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# Quaternary and Late Pliocene Geology of the Death Valley Region: Recent Observations on Tectonics, Stratigraphy, and Lake Cycles (Guidebook for the 2001 Pacific Cell—Friends of the Pleistocene Fieldtrip)

***Edited by***
Michael N. Machette, Margo L. Johnson, and Janet L. Slate

***Open-File Report 01-51***

2001

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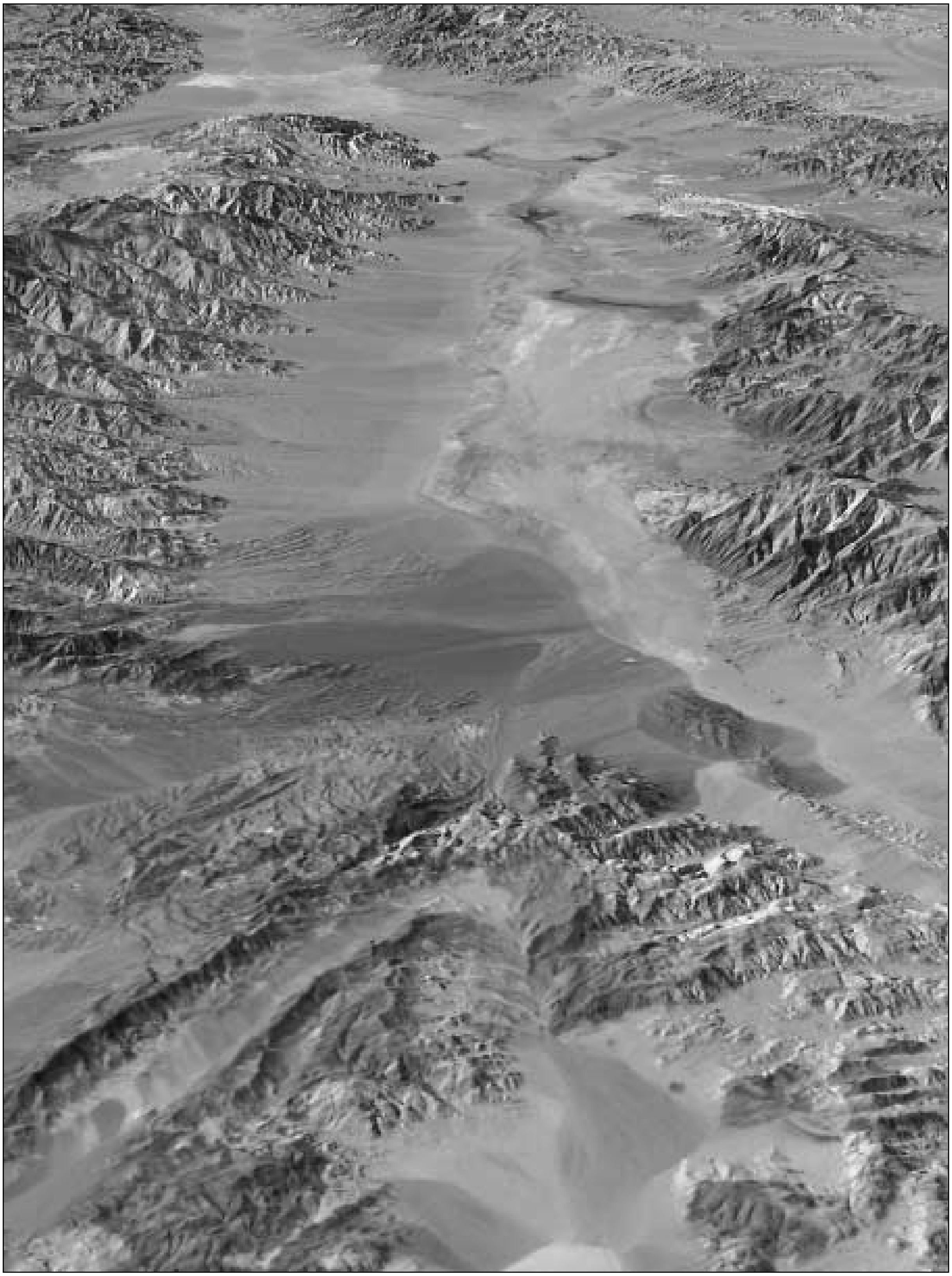

Frontispiece. Virtual oblique northward view of Death Valley from high above and a little south of the Owlshead Mountains. Shaded relief part of map was made using 30-m DEM data with Landsat TM (band 5) image draped over 3D shaded-relief map. Image created by Michael J. Rymer (USGS).

# Pacific Cell—Friends of the Pleistocene Field Trip
# February 17-19, 2001

# Quaternary and Late Pliocene Geology of the Death Valley Region: Recent Observations on Tectonics, Stratigraphy, and Lake Cycles

*Field Trip Leaders*

Ralph Klinger, Michael Machette, Jeff Knott, and Andrei Sarna-Wojcicki

Field-trip guidebook and selected papers dealing with various aspects of the Quaternary and Pliocene geology of the Death Valley region. This report has been released as U.S. Geological Survey Open-File Report 01-51 and may be obtained over the Internet from the following site: *http://geology.cr.usgs.gov*

## Guidebook Contributors

(In alphabetical order)


Debra L. Block
U.S. Geological Survey
2255 North Gemini Drive
Flagstaff, AZ
(dblock@usgs.gov)

James R. Budahn
U.S. Geological Survey
Mineral Resources Team, Central Region
P.O. Box 25026, MS 974
Denver, CO 80225-0046
(jbudahn@usgs.gov)

Anthony J. Crone
U.S. Geological Survey
Geologic Hazards Team, Central Region
P.O. Box 25046, MS 966
Golden, CO 80225-0046
(crone@usgs.gov)

John C. Dohrenwend
P.O. Box 141
Teasdale, UT 84773-014
(dohrenwend@rkymtnhi.com)

Robert J. Fleck
U.S. Geological Survey
Earth Surface Processes Team, Western Region
345 Middlefield Road, MS 937
Menlo Park, CA 94025
(fleck@usgs.gov)

Kurt Frankel
Department of Geological Sciences
Mitchell Hall
University of North Carolina
Chapel Hill, NC 27599-3315

(Present Address)
Dept. of Earth and Environmental Sciences
31 Williams Hall
Lehigh University
Bethlehem, PA 18015
(kuf2@lehigh.edu)

John W. Geissman
Dept. of Earth and Planetary Sciences
Northup Hall
University of New Mexico
Albuquerque, NM 87131
(jgeiss@unm.edu)

Allen F. Glazner
Department of Geological Sciences
Mitchell Hall
University of North Carolina
Chapel Hill, NC 27599-3315
(afg@unc.edu)

Angela S. Jayko
U.S. Geological Survey
Earth Surface Processes Team, Western Region
345 Middlefield Road, MS 975
Menlo Park, CA 94025
(ajayko@usgs.gov)

Margo L. Johnson
U.S. Geological Survey
Geologic Hazards Team, Central Region
P.O. Box 25046, MS 966
Golden, CO 80225-0046
(mjohnson@usgs.gov)

Dough La Farge
Humboldt State University
465 Tyende Ovi
Fkagstaff, AZ 86001
(doug@holdit.com)

Ralph E. Klinger
U.S. Bureau of Reclamation
Technical Service Center
P.O. Box 25007, D-8330
Denver, CO80225-0007
(rklinger@do.usbr.gov)

Jeffrey R. Knott
UNOCAL Corporation
Environmental Technical Group
376 S. Valencia Ave.
Brea, CA 92831
(jrknott@unocal.com)

Joseph C. Liddicoat
Department of Environmental Science
Barnard College, Columbia University
New York, NY 10027
(jliddico@barnard.edu)

Michael N. Machette
U.S. Geological Survey
Geologic Hazards Team, Central Region
P.O. Box 25046, MS 966
Golden, CO 80225-0046
(machette@usgs.gov)

Chris Menges
U.S. Geological Survey
Nevada Operations Programs
1180 Town Center Drive, MS 423
Las Vegas, NV 89134
(Christopher_Menges@notes.ymp.gov)

Paula Messina
Department of Geology
San José State University
One Washington Square
San José, CA 95192-0102
(pmessina@geosun.sjsu.edu)

Genne Nelson
P.O. Box 258
Amargosa Valley, NV 89030
(jerrynel@pahrump.com)

Lucy A. Piety
U.S. Bureau of Reclamation
Technical Service Center
P.O. Box 25007, D-8330
Denver, CO80225-0007
(lpiety@do.usbr.gov)

Michael J. Rymer
Earthquake Hazards Team, Western Region
345 Middlefield Road, MS 977
Menlo Park, CA 94025
(mrymer@usgs.gov)

Andrei M. Sarna-Wojcicki
U.S. Geological Survey
Earth Surface Processes Team, Western Region
345 Middlefield Road, MS 975
Menlo Park, CA 94025
(asarna@usgs.gov)

Janet L. Slate
U.S. Geological Survey
Earth Surface Processes Team, Central Region
P.O. Box 25046, MS 913
Denver, CO 80225-0046
(jslate@usgs.gov)

Philip W. Stoffer
U.S. Geological Survey
Library, Western Region
345 Middlefield Road, MS 955
Menlo Park, CA 94025
(pstoffer@usgs.gov)

Arthur G. Sylvester
Department of Geological Sciences
University of California
Santa Barbara, CA 93106-9630
(arthur@geol.ucsb.edu)

Emily M. Taylor
U.S. Geological Survey
P.O. Box 25046, MS421
Denver, CO 80225-0046
(emtaylor@usgs.gov)

Ren A. Thompson
U.S. Geological Survey
Earth Surface Processes Team, Central Region
P.O. Box 25046, MS 913
Denver, CO 80225-0046
(rathomps@usgs.gov)

John C. Tinsley, III
Earthquake Hazards Team, Western Region
345 Middlefield Road, MS 977
Menlo Park, CA 94025
(tinsley@usgs.gov)

James P. Walker
U.S. Geological Survey
Earth Surface Processes Team, Western Region
345 Middlefield Road, MS 975
Menlo Park, CA 94025
(jpwalker@usgs.gov)

Stephen G. Wells
Desert Research Institute
2215 Raggio Parkway
Reno, NV 89512
(sgwells@dri.edu)

Chris Wills
California Division of Mines and Geology
185 Berry Street, Suite 210
San Francisco CA 94107
(cwills@consrv.ca.gov)

Jeremiah B. Workman
U.S. Geological Survey
Earth Surface Processes Team, Central Region
P.O. Box 25046, MS 913
Denver, CO 80225-0046
(workman@usgs.gov)

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# INTRODUCTION

The Pacific Cell of the Friends of the Pleistocene (FOP) is a loosely knit group of geologists and other scientists who have an avid interest in the Quaternary history of the Earth. For the past 35 years, some willing souls have offered to host the next year's meeting, and in 1999 we made such an offer. We originally planned to run our Death Valley trip in late 2000, but a number of conflicts pushed the trip into the new Millennium. Although there was no Pacific Cell field trip in 2000, we hope that this one makes up for the gap.

## OVERVIEW OF FIELD TRIP

As the title indicates, the trip guide and accompanying papers focus on the Quaternary and late Pliocene geology of the Death Valley region, specifically on recent observations regarding tectonics, stratigraphy, and lake cycles. The principal leaders (Ralph Klinger, Michael Machette, Jeff Knott and Andrei Sarna-Wojcicki) have either recently completed major studies or are engaged in new research on these topics in the Death Valley region.

The last FOP trip to Death Valley was led in 1986 by Roland Brady III, Paul R. Butler, and Bennie W. Troxel (see Troxel, 1986, Quaternary Tectonics of Southern Death Valley, California). Most of that trip focused on the Confidence Hills region in southern Death Valley. Our only overlap with that excellent trip will be to make a long stop at Mormon Point with Jeff Knott, where Troxel had previously described the significance of fault patterns.

In anticipation of the great interest that the present trip generated, we decided to run all 3 days of the trip concurrently. This plan has the benefit of splitting the 150-plus participants into more manageable groups of 50-60 persons, which the National Park Service found to be more palatable for our special-use permit. The downside of this arrangement is that each day's leader sees only their part of the trip and repeats it for 3 days, a sacrifice that each leader is willing to make for the goodwill of the park.

Day A is to the northern part of Death Valley. Ralph Klinger of the U.S. Bureau of Reclamation will be the primary leader for this day. Ralph is completing his doctoral work at the University of Colorado, and much of the data and discussion for this day has been derived from his research. During this day, we will visit the source of a very young volcanic eruption, look at the folded and faulted late Pliocene and early Pleistocene stratigraphy along Death Valley Wash in the Rogers Lake basin, explore the Northern Death Valley fault zone at several places, and examine some enigmatic deposits of Lake Manly.

Day B is to the Furnace Creek area of central Death Valley. Michael Machette of the U.S. Geological Survey will be the primary leader for this day. Michael, along with Ren Thompson, Chris Fridrich, and Janet Slate (all USGS) are completing a new geologic map of the Death Valley Junction 30 x 60-minute quadrangle. As part of this compilation, they have been mapping parts of the Furnace Creek 7.5-minute quadrangle in detail, and focusing on dating air-fall tuffs that are markers in the Furnace Creek Formation in collaboration with co-leader Andrei Sarna-Wojcicki. Additional studies have contributed to a seismic-hazards assessment for the National Park Service, and plans are progressing for cosmogenic dating of alluvial-fan deposits and luminescence dating of constructional deposits of Lake Manly.

Day C is to the central part of Death Valley, specifically the area from Mormon Point north to Artists Drive. Jeff Knott of UNOCAL Corporation will be the primary leader for this day. Jeff, who completed his Ph.D. at the University of California–Riverside in 1998, will present new information on the late Pliocene and Pleistocene stratigraphy of basin-fill deposits exposed at Mormon Point and in the Artists Drive block. At Goblet Canyon, Jeff will use geomorphic and stratigraphic evidence to establish a late Pleistocene slip rate for the Black Mountains fault zone. Further north, at Hunt Canyon just off Artists Drive, Jeff and Andrei Sarna-Wojcicki will discuss the ages and sources of four well-exposed tuff beds, and at the north end of the Artists Drive block we will visit well-exposed lacustrine gravel of Lake Manly.

## OVERVIEW OF PAPERS

As part of our guidebook, we solicited short papers to supplement topics that would be discussed on the trip. Some papers were invited and some were volunteered. The 14 contributions (papers and images) in this volume present original data or significant revisions of previously published information that are pertinent to this field trip.

John Dohrenwend has prepared a page-size version of his popular poster size *Satelite image map of Death Valley* (Chapter D), which is locally available in Death Valley or from the author (see address information in list of contributors). This image provides a valuable introduction to the other papers that follow.

Andrei Sarna-Wojcicki and others have prepared a new summary article entitled *Weaving a temporal and spatial framework for the late Neogene of Death Valley* (Chapter E), which is the result of years of tephrochronologic research in the region and volcanic ash collections by numerous field geologists. Accompanying the article are two large format (11"x 17") plates that include a correlation chart, as well as a diagram showing the significant volcanic ash localities in the region. The plates are folded and inserted at the end of the volume.

Joseph Liddicoat has prepared a brief summary on his research on the *Paleomagnetism of the upper part of the Furnace Creek Formation, California* (Chapter F), which was done in the mid 1980's. The paleomagnetic signatures of strata in the upper part of the Furnace Creek Formation suggest that the rocks are of Pliocene age, which is similar to what Machette and others concluded based on Sarna and others work (Stop B5 and Chapter D, this volume). No direct tie, however, has been made between the deposits in both of these study areas.

In a paper entitled *Questions about Lake Manly's age, extent, and source* (Chapter G), Michael Machette, Ralph Klinger, and Jeffrey Knott grapple with the timing of Lake Manly, an ancient lake that once (or many times) filled Death Valley to fairly deep levels. As with other lakes in the Basin and Range, Lake Manly has oscillated from a shallow to a deep lake during marine oxygen-isotope stages II (Tioga Glaciation), stage IV (Tenaya Glaciation), and/or stage VI (Tahoe Glaciation). Geomorphic arguments and uranium-series dating of lacustrine tufas suggest an older lake (stage VI), whereas other geomorphic arguments and limited radiocarbon and luminescence ages suggest a younger lake (stage II or IV). The puzzle is yet to be solved, but this article discusses the merits and disadvantages of both supposed histories.

In an attempt to provide a regional framework for Quaternary geologic mapping in the Las Vegas-Death Valley-Mojave regions, Chris Menges and Emily Taylor have written an article on *Regional surficial-deposit mapping in the Death Valley area of California and Nevada in support of ground-water modeling* (Chapter H). This article is based on years of original geologic mapping in the Yucca Mountain-Nevada Test Site area, and on imagery-analysis mapping for a much broader area.

In the days of Charlie Hunt work (1950's-1960's), one could go just about anywhere in Death Valley that your vehicle or horse would take you. It's a different world now, and with the elevation of Death Valley to National Park status in 1995, 95 percent of the park is congressionally designated wilderness and therefore off limits to vehicles. But what is "taken away with one hand is returned with another" in the form of remote sensing. In *A short note on developing methods for regional mapping of surficial deposits in arid regions from remote-sensing and DEM data* (Chapter I), Chris Menges and Angela Jayko describe their strategy for mapping large areas using desktop computers.

Since Noble's first paper on the Death Valley fault (1926), there has been a tremendous interest in the Neogene to Holocene evolution of Death Valley and surrounding regions. In the subsequent 75 years, however, there has been no attempt to integrate or formulate a consistent, geographically defendable nomenclature for this long and important structural feature. To try to gain consensus and guide future work, Machette and others present a paper on *A proposed nomenclature for the Death Valley fault system* (Chapter J). The paper has a brief review of the history of fault names, usage by various authors, and suggests a unified nomenclature for the entire Death Valley fault system.

Although many think of Death Valley as an extensional regime, Ralph Klinger and Lucy Piety have documented an excellent example of localized compressional tectonics in their paper on the *Late Quaternary flexural-slip folding and faulting in the Texas Springs syncline, Death Valley* (Chapter K). This paper presents research the authors did for the U.S. Department of Energy in relation to the tectonic setting of the Yucca Mountain Repository, about 50 km to the northeast in Nevada. The paper details relationships we will see briefly at Stop B4. Similarly, these same authors' paper on *Holocene faulting and slip rates along the Black Mountains fault zone at Mormon Point* (Chapter L) uses surficial geologic mapping, morphometric analysis, and soil development to reconstruct late Holocene faulting and slip rates along the Black Mountains fault near Willow Creek, in the same general area as Knott and others' Stop C1.

While he was a visiting undergraduate student at the White Mountain Research Station (Bishop, Calif.) Kurt Frankel was looking for an interesting senior's thesis. USGS geologist Angela Jayko took Kurt under her wing, and guided him south into Death Valley. Frankel, Jayko, and Allen Glazner (his advisor at University of North Carolina) have offered *Some field observations of the morphology of scarps along the Black Mountains fault zone* (Chapter M), which complements field trip Day C and the aforementioned papers on active tectonics.

Art Sylvester reports on 30 years of geodetic research on the Death Valley fault system. Art's paper entitled *Search for contemporary fault creep in Death Valley, 1970-2000* (Chapter N) should establish him as a true "Friend of the late Holocene."

With the passage of the Alquist-Priolo Special Studies Zones Act in 1972, geologists with the California Division of Mines and Geology were required to conduct studies to determine which faults in California are "sufficiently active and well defined as to constitute a potential hazard to structures from surface faulting." In 1989, Chris Wills and William Bryant were assigned to Death Valley. As a result of interpretation of aerial photos and some quick exploration in Death Valley, Chris made a series of observations on the recency of fault movement and discovered evidence for *Liquefaction in the California desert—An unexpected geologic hazard* (Chapter O). Strange as it may seem, the dry basins of the southwest can and do experience liquefaction from strong-ground motion along major faults, such as the Black Mountains fault zone.

One of the most spectacular landscapes in Death Valley National Park is in a high valley in the western part of the Cottonwood Mountains, about 40 km west of Stovepipe Wells. This place is called Racetrack Playa, owing to the unusual phenomenon of rocks that slide across the playa's surface. In Chapter P, Paula Messina and Philip Stoffer report on their recent investigations of the sliding rocks in an article entitled *GIS-based terrain analysis of the Racetrack playa, and implications for the sliding rock phenomenon of Death Valley National Park.*

Finally, we turn our attention to a piece of latest Holocene history in the form of *A History of the Furnace Creek area (1849-1954)* (Chapter Q) by Genne Nelson. Using source materials from the National Park Service, Borax Company, and Furnace Creek Ranch and Inn's archives, Genne presents an engaging summary of this important part of Death Valley's history from its discovery by Mormon Pioneers in 1849 through 1953.

Although not included within the volume, each field trip participants at the FOP meeting received a T-shirt with a striking image on the front. The T-shirt was designed by Michael Rymer of the USGS in Menlo Park. The caption for the image is *Shaded relief map of Death Valley as envisioned during a high stand of Lake Manly.*

**ACKNOWLEDGEMENTS**

This volume was assembled in January 2001 through the hard work of our many authors (see list of contributors), three editors, and Lee-Ann Bradley (USGS-Denver), who revised and improved many of the photographs and illustrations supplied by the authors. In addition, content for the FOP web page that advertised the trip was developed by Debra Block (USGS-Flagstaff) and hosted by Doug La Farge. We appreciate the dedication, resources, and time that each of these individuals volunteered to the Friends of the Pleistocene.

The view is to the north, from high over the Owlshead Mountains in the southern part of Death Valley National Park. The image was created using 30-m DEM data and Landsat TM imagery. Lake Manly occupies an elevation of 30 m (about 100 ft) in this image." This image is similar to the frontispiece for the volume.

We all recognize that doing geology in Death Valley National Park is a wonderful opportunity, but it also presents special problems. Most of the park is designated as wilderness area, so access to vast tracts in the park is limited. Use of mechanized equipment (vehicles, bicycles, power drills, etc.) is restricted. For example, just checking Charlie Hunt's reported lacustrine gravel on Dinosaur Ridge requires a 16-km-long roundtrip hike across Cottonball basin to the base of the Panamint Mountains. Sampling is challenging, requiring special permits that sometimes take more than a year to acquire. Nevertheless, each of us feels that the opportunities greatly exceed the burdens. Staff of the National Park Service, particularly Mel Essington of the Natural Resources Division, have helped many of us over these hurdles, and we appreciate their assistance. In addition, some of the aerial views in this volume were photographed from the National Park Service's light aircraft, which is used routinely to check for stranded visitors in the park.

Over the past few years, the Death Valley Natural History Association has been extremely helpful to many of the geologists involved in the Friends of the Pleistocene. They provided beverages for a one-day field trip during a USGS-DOE-NPS-sponsored meeting on Death Valley geology in Las Vegas, Nevada in April 1999, and continue to provide logistical support and encouragement for our research in Death Valley. In particular, we would like to thank Janice Newton, Director of Death Valley Natural History Association.

# Field trip guide for Day A, northern Death Valley

*Ralph E. Klinger and Andrei M. Sarna-Wojcicki*



## OVERVIEW

For this part of the field trip we will be traveling to northern Death Valley to gaze into a volcanic crater, wander through a canyon cut into uplifted, folded, and faulted upper Pliocene and lower Pleistocene rocks, examine some fine examples of tectonic geomorphology along the Northern Death Valley fault zone, and finish off the day with a plunge into the Lake Manly enigma (fig. A-1). We will attempt to make five stops, two of which will include hikes several kilometers long; the other three stops are literally next to the road. The total driving for the day will be about 208 km (130 mi), for the most part on paved roads. The road to Stop A2 is graded gravel and can be a little rough, but it is usually passable in a passenger car. Services along the field trip route are essentially non-existent; so make sure you have plenty of gas, water, and all those other things you find necessary for your personal survival in remote places. Death Valley National Park encompasses the largest desert wilderness area in North America, and we will be driving on one of the roads into that wilderness. So please, remember where you are and be prepared!

Day A of the field trip has been structured so that we will drive to the northernmost stop and backtrack toward Furnace Creek, making several stops on the return trip. The first stop (A1) will be at Ubehebe Crater where we will look at the product of one of the youngest basaltic volcanic eruption in the continental U.S. The drive from Furnace Creek to Ubehebe Crater will take slightly more than an hour (about 100 km or 60 mi). Anticipating the long drive at the beginning of this day's field trip, the following road log was compiled to occupy your time, maybe help familiarize you with the geography, and perhaps stimulate some morning thought and/or discussion. Because we will be returning on the same route, some of you will undoubtedly figure out that you can catch up on your sleep knowing that anything you miss going north you can see coming back. In order to accommodate this inevitable behavior, the road log lists mileage going both directions and uses references to the highway mileage markers along NPS Route 5. Hopefully, this will also provide an opportunity to roughly follow the road log without having to rely completely on an odometer (or one could use a handheld GPS receiver). Occasionally there will be a road log reference to features that are difficult to see. Generally, these features can best be seen in the rear view mirror or while driving south. Lastly, interspersed into the road log are a few short commentaries, maps, and photographs of sites that are intended to stimulate discussion.

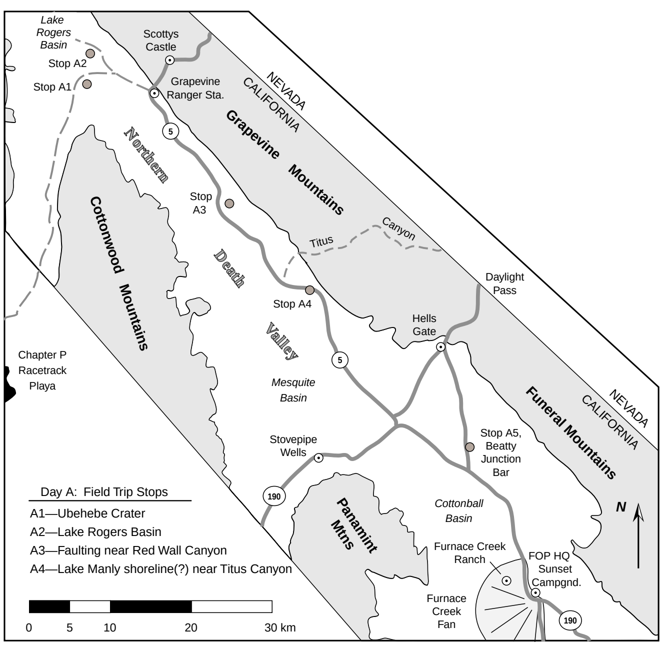


*Figure A-1: Map showing the location of Day A stops.*

## PRELUDE TO DAY A

Hopefully the weather will be warm and beautiful and the wind calm as we load up and get ready to leave the campground. While you're waiting for your other field trip partners and your trip leaders to get organized, you can gaze west across the valley at the Panamint Mountains. The mastiff at the northern end of the range is Tucki Mountain at 2,051 m (6,732 ft). The two large alluvial fans on the east flank of the mountain are the Tucki and Blackwater fans, on the north and south, respectively. The hills protruding through the alluvium between the two washes are comprised of the Cambrian Wood Canyon Formation and Zabriskie Quartzite, and unnamed Tertiary volcanic rocks. Hunt and Mabey (1966) described shingled gravel deposits found at 380 ft on the slopes of these hills as shoreline drift deposits, thus making it the location of the highest reported lacustrine features associated with Pleistocene Lake Manly. In the morning sun, our view of Tucki Mountain and the fans is one of the best in the valley.

If you are the least bit curious about the geology beneath your campsite or sleeping bag, both Texas Springs and Sunset campgrounds and the hotels in the area lie at the northern end of the Black Mountains and the Black Mountain fault zone, some closer than others. At this point in the valley, the Death Valley fault zone splits into numerous strands that are manifested as a series of northerly-trending linear troughs on the surrounding hills (fig. A-2; Stop B1.3). If you are staying in the Texas Springs Campground, several of these strands can be examined first hand in the lower part of the campground where they juxtapose Quaternary alluvium against the older rocks of the Furnace Creek Formation. Northwest of the campgrounds, there is little clear evidence in the surficial deposits of a distinct through-going trace of the Death Valley fault zone. In general, the fault traces are short and discontinuous, are of varying orientation, and exhibit differing styles of deformation. Due to the rather diffuse nature of faulting in the area and the evidence for young deformation in the Texas Spring Syncline, this area is considered to be a “transition zone” between the northern end of the normal Death Valley fault zone and the southern end of the strike-slip Northern Death Valley fault zone. For more details on the geology in this transition area, see the discussion by Machette and others in Chapter B of this guidebook.

Finally, if time permits, this might be a good time to check out the other Chapters in the guidebook. As the day progresses we will be looking at various aspects of the Quaternary geology and geomorphology described in other short articles. Even though we won’t necessarily be stopping at these sites, they certainly are potential topics of discussion throughout the day. Your questions and comments are encouraged.


## ACKNOWLEDGEMENTS

We would like to thank Richard Anderson and Linda Greene of the Natural Resources Office at Death Valley National Park for their help with permitting our studies. We would also like to thank the other trip leaders, contributors to the guidebook, and many of the participants that provided advice, and insightful discussions. The Nevada Operations Office of the U.S. Department of Energy in cooperation with the U.S. Geological Survey and the Bureau of Reclamation supported the work of Klinger as part of the site characterization studies for Yucca Mountain under Interagency Agreement DE-AI08-92NV10874.



*Figure A-2: Vertical aerial photograph of the campgrounds near Furnace Creek Ranch. Several strands of the Black Mountains fault pass through the lower part of the Texas Spring campground (see fig. B1-9). The light-colored beds along the left side of the photograph are lacustrine deposits associated with the 2,000-year-old Lake Manly.*

# Road log for Day A

# Northern Death Valley

*Ralph E. Klinger*

Furnace Creek 7.5' quadrangle
GPS: NAD 27, UTM Zone 11
$^{40}34^{000}$mN $^{5}12^{300}$mE
Elevation: -38.1 m (-125 ft) ASL

Road log on State Highway 190 north to Stop A1 (miles in parenthesis are for reverse trip, from Stop A1 south on State Highway 190).

| Miles | Description |
|---|---|
| 0.0 (51.0) | Reset your odometer at the intersection of the road to the Sunset and Texas Spring Campgrounds with California Highway 190. Drive north on highway 190. |
| 0.3 (50.7) | Furnace Creek Ranch is on the left. |
| 0.6 (50.4) | Death Valley National Park Visitors Center is on the left. Take some time to check out the museum at the Visitors Center. In addition to the usual interpretative displays, there is an amazing hand-made relief map of the valley and a good selection of books on the geology and natural history of Death Valley. |
| 0.9 (50.1) | Road to Furnace Creek Campground is on the left. |
| 1.1 (49.9) | Trace of a northwest-striking (N. 30° W.) fault approaches State Highway 190 on the right. The linear trough on the hillside and apparent right-laterally displaced channels suggest a predominately lateral sense of slip along this fault (Wills, 1989). An archaeological site of unknown age in the hillside trough also appears to have been disrupted by movement on the fault. |
| | The light-brown, salty sand beds along the road on the left (see fig. A-2) are lacustrine deposits that are associated with the late Holocene lake highstand (~2000 yrs B.P.) described by Hunt and Mabey (1966). The elevation of the deposits here is about 67 m (220 ft) below sea level, which immediately seems a little problematic. Hunt and Mabey (1966, p. A79) indicated that an elevation of 73 m (240 ft) below sea level for the late Holocene lake highstand along the west side of the valley near Trail Canyon. They also recognized that the elevation on the east side of the valley near Artists Drive was as much as 6 m (20 ft) lower (79 m or 260 ft below sea level). This 6 m difference in elevation was explained as the result of subsidence related to recent activity on the Death Valley fault zone. The shoreline elevation for the same highstand at the northern edge of Cottonball basin is also reported as 73 m (240 ft) below sea level (Hunt and Mabey, 1966; p. A81), but this is more than 16 km (10 miles) northwest of the northernmost mapped trace of the Death Valley fault zone. Therefore, the highstand elevation was probably about 73 m (240 ft) feet below sea level. The difference of about 6 m (20 ft) between Trail Canyon and Salt Creek on the west and north respectively, and the Furnace Creek campground on the east may be associated with the continuing deformation of the Texas Spring syncline and uplift of the Mustard Hills (see the discussion by Machette and Slate at Stop B2). |
| 1.9 (49.1) | The road to Harmony Borax Works and Mustard Canyon is on the left (this is Stop B2). Borax was discovered in Death Valley in 1873. Between 1883 and 1889 the borate minerals mined from the playa floor just west of here were refined at the Harmony Borax Works before being transported to the railhead at Mojave in wagons drawn by twenty-mule teams (Lingenfelter, 1986). |
| | For about the next mile, the road traverses through the “mustard-colored” mudstone and sandstone beds of the Pliocene Furnace Creek Formation. In this area, a thin veneer of Quaternary gravel caps the Furnace Creek Formation. The unconformable contact between the Furnace Creek Formation and the overlying Quaternary gravel defines an antiform that is associated with the deformation of the Mustard Canyon Hills (again, see discussion for Stop B2). |
| 2.5 (48.5) | The Mustard Canyon road returns to the highway on the left. The road starts at Harmony Borax and follows a short one-way loop through the highly deformed beds of the Furnace Creek Formation, west of the highway. |
| 3.0 (54.0) | Looking to the southwest, note the near-horizontal linear benches on the northeast flank of the Mustard Canyon Hills to the left. They are often assumed to be shorelines, but are actually formed |

by a series of northwesterly-striking (N. 55° W.) faults. The dominant sense-of-slip is assumed to be right-lateral strike-slip due to the near-vertical dip on the faults, their northwesterly strike, and upslope-facing scarps (see the discussion for Stop B2).

3.6 (47.4) The road to the National Park Service Headquarters at Cow Creek is on the right. This area is the subject of Stop B3, which focuses on a discussion of late Holocene faulting by Machette and Crone.

4.6 (46.4) Note the "shorelines" on Park Village ridge, the slope about 1 km to the right. Once again, these are widely cited as shorelines. However, the series of linear, horizontal benches are, in part, low scarps along a series of short, north-striking faults. The faults are exposed in several of the small channels cut into the slope where vertical separation of bedding across the faults is exhibited. Notice the nature of the desert varnish on the slope where the varnish alternates between light and dark across the tread and riser of the benches. This phenomenon has been credited to erosion of the varnish by wave action, but here it actually appears to be the product of soil creep. The lighter-colored areas on the slopes are lobate in plan form and sit topographically higher than adjacent darker varnished areas. Often, the lighter-colored gravel can be observed overlying darker varnished gravel at the toe of the lobes. Apparently, the down-slope movement of the surface soil disrupts the desert pavement, thus destroying or perhaps preventing the formation of rock varnish. The disruption of the desert pavement and associated differences in the varnish is fairly common on steep alluvial surfaces in Death Valley that are underlain by well-developed vesicular A horizons.

A similar disruption of the desert pavement and an accompanying change in the varnish can also be observed across the Echo Canyon fault scarp in Furnace Creek Wash (see Stop B4). On the Echo Canyon scarps, the change in the character of the varnish and desert pavement is attributed to the down slope movement of sediment as the result of recent activity on the fault.

5.9 (45.1) The highway crosses the Salt Spring scarp described by Brogan and others (1991; see fig. A-3). The strike of the scarp at this location is about N. 50° E. In general, the scarp is about 2.3 km long, but discontinuous, being breached by young stream channels. The scarp reaches a maximum height of 3.0 m with a maximum scarp-slope angle of 31°. However, these characteristics might be enhanced in part by fluvial erosion at the base of the scarp. Overall, the scarp is accurate, curving from this point to a strike direction of N. 50° W. about 1 km to the north. Brogan and others (1991) inferred that this scarp was the product of activity on the Death Valley fault zone. However, based on the location of the scarp relative to the Death Valley fault zone (to the south) and the dramatic change in orientation of the scarp to the north, the deformation here is consistent with movement on the southern end

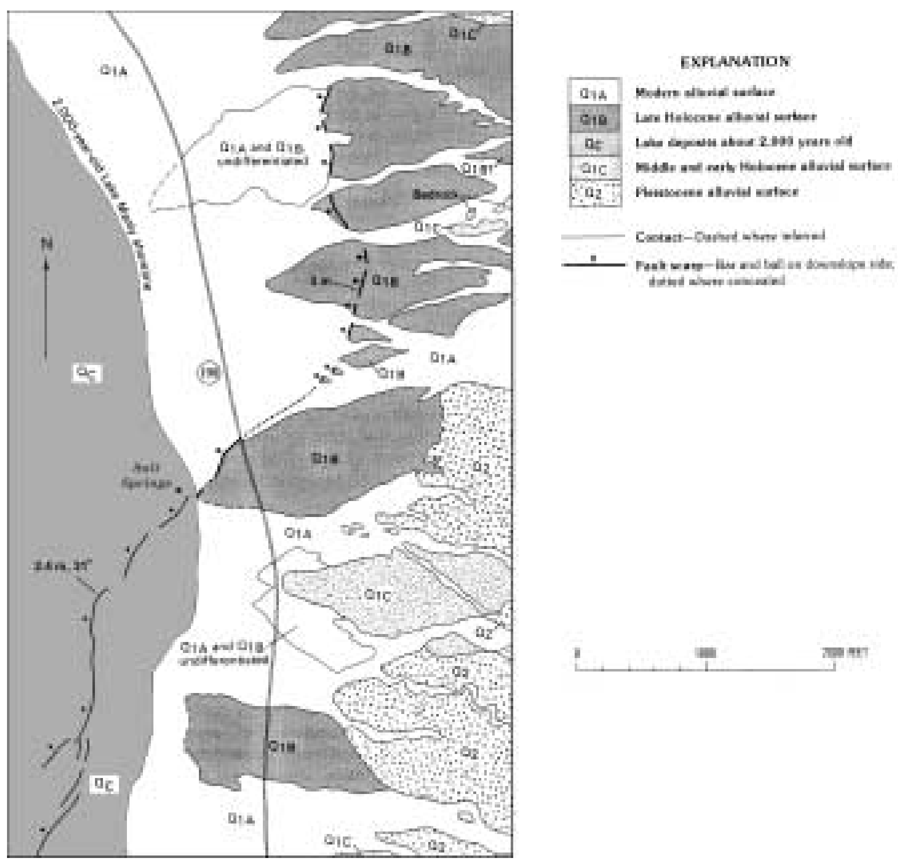


*Figure A-3: Surficial geologic map taken from Brogan and others (1991, p. 14) showing the location of fault scarps near Salt Springs. The elevation of the 2,000-year-old Lake Manly shoreline at this location is about 73 m (240 ft) below sea level.*

of the Northern Death Valley fault zone (see Chapter J for a discussion of fault nomenclature). Because the scarp displaces the late Holocene shoreline, the time of the most recent surface displacement on this section of the fault activity is clearly younger than several thousand years and on the basis of the scarp morphology may be less than a thousand years old (see the discussion of recent faulting at Cow Creek by Machette and Crone, Stop B3). The youthful appearance of the scarp might also be enhanced by the cementation of the alluvium by salts (see discussion on scarp morphology at Mormon Point by Klinger and Piety, Chapter L).

6.5 (44.5) The informally named "Three Bare Hills" are on the right. As many of you may know, Marith Reheis (USGS-Denver) maintained a series of dust traps in the southwestern U.S. for more than a decade to examine the character and influx rate of airborne dust. One of her transects ran from the middle of the Three Bare Hills across the Funeral Mountains into the Amargosa Valley, east of here. A second transect transversed the Grapevine Mountains in the northern part of the valley at Grapevine Canyon (mile 51.0 in the road log) into the Bonnie Claire Flat to the east. The results of her studies are summarized in a series of papers (Reheis and others, 1995; Reheis and Kihl, 1995; Reheis, 1997).

8.0 (43.0) Hunt and Mabey (1966) subdivided the central part of Death Valley into three basins on the basis of structure: the Badwater, Middle, and Cottonball Basins. The playa west of the highway is Cottonball basin, the northernmost of these basins. The saltpan deposits on the playa are considered to be late Holocene in age and are described in detail by Hunt and others (1966), and mapped by Hunt and Mabey (1966) and Wright and Troxel (1993). The Quaternary geology of Wright and Troxel (1993) for the most part follows that of Hunt and Mabey (1966).

Both maps subdivide the saltpan into three major zones on the basis of the dominant salt types that have formed concentrically around the basin. The formation of these major evaporate zones are directly related to the solubility of the dominate salt types with the least soluble salts precipitated around the edges of the playa and the most soluble salts precipitated in the center of the pan. Geochemical analysis by Hunt and others (1966) indicated that the primary salts present in each zone are 1) calcite (calcium carbonate), 2) gypsum (calcium sulfate), and 3) thenardite (sodium sulfate) and halite (sodium chloride). The relative percentages of the various salt types in Cottonball basin relative to other basins in Death Valley is also reported to be highly variable (Hunt and others, 1966). The variability appears to be due to differences in drainage basin characteristics and the geochemistry of the surface waters that flow into the basin (Hunt and others, 1966).

**Table A-1: Correlation Chart for Quaternary Stratigraphy in Northern Death Valley** †

| | HUNT AND MABEY, 1966 | REYNOLDS, 1969 | MORING, 1986 | KLINGER, 2001 |
|---|---|---|---|---|
| | | Q1 | Qf4/Qs | Q4b (historic) |
| **Holocene** | Qg4 | | Qmu | Q4a (0.2-2 ka) |
| | | Q2 | | Q3c (2-4 ka) |
| | Qg3 | | Qf3 | Q3b (4-8 ka) |
| | | Q3 | | Q3a (8-12 ka) |
| | | | | Qlm4/Qlr |
| **Pleistocene** | Qlm | | Qf2c | Q2c (35-60 ka) |
| | | | Ql | |
| | Qg2 | Q4 | Qf2b | Q2b (80-120 ka) |
| | | | Qf2a | Qlm3 |
| | | | | Q2a (>180 ka) |
| | | | | Qlm2 |
| | | | | Q1c (<760 ka) |
| | | | Qf1 | |
| | | | | Q1b (>0.760 ka) |
| | QTg1 | | | |
| | | | | Qlm1 |
| **Pliocene** | | | | |
| | | | Tg/Tb | QT1a (<3.7 Ma) |
| | Tfc | | (<4 to 7 Ma) | |

†For a complete discussion and correlation of the Quaternary sequences developed in the region, also see Menges and Taylor (Chapter H) regarding Quaternary units.

10.0 (41.0) Note that the alluvium along both sides of the road appears to be very young. It is considered to be latest Holocene in age (i.e., Q4b/Q4a; see table A-1) and it masks the trace of the Northern Death Valley fault zone in this area. From just north of Salt Spring (mile 5.9) to beyond Beatty Junction (mile 11.2) there is no clear trace of the fault in the surficial deposits. In this area, the fault is believed to lie southwest of the highway on the basis of aligned vegetation lineaments and a tonal contrast in the alluvium. The widespread occurrence of young alluvium is generally considered to be indicative of a high rate of erosion. However, based on the fact that about 1,300 $km^2$ (500 $mi^2$) of the valley floor is below sea level also suggests that the subsidence rate is outpacing the rate of deposition. The high peak on the skyline ahead is Corkscrew Peak (1,769 m or 5,804 ft), which marks the southern end of the Grapevine Mountains.

11.2 (39.8) Beatty Junction. After climbing the alluvial fans and crossing the pediment at the range front to Hells Gate, the Beatty Junction road continues through Boundary Canyon and over Daylight Pass (5,064 ft) to Beatty, Nevada, about 30 km (20 mi) to the east. The Beatty Junction bar complex is located about 1.8 miles up this road (see Chapter G). The Beatty Junction bar complex is comprised of a series of gravel spits at an elevation of about 46 m (150 ft). The main spit in the complex has been long recognized (Blackwelder, 1954; Clements and Clements, 1953) and is among the most cited examples of lacustrine landforms in Death Valley, following closely behind the shorelines at Mormon Point and Shoreline Butte.

11.9 (39.1) The highway crosses a prominent trace of the Northern Death Valley fault zone near here. The small hill ahead marks the southern-most feature currently recognized as being clearly associated with the fault. The line of low hills ahead delineates the fault to the northwest. Again, note that widespread occurrence of latest Holocene alluvium that masks the surface trace of the fault zone.

12.5 (38.5) On the left, Salt Creek can be seen emerging from the Salt Creek Hills. The Salt Creek Hills, an anticline in the Pliocene Furnace Creek and Pliocene-Pleistocene Funeral formations, forms the structural divide between the Cottonball basin and the Mesquite Flat basin, to the north. Salt Creek currently drains Mesquite Flat into Cottonball basin. The Salt Creek Hills anticline is a northwest-trending, southeast-plunging asymmetric fold that is controlled by the northerly-striking Salt Creek fault across its southeastern end. The faults structural relief on sediment of the Funeral Formation is at least 75 m (about 250 ft); on the older Furnace Creek Formation it is at least a 300 m (about 1,000 ft) (Hunt and Mabey, 1966). Separation of the fold axis across the fault is left lateral oblique with a larger component of vertical separation (Wright and Troxel, 1993). Late Pleistocene terraces along the lower part of Salt Creek on the northeast flank of the anticline have been raised between 3-8 m (10-25 ft) and provide evidence for late Quaternary deformation of the fold (Hunt and Mabey, 1966).

13.6 (37.4) The road to Salt Creek is on the left; the southern end of the Kit Fox Hills is on the right. The low ridge of hills that parallels the highway marks the surface trace of the Northern Death Valley fault zone. The overall morphology of the fault north from here is striking (pun intended), primarily due to the uplifted sequence of late Pliocene and early Pleistocene age terrestrial deposits that form the Kit Fox Hills (QT1a to Q1c; table A1). Hunt and Mabey (1966) originally mapped these hills as undifferentiated Miocene sedimentary rocks (their unit Ts) that were considered to be younger than the Titus Canyon Formation (less than about 22 Ma), but older than the Pliocene Furnace Creek Formation (>6 Ma). Wright and Troxel (1993) later mapped these rocks as the conglomerate facies of the late Pliocene-early Pleistocene Funeral Formation. However, in the southern part of the hills several interbedded rhyolitic ash beds that include the 0.66-Ma Lava Creek B suggest that the rocks may be correlative with the early Pleistocene Mormon Point formation that is informally described by Knott and others (1999; see also Stop C1).

