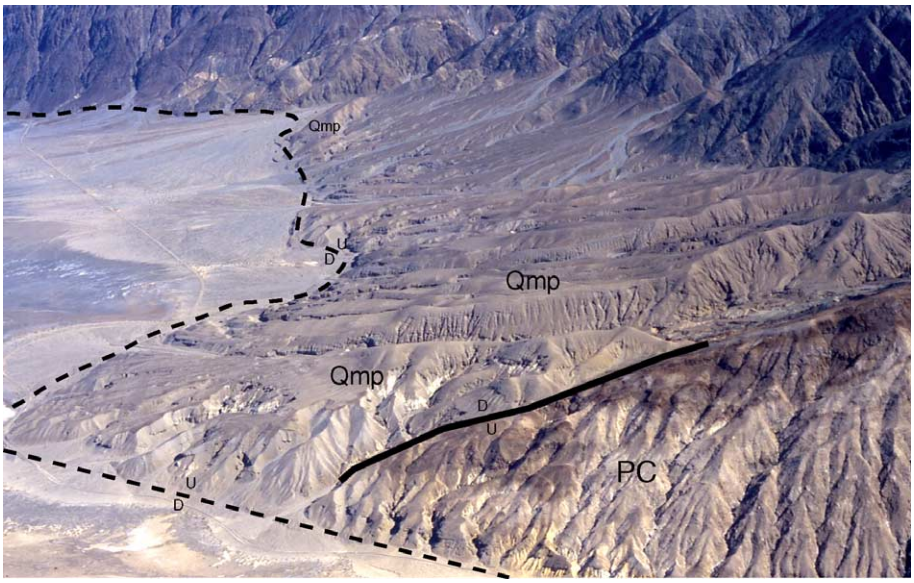


Fig. 8. Oblique aerial photograph of Mormon Point in the southern Black Mountains. The solid line is along the trace of the Mormon Point low-angle or turtleback fault. This fault separates Mormon Point Formation (Qmp) and metamorphosed Precambrian rocks (PC). The dashed line at the base of the Black Mountains shows the trace of the Black Mountains fault zone. Relatively upthrown (U) and downthrown (D) blocks across faults are also indicated.

Ma Bishop ash bed (Hayman et al., 2003). Like Mormon Point, the base of the Mormon Point Formation at Natural Bridge is in fault contact with a low-angle normal fault and overlain by the 120–180 ka deposits of Lake Manly (Knott et al., 1999a,b; Hayman et al., 2003).

The Mormon Point Formation is time equivalent to the upper part of the Ubehebe basin deposits and mudstones in the southern Kit Fox Hills (Figs. 2 and 3). In the Kit Fox Hills, Klinger (2001b) identified the Lava Creek B ash bed interbedded with fine-grained mudstones (See Section 2.8).

2.7. Lake Manly deposits

Lake Manly is the name used for the lake that intermittently occupied Death Valley during pluvial periods. In 1924, Levi Noble, W. M. Davis and H. E. Gregory described the first evidence of a lake in Death Valley (Noble, 1926). Means (1932) was the first to apply the name Lake Manly, honoring William Manly who lead a group of pioneers through Death Valley in 1849. Blackwelder (1933, 1954) and Clements and Clements (1953) described and speculated on the age of seven known outcrops known at that time. They all assumed that these outcrops were all related to a single lake stand of Lake Manly. The compilation of Machette et al. (2001a) nearly 50 years later identified 30 localities where evidence of Lake Manly (e.g., bars, spits or shoreline features) is found (Fig. 9); and this listing is probably incomplete.

Given the size of Death Valley, the geomorphic and stratigraphic evidence of various high stands of Lake Manly is relatively sparse and discontinuous, yet convincing where preserved (Figs. 9 and 10). These deposits are mappable (Hunt and Mabey, 1966), but have never been assigned formal formation status. This is probably due to the fact that the ages of discrete lake stands are poorly defined (Machette et al., 2001a) and confusion arising from distinguishing between shorelines and fault scarps (Klinger, 2001b; Machette et al., 2001c; Knott et al., 2002).

Drilled cores recovered from the valley floor have found evidence of two pluvial lakes. Hooke (1972) reported radiocarbon ages between 11 and 26 ka for lake-bottom sediments retrieved from shallow cores near Badwater. Lowenstein et al. (1999) found evidence of lakes at 10–35 ka and 120–186 ka in their 126-m-deep core near Badwater. Anderson and Wells (2003) found evidence of several small lakes that

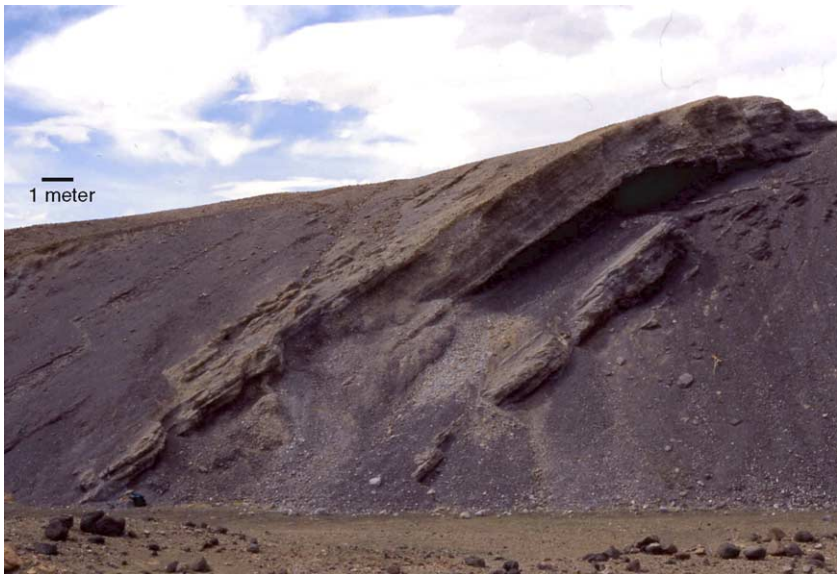


Fig. 9. South-dipping foreset beds in a spit of Lake Manly at Desolation Canyon (Loc. 17 on Fig. 10). Beds are composed of subrounded to rounded platey gravel and sand. Such outcrops are convincing evidence of Lake Manly.

occupied only the lowest parts of Death Valley between 10 and 35 ka. The 10–35 ka and 120–186 ka time frames are periods traditionally associated with large pluvial lakes in the western North America (i.e., Bonneville, Lahonton and Tecopa) and correlative with marine oxygen isotope stages 2 and 6, respectively (Smith, 1991).

