Geology of the Greenwater Range, and the Dawn of Death Valley, California

Field Guide for the Death Valley Natural History Conference, 2013

By J.P. Calzia, O.T. Rämö, Robert Jachens, Eugene Smith, and Jeffrey Knott

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U.S. Geological Survey

Cover: Photograph looking north from Dantes View across Death Valley toward the Panamint Range, October, 2015. Photograph by Pietari Skyttä, University of Turku, Finland.

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Contents

Figures

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By J.P. Calzia,[1] O.T. Rämö,[2] Robert Jachens,[1] Eugene Smith,[3] and Jeffrey Knott[4]

Introduction

Much has been written about the age and formation of Death Valley, but that is one—if not the last—chapter in the fascinating geologic history of this area. Igneous and sedimentary rocks in the Greenwater Range, one mountain range east of Death Valley, tell an earlier story that overlaps with the formation of Death Valley proper. This early story has been told by scientists who have studied these rocks for many years and continue to do so. This field guide was prepared for the first Death Valley Natural History Conference and provides an overview of the geology of the Greenwater Range and the early history (10–0 Ma) of Death Valley.

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STOP 1. GEOLOGY OF THE SHOSHONE PLUTON, DEATH VALLEY, CALIFORNIA

By J.P. Calzia,[1] O.T. Rämö,[2] and Bennie Troxel[3]

This stop is located at lat 35°58′50.72″N., long 116°20′18.20″W., the entrance to Death Valley National Park on Highway 178 (fig. 1-1).

Introduction

The Shoshone Pluton is located at the southern end of the Greenwater Range, approximately 40 kilometers (km) east of Death Valley and 9 km north of Shoshone, California (fig. 1-1). It is one of several granitic bodies that are synchronous with Late Tertiary to Quaternary crustal extension of the Death Valley region.

Figure 1–1. Google Earth image showing stop locations.

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Geology

The Shoshone Pluton is elliptical, 3 km long by 4 km wide, and consists of fine- to medium-grained equigranular to porphyritic quartz monzonite characterized by miarolitic cavities and rapakivi textures; feldspar phenocrysts (both plagioclase and potassium feldspar or K-spar) are less than 1 centimeter (cm) in diameter. Grain size and the abundance of biotite (generally less than 5 percent) increases from east to west across the pluton. Blebs and pods of fine- to medium-grained monzodiorite with occasional phenocrysts of dark mica are common in a "chill zone" as well as volatile-rich zones along the eastern margin and within the interior of the pluton. The intrusive relation between quartz monzonite and monzodiorite is not always clear. Locally, the quartz monzonite was injected between blebs of monzodiorite; in other areas, monzodiorite intruded quartz monzonite as synplutonic dikes. The number and size of the monzodiorite blebs decreases away from the dikes. We currently believe the quartz monzonite and monzodiorite are coeval but crystallized from different magmas (fig. 1-2).

Figure 1–2. Photograph showing quartz monzonite (light-colored, coarser grained rock) and monzodiorite (dark-colored, finer grained rock) from the Shoshone Pluton. Note rapakivi feldspars (white plagioclase rims around gray K-spar cores) and ambiguous contact relation between quartz monzonite and monzodiorite.

The Shoshone Pluton intrudes the Shoshone Volcanics around the south, east, and north margins of the pluton. The contact is nearly concordant to units within the Shoshone Volcanics and dips 50°–60° E to nearly horizontal (fig. 1-3). Haefner (1972) divided the Shoshone Volcanics into multiple cycles of lithic-rich felsic tuff, vitrophyre(s) with plagioclase phenocrysts, and flows of felsic to intermediate composition; he concluded that each cycle represents a single eruptive unit.

A *B*

Figure 1–3. Photographs showing contact between Shoshone Pluton and Shoshone Volcanics. Note that intrusive contact climbs section in Shoshone Volcanics (*A*). Also note that there are no clasts from the Shoshone Pluton in the Shoshone Volcanics (*B*). Combined, these observations indicate that the Shoshone Pluton intrudes the Shoshone Volcanics.

The Greenwater Volcanics overlie the Shoshone Volcanics (visible at this stop) and the Shoshone Pluton (visible at the next stop). At this latitude, the Greenwater Volcanics consist of very fine-grained equigranular basaltic flows locally characterized by subhorizontal cooling joints and stretched vesicles that define flow foliation.

The volcanic rocks dip away from the Shoshone Pluton in all locations and define a dome. The dome probably formed during isostatic uplift of the pluton during extension of the Greenwater Range. Timing of this extension is not certain; we believe it postdates gravels along the northern crest of the pluton (visible at the next stop), and is nearly synchronous with initiation of Greenwater volcanism.

Biotite from the Shoshone Pluton yields a $^{40}Ar/^{39}Ar$ plateau age of 9.76±0.25 Ma (Holm and others, 1992); in-place isotopic analyses of zircon yield a U/Pb age of 10.0±0.07 Ma (Rämö and others, 2011). These data indicate that the Shoshone Pluton is Late Miocene, and the World’s youngest rapakivi granite! Wright and others (1991) reported age ranges for the Shoshone and Greenwater Volcanics of 8.5 to 7.5 Ma and 7 to 5 Ma, respectively. The age range of Shoshone Volcanics is based on 15 conventional K/Ar dates determined by various laboratories from 1985 to 1995. A review of the analytical data, however, indicates that all but four ages were determined on mineral separates or vitrophyres with anomalous K_2O contents. The four samples with normal K_2O yield ages that vary from 9.74±0.2 (a 1988 date not reported by Wright and others [written commun., 1988]) to 7.6±0.2 Ma. These data, combined with intrusive relations, suggest that the Shoshone Pluton is coeval with the Shoshone Volcanics, and that the pluton intrudes its volcanic cover.

The Shoshone Pluton and Shoshone Volcanics are cut by numerous east-west-striking oblique-slip faults that have as much as 0.5 km of right-lateral, down to the south displacement. Low-angle fault(s) along the west side of the pluton may represent slip surfaces of slide blocks that shed off the pluton as it domed the volcanic rocks. High-angle normal faulting has developed as much as 1.1 km of relief in the area since then.

Almashoor (1980) and Haefner and Troxel (2002) concluded that the Shoshone Pluton was emplaced at crustal depth of 2.0–3.0 km and tilted to the east. Although the pluton intrudes the Shoshone Volcanics, these volcanic rocks were never more than 1 km thick (Haefner, 1972). This gap between the level of emplacement of the pluton and the thickness of its volcanic cover warrants further investigation.

STOP 2. MORE GEOLOGY, THEN ISOTOPE GEOCHEMISTRY OF THE SHOSHONE PLUTON, DEATH VALLEY, CALIFORNIA

By J.P. Calzia,[1] O.T. Rämö,[2] and Bennie Troxel[3]

This stop is located at lat 35°59′03.52″N., long 116°20′18.20″W. at a small campsite just east of the Greenwater Valley Road (fig. 1-1).

Geology

The oldest basaltic flows in the Greenwater Volcanics overlie alluvial gravels as well as lithic-rich and lithic-poor tuffs interbedded with sandstone along the northern crest of the Shoshone Pluton. The gravels include abundant clasts of quartz monzonite from the pluton; the basaltic flows are subhorizontal. The abundance of granitic clasts in the gravel suggests that the Shoshone Pluton was exhumed and eroded before Greenwater volcanism.

Note that scree slopes of basalt on the Shoshone Pluton give the illusion of chocolate sauce over vanilla ice cream. This illusion was immortalized by Gary Novak in 1967 when he informally named the Shoshone Pluton Chocolate Sundae Mountain; Calzia and others (this report) refer to the basalt as Chocolate Sauce.

Isotope Geochemistry

We analyzed 26 samples of magmatic rocks from the Greenwater Range for strontium (Sr) and neodymium (Nd) isotopes. These samples were collected (oldest to youngest) from a vitrophyre in Resting Springs pass, Sheephead Andesite, Shoshone Volcanics (andesite and four vitrophyres), quartz monzonite and monzodiorites intermingled with granitic rocks from the Shoshone Pluton, Deadmans Pass granite, Miller Spring granite, Greenwater basalts, and the Chocolate Sauce basalt. We also analyzed basalt from a cinder cone offset by recent faulting in Death Valley.

Initial $^{87}Sr/^{86}Sr$ ratios ($^{87}Sr/^{86}Sr_i$) are plotted versus ε_{Nd} in figure 2-1. It is immediately obvious that $^{87}Sr/^{86}Sr_i$ ratios and ε_{Nd} values vary considerably, ranging from isotopically juvenile monzodiorite ($^{87}Sr/^{86}Sr_i$ ~0.7075, ε_{Nd} ~ -2) to that of the Resting Springs vitrophyre with a relatively older source signature ($^{87}Sr/^{86}Sr_i$ ~0.7095, ε_{Nd} ~ -9). A closer look permits the following comparisons that independently shed light on the origin of these rocks as well as magmatic processes responsible for their formation:

- Quartz monzonite from the Shoshone Pluton and two other Miocene granite suites in the Basin and Range Province (the 12.4 Ma Granite of Kingston Peak, about 70 km southeast of the Shoshone Pluton, and the 20 Ma Spirit Mountain granite in the Newberry Mountains of southernmost Nevada [Calzia and others, 2008]) plot in different segments of the isotope diagram (fig. 2-1*A*) and were probably derived from distinct sources.

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- Monzodiorites in the Shoshone Pluton and vitrophyres in the Shoshone Volcanics are more juvenile than the quartz monzonites (fig. 2-1*B* and 2-1*C*) and thus originated from different magmas. The monzodiorites are isotopically similar to the vitrophyres (fig. 2-1*D*) and may have a common parent magma.
- The Shoshone, Deadmans Pass, and Miller Springs plutons have slightly different initial isotope compositions (fig.2-1*E*) and thus may be derived from different magmas and source rocks.
- Basalts from the Greenwater Volcanics, Chocolate Sauce, and split cinder cone are less juvenile than the Shoshone Pluton and Shoshone Volcanics (fig. 2-1*F*). This surprising result suggests that the basaltic magmas may have tapped a relatively ancient domain in the lithospheric mantle beneath the Death Valley region.

Conclusions

The Shoshone pluton consists of fine- to coarse-grained quartz monzonite, characterized by miarolitic cavities and rapakivi textures, with blebs and pods of fine- to medium-grained monzodiorite; field relations suggest that the quartz monzonite and monzodiorite are synplutonic. The pluton intrudes the Shoshone Volcanics, is overlain by the Greenwater Volcanics, and forms a dome defined by the outward dip of the volcanic rocks around the pluton. The dome probably formed during isostatic uplift of the pluton during extension of the Greenwater Range.

Sr and Nd isotopic data suggest that quartz monzonite in the Shoshone Pluton is derived from a less juvenile source than the synplutonic monzodiorite; the monzodiorite, however, is isotopically similar to the Shoshone Volcanics. K-Ar ages from the Shoshone Pluton and Shoshone Volcanics indicate that these rocks are the same age. Combined, the isotopic and K-Ar data suggest that the Shoshone Pluton and Shoshone Volcanics are cogenetic, and that the pluton intruded its volcanic cover. More work is required to test and confirm these conclusions.