Despite the apparent vertical sense of slip across the fault, evidence in the escarpment along the Kit Fox Hills, laterally deflected stream channels, small shutter ridges, and other geomorphic features along the fault indicate that the last several earthquakes have had predominately right-lateral strike slip motion. However, the relative uplift of the Kit Fox Hills, the formation and continued deformation of the Salt Creek Hills anticline, and the overall morphology of the valley where it narrows at the divide between Cottonball basin and Mesquite Flat are supportive of northeast-southwest directly compression across the fault zone in this area. It is believed that the relative shortening across the valley is related to rotation of the

Panamint Mountains with differential movement between the Panamint Mountain block and Mesquite Flat basin to the north being accommodated along the Towne Pass fault (Blakey and others, 1999; Klinger, 2001)

14.8 (36.2) Sea level sign

15.3 (35.7) The low hills along the left side of State Highway 190 for the next several miles are lacustrine deposits associated with one or more highstands of Lake Manly. The deposits are comprised of cross-stratified sand and sandy gravel that formed along the northern margin of the lake at elevations between sea level and about 165 ft above sea level. Hunt and Mabey (1966, p. A69) stated, "Late Pleistocene lake features in Death Valley are few, small and not at all distinct" (see discussion in Chapter G, this volume). However, it is believed that this statement simply reflects the general nature of the studies that had been completed at that time (Russell, 1885, 1889; Gilbert, 1890; Bailey, 1902; Gale, 1914; Noble, 1926; Means, 1932; Blackwelder, 1933, 1954). The terrestrial record of lakes in Death Valley will undoubtedly improve given enough attention. The number of studies focusing on the lakes in Death Valley has increased significantly in recent years (Hooke, 1972; Dorn and others, 1990; Li and others, 1996; Anderson, 1998; Knott, 1998; Ku and others, 1998; Hooke, 1999; Lowenstein and others, 1999; and several others).

15.9 (35.1) The green area on the valley floor to the left is known as the Devils Cornfield. This meadow-like environment is formed where the shallow groundwater has been forced towards the surface. Salt Creek heads at the upper end of this meadow near the southern end of the Stovepipe Wells dune field (visible to the west).

16.3 (34.7) The trace of the Northern Death Valley fault zone is against the base of the hills to the right (fig. A-4). The white silt bed on the slope overlies a 0.5-m-thick ash bed tentatively identified as the Lava Creek B (0.66 Ma). The ash bed is a single 50-cm-thick layer interbedded with Kit Fox Hills alluvium and older lacustrine sediment (the silt bed). At this particular location, the ash is exceptionally clean, nearly pure grayish-white ash; it contains large phenocrysts of biotite, and shows little indication of having been extensively reworked. The results of electron microprobe, energy-dispersive x-ray florescence, and instrumental neutron activation analyses compare well with the Lava Creek B in Lake Tecopa and five other ash beds in Death Valley identified as the Lava Creek B (see Sarna-Wojcicki and others, Chapter E in this volume).

17.3 (33.7) The low hills on the left are lacustrine deposits associated with a highstand of Lake Manly. The Stovepipe Wells dune field is visible ahead. The dune field is formed in the southern end of the Mesquite Flat structural basin between the "wells" at Stovepipe Wells and the "community" of Stovepipe Wells, 10 km (6 mi) to the southwest.

17.7 (33.3) Turn right (north) onto NPS Route 5. Note that the National Park Service has installed milepost signs at intervals that are occasionally a mile apart from this point northward. Due to the general lack of geographic place names and named landmarks in the northern part of the valley, these

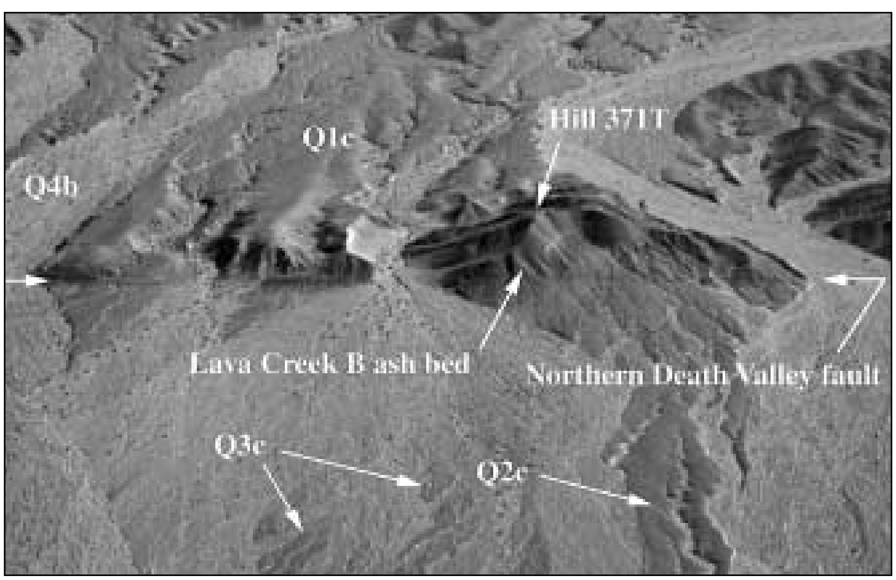


*Figure A-4: Oblique aerial view of the Kit Fox Hills about 1.9 km south of Mud Canyon. The thin, white bed crossing the slope on Hill 371T (see Stovepipe Wells NE 7½' quadrangle) is a Qlm2 deposit interbedded with the Q1c alluvium. This Qlm2 bed immediately overlies a 0.5-m-thick ash bed identified as the 0.66 Ma Lava Creek B. The Northern Death Valley fault lies at the base of the hills (horizontally across the center of the photograph) (photograph by J.R. Knott).*

mileposts are included as part of the road log to help you navigate.

18.2 (32.8) To the right is Mud Canyon Road. This road crosses the trace of the Northern Death Valley fault zone at the mouth of canyon and follows Mud Canyon through the Kit Fox Hills to Hells Gate, where it joins the Beatty Junction road. Hells Gate is at the apex of the fan and offers a great overview of Death Valley to the south. From Hells Gate, one can look down the axis of Death Valley more than 80 km (50 mi).

18.4 (32.6) "Rest Area" 50 km (32 mi) to the next enclosed space at the Grapevine Ranger Station. Having second thoughts about that last cup of coffee this morning?

18.6 (32.4) The low hills to the west of the highway (Route 5) are the remnants of sandy beach bars that formed along the ancient shorelines of Lake Manly. At this site, the beach bars are overlain by eolian sand and surrounded by latest Holocene alluvium (Q4). Although the bars have been dissected and eroded, a relict bar crest is preserved at this site at an elevation of about 165 ft. All of the alluvial-fan deposits along the highway appear to be of latest Holocene age based on the distinct bar-and-swale topography, the lack of desert pavement and varnish formation, and little or no soil development. Also note the lack of vegetation and the presence of sand in the channels formed on the fans in this area. In this area, the level of eolian activity may be responsible for the low vegetation density. Ventifacts (wind shaped clasts) are common on the fan surfaces.

For the about the next 25 km (15 mi) we will be driving along the eastern margin of the Mesquite Flat basin, the northern-most and highest basin of Lake Manly. Lacustrine deposits and shoreline landforms associated with high stands of Lake Manly are preserved along much of this margin.

19.7 (31.3) Milepost 2. The range on the skyline to the west is the Cottonwood Mountains. The large alluvial fan along the west side of the valley is the Cottonwood Canyon fan, which is relatively young (i.e., Q3/Q4), but it is one of the more spatially extensive fans in Death Valley covering about 65 km$^2$, very similar to the Furnace Creek fan. Much of the sand in the Stovepipes Wells

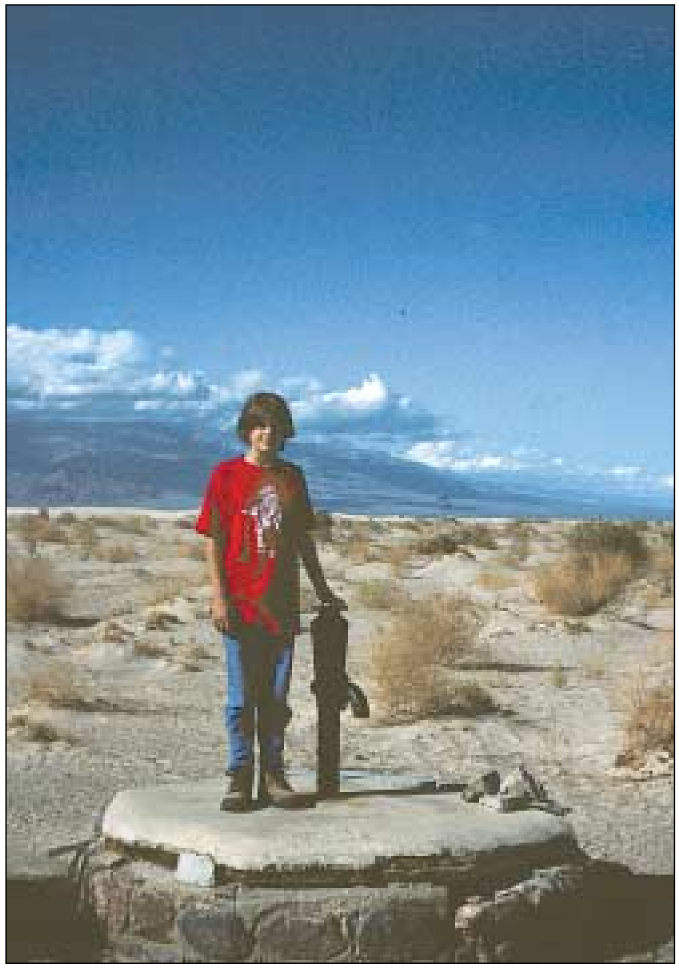

*Figure A-5: A young field assistant standing on the "well" at Stovepipe Wells.*

Table A-2: Archaeological chronology of Death Valley[1]

| Phase | Age | Characteristics |
|---|---|---|
| Death Valley I | Late Pleistocene (?) to Holocene | Lake Mojave projectile points |
| Death Valley II | About 3000 B.C. to 1 A.D. | Corner-notched projectile points |
| Death Valley III | About 500 A.D. | Bow-and-arrow technology, metates, manos, and pestles; rock alignments |
| Death Valley IV | About 1100 A.D. to historical | Pottery, basketry; side-notched triangular projectile points; rock art |

[1]Derived from Hunt, 1960.

dune field is derived from this and the other alluvial fans formed around the margins of the Mesquite Flat basin. The Stovepipe Wells dune field appears to be relatively young. Although its age is not precisely constrained, the dunes are estimated to be less than 2,000 years old. In other areas of the valley, the dunes overlie and contain archaeological artifacts associated with the Death Valley III period (see table A-2).

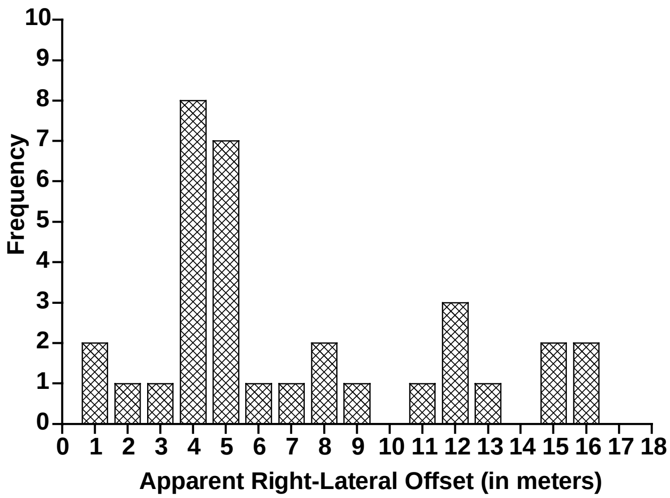


*Figure A-6: Frequency plot of apparent right-lateral offsets measured along the Northern Death Valley fault (n=33).*

20.6 (30.4) The Stovepipe Wells dune field and road to Stovepipe Wells (fig. A-5) are on the left. The sand in the dune field is between about 36 and 46 m (120 and 150 ft) thick and overlies young alluvium on the margins of Mesquite Flat and probably older lacustrine sediments in the center of the basin. The largest single dune in the field is a star dune whose crest rises to just over 24 m (80 ft) above sea level. Most of the dunes along the eastern margin of the field to the left are transverse and small nabkhas dunes.

21.2 (29.8) A low scarp along the Northern Death Valley fault zone is visible on the right. From Beatty Junction north to Sand Spring, a distance of about 105 km, the fault is marked by a shallow trough, offset stream channels, beheaded or truncated bars, and other tectonic features commonly associated with strike-slip faults. Right-lateral offset of streams in late Holocene deposits along the fault generally range from 1 and 8 m. Measurements along single strands of the fault indicate that the average right-lateral offset of distinct piercing points attributed to the youngest event is about 4.5 m (fig. A-6). This value certainty is not representative of the slip along the entire length of the fault, and is probably more an artifact of preferential preservation (i.e., the larger offsets are more likely to be preserved relative to smaller offsets). A crude estimate of the magnitude for an earthquake that ruptures the entire length of the fault (at least 105 km) with an average slip of about 2.5 m (considering the 4.5 m as a maximum instead of the average) is about Mw 7.2. Assuming that 6 m more closely approximates the maximum displacement, dePolo and Hess (1999) estimated the magnitude to be Mw 7.4. Either way, Las Vegas will certainly experience the ground shaking from such an earthquake when it happens.

22.6 (28.4) Milepost 5. On the right—another low scarp along the Northern Death Valley fault zone.

22.9 (28.1) Nabkhas dunes on the left formed around a small group of screwbean and honey mesquite (*Prosopis pubescens and Prosopis juliflora glandulosa*, respectively). The term “nabkhas” follows the usage of the North African word suggested by Cooke and others (1990; p. 356) for dunes formed around vegetation as opposed to the terms bush mounds or coppice dunes that have been used to describe these features. Nabkhas dunes are quite common along the margins of the Stovepipe Wells dune field and are the principle landform in the northern part of Mesquite Flat. The mesquite also provided a primary food source for prehistoric cul-

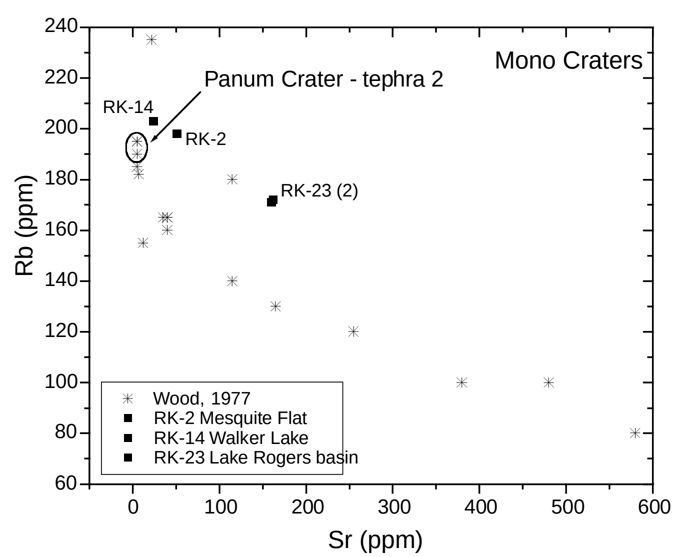


*Figure A-7: Comparison of rubidium and strontium ratios for tephra beds found in northern Death Valley to late Holocene ashes erupted from the Mono Craters volcanic chain.*

tures in the area and their abundance is also an obvious choice as a namesake for the basin.

At a site about 8.7 km (5.4 mi) northwest of here, a 2- to 3-cm-thick rhyolitic ash bed is interbedded with dune sand near the base of a nabkhas dune. The ash is exposed in a low, east-facing scarp along the fault. A comparison of the major element oxide composition of the volcanic glass indicates that the ash bed is similar to a number of the Mono Craters ashes erupted from the Mono-Inyo Craters volcanic field. Based on comparisons of the trace element composition, the ash bed is tentatively correlated to the tephra 2 ash bed of Wood (1977; see fig. A-7) that erupted from Panum Crater at about 1190 ± 80

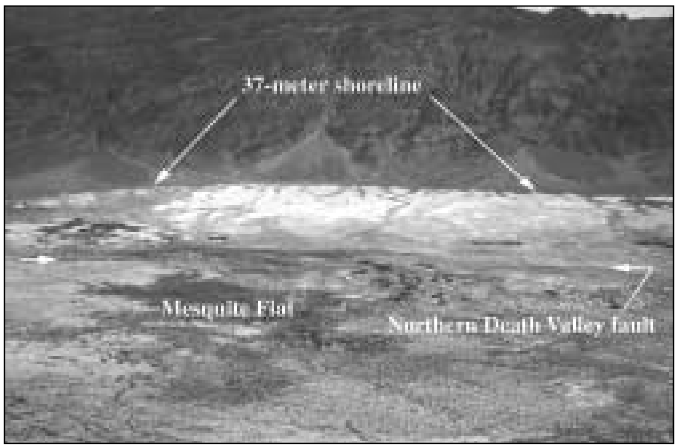


*Figure A-8: Oblique aerial view of the 37 m shoreline along the eastern margin of Mesquite Flat between Titus and Titanothere Canyons.*

$^{14}$C yrs B.P. (950 and 1270 cal years B.P.). The occurrence of a Panum Crater ash in Death Valley had not been previously reported, but is consistent with the direction of ash distribution reported by Wood (1977). The presence of a late Holocene Mono Craters ash bed near the base of the dunes also supports the 2,000 yr age interpretation of the dunes by Hunt and Mabey (1966) based on archaeological correlations.

23.9 (27.1) Another low scarp along the Northern Death Valley fault zone is visible on the right.

24.5 (26.5) Milepost 7. The highway crosses the Northern Death Valley fault zone in the gentle curve ahead. Northwest of the road, the fault is marked by the low ridge of hills and a small group of California desert fan palms (*Washingtonian filifera*) that can be seen growing at a spring along the fault. The highway climbs up the escarpment formed by the fault at the northern end of the Kit Fox Hills onto a Lake Manly beach preserved at about 34 m (110 ft) above sea level. At this site, the lacustrine sediment laps on the Q2c alluvium (this is one of those rear-view mirror opportunities).

As you drive along for the next several miles, the highway follows the contact between the alluvial fans shed off of the Grapevine Mountains on the right and the lacustrine deposits of Lake Manly on the left. This shoreline is nearly continuous from here to the toe of the Titus Canyon fan (see fig. A-8). Note that there are numerous sites along the road between here and Titus Canyon where Holocene alluvium (i.e., Q3/Q4) overlies or is inset into the lacustrine sediments, but no where in this area is there evidence of late Pleistocene or older alluvium (Q2c and older) overlying the lacustrine sediments.

26.0 (25.0) The mouth of Titanothere Canyon is on the right at the range front. This canyon is named after the large rhinoceros-like mammal (*Brontotherium*) found in Oligocene deposits in the area. Be sure to see the replica of the Titanothere skull when you go to the Death Valley Museum. Also note the remnants of Pleistocene alluvial fans preserved between the highway and the range front.

On the left is Mesquite Flat, which on the basis of geophysical evidence, is the deepest basin in Death Valley: it has at least 5 km and perhaps >7 km of alluvial fill (Blakey and others, 1999). The Mesquite Flat basin is a triangular-shaped block that is bounded by the Towne Pass fault and Salt Creek Hills anticline on the south, the Cottonwood Mountains on the west, the Grapevine fault on the east, and is bisected by the Northern Death Valley fault zone. Displacement on the Towne Pass fault appears to be primarily dip-slip, but probably includes a measurable component of left-lateral slip based on the orientation of the fault relative to the Northern Death Valley fault zone. The Grapevine fault was first described by Reynolds (1969) at the range front of the Grapevine Mountains between Titanothere Canyon and Red Wall Canyon. The Grapevine fault is a northwesterly-striking (N. 35° W.), normal dip-slip fault that parallels the Northern Death Valley fault zone; the Grapevine shows evidence of late Quaternary activity, but little is known about the structural relationship between the two faults. Reynolds (1969) proposed that the Mesquite Flat block had formed as the result of collapse on the basin-bounding normal faults in

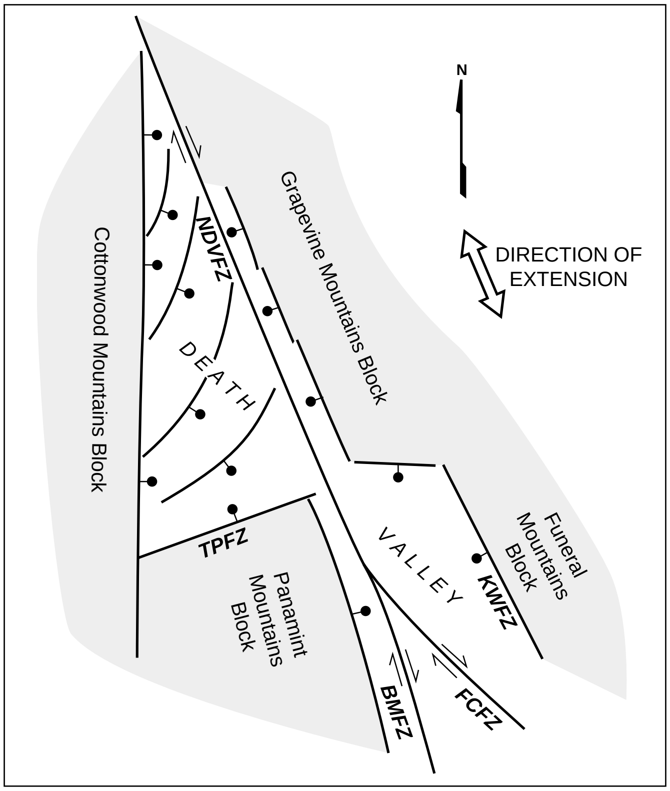


*Figure A-9: Reynolds (1969) schematic tectonic model for part of northern Death Valley (Mesquite Flat). The model illustrates the possible pull-apart and collapse of the valley along basin bounding normal faults (in KWFZ, Keane Wonder fault zone; TPFZ, Towne Pass fault zone) in response to lateral movement along the Northern Death Valley fault zone (denoted NDVFZ). The size of the bar and ball on the normal faults is proportional to amount of vertical displacement expected given this configuration. Some horizontal movement would also be expected on the faults bounding the east flank of the Cottonwood and Panamint Mountains blocks (BMFZ, Black Mountains fault zone; FCFZ, Furnace Creek fault zone) (modified from Reynolds, 1969).*

response to right-lateral displacement on the Northern Death Valley fault zone (fig. A-9). There are a few problems with this model, but there is some evidence to support it as well. More recently, Blakey and others (1999) on the basis of geophysical data, and Klinger (2001) on the basis of geomorphic evidence and Quaternary deposition, suggest that the basin may have been formed by rotation associated with the separation of the northern end of the Panamint Mountains and southern end of the Cottonwood Mountains.

28.3 (22.7) Note the difference in varnish formation on the different-aged lobes of the very steep alluvial fans shed off of Grapevine Mountains on the right. The degree of varnish formation on the alluvial-fan surfaces is one of the relative age criteria used to differentiate the alluvial deposits in northern Death Valley (Klinger and Piety, 1996). Other relative age parameters used in developing the stratigraphic sequence in the northern Death Valley include the preservation of bar-and-swale morphology, the relative extent of desert pavement evolution, and the degree of soil development. The nomenclature used follows that which Bull (1991) developed for the southwestern U.S., with a few age adjustments (see discussion for Stop A3).

28.5 (22.5) Milepost 11

29.4 (21.6) "Alluvial fan" pullout. The alluvial fan directly ahead is the subject of a classic paper written by Chester Beatty in 1961 in which he describes the topographic effects of faulting on alluvial-fan morphology along the Grapevine fault. He outlines the arguments regarding the entrenchment of alluvial fans in response to climate change, but makes a strong case in this instance for some of the dissection being the direct result of tectonics. We will be stopping near this site in the afternoon, so if you are not familiar with this paper, take a moment then to hike a little closer, take few pictures, and make a few observations. When you return home, get a copy of the paper and check it out: it is a very concise paper by a very observant scientist that is no longer with us. However, draw your own conclusions about the effects of climate versus tectonics.

29.5 (21.5) Milepost 12

30.7 (20.3) On the left is the Titus Canyon tufa deposit. We will be stopping here on the return trip (Stop A4) to look at a thinolitic tufa preserved along the shoreline of Lake Manly. The shoreline at this point is about 37 m (120 ft) above sea level. Lacustrine deposits associated with this shoreline west of this site have either been buried by Titus Canyon alluvium, and further west, by deposits from the south-flowing Death Valley Wash.

31.4 (19.6) The large alluvial fan directly ahead on the eastern flank of the Cottonwood Mountains is the Dry Bone Canyon fan. In 1933, Elliot Blackwelder described the white beds on the valley floor just south of this fan as deposits associated with Lake Manly. The eroded beds are comprised of silt and sand interbedded with chalk and dense limestone. The elevation at the top of these beds, now known as the niter beds, is also about 37 m (120 ft) above sea level. Nitrate salts in these beds are also found in the soils formed

*Figure A-10: Oblique aerial view of the scarp along the Northern Death Valley fault at the toe of the Titus Canyon fan (photograph by M.N. Machette).*

on the alluvial fans along the eastern margin of Mesquite Flat. On the return trip, this is a good spot to view the preserved shoreline along the eastern margin of Mesquite Flat (fig. A-8).

31.9 (19.1) A northeast-facing scarp of the Northern Death Valley fault is visible approaching the road from the left. The highway climbs the fault scarp and crosses the fault in the gentle curve ahead.

32.5 (18.5) On the right is Titus Canyon Road. This dirt road climbs the alluvial fan to the mouth of Titus Canyon. Throughout the park, the NPS has excavated a number of small gravel pits as a source of aggregate for road construction and maintenance. One of these pits is adjacent to the scarp just south of the Titus Canyon Road. The fault is exposed in several of the small rills that have formed on the western wall of the pit. Unfortunately, due to the coarse grained nature of the deposits and the predominately strike-slip movement of the fault, little information pertaining to the recent activity of the fault could be developed at this site. The low east-facing scarp along the Northern Death Valley fault parallels the highway for the next several miles (fig. A-10). Note the degree of desert varnish and pavement development of the alluvial fan surface adjacent to the scarp.

33.5 (17.5) Milepost 16. The south-flowing drainage on the left is Death Valley Wash, which connects the Lake Rogers basin in the northern part of Death Valley with Mesquite Flat. The elevation at the point where Death Valley Wash currently crosses the structural margin on the southern edge of the basin is about 680 m (2,230 ft). From that point, the wash drops more than 600 m (about 2,000 ft) over 32 km (20 mi) to an elevation of about 52 m (170 ft) near here; a gradient of about 19 m/km (110 ft per mile).

35.1 (15.9) The road crosses the trace of the Northern Death Valley fault zone. If you crane your neck around or look in the rear-view mirror, you can see the niter beds along the western margin of Mesquite Flat. Towne Pass is the low pass on the skyline that crosses between the Panamint Mountains on the south and the Cottonwood Mountains on the north.

At this point, we are about midway between Salt Spring and Sand Spring, the respective southern and northern ends of the Northern Death Valley fault zone. Between these points, the fault is generally marked by a clearly defined, linear surface trace. However, based on changes in the geomorphology, the fault can be divided into three sections, each about 30-35 km long. These sections are named the 1) the Kit Fox Hills, 2) the Mesquite Flat-Screwbean Spring, and 3) the Grapevine Mountain. The boundaries between each of these sections is marked by slight changes in strike and continuity of the surface trace, the position of the fault in the valley relative to the range, but primarily on the nature of the rocks found immediately adjacent to the fault.

The Kit Fox Hills section extends from the southernmost clear trace of the fault near Salt

Springs along the Kit Fox Hills to Triangle Spring (mile 5.9 to about mile 25). Along this section of the fault, both structural and geomorphic evidence is indicative of compression across the fault. The fault is marked by a very linear trace along the uplifted upper Pliocene and lower Pleistocene rocks that form the Kit Fox Hills. The valley in this area is markedly narrower and the elevation of the valley floor increases dramatically from less than 73 m (240 ft) below sea level at Salt Springs to more than 37 m (120 ft) above sea level at Triangle Spring. In addition, this section of the fault is associated with folding (e.g., Salt Creek Hills anticline) and secondary faulting.

The Mesquite Flat-Screwbean Springs section extends from Triangle Spring (about mile 25) northward across the valley floor, along the Grapevine Mountains piedmont to Screwbean Spring (at about mile 47). This section of the fault coincides with the valley axis and parallels the normal dip-slip Grapevine fault for much of its length. A low, linear scarp on latest Quaternary deposits generally marks the fault along this section.

The Grapevine Mountains section extends from Screwbean Springs (at about mile 47) to the area near Sand Spring (a point about 8 mi northwest of Stop A2). Much of this section is marked by a very linear trace along the base of the Grapevine Mountains, with Tertiary basaltic rocks and welded tuffs along the southern part of the section and Paleozoic carbonate rocks to the north. This section is similar to the Kit Fox Hills section in that structural and geomorphic evidence along this section is indicative of compression across the fault. The Death Valley Wash fault, an east-verging reverse fault, parallels much of this section of the Northern Death Valley fault zone.

35.5 (15.5) Milepost 18

36.6 (14.4) An old road can be seen to the left crossing Death Valley Wash. This road, which is now closed, used to cross the valley along the northern margin of Mesquite Flat to the lacustrine (niter) beds of Blackwelder (1933).

On the right, the canyon with the red rocks at its mouth is Red Wall Canyon. Our third stop today (A3) will be to look at an alluvial fan that has been offset several hundred meters across the Northern Death Valley fault zone. That alluvial fan has been loosely referred to as the Redwall fan (Brogan and others, 1991; Klinger and Piety, 1996), despite the fact that the fan is located

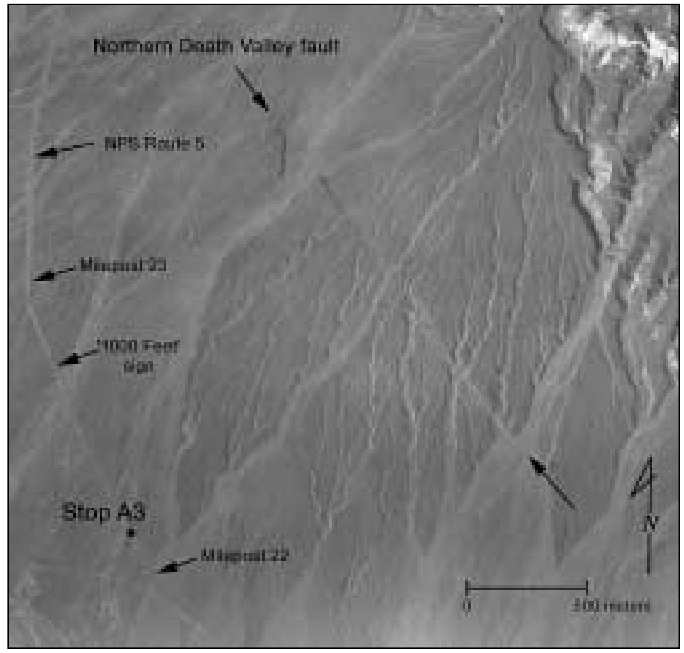


*Figure A-11: Vertical aerial photograph of an alluvial fan offset by the Northern Death Valley fault. The fault exhibits both east- and west-facing scarps, right-laterally offset drainages, sediment filled depressions, en echelon furrows, shutter ridges, and hillside troughs.*

more than 2.5 miles west of Red Wall Canyon. The misapplication of the name is part of the geographic place name problem.

37.4 (13.6) Milepost 20

38.0 (13.0) Note the Pliocene section along the front of the Grapevine Mountains to the right. Reynolds (1969) suggested that Mesquite Flat formed in response to lateral movement along the Northern Death Valley fault zone (i.e., a pull-apart) and collapse along normal faults on the margins of basin. This model would require that the greatest amount of vertical displacement on the Grapevine fault should be on the southern portion and that slip would decrease in a northerly direction along the fault. This hypothesis is supported by reports of Quaternary movement along the southern end of the fault and the deepest portion of the basin in Mesquite Flat (Brogan and others, 1991; Klinger and Piety, 1996; Blakely and others, 1999) with Pliocene rocks overlying the fault at its northern end.

38.5 (12.5) Milepost 21

39.4 (11.6) Milepost 22. We will be stopping at a point between Milepost 22 and the 1,000 feet elevation sign ahead on the return trip (Stop A3) to look at some textbook examples of the tectonic geomorphology along an active strike-slip fault (fig. A-11). In addition, we will take a look at the surface characteristics of the different-aged alluvial-fan surfaces and some archaeology on our short hike up the fan. The hike up the fan to the fault is much easier in this area where the desert pavement on the alluvial fan surface is well developed.

40.0 (11.0) "1000 feet" elevation sign

40.4 (10.6) Milepost 23

40.6 (10.4) "Radiator water" sign

41.5 (9.5) Milepost 24

41.6 (9.4) Radiator-water tank. For as long as I can remember this tank has been sitting along the road at this location (at least the past 25 years). If it becomes a historical feature, then we can call the canyon to the right "Water Tank Canyon." By then the alluvial fan might have moved several more meters to the northwest, and then we can call it the "Water Tank alluvial fan." Is this how we create geographic place names? The trace of the Northern Death Valley fault zone lies adjacent to the road on the right as we round the curve.

42.9 (8.1) The road crosses the Northern Death Valley fault zone. On the left for the next mile or so, the road follows a high scarp that forms a large shutter ridge. The shutter ridges formed where an older and topographically higher alluvial fan has been juxtaposed against younger and topographically lower terrain. Note that these deposits on the left (west) have a well developed calcic soil horizon, which is characteristic of Q2c alluvium in northern Death Valley.

43.4 (7.6) Milepost 26

43.9 (7.1) This point along the road is known to NPS personnel as the "Big Dip." The scarp at this location is about 23 m high and has a scarp-slope angle of about 31°.

44.1 (6.9) Highway crosses the Northern Death Valley fault zone.

44.4 (6.6) The next mile or so of the drive offers a great view of Death Valley Wash and the alluvial fan sequence along the east flank of the Cottonwood Mountains on the left. The high peak at the northern end of the Cottonwood Mountains is Tin Mountain at 2,728 m (8,953 ft). Death Valley Wash has incised the toes of the alluvial fans as much as 12 m (40 ft) and a sequence of low late Holocene terraces has formed adjacent to the wash in this reach. Also note that the alluvium along the road here is Holocene in age (Q3/Q4).

Most of the drop in elevation between Lake Rogers basin on the north and Mesquite Flat basin on the south has been over the last 15 km (about 10 mi). Remember that radiator water sign? We have seen many an overworked motor home or overloaded family sedan dragging a trailer boiling over on this stretch of road.

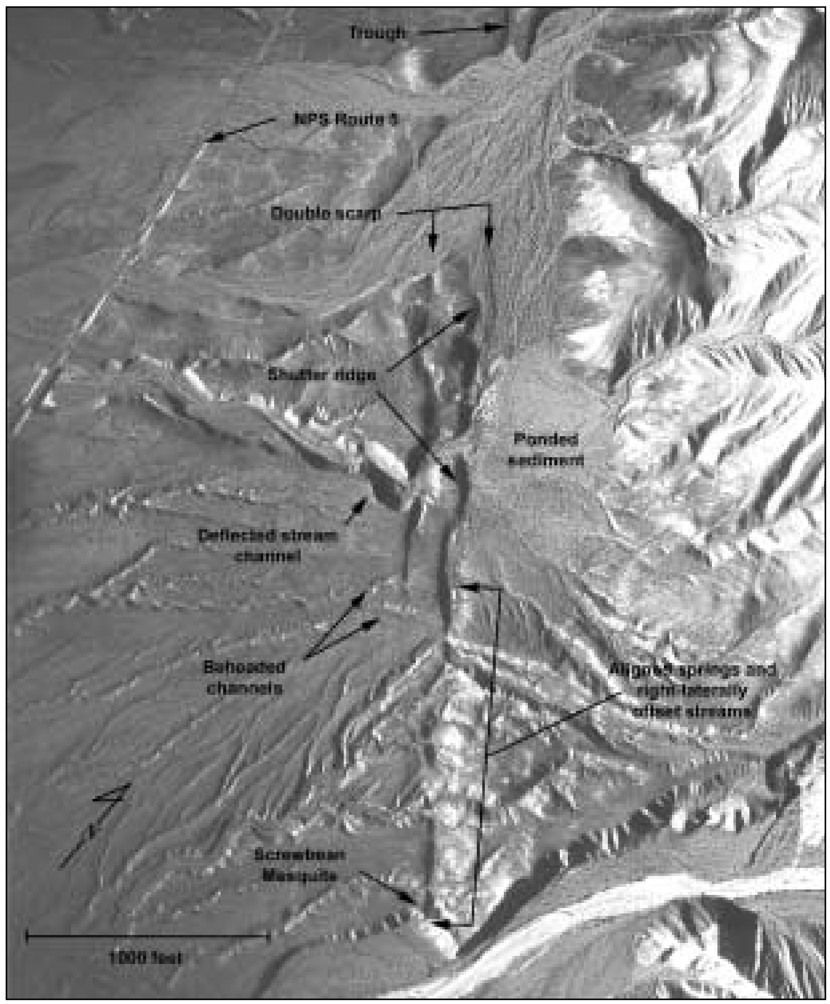


*Figure A-12: Vertical aerial photograph of the Northern Death Valley fault zone at a site referred to as Screwbean Springs. This site marks the northern end of the Mesquite Flat-Screwbean Springs section of the fault zone. Tectonic geomorphology preserved along the fault in this area provides a good example of recent and recurrent strike-slip deformation.*

46.4 (4.6) Milepost 29. On the return trip, there is also a great view down valley across Mesquite Flat of the Stovepipe Wells dune field and northern end of the Panamint Mountains.

47.0 (4.0) The Northern Death Valley fault zone lies against the hills about a kilometer up the wash, to the east (see fig. A-12). This area is referred to as Screwbean Springs because of the small group of Screwbean mesquite trees (*Prosopis pubescens*) found growing at several aligned springs along the fault. Deflected and beheaded stream channels, linear troughs, shutter ridges, and ponded sediment mark the fault northwest of Screwbean Springs. A number of stream channels have been right-laterally offset between 15-18 m (50-60 ft) at this site.

47.4 (3.6) Milepost 30. A late Pleistocene alluvial fan surface with well-developed desert pavement and varnish adjacent to the road on the right provides the easiest access to Screwbean Springs and the area illustrated in figure A-12.

47.9 (3.1) On the left, eight low hills can be seen protruding through the alluvium on the east flank of the Cottonwood Mountains. The 3.1-3.4 Ma tuff of Mesquite Spring caps the northern-most hill. The highly dissected beds at the northern end of the Cottonwood Mountains comprise the Ubehebe Hills of Snow and Lux (1999) and are underlain by Tertiary basin-fill sediments that record the early tectonic development and formation of northern Death Valley.

48.3 (2.7) Milepost 31

48.5 (2.5) The low discontinuous scarp that parallels the road for the next quarter mile marks the trace of the Northern Death Valley fault zone.

49.0 (2.0) Mesquite Spring and the Mesquite Spring campground are visible on the valley floor adjacent to Death Valley Wash. The white beds are deposits associated with a series of springs formed along the toe of the Grapevine Canyon alluvial fan. One of the mesquite trees growing near the spring at the entrance to the campground has been reported to be more than 1,000 years old. Although the source of the age is unknown (there is an interesting story behind this allegation), the largest tree in the bosque is about 80 cm in diameter at a meter above its base. Considering how slowly these trees grow in this environment, 1,000 years certainly seems like a reasonable estimate.

North of Mesquite Spring along the axis of the valley there is a low linear ridge of hills that have been uplifted and folded along Death Valley Wash fault. Brogan and others (1991) mapped linear features associated with this fault, but the fault was not specifically described in the text of their report. Bryant (1988) referred to the fault as the Death Valley Wash fault and cited Brogan (1979) as the source of the name. We will be examining the upper Pliocene and lower Pleistocene section that has been faulted and uplifted along the Death Valley Wash fault in the Lake Rogers basin at our second stop today (A2). Pumice fragments eroded from the Mesquite Spring tuff exposed at the base of the section have been carried to Mesquite Flat by Death Valley Wash.

49.8 (1.2) On the right is the original Grapevine Ranger Station site. Remnants of the concrete foundation and plumbing remain at on a "reconstructed" desert pavement. The hill on the right side of the road ahead is a large shutter ridge along the fault.

50.1 (0.9) The road crosses a stream channel that has been deflected by the shutter ridge more than 400 m along the fault.

50.4 (0.6) The road to the left leads to Mesquite Spring Campground. The campground is located adjacent to Death Valley Wash about 3 km (2 mi) down the Grapevine Canyon alluvial fan. If you enjoy camping, but want to avoid the masses of tourists that flock to the Furnace Creek area, this is a wonderful place to camp in the spring and fall. The elevation of the campground is about 600 m (about 2,000 ft), so the weather in the winter can be cold and occasionally snowy.

50.6 (0.6) Highway crosses the fault just north of the low pressure ridge on the right. The fault then passes through the parking lot between the NPS check station ahead and Grapevine Ranger Station on the left (fig, A-13).

51.0 (0.0) At the mouth of Grapevine Canyon, turn left (northwest) onto the road to Ubehebe Crater. Scotty's Castle is located about 5 km (3 mi) up Grapevine Canyon. There are minimal services available at the castle, but if you have more money than gas, this is where you need to go.

51.6 A low shutter ridge on the right marks the location of the fault.

51.9 The road crosses a fault scarp formed along a synthetic (or Riedel shear) associated with the main trace of the Northern Death Valley fault zone, which is located to your right at the range front.

52.6 The road to Scotty's Ranch turns off on the right. Scotty's Ranch is the lesser known contemporary to Scotty's Castle. Ranch buildings can be seen hidden in the vegetation growing around Grapevine Springs. The ranch is closed to the public due to its archaeological significance and the abundance of pre-historical and historical artifacts surrounding the springs.

53.8 Big Pine Junction. Take the left fork to Ubehebe Crater and our first stop (A1). We will return to this turnoff and travel about 6 km (4 mi) up this road to Stop A2.

54.1 The road crosses Death Valley Wash and the trace of the Death Valley Wash fault.

54.6 To your right, Death Valley Wash can be seen exiting the Lake Rogers basin through the folded and faulted Pliocene-Pleistocene section. The light-colored beds forming the vertical cut along the east side of the wash is the 3.1-3.4 Ma tuff of Mesquite Spring.

56.4 The road splits; stay to the right.

56.7 The road to Racetrack Playa turns off to the right.

57.0 Park in the lot along the rim of Ubehebe Crater (Stop A1).

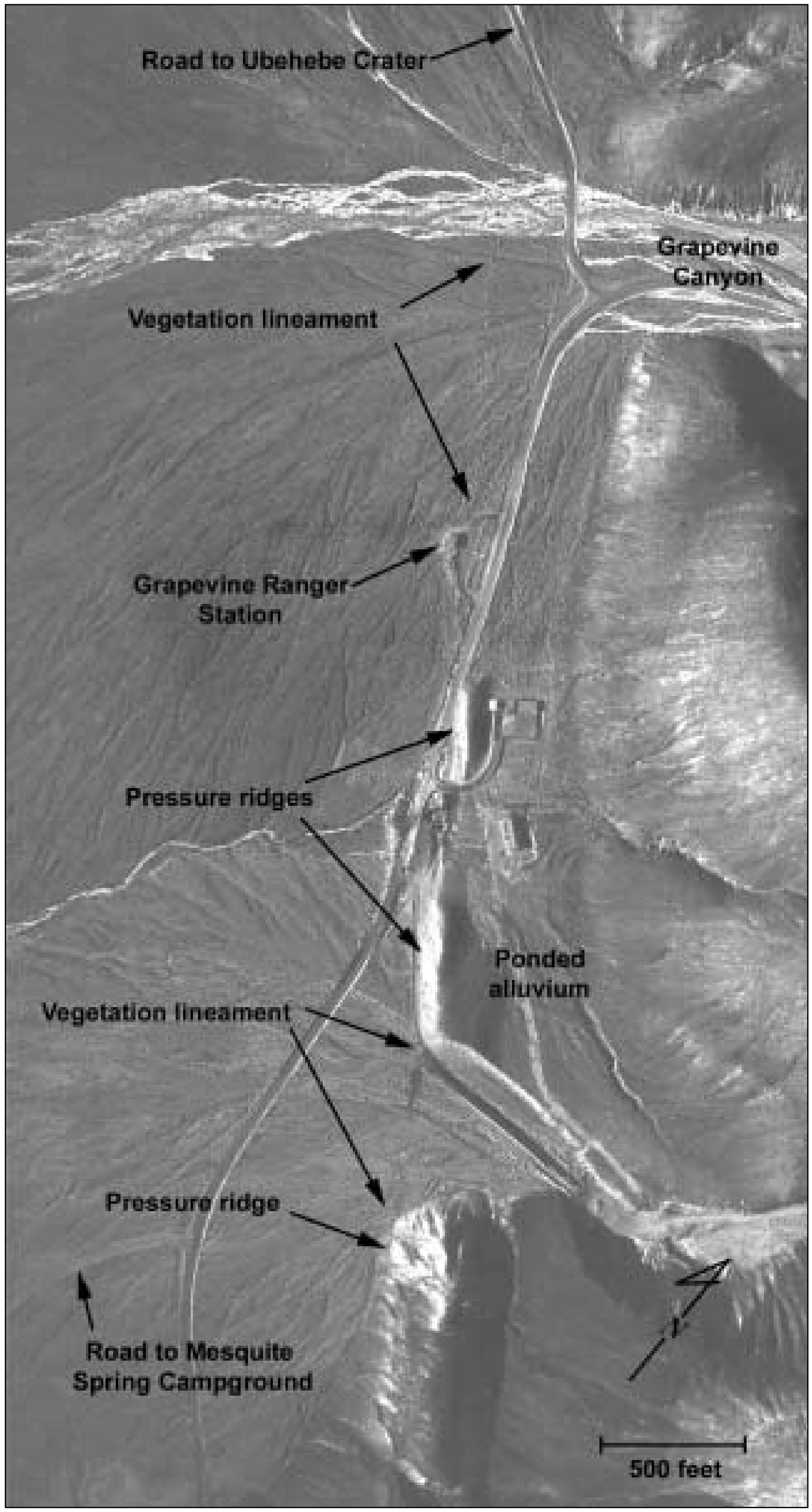


*Figure A-13: Vertical aerial photograph of the Northern Death Valley fault zone at the mouth of Grapevine Canyon near Grapevine Ranger Station. Note that the trace of the fault passes through the parking lot between the ranger station and the check station on the highway.*

# Stop A1 — Late Quaternary volcanism of Ubehebe Crater

*Ralph E. Klinger*
Ubehebe Crater 7.5' quadrangle
GPS: NAD 27, UTM Zone 11
$^{40}96^{150}$mN, $^{4}59^{625}$mE
Elevation: 792.5 m (2,600 ft) ASL

## OBJECTIVE

The main purpose for visiting Ubehebe Crater is to examine the morphology of the main crater in the volcanic field and discuss the evidence for its time of formation. An additional objective for this stop is to get a general overview of the Lake Rogers basin and the roles that the Northern Death Valley fault zone and Tin Mountain fault have played in the late Pliocene and Quaternary evolution of the basin.