Age dating of outcrops has yielded definitive evidence of only the 120–186 ka lake. Hooke and Lively (1979), cited in Hooke and Dorn (1992), used uranium-series disequilibrium to determine a preferred age range of 60 to 225 ka for tufa interbedded with near-shore facies gravels ~90 m above mean sea level (amsl) along the western Black Mountains piedmont. Ku et al. (1998) used uranium-series disequilibrium to date tufa deposits associated from this same ~90 amsl shoreline and found an age range between 128 and 216 ka. Ku et al. (1998) interpreted the clustering of shoreline tufa ages between 120 and 180 ka to correspond with the oxygen isotope stage 6 lake sediments found in the core.

Mormon Point Formation at Mormon Point and equivalent age sediments at the Kit Fox Hills and Ubehebe basin indicate at least two Pleistocene lake phases older than those found in the drilled cores (Knott, 1997). At Mormon Point, green, massive to laminated mudstones with reversed paleomagnetic polarity (>0.78 Ma) and containing 0.8–1.2 Ma Upper Glass Mountain ash beds are interpreted as lake deposits (Knott et al., 1999b). Lake facies are also found between the 0.77 Ma Bishop and the 0.62 Ma Lava Creek B ash beds at Mormon Point. In the Kit Fox Hills, Klinger (2001b) found the Lava Creek B ash bed interbedded with lacustrine facies. Fine-grained facies with an age of <0.77 Ma are also found in the Ubehebe–Lake Rogers basin. These lacustrine facies of Early to Middle Pleistocene age are referred to as Lake Manly phase 2 (Qlm2 on Fig. 1) by Klinger (2001b) and are equivalent to marine oxygen isotope stages 16 and 18.

Klinger (2001b) also extended usage of Lake Manly to include Pliocene (<3.7 and >0.77 Ma) lacustrine facies in the Ubehebe–Lake Rogers basin as well. Klinger designated these Pliocene to Pleistocene age deposits Lake Manly phase 1 (Qlm1 on Fig. 1). Blair and Raynolds (1999) referred to lacustrine facies in the northeast Furnace Creek basin as paleolake Lake Zabriske sediments. McAllister (1970) mapped these same sediments as the Furnace Creek Formation; however, the age of these sediments is poorly defined.

The two names (Lake Manly phase 1 and Lake Zabriske) for the Pliocene (?) to Pleistocene (?) paleolake could be referring to the same lake phase and illustrates the problem of attempting to name lake

phases. Given the lack of exposure and limited age control for the Pliocene lake sediments in Death Valley, it may be prudent to resist naming each new sequence of fine-grained deposits until better age control and mapping is completed. Similarly, given the rapid uplift of the Sierra Nevada Mountains in Pliocene time and incumbent climatic changes (Smith, 1991) and the post-Pliocene deformation throughout Death Valley, we now believe it is inappropriate to apply the term "Lake Manly" to deposits older than Pleistocene.

2.8. Alluvial-fan deposits

Numeric age control on the spectacular alluvial-fan deposits of Death Valley has remained sparse because of a lack of datable material (i.e., ^{14}C) in the fan deposits themselves and in the older formations (e.g., Funeral Formation). Early studies consistently inferred Quaternary ages for the alluvial fans based on limited fossil data and their relative lack of deformation (Noble and Wright, 1954; Hunt and Mabey, 1966; Denny, 1967; Hooke, 1972).

Rock varnish methods were used to estimate ages of Middle Pleistocene to Holocene for alluvial fans of the eastern Panamint Mountains piedmont (Dorn, 1988; Dorn et al., 1990; Hooke and Dorn, 1992). Rock varnish methods, however, have been challenged and their validity remains in question (e.g., Bierman and Gillespie, 1994; Beck et al., 1998; Watchman, 2000). As a result many questions regarding the age of Death Valley alluvial-fan deposits remained unanswered. These include: Are morphologically similar alluvial-fan units the same age?; What are the stratigraphic relations between the alluvial fans and Lake Manly?; What roles do climate and tectonics play in development of these alluvial fans?

The four-fold (Q1 [oldest], Q2, Q3 and Q4 [youngest]) relative stratigraphic framework that Hunt and

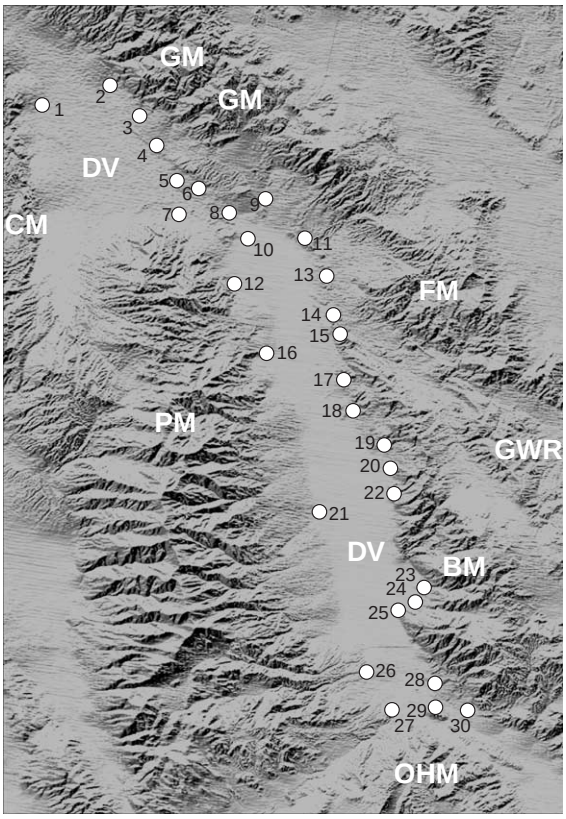


Fig. 10. Map showing selected locations where Lake Manly deposits or landscape feature have been identified. See Fig. 2 for abbreviations to geographic elements. After Machette et al. (2001a,b,c).

1. Niter beds
2. Titus Canyon
3. E. Mesquite Flat
4. Triangle Spring
5. Mud Canyon
6. NPS Rte 5 @ Hwy 190
7. Stovepipe Wells
8. Salt Creek anticline
9. Beatty Junction
10. Salt Creek
11. Three Bare Hills
12. North of Salt Spring
13. Park Village Ridge
14. Road to NPS landfill
15. Tea House
16. Unnamed ridge
17. Desolation Canyon
18. Manly terraces
19. Natural bridge
20. Nose Canyon
21. Tule Springs–Hanaupah Cyn
22. Badwater
23. Sheep Canyon
24. Willow Wash
25. Mormon Point
26. Warm Springs Canyon
27. Wingate Delta
28. East of Cinder Hill
29. Shoreline Butte
30. East of Ashford Mill

Mabey (1966) developed using empirical geomorphic observations has remained relatively unchallenged and viable. However, several subsequent workers (e.g., Hooke, 1972; Dorn, 1988; Klinger, 2001b; Menges et al., 2001) have subdivided the four original units of Hunt and Mabey (1966) (Fig. 1).