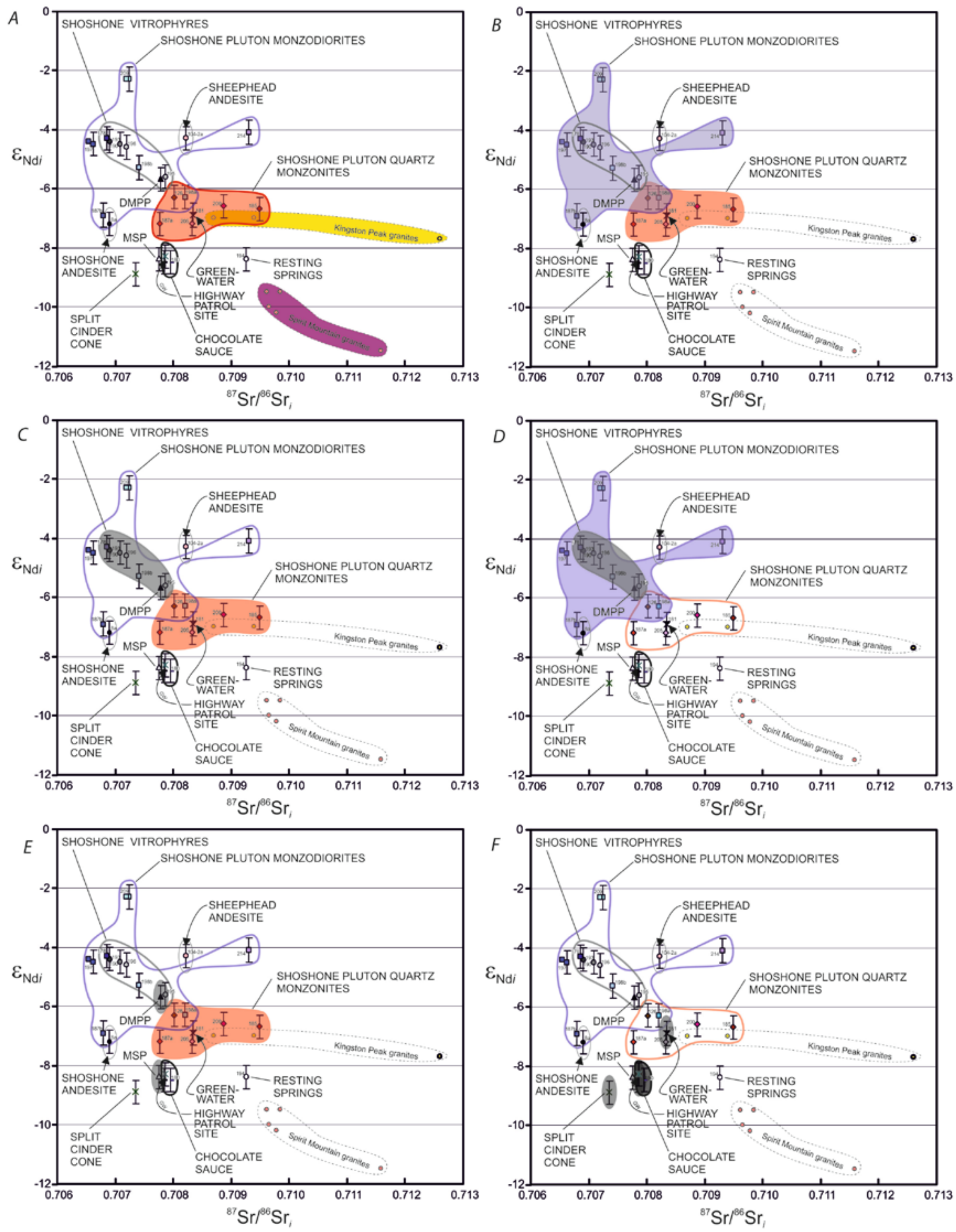


Figure 2–1. Graphs showing $^{87}Sr/^{86}Sri$ ratios versus εNd*i* for samples analyzed from Greenwater Range and vicinity. *A*, Granitic rocks from Shoshone, Kingston Peak, and Sprit Mountain plutons (data for latter two from Calzia and Rämö [2005] and Haapala and others [2005], respectively); *B*, Monzodiorites and granites of Shoshone Pluton; *C*, Shoshone Volcanics and Shoshone Pluton granites; *D*, Shoshone Volcanics and Shoshone Pluton monzodiorites; *E*, Shoshone, Deadmans Pass (DMPP) and Miller Springs (MSP) granites; and *F*, Basalt lava samples. Vertical error bar denotes external precision in εNd*i* values; precision on $^{87}Sr/^{86}Sri$ ratios matches symbol size.

STOP 3. GRAVITY FIELD OF GREENWATER VALLEY, GREENWATER RANGE, AND SURROUNDING RANGES, DEATH VALLEY, CALIFORNIA—IMPLICATIONS FOR SUBSURFACE DISTRIBUTION OF NEOGENE VOLCANIC AND PLUTONIC ROCKS

By Robert C. Jachens[1]

This stop is at the intersection of the Greenwater Valley and Deadman Pass Roads at lat 36°03′01.7″N., long 116°30′01.4″W. (fig. 1-1).

Introduction

The Greenwater Valley and adjacent Greenwater Range (here called informally the Greenwater province) and surrounding ranges east of Death Valley are characterized by a prominent gravity low surrounded by linear gravity highs (Roberts and others, 1990; Blakely and others, 1999). Gravity relief of more than 36 milligals (mGal) exists between extremes over the Greenwater province and its surrounding ranges. In detail, the gravity low consists of a northwest-trending trough punctuated by two localized lows (see gravity areas A and B, fig. 3-1). These two lows combine to form a central gravity low roughly 20 by 30 km in dimension. Two other gravity lows (gravity areas C and D, fig. 3-1) exist outside the high-low-high gravity triplet, to the southwest and northeast, respectively. These lows reflect the Death Valley basins (gravity area C, fig. 3-1) and basins of the Basin and Range Province (gravity area D, fig. 3-1), the latter likely associated with the Southern Nevada Volcanic Field.

Rocks exposed in the ranges northeast of the Greenwater province consist predominantly of Paleozoic carbonate rocks that have densities greater than those of typical crustal rocks. In the range southwest of the province, Precambrian rocks dominate although there is also a large outcrop of Miocene mafic intrusive rock, the Willow Springs diorite. The Precambrian rocks and Willow Springs diorite also tend to be denser than average crustal rocks. In contrast, the Greenwater province is dominated by outcrops of Cenozoic volcanic rock, mantled by alluvium. Tertiary granitic rocks, locally exposed throughout the province, have densities typically lower than those of most crustal rocks; the Cenozoic volcanic rocks even lower yet, and the alluvium tends to be the least dense of all.

[1]U.S. Geological Survey

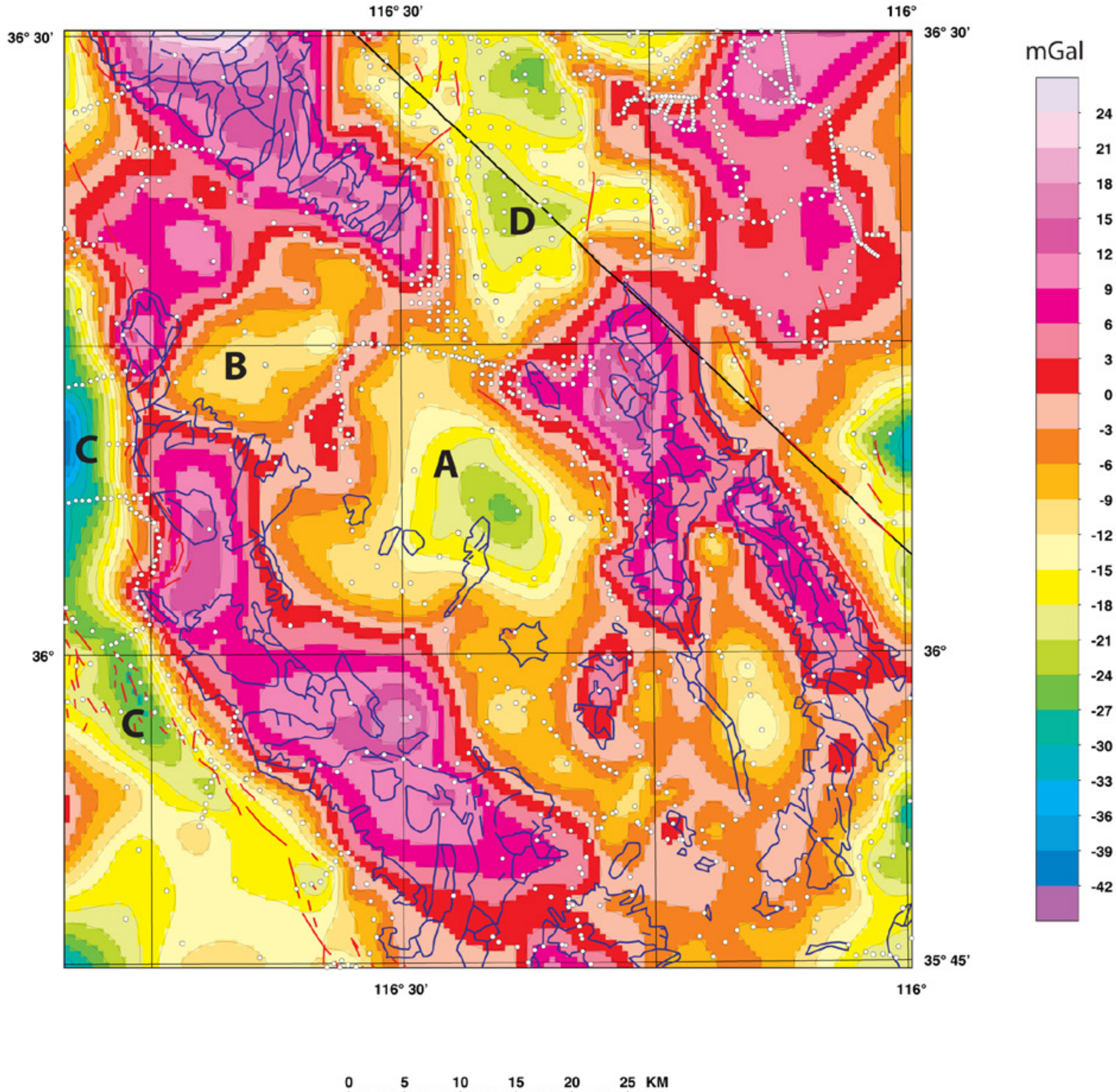


Figure 3–1. Map showing isostatic residual gravity field of Greenwater province and surrounding areas. Warm colors indicate gravity highs, cool colors indicate gravity lows. Color contour interval 3 milligals (mGal). White dots indicate locations of gravity observations. Blue lines enclose areas of mapped basement rocks—Precambrian rocks, Paleozoic rocks, and Tertiary plutonic rocks. Letters A, B, C, and D designate gravity areas discussed in report text.

Purpose and Method

The purpose of this gravity investigation is to answer two questions: (1) how thick are the Cenozoic volcanic rocks (and alluvium) and what is their three-dimensional distribution? (2) do scattered outcrops of Tertiary granitic rock reflect larger, concealed pluton(s) at depth, and if so, what is the likely shape? The method used to address these questions is one initially developed to define the three-dimensional shape of sedimentary basins (Jachens and Moring, 1990), but works equally well for any three-dimensional body that is convex, exhibits a density contrast with its surroundings, and has an upper surface that is exposed or definable by other information. The essential elements of the method are illustrated in figure 3-2, a sedimentary basin example. The total gravity field of this problem can be partitioned into a component produced by the body of interest (see basin gravity, fig. 3-2) and a component produced by its surrounding material (see basement gravity, fig. 3-2). Once the field has been partitioned, which is done iteratively while constrained by the surface geology and the gravity station distribution, the basin gravity is inverted directly to define a body in three dimensions, based on the density contrast between the body and its surrounding rock. A more detailed explanation of this method can be found in Jachens and Moring (1990).