## OVERVIEW

We are standing on the rim of Ubehebe Crater, the largest of numerous craters that form the Ubehebe volcanic field (fig. A1-1). The volcanic field covers a little more than 3 $km^2$ at the northeastern end of Cottonwood Mountains, near the intersection of the Northern Death Valley fault zone and Tin Mountain fault. As you can see, the basaltic cinders erupted from the field blankets much of the landscape in the immediate area. The high peak to the south of the crater is Tin Mountain at 2,728 m (8,953 ft) and the low, dissected hills between the range and us are known as the Ubehebe Hills. Snow and Lux (1999) described the rocks that form these hills as part of the Ubehebe basin, a Tertiary basin on the flanks of the Cottonwood Mountains. Deposition into the basin began about 22 Ma, but the uppermost part of the basin fill represents the syntectonic sequence of sediments associated with large-magnitude extension that began about 15 Ma and that ultimately formed Death Valley. The sedimentary rocks exposed in the walls of the crater are believed to be the lower part of the Navadu Formation (Snow and Lux, 1999), a newly defined formation in the syntectonic sequence that ranges from about 12.1 to 6.2 Ma.

To the west is the Last Chance Range; the high peak to the southwest is Dry Mountain at 2,644 m (8,674 ft). The valley southwest of us is bounded on the east side by the north-to-northeasterly striking Tin Mountain fault and separates the northern Cottonwood Mountains from the southern end of the Last Chance Range. The Tin Mountain fault south of here has a N-S strike and lies at the base of the Cottonwood Mountains, suggesting that the dominant mode of deformation is down-to-the-west dip-slip. However, north of here the fault bends to a N. 30° E. strike near its intersection with the Northern Death Valley fault zone and exhibits both northwest- and southeast-facing scarps, a characteristic more indicative of strike-slip faulting. We are currently standing on the footwall block and the fault is exposed in the northern wall of the crater. There is at least 120 m, but maybe as much as 400 m of vertical separation across the fault at this site. The scarp on the crater rim exhibits about 10 m of surface offset based on the vertical separation across the fault of the contact between the rim deposits and the underlying conglomerate.

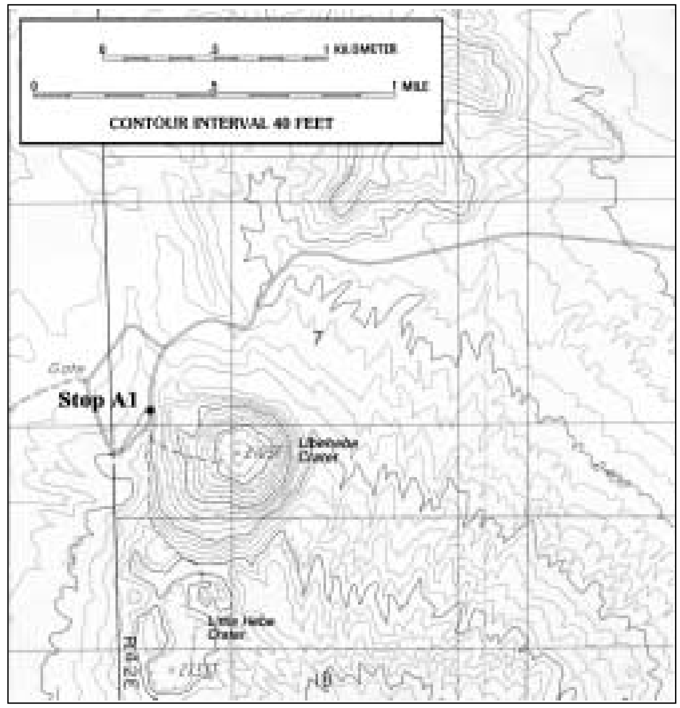


*Figure A1-1: Map showing the location of Stop A1.*

To the north we see the Lake Rogers basin (fig. A1-2). Lake Rogers is the name given by Thomas Clements in 1952 to the previously unrecognized white silt and sand beds he interpreted as lacustrine sediments. The name was in honor of John Rogers, a compatriot of William Manly, after whom Lake Manly is named. Together Manly and Rogers lead the Bennett-Arcane party out of Death Valley in 1849. Unfortunately, Lake Rogers was probably never a lake *per se*, but more of a marsh or wet meadow as the beds contain interbedded humic layers, plant, and large mammal fossils (*Proboscidea*). Also, you may get the sense that the beds along on the west side of the basin are higher than on the east side. In fact, they are about 37 m (120 ft) higher on the west than on the east side of the basin and the top of the Lake Rogers beds also slopes in a downstream (southeasterly) direction. This certainly could be the result of tectonic deformation, for which there seems to be ample evidence in the area, but this deformation would require

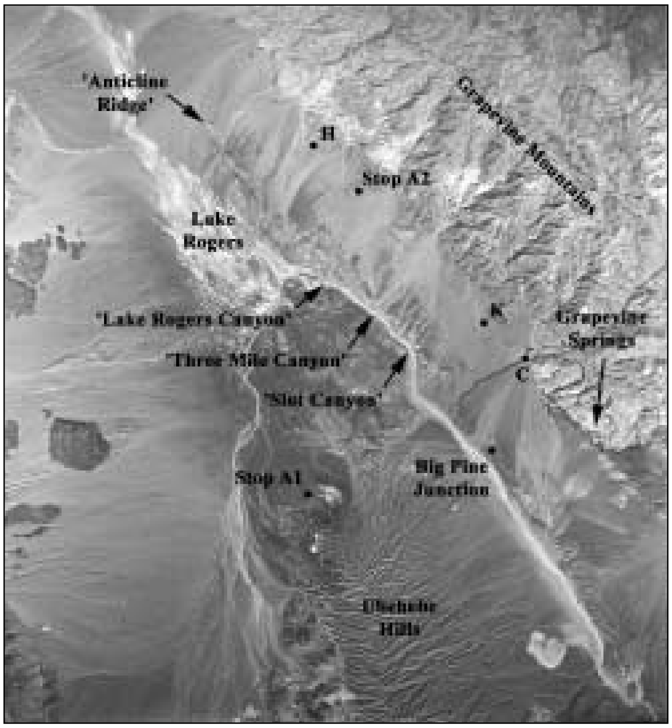


*Figure A1-2: Vertical aerial photograph of the northern end of the Cottonwood Mountains showing the location of sites described in the text for Stops A1 and A2.*

a basin subsistence rate of more than 1 mm/yr. We will talk more about this at our next stop (A2).

Finally, to the east we are looking at the northern end of the Grapevine Mountains and the Northern Death Valley fault zone. The high peak visible on the skyline to the southeast is Grapevine Peak at 2,663 m (8,738 ft). From Grapevine Springs, which is directly to the east, northward the range is composed primarily of Paleozoic carbonate rocks whereas to the south younger Tertiary volcanic rocks, primarily basalts, outcrop along the range front (fig. A1-2). We drove along these basaltic rocks from just north of Screwbean Springs to Big Pine Junction. This change in lithology as you move northward along the range is also preserved in the alluvium shed off of the range. At our next stop, we look at the evidence this change provides for large scale dextral slip along the Northern Death Valley fault zone. The low hills between the Grapevine Mountains and this stop is a sequence of moderately northeast-dipping Tertiary rocks that are in part correlative with the Nova Formation (Snow and Lux, 1999). The Tin Mountain fault can be traced across these hills to the northeast as far as Death Valley Wash where it appears to be truncated by the Death Valley Wash fault.

## UBEHEBE CRATER

Undoubtedly, the Shoshones that lived in Northern Death Valley before contacts with Europeans were keenly aware of the Ubehebe volcanic field since its volcanic cinders bury archaeological artifacts. The name “Ubehebe” has been attributed to the Native Americans as their name for the crater (Clements, 1954), but Bob and Barbara Decker (Decker and Decker, in press) indicate that the Shoshone name for the crater is “Tempintta Wosah” meaning “basket in the rock.” It is not particularly clear where the name “Ubehebe” originated other than a reference by an early geologist working in the area that said they were well known locally by this name (von Engeln, 1932).

Despite its popularity as a tourist attraction, the scientific literature dealing specifically with Ubehebe Crater is actually quite limited and the earliest reports were primarily reconnaissance in nature (von Engeln, 1932; Clements, 1954). In the earliest known report on the Ubehebe Craters, von Engeln (1932) recognized two explosion craters and provides an interesting interpretation for the fractured clasts found in the walls of the main crater. Clements (1954) later recognized seven craters, naming von Engeln’s second smaller crater “Little Hebe.” The most extensive study so far of the Ubehebe volcanic field is a 1972 Master’s thesis by Bruce Crowe at University of California—Santa Barbara, and later described in a Geological Society of America Bulletin paper (Crowe and Fisher, 1973). The principle topic of his study was the sedimentological character of the base-surge deposits associated with Ubehebe volcanic field, but it also included many other important data pertaining to the formation of the volcanic field, the character of the volcanic deposits, and the surrounding geology. Crowe (1972) also acknowledged the existence of as many as 16 craters and, recognizing the stratigraphic relationships between craters, grouped them into clusters on the basis of their location and relative ages (fig. A1-3).

With the exception of two of the craters (no. 3 and 7; fig. A1-3), each of the volcanoes appears to have formed as the result of a phreatic eruption. Ejecta erupted from the main crater is reported to overlie all of the craters in the volcanic field (Crowe and Fisher, 1973). Roddy (1968) estimated that the total energy required to eject the volume of rock in the main crater as about 8 x $10^{21}$ ergs. The crater is about 760 m (2,500 ft) wide and 152-213 m (500-700 ft) deep depending on where on the rim you’re standing. Rim deposits around Ubehebe Crater are about 50 m thick with the majority of these deposits coming from the eruption of the main crater (Crowe and Fisher, 1973). Ejecta associated with this eruption covers almost 40 $km^2$ the valley floor, primarily to the north-northeast, making it an important local stratigraphic marker.

## TIME OF THE CLIMATIC ERUPTION

Previous estimates for the time of eruption of the volcanic field have been mostly speculative and range from as young as several hundred years (Little Hebe; Clements, 1954, p. 55); several thousand years (the remainder of the field; Clements, 1954); more than 10,000 years (Crowe and Fisher, 1973; Moring, 1986) to perhaps several million years (Waring, 1917, as cited by von Engeln, 1932). Many descriptions of Ubehebe Crater cite the relatively youthful appearance of the crater, but no


*Figure A1-3: Map of the craters in the Ubehebe volcanic field. The volcanic field is subdivided into the southern, western, and main clusters. Numbers denote the relative age of each crater within the clusters with 1 being the youngest, 16 the oldest (modified from Crowe and Fisher, 1973). Relative ages are based primarily on the superposition of the craters relative to each other, but include other criteria such as the preservation of symmetrical form, degree of erosion of the crater rims, and extent of deposition on the crater floor.*

numerical age determinations or detailed studies of the morphologic character of the craters have been previously published. Two of the previous studies (von Engeln, 1932; Clements, 1954) noted that Little Hebe still retains a nearly perfect symmetrical form, although in large part, the main crater also retains its original constructional morphology. Large parts of the main crater wall are vertical or near-vertical and debris eroded from the walls and redeposited on the floor of the crater are limited to the small debris fans formed around the inside of the crater. The tuff ring surrounding the crater also remains almost entirely intact and erosion of the crater rim is limited to group of slumps on the southwest and east sides of the crater.

As noted above, basaltic ash erupted from Ubehebe Crater covers more than 40 km$^2$ of the valley floor and overlies all but the youngest alluvium (Q4b). Estimates based on relative age criteria for the Q4b alluvium suggests that the eruption is certainty less than several thousand years old and perhaps as young as several hundred years. This of course is consistent with previous estimates, but not very precise.

At several locations along the Northern Death Valley fault zone, offset alluvial fans have formed prominent shutter ridges (fig. A1-2). In turn, the areas behind these shutter ridges form a low energy environment that is conducive to the preservation of finer-grained sediment, such as volcanic ash. The National Park Service utilized the area behind two of these shutter ridges as borrow pits for road construction materials (H and K; fig. A1-2). The NPS excavation exposed a section of uppermost Holocene alluvium ponded behind the shutter ridge. In each of these pits, a bed of airfall Ubehebe Crater tephra is preserved under about 25 cm of pebbly silty sand ponded behind the shutter-ridge. A small fragment of charcoal (0.12 g) was recovered from the gravel pit located about 2.7 km (1.7 miles) north of Big Pine Junction (K; fig. A1-2). The charcoal was collected from a light brown, well-sorted fine-to-medium grained sand bed (unit 3; fig. A1-4) about 3 cm below the air-fall Ubehebe Craters ash bed. The charcoal was identified as *Atriplex* (saltbush), a native species that is relatively common in this part of Death Valley (Puseman, 1997). AMS analysis of the charcoal fragment yielded a radiocarbon age 210±30 $^{14}$C yrs B.P. (300-140 cal yrs B.P.). This age is consistent with the estimated min-

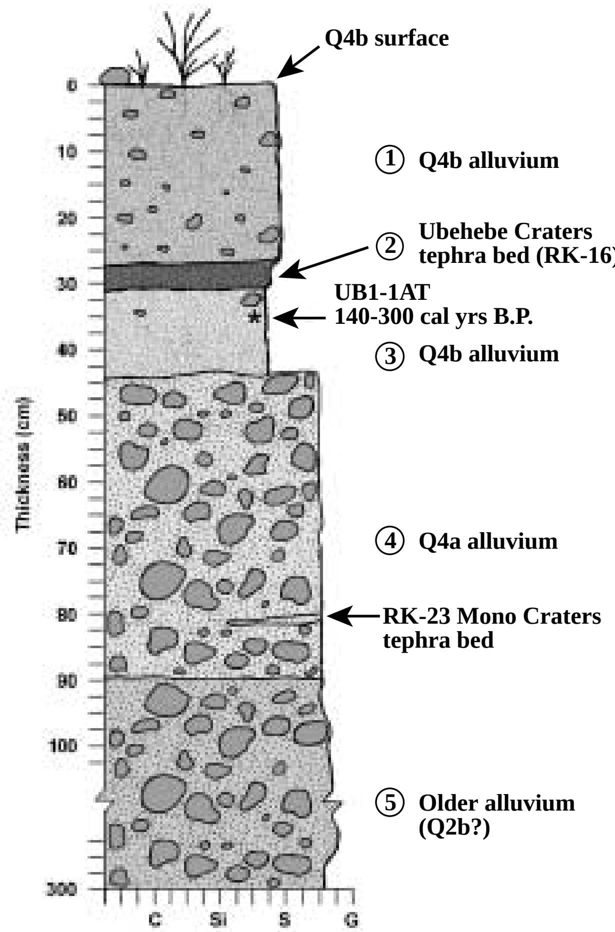


*Figure A1-4: Composite stratigraphic section of Q4 and Q3 alluvial deposits exposed in gravel borrow pits H and K along the Big Pine road in northern Death Valley (see fig. A1-2).*

imum age of the Q4a deposits that are blanketed by the ash in the area.

At a shutter ridge about 5.0 miles north of Big Pine Junction, a similar section is exposed in a second gravel pit. In this excavation, a thin rhyolitic ash bed is interbedded with a gravelly sand unit (unit 4; fig. A1-4) about 50 cm below the airfall Ubehebe Crater ash bed. The gravelly sand unit that contains the rhyolitic ash also contains abundant archaeological debris (primarily chert flakes and small core stones). Based simply on the major element composition, the rhyolitic ash has been identified as one of the upper Holocene Mono Craters ashes (<1200 yrs) and the trace element composition is similar to the Mono Craters ash bed in Mesquite Flat (see fig. A-7).

## IMPORTANCE

In addition to overlaying all but the youngest alluvial deposits in the area, the Ubehebe tephra also buries alluvial deposits that contain abundant archaeological artifacts, so the age of the crater has important implications in regards to local archaeology. The precise age of Ubehebe Crater tephra is not only important to the upper Holocene stratigraphy in Northern Death Valley, but Ubehebe Crater may also represent the youngest basaltic eruption in the continental U.S. Until now, the Pisgah volcano, a cinder cone and alkali basalt flow in the Mojave Desert, estimated to be about 390 years old was considered the youngest (Katz and Boettcher, 1980). In regards to the tectonic activity on the Northern Death Valley fault zone, the ash also appears to have been displaced by the most recent ground-rupturing earthquake.

The age of the most recent ground-rupturing earthquake along the Northern Death Valley fault zone has also been the topic of some speculation. Although there is no evidence to suggest that earthquakes on the Black Mountains fault zone are spatially or temporally linked to earthquakes on the Northern Death Valley fault, the morphology along both faults is certainly suggestive of very young activity. In the earliest report of youthful faulting, Clements (1954, p. 58-60) suggested that the young scarps along the Black Mountains fault zone just south of Furnace Creek were the result of the November 4, 1908, M6.5 earthquake based on newspaper accounts and other turn-of-the-century written records. Although this is entirely plausible, the records for this particular earthquake are not very good and the location of the event is poorly constrained (Stover and Coffman, 1993, p. 75). Hunt and Mabey (1966, p. A100) later estimated that the most recent activity along the Death Valley fault south of Furnace Creek to be just prehistoric based on the relationship of archaeological sites to the fault. Brogan and others (1991) also suggested that the youngest ground-rupturing earthquake along the fault occurred sometime within the last several hundred years based on observations from scattered localities along the fault. In Mesquite Flat, the trace of the Northern Death Valley fault cuts nearly to the ground surface being overlain by only several centimeters of mud-cracked sediment. Machette and Crone (Stop B3) estimate that the most recent faulting in the transition zone between the northern Death Valley and Black Mountains fault zones occurred between 500 and 840 years ago.

Along the Grapevine Mountains north of Ubehebe Crater, the Ubehebe Crater tephra has commonly been washed into the active channels and concentrated as beds of basaltic sand on low terraces. At several sites along the Northern Death Valley fault zone in this area, reworked ash can be found infilling fault fissures where it is exposed in stream cuts and the tephra preserved on low stream terraces appears to have been right-laterally offset (fig. A1-5). The presence of the Ubehebe Craters tephra in fissures associated with the fault suggests that the age of the most recent faulting event closely followed the eruption of Ubehebe Crater. Hence, the importance for the age of the Ubehebe Craters tephra becomes quite apparent. Based on radiocarbon results and the stratigraphic position of the Ubehebe Craters tephra relative to faulted deposits, the last ground-rupturing event along the Northern Death Valley fault zone appears to have occurred within the past 300 years.


*Figure A1-5: Ubehebe Craters air-fall tephra overlying Q3c terrace surface along the Northern Death Valley fault. The apparent right-lateral offset of the tephra is about 1.2 m at this location. North of this site the tephra appears to be offset about 2.6 m.*

# Stop A2

# Active tectonics and deposition in the Lake Rogers basin

*Ralph E. Klinger and Andrei M. Sarna-Wojcicki*

Ubehebe Crater 7.5' quadrangle
GPS: NAD 27, UTM Zone 11
$^{41}02^{250}$mN, $^{4}60^{840}$mE
Elevation: 835.2 m (2,740 ft) ASL

This stop takes us off the road log shown in the beginning of Chapter A, so use this supplemental road log for Stop A2.

| Miles | Description |
|---|---|
| 0.0 | Reset your odometer before leaving the parking lot at Ubehebe Crater then back track to Big Pine Junction (mile 53.8 in the road log). |
| 0.2 | The loop road from Ubehebe Crater parking lot rejoins main road. |
| 2.4 | The road crosses Death Valley Wash. |
| 2.8 | Turn left onto graded gravel road at Big Pine Junction. The National Park Service grades this road periodically, so it can be traveled in a regular passenger car if care is taken. However, keep your eyes open for the occasional heat-seeking boulder laying in wait for the unsuspecting low-slung passenger-car oil pan and standard-equipment tires. If you are planning to leave the park by this route, be sure to check on road conditions at the Grapevine Ranger Station. The road is commonly closed for extended periods due to wash outs.<br><br>As you travel up the alluvial fan from Big Pine Junction toward the range front, notice that for about the next mile the road crosses an alluvial-fan surface that is primarily covered with basalt boulders (fig. A1-2). |
| 3.8 | Near this point on the alluvial-fan surface the dominant rock type suddenly changes from basalt to gray dolomite. From this point northward for about 6 mi (10 km), the alluvium shed off the Grapevine Mountains is comprised of dolomite (light gray to reddish brown) and volcanic tuffs (about 2:1 dolomite to tuff). |
| 4.1 | The road bends gently to the left. The active traces of the Northern Death Valley fault zone is about halfway between the road and the range front and is marked by high scarps and shutter ridges. For the next several miles, the road will follow the fault, crossing it several times. |
| 4.5 | The shutter ridge on right hides a gravel pit excavated by the NPS for road construction material. The composite section described at Stop A1 (fig. A1-4) was in part described at this site. |
| 5.5 | The road crosses the Northern Death Valley fault zone and drops behind a high shutter ridge formed by an offset older alluvial fan (“Big Dip II, the sequel”). The road crosses the fault again as it climbs out of the canyon ahead. The drainage at the bottom of the dip is informally referred to as “Three Mile Canyon,” because it is 3 mi from Big Pine Junction. It is one of several tributary canyons to Death Valley Wash and provides easy access to the valley floor (fig. A1-2). The intersection of the Death Valley Wash fault with the northeastward projection of the Tin Mountain fault and the southernmost of the Lake Rogers beds are preserved along the wash in the area near the mouth of this canyon. |
| 6.7 | The road crosses the fault again and passes behind a low shutter ridge on the left. This is Stop A2. Turn around and park as far to the right as you can without leaving the graded road. From here we will be hiking about 1.5 miles down the fan, through Lake Rogers Canyon to Death Valley Wash. We will be away from the vehicles for about 2 hours so take water. The hike back out of the canyon will have an elevation gain of about 400 ft in about a mile. |

### OBJECTIVE

The primary objective at this stop will be to look at the influence of Quaternary tectonics on the formation of the Lake Rogers basin and the deposition along the Northern Death Valley fault zone. This will include examining the late Pleistocene Lake Rogers beds on the valley floor and the upper Pliocene and lower Pleistocene stratigraphy in Lake Rogers Canyon, which has been uplifted along the Death Valley Wash fault and translated northwestward along the Northern Death Valley fault zone.

## OVERVIEW

We are standing near the midpoint of the Grapevine Mountain section of the Northern Death Valley fault zone (see Chapter J, fig. J-5 in this volume). As previously stated, these sections are delineated on the basis of their overall morphology and the nature of strata found along the fault: they do not necessarily represent fault segments as they are commonly denoted in neotectonic studies (e.g., Machette and others, 1991). The trace of the fault in this section is linear and, between here and Screwbean Springs to the south, the fault is adjacent to the Grapevine Mountains, which at this end of the range are comprised of Paleozoic carbonate and Tertiary volcanic rocks (see fig. A1-2). To the north, given the right lighting conditions (early morning or winter skies), the trace of the fault can be seen on the Q3 alluvial fan.

On the valley floor to the west, we see the Lake Rogers beds. These beds have been previously described as lacustrine deposits that delineate the maximum extent of late Pleistocene Lake Rogers in northern Death Valley (Clements, 1952; Moring, 1986). These beds are composed of thinly bedded, pale brown to light gray silt, intercalated with humic layers and silicic ash beds (fig. A2-1). The entire section of Lake Rogers beds is exposed where they have been incised by Death Valley Wash and its tributaries (fig. A1-2). Moring (1986) estimated the total thickness of the section is about 13 m thick. We will see the base of the Lake Rogers section in Death Valley Wash near the mouth of Lake Rogers Canyon and along Death Valley Wash where it rests unconformably on olivine basalt (Basalt of Ubehebe Hills (?); Snow and Lux, 1999) and QT1a alluvium.

To the southwest, we look along strike of the Tin Mountain fault. Moring (1986) mapped the low hills along the southern margin of the Lake Rogers basin as older Miocene (?) continental deposits (his unit Tc) and Neogene basalts (his unit Tb). Interbedded near the top of the Tc conglomerate is the 3.3 Ma tuff of Mesquite Spring. Snow and Lux (1999) recently refined the stratigraphy on strata that are exposed on the flanks of the Cottonwood Mountains. These strata contain the tuff of Mesquite Spring in the sequence and, thus, correlate with the Nova Formation farther south.


*Figure A2-1. Lake Rogers beds north of Ubehebe Craters. Note thin layer of basaltic Ubehebe Crater tephra blanketing landscape (photograph by R.E. Klinger).*

Before we head down the canyon for the next kilometer or so, take a moment to look at the alluvium. Note that it is comprised almost entirely of dolomite (about 99.9%) with the exception the black Ubehebe Crater ash (basaltic) that mantles the landscape. As we drop into the upper end of the canyon, also pay close attention to the character of the deposits, both their composition and texture. Lastly, as we walk down through the canyon, look at the position of the Ubehebe Crater tephra on the landscape and its relationship to the latest Holocene alluvium. Is this consistent with an age of less than 300 years?

## LAKE ROGERS BASIN

The Lake Rogers basin is the Quaternary structural depression that is forming northwest of the intersection between the north- to northeast-striking Tin Mountain fault and the northwest-striking Northern Death Valley fault zone. The Lake Rogers beds mark the depositional center of the basin, whereas the uplifted and deformed upper Pliocene and lower Pleistocene strata delineate the southern and eastern margins of the basin. We will be walking through an uplifted section of the Pliocene-Pleistocene rocks on our way to the valley floor. We will take some time to look at them in detail on our walk back to the cars.

The Lake Rogers basin is spatially removed from the main structural trough that forms Death Valley proper, being more than 30 km (about 19 mi) northwest and about 600 m (2,000 ft) higher than the northern margin of Mesquite Flat. The elevation of the floor of the Lake Rogers basin is between 640 and 765 m (2,100 and 2,500 ft) and is currently connected to Mesquite Flat by Death Valley Wash. Tributaries that flow into Death Valley Wash head in the Last Chance Range and the northern end of the Grapevine Mountains. Blakely and others (1999) described the subsurface characteristics of three subbasins in northern Death Valley (Sand Spring, Mesquite Flat and Cottonball basins, from north to south) on the basis of regional gravity data. They reported that the Sand Spring basin (roughly equivalent to the Lake Rogers basin) contains less than 300 m of basin-fill sediment, but it deepens in a southerly direction to about 1,000 m under Lake Rogers. The Sand Springs basin is the shallowest of the three subbasins in northern Death Valley. Sand Spring is located about 16 km (10 mi) northwest of Stop A2.

## LAKE ROGERS BEDS

Until recently, the age of the Lake Rogers beds was not very well constrained. Clements (1952) suggested that the beds were late Wisconsin age on the basis of fossils and that the beds might be contemporaneous with Lake Manly deposits found in central Death Valley. Moring (1986) similarly reported that the Lake Rogers beds were late Pleistocene on the basis of the fossil remains described by Clements (1952) and on the stratigraphic relationship he observed between late Pleistocene fan gravels (his unit Qf2c; see table A-1 in road log). Along the northeastern margin of the basin, deposits of Lake Rogers bury Qf2c alluvium, whereas at the mouth of Lake Rogers Canyon, the Lake Rogers beds are overlain by Q3a alluvium (fig. A2-2). A late Pleistocene age is confirmed by a silicic ash bed in the Lake Rogers beds that has been tentatively identified as a 14-25 ka Mono Craters ash (see Wilson Creek tephra of Sarna-Wojcicki and others, Chapter E in this volume).

In addition to the 14-25 ka Mono Craters ash, other thin ash layers are interbedded with the Lake Rogers beds. However, analyses of the composition of the shards indicate they are heterogeneous and are probably reworked from several tephra layers. Numerous tephra beds are found interbedded with the uplifted QT1a and Q1b alluvium along the eastern margin of the Lake Rogers basin. Given the topographic relationship of these tephra beds to Lake Rogers, it seems logical that some of the ash layers in the Lake Rogers beds are reworked from these older tephra deposits. Pumice clasts several centimeters in diameter that have been eroded from a Mesquite Spring tuff can be found along Death Valley Wash and in the adjacent, low-lying Q4a and Q3c terraces between here and Mesquite Flat, about 30 km (about 19 mi) to the south.

## DEPOSITION IN LAKE ROGERS BASIN

It is unclear exactly how a lake would have formed in the Lake Rogers basin given its current physiography (fig. A1-2). Death Valley Wash, which currently connects the Lake Rogers basin with Mesquite Flat, has cut a canyon into the uplifted QT1 deposits at the southern margin of the basin. Near the mouth of Slot Canyon (fig. A1-2), the canyon is about 60 m (200 ft) wide and more that 45 m (150 ft) deep. Lake Rogers beds extend into the canyon and up the side tributary canyons as far south as Three Mile Canyon (fig. A1-2). Clearly, Death Valley Wash and many of the tributary canyons that cut into the uplifted QT1a alluvium (east of the Lake Rogers basin) existed prior to the formation of Lake Rogers. Thus, the formation of a shallow lake in the Lake Rogers basin becomes problematic given that the basin does not appear to be or have been closed.

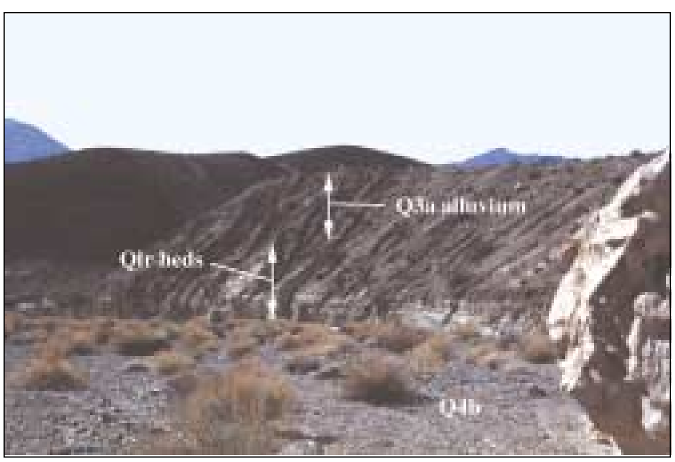


*Figure A2-2. Flat-lying Lake Rogers beds (Qlr) buried by Q3a alluvium at mouth of Lake Rogers Canyon (photograph by R.E. Klinger).*

The elevation at the top of the Lake Rogers beds in Death Valley Wash near Three Mile Canyon is about 2,245 ft and rises to about 2,400 ft near the center of the basin. Along the western margin of the basin, the elevation of the top of the beds varies from about 2,450 to 2,,500 ft and rises to almost 2,600 ft at the upstream end of the basin. The gradient on the top of the beds across Lake Rogers is about 13 m/km (68 ft/mi) in a west to east direction. Beds within the Lake Rogers sequence exposed by the incision of Death Valley Wash and its tributaries also clearly slope towards the center of the basin and in a down-valley direction, subparallel to the current channel of Death Valley Wash. This gentle down-valley slope, combined with the elevation difference across the basin, could be attributed to deformation associated with the faults that surround the basin. However, the presence of large mammal, aquatic mollusk, and plant fossils (Clements, 1952), and the character of the sediment suggest that the Lake Rogers was a shallow marsh or wet meadow rather than a lake in the strictest sense. Quade and others (1995) described similar sediment characteristics in fossil spring deposits found elsewhere in the region. The high position of the Lake Rogers beds along the western margin of the basin is also suggestive of spring flow into the basin from the Last Chance Range to the west. This type of spring flow is presently occurring along the toes of the alluvial fans in central Death Valley.

The position of Death Valley Wash in the Lake Rogers basin is also coincident with the steeply northeast-dipping Death Valley Wash fault that cuts the lower part of the QT1a alluvium (fig. A2-3). In addition, the mouth of Three Mile Canyon, which marks the southernmost extent of Lake Rogers beds, is coincident with the northeastward projection of the Tin Mountain fault. Thus, both the eastern and southern margins of the Lake Rogers basin are bounded by steeply dipping faults, whereas the western and northern margins are depositional. The stratigraphic relationship of the Lake Rogers beds preserved along Death Valley Wash and given the character of the Pliocene strata along the southern margin of the basin, suggest that damming of the ground water flow along the southern margin of the basin in combination with a rise in the local water table during wetter climates would produce the conditions needed to form a marsh or shallow lake in the Lake Rogers basin. A similar situation exists today at Devils Cornfield along the southern margin of Mesquite Flat (see road log at mile 15.9). Along the margins of the Lake Rogers basin, gravelly deposits that interfinger with the Lake Rogers beds fine laterally from matrix-supported gravel to well-sorted sand and silt towards the center of the basin. Therefore, the name Lake Rogers is


*Figure A2-3. Oblique aerial view of Lake Rogers basin looking to southeast. Tuff of Mesquite Spring is exposed in core of Anticline Ridge in foreground (photograph by L.W. Anderson).*

retained because there was undoubtedly standing water in the area at the time.

## LAKE ROGERS CANYON

As we walk up Lake Rogers Canyon, we will be looking at clastic sediment shed off the Grapevine Mountains and deposited along the eastern margin of northern Death Valley. Subsequently, these deposits were gently folded, faulted, and uplifted between the Death Valley Wash fault and Northern Death Valley fault zone. In general, the deposits are categorized in four broad units on the basis of their age, textural characteristics, and extent of deformation as exposed in Lake Rogers Canyon. From the base upward, this section includes 1) upper Pliocene strata (QT1a), 2) a sequence of lower to middle Pleistocene gravel with interbedded sand, silt, and mud beds (Q1b/Qlm1), 3) a upper Pleistocene gravel (Q1c); and 4) upper Pleistocene to Holocene alluvium (Q2 and younger rocks) (fig. A2-4).

At the bottom of Lake Rogers Canyon, we see a reworked bed of the tuff of Mesquite Spring (fig. A2-5). The Mesquite Spring also outcrops up a side tributary on the west side of Death Valley Wash opposite the mouth of Lake Rogers Canyon. At this site, the tuff bed is several meters thick and appears to be composed of clean water laid pumice. An $^{40}Ar/^{39}Ar$ analysis on plagioclases from this tuff yielded an age of $3.27 \pm 0.03$ Ma (see Sarna-Wojcicki and others, Chapter E in this volume). Dates from the tuff of Mesquite Spring (which has multiple beds at other sites) in Death Valley range from 3.17 to 3.35 Ma (Snow, 1990, 1993; Holm and others, 1994; Knott and others, 1999; Snow and Lux, 1999).

The Mesquite Spring group of tuffs are distinct upper Pliocene marker beds in the region. Snow (1990) originally identified the tuff, describing it in a type locality on the eastern flank of the Cottonwood Mountains just west of Mesquite Spring (see mile 50.4 in the road log). The tuff has also been identified in the Nova basin on the northwestern flank of the Panamint Mountains (Snow and Lux, 1999), in central part of Death Valley (Stop C3; Holm and others, 1994; Knott and others, 1999), in the Furnace Creek basin (Stop B4), and in Fish Lake Valley (Reheis and others, 1991). The eruptive source for the Mesquite Spring tuff is not known, but the chemical similarities between it and many of the Glass Mountain tuffs suggest that they have a close affinity. Due to the very coarse-grained character of the tuff, it is more than likely that the Mesquite Spring tuff erupted from a much closer source than from the Long Valley-Glass Mountain volcanic field (>150 km to the northwest). For additional details on the characteristics of the Mesquite Spring tuffs and a discussion of their possible source, see Chapter E in this volume (Sarna-Wojcicki and others).

*Figure A2-4. Generalized composite stratigraphic section along eastern margin of Lake Rogers basin.*

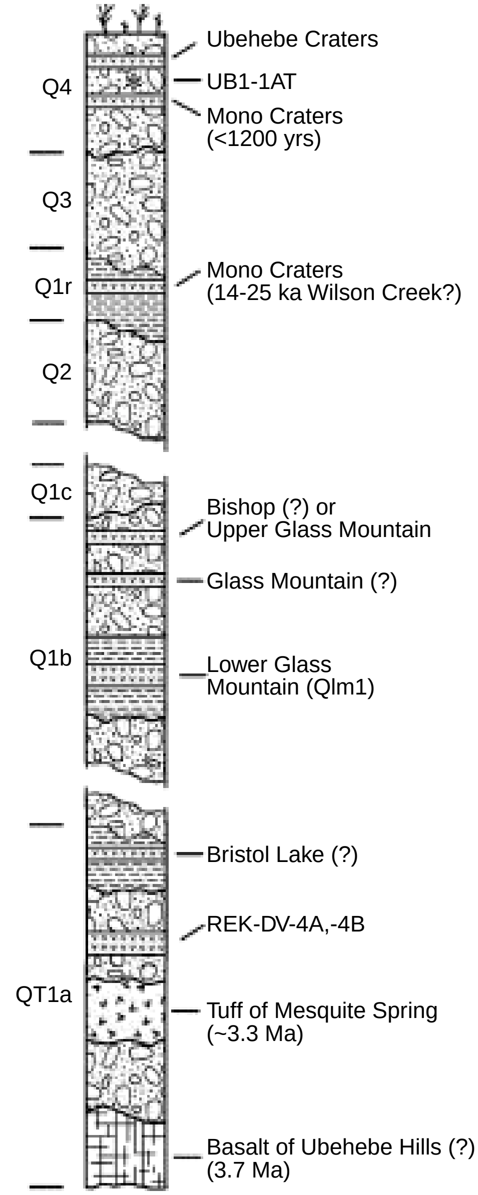

*Figure A2-5. Reworked bed of tuff of Mesquite Spring outcropping at mouth of Lake Rogers Canyon. Tuff bed at this location is about 15-20 m thick and contains lithic fragments and pumice several centimeters in diameter. Note position of Ubehebe Craters ash on young landscape at this location. Backpack for scale (photograph by R.E. Klinger).*

In northern Death Valley, the tuff of Mesquite Spring outcrops nearly continuously along the east side of Death Valley Wash, specifically on the southwest side of the low linear ridge that extends from Mesquite Spring Campground to Anticline Ridge (fig. A2-3). West of Mesquite Spring at its type locality, Snow and White (1990, p. 438) described the tuff of Mesquite Spring as a single white bed of pumice lapilli that is about 7.6 m thick. In Lake Rogers Canyon, the tuff bed has been reworked and deposited in beds about 15-20 m thick that strike about N. 55° W. and dips steeply 70° NW. The basal part of the tuff bed is relatively clean and is comprised of nearly pure white air-fall ash with large biotite phenocrysts. The upper part of the ash bed contains large pumice clasts and angular lithic fragments several centimeters in diameter. This part of the tuff bed is clearly reworked in as much as it has weak stratification and inverse-graded bedding showing strong evidence for deposition into standing water. Snow (1993) also reported that the tuff bed grades laterally to the northeast from the type locality into a tufaceous marl where it appears to have been deposited into a shallow playa lake. In Slot Canyon, a 25- to 30-cm-thick white ash is interbedded with pink muddy playa deposits just up section of the Mesquite Spring tuff. The ash bed appears to be very similar to an ash bed found in the Bristol (dry) Lake just below the Nomlaki Tuff (see Sarna-Wojcicki and others, Chapter E, this volume). Unit QT1a, which at the mouth of Lake Roger Canyon includes all of the deposits from the basal olivine basalt up to the conglomerate that overlies the Mesquite Spring tuff (fig. A2-4), is considered correlative to the Nova Formation.

As we continue walking up Lake Rogers Canyon, we see a thick sequence of basaltic conglomerates that grade upward into silty sand and silty mud beds (unit Qlm1). In Lake Rogers Canyon, this sequence of younger strata are separated from the older upper Pliocene strata by an angular unconformity. The character and thickness of unit Qlm1 deposits in this area is variable, but the unit can be traced for several kilometers between the tributary canyons east of Death Valley Wash (fig. A2-6). In Lake Rogers Canyon, the fine-grained beds (Qlm1) are about 32 m thick and contain at least four ash beds. On the basis of EMA and INAA analyses, two of these tephra layers match most closely with the lower Glass Mountain tuff exposed in the Confidence Hills (see Sarna-Wojcicki and others, Chapter E in this volume).

The fine-grained Qlm1 deposits in Lake Rogers Canyon are in turn overlain by another thick basaltic conglomerate that outcrops from about midway in the canyon to the top of the canyon. Near the top of the section, another tephra layer is found interbedded with the coarse alluvial-fan gravel (fig. A2-


*Figure A2-6. Q1b alluvium overlying Qlm1 lacustrine deposits near mouth of Three Mile Canyon. Note that dip of bedding in Qlm1 deposits is steeper at base of the unit than at upper contact with Q1b alluvium. Correlative deposits in Lake Rogers Canyon contain at least one of lower Glass Mountain ash beds (photograph by R.E. Klinger).*

7). This ash was originally identified as the Bishop Tuff based on major oxide element composition. However, additional analyses indicate that although the ash has a strong affinity to the Bishop, the scandium composition of the glass is more indicative of a slightly older and rare 1.2-Ma Middle Glass Mountain ash (see Sarna-Wojcicki and others, Chapter E in this volume). In Slot Canyon, 30-cm-thick lenticular ash bed is interbedded with coarse basaltic gravels. The upper half of the bed is dirty and thinly bedded indicating that it has been reworked, but the lower half of the bed is nearly pure white ash. This ash layer matches closely with the 0.76-0.9 Ma upper Glass Mountain ashes. Through much of the Lake Rogers Canyon, unit Q1b is composed of a basaltic conglomerate interbedded with finer-grained silty sand and silty mud that has been uplifted and deformed to varying degrees. At the top of the canyon, the contact between unit Q1b and the overlying unit Q1c is marked by a dramatic change in composition and an unconformity (fig. A2-7). At this location, unit Q1c is composed of gray dolomite that is found along the range from a point just north of Grapevine Springs (fig. A1-2).

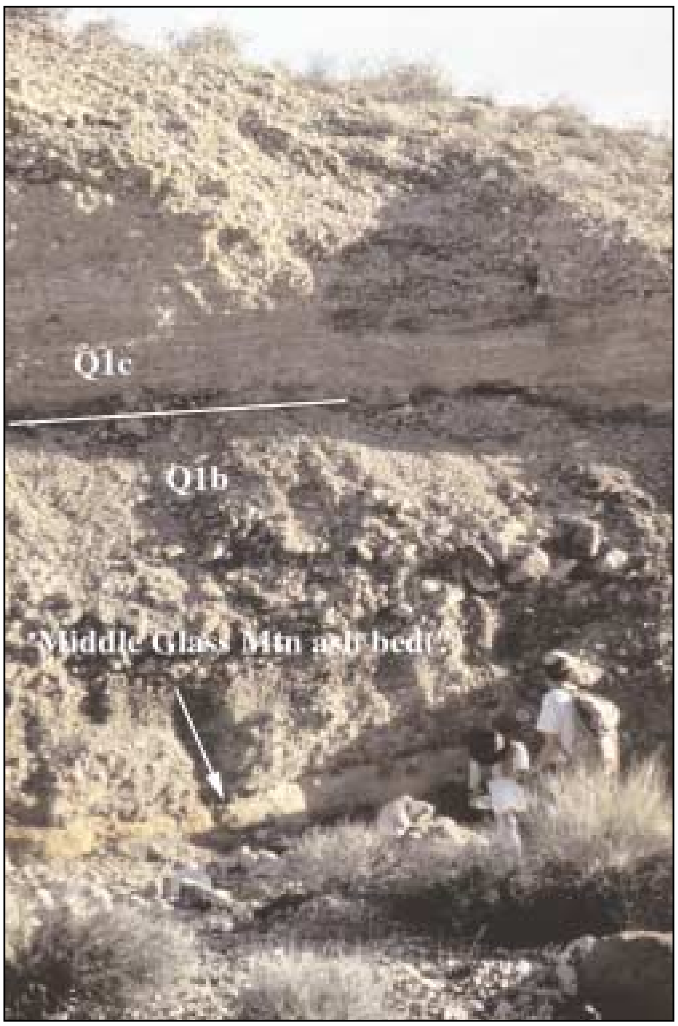


*Figure A2-7. Middle Glass Mountain (?) ash layer interbedded with Q1b basaltic alluvium at top of Lake Rogers Canyon near contact with overlying Q1c carbonate conglomerate (photograph by M.C. Reheis).*

## POTENTIAL SLIP ALONG THE NORTHERN DEATH VALLEY FAULT ZONE

The largest amount of dextral offset of Quaternary deposits along the Northern Death Valley fault zone was measured north of Grapevine Springs. In the thick sequences of Q1b alluvial-fan gravel exposed in the tributary canyons to Death Valley Wash, monolithologic basaltic gravel appears to have been dextrally offset from its source to the south. Because the western flank of the Grapevine Mountains north of Grapevine Springs is composed primarily of Paleozoic limestone and dolomite, the basaltic gravel exposed in Lake Rogers Canyon could not have been derived from the Grapevine Mountains in this area. A detailed examination of gravel on the active alluvial fans along the range front between Grapevine Springs and Anticline Ridge indicates that the closest source for basaltic gravel is the small drainage immediately north of Grapevine Springs (C on fig. A1-2). The distance between this drainage and head of Lake Rogers Canyon is about 4,050 m. The ash bed near the top of the section exposed in Lake Rogers Canyon (fig. A2-7) that was initially identified as the Bishop Tuff was used to develop a Quaternary slip rate of about 5 mm/yr along the Northern Death Valley fault zone (Klinger, 1999). However, the subsequent analyses discussed above suggest that the ash bed may be slightly older (>1.2 Ma?), thus the Quaternary slip rate may be more on the order of 3 mm/yr. The Upper Glass Mountain ash layer at the top of the section in Slot Canyon may be the 0.76 Ma Bishop, but the ash is interbedded with the basaltic gravel much further below the contact with the overlying carbonate gravel. Therefore, the uncertainty in the piercing point across the fault is unknown, so a meaningful estimate cannot be derived from the Upper Glass Mountain ash layer.