Studies of soil development and tephrochronology (Klinger, 2001b), fan morphology (Klinger, 2001b; Menges et al., 2001) and cosmogenic radionuclide surface exposure dating (Nishiizumi et al., 1993) are providing relative and numeric ages for some alluvial-fan deposits (Table 1). In addition, the stratigraphic relations between Lake Manly (Ku et al., 1998) and alluvial-fan deposits have improved age control for the alluvial fans as well.

In order to facilitate a review of the stratigraphic framework, the four main units of Hunt and Mabey are described below with subdivisions noted as identified where appropriate.

2.8.1. Q1

In the four-fold nomenclature of Hunt and Mabey (1966), the oldest alluvial-fan unit is the QTg1, or the Funeral Formation. However, the Funeral Formation lacks alluvial-fan morphology and the map symbol is unconventional (QTg1 instead of QTf). As a result, we recommend that the Funeral Formation should no longer be regarded as an alluvial-fan gravel, but should remain as a formation rank geologic unit. Later studies have described an alluvial-fan unit on the eastern Panamint piedmont that has fan morphology and is older than Q2 (Hooke, 1972; Dorn, 1988; Jayko and Menges, 2001; Klinger, 2001b). We recommend that this alluvial-fan unit along with morphologically similar deposits (described below) be identified as Q1.

Our recommended Q1 is found near the mouth of Hanaupah Canyon along the eastern Panamint piedmont (Hooke, 1972). Here, Hooke (1972) described an alluvial-fan unit (older surface facies) that is older than Q2 and, unlike the Funeral Formation, has alluvial-fan morphology. Dorn (1988) labeled this unit Q1. Jayko and Menges (2001) used remote sensing and surface morphology to map this unit (their QTa) and its equivalents along the eastern piedmont of the Panamint Mountains, thereby showing the regional extent of the unit. As a result, we recommend that this upper alluvial-fan deposit along the eastern Panamint piedmont be Q1.

Menges et al. (2001) described the surface morphology of Q1 as highly degraded, having none to weak or no desert pavement development and weakly

Table 1
Compilation of age control and geochronologic methods used on alluvial-fan deposits of Death Valley

Alluvial-fan unit/location	Age	Method	Reference
Q1			
Hanaupah Fan	≥0.3 Ma	Cosmogenic radionuclides	Nishiizumi et al. (1993)
Kit Fox Hills	≤0.62 Ma	Tephrochronology	Klinger (2001b)
Six Springs Canyon	≤3.1–3.35 Ma	Tephrochronology	Knott et al. (2000)
Q2			
Northern Death Valley	30–180 ka	Soil development	Klinger (2001b)
Hanaupah Fan	260–318 ka	Cosmogenic radionuclides	Nishiizumi et al. (1993)
Mormon Point	<120–180 ka	Stratigraphic relations	Knott et al. (1999a,b)
Q3a			
Hanaupah Fan	117 ka	Cosmogenic radionuclides	Nishiizumi et al. (1993)
Central Death Valley	<125 ka	Archeology	Hunt and Mabey (1966)
Northern Death Valley	<12 ka	Soil development	Klinger (2001a)
Q4a			
Northern Death Valley	<1.2 ka	Tephrochronology	Klinger (2001a)
Q4b			
Northern Death Valley	0.14–0.30 ka	^{14}C	Klinger (2001a)

preserved varnish with chips of pedogenic carbonate commonly found on the surface. Soils developed on the Q1 have Stage III–V petrocalcic horizons (See Machette, 1985 for nomenclature) and are commonly dissected (Menges et al., 2001).

Numeric age control on the Q1 unit is sparse (Table 1). Nishiizumi et al. (1993) determined a minimum age surface exposure age of ~0.3 Ma for clasts on the Q1c surface using cosmogenic ^{10}Be and ^{26}Al. In the Kit Fox Hills, Klinger (2001b) mapped Q1 deposits unconformably overlying the 0.62 Ma Lava Creek B ash bed (Fig. 11). This relation shows that the maximum age for Q1 in the Kit Fox Hills is 0.62 Ma or younger than the Mormon Point Formation.

At Six Springs Canyon, Knott et al. (2000) found a Mesquite Springs tuff (3.1–3.35 Ma) in a terrace deposits at Six Springs Canyon along the eastern Panamint Mountains piedmont. The upper surfaces of the terraces, which have Stage IV–V petrocalcic horizons, are the upstream extension of the Q1 surface on the piedmont. Based on the soil development and tephrochronology, Knott et al. (2000) inferred a Pliocene age for the Q1 deposits at Six Spring Canyon and along the eastern Panamint piedmont. Thus, the Q1 at Six Springs Canyon is equivalent to the Furnace Creek Formation at Furnace Creek, the upper part of the Nova Formation and the lower part of the Funeral Formation at Artists Drive.

The broad range in ages (>0.3 to <3.35 Ma) for Q1 (Table 1) and sparse data illustrates the challenge that obtaining reliable numeric ages has been so far. The age range may also show the time-transgressive character of this morphological unit. These ages and the correlation of Q1 to other formations and units in Death Valley should be considered tentative and clearly shows that additional research is warranted.

2.8.2. Q2

The Q2 alluvial fans are some of the most distinctive geomorphic landforms in Death Valley. This extensive fan unit has a well developed desert pavement (Fig. 12) and is comprised of darkly varnished (2.5YR4/8), tightly packed clasts (Hunt and Mabey, 1966). Soils on Q2c deposits (youngest of three subunits) in northern Death Valley show Avkz/Btkz/2Bkz horizon profiles. The carbonate dominated profiles demonstrates significant pedogenesis mainly from the addition and redistribution of airborne materials such as silt, calcium carbonate and salt (Klinger, 2001b).