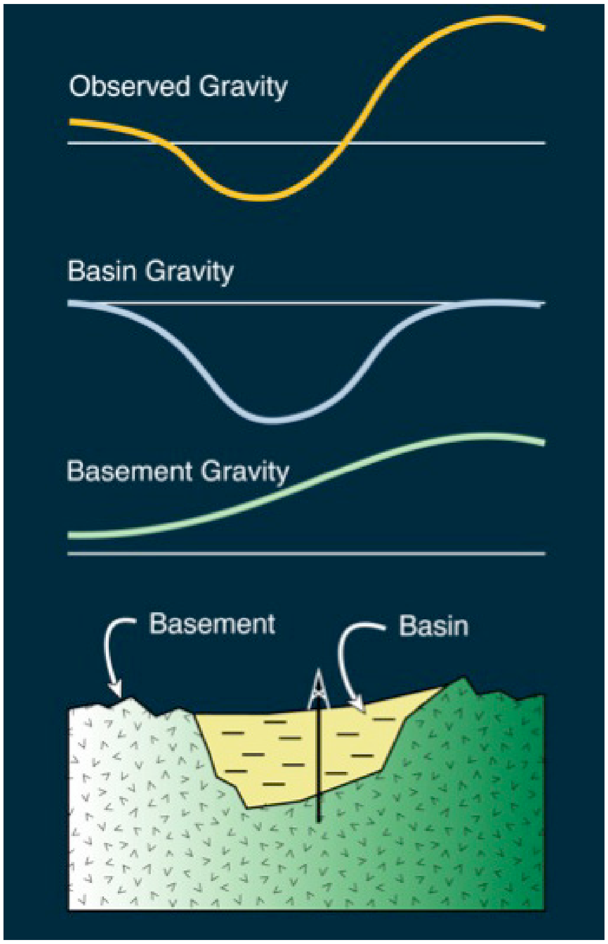


Figure 3–2. Schematic diagram illustrating method used to interpret gravity data. Method is discussed in text, and a more detailed explanation of method can be found in Jachens and Moring (1990).

Defining the distribution of the Cenozoic volcanic rocks and alluvium in the Greenwater province is completely analogous to the sedimentary basin example shown in figure 3-2, with the basement gravity component defined by all gravity measurements made on outcrops of pre-Tertiary rock plus Tertiary plutonic rock. In order to define the shape of Tertiary granitic pluton(s), the basement gravity component was defined by all measurements made on pre-Tertiary outcrop plus those made on the Willow Springs diorite.

Interpretation

The results of applying this technique to the gravity field of the Greenwater province are shown in figures 3-3 and 3-4. Figure 3-3 is a map of the thickness of Cenozoic volcanic rocks (plus minor amounts of Tertiary sedimentary rocks and alluvium) whereas figure 3-4 shows the shape of a Tertiary granitic pluton inferred to lie beneath the province (color contours of depth to bottom).

Volcanic rocks within the Greenwater province are inferred to form a relatively uniform layer as thick as 500 meters (m) and locally reach thicknesses of roughly 750 m in the northwest. Thicker Cenozoic volcanic and sedimentary sections are inferred for areas outside the province, in the Death Valley basins to the southwest (gravity area C, fig. 3-1) and in the Basin and Range to the northeast (gravity area D, fig. 3-1). The two local, circular, very thick sections (lat 36°15′N., long 116°35′W.; lat 36°5′N., long 116°12′W.) in the Greenwater province likely result from inaccuracies or outliers in gravity measurements.

The gravity inversion for the granitic pluton suggests a primary body, roughly circular in horizontal cross section, crudely mushroom-shaped near the surface, and extending deep into the crust. A possible second shallow lobe, slightly smaller in horizontal cross section, is predicted west of the main body. This body accounts for the largest part of the gravity low over the Greenwater province.

Discussion

The gravity low over the Greenwater province may be produced by a large, deeply penetrating low-density granitic pluton with at least one possible side lobe, overlain by a modest layer of Cenozoic volcanic rocks that extend beyond the lateral limits of the subsurface pluton. A bit of caution, however, is warranted concerning the inferred shape of this pluton. Based on experience, this gravity method has trouble fitting steeply sided bodies; therefore, if total depth of the pluton exceeds its cross-sectional dimension, then the total depth should be considered with caution. A more conservative interpretation is that the granitic pluton is shaped like a 10-km-deep vertical cylinder and is circular in cross section. It does appear to be somewhat mushroom shaped near the surface and may have at least one additional lobe off to the west, based on the gravity data

An interpretation dilemma of gravity area B (fig. 3-1) results from the fact that we do not know whether volcanic rocks in area B overlie very dense basement rocks similar to those exposed in the ranges to the northeast and the southwest, or whether these volcanic rocks overlie part of the granitic pluton (moderately dense rock). If the former is the case, then the volcanic layer could be twice as thick as shown in figure 3-3. If the latter is the case, then the volcanic layer would be thinner than that shown. Additional subsurface information is needed to resolve this dilemma.

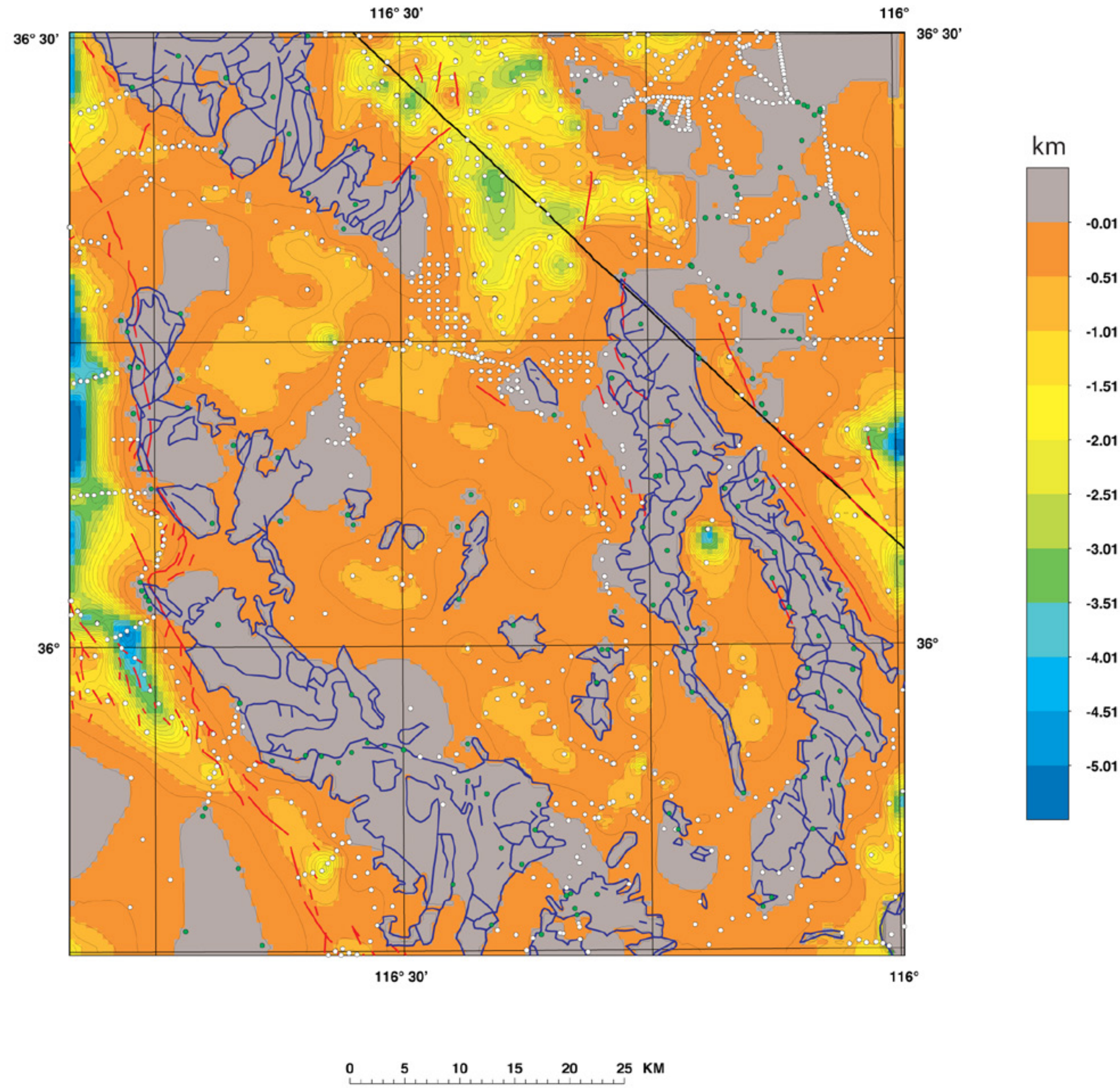


Figure 3–3. Map showing inferred depth to bottom (thickness) of Cenozoic volcanic rocks (plus minor amounts of Cenozoic sedimentary rocks and alluvium) of Greenwater province. Color contour interval 0.5 kilometer (km). Green dots indicate locations of gravity measurements made on basement rock outcrop.