A similar stratigraphic situation also exists at the northern end of the Lake Rogers basin. Alluvial-fan gravel has been folded and uplifted into a north-plunging anticline that is referred to as Anticline Ridge (fig. A2-3). Anticline Ridge is the northernmost surface expression of compression along the Northern Death Valley fault zone. Erosion along drainages that cut into the eastern limb and across the axis of the anticline has exposed the tuff of Mesquite Spring in the core of the anticline. Immediately overlying the tuff bed is the bouldery, basaltic gravel identified farther to the south at the mouths of several tributary canyons. This gravel can be traced continuously to this location. Assuming a similar relationship between the basaltic conglomerate and the 3.1-3.4 Ma Mesquite Spring tuff as described previously, the minimum dextral offset of the basalt gravel at this site is a little less than 8 km. These data yield an average late Cenozoic slip rate of about 2.4 mm/yr since 3.3 Ma.

## TECTONIC MODEL FOR THE DEVELOPMENT OF THE LAKE ROGERS BASIN

The Lake Rogers basin described here and the Ubehebe basin of Snow and White (1990) are in the same general area, but are distinctly different in terms of age and origin. The Ubehebe basin is on the northern flank of the Cottonwood Mountains and includes a thick sequence of Tertiary strata (Snow, 1990; Snow and White, 1990; Snow, 1993; Snow and Lux, 1999) that record large magnitude extension that was responsible for the formation of Death Valley. This large-scale extensional deformation occurred on a listric normal fault(s) that separated the Cottonwood Mountains from the Funeral Mountains (Snow and White, 1990). The Lake Rogers basin described herein is a younger feature that formed in response to Quaternary deformation along the Northern Death Valley fault zone, north of the northeast-striking, down-to-the-northwest Tin Mountain fault.

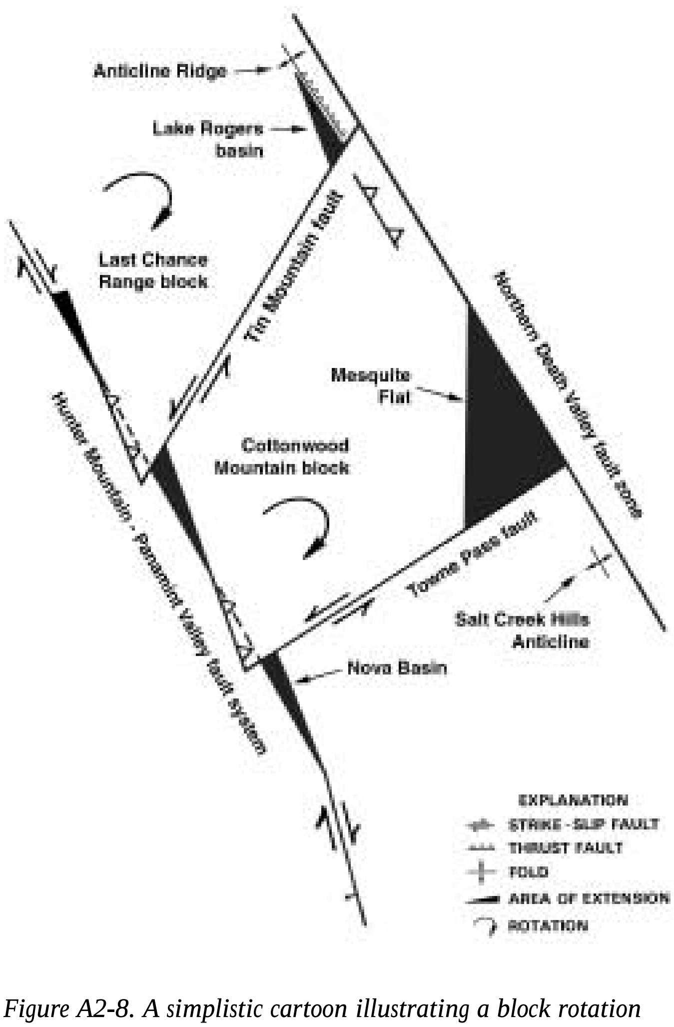


*Figure A2-8. A simplistic cartoon illustrating a block rotation model between Northern Death Valley fault zone and faults of Hunter Mountain-Panamint Valley fault system (not to scale or true orientation).*

Along the eastern margin of the Lake Rogers basin, the trace of the Northern Death Valley fault zone cuts a series of alluvial fans shed eastward off the western flank of the Grapevine Mountains. The surface trace of the fault is linear, nearly continuous, marked by prominent east- and west-facing scarps on all deposits except the youngest alluvium in active channels. As pointed out at Stop A1, the Tin Mountain fault appears to be primarily dip-slip, but alternating northwest- and southeast-facing scarps along the northeastern end of the fault suggest a significant component of lateral slip. We believe that a model of block rotation between the Northern Death Valley fault zone and the Hunter Mountain-Panamint Valley fault system to the west (fig. A2-8) is supported by 1) the relative orientation of the two faults, 2) evidence for compression on the Death Valley Wash fault, Anticline Ridge, and the uplifted upper Pliocene and lower Pleistocene rocks (that we just looked at), and 3) juxtaposition of these compressional features next to the actively subsiding Lake Rogers basin.

The thick sequence of interbedded alluvial-fan gravel, lacustrine and playa sediment, and volcanic tuffs in Lake Rogers Canyon appear to have been deposited along a relatively stable margin of northern Death Valley; part of the post-syntectonic sequence described by Snow and Lux (1999). Following their deposition, these strata were folded, faulted, and uplifted by localized compression south of the Tin Mountain fault (sinistral oblique slip on the fault associated with clockwise motion of the Cottonwood Mountains; see fig. A2-8). Deposition from the Grapevine Mountains continued through the early Pleistocene, being punctuated by long periods of lacustrine sedimentation in the area. This lacustrine deposition may have been made possible by the formation of a tectonically controlled closed basin. Deformation would have continued during the deposition of the lacustrine sediment and the Q1b gravel. Evidence for this is exhibited as a decrease in the amount of deformation as you move up section (see fig. A2-6). At the same time, these strata were being transported northwest to their current position by dextral slip along the Northern Death Valley fault zone. Compression south of the Tin Mountain fault is exhibited as a northeast-dipping reverse fault at the base of the hills that protrude through the alluvial apron south of Mesquite Flat (see mile 47.9 in the road log) and the linear ridge that extends more than 15 km along the axis of the valley and terminates in a broad, northwest-plunging anticline at Anticline Ridge. The structural architecture of Mesquite Flat is very similar, having the southern end of the basin bounded by the Towne Pass fault and the southeastern edge of the basin bounded by the uplifted Kit Fox Hills and the Salt Creek Hills anticline (fig. A2-8).

# Stop A3

# Evidence for large dextral offset near Red Wall Canyon

*Ralph E. Klinger*

Dry Bone Canyon 7.5' quadrangle
GPS: NAD 27, UTM Zone 11
$^{40}79^{740}$mN $^{4}75^{665}$mE
Elevation: 268 m (880 feet) ASL

From Stop A2, back track to NPS Route 5 at the mouth of Grapevine Canyon (mile 51.0 in the road log). Turn right onto NPS Route 5 and continue south for about 11.2 mi (18 km). If you reset your odometer at the intersection with NPS Route 5, you can follow the road log in reverse. Stop A3 will be about half a mile beyond the "1000 feet" elevation sign (near route milepost 22). Pull over on the right shoulder and park as far off of the pavement as is reasonable. From this point we will be hiking about 2.5 km (1.5 mi) up the fan to spectacular scarps along the Northern Death Valley fault zone. There is an elevation gain of about 150 m (500 ft) and we will be away from the vehicles for about 2 hours, so take water. As we assemble and begin our trek up the alluvial fan, please pay attention to your footing. Although we will be walking on an older well-developed (smooth) pavement for most of our hike, we will cross younger (rough) parts of the fan and active channels. When we reach the fault, please avoid walking on the fault trace and scarps in order to minimize our impact on these fragile geomorphic features. In addition, there are archaeological artifacts on the higher parts of the fan, so tread lightly.

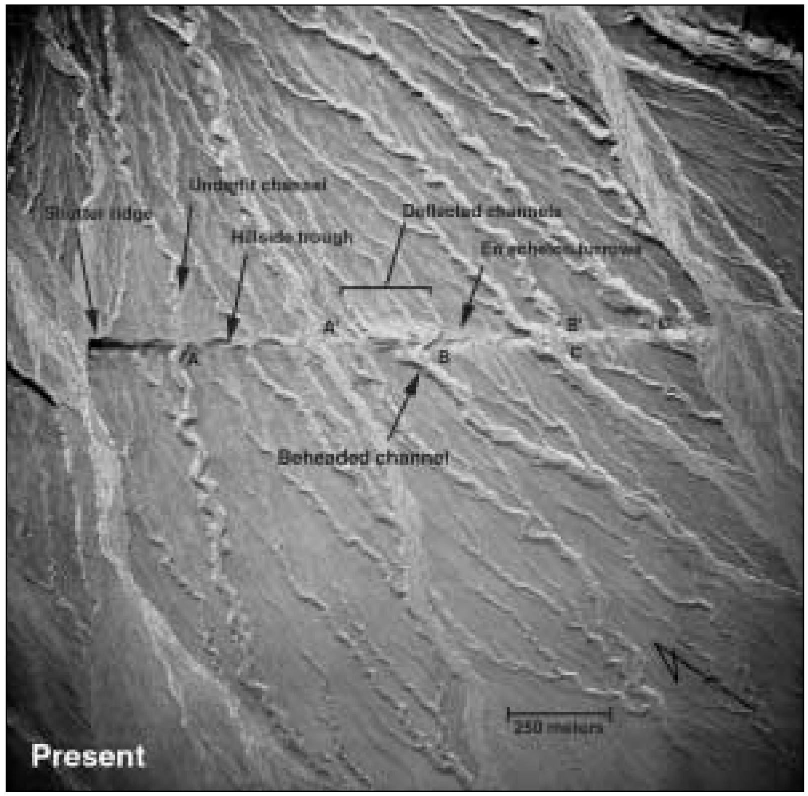


*Figure A3-1.Vertical aerial photograph of faulted alluvial fan at Stop A3 showing geomorphic features associated with long-term activity along Northern Death Valley fault zone. Points labeled A, A', B, B', C,and C' are piercing points used for palinspastic reconstruction shown in fig. A3-8.*

## OBJECTIVE

The principle objective at this singular stop (A3) is to examine the tectonic geomorphology that provides evidence for large dextral offset of the alluvial fan by the Northern Death Valley fault zone. In addition, we will look at evidence for repeated Holocene offset and at the relative age criteria used to estimate the age of the alluvial fan.

## OVERVIEW

We are about 12 km (7.5 mi) south of Screwbean Springs, which places us in the northern third of the Mesquite Flat-Screwbean Springs section of the Northern Death Valley fault zone (see discussion of fault nomenclature in Chapter J of this volume).In this area, the fault is expressed as a single linear trace about 1 km southwest of the range front, which trends about N. 35° W. We are standing on the toe of a late Pleistocene alluvial fan that has been offset by the fault (see fig. A-11 in the road log). Previous workers (including myself) have referred to this offset alluvial fan as the "Redwall" fan (original usage of Brogan, 1969), when in actuality we are about 4 km (2.5 mi) west of Red Wall Canyon. Classic tectonic geomorphic features, such as en echelon furrows, small closed depressions, shutter ridges, notches, hillside troughs, and deflected and offset drainages, are present along this part of the fault (fig. A3-1). These features are confined to a relatively narrow zone of predominately dextral strike-slip deformation.

Across the valley to the west are the northern Cottonwood Mountains. The older alluvium on the bajada to the northwest forms part of the alluvial fan of Bighorn Gorge, one of the larger drainages on the east side of the northern Cottonwood Mountains. At this point in the valley, Death Valley Wash forms a distributary channel as it flows into Mesquite Flat. To the north the valley is narrower, so Death Valley Wash flows in a narrow, incised channel that is confined by the alluvial fans shed off of the Cottonwood and Grapevine Mountains. This narrow channel has incised into the late Pleistocene alluvium by as much as 12 m (40 ft) and formed a sequence of low Holocene terraces adjacent to the channel.

To the south we are looking across Mesquite Flat, the deepest basin in Death Valley, at the northern end of the Panamint Mountains. The southern margin of the basin is bounded by the NE-trending Towne Pass fault, which separates the northern Panamint Mountains from the southern Cottonwood Mountains. Hunt and Mabey (1966) estimated there is about 3,200 m of basin fill in Mesquite Flat, but more recently Blakely and others (1999) proposed the basin may contain more than 7,000 m of sedimentary fill. If you recall the discussion of the model proposed by Reynolds (1969; see road log fig. A-9 and related text at mileage 26.0), his model for the formation of Mesquite Flat requires a fairly substantial normal fault along the eastern flank of the Cottonwood Mountains. Although there is evidence of Quaternary movement along the Grapevine fault on the eastern margin of Mesquite Flat, the only evidence for young faulting on the western side of the basin is limited to a wide zone of very short (<<1 km) and discontinuous faults in the alluvium along the range.

## QUATERNARY ALLUVIUM

I mapped a sequence of gravelly alluvial-fan deposits of different ages along the northern Death Valley fault zone (fig. A3-2). These deposits were divided into four major groups, Q4 to Q1 in order of increasing age, that were distinguished from each other on the basis of various relative age properties. The most useful of these properties includes desert-pavement formation,

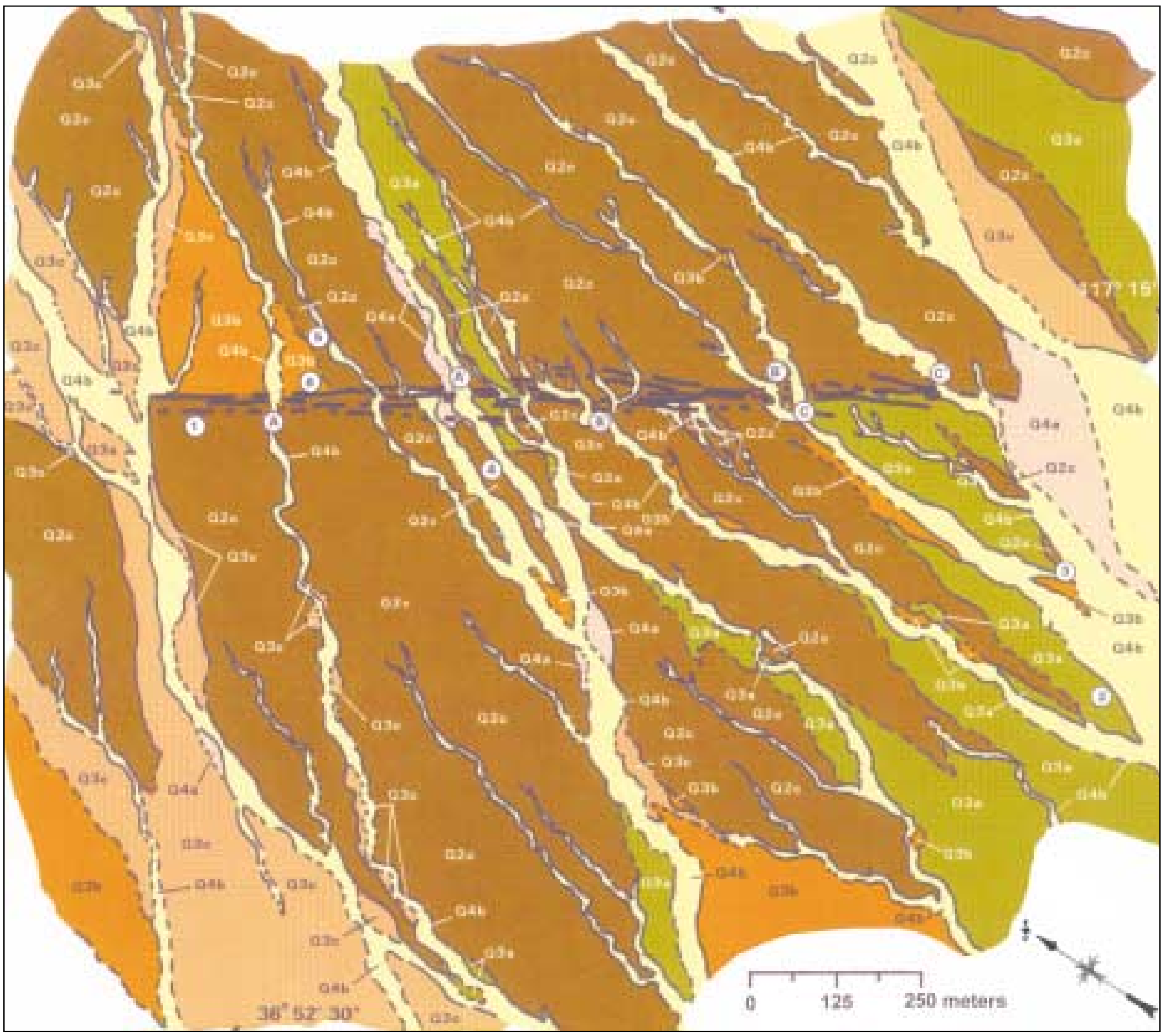


*Figure A3-2.Surficial geologic map of faulted alluvial fan at Stop A3. Unit descriptions are summarized in table A3-1 and outlined in greater detail in text. Numbered locations denote soil profiles; lettered locations are offset channels described in text.*

rock varnish color, bar-and-swale topography, and soil development.Each of the four major stratigraphic groups (Q4-Q1) were locally subdivided based on their topographic relationships to each other and subtleties in the relative-age properties used to define each major unit (table A3-1). Correlations between these units and those of previous workers in the area are outlined in table A-1 in the road log.

For the most part, the stratigraphic nomenclature and age assignments for the Quaternary alluvial stratigraphy follow that of Bull (1991). Bull used these same relative-age properties in addition to numerical ages from a variety of methodologies to establish a regional framework for the alluvial stratigraphy in the southwestern United States. This regional framework was established primarily in the Lower Colorado and Mojave Deserts, but included data from Death Valley. Minor adjustments in his age assignments were made in northern Death Valley based on stratigraphic relationships of specific units to dated lacustrine and/or spring deposits and tephra beds of known age (table A3-1).

The youngest deposits in northern Death Valley are the latest Holocene Q4b/Q4a alluviums: this includes all the gravelly deposits found in the active channels, associated bars, and the adjacent low terraces. Fine-grained material (silt and sand) is commonly present only as matrix material. The Q4b/Q4a alluvial deposits display distinct bar-and-swale topography, but seldom exhibit even a weakly developed desert pavement. Occasionally, weak-to-moderately developed pavements form over small areas, but a silty sand matrix commonly underlies these areas. The Q4b/Q4a alluviums typically have little or no varnish development, but in some instances very thin, faint coats of salt can be observed on the bottoms of clast on the ground surface. Soil development on Q4a deposits is very weak with thin A/C profiles. Vesicular A horizons can develop rapidly (within a few tens of years) in fine-grained materials (silt and fine-sand) and are commonly less than 1-2 cm thick.

The age of the Q4a deposits in northern Death Valley is constrained by ash beds from the Ubehebe Craters and Mono Craters. In the Lake Rogers area (Stops A1 and A2), the Ubehebe Craters tephra overlies everything except the Q4b deposits. Air fall and thin beds of reworked Ubehebe Crater tephra are common on the surface of and interbedded with Q4a deposits. In Mesquite Flat, an ash bed tentatively correlated to a 1.2-ka Mono Craters ash is interbedded in a Q4a-age dune (fig. A3-3).

The slightly older late Holocene deposits (Q3c) display surface characteristics distinctly different from Q4b/Q4a deposits. Bar-and-swale topography is still distinct, but desert pavement has begun to form on finer-grained materials. Rock varnish is recognizable as a light brown patina. Although the varnish is noticeably better than on the younger alluvial-fan deposits (Q4b/Q4a), it was still weakly developed compared with older (Q3) deposits. The best varnish development on Q3c deposits was observed on the upper surface of rocks: the maximum color on quartzite was light brown (7.5YR6/4). The soils developed on Q3c deposits generally exhibit thin A/B/C profiles. Vesicular A horizons are about 2-3 cm thick and the morphology of salts (both $CaCO_3$ and NaCl) reach a maximum of stage I.

TABLE A3-1. GENERALIZED DESCRIPTIONS OF LATE QUATERNARY STRATIGRAPHIC UNITS IN DEATH VALLEY

| Unit | Age (ka) | Desert Pavement[1] | Bar/Swale Morphology[2] | Rock Varnish Color[3] | Soil Profile Development[4] | Profile Thickness (cm) | Maximum Profile Color[5] | Soil Development Index[6] |
|---|---|---|---|---|---|---|---|---|
| Q4b | <0.2 | None | Prominent | None | None | None | 10YR6/3 | 0 |
| Q4a | 0.2-2 | None | Prominent | None | Thin Av/2C | 4 | 10YR7/2 | 0.5 |
| Q3c | 2-4 | PP | Distinct | 5YR6/6 | Avk/2Bkz/2C | 20 | 10YR7/3 | 5.2 |
| Q3b | 4-8 | MP | Subdued | 5YR5/8 | Avk/2Bkz/2C | 50 | 10YR7/3 | 12.8 |
| Q3a | 8-12 | MP-WP | Subdued | 5YR5/8 to 2.5YR4/8 | Avk/Bkz/2C | 72 | 10YR6/4 | 30.4 |
| Q2c | 35-60 | WP | None | 2.5YR4/8 | Avkz/Btkz/2Bkz | 100 | 7.5YR5/6 | 45.0 |

[1]Desert pavement development is rated on the basis of stone packing on the pavement surface and is dependent upon particle size and clast shape of the original deposit: PP, poorly-packed; MP, moderately packed; WP, well-packed.

[2]Bar-and-swale morphology as a relative measure of the original depositional topography and its degree of preservation.

[3]Maximum rubification color on the bottom of clasts in the pavement using Munsell color notation (Munsell Color, 1975).

[4]Typical profile development; described in the field as outlined by the Soil Survey Staff (1993) and by Birkeland (1999).

[5]Maximum profile thickness observed.

[6]Dry color on <2 mm soil fraction using Munsell color notation (Munsell Color 1975).

[7]Profile development index was calculated following the methodology of Harden (1982) and Harden and Taylor (1983). The five best developed properties averaged from profiles described in Death Valley; texture, rubification, profile lightening, dry consistence, and soluble salt accumulation (as measured by electrical conductivity) were used.


*Figure A3-3.Mono Craters ash layer interbedded with dune sand (equivalent to unit Q4a) in Mesquite Flat (brush in the foreground is about 25 cm long).*


*Figure A3-4.Differences in bar-and-swale topography and varnish development on surface of Q3b alluvium relative to the adjacent Q4b/Q4a alluvium. Note the weak incipient desert pavement on the Q3b surface.*

On the middle Holocene deposits (Q3b), the bar-and-swale topography becomes slightly more subdued (fig. A3-4). Although bar-and-swale morphology is still relatively distinct, the relief between the top of the bars and the bottom of the swales is less than 25-50 cm. Rock varnish formation is moderate and the maximum color on quartzite was dark brown (7.5YR4/4). Soil development on Q3b deposits is similar to soils developed on Q3c deposits, but generally the vesicular A and calcic B horizons are slightly thicker. Soluble salt (primarily halite) accumulation in the B horizon reaches stage I-I+.

Desert pavements formed on early Holocene and late Pleistocene alluvial-fan deposits (Q3a and Q2c alluvium) are well-developed relative to the younger Q3 alluvium (fig. A3-5). Pavements formed on Q3a deposits are often very difficult to distinguish from the older Q2c surfaces. In general, the bar-and-swale topography on the Q3a geomorphic surfaces is very subtle and faint. On the Q2c deposits, the desert pavements are very planar with no evidence of bar-and-swale topography remaining. Both the Q3a and Q2c deposits have well-developed rock varnish.The maximum color observed was dark reddish brown (5YR3/4) to black (5YR2.5/1) on the upper surfaces of rocks and reddish yellow (5YR6/8) to red (2.5YR5/8) on the bottom surfaces of the Q3a and Q2c deposits, respectively. Soil profiles on Q2c deposits are also better developed than on Q3a deposits. Although the vesicular structure in the surface horizons extends slightly deeper in the profile (10-15 cm), the lower part of the vesicular horizons in the Q2c profiles are being engulfed by thick accumulations of clay in the vesicles. Soils developed on Q3a deposits generally lack a well-developed argillic horizon. Salt accumulation in Q2c profiles is also appreciable having stage III development (both calcium carbonate and sodium chloride) relative to the stage II development common in Q3a profiles. The total profile thickness of soils developed on both the Q3a and Q2c deposits are similar, as much as 1.5 meters depending on location.


*Figure A3-5.Well-developed desert pavement and rock varnish on surface of Q2c alluvium. Due to tightly packed nature of stones in pavement and thick accumulation of silt immediately under surface, infiltration of moisture is dramatically decreased. As a result, Q2c surfaces are almost completely devoid of vegetation.*

The age of the Q3a and Q2c deposits is constrained by their stratigraphic position relative to late Pleistocene lacustrine and/or spring deposits. Radiocarbon analysis of the inorganic carbon fraction of a tufa bed that overlies Q2c alluvium along the eastern margin of Mesquite Flat yielded an age of 13,450±80 14C yrs (15,750-16,400 cal yrs B.P.). This tufa will be the topic of our next stop (Stop A4). In the Lake Rogers area, a tephra bed tentatively correlated to a 14-25 ka Mono Craters ash is interbedded with the Lake Rogers beds, which also overlie the Q2c alluvium.Thus, Q2c alluvium appears to be older than about 14 ka and perhaps older than 25 ka.

Desert pavements and the maximum development of rock varnish on Q2b alluvium is quite similar to those formed on Q2c deposits. The desert pavement surfaces are also planar, but generally appear lighter in tone due to an increase in calcium carbonate clasts (rubble) in the pavement (fig. A3-6). The carbonate rubble is comprised primarily of stones with carbonate coats or pieces of carbonate rinds that are derived from the underlying calcic horizons that have been brought to the ground surface by bioturbation and other processes. The Q2b surfaces are also noticeably more dissected than Q2c surfaces. The packing of the pavement and the related decrease in infiltration on Q2c surfaces has resulted in an increase in runoff and the formation of rills and small drainages that are typical of the Q2b surfaces.

At lower (drier) elevations and downwind of playas, the Q2b surfaces commonly have abundant salt-cracked and pitted stones in the pavement. North of Mesquite Flat, the effects of salt weathering are not as well developed. Soils developed on Q2b deposits are characterized by thick Av horizons (as much as 10 cm thick), argillic horizons, and thick calcic horizons with strong stage III development. Overall, the thickness of any particular soil horizon developed on Q2b deposits is thicker than the equivalent soil horizon on Q2c deposits.

## NORTHERN DEATH VALLEY FAULT ZONE

Curry (1938) appears to be the first to recognize the relative youthfulness of the fault zone in Northern Death Valley noting


*Figure A3-6. Offset of Q2b surface along Northern Death Valley fault near Anticline Ridge (see fig. A1-2). Note that Q2b deposits have a lighter tone due to carbonate rubble and retain alluvial fan morphology unlike deeply dissected older Q1 deposits that form ballenas near fan apex (photograph by J.R. Knott).*

Table A3-2. Late Quaternary slip rates on the Northern Death Valley fault zone

| Location | Distance | Age | Slip Rate |
|---|---|---|---|
| Near Site C (Stop A3) | 12.2 m | 2-4 ka | 3-6 mm/yr |
| Channels A-C (Stop A3) | 250-330 m | 35-60 ka | 4-9 mm/yr |
| Lake Rogers Canyon (Stop A2) | 4.0 km | 0.76-1.2 Ma | 3-5 mm/yr |
| Anticline Ridge (Stop A2) | 6-8 km | 3.3 Ma | 2-3 mm/yr |

that " …the fault is marked by a churned-up furrow in the recent alluvium." However, specific details regarding possible late Quaternary activity along the fault were not reported until Reynolds (1969, p. 238) noted that the southeastern margin of a Pleistocene alluvial fan had been offset about 46 m in a dextral (right-lateral) sense (see fig. A3-1). Reynolds suggested that there had been late Holocene activity along the Northern Death Valley fault zone, but interpreted the displacement of the alluvial fan north of Red Wall Canyon as having accumulated since the middle to late Pleistocene.

Bryant (1988, p. 8-9) later reevaluated the offset fan margin described by Reynolds (1969) and acknowledged the 46 m offset, but assumed that the stream incision that produced the alluvial-fan margin occurred about 20,000 years ago and that the dextral movement that displaced the fan margin followed this incision. He also emphasized that the fan margin was probably eroded laterally an unknown amount. Bryant (1988, p. 8-9) estimated a lateral slip rate of 2.3 mm/yr for this part of the fault zone, but emphasized that the slip rate was only a crude estimate. Although Brogan and others (1991) did not report any new slip rates for the fault, they acknowledged Bryant's (1988) minimum rate of 2.3 mm/yr. Later estimates by Klinger and Piety (1996a) suggested that the minimum slip rate of 2.3 mm/yr of Bryant (1988) might actually underestimate the late Pleistocene slip rate by a factor of three or four.

## RECURRENT HOLOCENE OFFSET

At a location about 250 m northwest of the southeast margin of the alluvial fan (fig. A3-2) repeated movement on the fault has offset a latest Holocene channel margin 12.2 m and preserved evidence for the last three surface-rupturing events. At this site, the fault is comprised of several strands, but a channel margin preserved on the northeast side of the main fault trace appears to have been progressively offset at least three times. Following each faulting event, a new channel margin forms adjacent to the active channel. The progressively greater offset of each successively older channel margin also provides an excellent estimate for the amount of slip accompanying each of the past three ground-rupturing events. Orientation of the original channel margin on the downhill side of the fault versus the offset margin on the uphill side of the fault indicates there was 2.5-3.5 m of lateral displacement during the last event. These values are consistent with measured offsets between the offset channel margins stranded on the uphill sides of the fault and elsewhere along the Northern Death Valley fault zone (see fig. A-6 in the road log). However, at this location the fault is comprised of several strands, all of which may have experienced some slip during this youngest event. Therefore, these measured dextral offsets are considered minimum values for the wider fault zone

The relative timing between this sequence of faulting events is also reflected in the progressively greater degree of varnish developed on each successively older channel margin (fig. A3-7). Based only on the varnish formation, the oldest channel margin appears to be equivalent to Q3c deposits in age (2-4 ka). Although this age is poorly constrained, the varnish formed on the oldest channel margin at this site is comparable to varnish formed on alluvial deposits that are buried by dune sand that elsewhere contains the 1.2 ka Mono Craters ash. The total dextral offset of the oldest channel margin measured across the fault is 12.2 m. If one uses a time frame of 2-4 ka (as represented by the varnish formation), the calculated late Holocene slip rate is 3-6 mm/yr. Evidence for a minimum of three earthquakes over the same time frame indicates that the return period for 2.5- to 3.5-m-offset earthquakes on the Northern Death Valley fault zone is between 700 and 1,300 yrs at this location, assuming characteristic fault behavior.

## LARGE PLEISTOCENE DEXTRAL OFFSET

The mainly Q2c surface of the alluvial fan that is the topic of our stop has a number of large drainages incised into its surface that have been dextrally offset across the fault (A, B, and C on fig. A3-2). As we walk along the fault, note that these and other incised channels are beheaded and mismatched along the fault. Several narrow "underfit" channels on the uphill side of the fault now flow into wider or more deeply incised "overfit" channels on the downhill side of the fault (fig. A3-1). A palinspastic reconstruction of the original alluvial fan utilizing low-altitude aerial photography permits an analysis of the movement across the fault over the time since the fan surface stabilized. Because the alluvial-fan surface on the southwest side of the fault moved to the northwest (relative to the surface on the northeast side of the fault), established drainages on the fan moved progressively farther apart and in turn influenced the development of other channels on the fan. A reconstruction aligning the three largest drainages incised into the alluvial-fan surface (fig. A3-8) indicates that drainages incised into the late Pleistocene Q2c alluvial-fan surface have been dextrally offset between 250-330 m by the fault. (Distances measured on fig. A3-8 are A-A', 310 m; B-B', 290-330 m; and C-C', 250 m.)

The current position of the larger drainages incised into the late Pleistocene surface is interpreted to relate directly to total offset of the fault following the abandonment and stabilization of the alluvial-fan surface. This interpretation is supported by the nearly perfect alignment of the reconstructed drainages (fig. A3-8). Because the drainages were displaced soon after their incision, the time of stabilization of the late Pleistocene surface provides a maximum age for the drainages and a maximum age for the total dextral displacement of the drainages. The age of the late Pleistocene alluvial fan (Q2c) was estimated on the basis of its relative age characteristics described above. Surface characteristic were described at several sites on the late Pleistocene surface (Klinger and Piety, 1996b), as well as the degree of soil development across the surface of the fan (Klinger, 2001). Based on the degree of soil development and the extent of formation for other relative age criteria, and the stratigraphic relationship of the alluvial-fan surface to lacustrine deposits, the age of the late Pleistocene Q2c alluvial-fan surface is estimated to be about 35 to 60 ka (table A3-1). Given a total offset of 250-330 m for the large incised channels since 35 to 60 ka, the average minimum late Pleistocene slip rate is between 4 and 9 mm/yr. This is consistent with the late Holocene slip rate of 3 to 6 mm/yr provided by offset of late Holocene stream channels (see table A3-2).


*Figure A3-7.Dextrally offset stream channel margins along main trace of Northern Death Valley fault zone. Note increasing darker desert varnish formed on the deposits adjacent to the channel margin. Distance between channel margins is about 2.5 m.*

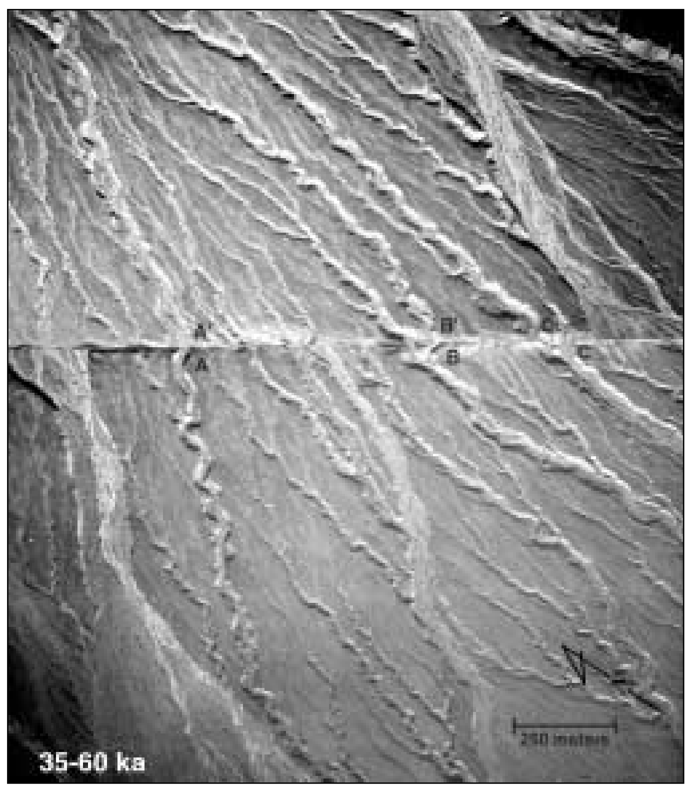


*Figure A3-8.Palinspastic reconstruction of faulted alluvial-fan deposits at about 35-60 ka. Note realignment of original channels (denoted by letters) as shown in fig. A3-1.*

# Stop A4 — Lacustrine deposition of Lake Manly or springs near Titus Canyon?

*Ralph E. Klinger*

Fall Canyon 7.5' quadrangle
GPS: NAD 27, UTM Zone 11
$^{40}70^{885}$mN, $^{4}86^{000}$mE
Elevation: 36.9 m (121 ft) ASL

From Stop A3, continue south on NPS Route 5 for almost 15 km (9 mi) or to a point about 2.9 km (1.8 mi) past the Titus Canyon road (to mile 30.7 in the road log). Again, park as far off of the pavement on the right as is reasonable. This will be a very short stop; we might walk a 60-70 m (couple hundred feet).

## OBJECTIVE

The primary objective at this stop is to examine the fine-grained sediments and tufa deposits preserved along the eastern margin of Mesquite Flat and discuss their possible origin.

## OVERVIEW

We are standing on the toe of the Titus Canyon alluvial fan in the northeast corner of Mesquite Flat at an elevation of about 37 m (121 ft) (fig. A4-1). At this location, upper Pleistocene tufas overlie a poorly sorted sand that can be traced from this location for more than 7 km (4.5 mi) south along the eastern margin of Mesquite Flat. At a point to the west along the eastern flank of the Cottonwood Mountains at the same elevation there is a sequence of silt and sand beds intercalated with chalk and dense limestone that were previously interpreted by Blackwelder (1933) as lacustrine beds associated with Lake Manly. The sequence of sediments that we will be looking at here is very similar to those described by Blackwelder to the west.

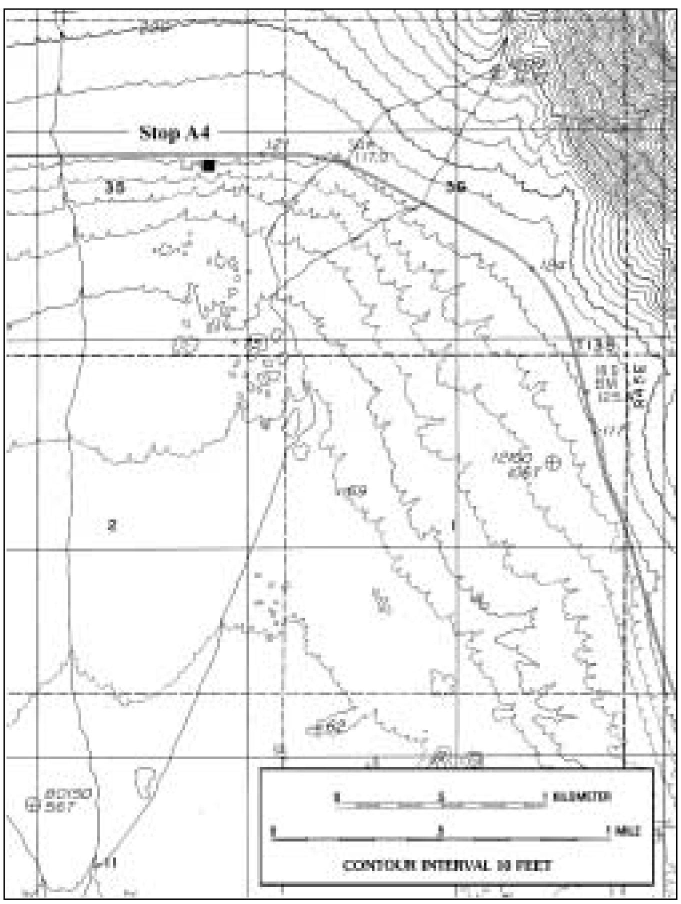


*Figure A4-1. Map showing the location of Stop A4.*

We are also standing near the Grapevine fault. The Grapevine fault forms the eastern margin of Mesquite Flat and shows evidence of late Quaternary movement. About a 1 km to the east is an alluvial fan formed at the range front (NE ¼ of section 36; fig. A4-1). This fan was the subject of Chester Beatty's 1961 paper on the influence of tectonics on alluvial-fan morphology (described at mile 29.4 in the road log). The discussion at this stop will be focused on differentiating fossil spring deposits from lacustrine sediments and the implications each has on the late Pleistocene history in Mesquite Flat. If your interests lie in faulted alluvial fans, hike to the east to the fan and take a quick look.

## TITUS CANYON FAN—TRIANGLE SPRING COMPOSITE SECTION

Over 7 m of upper Pleistocene lacustrine or fossil spring deposits (?) are preserved near the mouth of Titus Canyon. A composite section (fig. A4-2) was reconstructed from a measured section at this site and an exposure near Triangle Spring, about 7 km (4.5 mi) to the south. A laterally continuous sand bed (unit 3; fig. A4-2) was used to tie the two sites together. The relationship between units 2 through 5 (fig. A4-2) and Q2c alluvium (unit 6; fig. A4-2) in the composite section is based on the association of a poorly sorted, salty sand bed (unit 3?) that directly overlies the Q2c alluvium near Triangle Spring (fig. A4-3). Units 2, 4, and 5 were not observed near Triangle Spring.

## UNIT 1-Q4B

0-25 cm. Unconsolidated, light gray (10YR 7/2) gravelly silty very coarse sand. Silty matrix reacts strongly to hydrochloric acid. Gravel in the deposit is about 42 percent dolomite, 30 percent quartzite, 20 percent sandstone, 5 percent welded tuff, and the 3 percent chert. Desert pavement and rock varnish

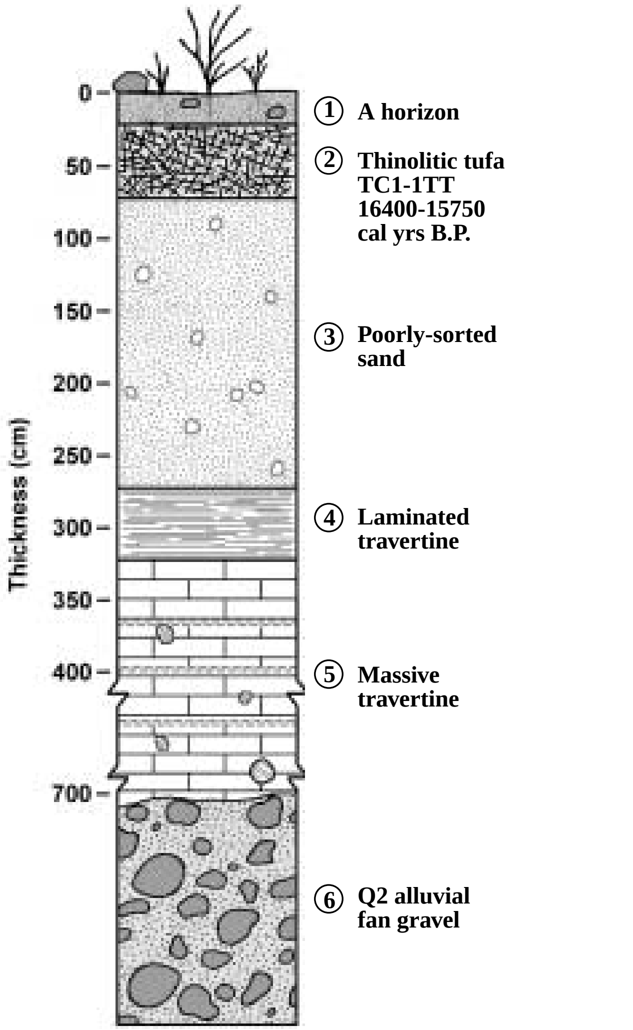


*Figure A4-2. Stratigraphic section of upper Pleistocene lacustrine or fossil spring deposits (?) preserved at 37 m at the toe of the Titus Canyon alluvial fan (see fig. A4-1).*

are non-existent; bar-and-swale morphology is very prominent. This upper Holocene deposit is derived primarily from reworked alluvium on the Titus Canyon alluvial fan.

## UNIT 2-QLM4

25-75 cm. Dark yellowish-brown (10YR 4/4), 50-cm thick, thinolitic tufa. The contact with unit 1 is abrupt, but quite irregular due to post-depositional erosion. The thinolitic tufa bed is locally well preserved, but is being buried by sandy gravel (unit Q4b) along the distal margin of the Titus Canyon alluvial fan. A sample of crystalline thinolite was collected from the top of the tufa bed for radiocarbon analysis. The age of the tufa sample was determined in a scintillation spectrometer using by conventional radiocarbon methods and 14C activity was measured over an extended period to reduce the analytical error. The resultant analysis yielded an apparent 14C age of 13,450 ± 80 yrs B.P.; its calibrated age of 16,400-15,750 cal yrs B.P. was determined using Oxford University's radiocarbon calibration program OXCAL.

This bed forms the upper-most lacustrine or spring (?) deposit at this location. The tufa sample is interpreted as thinolite on the basis of the dark brown, euhedral crystals of indurated, very thinly laminated and dense calcite that form clusters on the surface. Individual crystals are commonly hollow, triangular in cross-section, and as much as 8 cm long (fig. A4-4). These characteristics are similar to those described by Morrison (1964) for thinolite formed in Lake Lahontan. Thinolitic beds are believed to form in relatively shallow water (3-30 m; 10-100 ft) near the margin of the lake and reflect distinct changes in the thermal and chemical characteristics of the lake (Morrison, 1964; Benson, 1994).