Based on soil development and relative stratigraphic position, Klinger (2001b) estimated that Q2 has an age range between 35–180 ka (Table 1). The maximum age is assumed because the Q2 deposits appear to be overlain by the Lake Manly deposits that are dated at 120–180 ka by Ku et al. (1998). Along the

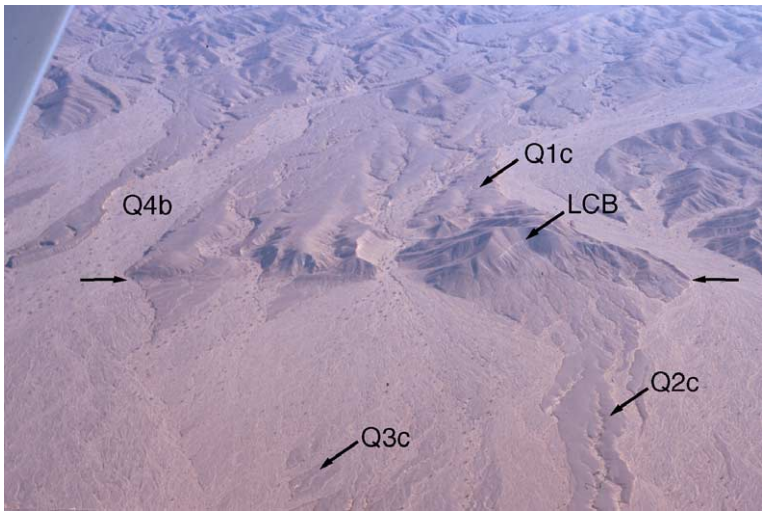


Fig. 11. Oblique aerial photograph of southern Kit Fox Hills showing relations between 0.62 Ma Lava Creek B ash bed (LCB) and younger alluvial fan units. See text for unit definitions and ages. Horizontal arrows show location of Northern Death Valley fault zone (after Klinger, 2001b).

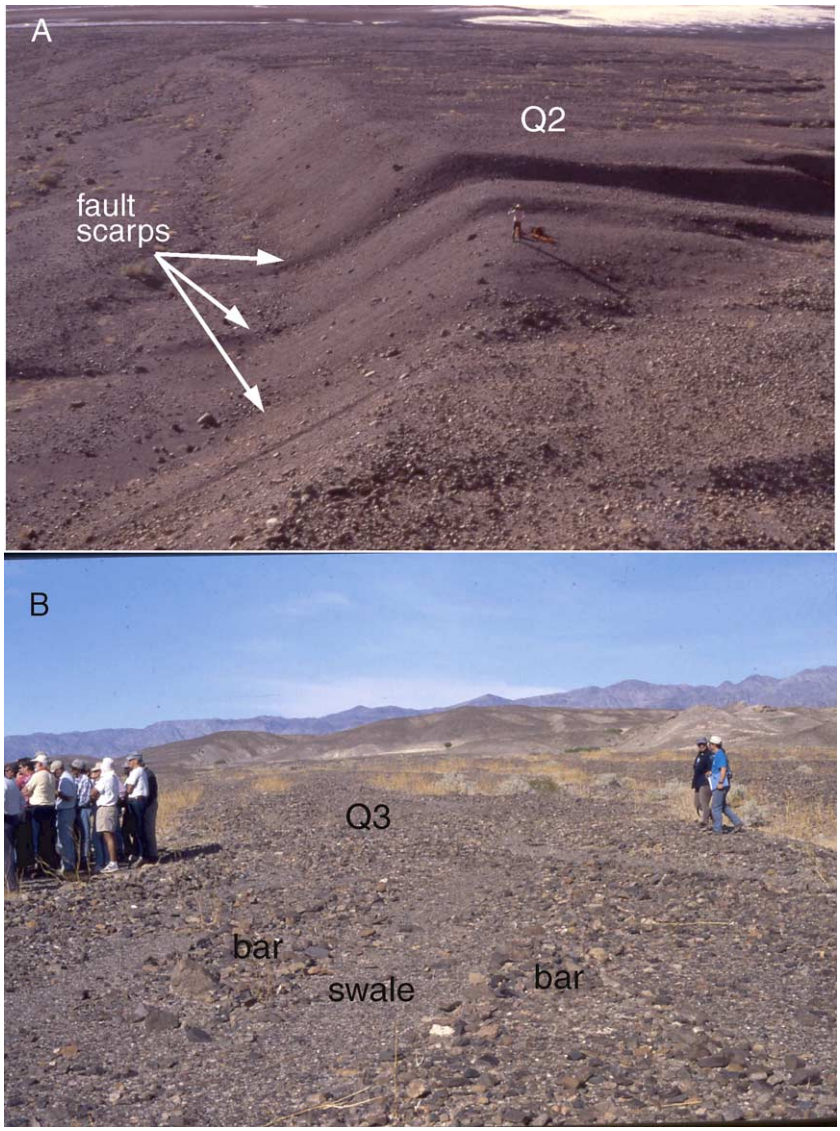


Fig. 12. Typical alluvial fan morphology for units Q2 (A) and Q3 (B). The Q2 surface has a characteristic level, well-developed desert pavement. Traces of the oblique normal Black Mountains fault zone offset the surface. Q3 shows the characteristic remnant bar-and-swale morphology.

eastern Panamint piedmont, Nishiizumi et al. (1993) measured minimum surface exposure ages of 260 ± 9 and 318 ± 12 ka (^{10}Be and ^{26}Al) for clasts on Q2 surfaces; however, the clasts on which these exposure ages were analyzed may have had a complex prior exposure history (i.e., inherited cosmogenic radionuclides), potentially leading to a greater exposure age for the clast than the age of the surface.

2.8.3. Q3

Alluvial fan unit Q3 is also found throughout Death Valley, albeit less extensively than Q2 (Hunt and Mabey, 1966). Q3 typically displays various forms of bar and swale morphology. Surface clasts are only partially coated with a light colored (2.5YR4/8 to 5YR6/6) desert varnish (Fig. 12). Soils have Avk/Bkz/2C horizons with a profile ran-

ging from 20 cm (Q3c) to 72 cm (Q3a) thick (Klinger, 2001b).

Based on archeological evidence from the western Black Mountains piedmont, Hunt and Mabey (1966) estimated that the age of unit Q3 is latest Pleistocene to Holocene. Based on soil development and morphology, Klinger (2001b) suggested an age of 2–12 ka for Q3. Nishiizumi et al. (1993) determined a minimum exposure age of 117 ± 4 ka for clasts on the Q3a surface along the eastern Panamint piedmont. The surface exposure age, however, may be too old due to inherited cosmogenic radionuclides (Nishiizumi et al., 1993). This explanation seems plausible because unpublished mapping by Machette and Janet Slate (USGS) suggest that the sampled surface is underlain by Q2.

2.8.4. Q4

Q4 deposits are found in both the active stream-channels and flood plain. The Q4 deposits have surfaces that have prominent bar-and-swale topography. Thin (4 cm), poorly developed soils with Av/2C horizons are developed on these deposits (Klinger, 2001b). Based on the soil development, Klinger (2001b) suggested that Q4 was several hundred years old or less.

Age control on Q4 is sparse as well. In northern Death Valley, Klinger (2001a) correlated an ash bed within the Q4a (older) unit with a <1200-yr-old Mono Craters ash. In the overlying Q4b alluvium, Klinger (2001a) obtained a ^{14}C age of 140–300 cal. yr. B.P. from a fragment of charcoal. The charcoal fragment underlies the Ubehebe Craters tephra bed, which also provides a maximum age for the most recent eruption of Ubehebe Crater.