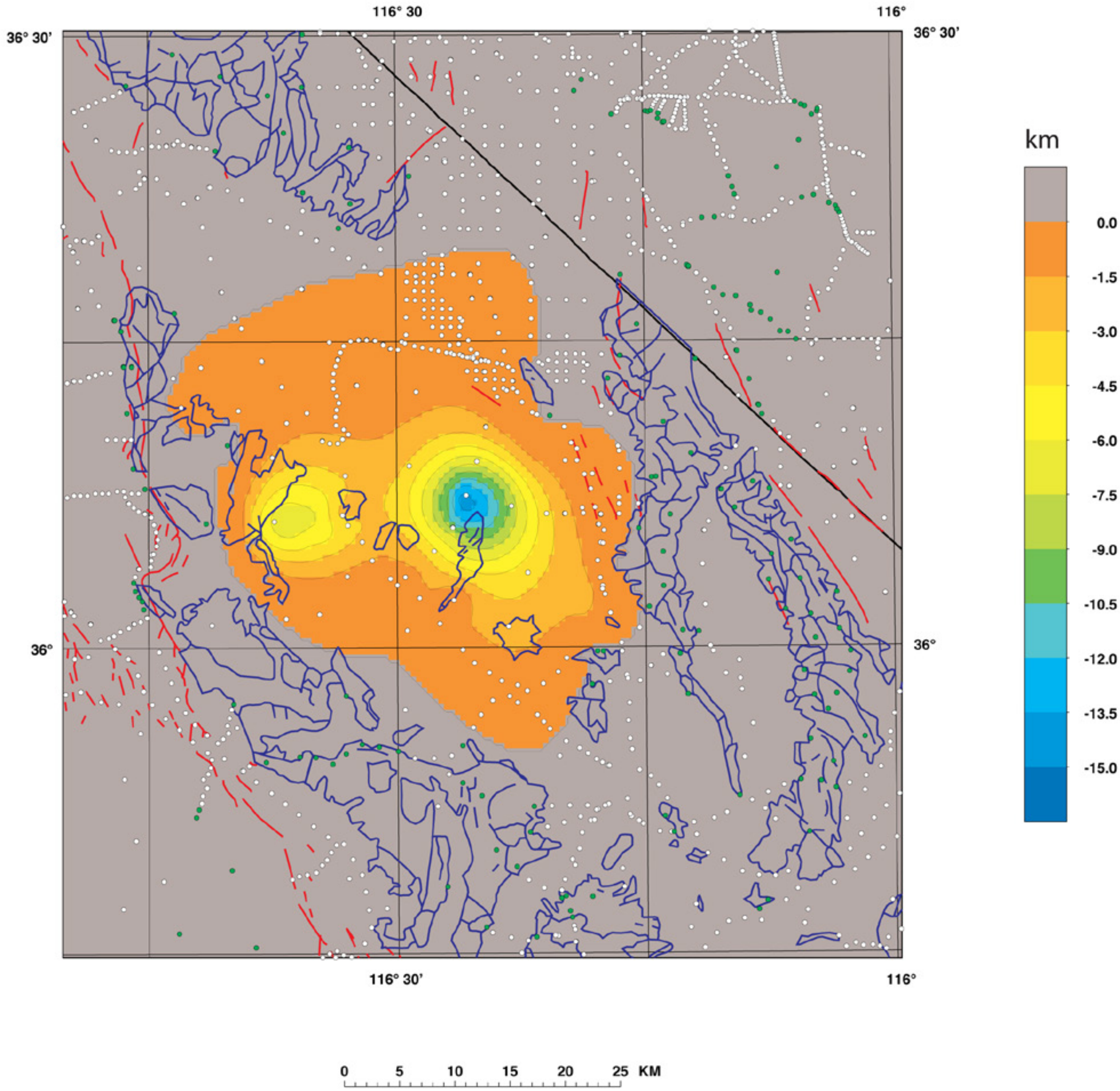


Figure 3–4. Map showing inferred depth to bottom of Tertiary granitic pluton beneath Greenwater province. Color contour interval 1.5 kilometers (km). Green dots indicate locations of gravity measurements made on basement rock outcrop, exclusive of those measured on outcrops of Tertiary granitic rock.

STOP 4. PLIOCENE CRATER OR CALDERA IN THE GREENWATER RANGE

By Eugene Smith[1] and Hugo Belmontes[1]

This stop is along the Greenwater Valley Road at lat 36°15′14.4″N., long 116°39′06.3″W. (fig. 1-1). This location is near the center of a 9-km-diameter crater or caldera; the source of the Greenwater rhyolite.

Greenwater rhyolite domes and flows filling the caldera are just to the east of this stop. Domes intrude volcaniclastic sedimentary rocks, pyroclastic surge, carapace breccia, and debris-flow deposits. The ridge on the skyline to the east is formed by numerous lens-shaped (in cross section) rhyolite flows; each with a vitrophyric base and top. Flows are interbedded with volcaniclastic sediments, pyroclastic flows, and surge deposits.

Introduction

Bimodal volcanism characterized by the eruption of rhyolite (or dacite) and basalt without the presence of intermediate rock types was common during the late Miocene to Pliocene epochs in western North America but has not been previously described in the Death Valley area. One of these bimodal fields is in the Greenwater Range located on the eastern margin of Death Valley National Park. Although our work in the Greenwater Range originally focused on Pliocene basalts of the Funeral Formation, the recognition of similar-aged and significantly larger volumes of rhyolite in the Greenwater Range changed our perception of the area from a field of monogenetic basaltic volcanoes to a more complex volcanic field that warranted more detailed study.

This stop provides the opportunity to discuss the volcanic geology of the Greenwater Range and to view from a distance rhyolite related to a 9-km-diameter crater or caldera as well as basalt that formed a monogenetic volcanic field around the crater or caldera.

Geologic Setting of the Greenwater Range

The Greenwater Range lies between two segments of the Death Valley Fault system, the Furnace Creek and Greenwater Valley Faults (Knott and others, 2005), which formed during the later stages of a regional extensional episode that began in the Death Valley area 16 million years ago (fig. 4-1). The greatest extension rate was 20–30 millimeters per year (mm/yr) between 16 and 5 Ma and slowed to 10 mm/yr from 5 Ma to the present (Daley and DePaolo, 1992; Serpa and Pavlis, 1996; DePaolo and Daley, 2000). Earlier extension was accommodated mainly by low-angle normal faults (detachment faulting) and more recent extension by strike-slip faults perhaps related to the Eastern California Shear Zone (Frankel and others, 2008). The lithosphere beneath the Greenwater Range is 45 to 50 km thick (Jones, 1987; Zandt and others, 1995; DePaolo and Daley, 2000). According to DePaolo and Daley (2000), the lithosphere-asthenosphere boundary rose during the extensional episode as the lithosphere thinned from approximately 100 km to 45–50 km and the asthenospheric mantle rose to fill the resultant space.

[1]University of Nevada Las Vegas

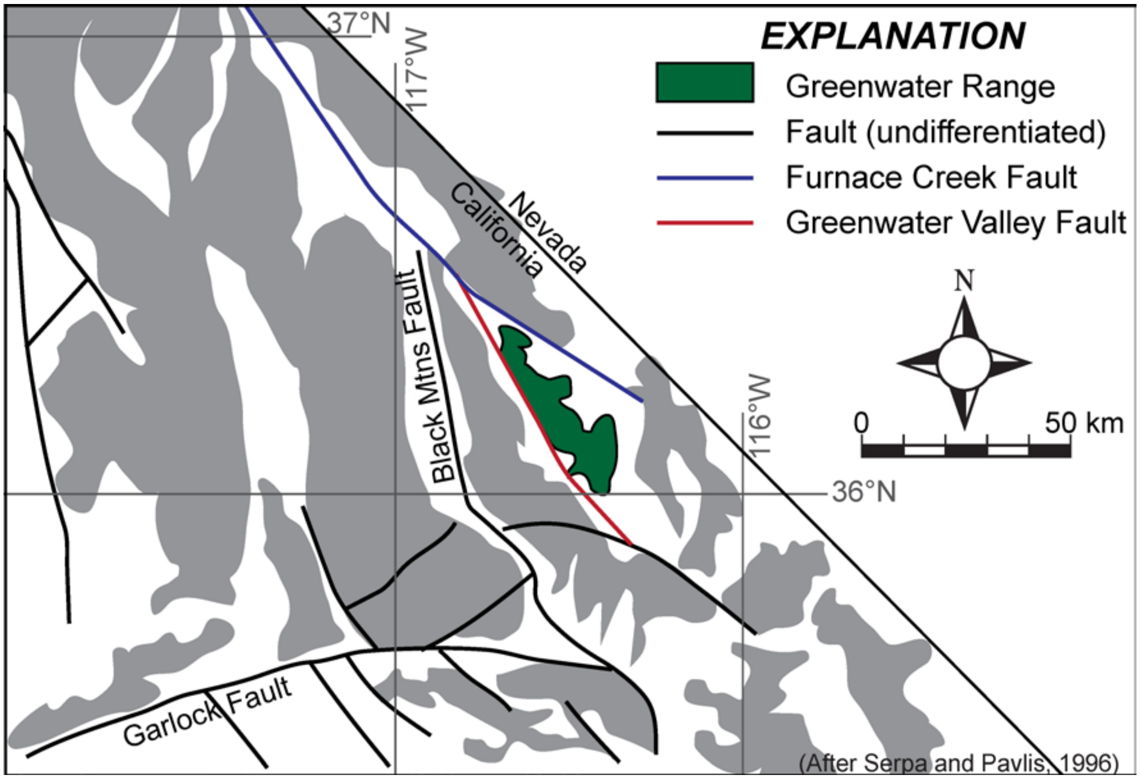


Figure 4–1. Map showing location of Greenwater Range with respect to Greenwater Valley and Furnace Creek Faults (modified from Serpa and Pavlis, 1996). These faults are components of the Death Valley Fault system.

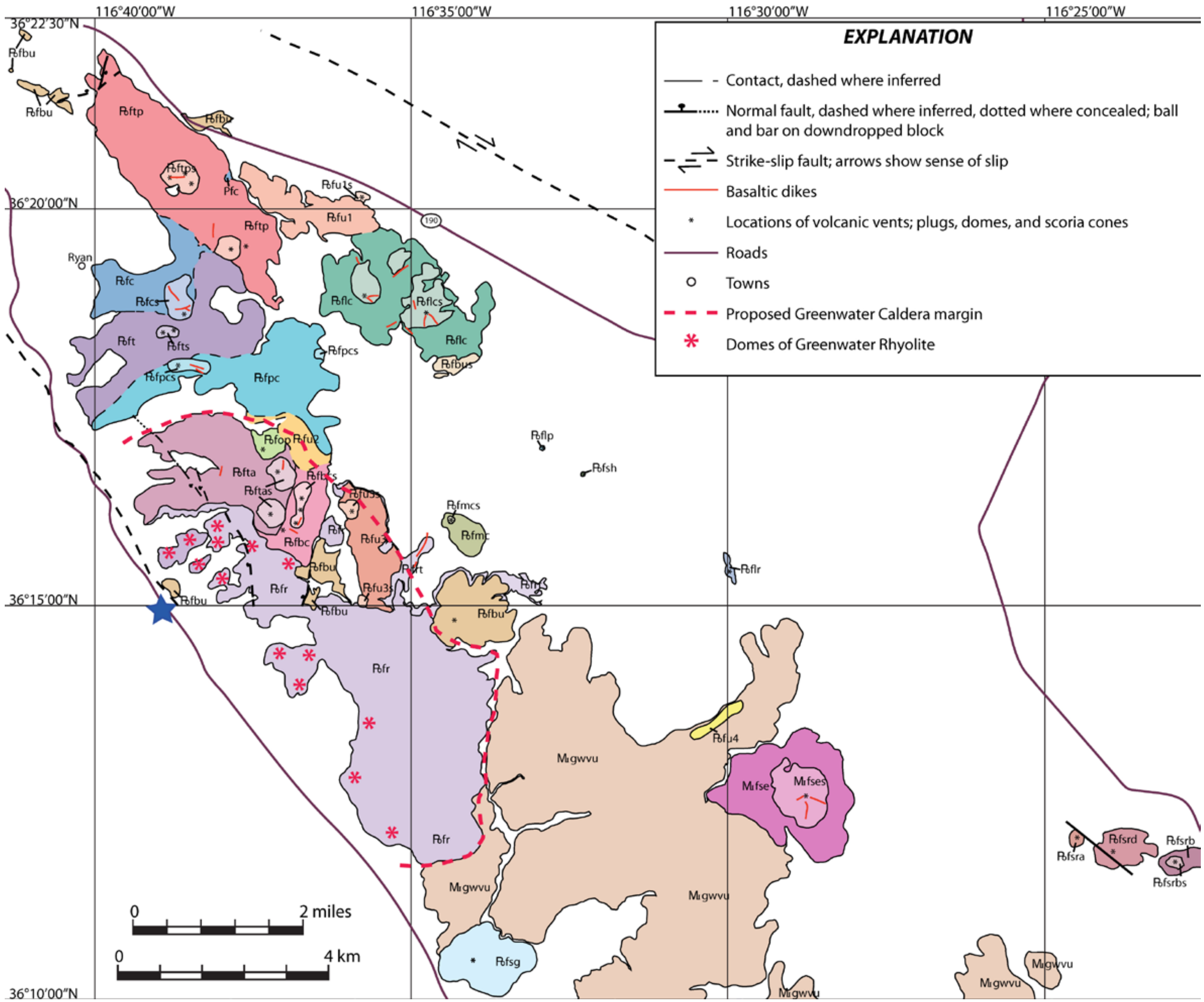
Previous mapping by McAllister (1970a,b) and Streitz and Stinson (1977) placed the Pliocene Greenwater Range basalt and basalt in the neighboring Black Mountains in the Funeral Formation and divided it into lava flows and accumulations of scoria. Basalt of the Funeral Formation overlies sedimentary rocks of the Miocene-Pliocene Furnace Creek Formation in the northern part of the Greenwater Range; to the south and west, however, Funeral Formation basalt overlies rhyolite flows, domes, and pyroclastic units as well as a Miocene volcanic section (fig. 4-2). The age of Funeral Formation basalt is nicely constrained by K-Ar ages of 4.03±0.12 Ma for a basalt flow near Ryan, California (McAllister, 1970b) and a 4.00±0.10 Ma $^{40}Ar/^{39}Ar$ age from the Three Peaks volcano, both in the northern Greenwater Range. Funeral Formation basalt overlies rhyolite that yields a U-Pb zircon age of 4.9±0.2 Ma (Tibbetts, 2010); therefore, basalt was erupted between 4.9 and 4.03 Ma. The age of the rhyolite is constrained by the above-mentioned U-Pb age and two K-Ar biotite ages of 5.18±0.15 Ma and 5.88±0.20 Ma (McAllister, 1970b). On the basis of these data, rhyolite straddles the boundary between the Funeral Formation and the underlying Greenwater volcanic section. In this paper, we place the rhyolite in the Funeral Formation on the basis of the close petrogenetic relationship between rhyolite and overlying basalt (see accompanying paper).