A variety of phytoliths were also recovered from a sample of the tufa (L. Scott Cummings, personal communication, 1999). Phytoliths types observed included smooth elongate forms typi-

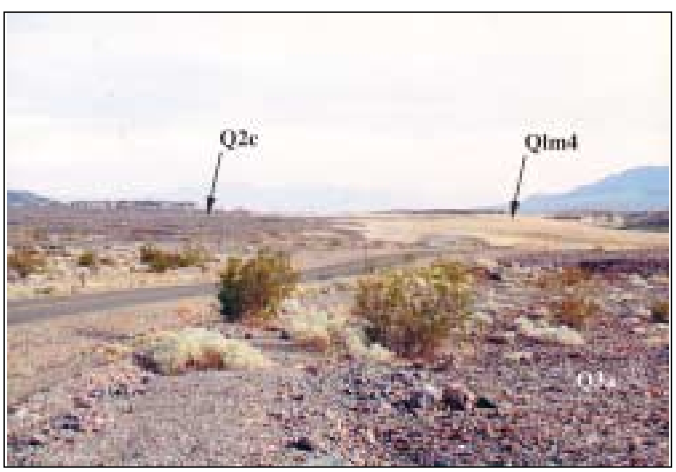


*Figure A4-3. Stratigraphic relationship between Q2c alluvium and upper Pleistocene deposits (Qlm4?) located about 34 m south of Triangle Spring.*

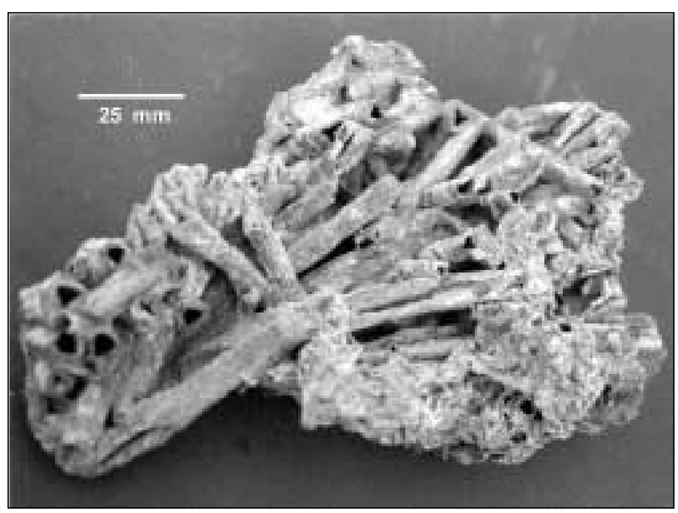


*Figure A4-4. Cluster of thinolitic tufa crystals from unit 2 at the top of the section near Titus Canyon (photograph by A.M. Klinger).*

cal of many grasses, crenate forms common in festucoid or cool season grasses, and a few buliforms. Recovery of this variety of phytoliths indicates that the tufa incorporated organic fragments derived from a variety of plants growing along the margins of a shallow lake or marsh and not a single type or form of vegetation.

#### UNIT 3-QLM4

75-275 cm. Pinkish gray (7.5YR 6/2), poorly-sorted, calcium carbonate cemented, coarse angular sand. The unit contains clasts of dense, laminated travertine reworked from underlying unit 4. The upper contact with unit 2 is abrupt and smooth suggesting a conformable relationship with overlying unit 2. Correlative deposits form a prominent "shoreline" along the eastern margin of Mesquite Flat that extends to the south for more than 7 km (4.5 mi) and overlie Q2c alluvial fan gravel near Triangle Spring.

#### UNIT 4-QLM4

275-325 cm. Laminated travertine bed.

#### UNIT 5-QLM

325-700 cm. Very dense, massive, white marl interstratified with several thin, silt beds and gravel-sized fragments of reworked older travertine. The unit is brecciated in places and displays many dissolution pits, pipes, and desiccation cracks.

#### UNIT 6-Q2C ALLUVIUM

Weakly consolidated, fine to coarse sandy subangular gravel. Typically, a gravel-free silty fine sand vesicular A horizon has developed at the top of these deposits. Near Triangle Spring, the A horizon is much sandier due to its location adjacent to and immediately downwind of the Stovepipe Wells dune field. Soluble salt accumulation in the upper meter of the soil is readily apparent and the matrix throughout the entire profile reacts strongly to hydrochloric acid (Klinger, 2001). The calcium carbonate morphology reaches stage I+ to II+ development in the lower B horizons. Gravel in the desert pavement and in the lower soil horizons of deposit are about 65 percent dolomite, 20 percent quartzite, 8 percent sandstone, and 7 percent chert. Desert pavement on Q2c surfaces is generally very well developed. Rock varnish formation is also very well developed reaching a maximum dark reddish brown (5YR 3/3) color on quartzite clasts. Dolomite clasts in the pavement have shallow (<5 mm) dissolution pits (see table A3-1; Stop A3). The age of the tufa bed provides a minimum age for the underlying Q2c gravel and a maximum age for Q3a gravel that overlies unit 3 near Triangle Spring (see fig. A4-3).

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## Stop A5

## Beatty Junction bar complex

*Ralph E. Klinger*

Beatty Junction 7.5' quadrangle
GPS: NAD 27, UTM Zone 11
$^{40}51^{875}$mN, $^{5}04^{830}$mE
Elevation: 42.7 m (140 ft) ASL

From Stop A4, continue south on NPS Route 5 to California Highway 190 (mile 17.7 in the road log). At the intersection, turn left and continue south about 6.5 miles to Beatty Junction (mile 11.2 in the road log). At Beatty Junction, turn left and continue up the Beatty Cutoff Road about 1.6 miles to the highest of several lacustrine bars, which are named the Beatty Junction bar complex. Once again, park as far off of the pavement on the right as is reasonable.

The objective at this stop is to examine soils, other relative age indicators, and some numeric ages from one of the most cited examples of lacustrine deposition in northern Death Valley. As a result, we will also discuss some of the problems surrounding Lake Manly (see also Chapter G in this volume). We will hike to the top of the hill west of the road for a quick overview of the area. At this stop, we will examine the complex of spits built into Lake Manly from the hill on the left side of the road. We will observe the internal stratification of the gravel as well as the soil that has formed on the main (and highest) spit in the road cut and in stream cuts at both ends.

#### GEOLOGIC SETTING

We are at the southern end of the Kit Fox Hills on a isolated hill that once formed a small peninsula in Lake Manly along its northeastern shoreline (fig. A5-1). Hunt and Mabey (1966) originally mapped this hill as undifferentiated Miocene sedimentary rocks (their unit Ts) that were considered to be younger than the Titus Canyon Formation (less than about 22 Ma), but older than the Pliocene Furnace Creek Formation (>6 Ma). Wright and Troxel (1993) later mapped these rocks as the conglomerate facies of the late Pliocene-early Pleistocene Funeral Formation. However, the presence of the 0.66-Ma Lava Creek B in the southern part of the hills suggests that these rocks may in part be as young as middle Pleistocene.

To the east, there is an expansive piedmont at the northern end of the Funeral Mountains. The underlying pediment is formed on strata of the Pliocene to Pleistocene Funeral Formation and

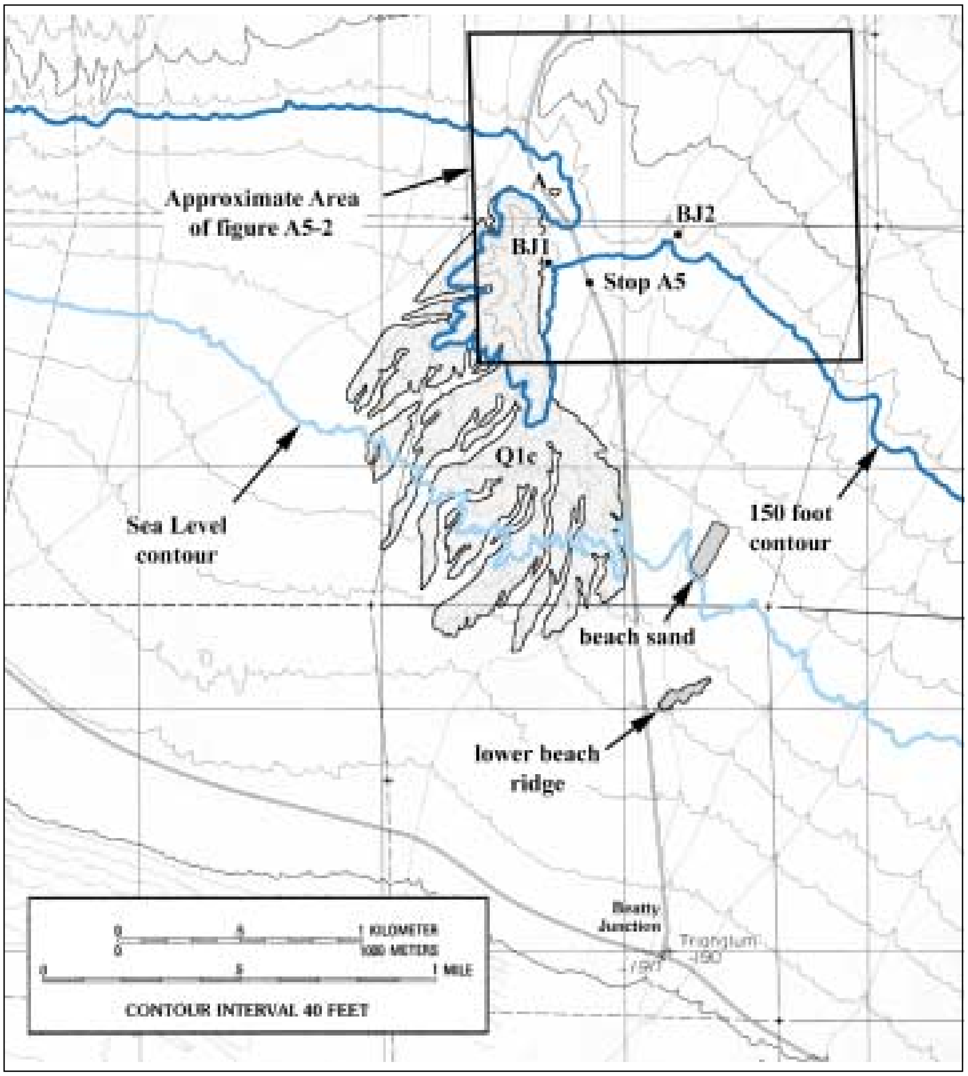


*Figure A5-1. Map showing the location of Stop A5 and constructional lacustrine features in northern Death Valley.*

older sedimentary rocks, and is covered by a thin veneer of Holocene and Pleistocene alluvium. The alluvial cover is generally about a meter thick near the range front and thickens down slope toward the valley. The contact between the overlying alluvium and the pediment surface is well exposed in many of the incised drainages along the road between here and Hells Gate to the north. Both Hunt and Mabey (1966) and Wright and Troxel (1993) show a fault that parallels the Northern Death Valley fault between this stop and the front of the Funeral Mountains that down drops strata of the Kit Fox Hills on the west relative to the less resistent rocks that underly the pediment on the east. Owing to topographic reversal, the more resistent strata west of the fault maintain the positive relief of the Kit Fox hills.

On the valley floor to the southwest of here, we see the Salt Creek Hills and Salt Creek. The Salt Creek Hills, an anticline formed in the Pliocene Furnace Creek and Pliocene-Pleistocene Funeral Formation, forms the structural divide between Cottonball basin to the south and the Mesquite Flat basin to the north. Salt Creek cuts across the northeast limb of the anticline and connects the Mesquite Flat basin with the Cottonball basin. Uplift of the Salt Creek Hills and Kit Fox Hills appears to be the result of localized northeast-southwest directed compression in response to the rotation of the Panamint Mountains between the Northern Death Valley fault zone and the Hunter Mountain fault to the west (refer to the discussion regarding formation of the Lake Rogers basin at Stop A2).

To the south, we see Cottonball basin and into what would have been the long and narrow fetch of Lake Manly along the axis of Death Valley. Deposits associated with highstands of Lake Manly are more common than reported in this area. They are found around the margins of Cottonball basin at elevations between 73 m (240 ft) below sea level (the 2,000-year-old lake of Hunt and Mabey, 1966) to more than 46 m (150 ft) above sea level. These deposits consist of gravelly cross-stratified sand and imbricated, sandy gravel with tufa and beds of salty sand. The ages of these deposits are very poorly constrained, owing to poor access and lack of datable materials. Besides the deposits in the immediate area (fig. A5-1), about 5 km (3 mi) to the southeast is an extensive deposit of imbricated, cross-stratified gravel tucked behind the northernmost of the Three Bare Hills. Hunt and Mabey (1966) describe this deposit as forming an arcuate bar with foreset beds that dip 10∞ to the northwest. Exposures in channel cuts show that these deposits overlie their Qg2 alluvium (see table A-1).

## BEATTY JUNCTION BAR COMPLEX

Some of the most prominent and well-known constructional landforms in northern Death Valley are the group of spits and beach bars along the Beatty Cutoff road, north of Beatty Junction (Blackwelder, 1954; Hunt and Mabey, 1966; Orme and Orme, 1991; Wright and Troxel, 1993; Galvin and Klinger, 1996; see fig. A5-2). Klinger (2001) refers to these gravel spits and sandy beach ridges (bars) collectively as the Beatty Junction bar complex. Galvin and Klinger (1996) had previously described the spits and ridges at this location, made

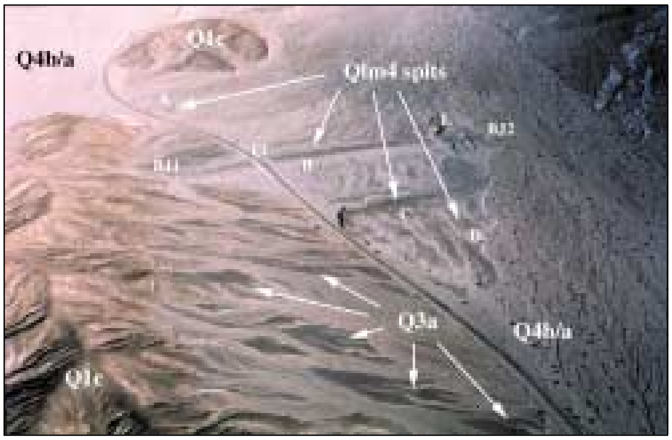


*Figure A5-2. Oblique aerial photograph of bars and ridges A, B, C, and D that comprise part of Beatty Junction bar complex. BJ1 and BJ2 mark location of soils described on main spit (see table A5-1). TL and Cl mark approximate location of sampling for thermoluminescence and chlorine-36 age determinations made by Anderson (1998) and Phillips and Zreda (1999) (photograph by C. Galvin).*

a case for their relative age based on stratigraphic relationships, and argued that they formed during the transgression of a lake.

It is clear that the hills west of the bar complex would have formed a small peninsula or headland that extended into Lake Manly at lake elevations above sea level (fig. A5-1). In general, the bars and ridges in the complex are composed of imbricated, and cross-bedded sand and gravel derived from the eastern side of hill that were transported by currents north- and eastward, and deposited as spits into Lake Manly. Evidence of shoreline erosion and the stratification exposed in the road cut and along the margins of the spits are consistent with these transport directions. Each of the four spits preserved at this site (A, B, C, and D in fig. A5-2) are considered to be of similar age although it is clear that the main bar (B) is the youngest based on stratigraphic relationships between them (Galvin and Klinger, 1996). Another isolated spit is exposed on the east side of the road near Beatty Juncion, at about 19.1 m (62.5 ft) below sea level.

There four spits and ridges formed at this location that trend approximately east-west and have crest elevations from north to south of about 44.97 m (147.6 ft), 45.97 m (150.8 ft), 36.30 m (119.1 ft), and 33.78 m (110.8 ft) above sea level (fig. A5-3A). The most northerly of the ridges (A in fig. A5-2) is an eroded remnant of a larger spit that extended off the northern end of the hills. The most prominent and longest of the spits (B in fig. A5-2) is a meter higher than ridge A, but is very well preserved and retains much of its original morphology. The internal stratification of the spit, as well as the soil formed on it, can be seen in the road cut through ridge B and in stream cuts across the spit. Ridge C is also fairly well preserved, but is shorter, more dissected and is no longer attached to the hills that formed the peninsula. The southernmost ridge (D) is more dissected than ridge C and is only preserved as a gentle crest on the lakeward side of ridge C. Galvin and Klinger (1996) hypothesized that the ridges formed in order of increasing crest elevation (D, C, A, and B). This is supported by the superposition of deposits associated with each higher ridge or spit over the next lower ridge (fig. A5-3B. It is also clear that spit A formed prior to spit B because waves could not reach A if B were already in place.

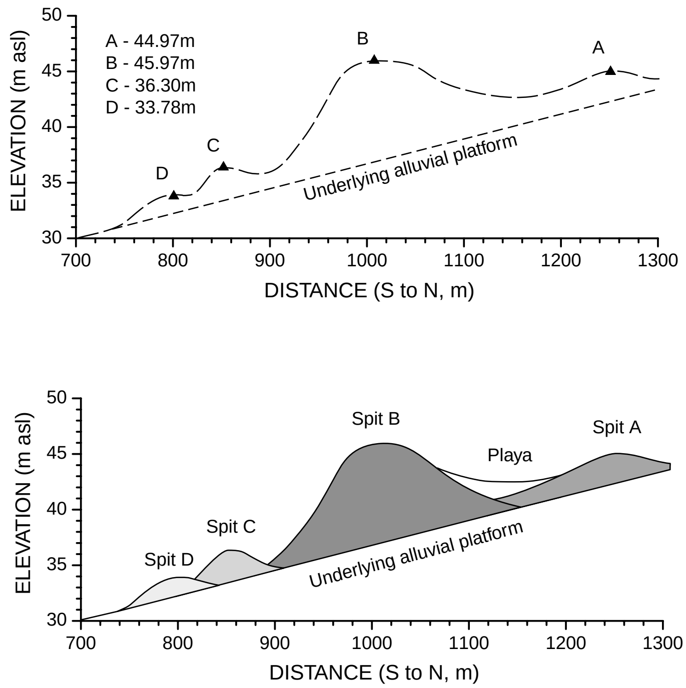


*Figure A5-3. A) North-south profile of Beatty Junction bar complex showing crest elevations. B) Superposition of deposits associated with spits and playa. Vertical exaggeration is about 12.5x for both plots.*

## AGE OF THE BEATTY JUNCTION BAR COMPLEX

The age of the bar complex was assumed to be late Pleistocene (10-35 ka) on the basis of the soil development on the main spit (B). The soil properties developed on the main spit (see table A5-1) also seem to be consistent with the extent of the soil development described on a sequence of late Pleistocene beach ridges in the Mojave Desert, south of Death Valley (McFadden and others, 1992). Without numerical dating, a last pluvial age (marine oxygen-isotope stage II, OIS2) for the Beatty Junction bar complex seemed to be a viable assumption since the only other lake known to exist in Death Valley occurred during OIS 6, 128-180 ka (revised Blackwelder stand of Hooke, 1999). The soil development on the Beatty Junction bar complex was not considered representative of a >100 k.y. soil, particularly given the advanced degree of soil development seen elsewhere on Q2c alluvium that are related to sediment of known age (see discussions at Stops A2 and A4).

**Table A5-1. Field descriptions of soil properties for sites BJ1 and BJ2**

Profile No. BJ1 Described by Ralph E. Klinger Date 3/4/95 Time PM
Map Unit Qlm4 Parent Material Mixed well-rounded sandy gravel Slope 1 Aspect E
Location Western end of the main Lake Manly beach ridge
Quadrangle Beatty Junction 7 1/2' Longitude 116° 54'54" Latitude 36°36'51" Elevation 170'

| Horizon | Depth (Thickness) | Boundaries | Structure | Clay Films | Consistence: Stickiness | Consistence: Plasticity | Consistence: Dry | Texture | Gravel % | CaCO3 (NaCl) | Color (dry) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Avkz | 0-3 (3) | aw | 2mpl | 1fpo | ss | ps | sh | fSL | 25 | ev | 10YR7/3 |
| Btk | 3-11 (8) | aw | 2m-csbk | 3ppo-pf | ss | ps | so | fL | 25 | ev (I+) | 7.5YR6/4 |
| Bkz1 | 11-24 (13) | - | 1csbk | none | so | po | so | fL | 50 | e (I+) | 7.5YR6/6 |
| Bkz2 | 24-50 (26) | - | 1csbk | none | so | po | so | mSL | 50 | e (I) | 7.5YR6/6 |
| Bkz3 | 50-75 (25) | - | 1csbk | none | so | po | so | mSCL | 50 | e (I) | 7.5YR5/4 |
| Bkz4 | 75-100+ (25+) | - | 1csbk | none | so | po | so | mSCL | 50 | e (I) | 7.5YR5/6 |

**Notes:** Estimated to be latest Pleistocene based on the degree of soil development. Relates to well-preserved lacustrine landforms and deposits at same elevation in northern Death Valley. Thermoluminescence analysis of sandy silt deposits interpreted as back bar deposits behind the main beach ridge B yielded an age 24.0 ± 2.5 ka and 20-85 ka (Anderson, 1998; Phillips and Zreda, 1999).

Profile No. BJ2 Described by Ralph E. Klinger Date 3/4/95 Time AM
Map Unit Qlm4 Parent Material Mixed gravel Slope 1 Aspect E
Location Eastern end of the main Lake Manly beach ridge
Quadrangle Beatty Junction 7 1/2' Longitude 116° 56'35" Latitude 36°36'54" Elevation 150'

| Horizon | Depth (Thickness) | Boundaries | Structure | Clay Films | Consistence: Stickiness | Consistence: Plasticity | Consistence: Dry | Texture | Gravel % | CaCO3 (NaCl) | Color (dry) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Avkz | 0-3 (3) | aw | 2f-msbk | 1fpo | so | po | so | fL | <1 | es (I) | 10YR7/4 |
| Btk | 3-12 (9) | aw | 2msbk | 4dpo-pf | s | ps | sh | vcSL | 10 | ev (II) | 10YR6/4 |
| 2Bk | 12-24 (12) | as | sg-1f-csbk | none | ss | po | so | vcSL | 25 | es (I) | 7.5YR6/6 |
| 3Bkz | 24-42 (18) | as | sg-1msbk | none | so | po | so | cLS | 50 | e (II) | 10YR7/4 |
| 3Bkyz | 42-61 (19) | as | sg-1msbk | none | ss | ps | so | cLS | 50 | e (I) | 10YR6/3 |
| 4BCkz | 61-78 (17) | as | sg | none | so | po | lo | cLS | 25 | e (I+) | 10YR7/3 |
| 5C | 78+ | - | sg | none | so | po | lo | cS | 50 | es | 10YR7/2 |

**Notes:** Primary stratification is visible in all horizons below 24 cm; color laminae present in 2Bwk-3Bkz-3Bkyz horizons; varies from 10YR7/4 to 7.5YR6/6; appears to be associated with primary stratification.

A late Pleistocene age for the Beatty Junction bar complex also seems to fit with the chronology derived from the Badwater core by Li and others (1997). In their analysis of the core, the deepest lake in the past 100,000 years occurred during their Period II (OIS 2). Time constraints for this lake are provided by U-series ages of 9.6±3.3 and 30.1±3.3 ka on calcareous material in mud). The interpretation for a deep lake during OIS2 was based on the occurrence of ostracode species Candona and Limnocythere ceriotuverosa identified by Forester and others (1996) in the same sequence of sediments. The depth of the lake was estimated to be about 90 m based on a correlation to dated shorelines at about sea level whose ages fall within this time interval (12,630±1,100 and 12,970±185 14C yrs B.P.; Dorn and others, 1990; Hooke and Dorn, 1992). However, Knott (Stop C1 in this volume) places doubt on this correlation, suggesting instead that the “dated shorelines” are in fact fault scarps. In addition, no consideration was made for changes in the shoreline or basin elevations over the past several tens of thousands of years due to uplift and subsidence associated with either the Black Mountains or Northern Death Valley fault zones.

In northern Death Valley, few numerical age determinations have been made on lacustrine constructional landforms. Two types of age estimates have been made for the main gravel spit (B) in the Beatty Junction beach complex (Anderson, 1998; Phillips and Zreda, 1999; see table A5-2). Knott (unpubl. data, 1998) and Anderson (1998) reported luminescence age of 24.0±2.5 ka (TL) and about 68 ka (OSL) for fine-grained sediment ponded behind the main gravel spit near its eastern end (fig. A5-2; see also Chapter G, Table G-2). This sediment was interpreted to be deposited in the playa behind the spit, thus the TL age post-dates the formation of the spit. Interestingly, the age obtained on the tufa at Titus Canyon (Stop A4) is not inconsistent with these ages and the age range reported for the last deep lake (OIS2) in the Badwater core (Li and others, 1997).

Zreda (cited in Orme an Orme, 1991) and Phillips and Zreda (1999), using a relatively new approach, examined the accumulation of cosmogenic chlorine gravel clasts on the spit and in a profile through the gravel at the crest of the same spit (fig. A5-2). Their surface age was reported as 153±13 ka, which correlates well with OIS 6.However, more recent age estimates from a few samples yield an age range of 20-85 ka (OIS2 to OIS4), which initially appears to be consistent with the results reported by Anderson (1998). However, there were problems of determining the level of inherited cosmogenic chlorine in the lacustrine the gravel that makes up the spit. Phillips’ (written commun., 2001) is analyzing additional profile samples in the spit in order to solve the inheritance problem.

## SOIL DEVELOPMENT AND RELATIVE AGE CRITERIA

The soil development on the main spit (B) in the Beatty Junction bar complex and other constructional landforms in northern Death Valley were described in order to calibrate a soil chronosequence, which in turn was used to evaluate the late Quaternary activity on the Northern Death Valley fault zone (see Stop A3). Three soil profiles were described on constructional lacustrine landforms (unit Qlm4) in northern Death Valley, two on spit B at this location (see fig. A5-2) and the third on a beach ridge near the mouth of Mud Canyon. The desert pavement on the Mud Canyon beach bars is poorly developed, but this is considered to be an artifact of the generally sandy nature of the material comprising the beach ridges. In addition, the beach ridges are located along the eastern margin of the Stovepipe Wells dune field, so there has been a very rapid influx of sand during dry periods. The gravel on the surface of these ridges is quite coherent, shows little or no sign of salt weathering or disintegration, and lacks any significant formation of rock varnish. The lack of significant weathering and varnish is attributed to wind abrasion, in as much as ventifacts are abundant in the area. On the other hand, soils are well developed on similar age alluvial materials. The parent material at Mud Canyon differs slightly in that the beach bars are composed of fine-grained sand and gravelly sand rather than sandy gravel found on the Beatty Junction bars. Overall, the profile development is very similar at the two sites, which have similar elevations, aspect, climate and vegetation. The B horizon at Mud Canyon is more than 50 cm thick, with generally more halite than gypsum in the upper part of the horizon (fig. A5-4). Salt morphology reaches a maximum of stage II, with a maximum of 5-mm-thick crusts on gravel and abundant flecks and nodules as much as 2 cm in diameter in the soil matrix.

The Beatty Junction bar complex is, as described above, composed of imbricated gravel and cross-stratified sandy gravel (unit Qlm4). Although only preserved along their crests, the pavement and varnish on the spits and ridges in the Beatty Junction bar complex are better developed than

**Table A5-2. Numerical ages from spit B (highest) of the Betty Junction bar complex**

| Location Reference | Elevation in m (ft) | Analytical technique | Age (ka or 1,000 yrs ago) |
|---|---|---|---|
| Back bar, eastern end (Anderson, 1988) | 45.0 (148) | Thermoluminescence | 24.0±2.5 |
| Back bar, eastern end (Knott, unpubl data, 1988) | 45.0 (148) | Optically stimulated luminescence | ca. 68 |
| Crest of spit in road cut (Phillips and Zreda, 1999) | 46.0 (151) | $^{36}$Chlorine (gravel in profile) | 20-85 (min-max) |
| From crest of spit (Zreda, 1991, cited in Orme and Orme, 1991) | 46.0 (151) | $^{36}$Chlorine (gravel on surface) | 153±13 |

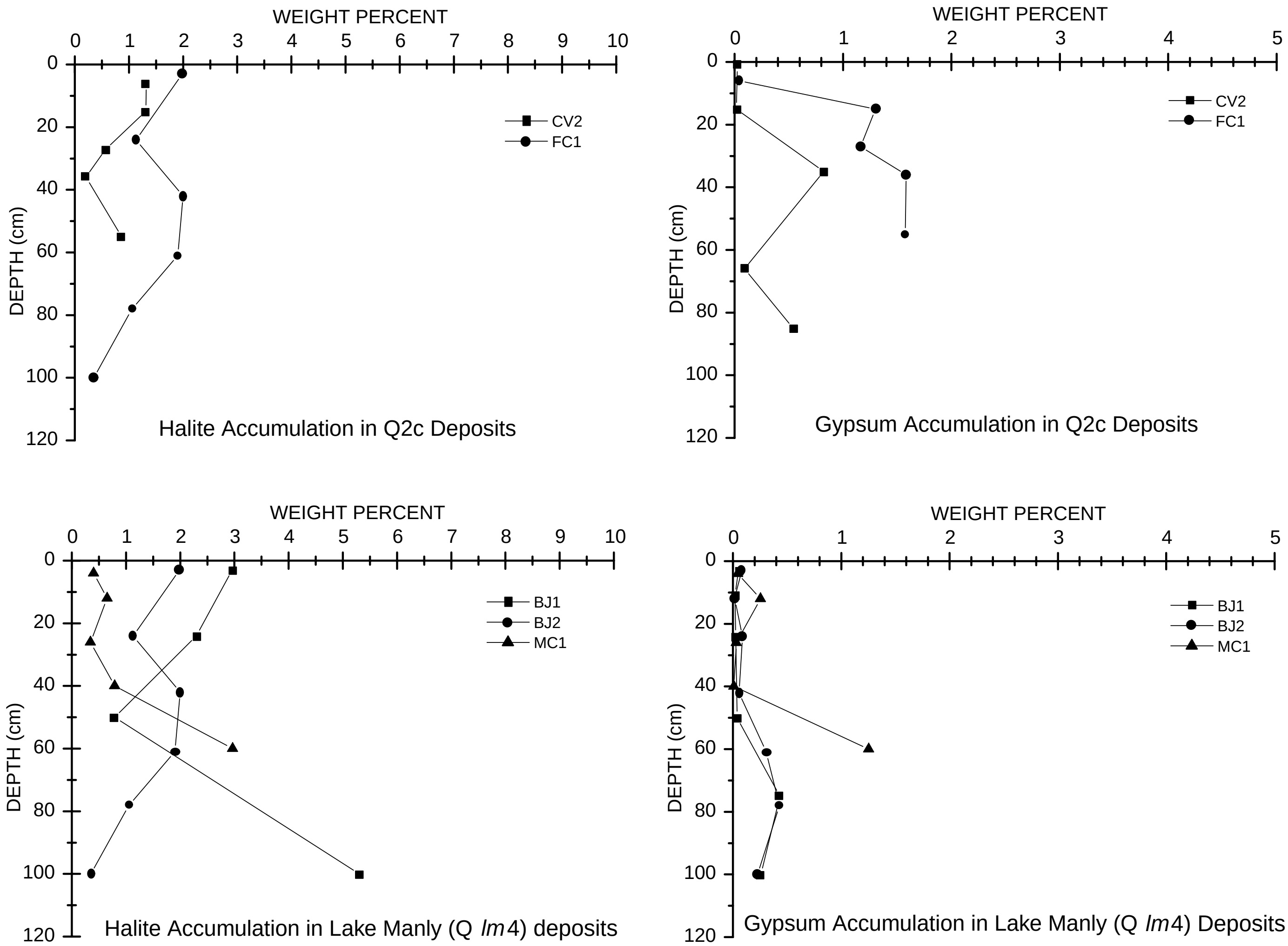


*Figure A5-4. Plots of soluble salt distribution with depth in Qlm4 deposits and in Q2c alluvium in northern Death Valley.*

at Mud Canyon. The gravel on the surface of the main spit is coherent, but it shows more evidence of salt weathering and disintegration than on the Mud Canyon ridges. Despite these differences, the pavement and varnish formation at the Beatty Junction bar and Mud Canyon sites do not appear to be as well developed as the pavement and varnish on Q2c alluvium (Q2c at Stop A3), which is considered to be 12-70 ka in Northern Death Valley (see table A-1). This may be due in part to the relative instability of the spit crests and erosion on the adjacent spit slopes, but exposures of the soil developed across the main spit suggest that the landform has been relatively stable.

As previously noted, with the exception of the parent material, soil development on the main spit is similar to that on the beach ridges near Mud Canyon. If fact, there appears to be a greater difference in the soils formed on opposite ends of the main spit (table A5-1) than between the two sites. The B horizon on the main bar is 75-100 cm thick with more halite than gypsum in the upper part of the profiles. The B horizon on the upper end of the spit is slightly thicker than on the lower end of the spit, but the salt morphology reaches a maximum of stage II on the lower end of the spit.

Overall, the most notable differences between the soils on the lacustrine gravel (unit Qlm4) and on unit Q2c alluvium in northern Death Valley is in the weight percent of the soluble salt accumulation in the B horizon (fig. A5-4). The loam textured vesicular A horizons are also generally thicker on Q2c deposits and argillic horizons are slightly more clayey. Overall, the soil developed on lacustrine deposits in northern Death Valley appear quite similar to those described on a sequence of late Pleistocene beach ridges at Silver and Soda Lakes in the Mojave Desert south of Death Valley (McFadden and others, 1992). Based on the soil development and other relative age properties, the Q2c alluvium appears to correlate to the Late Black Cones alluvium in Crater Flat east of Death Valley (Peterson and others, 1995) that is attributed to climatically induced alluviation.

## POSSIBLE HIGH SHORELINE DEPOSITS

The most prominent shorelines along the Black Mountains in central Death Valley are at about 90 m (295 ft; the revised Blackwelder highstand of Hooke, 1999). They have been dated by U-series at about 120-186 ka (OIS 6) and correlated to deep-lake sediment in the Badwater core (Ku and others, 1998; Lowenstein and others, 1999). However, neither shorelines nor terrestrial deposits at similarly high elevations are found in northern Death Valley. In fact, the highest constructional deposits in the region are those of Spit B (+46 m); most of the other lacustrine gravels are at maximum elevations of 33-37 m. However, this nonconcordance of elevations may in part be explained by uplift and/or subsidence along one or more of the faults in the Death Valley system. In addition to the eastward tilting described in the road log (Chapter A, mile 1.1), Hunt and Mabey (1966) also noted that there is an apparent tilting of the basin to the north as well. Although they admit that the evidence is less than convincing, it is a structurally reasonable supposition. More recently, Hooke (1999) brought additional information to bear on this situation in the southern part of Death Valley. The primary point here is that it is very important to recognize that deformation along parts of the Death Valley fault system introduces a complicating factor into the interpretation of shorelines and construction landforms of Lake Manly.

It is possible that evidence for old highstands of Lake Manly in northern Death Valley is very subtle but right under our noses, literally. In the Kit Fox Hills, gravelly alluvium at elevations between about 49 and 122 m (160 and 400 ft) is often very strongly cemented. The cementation is usually limited to the upper half meter of the deposit where it forms a resistant ledge that parallels the ground surface. These ledges can be seen on the slopes of the hill above Stop A5 (fig. A5-5). In places, the cemented gravel appears to coincide with a relict B horizon, but the uppermost argillic horizons appear to be truncated or missing. Horizontal fabric within the cemented gravel is similar to the fabric found in argillic horizons that has been engulfed by calcium carbonate (K horizons) that are found in middle Pleistocene and older soil profiles described in the region. Because of the similarities to older soil profiles, these ledge-forming deposits were referred to as the "Ts soil" by Klinger (2001), the name coming from undifferentiated Tertiary strata (unit Ts) of Hunt and Mabey (1966) on which the soils are commonly found.

The origin of the Ts soil is well unknown, but because the soil is limited to gravelly deposits older than the Q2c alluvium at elevations of about 160 and 400 ft, the Ts soil may be related in part to the inundation by calcite-rich lake waters associated with older lake highstands. If this is the case, the soil in actually nonpedogenic and should be referred to as a calcrete (no genetic implications), or a ground-water calcrete. This lacustrine origin is supported by the truncated nature of the soil and the cemented character of the alluvium. In places, it bears a striking similarity to the calcite-cemented beach rock and tufa-encrusted gravel commonly associated with other construction landforms in Death Valley and along shorelines of Lake Lahontan. Hunt and Mabey (1966) were certainly right in their observation that the lake features are "… not at all distinct." It is important to recognize the fundamental role of physical stratigraphy and how it helps resolves these types of problems. Until additional work on the terrestrial deposits in northern Death Valley is undertaken, and the role of active tectonics is considered, a coherent picture of the middle to late Pleistocene history of Lake Manly cannot be fully developed for Death Valley.

*Figure A5-5. "Ts soil" found on the hills west of the Beatty Junction bar complex.*

## DAY A—REFERENCES CITED


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# Field trip guide for Day B, Furnace Creek area

*Michael N. Machette, Christopher Menges, Janet L. Slate, Anthony J. Crone, Ralph E. Klinger, Lucille A. Piety, Andrei M. Sarna-Wojcicki, and Ren A. Thompson*

CHAPTER B

## OVERVIEW

This part of the field trip will focus on the Quaternary geology, geomorphology, tectonics, and upper Pliocene stratigraphy of the area around Furnace Creek, in the central part of Death Valley. Although each of the five stops (fig. B-1) covers only some of these topics, the overall emphasis of the day will be on developing an appreciation for the upper Cenozoic geologic and tectonic history of this fascinating area. The guides for Days A and C have narrative road logs because their first stops are a long way north and south (respectively) from the starting point of the field trip (FOP headquarters at Sunset Campground). This day's guide instead uses detailed maps of each stop, the farthest of which is near Zabriskie Point, about 10 km to the southeast of Sunset Campground.

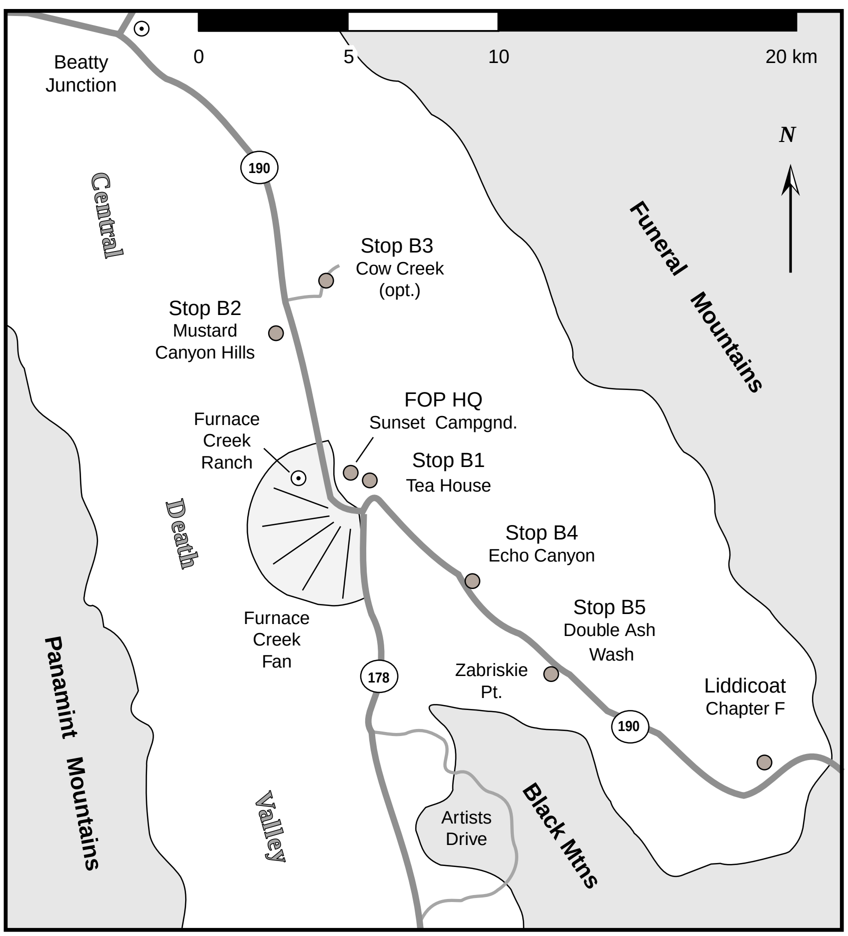


*Figure B-1. Generalized map of central Death Valley showing stops for Day B.*

Stop B1 is in the foothills, several hundred meters north of the Furnace Creek Inn. On our short walking tour, we will overview the central part of Death Valley and the adjacent Furnace Creek basin from the Tea House, see evidence for deposits of ancient Lake Manly, and discuss the northern part of the Black Mountains fault zone.

Traveling north to Stop B2, we will park at the Harmony Borax Works, and walk north and east into the Mustard Canyon hills. Here we will see evidence for domal uplift of the hills, solution collapse of their cores, and fault control on their margins. This area lies in a structurally complex transition zone between the Northern Death Valley and Black Mountains fault zones (for fault nomenclature, see Chapter J by Machette and others, this volume).

Stop B3 (which is optional) is the northern turn-around point for the day. Here, at the National Park Service's Cow Creek facility (administration and maintenance area), we will look at the geomorphology of late Holocene alluvial-fan deposits that have been displaced by recent faulting, see evidence for longer-term fault displacement, and briefly discuss seismic hazards issues pertinent to this and other NPS facilities.

Returning to the south, Stop B4 is along Furnace Creek Wash at the junction of State Highway 190 and the Echo Canyon Road (Stop B4). Echo Canyon Road is one of only two gravel roads that provide access to the western front of the Funeral Mountains. Walking from the road junction, we first see an excellent exposure of the Echo Canyon thrust fault. We will then climb across several thrust-fault scarps that are on the southwestern, uplifted limb of the Texas Springs syncline.

Our last stop (B5) will be at the parking lot for Zabriskie Point, which provides a jumping off point for a 2-km-long hike to the east, across State Highway 190 into gravel-covered hills. These hills contain spectacular exposures of two volcanic air-fall tuff beds that correlate with the tuffs of Mesquite Spring, which are dated at about 3.3-3.35 Ma. Four additional tuff beds are found in this section of the Furnace Creek Formation (see paper by Sarna-Wojcicki and others, Chapter E of this volume). This part of the Furnace Creek Formation has also been the subject of a paleomagnetic investigation by Liddicoat (Chapter F, this volume), although the two stratigraphic sections have not been tied together yet.

### ACKNOWLEDGEMENTS

The leaders and authors of this days trip would like to thank the staff of Death Valley National Park, particularly the Resource Management Division, for assistance with sampling permits, logistics for field work, and administrative support.

Michael Machette, Chris Menges, Andrei Sarna-Wojcicki, Janet Slate, and Ren Thompson are indebted to the National Cooperative Geologic Mapping Program for supporting their mapping project in the Death Valley Junction 1:100,000-scale quadrangle, under which most of their research is being conducted. Machette and others (1999) study of the Cow Creek area (Stop B3) and Machette and others (2000) study of the hydrology of the Texas Springs syncline (Stop B4) were supported by an interagency agreement between the National Park Service and U.S. Geological Survey. Mel Essington (NPS) provided administrative and logistic support for both of these specialized studies. The Nevada Operations Office of the U.S. Department of Energy in cooperation with the U.S. Geological Survey and the Bureau of Reclamation supported Ralph Klinger and Lucy Piety's work on the Echo Canyon thrust and Texas Springs syncline (Stop B4) as part of site characterization studies for Yucca Mountain under Interagency Agreement DE-AI08-92NV10874. Pete Birkeland and Karl Mueller, as well as some of the trip leaders and participants provided advice, insightful discussion, and review for Stop B4.

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## Stop B1 — Tea House above Furnace Creek Inn

*Michael N. Machette and Christopher Menges*

Furnace Creek 7.5' quadrangle
GPS: 27 NAD, UTM Zone 11S
$^{40}34^{335}$ mN, $^{5}12^{615}$ mE
Elevation -35 m (-115 ft) ASL

### INTRODUCTION

At this stop, we will view the late Cenozoic geology of the central part of the Death Valley basin, particularly the northern part of the Black Range, the Texas Springs syncline, and the Furnace Creek drainage. From our starting point in Sunset Campground (Stop B1), we will climb about 0.5 km to the east to the Tea House (fig. B1-1). At this point (Stop B1.1), we will be on top of a small gravel-capped hill (elev. 76.4 m), about 60 m above the present channel of Furnace Creek Wash. The intersection of State Highways 190 and 178, below the Furnace Creek Inn (south of us), is at sea level. Pacific Borax Company constructed the Inn in 1926 and 1927, after closing mining operations in the valley (see Chapter Q, this volume). The Inn opened in early 1927, but construction continued until 1938. The Tea House, which is the old wooden structure above the Inn on top of the hill, is this

*Figure B1-1. Photograph of the remains of the Tea House (photograph by M. Machette, Nov. 2000).*

stop's primary objective as an overlook. During the 1930's and 40's, the Inn's guests would take tea in this small building, a tradition established by Chinese staff at the Inn.

At several points along our route down the hill from the Tea House (Stop B1, figure B1-2) we will discuss the upper Pliocene through Pleistocene history of the basin, focusing on the basin-filling strata of the Furnace Creek and Funeral formations and remnants of several Quaternary deposits and associated erosion levels. In addition, we will see high-level lacustrine deposits of ancient Lake Manly at Stop B1.2, and ruptures of the basin-marginal Black Mountains fault zone at Stop B1.3.