3. Tectonic implications

The Late Neogene tectonics of Death Valley is a topic of great interest, particularly since 1966. In that year, Burchfiel and Stewart (1966) proposed the term "pull-apart" basin for Death Valley. They envisioned the Furnace Creek, Northern Death Valley, Black Mountains, and Southern Death Valley fault zones as the main structural components (see Machette et al., 2001b for discussion). In addition, Hill and Troxel (1966) suggested that the regional extensional stress field had a NW–SE orientation. In this same year, Hunt and Mabey (1966) published their seminal geophysical and geologic study, which provided a more detailed map of the Late Neogene faults and described Quaternary fault scarps as well.

Interest in the Late Neogene tectonics of Death Valley was reinvigorated by the Eastern California shear zone hypothesis (Dokka and Travis, 1990). The Eastern California shear zone appears to transfer ~25% of the San Andreas right-lateral plate boundary motion to strike slip fault systems in the southwestern Basin and Range. The Death Valley fault system is thought to be the easternmost fault system of the Eastern California shear zone.

The tephrostratigraphy and alluvial-fan stratigraphy provide age control for the deformation and translocation of basinal deposits uplifted throughout Death Valley. They also provide age control for Pleistocene and younger faulting events. In the following sections, we describe some of the more recent hypotheses and interpretations of Late Neogene tectonics that have taken advantage of the numeric stratigraphy.

3.1. Death Valley fault system

Machette et al. (2001b) propose a revision to the nomenclature for the Death Valley fault system based on Quaternary structural/stratigraphic studies during the last decade. They propose that the Fish Lake Valley, Northern Death Valley, Black Mountains and Southern Death Valley fault zones be collectively referred to as the Death Valley fault system (Fig. 13). This also suggests limiting the use of the term Furnace Creek fault zone to the largely pre-Quaternary fault southeast of Furnace Creek. Further, they recommend returning to the original name, Black Mountains fault zone. Black Mountains fault zone was originally proposed by Noble and Wright (1954) for the oblique–normal fault along the western piedmont of the Black Mountains.

The north–south to northeast–southwest trending, dextral slip fault zone that bounds the northeast margin of northern Death Valley has had several names including Northern Death Valley fault zone (Wesnousky, 1986); Furnace Creek fault zone (Hill and Troxel, 1966; Hunt and Mabey, 1966; Wright and Troxel, 1993); and Death Valley–Furnace Creek fault zone (Burchfiel and Stewart, 1966; Wright and Troxel,

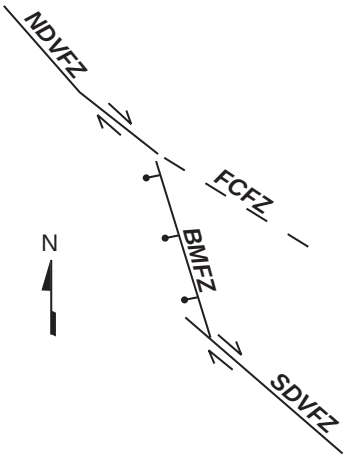


Fig. 13. Schematic diagram showing proposed nomenclature for the Death Valley fault system. Northern Death Valley fault zone (NDVFZ); Furnace Creek fault zone (FCFZ); Black Mountains fault zone (BMFZ); and Southern Death Valley fault zone (SDVFZ); after Machette et al. (2001b).

1967). The different names for the same fault zone have been confusing. In an attempt to clarify this issue, Machette et al. (2001b) divided this fault zone into pre-Quaternary and Quaternary sections. The dividing line is roughly at Furnace Creek where the Black Mountains fault zone abuts this strike-slip fault from the south (Machette et al., 2001b).

Machette et al. (2001b) advocate the name Furnace Creek fault zone for the major fault zone southeast of Furnace Creek Ranch. The Furnace Creek fault zone was an important structural element in the development of Death Valley and the Furnace Creek basin during the Late Miocene and Pliocene. The Furnace Creek fault zone, however, has been largely inactive during the Quaternary (Burchfiel and Stewart, 1966; Hamilton, 1988; Klinger and Piety, 1996).

Northwest of Furnace Creek, Machette et al. (2001b) proposed the name Northern Death Valley fault zone for the dextral oblique fault zone that exhibits Late Pleistocene–Holocene slip. The Northern Death Valley fault zone merges with the Fish Lake Valley fault zone, which is essentially a northward extension of the Death Valley fault system into Nevada.

Machette et al. (2001b) recommended using Furnace Creek–Northern Death Valley fault zone when discussing pre-Pliocene tectonics of the region. These two fault zones appear to have formed the tectonically-active northeast margin of Death Valley during that time.

Machette et al. (2001b) also propose that the oblique–normal fault zone found at the western foot of the Black Mountains be called the Black Mountains fault zone. This returns to the name originally proposed on the map of Noble and Wright (1954). Likewise, Machette et al. (2001b) proposed that the names Death Valley fault zone (now system) and Central Death Valley fault zone (now Black Mountains) be discontinued with respect to this fault.

Although this change is nomenclature seems cumbersome and unnecessary, we think that this change will provide clarity and consistency for future studies. The recommended fault zone definitions are especially important in terms of defining seismic hazards associated with these fault zones and the overall fault system. In the case of the Northern Death Valley and Furnace Creek fault zones, the nomenclature proposed by Machette et al. (2001b) provides a useful discrimination between the pre-Pliocene and Quaternary faults, potential fault hazards and regional tectonics.

3.2. Breakup of the Furnace Creek basin

The Miocene–Pleistocene Furnace Creek basin had a northwest–southeast trend and was located between the dextral–oblique Grandview and Furnace Creek fault zones (Wright et al., 1999). Clast provenance and paleocurrent data from the lower part of the Furnace Creek Formation indicate that a northwest- to southeast-flowing fluvial system occupied the Furnace Creek basin during the Late Miocene (Hunt and Mabey, 1966; Prave and Wright, 1996; Wright et al., 1999). In contrast, provenance and sedimentary structures in the upper part of the Furnace Creek Formation record southerly and northerly progradation of alluvial fans from the Funeral and Black Mountains, respectively, into a perennial lake/playa (Hunt and Mabey, 1966; Blair and Raynolds, 1999).