The stratigraphic nomenclature for the Greenwater Range and surrounding areas is confusing. Drewes (1963) and McAllister (1970b) are responsible for the current stratigraphy, but age assignments for units have been modified numerous times. We use the following stratigraphic nomenclature: Artist Drive Formation (10 to 6 Ma), Furnace Creek Formation (6 to 5 Ma), and Funeral Formation (5 to 3 Ma) in part synchronous with Miocene volcanic rocks including Shoshone Volcanics (8.5 to 7.5 Ma) and Greenwater Volcanics (7 to 5 Ma) mainly at the south end of the Greenwater Range. McAllister (1970b) mapped most of the southern part of the Greenwater Range and was one of the first to recognize rhyolite exposures. He placed the rhyolite in the Greenwater Volcanics stratigraphically below basalts of the Funeral Formation and assigned them a Tertiary age. McAllister (1970b) also subdivided rhyolite into upper and lower tuff breccia and vitrophyre. He recognized flows, "near-vent intrusions," and pumice within the vitrophyre unit. McAllister (1970b) recognized angular unconformable contacts between rhyolite and underlying sedimentary rocks and tuffs of the Furnace Creek Formation. Further, he noticed that a thin basalt flow locally crops out just below the lower tuff breccia unit. Drewes (1963) described the contact between rhyolite of the Greenwater Volcanics and the underlying Furnace Creek Formation as an unconformity traced for several miles along Greenwater Canyon. He also suggested that the rhyolites and tuffs of the Greenwater Formation accumulated in a local basin.

Basalt and Rhyolite Volcanoes of the Greenwater Range

Reconnaissance studies by Tibbetts (2010) identified numerous basalt lava flows and twenty-four volcanic centers over an area of 200 square kilometers (km^2). Flows consist of alternating layers of agglomerate and massive basalt that vary in thickness from approximately 200 m in the northeast to 25 m in the southwest. Confidence for identifying volcanic centers varies from probable centers that are accumulations of scoria and bombs (up to 2 m in size), to definite centers with well-defined cinder cones and eroded plugs. In definite centers, dikes radiate from central vents and connect closely spaced centers. Several of the most prominent centers, including the Three Peaks volcano and Ryan Cone (a volcanic plug), stand out as distinct peaks just to the west of California State Highway 190 (fig. 4-2). The largest volcanic complex is the Southeast Center, composed of several coalescing cinder cones and related flows and dikes (Tibbetts, 2010). The Southeast Center lies on, and is separated from the central and northern Greenwater Range by exposures of Miocene Greenwater volcanic section. Basalt from the vent area of the Southeast Center yields a $^{40}Ar/^{39}Ar$ isochron age of 7.02±0.08 Ma, placing this volcano at the base of the Greenwater volcanic section. Correlation of flows to volcanic centers is based on photo interpretation and chemical characteristics. Figure 4-2 shows flow boundaries and relates flows to specific centers but does not imply age relationships between units.

Rhyolite erupted from 8 to10 volcanic domes located just to the east of Greenwater road. Rhyolite in volcanic domes varies from flow banded to vitric with carapace breccia common about dome margins. Locally, breccia with rhyolite clasts as large as 8 cm in diameter dominates the section. Clasts are matrix supported and occupy 70 to 80 percent of rock volume. Flow banding is common and can be complexly folded.



116°40′00″W
116°35′00″W
116°30′00″W
116°25′00″W
36°22′30″N
36°20′00″N
36°15′00″N
36°10′00″N
EXPLANATION
Contact, dashed where inferred
Normal fault, dashed where inferred, dotted where concealed; ball and bar on downdropped block
Strike-slip fault; arrows show sense of slip
Basaltic dikes
Locations of volcanic vents; plugs, domes, and scoria cones
Roads
Towns
Proposed Greenwater Caldera margin
Domes of Greenwater Rhyolite
Ryan
190
Pfbu
Pftp
Pftps
Pfc
Pfu1s
Pfu1
Pfcs
Pft
Pfts
Pfpcs
Pfpc
Pflc
Pflcs
Pfbus
Pfop
Pfu2
Pfta
Pftas
Pfbcs
Pfbc
Pfu3s
Pfu3
Pfr
Pfmcs
Pfmc
Pflp
Pfsh
Pflr
Pfsg
Pfu4
Migwvu
Mifse
Mifses
Pfsra
Pfsrd
Pfsrb
Pfsrbs
0
2 miles
0
4 km

MAP EXPLANATION

	FUNERAL FORMATION
Poftp, Poftps	Pliocene basalt and basaltic scoria of Three Peaks, Ryan Cone, and Ryan Plug
Pofc, Pofcs	Pliocene basalt and basaltic scoria of The Crater
Poft, Pofts	Pliocene basalt and basaltic scoria of Two Peaks
Pofpc, Pofpcs	Pliocene basalt and basaltic scoria of Point Cone
Poflc, Poflcs	Pliocene basalt and basaltic scoria of Lower Cone 1 and Lower Cone 2
Pofop	Pliocene basalt of Old Peak
Pofta, Poftas	Pliocene basalt and basaltic scoria of Tall Peak and West Twin Peak
Pofbc, Pofbcs	Pliocene basalt and basaltic scoria of Buried Peaks and East Twin Peak
Pofmc, Pofmcs	Pliocene basalt and basaltic scoria of Mesa Center
Poflp	Pliocene basalt of Lower Plug
Pofsh	Pliocene basalt of Lower Scoria Hill
Poflr	Pliocene basalt of Lower Ridge
Pofsrb, Pofsra, Pofsrd	Pliocene basalt, andesite, and dacite of Shoshone Ridge
Pofr, Pofrt	Pliocene rhyolite of the Greenwater Range
Pofsg	Pliocene andesite of Southern Greenwater Canyon
	Unnamed Pliocene basalt centers
	Undifferentiated Pliocene basalt
Mlfse, Mlfses	Miocene basalt and basaltic scoria of Southeast Center
	GREENWATER VOLCANICS
Mlgwvu	Undifferentiated basalt, andesite, dacite, rhyolite, and intrusions

Figure 4–2. (previous page) Geologic map of Greenwater Range showing Funeral Formation basalt centers and related flows, Greenwater caldera, locations of major rhyolite domes, and Miocene volcanic section. Blue star shows location of field trip stop.

Domes are 50 to 150 m in diameter and are either circular or elongate in map view. They intrude and are covered by a thick section of rhyolite flows, volcaniclastic breccia, and tuff. As many as 10 lens-shaped (in cross section) flows, composed of light- to dark-gray massive to flow-banded plagioclase-biotite rhyolite, cap the section of rhyolite domes and tuffs. Brecciated rhyolite and vitrophyre occur at the base and locally at the top of each flow. Tuff and volcaniclastic deposits underlie the stack of rhyolite flows and vary in thickness from 70 m (in the south) to less than 10 m in the north. The tuff is finely bedded (2–3 cm thick) and cross stratified in places and contains massive beds 3–5 m thick in other parts of the section. Volcaniclastic units vary in thickness and contain rhyolite clasts (usually 1 to 5 cm in diameter) floating in a finer grained matrix. In the northern part of rhyolite exposures, volcaniclastic units are interbedded with a 3–5-m-thick pyroxene-olivine basalt flow.

Evidence for a Crater or Caldera in the Greenwater Range

The basin-like geometry of the Greenwater rhyolite was first recognized by Drewes (1963) and angular unconformities at contacts between rhyolite and older rocks were clearly shown by McAllister (1970b) on map cross sections. Our mapping demonstrated that the contact between rhyolite and older units is an inward-dipping angular unconformity that bounds a semicircular exposure of rhyolite, tuffs, an interbedded basalt flow, and volcaniclastic rock. In the north and east, the unconformity dips 30 degrees to the south and west, respectively, and places intrabasin rocks on borax-bearing sediments of the Furnace Creek Formation. At one locality, the contact resembles a crater wall or rim with intrabasin tuff appearing to flow up and over the rim (fig. 4-3). In the south, tuff and volcaniclastic units lap against a north-dipping wall (40–60°) formed by steeply dipping Miocene volcanic rock. In this locality, the intrabasin volcaniclastic unit contains large matrix-supported blocks of Miocene volcanic rock (5–10 m), which we suggest represent a megabreccia deposit. Megabreccia commonly forms adjacent to caldera margins and results from the gravitational collapse of caldera walls (Lipman, 1976). The thickness of the rhyolite and related rocks within the basin is unknown because the base of the section is not exposed. On the west side of the Greenwater Range, the thickness of rhyolite, tuff, and volcaniclastic rock is at least 200 m. Here, rhyolite flows, domes, and breccia make up most of the section with tuff comprising no more than five percent of the total erupted volume. Tuff is thicker in the southern part of the basin where we measured a section 45 m thick.