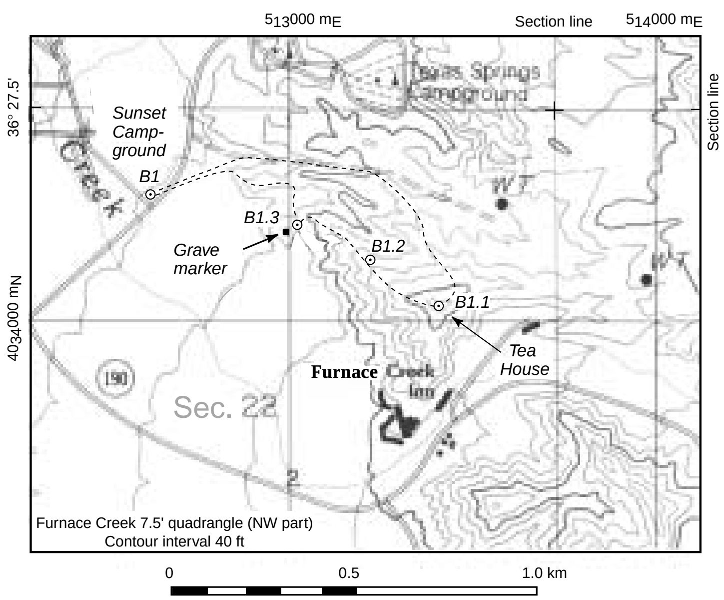


*Figure B1-2. Index map for Stop B1 area B1.1, B1.2, and B1.3 indicate places we will stop for discussion.*

## PLIOCENE BASIN FILL

From Sunset Campground, we will walk east up the service road past exposures of the Black Mountains fault zone in Pliocene strata. From here we will turn south, going down section through the upper part of the Furnace Creek Formation (Pliocene). At Texas Springs Campground, most of the deposits are playa and quiet-water lacustrine beds (mudstone, siltstone, and minor sandstone). However, as we proceed up hill to Stop B1.1, these beds become progressively coarser grained with the clasts having been derived from the Panamint Mountains (as reported by Hunt and Mabey, 1966).

The crest of the hill on which the Tea House is located (Stop B1.1) is underlain by predominantly coarse alluvial-fan sediment (conglomerate), which dip 20°-30° NE. These deposits have a characteristic greenish cast to them, and can be seen both down section to the south and in section to the southeast,

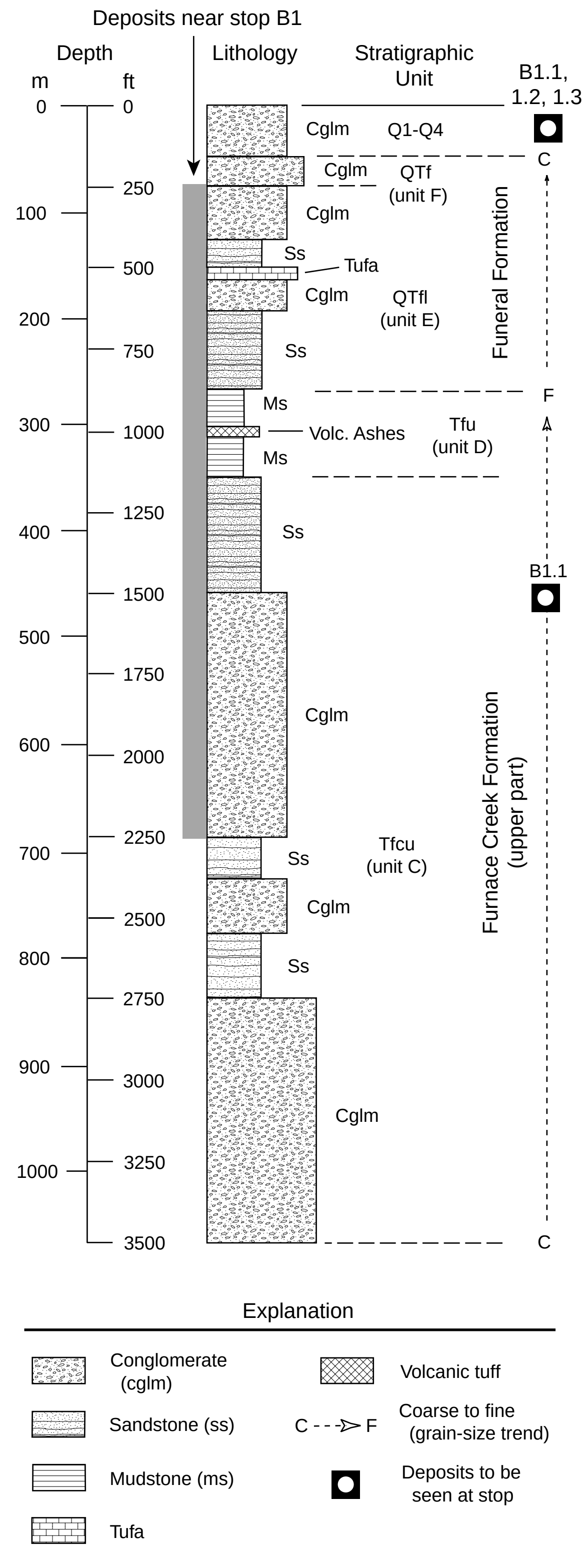


*Figure B1-4. Schematic columnar section showing facies of Furnace Creek and Funeral formations northeast of Stop B1. Section derived from mapping of McAllister, 1970 (modified from Machette and others, 2000).*

along Furnace Creek Wash (fig. B1-3). These conglomerates comprise the upper of two major coarse-grained sedimentary units of the Furnace Creek Formation (fig. B1-4). They are separated by a thick fine-grained section of lacustrine and sandstone and playa mudstone that is well exposed in Golden Canyon, south and west of Zabriskie Point (near Stop B5).

*Figure B1-3. View to southeast of Furnace Creek Wash and sedimentary rocks of Furnace Creek Formation (photograph by M. Machette, Nov. 2000).*

# Stop B1.1 Overview of the Furnace Creek area

UTM 11S $^{40}34^{040}$ mN, $^{5}13^{405}$ mE
Elevation 76 m (251 ft) ASL

The Tea House provides a wonderful vantage point for a 360° view of the Furnace Creek area. Below us to the west is the large alluvial fan of Furnace Creek, which extends about half way across the basin. Aerial photographs of the fan indicate that no obvious Pleistocene shorelines are etched across it, although there is a prominent vegetation line from small springs and seeps at the fan/playa interface at about -65 m (-213 ft) elevation. According to mapping of Hunt and Mabey (1966), the entire surface of the fan is Recent (i.e., Holocene), and our mapping suggests it is probably mostly late Holocene.

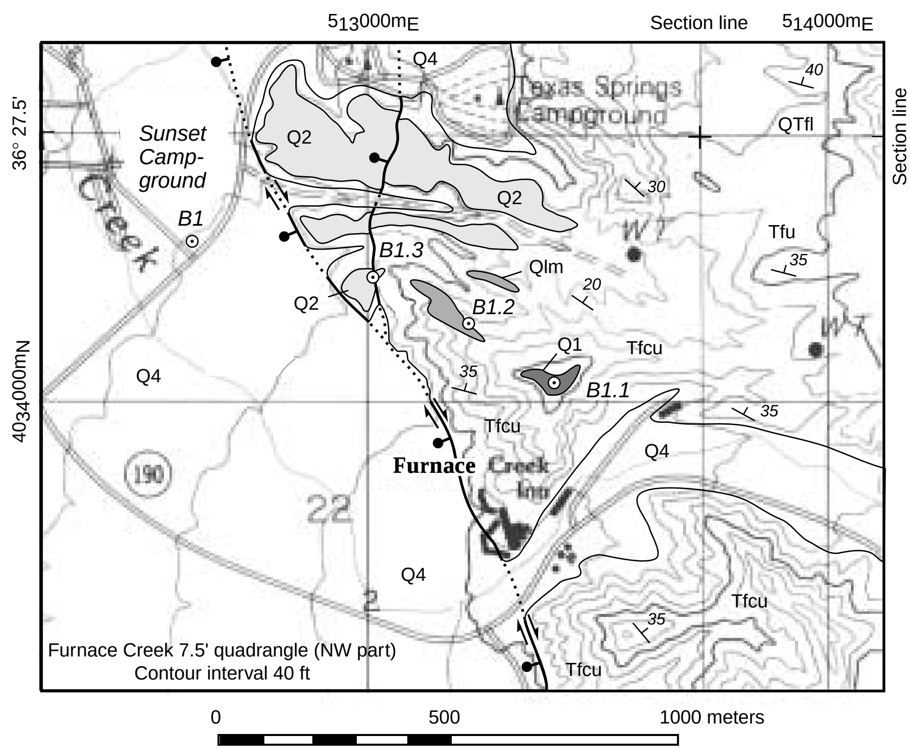


*Figure B1-5. Map showing Q2 deposits and generalized bedrock geology of Stop B1 (derived from mapping by McAllister, 1970, and unpublished surficial geology by Machette, Nov. 2000).*

The Black Mountains fault zone lies at the base of the hill that we are standing on (fig. B1-2). Young and repeated movement on the faults produced the distinct and prominent margin of the Black Mountains to the south, but north of us, the fault bifurcates into multiple strands (fig. B1-5). The westernmost trace of the fault has the largest scarp, (although the fault is actually concealed), whereas the eastward strands form distinct horsts and grabens on uplifted alluvial surfaces (at and north of Stop B1.2). No trace of these fault strands can be found on the young (late Holocene) alluvium that mantles the Texas Springs fan, although these faults project northward along the east side of Sunset Campground (the site of the annual 49'ers encampment), about a kilometer northwest of us.

To the northeast, several different Quaternary alluvial deposits are unconformable on the northeast dipping fine-grained part of the Pliocene Furnace Creek Formation. The main and most extensive deposit is mapped as Q2, which elsewhere consists of as many as three subunits (see Stop B5.1). In the middle distance to the northeast, the high-level hills comprise either (1) ancient tufa-rich spring deposits (white colored) in the lowermost part of the Funeral Formation (unit QTfl) or (2) travertine-cemented gravel (cliff-forming conglomerate) slightly higher in the Funeral Formation (unit QTf). This conglomerate forms the surface expression of the Texas Springs syncline, which strikes north-northwest and plunges gently to the south-southeast in this area.

Due east, almost all the strata in our view are within the upper part of the Furnace Creek Formation (Tfu), which dips northeast along the southwestern flank of the Texas Springs syncline. The prominent alignment of palms and springs are along the surface trace of the Echo Canyon thrust (Stop B4.1). These springs are at a nearly a constant elevation of about 122 m (400 ft on topographic maps), which suggests that the water table within the bath-tub like Texas Springs syncline is at the same or a slightly higher elevation (see Machette and others, 2000). The springs are a major source of water for the Furnace Creek Ranch and Inn, as well as the National Park Service (NPS) Visitor Center. Current water usage from the combined Texas and Travertine Springs varies from about 40-50 million gallons a month, or about 0.5 billion gallons a year.

To the southeast, we see the upper and middle parts of the Furnace Creek Formation, which is well exposed adjacent to Furnace Creek (its namesake). The coarse conglomerate beneath us (unit Tfcu, fig. B1-5) becomes progressively finer grained to the southeast and, likewise, this wedge of clastic debris thins in that same direction, presumably away from its source in the Panamint Mountains.

To the south, we look down section into the middle and lower parts of the Pliocene Furnace Creek Formation (light-colored strata), and the Miocene Artists Drive Formation (dark-colored sedimentary, pyroclastic, and volcanic rocks). The highest rocks in view, in the northern part of the Black Mountains, are Miocene to Pliocene volcanic rocks that form the upper plate of the Badwater Turtleback (see fig. C-1, Chapter C).

Finally, to the southwest, we have a spectacular view of the geology of the central part of Death Valley, the Black Mountains fault zone at the western front of the Black Mountains, and the playas within the larger Death Valley pull-apart basin. Most of the low ground here is below -60 m (-200 ft), with Badwater (out of view to the south), being close to the lowest point in Death Valley (-86 m or -282 ft).

Although the hill we are standing on is underlain by conglomerate of the Furnace Creek Formation, the top is mantled by flat-lying sandy pebble to cobble gravel that is as much as 10-13 m thick. This gravel lies in an ancient northwest- (?) flowing channel of Furnace Creek that is now topographically inverted (fig. B1-5). Based on its surface elevation of about 76 m (250 ft) above sea level, we suspect that the alluvium is from the oldest part of the Quaternary sequence (Ql, early to middle? Pleistocene) or perhaps from the younger part of the Funeral Formation (early? Pleistocene, unit QTf). Furnace Creek drains one of the largest catchment basins along the eastern side of central Death Valley.

## Stop B1.2 Lacustrine deposits of Lake Manly

UTM 11S $^{40}34^{185}$ mN, $^{5}13^{225}$ mE
Elevation 24 m (79 ft) ASL

From the Tea House, our route takes us down to the northwest, along a well established trail that leads to a grave marker (and Indian burial grounds) at the base of the hill (Stop B1.3). Quaternary gravel with topset and foreset-bed geometries are exposed about half way down the north slope of the hill (fig. B1-6). This gravel may be confused with the northeast-dipping conglomerate of the Furnace Creek Formation, except that they are less consolidated, dip to the north rather than the northeast, and lie in angular unconformity on the Furnace Creek conglomerate (unit Tfcu). This unconformity (fig. B1-7) is best observed from the ridge about 150 m to the northeast of Stop B1.2 (GPS location $^{40}34^{230}$ mN, $^{5}13^{355}$ mE).

The lacustrine deposits are exposed in steep slopes on the north and west sides of the Tea House hill. Figure B1-7 shows the stratigraphy of these deposit as viewed from the northeast. These deposits have not been mapped in detail. From top to bottom this exposure consists of five sedimentary units:

*Figure B1-6. Northwest view of lacustrine deposits at Stop B1.2 from trail leading down from Stop B1.1. Downfaulted remnants of Q2 surface are in the middle ground; Sunset Campground and NPS Visitor Center are in background (photograph by M. Machette, Nov. 2000).*

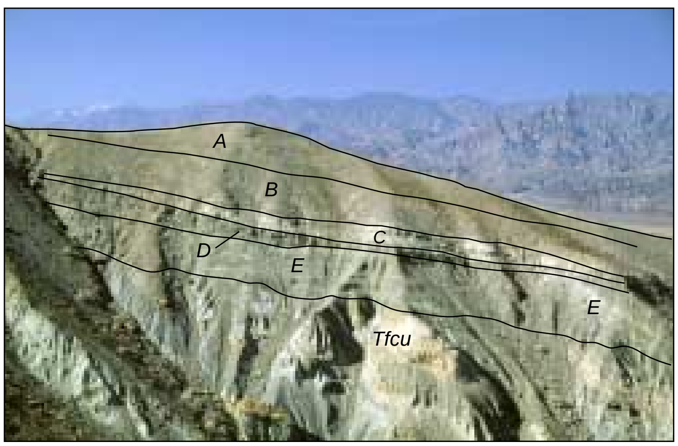


*Figure B1-7. Southwest view of lacustrine deposits at Stop B1.2. Photograph (by M. Machette, Nov. 2000) taken from a ridge about 150 m north-northeast of B1.2. Units shown are keyed to discussion in text.*

A) A mantle of coarse fan gravel (2 m thick) and topset gravel (1- to 2-m thick) that slope to the northwest.

B) Weakly bedded foreset beds of well-rounded, sandy pebble to cobble gravel, about 2-3 m thick.

C) Light-grayish green sand and silt about 0.4-0.8 m thick; possibly bottomset beds of unit B or a deep-water phase of unit D.

D) Well-sorted, well-rounded cobble to boulder beach gravel, about 0.5-1 m thick with tufa cement.

E) About 2 to 3 m of basal cross-bedded sandy pebble gravel resting unconformably on conglomerate and sandstone of the Furnace Creek Formation (unit Tfcu).

These units may represent a transgressive (E to D) and regressive (C to A) shoreline sequence of the Blackwelder stand of Lake Manly, which we believe occurred during marine oxygen-isotope stage VI (about 128-180 ka) (see Stops C1, C4, and Chapter G in this volume). The gravel in unit D is well rounded, cemented by tufa, has an open-work structure, and sandy pea-size gravel interbeds. These characteristics are indicative of a high-energy beach (shoreline) environment. We have sampled unit C (fig. B1-7) for luminescence dating (results pending), but other dating has not been done on this lacustrine sequence.

We used a laser theodolite (EDM) to make precise determinations of the vertical positions of these units since the published topographic map has 40 ft contours. We started from a benchmark at State Highway 190 (stated elevation of 0.96 ft or about 0.3 m), with a turning point near the grave marker (Stop B1.3). The base of the stone marker is at -10 m (-33 ft). The luminescence sample is at 24.1 m (79 ft) elevation, but we traced the uphill extent of unit A (topset beds) nearly 6 m higher to 30.8 m (102 ft) elevation. Thus, the uppermost extent of these lacustrine deposits is at about 30-32 m elevation (about 98-105 ft ASL). However, these deposits have probably been uplifted by the Black Mountains fault zone some unknown amount, so it is impossible to determine the true elevation at which they were deposited into Lake Manly. This problem is inherent with most lacustrine deposits that are preserved along the eastern side of Death Valley. The lacustrine deposits extend down the ridge to the northwest to an undetermined elevation. We suspect that their base may approach sea level, which would require a lake at least 30 m (100 ft) deep.

## Stop B1.3 Scarps of the Black Mountains fault zone

UTM 11S $^{40}34^{260}$ mN, $^{5}13^{010}$ mE
Elevation -10 m (-33 ft) ASL

This stop is adjacent to a stone grave marker (fig. B1-8). Interestingly, the marker identifies the grave of Stephen Esteves, a Spanish mason hired to do the stone work on the Inn (see Chapter Q, this volume). Esteves died in 1938 after completing the masonry work. He is the only Westerner in this largely Indian burial ground. Please stay near the trail and respect the historic and ceremonial nature of this site (fig. B1-8).

*Figure B1-8. North view of stone marker built in 1938 to honor Steve Esteves, the Spanish stone mason who supervised construction of Furnace Creek Inn. Small ridge on right (east) side is a fault scarp (photograph by M. Machette, Nov. 2000).*

At this stop, the downdropped alluvial surface that we are on is a remnant of alluvial unit Q2, which has a typical highly varnished and well-developed desert pavement. More extensive remnants of this surface are present for a half kilometer to the north between divergent traces of the Black Mountains fault zone. This area represents an intermediate structural level between the uplifted foothills block to the east (Stops B1.1 and B1.2) and the downdropped block (Death Valley basin) (see fig. B1-5).

At Stop B1.3, we are standing on the easternmost splay of the Black Mountains fault zone. This splay forms a 6-8 high scarp, which relates to about 5-7 m of surface offset, and has a small graben at its base. In contrast, the main trace of the fault zone (to the west) has a 15-20 m high scarp, but the amount of offset on the Q2 surface cannot be determined because the downdropped fault block is entirely buried by Holocene alluvium. Nevertheless, there must be a minimum of 30 m of offset on the Q2 surface.

The subtle undulations in the surface around the grave markers trend in a north-south direction. These undulations are small fault scarps (0.5-1 m high) that define a series of horsts and grabens that are well preserved here and to the north (fig. B1-9). These features are easily seen in cross section on the Q2 surface to the north. Inasmuch as the original Q2 was gently west-dipping but smooth, all the topographic relief on the surfaces here is the result of faulting (see long profiles on fig. B1-10). The map in figure B1-9, which was constructed from special 1:1,200-scale NPS topographic base maps, clearly shows the tectonic signature of the faulting on the Q2 surface north of Stop B1.3. It is hard to tell how young these scarps are or how recently they were reactivated. Most of the larger ones (>2 m) are probably the result of multiple faulting events, whereas the smaller ones (<2 m) may be either single- or multiple-event scarps. On the Q2 surface several hundred meters southwest of Texas Springs Campground, one of the grabens is bounded by two closely spaced scarps that have maximum scarp-slope angles of 34° (1.5 m high) and 28°-30° (5 m high). These data suggest that both scarps are relatively young (probably late Holocene) and that the larger scarp is the product of multiple events. Conversely, some faults in the adjacent arroyos cut the Furnace Creek Formation but not the Q2 surface, indicating that not all strands of the Black Mountains fault zone in this area continue to be active.

The intricate pattern of surface deformation along this part of the Black Mountains fault zone is only preserved for about 500 m, between this stop and the access road to the Texas Springs Campground (fig. B1-9). South of Stop B1.3, the fault strands are entirely within soft strata of the Furnace Creek Formation or buried by young alluvium of Texas Springs Canyon. To the north, young scarps are preserved near the north end of the old Furnace Creek airstrip (north end of Sunset Campground). The large hill north of the airstrip is called Ant Hill, informally named so for the numerous tourists that can be seen climbing it. Fault strands extend through the west flank of this hill, where Wills (1989) reported right-lateral offset of drainages and ridges. This is the closest approach of the fault zone to the NPS Visitor Center, which is located 400 m southwest of Ant Hill.

The seemingly young morphology of scarps along the Black Mountains fault zone changes markedly at Furnace Creek Wash. To the south along the Black Mountains, the youngest fault scarps are on Holocene alluvial fans at the mouths of active stream channels. These scarps are fresh and have steep faces, especially considering their relatively small size (typically <1 m high). Noble (1926) was struck by the apparent youthfulness of the scarps and mentioned that these are "fresher than any other scarps of similar magnitude [height] in the West." Having seen many young faults in the Basin and Range province, we have to agree with Noble's assessment. However, almost 75 years after his perceptive observations, we still haven't determined the precise time of the most recent faulting event along this part of the Black Mountains fault zone.

The Furnace Creek Inn is perched on a hillslope that is bounded on the west by a large, multiple-event fault scarp, which is now largely obscured by the Inn's buildings, pool, and tennis courts. Here and to the north, evidence for the youngest faulting on the main fault strand is not visible, either because it is superposed on the much larger scarps, or because it has been buried by alluvium of Furnace Creek and Texas Springs Canyon.

North of the NPS Visitor Center, the Black Mountains fault zone displays a strikingly different geometric pattern of rupturing and has seemingly older scarps. On both large and small scales, the fault zone has a right-stepping pattern, which given the commonly accepted NW-SE axis of extension, suggests that contractile elements should be apparent within the steps. Evidence for these contractile features will be seen at Stop B2 in the Mustard Canyon hills.

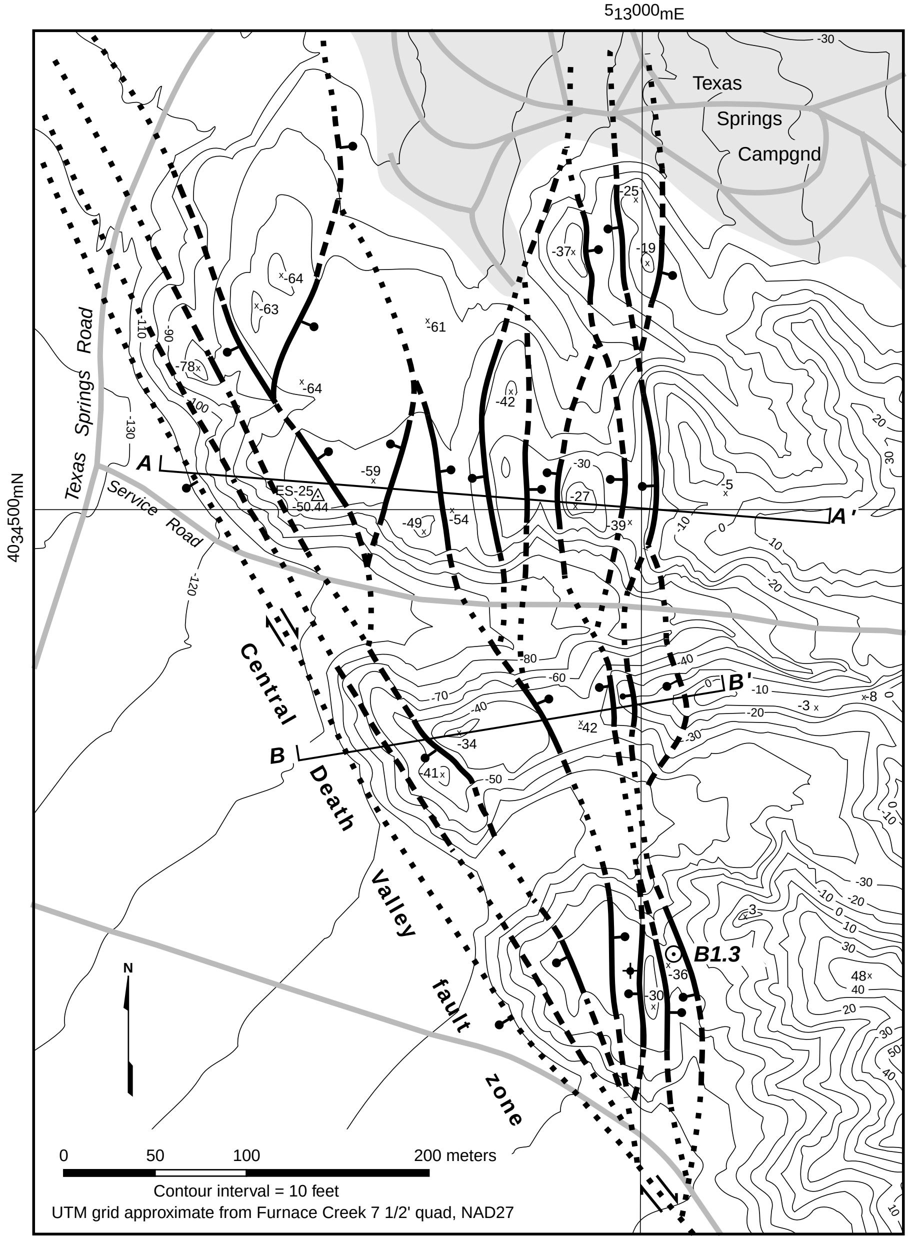


*Figure B1-9. Detailed topographic map showing tectonic deformation of Q2 surfaces at and north of Stop B1.3. Contour interval is 5 ft. Derived from NPS 1:1,200 scale maps with 2-ft contour interval. Topographic sections A-A' and B-B' are shown in figure B1-10.*

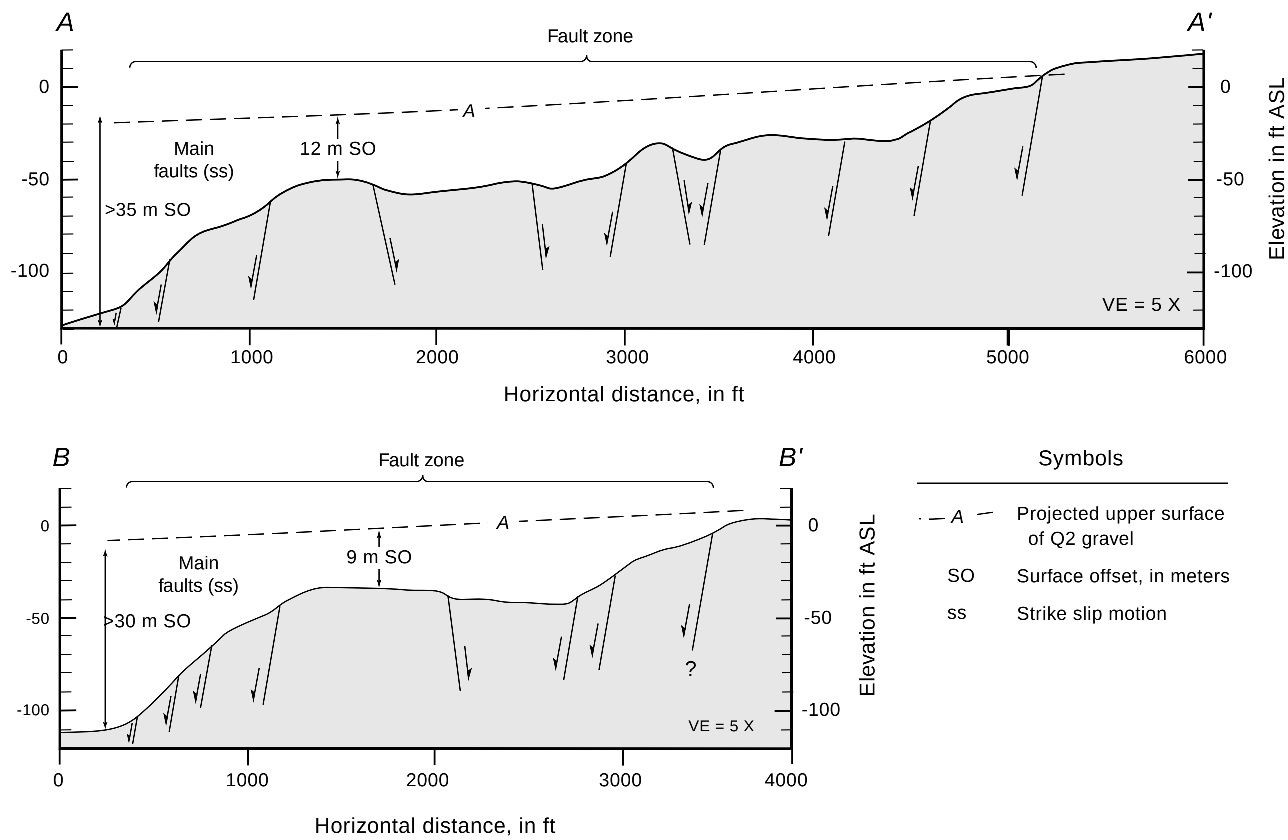


*Figure B1-10. Topographic profiles across deformed Q2 surface north of Stop B1.3. Location of profiles shown in figure B1-9.*

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# Stop B2

# Late Quaternary uplift of the Mustard Canyon hills—tectonic, diapiric, or both?


*Michael N. Machette and Janet L. Slate*


Furnace Creek 7.5' quadrangle
GPS: 27 NAD, UTM Zone 11S
$^{40}37^{030}$ mN, $^{5}11^{445}$ mE
Elevation about -73 m (-240 ft) ASL

## INTRODUCTION

At Stop B2 we will see evidence for rapid uplift and deformation of Quaternary gravels that underlie the extensive piedmont surfaces in and around the Mustard Canyon hills. The hills are broad, elongated domes that protrude from the generally low-lying piedmont slope and basin floor.

The Mustard Canyon hills are herein defined as the NW-SE trending group of hills that are dissected by Mustard Canyon; also included is the extension of these hills to the southeast across State Highway 190 and the isolated hill to the south of the Harmony Borax Works. These hills are not named on present topographic maps, but were shown and labeled on the geologic map by Hunt and Mabey (1966, pl. 1). They are the northwestward extension of the East Coleman hills, a now abandoned term shown on maps by Hunt and Mabey (1966) and McAllister (1970).

The starting point for Stop B2 is the parking lot of the Harmony Borax Works (see GPS coordinates above; fig. B2-1). We will visit tilted Quaternary gravel and Pliocene mudstone on the southwest margin of the main Mustard Canyon hills (Stop B2.1). At Stop B2.2 we will be on top of one of the gravel covered domes. At the final Stop (B2.3 on the southwest margin of the Mustard Canyon hills) we will observe relations that suggest fault control of the hills.

We'll focus on several interesting characteristics of the Mustard Canyon hills that at these stops.

1) The hills are generally covered by 1- to 3-m-thick deposits of Quaternary gravel (Stop B2.2) that are laterally continuous several kilometers to the southeast, but which oppose their original depositional gradient.

2) These gravel is both uplifted and deformed by faults, especially along their northeast and southwest margins (Stops B2.1 and B2.3).

3) The underlying strata of the Furnace Creek Formation (Tf) is extensively deformed into elongate dome-shaped hills (Stop B2.2).

4) The cores of the hills are commonly eroded and/or have collapsed as a result of piping and subsurface dissolution. This is an active process as suggested by open depressions and pipes. We will see these features at many places along our route.

Because these characteristics are all associated with positive topography, we believe that the Mustard Canyon hills are the result of tectonic and possibly diapiric processes that have been active during the late Quaternary.

## PLIOCENE BASIN FILL

The Mustard Canyon hills are cored by mudstones that are characteristic of the upper fine-grained part of the Pliocene basin-filling Furnace Creek Formation (unit Tf on fig. B2-2). According to the mapping and cross sections of McAllister (1970), this mudstone is probably several hundred meters above the upper conglomeratic facies (Tfcu) of the Furnace Creek Formation that we saw at Stop B1 and several hundred meters below the base of the Pliocene-Pleistocene Funeral Formation (see fig. B1-4). McAllister (1970) mapped the mudstone in the Mustard Canyon hills as the main body (facies) of the Furnace Creek Formation, although here it clearly is located in the upper part. The mudstone lies stratigraphically above syntectonic conglomerate (possibly finer grained in the subsurface here) and below a coarsening-upward unit (QTfl) that marks the base of the Funeral Formation. The upper part of the Funeral Formation (QTf), comprising travertine-cemented conglomerate, is exposed in the high cliffs both to the northeast near Cow Creek (Stop B3) and in the Texas Springs syncline, east of Stop B1.

The basin-fill strata that core the Mustard Canyon hills are predominately mudstone, but locally there is fine-grained sandstone and abundant saline minerals including halite, anhydrite, and borates. Although hand-dug exploration shafts for borate minerals are common in the Mustard Canyon hills; there probably was little tangible production from the hills. We will see one such mine on our route between stops B2.1 and B2.2. The bulk of the borates in this area came from the modern playa of Cottonball basin and mines in the upper part of Furnace Creek Wash (near Twenty Mule Team Road, south of Stop B5). Beginning in 1882, about 2.5 million pounds of cottonball borax (ulexite) were collected by Chinese laborers from Cottonball basin, which is 2-3 km west of Stop B3. The ore was refined and concentrated at the Harmony Borax Works (fig. B2-3) during all but the summer months. The famous 20-mule-team wagons were used to carry the concentrated borax ore 265 km (165 miles) to Mojave until 1888, when other more economically viable deposits were found and exploited in southern California.

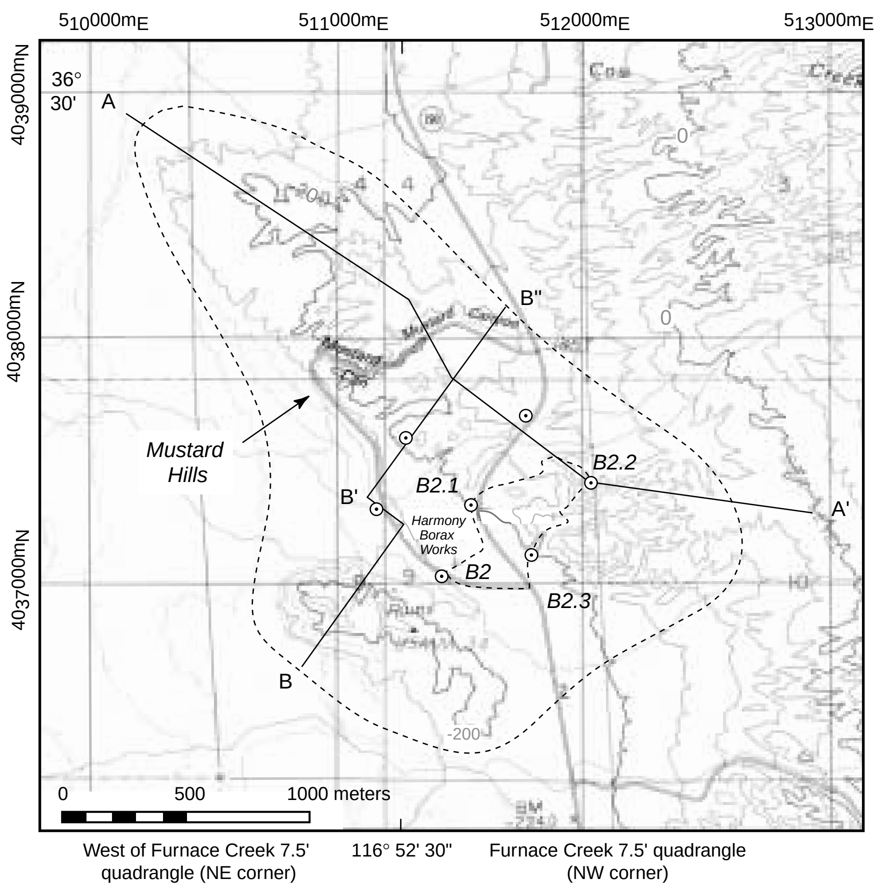


*Figure B2-1. Index map for Stop B2 in the Mustard Canyon hills. B2.1, B2.2, and B2.3 indicate discussion stops*

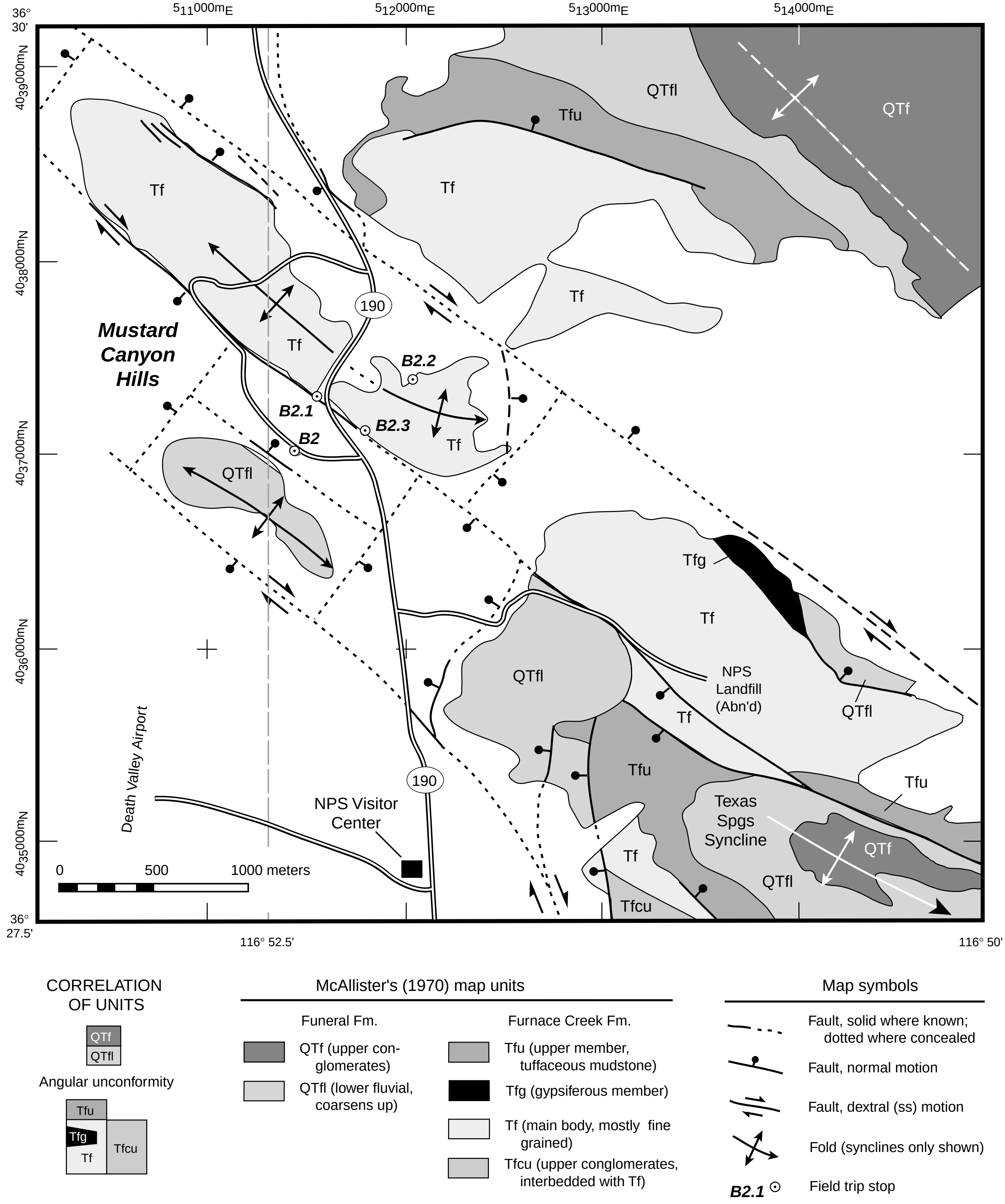


*Figure B2-2. Generalized map of bedrock geology and structure near Stop B2 (derived from mapping by Hunt and Mabey, 1966; McAllister, 1970; and unpublished mapping by Machette, 1999).*

*Figure B2-3. View to southwest of Harmony Borax Works (restored). Slopes behind (south of) works are underlain by northeast-dipping faulted alluvial gravel (photograph by M. Machette, Nov. 2000).*

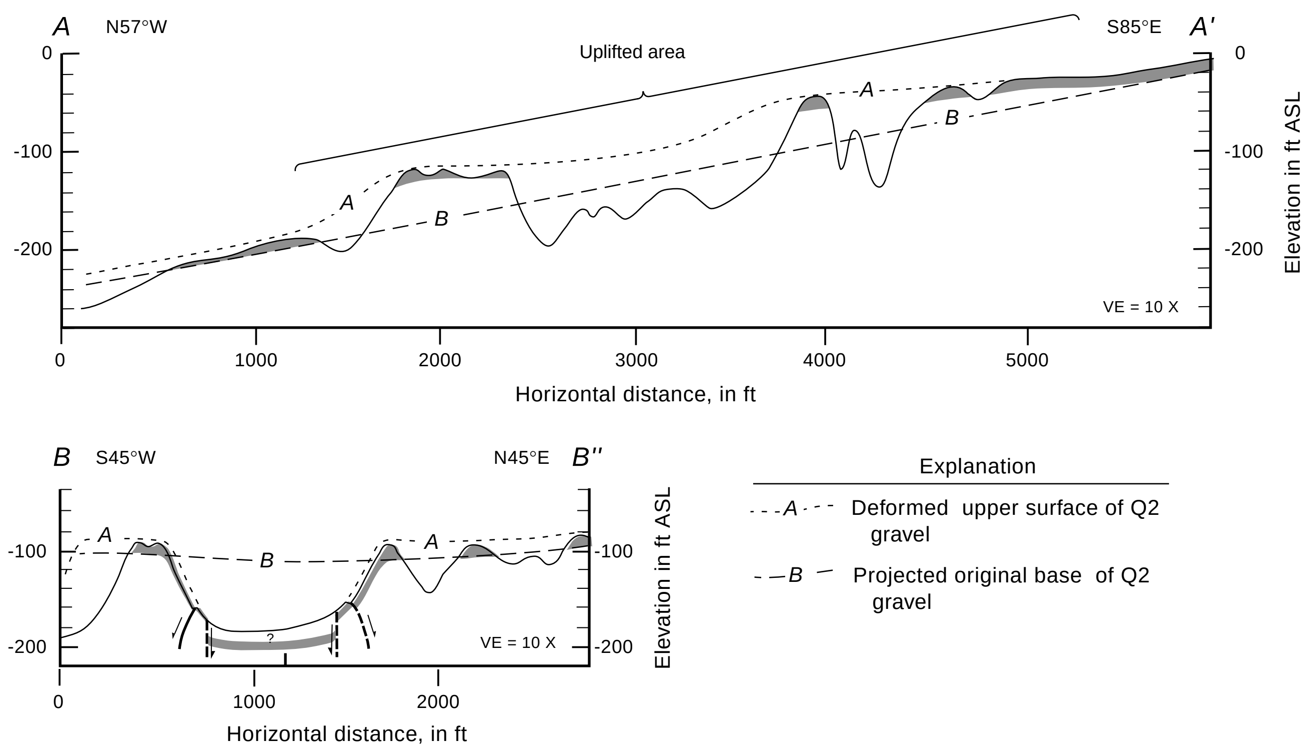


*Figure B2-4. Longitudinal (A-A') and cross-axis (B-B'') profiles of deformed surface of Q2 gravel in Mustard Canyon hills. For location of profiles, see figure B2-1. Derived from mapping by Hunt and Mabey, 1966, and unpublished mapping by Machette, 1999.*

### QUATERNARY GEOLOGY

The Quaternary deposits in this area consist predominately of gravelly alluvium (units Q2-Q4) that form broad piedmont slopes. These deposits are derived (recycled) from older alluvial fans upslope (east) and from bedrock of the Funeral Mountains. Within the Mustard Canyon hills, the uplifted surfaces are mantled by a relatively thin (2- to 5-m-thick) cover of angular alluvial-fan gravel that is herein considered to be the middle(?) to late Pleistocene unit Q2 (fig. B2-4). Younger deposition has been deflected around the hills, so that Q3 (late Pleistocene to Holocene) and Q4 (late Holocene) gravel is largely restricted to the valleys around and between the hills.

The main focus of this stop is on the uplifted remnants of Q2 gravel. Unit Q2, which is entirely pre-Holocene, has been subdivided into three units elsewhere in Death Valley: Q2c (younger), Q2b (middle), and Q2a (older). These divisions are made on the basis of relative topographic position, degree of preservation, and the presence of different-colored rock varnish on desert pavements, and the development of soils beneath their relict surfaces. None of these units has been precisely dated, but Klinger and Piety (1996) suggested age ranges for the Quaternary units based on regional correlations and dating efforts elsewhere (see discussion at Stop B3).

Units Q2c and Q2b are probably more widespread in this area, with Q2a only being preserved at elevations above sea level, such as along the west side of Park Village Ridge (east of Cow Creek, Stop B3). In the Cow Creek area, Machette and others (1999b) mapped alluvial fans of Q2b age that did not appear to have been modified by shoreline processes of Lake Manly. The last high stand of the lake is referred to as the Blackwelder stand, which we suspect may correlate with marine isotope stage VI (128-180 ka). Remnants of alluvium on lacustrine erosion surfaces (benches) on the west side of Park Village Ridge are probably time equivalents to unit Q2a of Klinger and Piety (1996). By this argument, unit Q2b postdates the Blackwelder stand (<128 ka) and unit Q2a predates the stand (>128 to 180 ka). On the basis of the few exposures of Q2 gravel we have seen in the Mustard Canyon hills, we suspect that the gravel is equivalent to unit Q2b in the Cow Creek area (see Stop B3).

## Stop B2.1 Deformation of Quaternary gravel and Pliocene mudstone

UTM 11S $^{40}37^{350}$ mN, $^{5}11^{590}$ mE
Elevation -55 m (-180 ft) ASL

The faulted margins and anticlinal form of the Mustard Canyon hills were first mentioned by Wright and Troxel (1954) in a field trip guidebook. Hunt and Mabey (1966) mapped the faults (mainly as concealed), but Wills (1989) remarked on their apparent young movement. McAllister (1970) didn't appear to notice the recently uplifted nature of the hills, but instead concentrated on the basin-fill stratigraphy and occurrence of borates.