The exact timing of the end of the Furnace Creek basin as well as the extent of the basin has been problematic because of the lack of age control on the Furnace Creek Formation, Funeral Formation and deposits of the Kit Fox Hills and Ubehebe–Lake Rogers areas to the northwest. Correlation of the Mesquite Spring tuffs in each of these locations has

helped to resolve this problem. The Mesquite Spring tuffs are interbedded with perennial lake/playa deposits at Furnace Creek, in the Kit Fox Hills, and in the Ubehebe/Lake Rogers basin. Identification of the Mesquite Spring tuff and Nomlaki-like tuffs interbedded with alluvial fan deposits in the Nova Formation of the northern Panamint Mountains, Funeral Formation at Artists Drive and along the eastern Cottonwood Mountains piedmont provides broad limits on the playa dimensions. This is interpreted as evidence of either a continuous basin or multiple, contemporaneous basins along a northwest–southeast trend separated by intervening alluvial fans, much like the present Death Valley playa (Fig. 14). The basin axis appears to roughly parallel the trend of the Northern Death Valley–Furnace Creek fault zone.

Correlation of the Mesquite Spring tuff and the underlying lower Nomlaki tuff at Artists Drive (Fig. 2) shows that alluvial-fan deposition began there >3.58 Ma (Knott et al., 1999b; Knott and Sarna-Wojcicki, 2001a). Knott et al. (1999a,b) interpreted the onset of alluvial-fan deposition at Artists Drive coincided with uplift of the Black Mountains and downdropping of the Artists Drive block. They hypothesized that this uplift was related to along-strike growth of the Black Mountains fault zone from south to north. Knott (1998) also inferred that this along-strike growth of the Black Mountains fault zone uplifting the Furnace Creek basin and the northernmost part of the Black Mountains. This may have lead to the eventual deactivation of the Furnace Creek fault zone as well.

Northward growth of the Black Mountains fault zone generated a zone of compression as it impinged on the Northern Death Valley–Furnace Creek fault zone (Machette et al., 2001b). This is expressed as the NNW-trending Texas Spring syncline and Echo Canyon thrust fault on the north side of Furnace Creek and a series of en-echelon faults that transfer slip from the Furnace Creek fault zone to the Black Mountains fault zone (Klinger and Piety, 2001; Machette et al., 2001c).

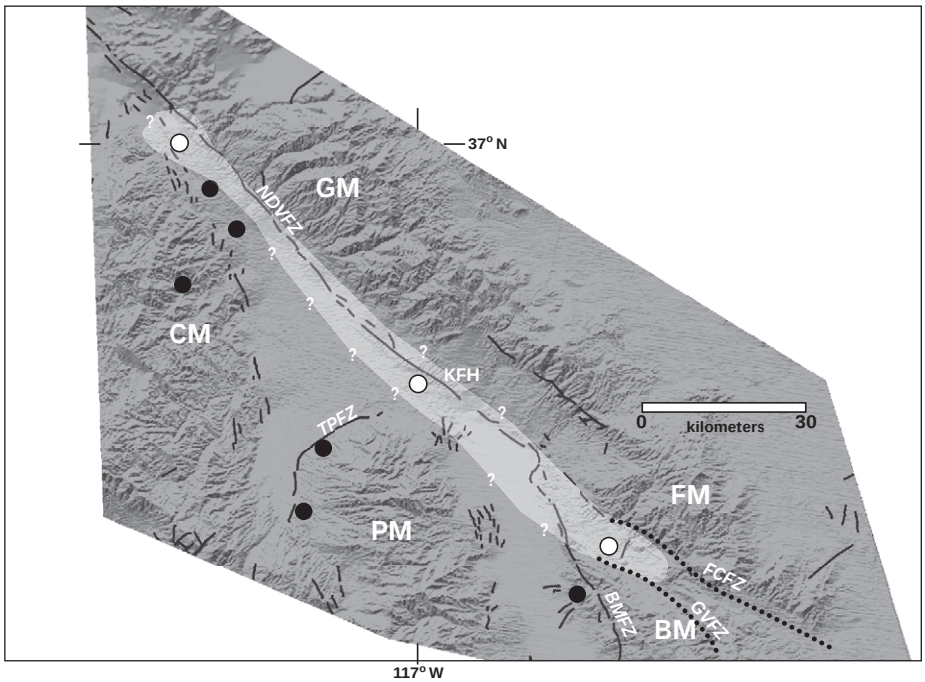


Fig. 14. Map of northern Death Valley showing the distribution of the Furnace Creek lake about 3.2 Ma along with Quaternary fault traces (black lines). White circles indicate locations where Late Pliocene tuffs are interbedded with lake sediments. Black circles indicate where Late Pliocene tuffs are interbedded with alluvial-fan deposits. The shaded area is the aerial extent of the postulated lake. See Fig. 2 for key to abbreviations to geographic elements and fault zones. Shaded relief base map derived from digital elevation model.

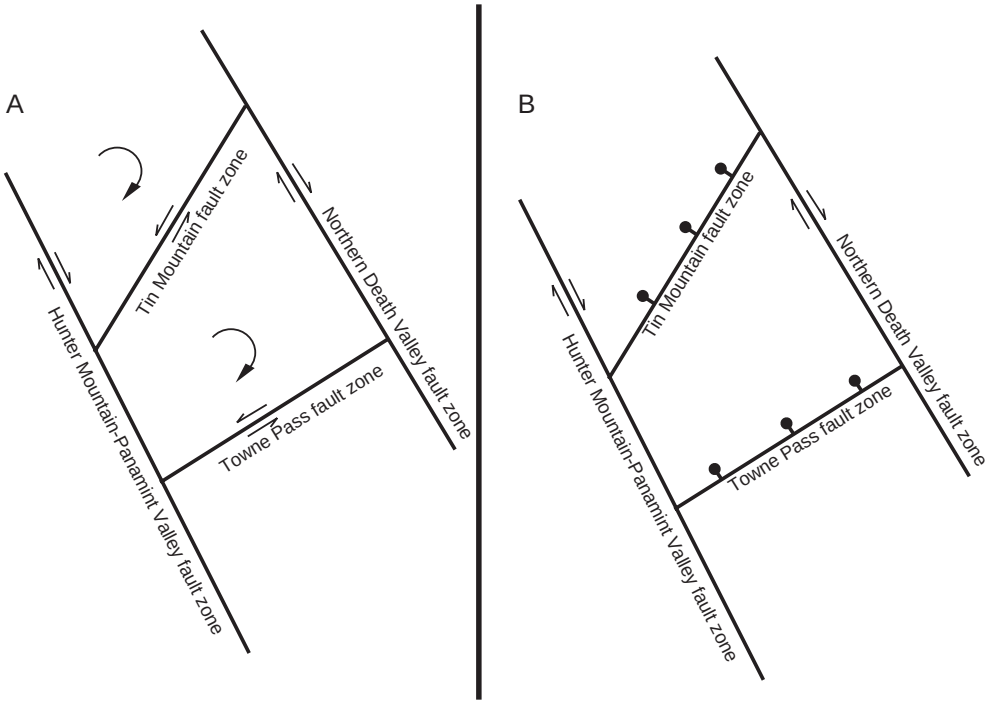


Fig. 15. Schematic diagram showing two dextral shear models proposed for the Late Neogene tectonic evolution of northern Death Valley. A. Following McKenzie and Jackson (1983, 1986), Klinger and Sarna-Wojcicki (2001) propose oblique left-lateral slip on the Towne Pass and Tin Mountain fault zones resulting in clockwise rotation of discrete blocks. (B) After Oldow et al. (1994), Lee et al. (2001) propose pure normal slip on the Towne Pass and Tin Mountain fault zones.