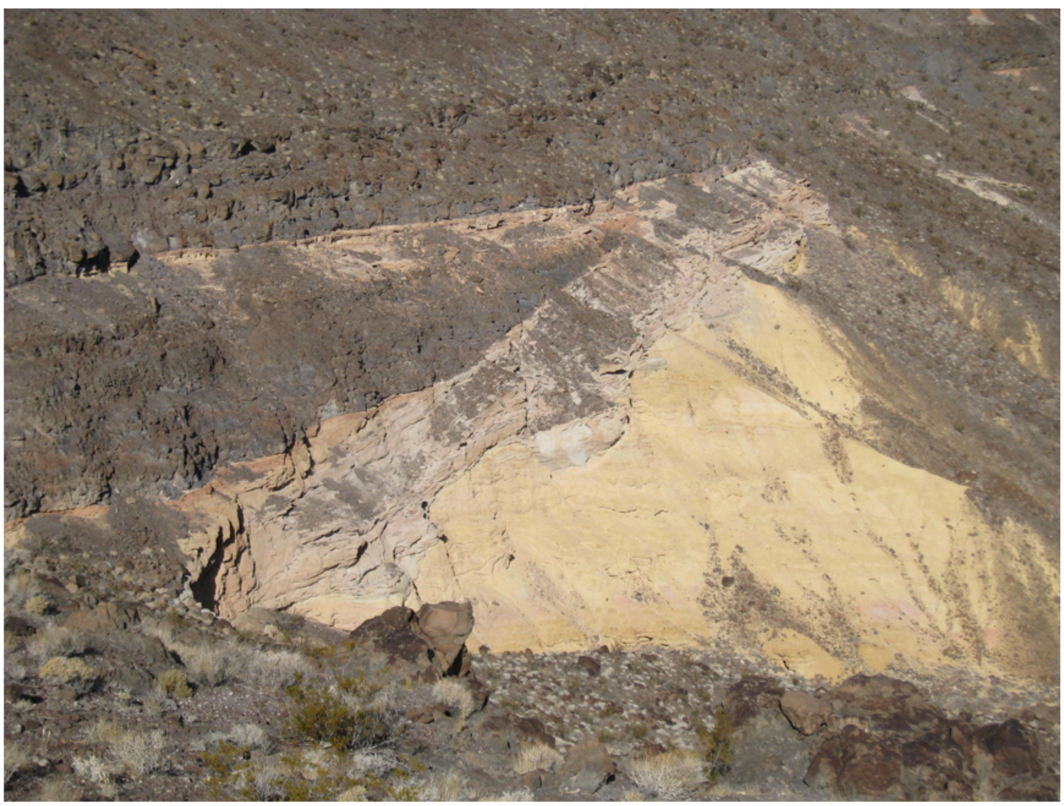


Figure 4–3. Photograph showing rhyolite and basalt pinch out against borax-bearing sediments of Furnace Creek Formation (flat-lying light-yellow rocks to right). A rhyolitic tuff is plastered against the caldera wall and is overlain by a basalt flow. Younger Funeral Formation basalt caps the section.

Isostatic gravity data provided by Robert C. Jachens (this report) displays a 36 mGal gravity low associated with the Greenwater Range (fig. 4-4). This anomaly extends into Greenwater Valley to the west and may represent a continuation of the Greenwater rhyolite-filled basin into the valley. Jachens (oral commun., 2011) indicated that the anomaly is best interpreted as representing a shallow pluton rather than a thick section of tuff.

On the basis of geological and geophysical data, we suggest that the rhyolite basin is a 9-km-diameter volcanic crater or caldera. It is not a caldera in the traditional sense as described by Smith and Bailey (1968), but may be better interpreted as the volcanic response to a pluton rising to the surface. This type of caldera was originally described by Hamilton and Myers (1967) as the surface expression of a granitic batholith that rose to the surface, cut through its volcanic cover, and eventually erupted as rhyolite flows and tuffs.

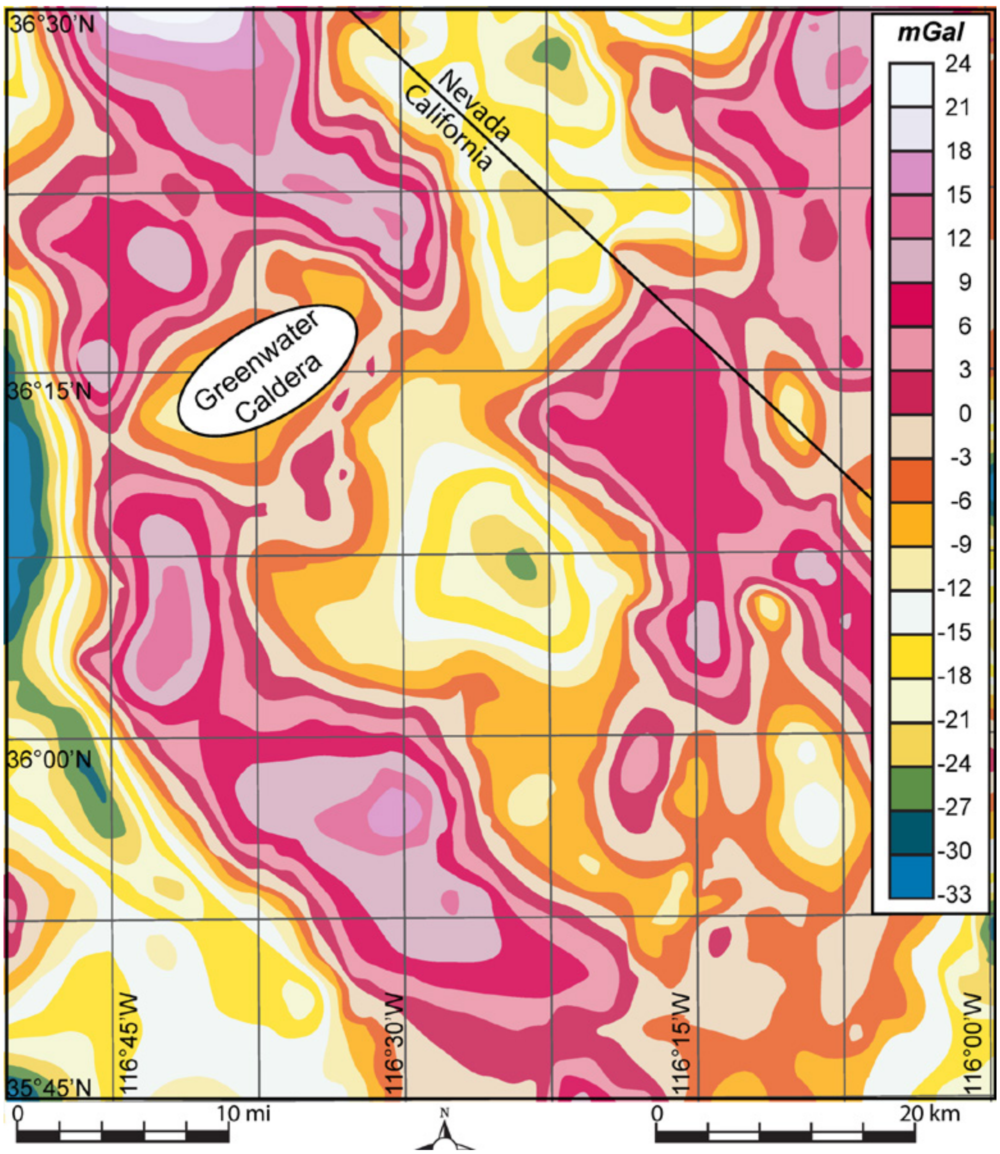


Figure 4–4. Map showing isostatic gravity survey of eastern Death Valley area (R.C. Jachens, written commun., 2011). The Greenwater caldera (blue shading on figure) overlies a 36-milligal (mGal) negative gravity anomaly interpreted by Jachens as a shallow granitic pluton.

STOP 5: THE ANCIENT FURNACE CREEK BASIN AT ZABRISKIE POINT

By Jeffrey R. Knott,[1] Michael N. Machette,[2] Joseph C. Liddicoat,[3] Elmira Wan,[2] and Andrei Sarna-Wojiciki[2]

This stop at Zabriskie Point is located at lat 36°25′12.3″N., long 116°48′43.9″W. (fig. 1-1). Here, we will discuss the Pliocene Furnace Creek Formation which records evidence of an early basin fill in Death Valley that formed between the uplifting Funeral Mountains on the north and Black Mountains on the south. Time permitting, we will take a 2.4-km (1.5 mi) hike (round trip) up Zabriskie Wash (30 m of elevation gain) to see tephra layers erupted from Long Valley caldera and the southern Cascade Range interbedded with lake deposits.

The light-colored, fine-grained sedimentary rocks at Zabriskie Point, including Manly Beacon, were deposited in an ancient playa lake setting. In higher hills to the northwest, sedimentary beds darken and coarsen as playa lake deposits give way to alluvial-fan deposits. Dipping beds composed of these alluvial-fan deposits form the walls of Zabriskie Wash to the northeast. About 1.2 km up-section along Zabriskie Wash, the beds become finer and record another playa lake sequence. Interbedded with these upper lake deposits are a series of six (or more) volcanic ashes ranging from just a few centimeters to more than two meters thick. Geochemical and paleomagnetic data indicate that the upper lake deposits are about 3.5 Ma and that sediments at Zabriskie Point are about 4.1 Ma. All of these sediments were uplifted and folded as the Black Mountains Fault uplifted the Black Mountains and allowed the main Death Valley basin to subside.

Introduction

The Furnace Creek basin is best known for its world-famous borate deposits, but it is also important because it records the past eight million years of climate and tectonics in Death Valley. Located between the Funeral Mountains in the north and the Black Mountains in the south (fig. 5-1), the northwest-elongated Furnace Creek basin includes spectacular vistas of multicolored rocks and steep canyons characteristic of badland topography. The geologic story of Death Valley spans more than a billion years, and the past four million years is recorded by the upper half of sediments in the Furnace Creek basin.

The Tertiary stratigraphy of Death Valley is based on two rock formations found in the Furnace Creek basin (fig. 5-2). The first is the Furnace Creek Formation, which contains dominantly fine-grained playa deposits interspersed with distal conglomerates, lake deposits, and locally derived basalt flows. The second is the Funeral Formation, which overlies the Furnace Creek Formation and consists of dominantly coarse-grained proximal alluvial-fan conglomerates along with basalt flows and locally derived landslide deposits. As independent geologic mapping progressed to other areas of Death Valley, this simple distinction of Furnace Creek Formation (fine-grained playa deposits) and Funeral Formation (coarse-grained alluvial fan deposits) continued without regard to age.