The most compelling evidence for deformation of the gravel covered hills is seen in the natural exposure on the west side of State Highway 190, at the prominent bend about 400 m northwest of the turn off to the Harmony Borax Works (see fig. B2-1). This exposure shows southwest-dipping alluvial gravel unconformably on mudstones; the gravel dips about 20° and the mudstone dips about 30° to the SE, away from the hills (fig. B2-5). Evidence that the gravelis clearly offset along near-vertical(?) faults can be seen if one walks less than 100 m to the NW or SE (Stop B2.3). The vertical nature of these faults suggest that they are primarily strike-slip, although a local component of reverse motion must be present. These faults appear as prominent alignments on aerial photographs (fig. B2-6).

These same relations are seen in steeply dipping gravel southwest of the Harmony Borax Works and at Stop B2.3. In many cases, the faults form uphill-facing scarps, either as a result of

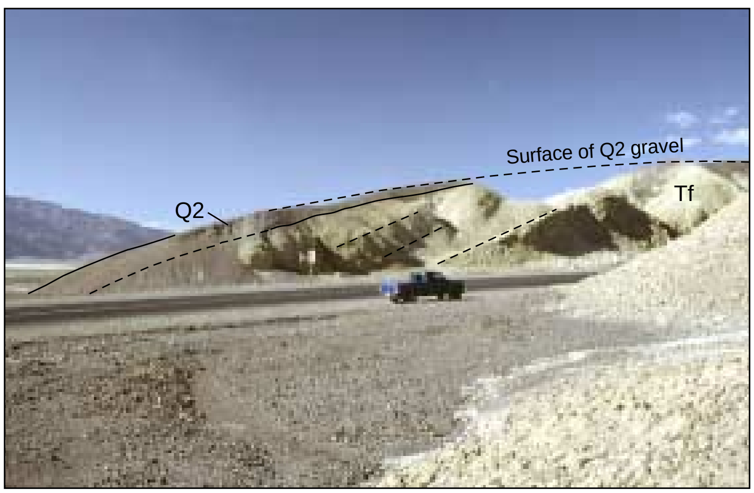


*Figure B2-5. West view of deformed basin-fill mudstone (Furnace Creek Formation) and Quaternary gravel at Stop B2.1 (photograph by M. Machette, Nov. 2000).*

marginal collapse of the hills or lateral displacement of the gravel (see fig. B2-4).

On the NE and SW sides of the Mustard Canyon hills, one can see Q2 gravel that dips to the northeast and southwest away from the elongated NW-SE axes of the anticlinal hills. Hunt and Mabey (1966) mapped many of these faults as being concealed, but the ones on the north side of the hills are quite obvious. A photograph of these fault scarps appears in the NPS Visitors Center, but is mistakenly labeled as shorelines of Lake Manly.

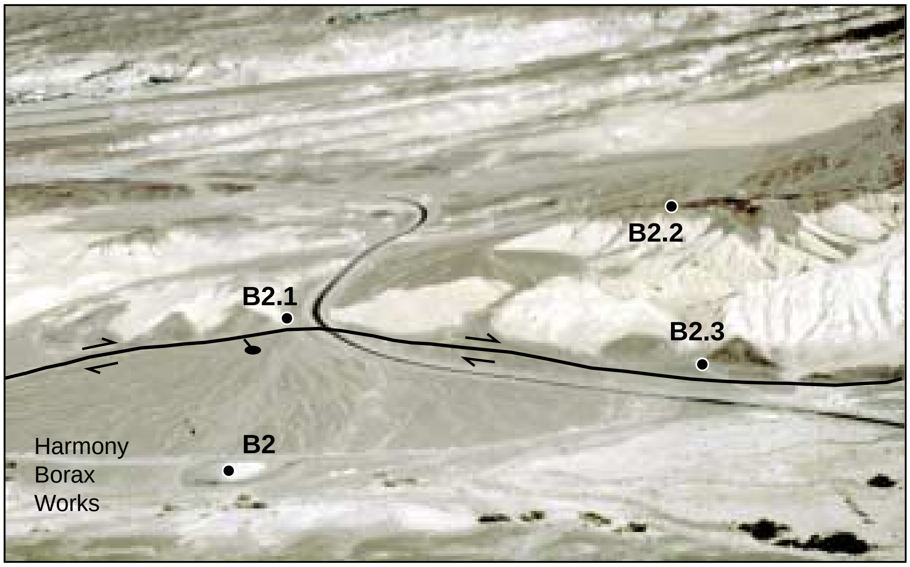


*Figure B2-6. Oblique aerial view of Mustard Canyon hills. Harmony Borax Works and parking lot (at B2) are in lower left-hand part of photograph. Road that winds from south (bottom) to north in photograph is State Highway 190. B2.1, B2.2, and B2.3 show locations of stops. (Photograph by M. Machette, Nov. 2000.)*

## Stop B2.2 — Uplift and collapse of Quaternary gravel

UTM 11S $^{40}37^{400}$ mN, $^{5}11^{040}$ mE
Elevation -12 m (-40 ft) ASL

At this stop, we are near the highest point in the Mustard Canyon hills (elev. about -8 m or -25 ft). This overlook provides a good view of the hills and the geologic evidence of both their uplift and subsequent collapse. If we look to the southwest toward the hill beyond the Harmony Borax Works (Stop B2), we see the remnant of a NW-trending dome, the southwestern half of which has been eroded. To the northwest is the main part of Mustard Canyon hills, which are bisected by Mustard Canyon. These hills are largely intact (fig. B2-7), although their rumpled surfaces reflect a history of uplift and collapse (see fig. B2-4). Where we are standing, the general structure is one of a NW-ramping dome, but the core has almost entirely collapsed and been subsequently eroded by internal drainage (fig. B2-8). Our route from here to Stop B2.3 will be down into the canyon and out to the southwest, where abundant active collapse pits are present.

There is little mentioned in the literature of the possible uplift and subsequent collapse of the Mustard Canyon hills. Hunt and Mabey (1966, p. 66) made a vague reference to such collapse features, mentioning that "Karstlike solution features are common where Tertiary rocks [sic. Furnace Creek Formation] are overlain by the No. 2 gravel [Q2] such as near Furnace Creek Ranch." So pervasive is the collapse in the Mustard Canyon hills, that bedding attitudes are hard to determine, and even then are relatively meaningless, being steep and chaotic. In

*Figure B2-7. Elongate domed Mustard Canyon hills with discontinuous mantle of Quaternary gravel. View northwest from Stop B2.2 (photograph by M. Machette, Nov. 2000).*

*Figure B2-8. View of collapsed core of dome southeast of Stop B2.2 (photograph by M. Machette, Nov. 2000).*

addition, where the gravel cover has been removed, deep weathering has resulted in a puffy surface, thereby masking the nature of the underlying sedimentary rocks.

As we walk up to this point, there is abundant evidence for localized collapse of the underlying halite-bearing mudstone. For example, young talus-like accumulations of gravel are actively subsiding into pits on steep valleys and side slopes. Similar features are seen throughout the Mustard Canyon hills, especially south of the Harmony Borax Works.

The gravel mantle that now lies at various elevations on the Mustard Canyon hills has a well developed smooth, planar, desert pavement with clasts having well-developed dark to black rock varnish. The surface is similar to those described by Klinger and Piety (1996, table 2) on alluvial unit Q2b. In some areas, the remnants of the Q2 gravel surface are almost planar and flat, but on the southeast margin of this particular hill the gravel slopes anomalously to the east. It merges with the undisturbed surface of Q2b gravel that slopes northwest and is graded to a base level at least 200 ft (60 m) below sea level in Death Valley.

From our perspective on this hilltop, the evidence is compelling that the Q2 gravel surfaces have been uplifted into a series of elongate domes. Virtually every non-NW sloping Q2 surface in this area is the result of differential uplift or collapse. However, the question of just how young or active the uplift of these hills is remains difficult to answer. As previously mentioned, we suspect that the uplifted gravel is equivalent to unit Q2b (70-200 ka) of Klinger and Piety (1996). Clearly, the uplift postdates deposition of the gravel. The highest elevation of the Q2b gravel on these hills is about -8 m (-25 ft), although an elevation of -12 m (-40 ft) is more common. This elevation represents at least 50 m (160 ft) of localized uplift (from -60 m to -8 m). So, if Klinger and Piety's (1996) age estimates for Q2b and our correlations are correct, then the minimum uplift rate is about 0.25 mm/yr (50 m/200 k.y.), whereas the maximum rate could be as much as 0.7 mm/yr (50 m/70 k.y.).

From exposures elsewhere in the area (stops B1 and C4), it is clear that Lake Manly would have risen across and above these hills. However, we have not seen any shorelines preserved on the hills. If the uplift of the Mustard Canyon hills post-dates the Blackwater (high) stand of Lake Manly (which may have ended at marine isotope stage VI, 128 ka), then the uplift rate must be 0.4 mm/yr or higher (50 m/128 k.y.). These three uplift rates (0.25-0.7 mm/yr) are in line with documented vertical slip rates on faults in extensional regimes, such as the Basin and Range. However, precise determination of the rates awaits cosmogenic dating of the Q2b gravel that we plan to sample from a locality near Stop B2.2

# Stop B2.3

# Faulting along the margin of the Mustard Canyon hills

UTM 11S $^{40}37^{095}$ mN, $^{5}11^{810}$ mE
Elevation -64 m (-210 ft) ASL

At this stop, we will see a series of tilted gravel that appears to be controlled by faulting. At the canyon mouth, the gravel dips 15°-20° to the southwest and are repeated by up-to-the-southwest displacement along northwest-striking faults. The inboard (NE) gravel forms flatiron-like ramps, whereas the outboard (SW) gravel forms ridges that are bisected by active and abandoned streams (fig. B2-9).

The gravel ramps show some suggestion of tilting during deposition because they seem to thicken downslope. For example, in the south bank of the stream cut at this stop, the gravel appears to thicken from about 0.5 m to nearly 3 m. This may be the result of erosion, redeposition (i.e., reworking), or syntectonic deposition. If the latter case is true, then growth of the domes must have started at the time of deposition of the Q2 gravel, rather than much later. However this seems unlikely owing to the presence of rather planar remnants of the Q2 gravel surface, suggesting deposition in a tectonically stable environment.

*Figure B2-9. Tilted Quaternary gravel (Q2) along fault. View to northwest from about 60 m southeast of Stop B2.3 (photograph by M. Machette, Nov. 2000).*

Tens of meters southwest of the stream cut, there are several exposures in gravel ridges that show steep southwest-dipping bedding surfaces. These gravel ridges have been obviously faulted, but in a down-to-the-northeast direction. As such, they form uphill-facing scarps that have impounded younger alluvium from the adjacent streams.

The general alignment of the wind gaps between the ridges and adjacent stream canyons or channels suggests an apparent left-lateral (dextral) sense of displacement on the faults. However, we think that the true sense is right-lateral as suggested by about 40 m of deflection (offset?) of an ancient channel that trends southwest, past the stream cut first mentioned. Proving either sense of movement is very difficult along the margins of the domes, owing to both lateral erosion from northwest-trending streams and local deposition from streams headed within the domes. At one point about 150 m northwest of Stop B2.1, we measured an apparent 3 m of right-lateral separation in a small saddle developed on soft sediment of the Furnace Creek Formation. This type of geomorphic feature is so ephemeral as to suggest recent (probably late Holocene) offset. A systematic effort to record the amount and sense of lateral offset along the margins of the Mustard Canyon hills is needed to better characterize these faults and their structural setting.

Outboard of the gravel ridges there is probably a more fundamental (i.e., larger offset) fault or zone of faults that carries most of the lateral offset that we infer to be taking place along the margins of the Mustard Canyon hills (see fig. B2-2).

Evidence for this faulting is readily apparent on the north side of the hills and the scarps were mapped by Hunt and Mabey (1966) 35 years ago. The fault scarps are easily seen during times of low-sun illumination (early am or late pm), or during the winter. As viewed from State Highway 190 northeast of the hills (near the turn off to Stop B3), the scarps could be interpreted as shorelines, but they do not maintain a constant elevation; instead, they dip at anomalously steep angles (i.e., 5° NW). In addition, in the late afternoon, one can see steep slope elements (young ruptures) superposed on the older more degraded fault scarps.

It is clear that the basic form of the Mustard Canyon hills is controlled by faulting, perhaps predominately right-lateral faulting. If so, then the NW-directed extension in Death Valley should be resolved into a northward shortening element (i.e., restraining stepover) and a westward strike-slip element. The hills may also be en echelon folds within a large right step between the Furnace Creek and Black Mountains fault zones.

An additional process that may be either the result of faulting or associated with the faulting is localized diapiric flow. Uplift and collapse is most common in the halite- and/or anhydrite-rich borate member in the upper part to the Furnace Creek Formation, as shown by McAllister's (1970) mapping. Perhaps crustal shortening has allowed the overlying Funeral Formation and higher parts of the Furnace Creek Formations to be uplifted and eroded, thus promoting unloading, diapiric uplift, and ultimately progressive dissolution of the cores of the uplifts.

# Stop B3

# Late Holocene faulting on the Old Ghost alluvial-fan complex (optional stop)

*Michael N. Machette and Anthony J. Crone*

Furnace Creek 7.5' quadrangle
GPS: 27 NAD, UTM Zone 11S
$^{40}39^{650}$ mN, $^{5}11^{590}$ mE
Elevation about -44 m (-145 ft) ASL

## INTRODUCTION

Stop B3 is located on the northern margin of the National Park Service's Cow Creek Administrative area, about 5 km north of Furnace Creek (fig. B3-1). The landscape here is dominated by the Old Ghost alluvial-fan complex, which consists of Holocene to middle (?) Pleistocene alluvium (units Q2-Q4) that have been deformed by surface faulting. We will visit the site of a back-filled trench (the Old Ghost site) across a small fault scarp and observe the scarps young morphology. The scarps here are fragile—*please make every effort to stay off the scarps in order to preserve their morphology*. Most of the distal part of the fan consists of the youngest alluvial units (Q4 and Q3), whereas remnants of various Q2 surfaces are mainly preserved to the north and upslope to the east.

There are three main objectives for Stop B3:

1) Compare the geomorphic expression of various Quaternary alluvial surfaces that form the Old Ghost alluvial-fan complex (Stops B3.1 and B3.3).

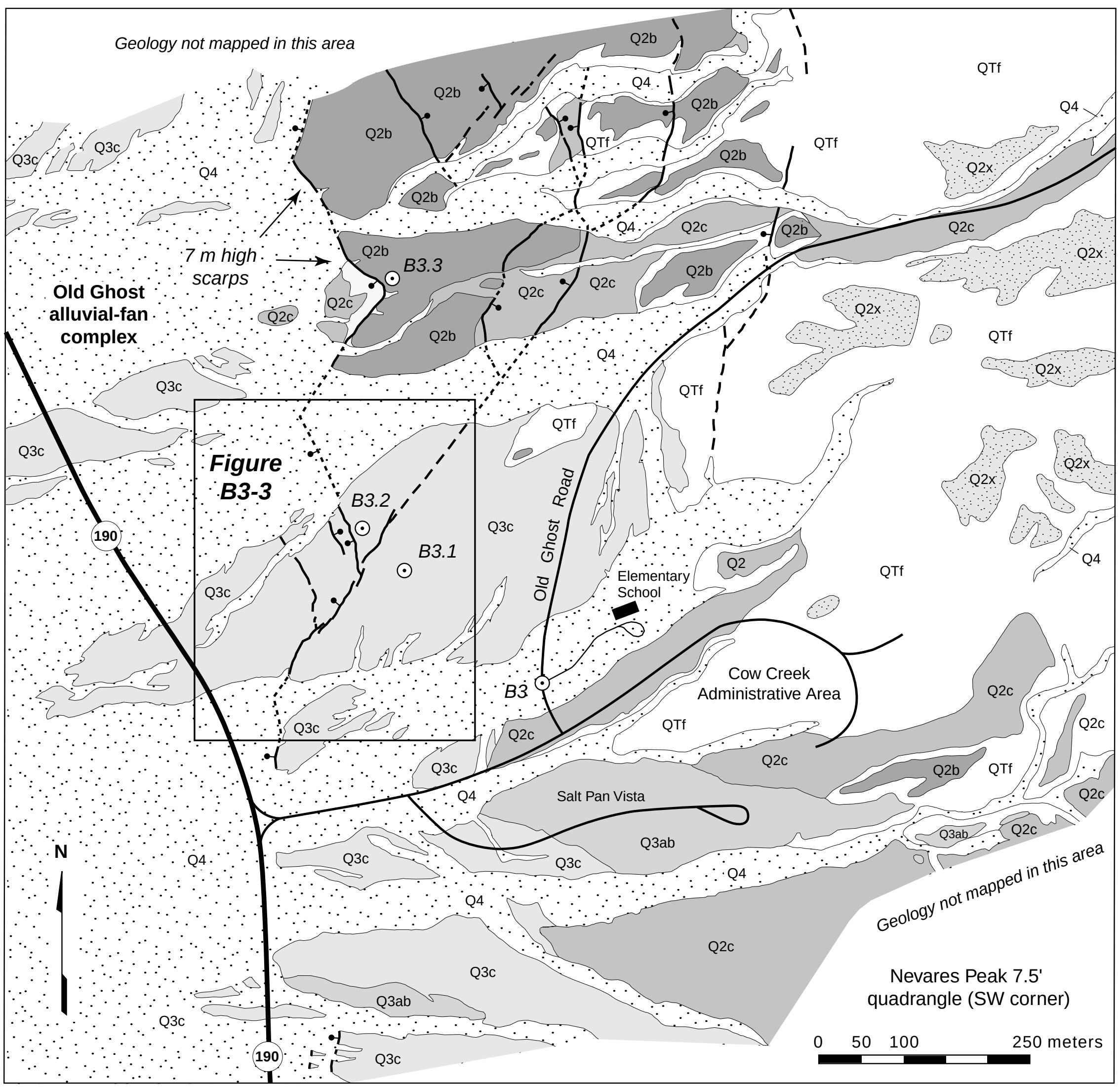


*Figure B3-1. Generalized geology map of Old Ghost alluvial fan complex at Stop B3. Subdivision of units Q2, Q3 or Q4 are possible at this scale. QTf is undifferentiated bedrock of Funeral and Furnace Creek formations. Stops B3.1, B3.2, and B3.3 indicate opportunities for discussion. Modified from detailed mapping of Machette and others, 1999a, b.*

2) Study the small (<1 m) fault scarps that are on a late Holocene alluvial surface (Stop B3.2), and compare them to large (about 7 m high) composite (multiple-event) scarp that is formed on a mature uplifted alluvial surface (Stop B 3.3)

3) Discuss the structural setting of these faults, their relationship to the major faults to the north and south, and the potential seismic hazards to the adjacent NPS facilities.

## QUATERNARY GEOLOGY

Most previous surficial geologic mapping of the area used a four-fold division of Quaternary units (oldest Q1 through youngest Q4). This scheme was devised by Hunt and Mabey (1966) for 1:96,000-scale reconnaissance mapping of the valley and was further utilized during more detailed (1:48,000-scale) geologic mapping by Wright and Troxel (1993). For quadrangle (1:24,000) scale) or site-specific studies such as those by Machette and others (1999a, b; 1:2,000 scale), further subdivision is based on geomorphic and soil characteristics as outlined by Klinger and Piety (1996, table 2). For example, Dorn and others (1987), Moring (1986), and Klinger and Piety (1996) all proposed subdivision of units Q4 through Q2. In the Cow Creek and Furnace Creek areas, we have been using a modified version of Klinger and Piety's (1996, table 1) stratigraphic column, which reproduced here as table B3-1. The three younger units (Q4, Q3, and Q2) were mapped at the Old Ghost site, but unit Q1 was not recognized in this area.

The youngest alluvial unit Q4 underlies about 50 percent of the Old Ghost alluvial-fan complex. Although not differentiated on figure B3-1, unit Q4 has been subdivided into Q4b and

**Table B3-1. Stratigraphic correlation chart for Quaternary units in Death Valley and at Old Ghost alluvial-fan complex.**

| Time Terms and Age Limits | | [‡]Machette (this report, 2000) | Klinger and Piety (1996) (Death Valley) | Wright and Troxel (1993) (North-central Death Valley) | Dorn and others (1987) (Hanaupah fan, Death Valley) | Moring (1986) (Northern Death Valley) | Hunt and Mabey (1966) (Death Valley) |
|---|---|---|---|---|---|---|---|
| HOLOCENE | Holoceene (0-10 ka) | | Q4b (historic) | | Modern | | |
| | | Q4 | Q4a (0.1-2 ka) | Qg4 | Q4c (0.5-2.5 ka) | Qf4 | Qg4 |
| | | Q3c (mid Holocene, 5±5 ka) | Q3c (2-4 ka) | | Q4b (2-4.5 ka) | Qf3 | |
| | | | Q3b (4-8 ka) | Qg3 | | | Qg3 |
| | | | Q3a (8-12 ka) | | Q4a (6-11 ka) | | |
| PLEISTOCENE | Late (10-130 ka) | Q3b (25± 10 ka) | | | | | |
| | | Q3a | Q2c (12-70 ka) | | Q3 (13-50 ka) | | |
| | | Q2c | Q2b (70-200 ka) | Qg2 | Q2a/Q2b (110-190 ka) | Qf2c Qf2b Qf2a | Qg2 |
| | Middle (130-730 ka) | Q2b | | | | | |
| | | Q2x | Q2a (400- 730 ka) | | Q1/Q1b (>500->800) | | |
| | Early (730 ka-1.6 Ma) | | | | | Qf1 | |
| | | Q1 (not mapped) | Q1 (>1200 ka; 1.2 Ma) | Qg1 | | | QTg1 (Funeral Fm., upper part) |
| | | QTf (Funeral Fm., Plio- Pleist.) | | QTfs (Funeral Fm.) | | | |

[‡]Note: Modified from Machette and others (1999b) based on geologic mapping and dating work in progress. Scheme likely to change as a result of dating results.

Q4a elsewhere. Deposits of unit Q4b represent areas where historic debris-flow and flooding have occurred. The older deposits (unit Q4a) have slightly modified surface morphology (expressed as nearly fresh bar-and-swale topography), light rock varnish on poorly developed desert pavement, but lack zonal soils; that is, no B horizon (see Klinger and Piety, 1996, table 2).

Alluvial unit Q3 and its three subunits (Q3c, Q3b, and Q3a of increasing age) form about 30 percent of the piedmont-slope west of Park Village Ridge, which is the high ridge east of Stop B3. The surfaces underlain by subunits of Q3 are characterized by subdued bar-and-swale topography (typically equal parts bar-and-swale), medium- to dark-rock varnish on well-developed desert pavements (see Stop B3.1), medium to thick vesicular A horizons, but weakly developed zonal soils are found only on subunits Q3b and Q3a.

Unit Q2, which is entirely pre-Holocene, has been divided into subunits Q2c, Q2b, and Q2a on the basis of topographic position, geomorphic preservation, and their characteristically dark-varnished desert pavement. Subunits Q2c and Q2b (differentiated on fig. B3-1) form about 20 percent of the Old Ghost alluvial-fan complex. No Q2a surfaces were recognized in the immediate area of the Old Ghost fan, but aerial photographs of the Park Village Ridge (to the east) show several erosion levels that appear to be capped by thin (<1 m) to moderate (1-5 m) thickness of gravel (designated as unit Q2x) that has been reworked from the upper part of the Pliocene-Pleistocene Funeral Formation. These surfaces project westward into the air and do not appear to have been extensive, but rather may be erosion platforms and ramps that graded to former levels of Lake Manly. They are probably equivalent to unit Q2a of Klinger and Piety (1996). The surface of unit Q2b, which forms black smoothly paved surfaces to the north of the Old Ghost trench site, has been offset at least 7 m by multiple faulting events as we will see at Stop B3.3.

## STRUCTURAL AND PALEOSEISMIC STUDIES

In the summer of 1998, the USGS and NPS entered into a cooperative agreement to address short-term seismic hazards at the Cow Creek Administrative area. Their immediate plans called for construction of a new Museum Curator's building, a new building for the Death Valley Natural History Association (DVNHA), and relocation of the existing NPS maintenance yard. The Museum Curator's building was completed in 1999, and the DVNHA building was in an early stage of construction as of November 2000. In addition, some of the existing buildings at the Cow Creek site are constructed of adobe, and they are particularly vulnerable to ground shaking. (For a more complete discussion of seismic hazards in this area, see Machette and others, 1999b).

The Cow Creek Administrative area is located in the transition zone between the southern end of the Northern Death Valley fault zone (see Chapter J this volume) and the north end of the Black Mountains fault zone. Klinger and Piety (1996) first pointed out the general geometry and importance of this structurally confusing area. This transition zone accommodates a transfer of right slip from Northern Death Valley fault zone to the Black Mountains fault zone, which is considered to be a predominately normal fault. The geology of this transition zone has been mapped at intermediate detail by Hunt and Mabey (1966) and Wright and Troxel (1993), but little is known about their subsurface linkages or respective faulting histories. McAllister's (1970) detailed (1:24,000 scale) map does not focus on either Quaternary geology or young structural deformation.

Excellent preservation of fault scarps on the Old Ghost fan indicates a pattern of small right steps and rhomboids (see fig. B3-3). The east and west sides of the rhomboids are defined by prominent normal faults, and the north and south sides being defined by subdued northeast-trending faults of unknown sense. The latter faults are typically parallel or sub-parallel to drainage channels, making their recognition difficult. This pattern, although most apparent at the Old Ghost trench site (Stop B3.2), is also seen on older deposits (unit Q2b) at Stop B3.3 to the north. This right-stepping pattern may allow motion to be transferred from basin-margin faults that are mapped along the western boundary of Park Village Ridge (the gravelly hills to the northeast of this stop) to similar faults that extend south through and around the Mustard Canyon hills and ultimately connect to the Black Mountains fault zone near Texas Springs Campground (see Stop B2.3).

Three sites at the Cow Creek Administrative area were investigated by exploratory trenching in 1999. Two 20- to 40-m-long backhoe trenches exposed alluvial deposits and the underlying lacustrine or bedrock materials. These trenches were positioned to provide conclusive evidence as to whether the underlying Quaternary materials were deformed by fault-related lineaments that project through the facility. No evidence of faulting was found in either trench (see Machette and others, 1999b for complete trench logs and descriptions) and, as such, these sites were cleared for construction.

Although evidence of young faults was not found within the facility, evidence for young faulting is preserved at the Old Ghost site (Stop B3.2), ½ km to the north of the NPS buildings. A small trench at this site (Machette and others, 1999b) exposed faults associated with morphologically fresh (i.e., young) scarps (herein named the Old Ghost scarps). We found no evidence for displacement of unit Q4 (late Holocene), thus precluding extremely young offset (i.e., historic to several hundred years). However, the steep slopes associated with the scarps, which are typically <1 m high, suggest that they formed in late Holocene time.

# Stop B3.1

# Surficial geology of the Old Ghost fan

UTM 11S $^{40}139^{730}$ mN, $^{5}11^{415}$ mE
Elevation -47 m (-155 ft) ASL

The location of this stop was somewhat arbitrarily chosen; it is at a NPS survey marker that is easy to relocate (USDI #21, elevation 154.80 ft). At this site, we will look closely at alluvial unit Q3c. Its surface is characterized by as much as 20 cm high bar-and-swale topography (roughly equal parts), medium to dark rock varnish on well-developed desert pavement (fig. B3-2), and a 3- to 5-cm-thick silty vesicular A horizon. Zonal soils are not present on unit Q3c, whereas weak to moderately developed Bw (cambic), Bt (argillic), and/or Bk (calcic) horizons are present on units Q3b and Q3a to the south on Salt Pan Vista. In contrast, unit Q4 occupies active and prehistoric alluvial channels cut into unit Q3c. Characteristically, unit Q4 shows weak to no development of pavement and varnish and is not faulted in this area. Unit Q3c is the youngest unit that shows evidence of surface faulting, as we will see at Stop B3.2.

Preliminary results from analysis of the cosmogenic chlorine content of shallow (5 cm) and deep (1.7 m) samples from the Q3c gravel suggest relatively little accumulation of *insitu* cosmogenic chlorine (Fred Phillips, written commun., 1999, in Machette and others 1999b). This alluvium is probably too young to yield a meaningful $^{36}$Cl age due to high levels of inherited cosmogenic chlorine in clasts within the alluvium. However, on the basis of numerical dating by others, Klinger and Piety (1996) suggested that the youngest part of unit Q3 (Q3c) is probably 2-4 ka (i.e., late Holocene). Additional cosmogenic chlorine dating of the Q3b alluvium that forms Salt Pan Vista (the piedmont area about 1 km south of Stop B3.1) yielded an age of about 25 ka ± 5-10 k.y., (Fred Phillips, written commun., 1999, in Machette and others 1999b), whereas Klinger and Piety suggested an age of 4-8 ka for this unit.

One of the inherent problems with cosmogenic dating in this area is the recycled nature of the alluvial sediment. As a result, the latest Pleistocene and Holocene gravels have a relatively small accumulation of *in situ* cosmogenic chlorine in comparison to their large inherited component. The alluvium of Old Ghost fan is largely derived from reworking older alluvium (Q2) and gravel of the Funeral Formation to the east. The alluvial gravel is being deposited with cosmogenic chlorine contents equivalent to about 65-70 k.y. of surface exposure (Fred Phillips, written commun., 1999). Clearly, this relatively new dating technique is best used in areas of high erosion rates (i.e., deep incision) or in bedrock dominated drainages where the inherited component will be smaller, or on landscapes of greater age (and thus proportionately greater *in situ* cosmogenic chlorine content). On the basis of these observations, Michael Machette, Janet Slate, and Fred Phillips (NMT) are planning to date the older parts of alluvial unit Q3 and the various parts of alluvial unit Q2 within the central part of Death Valley. We have chosen surfaces that we expect are many tens of thousands to hundreds of thousands of years old (i.e., units Q3a through Q2a, table B3.1).

*Figure B3-2. Surface of Q3c gravel showing typical relief of only 10-20 cm. Photograph by M. Machette, Nov. 2000).*

# Stop B3.2 Estimating the time of most recent faulting

UTM 11S $^{40}39^{780}$ mN, $^{5}11^{360}$ mE
Elevation -47 m (-153 ft) ASL

At the Old Ghost site, the fault zone consists of a main, down-to-the west fault and an opposing antithetic fault that defines a shallow 20-m-wide graben. There are numerous sediment-filled fissures (fig. B3.3) in the area, many of which are marked by preferential growth of vegetation. The main and largest scarp is 1.0-1.1 m high and has maximum slope angles of 32-35° (fig. B3-4). In 1998, Tony Crone (USGS-Denver) hand-dug a trench across the main scarp because the use of mechanized equipment is not allowed within wilderness areas of the Park. The trench revealed only one colluvial deposit, which is direct evidence that a single faulting event formed the existing scarp on alluvial unit Q3c (Machette and others, 1999b). Based on the ages assigned to unit Q3c by Klinger and Piety (1996), the maximum age of the scarp would be late to middle Holocene (2-4 ka).

The apparent youthfulness of the Old Ghost scarps is obvious both to the eye and from their scarp heights and slope angles. Using Bucknam and Anderson's (1979) "scarp-height—slope angle" relationship, older fault scarps plot in the lower right-hand part of the diagram (i.e., Bonneville shoreline at 14.5 ka) because maximum slope angles degrade with time and scarp height remains relatively unchanged. Conversely, younger scarps, such as those along the 2-ka Fish Springs fault of western Nevada (Bucknam and others, 1989) plot in the upper left-hand part of the diagram; they have steeper (not as degraded) maximum slope angles for the same scarp heights.

The Old Ghost scarps are clearly young, but the question is how young? Are they tens, hundreds, or perhaps a thousand years old? The larger of the Old Ghost scarps (which are only about 1 m high) have maximum slope angles that are at or exceed the angle of repose (commonly assumed to be about 33° for unconsolidated sandy gravel). However, we can only use scarps with maximum slope angles (θ, fig. B3-5) of less than 33° for comparison because the model conditions assume that value as a starting condition (see Bucknam and Anderson, 1979; Machette, 1989; Hanks, 2000).

There are several methods for determining the time at which a prehistoric faulting event occurred. The first is a stratigraphic approach that relies on numerical age determinations from faulted and unfaulted deposits, thereby bracketing the probable time of a faulting event. If appropriate materials are present

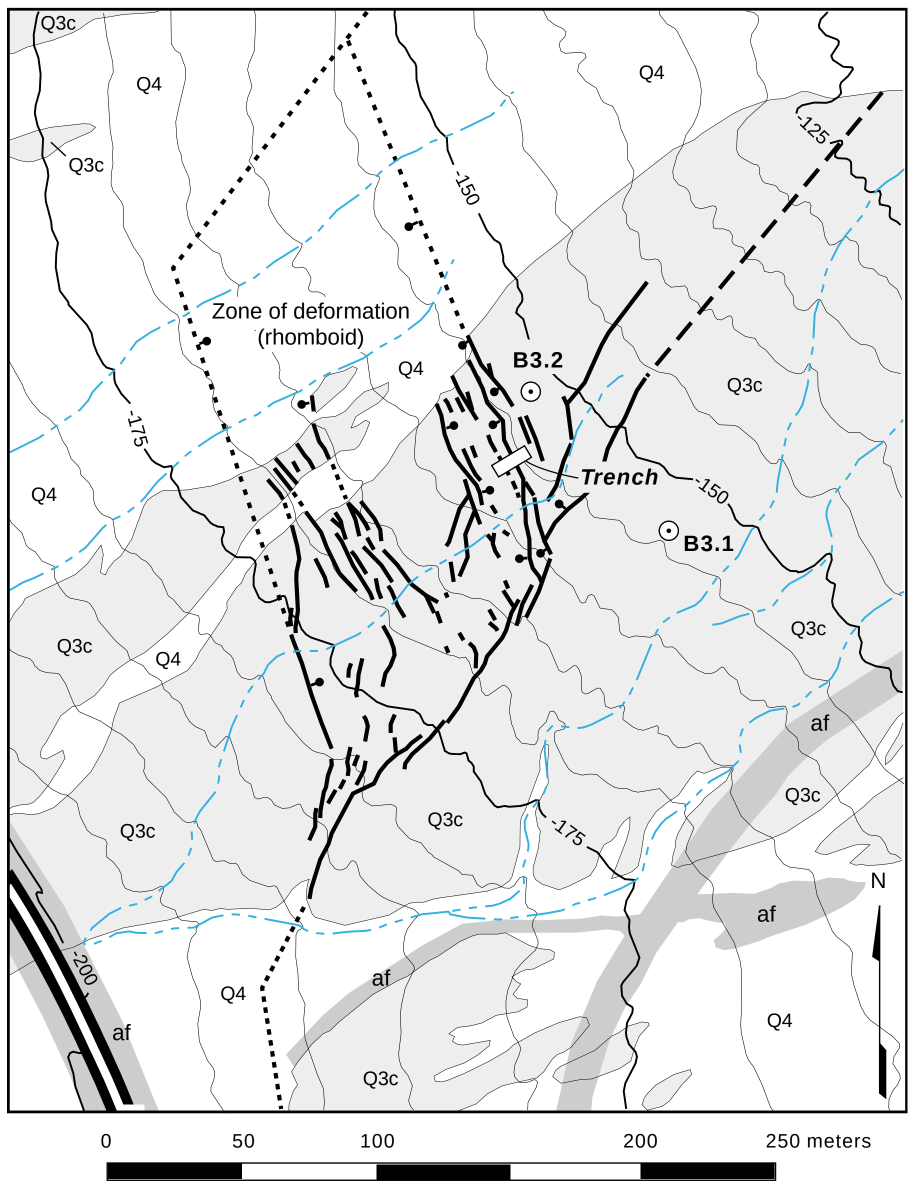


*Figure B3-3. Detailed map of young faults on Old Ghost alluvial-fan complex, Cow Creek area, Death Valley, California. Refer to table B3-1 for geologic units. Taken from Machette and others (1999b).*

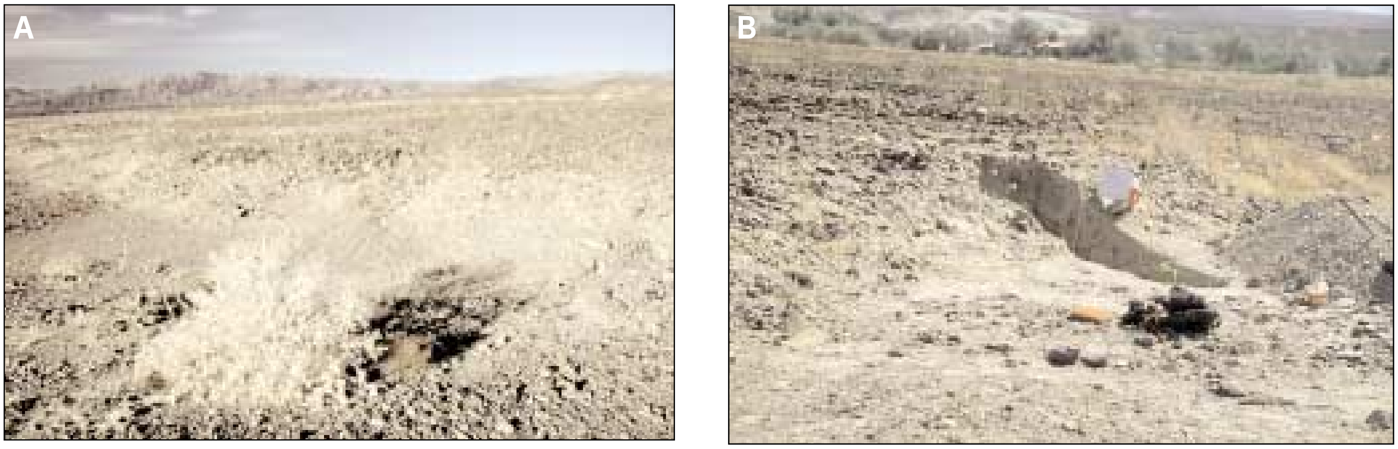


*Figure B3-4. Main down-to-the-west fault scarp at Stop B3.2. A) View is to north; scarp height is about 0.6 m. B) View to south showing trench excavation across 1-m high scarp (Machette, Oct. 1998).*

(charcoal, organic matter, volcanic tuff, eolian sand or silt, etc.) for numerical dating methods (i.e., radiocarbon, lumiscence, tephrochonology), the data can provide limits of as little as several hundred years for the time of faulting (see for example, Machette and others, 1991). More commonly, however, the data only provide limits that span a thousand years or more or that are couched in stratigraphic terms, such as older than Q4b (200-2,000 years) and younger than Q3c (2,000-4,000 years), as in this case.

The second method for determining the timing of a prehistoric faulting event is a geomorphic approach that relies on systematic degradation of fault-generated topography (fault scarps) through time. This approach is known as "morphometric analysis" and it relies on empirical morphometric relations from known "calibration points," such as dated late Pleistocene and Holocene scarps and scarp-like features (shorelines and fluvial terraces) in the Basin and Range Province. The analysis yields the relative time of scarp formation, rather than bracketing the time of the event. Used in conjunction with the stratigraphic approach, the morphometric technique yields a non-evasive, powerful reconnaissance tool that is relatively easy to apply. Bucknam and Anderson (1979) were the first to champion this empirical approach to scarp morphology, building on fundamental observations that Bob Wallace made from fault scarps and lacustrine shorelines in northwestern Nevada (Wallace, 1977). Many investigators have implemented this approach in the past 20 years (see Machette, 1989, for a review), but a second quantitative approach based on the diffusion equation (i.e., heat flow) has gained favor with modelers (Nash, 1980, 1987; Hanks, 2000). Comparisons of geomorphic data are presented briefly here in order to provide a relative framework for the youngest faulting event recorded at the Old Ghost site. Unfortunately, neither the diffusion-equation or empirical methods can provide ages owing to non-equilibrium conditions at this site because the larger (1 m) scarps have slope angles greater than the assumed starting condition of 33°.

The two parameters used for Bucknam and Anderson's (1979) empirical analysis of fault-scarp morphology are maximum scarp-slope angle ($\theta$, in degrees) and scarp height (SH, in meters). In contrast, diffusion-equation analysis of fault-scarp morphology uses the far-field (fan) slope angle ($\gamma$, in degrees) and surface offset (SO, in meters), so these values were also calculated for the Old Ghost scarps. In the empirical analysis, morphometric data for scarps of the same age will plot as linear fields with values for maximum scarp-slope angle (y-axis) increasing as scarp height (x-axis) increases. Bucknam and Anderson (1979) showed that four sets of scarp-like features (three fault scarps and the Bonneville shoreline) behave in a predictable manner, with the older more degraded scarps plotting to the right of the younger more degraded scarps (see fig. 5 of Bucknam and Anderson, 1979).

Scarp morphology data were collected from three topographic traverses (Machette and others, 1999b, Appendix A, tables 1-3) perpendicular to the graben that is formed on unit Q3c of the Old Ghost fan (fig. B3-3). The traverses crossed the antithetic and main faults, as well as a small displacement fault about 5 m east of the main fault. From the long profiles, we identified five small scarps for analysis (three down-to-the-west and two smaller down-to-the-east antithetic scarps). In addition, we collected a short profile across a <1 m high scarp formed on unit Q3 (undivided), and two profiles across a 7-m-high scarp on unit Q2b. The latter profiles are located near Stop B3.3 (fig. B3-1), 245-440 m north of the Old Ghost trench site. The profiles characterize displacement of units Q3 (total amount) and Q2b (minimum amount) and further demonstrate that young faults extends north and northeast across the Old Ghost alluvial-fan complex.

Data for the Old Ghost scarps are shown in figure B3-5, along with calibration lines for the Fish Springs scarp (about 2 ka), the Drum Mountains scarp (7-10 ka), and the highest shoreline of Lake Bonneville (14.5 ka). (See Machette, 1989, for discussion of calibration lines and treatment of morphometric data.)

The apparent youthfulness of the Old Ghost scarps is obvious from the empirical relations shown in figure B3-5. The Old Ghost scarps are clearly younger that those of the 2-ka Fish Springs fault, but the question is how much younger? The larger of the Old Ghost scarps (which are only about 1 m high) have maximum slope angles that are at or exceed the angle of repose. No free faces (i.e., near vertical elements; Wallace, 1977) were observed along the scarps.

In order to estimate the time of formation of the Old Ghost scarps, we fit an exponential scale to the data shown in figure B3-5. We fixed the age of the Fish Creek scarps at 2.0±0.5 ka, the Drum Mountains scarps at 8.5±1.5 (early Holocene), and the Bonneville scarps (shorelines) at 14.5±0.5 ka; the assigned error limits reflect varying degrees of geologic uncertainty with the individual data sets (see Machette and others, 1999b). (The data from the Panguitch scarps were not used owing to uncertainties in their age.) Figure B3-6 shows the results of our analysis. We plotted time of formation on the x-axis (log scale) and scarp height on the y-axis (log scale) for the three sets of scarp calibration data by using 12° and 26° maximum scarp-slope angles as control points (see date on fig. B3-5). We then fit lines through the data that minimized their variation (inclined gray lines, fig. B3-6). Finally, for the Old Ghost scarps, we plotted the anticipated scarp heights at 12° and 26° maximum slope angles (data from fig. B3-5) on the appropriate lines of best fit. The predicted time of formation of the Old Ghost scarps is about 400±100 years. Some interval of time must be added to this for the vertical scarps to collapse to the angle of repose. We estimate this interval to be no more than 100-200 years for these size scarps in the Basin and Range Province. Thus, the time of most recent faulting on the Old Ghost fan complex is roughly estimated to be 500-600 years ago. This estimate reflects a *minimum time* because the empirical approach compares the Death Valley scarps with similar features formed in the northern Basin and Range Province,

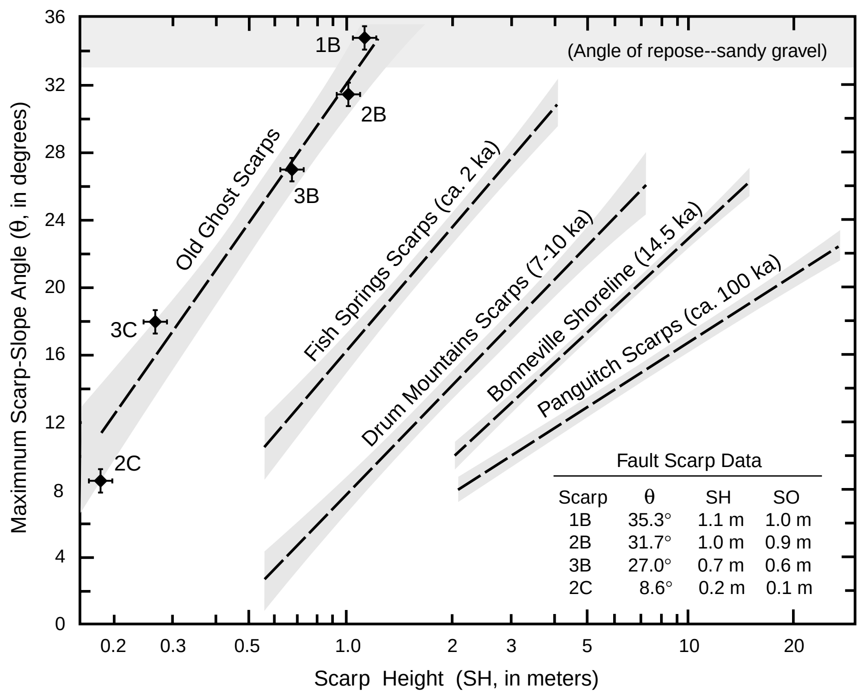


*Figure B3-5. Morphometric data for fault scarps at the Old Ghost site (Stop B3.2) compared with other calibrated scarps in the Basin and Range province. Abbreviations: θ, maximum scarp-slope angle; SH, scarp height (m); and SO, surface offset (m). Taken from Machette and others (1999b).*

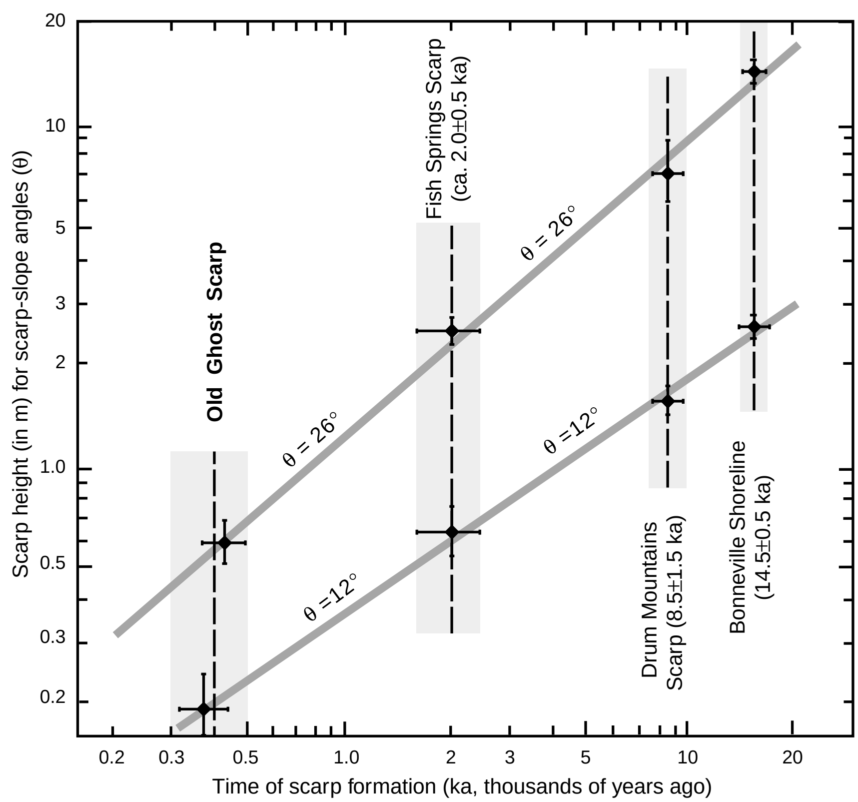


*Figure B3-6. Data for estimating time of scarp formation at Old Ghost site, northwest of Cow Creek facility. Crosses indicate errors associated with scarp height data on figure B3-5. (Taken from Machette and others, 1999b).*

where the climate is cooler and considerably moister (8-12 inches of annual precipitation).