3.3. Tectonic development of Northern Death Valley

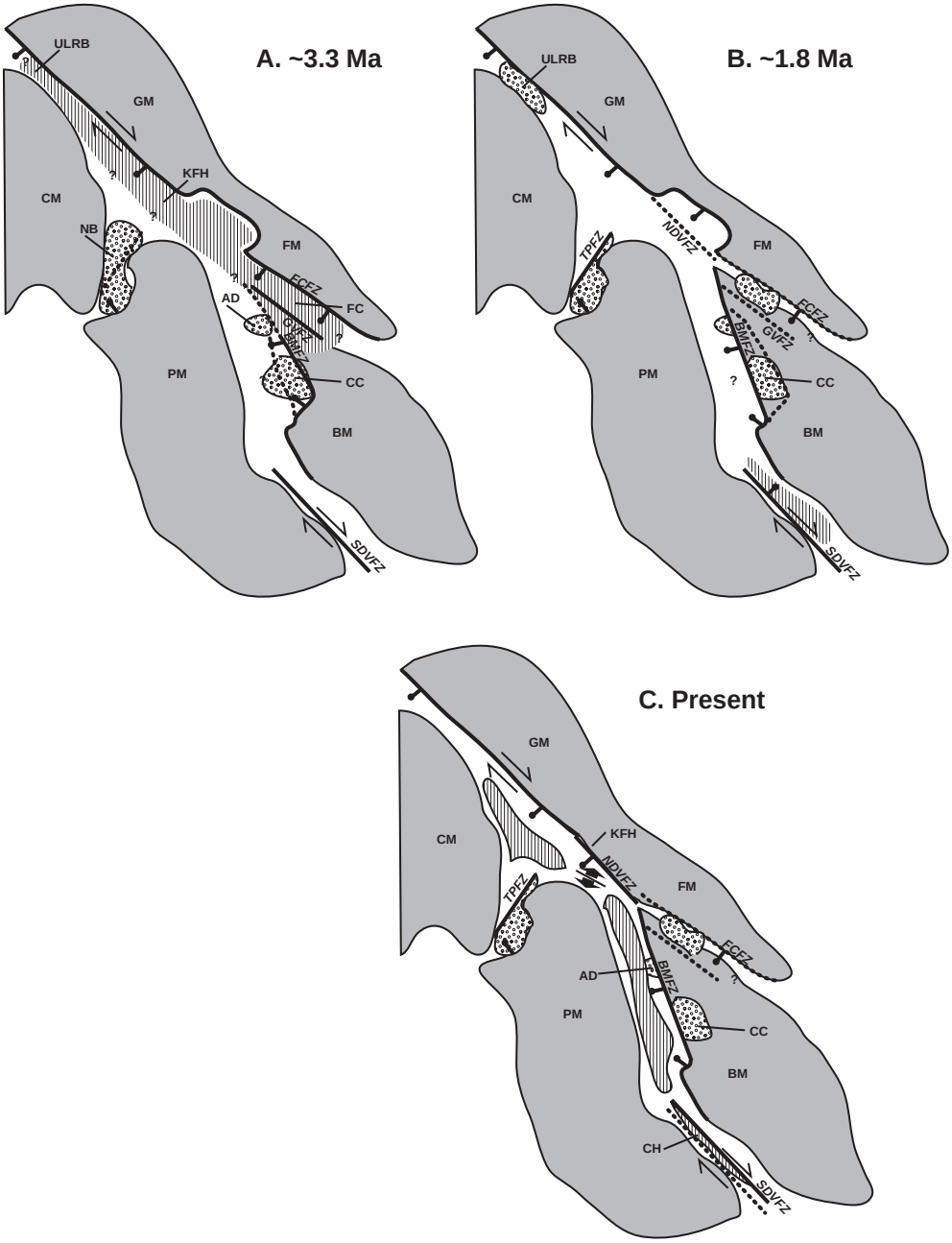
Klinger and Sarna-Wojcicki (2001) proposed that regional dextral shear in Northern Death Valley between the Northern Death Valley and Hunter Mountain–Panamint Valley fault zones is accommodated by a set of discrete rotating blocks bounded by the Towne Pass and Tin Mountain fault zones (Fig. 15). Klinger and Sarna-Wojcicki's model is similar to models proposed by McKenzie and Jackson (1983, 1986) where blocks are rotating between two strike-slip faults and are either rotating about a fixed or shifting vertical axis. The Tin Mountain and Towne Pass faults would be left-lateral accommodating faults and both show evidence of Quaternary movement.

According to Klinger and Sarna-Wojcicki (2001), the northeast corners of the rotating blocks generate compressive structures along the Northern Death Valley fault zone where the rotating block impinge on the bounding Funeral Mountains blocks. In contrast, in the southeast corners (or regions) are extensional, generating deep structural depressions, such as the

Fig. 16. Schematic map showing Death Valley during the Late Neogene. (A) ~3.3 Ma or the time of eruption of the Mesquite Spring tuffs. A lake (lined region) occupied the Furnace Creek basin from Furnace Creek (FC) to the Ubehebe–Lake Rogers (ULRB) area. Alluvial fan deposits of the Nova basin (NB), Artists Drive (AD) and Copper Canyon (CC), flank the lake. Solid thick black lines show active faults at the time. Dotted lines show the future locations of faults that are inactive 3.3 Ma. (B) ~1.8 Ma or the time of eruption of the lower Glass Mountain ash beds. Black Mountain (BMFZ) fault zone has extended along strike to the north cutting through the Furnace Creek basin and making the Grandview (GVFZ) and Furnace Creek (FCFZ) fault zones inactive. stepped basinward uplifting the Copper Canyon basin. The Towne Pass (TPFZ) fault zone has cut and is uplifting the Nova basin. Alluvial fans are depositing in both the Ubehebe and Furnace Creek basin. The playa and alluvial fan deposits of the Confidence Hills Formation (CH) are being deposited along the Southern Death Valley fault zone (SDVFZ). (C) Present. The SDVFZ has stepped to the northeast uplifting the Confidence Hills Formation. The Northern Death Valley fault zone (NDVFZ) is now active causing uplift of the Kit Fox Hills. Compression between the NDVFZ and the BMFZ creates the Salt Creek anticline and Texas Spring syncline. Playas are formed in both Northern and central Death Valley.