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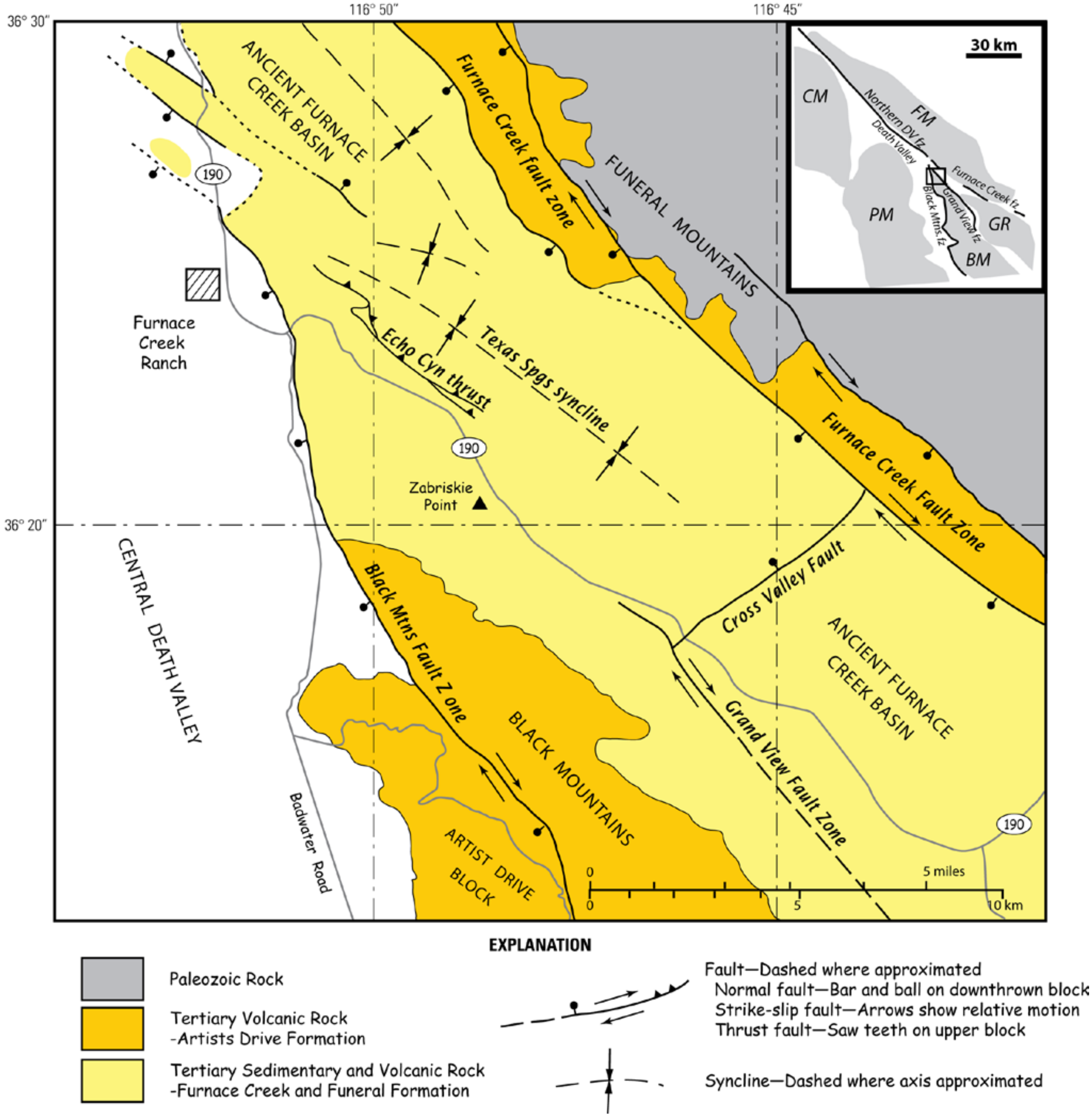

Figure 5–1. Generalized geologic map of northwest-elongated Furnace Creek basin near Zabriskie Point showing major rock groups and geologic structures. Inset map shows location of the Black Mountains (BM), Cottonwood Mountains (CM), Funeral Mountains (FM), Greenwater Range (GR), Panamint Mountains (PM), and main fault zones (fz). Square on inset map shows location of larger map.

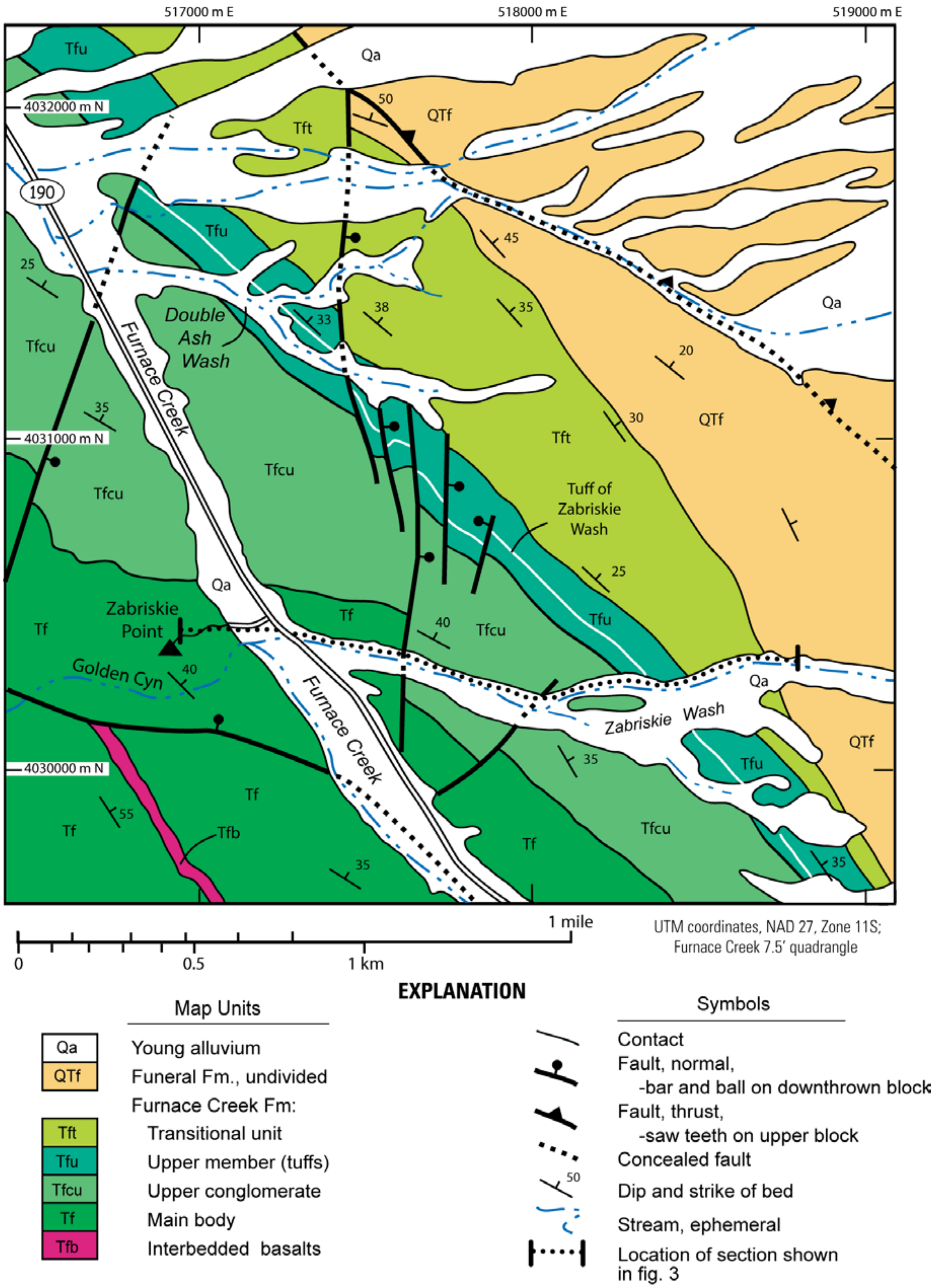

Figure 5–2. Generalized geologic map of the Zabriskie Point area (modified from McAllister, 1970b).

Historically, the lack of age control was a consequence of the absence of fossils in both the Furnace Creek and Funeral Formations. As technology improved, some age control was gained by dating interbedded basalt flows. McAllister (1970b) determined a K/Ar age of 4.0±1.0 Ma for the uppermost basalt flow in the Funeral Formation near Ryan, California. Cemen and others (1985) obtained a K/Ar age of 5.87±1.5 Ma for a basalt flow in the lower third of the Furnace Creek Formation. The exact basalt flow is unclear; Wright and others (1999) indicate that the basalt flow is below the gypsum-rich member of the Furnace Creek Formation, which is stratigraphically lower than this field stop at Zabriskie Point.

Tephrochronology and paleomagnetics have been used to determine the age of the Furnace Creek and Funeral Formations in the Furnace Creek basin. Tephrochronology is the characterization of the chemical composition and other characteristics of volcanic ash beds, tephra beds, or tuffs as a correlation tool to dated volcanic sources. Sometimes this is referred to as volcanic "fingerprinting." Volcanic ash beds, tephra beds, and tuffs are all similar terms for volcanic glass (quenched magma) and minerals erupted from a volcano. A volcanic ash bed contains mineral and glass particles less than 2 mm in diameter. A tephra bed is composed of uncemented volcanic material that has a range of particle sizes, some exceeding 2 mm. A tuff, on the other hand, is a bed of cemented volcanic material. For our purposes here, we will use the term "tephra layer" for uncemented volcanic debris and the term "tuff" for cemented deposits.

Paleomagnetics is another correlative dating tool. Paleomagnetics is based on the fact that iron-rich minerals will align themselves with Earth's magnetic field at the time of their deposition. Today, Earth's magnetic field has a north (or "normal") declination whereby magnetic minerals point north. In the past, Earth's magnetic field pointed south or was "reversed" many, many times. The pattern and timing of magnetic reversals may be used to correlate with intervals of geologic time. For example, if the paleomagnetic field of a rock shows iron-rich minerals pointing south, then the rock must have formed at least 780,000 years ago because that was the end of the last reversal.

Our tephrochronology and paleomagnetic data show that the upper members of the Furnace Creek Formation are about >3.5 to 3.2 Ma. This implies that the overlying Funeral Formation and tectonic folding and faulting that generated the present landscape are younger than 3.2 Ma rather than 4 Ma as previously determined by McAllister (1970b).

Furnace Creek Formation

Zabriskie Point is underlain by fine-grained sedimentary rocks that constitute the main member of the Furnace Creek Formation. These mudstone to sandstone beds, including a thick bed of gypsum, were deposited in a playa lake environment (McAllister, 1970a). These tilted and folded beds strike northeast-southwest, so as you look to the north, you are looking at the younger, upper member of the Furnace Creek Formation. The upper member of the Furnace Creek Formation is mainly conglomeratic with interbeds of sandstone to mudstone. About 1.2 km up Zabriskie Wash, the conglomerate gives way to mudstone and sandstone again (lake sediments) and finally coarsens upwards into sandstone and conglomerate beds that form the preserved top of the Furnace Creek Formation (fig. 5-2).

There are a number of volcanic tephra beds within lake sediments of the upper Furnace Creek Formation. The most prominent tephra bed is the tuff of Zabriskie Wash lake sediments (Sarna-Wojcicki and others, 2001), which is dated by $^{40}Ar/^{39}Ar$ in the Cottonwood Mountains at 3.35 Ma (Snow and Lux, 1999). Also found higher (eastward) in Zabriskie Wash are the Nomlaki Tuff Member and the Putah Tuff of the Tuscan and Tehama Formations of northern

California (Knott and others, 2008). These tuffs erupted from the southern Cascade Range and Sonoma Volcanic Field (north of San Francisco), respectively.

Paleomagnetic data show several magnetic field reversals (fig. 5-3) and the 3.35 Ma age of the Zabriskie Wash tuff provides a starting point for correlation to the magnetic polarity time scale. Rocks below the Zabriskie Wash tuff are normal polarity (north-pointing inclination) indicating that this is the Lower Gauss subchron (3.596–3.330 Ma). About 30 m below the Zabriskie Wash tuff, rocks have reverse polarity (south-pointing inclination), all the way to Zabriskie Wash (westward) and across Route 190. This interval of reverse polarity is correlated with the upper Gilbert subchron (4.187–3.596 Ma). Near Zabriskie Point, the rocks are again normal polarity and are thus correlated with the Conchiti subchron (>4.187 Ma).

Rocks stratigraphically above the Zabriskie Wash tuff (northeast up Zabriskie Wash) are reverse polarity for more than 100 meters. Eventually, the rocks return to normal polarity. This reverse polarity zone above the Zabriskie Wash tuff correlates to the Mammoth subchron of the magnetic polarity time scale (3.330–3.207 Ma). The uppermost paleomagnetic sample is in the Funeral Formation and indicates that the base of the Funeral Formation in Zabriskie Wash is ~3.2 Ma.