Mesquite Flat basin. This interpretation is supported by gravity data from Blakely et al. (1999) who estimates that the Mesquite Flat basin is ≥5 km deep.

In contrast, Lee et al. (2001) observed that movement on the accommodating faults further north in this region, such as the Deep Springs further north and Towne Pass fault zones, is predominantly dip slip with no oblique component. Based on this observation, Lee et al. (2001) proposed a model modified from Oldow et al. (1994), in which displacement on the accommodating faults is normal or dip slip with little rotation.



3.4. Spatial and temporal development of the Black Mountains fault zone

The Black Mountains faults zone (BMFZ) is the oblique–normal fault zone found at the base of the Black Mountains. Slip on the BMFZ has created a created a mountain-front morphology of triangular facets, wineglass canyons and fault scarps indicative of active faulting (Bull and McFadden, 1977). However, the fault zone is a complex mixture of faults dipping both at high-angles and low-angles (Drewes, 1963; Hunt and Mabey, 1966; Noble and Wright, 1954). In addition, a paucity of earthquakes and age control left the level of Quaternary activity in question (Knott et al., 1999b).

Knott et al. (1999a,b) established a geochronology for the Late Neogene deposits faulted by the BMFZ that resulted in two main findings. First, the low-angle normal or turtleback fault at Mormon Point offset the Quaternary Mormon Point Formation. Lake beds within the Mormon Point Formation show that the fault was at its present low-angle dip and had not tilted. High-angle faults that offset the 120–180 ka Lake Manly deposits are kinematically linked to the low-angle fault and demonstrate low-angle slip in the Late Quaternary (Hayman et al., 2003). These same temporal and fault relations are found at Natural Bridge above the Badwater turtleback fault as well (Hayman et al., 2003).

Another main finding of Knott et al. (1999a,b) is that the BMFZ is a dynamic structure. After 3.35 Ma, the BMFZ stepped basinward at Copper Canyon and grew northerly along strike northerly Natural Bridge. The along strike growth effectively broke up the Furnace Creek basin. After ~1.8 Ma, the BMFZ changed from a normal mountain front to a graben-bounded front at Artists Drive (Knott and Sarna-Wojcicki, 2001a,b). In addition, over the last ~1 Ma, the BMFZ west of Mormon Point has grown along strike to the north. This has resulted in the uplift of the Mormon Point Formation into the Black Mountains footwall.

4. Summary

Correlations of tephra beds that range in age from Late Pliocene to Holocene provide an unparalleled opportunity to reconstruct the tectonics and paleogeography of the Death Valley pull-apart basin. In particular, the 3.1–3.35 Ma Mesquite Springs group tuffs and 1.7–1.9 Ma lower Glass Mountain ash beds are keys to understanding the breakup of the Furnace Creek basin and development of the Death Valley fault system.

The 3.1–3.35 Ma time line provided by the Mesquite Springs tuffs shows that a northwest–southeast trending lake occupied northeastern Death Valley (Fig. 16). This area included what is presently the Furnace Creek, Kit Fox Hills and Lake Rogers areas (Klinger and Sarna-Wojcicki, 2001; Knott et al., 1999b; Machette et al., 2001c). The margins of this lake are broadly constrained and could have extended to the south. However, any lake extending to the south was probably limited to the valley center because the Mesquite Springs tuffs are found in alluvial fan deposits along the western Black Mountains at Artists Drive and Copper Canyon. The ~3 Ma lake did not extend into Emigrant Canyon between the Cottonwood and Panamint Mountains where alluvial-fans, which now comprise the Nova Formation were being deposited. Alluvial-fan deposits containing the 3.28 Ma Nomlaki Tuff along the eastern piedmont of the northern Cottonwood Mountains also limit the lake to the center of northern Death Valley.

The presence of a lake in Death Valley ~3 Ma is consistent with data from Searles Valley. A ~3.1 Ma tephra layer is found in the Searles Lake core during the longest lake phase identified in the 3.5 Ma long core record (Smith, 1991). Knott et al. (1997) correlated this tephra layer with the Mesquite Springs tuffs. The location of the lake along the Furnace Creek–Northern Death Valley fault zone suggests that there was a vertical slip component to slip on this fault zone that created this elongate lake.

The time line provided by the 1.7–1.9 Ma lower Glass Mountain tephra beds shows the dynamic climatic and tectonic history of Death Valley. In the Furnace Creek basin, the lake that existed ~3 Ma has given way to alluvial fans, which are prograding from both the Black and Funeral Mountains (Fig. 16). This progradation and uplift is interpreted to be coincident with a decrease in activity on the Furnace Creek fault zone and along-strike growth of the Black Mountains fault zone (Machette et al., 2001b). Alluvial fans are also being deposited in the Kit Fox

Hills and to the north in the Ubehebe–Lake Rogers areas (Klinger and Sarna-Wojcicki, 2001; Knott and Sarna-Wojcicki, 2001b). To the south in the Confidence Hills, alluvial-fan and playa sediments are being deposited (Beratan et al., 1999). The alluvial fans are interpreted to record a relatively dry climatic period, which is consistent with a dry climate at Searles Valley (Smith, 1991).

Data on younger deposits remains sparse, but continues to improve. Uplift and tilting of the Confidence Hills has occurred entirely since the end of the Pliocene. During this same time period, the Black Mountains fault zone has stepped basinward at Mormon Point and Natural Bridge and developed a graben at Artists Drive (Knott et al., 1999a,b). At the transpressive zone between the Black Mountains and Northern Death Valley fault zone, uplift of and development of the Texas Spring syncline has continued through the Quaternary (Machette et al., 2001c). In northern Death Valley, the data are consistent with either oblique left lateral slip or normal slip on cross faults within a right lateral shear zone (Klinger and Sarna-Wojcicki, 2001; Lee et al., 2001).

Acknowledgements

The authors have benefited from entertaining and fruitful discussions with many individuals through the years including Lauren Wright and Bennie Troxel, Janet Slate, Angela Jayko, Chris Menges, John Tinsley, Steve Wells and a host of others. The participants of the 2001 Friends of the Pleistocene field trip stimulated and challenged many of our hypotheses as well. Support for work by Knott has been from NSF (EAR 94-06029) and the U.S. Geological Survey. We thank Matthew Kirby and Lewis Owen for constructive reviews of the manuscript.

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