Source of Furnace Creek Formation Sediments

Hunt and Mabey (1966) hypothesized that clasts in conglomerate and sandstone of the lower Furnace Creek Formation (south of Zabriskie Point) originated in the Cottonwood Mountains, which are now located about 67 km northwest of Zabriskie Point. These clasts were transported toward the southeast by an ancient river system (fig. 5-4). Distinguishing the source of the clasts is possible because the Black Mountains to the south are composed predominantly of volcanic rocks. In contrast, the Funeral Mountains to the north are composed of Paleozoic dolomite, quartzite, and shale. Most importantly, the Hunter Mountain batholith in the Cottonwood Mountains has is a very distinctive igneous rock—a leuco monzogabbro (light-colored monzogabbro)—similar to clasts in the lower Furnace Creek Formation.

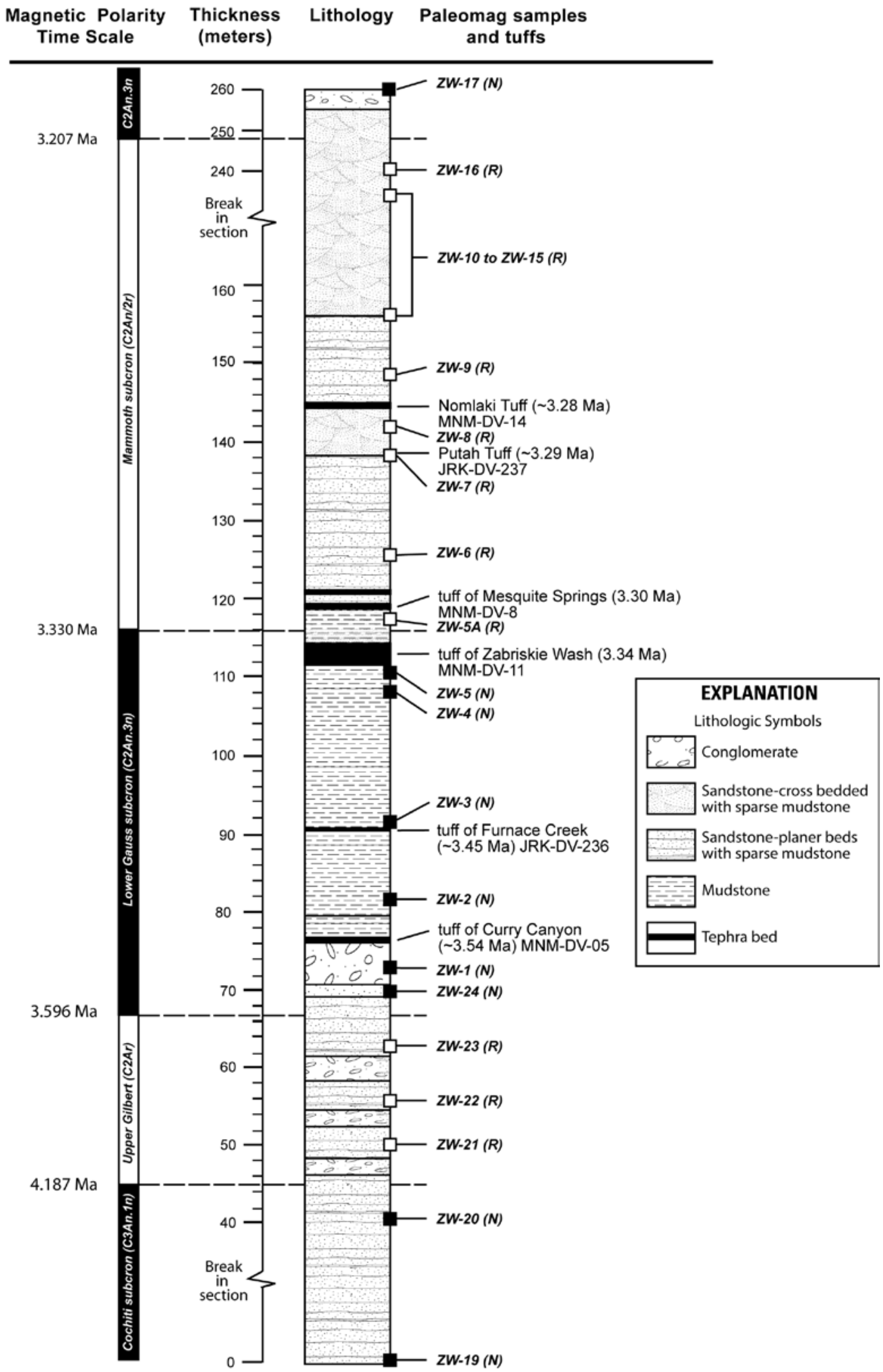

Figure 5–3. Stratigraphic section up Zabriskie Wash (ZW) showing correlation to magnetic polarity time scale. Subchron boundary ages are from Ogg and Smith (2004). Section thickness determined from mapping by McAllister (1970b). Subchron boundaries are estimated in most cases.

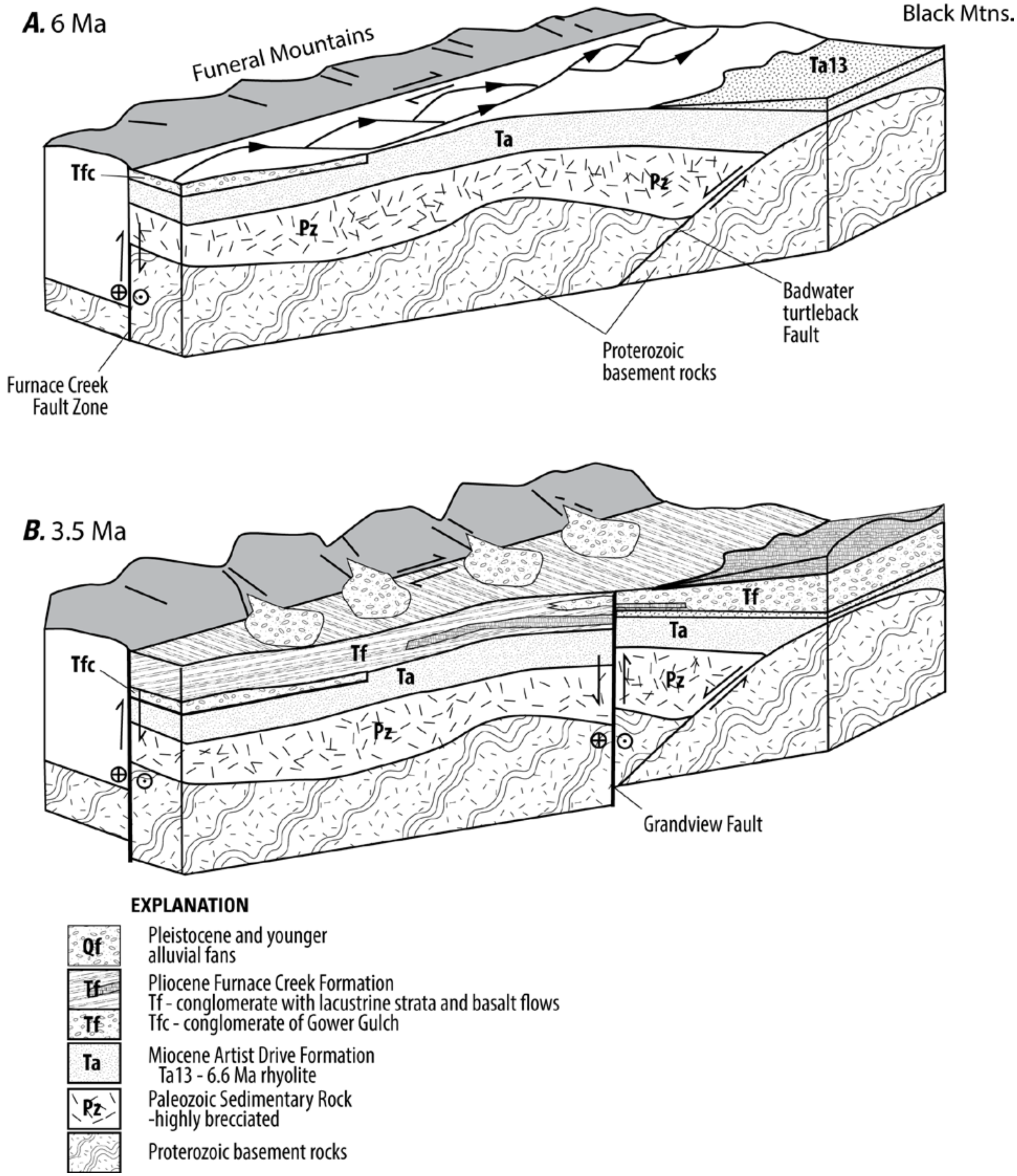

Figure 5–4. Block diagrams showing depositional and tectonic setting of Furnace Creek Formation (after Wright and others, 1999). *A*, Deposition of Conglomerate of Gower Gulch (Tfc) at base of formation is shown in northwest-southeast-flowing fluvial (river) system. *B*, Uplift of Funeral and Black Mountains by movement on Furnace Creek, Grand Valley, and Black Mountains (not shown) faults formed a playa lake (Tf) and alluvial fan environment by 3.5 Ma. Paired arrows show relative motion; circle-plus and circle-dot symbols show fault block motion away from and toward (respectively) the viewer.

Confirmation of sediment sources for the lower Furnace Creek Formation was established by a series of studies of the various clast types (Prave and Wright, 1996; Wright and others, 1999). Hunter Mountain batholith clasts are found in the Conglomerate of Gower Gulch (Tfc), which represents the base of the Furnace Creek Formation (fig. 5-4*A*; Wright and others, 1999). Above this lowermost conglomerate, clasts progressively include more volcanic clasts from the Black Mountains and Paleozoic rocks of the Funeral Mountains (fig. 5-4*B*). Clast counts, in the stratigraphic section of Zabriskie Wash that spans upper Furnace Creek from ~4.1 to ~3.2 Ma, support observations that sediment sources were divided between the Funeral and Black Mountains. Clast counts of sediments surrounding the Zabriskie Wash tuff at three locations (Zabriskie Wash, Dantes View Road, and Artists Drive) show that sediments were shed from different parts of the Black Mountains. Clast counts show that a drainage divide existed in the Black Mountains with the eastern terrain underlain by black, red, and gray basalts, and the western terrain underlain by red, purple, and green tuffs of the Artists Drive Formation.

Interpretations and Conclusions

Tephrochronologic and paleomagnetic data indicate that the upper member of the Furnace Creek Formation in the Furnace Creek basin is between ~4.1 and ~3.2 Ma and the Funeral Formation is less than 3.2 Ma. This age is younger than the K/Ar age of ~4 Ma that McAllister (1970b) obtained for the basalt in the overlying Funeral Formation and is likely more accurate because a number of improvements have been made to the K/Ar dating system since the 1970s (Renne, 2000).

The clast composition of the Furnace Creek Formation indicates that at ~6 Ma a river flowed from northwest to southeast across Death Valley with headwaters in the Cottonwood Mountains. Between 4 and 3 Ma the Furnace Creek basin received sediments from both the Funeral and Black Mountains—much like modern Furnace Creek does today. Sediments shed to the west drained areas underlain by multicolored Artists Drive tuffs; sediments shed to the north and from the east side of the Black Mountains were underlain by basalt flows. We infer that the change from a northwest-southeast-flowing river to a playa-lake-alluvial fan depositional environment was in response to tectonic uplift along the Furnace Creek, Grand View (Greenwater Valley), and Black Mountains Faults and lateral expansion of the Death Valley basin.

Acknowledgments

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