There are a multitude of problems associated with estimating the time of formation of these scarps, the most significant being the climatically controlled rates of diffusivity (scarp modification) in Death Valley's hyperarid late Holocene climate. Scarps here most likely degrade more slowly than comparable-size scarps in the Basin and Range Province, so the empirical comparisons are probably flawed. Recent analysis of dated fault scarps in Israel's Dead Sea rift (Enzel and others, 1994, 1996) yielded five diffusivity (*k*) rates, the most appropriate being a lower limit of about 0.4 $m^2$/ka (see Hanks, 2000, table 2.6.3-2 for a compilation of published diffusivity rates). Diffusivity rates for scarps in the Basin and Range Province are commonly around 1.1 $m^2$/ka, although Hanks (2000) cited a value of 0.64 $m^2$/ka for some small (1 m) shoreline scarps of Lake Bonneville. For estimating the age of the Old Ghost fault scarps, we expect that they may have degraded at rates between 0.4-0.64 $m^2$/ka. The 0.64 $m^2$/ka rate would yield a minimum scarp age as stated above (400 years, plus 100-200 years for collapse), whereas the 0.4 $m^2$/ka rate would yield a maximum age about 1.6 times greater, or 740-840 years (400 years x 1.6, plus 100-200 years). In summary, the morphometric analysis of small (<1 m high) scarps on the Old Ghost alluvial-fan complex yields time estimates of 500-600 years (minimum) to 740-840 years (maximum) for the most recent faulting event.

## Stop B3.3

## Long-term deformation and seismic hazards at Cow Creek

UTM 11S $^{40}40^{080}$ mN, $^{5}11^{420}$ mE
Elevation -37 m (-120 ft) ASL

We know that the most recent faulting on the Old Ghost fan is young, probably latest Holocene, but more importantly we need to know how often such faulting events occur and how large the associated earthquakes are. This information is not recorded at Stop B3.2 because of the youthfulness of the landscape. However at Stop B3.3, older alluvial surfaces record a history of recurrent faulting that can provide answers to such questions.

From Stop B3.2, we will walk about 300 m north to a large (7 m) fault scarp that is preserved on the Q2 surfaces (fig. B3-7). The bulk of the uplifted surface was mapped as Q2b by Machette and others (1999b), although no age data exist here. The Q2b surface has an excellent desert pavement (essentially flat), with extremely well-developed rock varnish on the top of clasts and brick red colors on the base of clasts. In addition, exposures along some of the arroyos contain soils having well-developed stage III to IV calcium carbonate morphology, suggesting significant antiquity.

At this stop there is one main down-to-the-west fault, and a number of lesser subsidiary faults to the east and west. Most of the faults to the east offset the Q2b surface small amounts (<0.5 m), but there is morphologic evidence for repeated and recent movement on some of these subsidiary faults. The Q2b surface is buried on the downdropped block, so the net offset is probably much larger, perhaps twice as much as the observed scarp height (i.e., 14 m).

At Stop B3.2, the larger single-event scarps are commonly 0.7-1.1 m high and have surface offsets of about 0.6-1.0 m; on average, the net surface offset per event was probably about ⅔ m considering the antithetic faults that bound the graben.

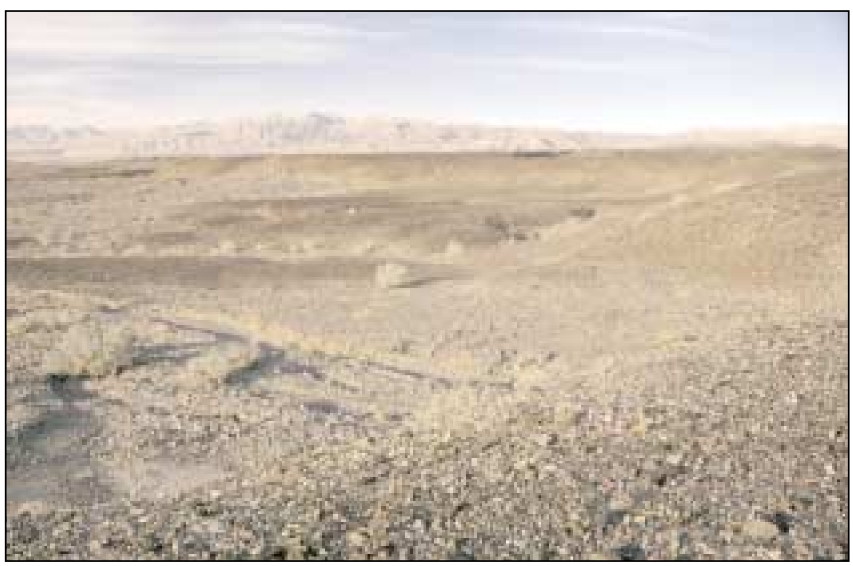

*Figure B3-7. North view of 7-m-high fault scarp at Stop B3.3. Photograph by M. Machette, Nov. 2000.*

Thus, the boundary conditions for reconstructing fault recurrence are; 1) an average offset of ⅔-m per event, 2) an estimated age of 70-200 ka for the faulted Q2b deposit, and 3) a net offset of 7 m to 14 m for the surface of Q2b at Stop B3.3. From these data Machette and others (1999b) derived a preferred (mid-range) slip rate of 0.1 mm/yr and an average recurrence interval of 6,700 years (table B3-2). Although these values are largely back of the envelope estimates, they are founded on realistic geologically reasonable estimates of surface age and net surface offset.

These slip rate and recurrence values represent a fraction of that estimated for the main range-bounding faults in the Death Valley fault system to the north and south. Slip rates are typically several mm/yr on the Southern Death Valley fault zone (see Chapter L) to as much as about 7 mm/yr on the Northern Death Valley fault zone (see Stop A3). Clearly, not all the slip that is accumulating to the south and north on the Death Valley fault system as a result of continued NNW-SSW-directed extension is being recognized within this right-stepping transition zone. Some slip is probably being taken up by other faults (such as those along Park Village Ridge), by uplift of the Mustard Canyon hills, by oblique strike-slip faults that bound these hills, and by faults that lie concealed beneath the valley floor (see Stop B2).

**Table B3-2. Bounds on fault slip rate and recurrence intervals at Old Ghost alluvial-fan complex, Stops B3.2 and B3.3**

| Duration of faulting (k.y.) | Offset (in m) | † Number of events | Slip rate (in mm/yr) | † R.I. (in k.y.) |
|---|---|---|---|---|
| 1) Short, <70 | 14 (max.) | 21 (max.) | 0.20 (max.) | 3.5 (min.) |
| 2) Long, <200 | 7 (min.) | 10-11 (min.) | 0.04 (min.) | 20 (max.) |
| 3) Mid, about 100 | 10 (mid.) | 15 (mid.) | 0.10 (mid.) | 6.7 (mid.) |

† Note: Recurrence interval (R.I.) is based on net offset and inferred 2/3-m slip per event. If slip at this site averaged less (i.e., 1/2 m), then the number of events increases and recurrence interval decreases, proportionately.

# Stop B4

# Late Quaternary growth of the Echo Canyon thrust and Texas Springs syncline

*Ralph E. Klinger, Lucille A. Piety, and Michael N. Machette*

Furnace Creek 7.5' quadrangle
GPS: 27 NAD, UTM Zone 11S
$^{40}32^{300}$ mN, $^{5}15^{830}$ mE
Elevation about 123 m (405 ft) ASL

## INTRODUCTION

Stop B4 is along Furnace Creek Wash at the junction of Echo Canyon Road and State Highway 190, about midway between Travertine Springs and Zabriskie Point (near Stop B5). Here we will see evidence for thrust faulting and uplift and deformation of Quaternary alluvial gravels that form extensive piedmont surfaces that once extended from the Funeral Mountains (on the east) to Furnace Creek (on the southwest). These alluvial deposits, the underlying gravel of the Funeral Formation, and the finer-grained strata of the Furnace Creek Formation have been deformed into a broad elongate synclinal basin, which is referred to as the Texas Springs syncline. This syncline lies between the Funeral Mountains on the east and the northern end of the Black Mountains on the southwest. The Miocene Artists Drive Formation on the northern flank of the Black Mountains (to the south) forms the spectacular backdrop for Zabriskie Point.

The Texas Spring syncline is a northwest-trending, southeast-plunging asymmetric fold that controls the course of Furnace Creek as it flows northwest to Death Valley. Furnace Creek presently flows parallel to the axial plane of the syncline, against the steep northeast-dipping strata of the Furnace Creek Formation in the southwest limb of the syncline. The hinge of the fold is at the northwest end of a large structural trough mapped in detail by McAllister (1970) and later described as the Furnace Creek basin by Cemen and others (1985). The Furnace Creek basin contains a thick section of upper Cenozoic sedimentary rocks mainly comprising the Miocene Artists Drive Formation and the largely Pliocene Furnace Creek Formation (see fig. B5-4), which will be the subject of our next field trip stop (B5). This basin is wedged between the modern north-striking, down-to-the-west normal Black Mountains fault zone to the southwest and the ancient (largely Pre-Quaternary) northwest-striking, right slip Furnace Creek fault zone to the northeast (see paper on fault nomenclature, Chapter J in this volume). The uplifted Black Mountains (which form the footwall block of the Black Mountains fault zone) form the southwest margin of the Furnace Creek trough (Cemen and others, 1985).

Northeast-dipping, fine-grained strata of the Furnace Creek Formation are exposed on the overthrust (footwall) block of the Echo Canyon fault. Because of the limited and discontinuous nature of the exposures, it is difficult to know what part of the Furnace Creek is adjacent to the fault, although McAllister (1970) mapped these rocks as being in the uppermost part of the formation (unit Tfu). However, Ralph Klinger found two tuff beds exposed in the bluff east of our first stop (B4.1), and analysis by Andrei Sarna-Wojcicki suggests that the upper white tuff (sample MNM-DV-9-FC) is correlative with a tuff from the Coso eruptive field that has an $^{39}Ar/^{40}Ar$ date on sanidine of 3.09 Ma (see paper by Sarna-Wojcicki and others, Chapter E in this volume). This white tuff is several meters above a gray tuff that may also be present in Double Ash Wash (see Stop B5.3). Samples of gray tuff from this wash have an interpolated age of about 3.15 Ma (Sarna-Wojcicki and others, this volume). Thus, it appears that the footwall rocks of the Echo Canyon thrust (at this stop) are in the range of about 3.2 to 3.0 Ma.

Stratigraphic relationships indicate that deformation across the syncline occurred periodically from about 25 Ma (Hunt and Mabey, 1966; McAllister, 1970; Cemen and others, 1985) into the Quaternary. Late Pleistocene, and possibly Holocene, NE-SW-directed shortening is evidence by continued folding of the syncline and thrusting (fig. B4-1) along the Echo Canyon thrust, which bounds the southwestern margin of the syncline. This thrust, which was named after Echo Canyon by Klinger and Piety (1996), is well exposed at our first stop (B4.1). The thrust forms young scarps on moderately old Quaternary gravel (unit Q2, Stop B4.2). In addition, the geomorphic relations between various ages of alluvial deposits that cross the axis of the syncline (as seen from Stop B4.3) indicate that the syncline has been undergoing progressive deformation throughout the late Quaternary.

In addition to the material for this stop, Klinger and Piety prepared a more thorough paper on the Quaternary history of the Echo Canyon thrust fault, the Cross Valley fault, and the Texas Springs syncline, which is included as Chapter K in this volume.

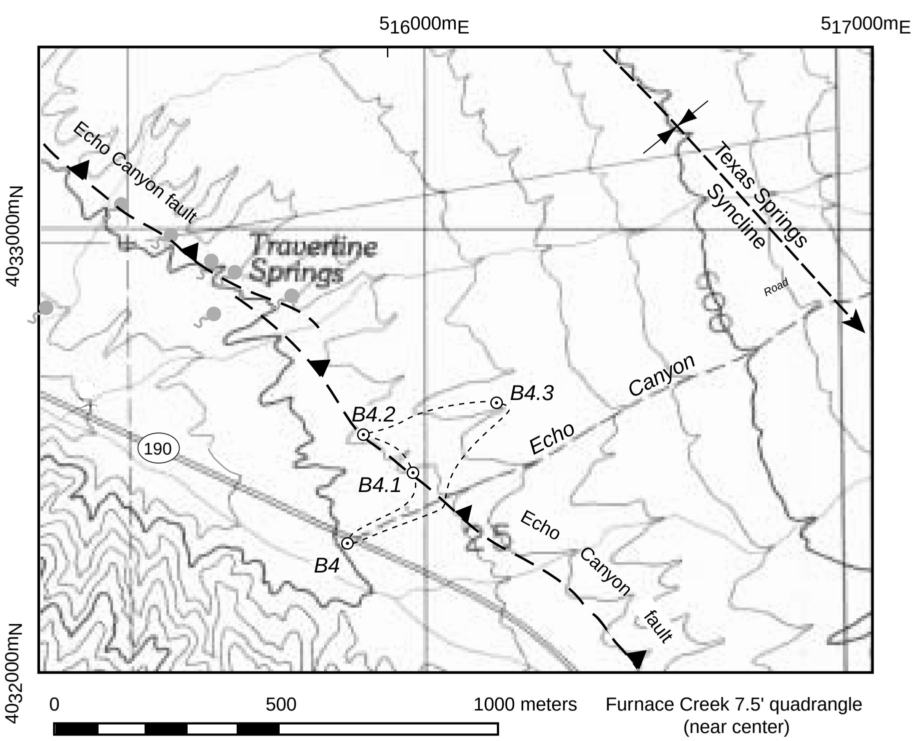


*Figure B4-1. Index map for area around Stops B4. B4.1, B4.2, and B4.3 indicate places we will stop for discussion.*

# The Echo Canyon thrust

UTM 11S $^{40}32^{450}$ mN, $^{5}15^{980}$ mE
Elevation 133 m (435 ft)

The Echo Canyon thrust is well exposed in a stream cut exposure north of the Echo Canyon Road (fig. B4-2), about 150 m northeast of its intersection with State Highway 190. The fault was first noticed by Klinger and Piety (1996) during mapping of young faults in the Death Valley area, and several subsequent articles have focused on this structure and the adjacent Texas Springs syncline (Klinger, 1998, 1999; Machette and others, 2000). The fault (or more probably, faults) dips to the northeast, subparallel to sedimentary bedding in the upper part of the Furnace Creek Formation. At the fault, the sedimentary beds are locally folded and dragged against the thrust fault. Scarps associated with the fault can be traced about 0.6 km to the southeast, and at least 1.6 km to the northeast (fig. B4-2), well past Travertine Springs (Machette, 1999b, fig. 3).

The natural exposure of the fault at Stop B4.1 (fig. B4-3) is about 7-m high on the upthrown block, which is cored by moderately to steeply dipping fine-grained sedimentary rocks of the upper part of the Furnace Creek Formation (unit Tfu) and a thin mantle (2-3 m) of Q2 gravel. Klinger and Piety (1996) mapped this gravel unit as Q2c(?), which they suggest was deposited in the range of 12-70 ka.

The fault extends nearly to the surface and its sense of slip is readily apparent in the exposures. The Av and B horizons developed beneath the Q2c(?) surface are clearly disrupted and the previously exposed desert pavement is now buried (and preserved as a stoneline) by material that has been thrust up along the fault and over the footwall block.

The observed surface displacement at this site most likely did not occur during a single event, but rather represents the cumulative deformation from numerous events. Klinger and Rockwell (1989) measured the amount of coseismic deformation in a fold accompanying ground rupture during the 1987 Superstition Hills earthquake sequence in the Salton Trough. This modern analog suggests that movement on the Echo Canyon thrust and bedding-parallel slip on deformed beds within the Texas Springs syncline probably occur during major faulting events on the Black Mountains fault zone, inasmuch as the Furnace Creek fault zone (*restricted sense*) to the northeast is largely inactive.

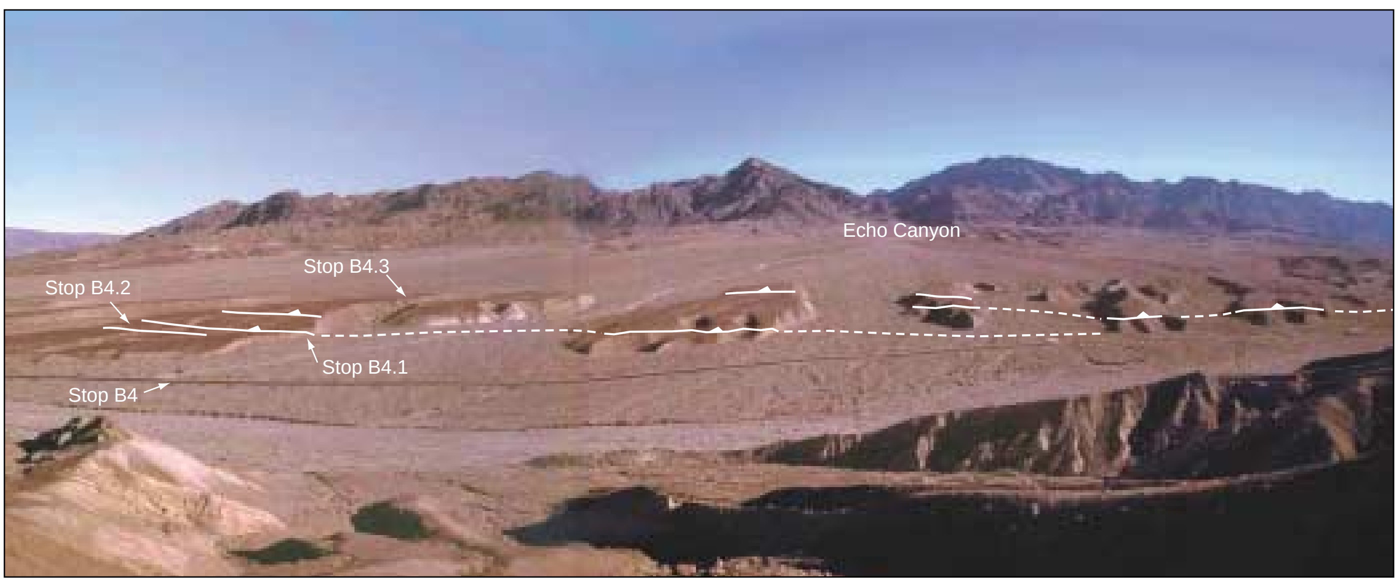


*Figure B4-2. Oblique panoramic view of Texas Springs thrust fault at Echo Canyon Road. The road that crosses bottom of photograph is State Highway 190. (Photograph by M. Machette, Nov. 2000.)*

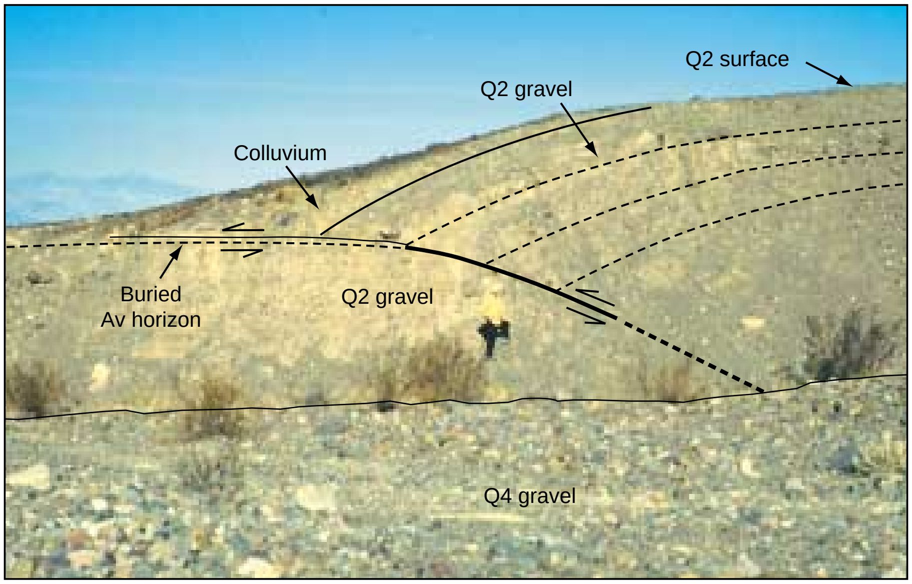


*Figure B4-3. Northwest view of Echo Canyon thrust, which deforms Q2c(?) gravel and its associated surface. The fault surface, bedding in gravel, and depositional contacts are shown (photograph by M. Machette, Nov. 2000).*

## Stop B4.2 — Fault scarps on Quaternary gravel (unit Q2)

UTM 11S $^{40}32^{540}$ mN, $^{5}15^{875}$ mE
Elevation 136 m (445 ft) ASL

The morphology of the uplifted Quaternary surfaces and the scarps associated with thrust faulting indicate that deformation has occurred since the late Pleistocene and perhaps as recently as the late Holocene. The rock varnish and desert pavement formed on the upper Pleistocene Q2c(?) surface are disrupted at the scarp; varnish on the scarp slope is poorly developed. A scarp height of 5.4 meters and maximum scarp-slope angles of 22°-25° were measured along the Echo Canyon thrust fault (see Klinger and Piety, Chapter K in this volume). Considering the geometry of the fault, the 5.4-m-high scarp height probably relates to about 5 m of vertical slip, or about 10 m of dip slip separation (assuming an angle of about 30° on the thrust).

At this stop, each of several scarps are associated with separate strands of the Echo Canyon thrust. The lower scarp is small (<1 m) but is rather steep, whereas the upper scarp is larger (about 1.5 m) but has more gentle slopes. It appears that the lower scarp has younger movement, but the comparison of thrust faults with morphometric data from normal faults (see Stop B3.2) is problematic. Thrust faults commonly produce ramp-like scarps that appear old compared with the near vertical scarps of normal faults of the same age. Nevertheless, because of the large amount of separation (estimated 10 m horizontal), the fault scarps along the Echo Canyon thrust are clearly the products of multiple faulting events along as many as 3 or 4 fault strands.

These faults continue to the several kilometers to the northwest, where they control the location of Travertine Springs. Here, the fault puts older Quaternary alluvium (or Funeral Formation conglomerate) over fine-grained strata of the Furnace Creek Formation. The fine-grained strata act as an aquitard to ground water that is pooled in the Texas Springs syncline. Palm trees mark the major spring-discharge areas, the upper limit of which is at 120 m (400 ft) elevation. Even farther northwest, the Echo Canyon thrust appears to be the source of massive travertine springs that form a high buttress on the north side of Furnace Creek Wash (Machette and others, 2000).

## Stop B4.3

# Quaternary deformation of the Texas Springs syncline

UTM 11S $^{40}32^{610}$ mN, $^{5}16^{145}$ mE
Elevation 150 m (495 ft) ASL

From this location, we have an excellent view to the northeast across the axis of the Texas Springs syncline. Along the length of Furnace Creek Wash, gravelly alluvial-fan deposits are being transported from the Funeral Mountains into the structural trough to the southwest. These young gravelly deposits on the northeast limb of the fold are typically inset into ridge-forming conglomerate of the Pliocene-Pleistocene Funeral Formation, but near the axis of the syncline, the younger alluvial deposits have progressively buried older Quaternary alluvial deposits as a result of localized subsidence along the axis of the fold. These relations are illustrated by topographic profiles of upper Pleistocene and Holocene surfaces that are almost continuous across the axis of the syncline (fig. B4-4A).

Tectonic deformation of the middle and upper Pleistocene alluvium is indicated their pattern on aerial photographs (see Klinger and Foley, Chapter K in this volume) and by profiles across remnants of the Q2 and Q3 surfaces within the Texas Springs syncline. The profiles of late Pleistocene surfaces that cross the syncline show varying heights above the active channels of Echo Canyon Wash (fig. B4-4, part B). The upper Pleistocene Q2 surface, which is well above younger surfaces near the range front (to the east), is buried by the lower and middle Holocene alluvium (Q3) near the axis of the syncline. Toward this stop (B4.3), the older surfaces rise progressively above the younger surfaces on the southwest limb of the syncline. The configuration of the upper Pleistocene surface mimics that of the larger syncline and the deformed strata of the underlying Furnace Creek and Funeral formations (McAllister, 1970), although the amount of deformation of the Pleistocene surface is much less than that of the syncline is underlying rocks. It is difficult to explain these relationships by erosion and alluvial deposition; the only logical explanation is continued Quaternary tectonic deformation of the Texas Spring syncline.

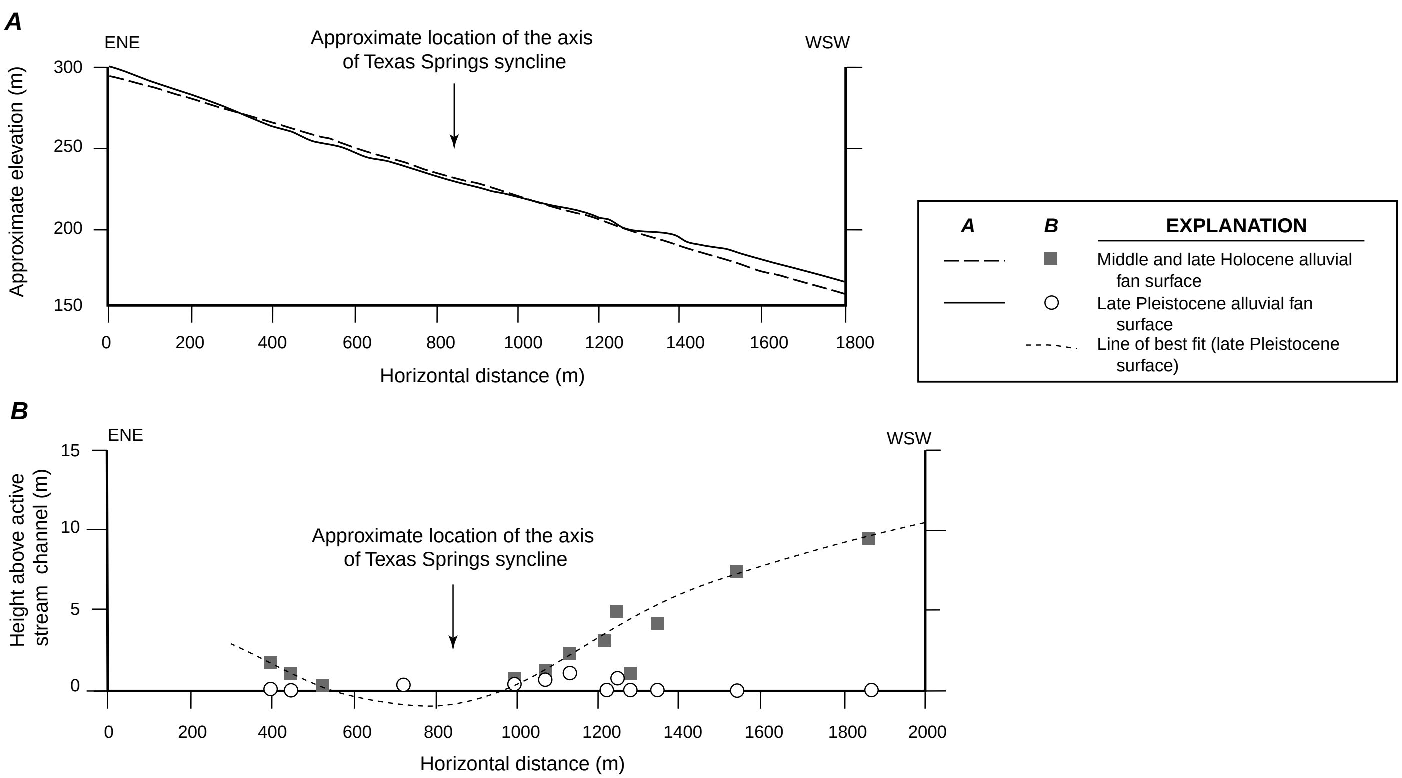


*Figure B4-4. A) Topographic profiles on late Pleistocene and Holocene alluvial-fan surfaces across the axis of Texas Spring syncline near Echo Canyon road; B) Heights of surfaces above active wash. Taken from Klinger and Piety, 1999.*

# Stop B5

# Late Pliocene volcanic tuffs in the upper part of the Furnace Creek Formation

*Michael Machette, Andrei Sarna-Wojcicki, and Ren Thompson*

Furnace Creek 7.5' quadrangle
GPS: 27 NAD, UTM Zone 11S
$^{40}30^{780}$ mN, $^{5}17^{485}$ mE
Elevation about 198 m (650 ft) ASL

## INTRODUCTION

At Stop B5 we will see a sequence of Pliocene volcanic tuffs that yield the first definitive age control for the upper part of the Furnace Creek Formation, and thus place limits on the age of the overlying Funeral Formation in this area. These tuffs are exposed along and in the upper reaches of Double Ash Wash (informally named herein), which has a small drainage basin that we will overlook during our several kilometer-long walk. The Furnace Creek Formation is well exposed in this, its type area (there is no type locality). Detailed mapping by McAllister (1970) is the best source of currently published data on the Furnace Creek Formation, although Machette, Thompson, and Chris Fridrich (USGS-Denver) are currently engaged in remapping the Furnace Creek 7.5-minute quadrangle with an emphasis on the refining the volcanic stratigraphy and Quaternary geology and tectonics.

The starting point for Stop B5 is the parking lot for the Zabriskie Point overlook. At this location in 1941, the National Park Service purposely diverted Furnace Creek into a tributary channel of Gower Gulch, which drains the topographic basin south of Zabriskie Point. The diversion was intended to protect the Furnace Creek Inn and Ranch, as well as water diversion and other built structures from flash floods. This diversion hastened what nature would have accomplished in time, since the new flow path has a much steeper gradient in softer sediment. To no one's surprise, the diversion has caused dramatic changes in the channels of Furnace Creek Wash and Gower Gulch. The wash has downcut at least 6-7 m (by late 2000) and incised a deep gash in the fine-grained sedimentary rocks of the Furnace Creek Formation (fig. B5-1). Each major runoff event that produces flooding cuts deeper into the gulch, so that remediation becomes less likely each year. This environmental conundrum is the subject of an interesting article by Troxel (1974). We are not aware of any attempts to quantify the changes that are occurring on year- to-year or decadal time scales.

From the parking lot (fig. B5-2), we will walk about a ½ km to the northeast across darkly varnished Quaternary alluvial surfaces (subunits of Q2, Stop B5.1) and then several hundred meters north to overview well exposed volcanic tuffs that are in the uppermost part of the Furnace Creek Formation along Double Ash Wash (Stop B5.2). We will see these tuffs at Stops B5.3A and B5.3B, where they have been deposited in a quiet-water (lacustrine) environment or playa. These deposits now dip moderately (typically 30°-40°) to the northeast along the southwest limb of the Texas Springs syncline (see Stop B4).

*Figure B5-1. View of Furnace Creek Wash about 20 m above its diversion into Gower Gulch (photograph by M. Machette, Nov. 2000).*

There are four topics to discuss at this stop.

1) Well developed rock varnish and desert pavement on the various Q2 gravel surfaces (Stop B5.1),

2) Two volcanic tuffs (Stop B5.2 and 5.3) that provide age control for the upper part of the Furnace Creek Formation and the overlying Funeral Formation,

3) Lithologic and chemical characteristics of the tuffs, and possible correlations with other volcanic tuffs in the area (i.e., Stops A2 and C3), and

4) Interpretations on how the contact between the Furnace Creek and Funeral formations should be defined.

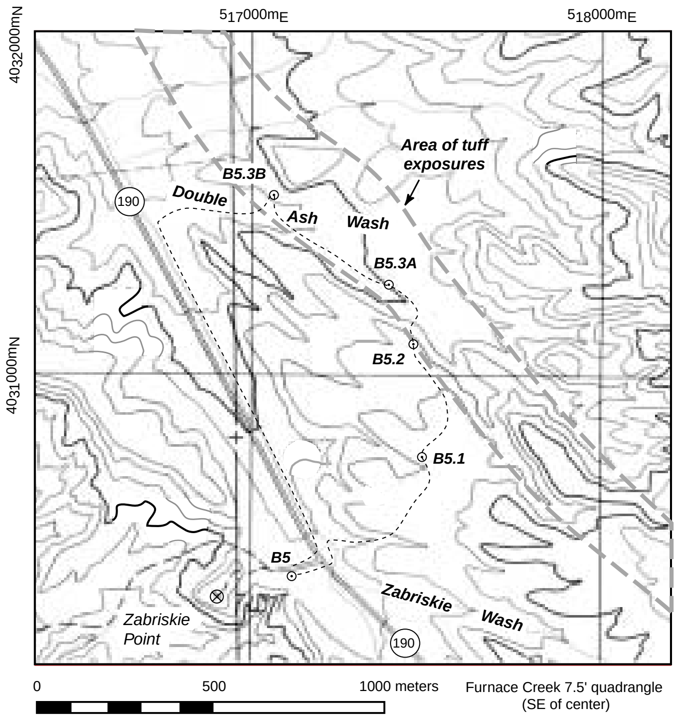


*Figure B5-2. Index map of Double Ash Wash drainage basin, near Stop B5. Stops B5.1, B5.2, and B5.3 indicate places we will stop for discussion. Also shown is extent of Pliocene tuff exposures in unit Tfu.*

# Stop B5.1

# Quaternary gravel deposits (Q2)

UTM 11S $^{40}30^{780}$ mN, $^{5}17^{485}$ mE
Elevation 225 m (740 ft) ASL

This stop, which is largely a gathering point for our trek to Stops B5.2 and B5.3, is on top of a series of high Q2 gravel surfaces. These alluvial gravels were deposited by Furnace Creek Wash and since have been dissected by its side streams and headward erosion of Double Ash Wash. As we climb up to this stop, we cross two lower levels of Q2 alluvium, each of which has relatively intact constructional surfaces. However, this higher surface is more of a ridge that is now characterized by numerous large relict basalt boulders that have been both sand blasted and varnished. The bouldery nature of this surface suggests that it is more likely eroded than relict.

Without seeing the soils developed on these three Q2 surfaces, it is hard to make correlations with the stratigraphy suggested by Klinger and Piety (1996). However, it seems reasonable that the deposit we are standing on is the oldest of the Q2 deposits (Q2a?), because there is little original surface preserved (see fig. B5-3A). The lower surface to the south is probably a remnant of Q2b, and the even lower surface, which is the most extensive in this area, would be Q2c. Both the Q2b and Q2c surfaces, which were deposited in a NW-trending direction by Furnace Creek, appear to have a slight NE component of dip, which has probably been induced by uplift along the western limb of the Texas Springs syncline (see Stop B4).

At this stop, unit Q2a has a well paved and varnished surface that is characterized by abundant, large (0.5-1 m), "chocolate" covered basalt boulders (the chocolate descriptor comes from the color and feel of the varnished surfaces; indulge if you wish). This surface is about 5-8 m above the adjacent Q2b surface. The Q2b gravel, which is mainly south of here, are about 5 m above the even lower Q2c, but converge to within 2 m about 500 m to the west (near the western end of these surfaces; see fig. B5-3A). Unit Q2c, which is exposed along the eastern and northern rim of this surface, is generally 2-8 m thick. Q2c alluvium is less bouldery than Q2b, has less varnish, and only minor incipient drainage development; features that all suggest less antiquity. Klinger and Piety (1996) suggested ages of 12-70 ka for unit Q2c (late Pleistocene), 70-200 ka for unit Q2b (late to middle Pleistocene), and 400-730 for unit Q2a (middle Pleistocene). No dating or description of soils has been conducted in this area to confirm these correlations.

# Stop 5.2

# Overview of Late Pliocene basin fill

UTM 11S $^{40}31^{100}$ mN, $^{5}17^{470}$ mE
Elevation 207 m (680 ft) ASL

At this stop we have a nice view of the area between Double Ash Wash to the north (sites of Stops B5.3A and B) and Zabriskie Wash to the south (fig. B5-2). This area was once covered by extensive alluvial piedmont gravels (Q2a-Q2c, Stop B5.1) that were eroded from the adjacent Funeral Mountains and the north-trending ridge of Funeral Formation conglomerate about 1 km to the east of us. Basin-fill strata of the Furnace Creek Formation is well exposed below the relatively thin mantle of Q2c gravel (here) and in the washes and dissected region between them.

McAllister (1970) mapped the bedrock section from State Highway 190 at Zabriskie Point east to the conglomeratic ridge as a generally upward-fining sequence of middle to late Pliocene alluvial-fan deposits (unit Tfcu, fig. B5-3B). These are overlain, in turn, by an upward-coarsening sequence of playa, lacustrine with volcanic tuffs (unit Tfu), and alluvial-fan deposits (unit QTfl). The gradual change from deposition in a lacustrine environment to an alluvial-fan environment was taken as the contact between the Furnace Creek Formation (unit Tf) and the overlying Funeral Formation (unit QTf). As such, it probably reflects rapid uplift and progressive unroofing of the Funeral Mountains to the east. However, as will be emphasized later, there is a significant change of provenance up section and to the east, toward the front of Funeral Mountains. To the northwest, the grain-size contrast (coarse over fine) is more extreme and may occur higher in the section.

Although we have not measured section in this area, the general lithologic characteristics and inferred thicknesses of the upper part of the basin-filling Furnace Creek Formation (Tf) and Funeral (QTf) Formation are shown in figure B5-4, which is a schematic stratigraphic column based on McAllister's (1970) mapping and cross sections.

Units Tfcu and Tfu (upper Furnace Creek Formation, fig. B5-3B) are well exposed along Double Ash and Zabriskie Washes. The strata grade upward from gray

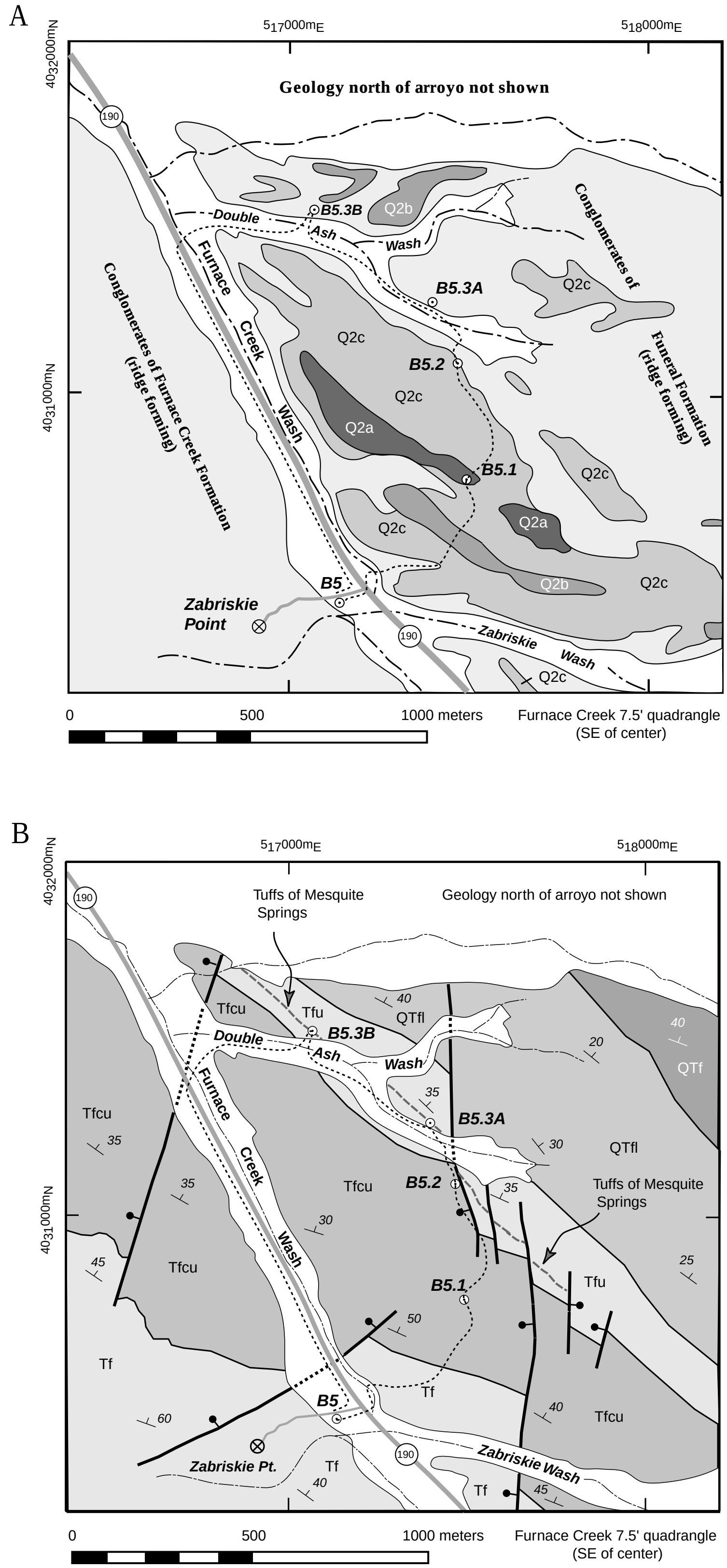


*Figure B5-3. Geologic maps of the Double Ash Wash drainage basin: A) surficial geology from unpublished mapping of Machette (1999-2000); and B) bedrock geology (surficial units removed) from McAllister (1970).*

to greenish, medium- to coarse-grained conglomerate that is exposed on the north side of State Highway 190 to light-brown and red-brown (oxidized) sandstone and mudstone (unit Tfcu) that crop out beneath alluvial gravel at Stop B5.1. The conglomerate contains clasts that seem to have been derived from the Panamint Mountains (Hunt and Mabey, 1966). However, it becomes more local in origin upward in the section, being derived mainly from volcanic rocks in the northern Black Mountains. Above these coarse (pebble-bearing) strata, the basin fill consists of conspicuous white to light brown siltstone and mudstone (unit Tfu) that contain at least six discrete volcanic tuff (tephra) beds (see Sarna and others, Chapter E in this volume). McAllister (1970) characterized unit Tfu (uppermost part of Furnace Creek Formation) as being marked by a basal pumiceous tuff, which is, in fact, two separate tephras that we will see at the next stop.

The transition from fine strata (siltstone and mudstone) in the upper Furnace Creek Formation (unit Tfu) to the overlying coarse-grained sediment (gravel to conglomerate) of the Funeral Formation (unit QTfl) is considered to be a formational marker. However, several other equally important changes may argue for moving the formation contact higher in the section.

1) Sedimentary onlap. The basal member of the Funeral Formation (unit QTfl) goes from zero thickness north of State Highway 190 (2.0 km SE of Stop B5), to 100 m at Zabriskie Wash and to about 250 m at Double Ash Wash (thickness determined from McAllister's 1970 mapping).

2) Decrease in dip (upward fanning of dip) from the lower to upper members of the Funeral Formation.

3) A change from predominately volcanic clasts derived from the Black Mountains (source to the south) in the lower member of the Funeral Formation (unit QTfl) to Paleozoic and Precambrian clasts derived from the Funeral Mountains (source to the east) in the upper member of the Funeral Formation (unit QTf).

The first and second changes suggest progressive growth of and deposition into the Texas Springs syncline in late Pliocene and early Quaternary(?) time. The third change probably reflects a spatial shift in tectonism, as uplift of the Black Mountains slows and uplift of the Funeral Mountains starts (or accelerates).

Thus, two different transitional contacts are of interest here, either of which might be considered to separate the Funeral and Furnace Creek Formations. The lower transitional contact of McAllister (1970), which is based on grain size (fine to coarse) and environment (lake and playa versus alluvial fan) represents the currently mapped boundary between the Funeral and Furnace Creek formations. The upper transitional contact, which is generally concordant with McAllister's (1970) boundary between the lower and upper members of the Funeral Formations, is consistent with a marked change in provenance and basin geometry, although the former is not mentioned by McAllister and lies just above the base of the conglomeratic ridge, 500 m northeast of this stop.

The reason we've taken the time to discuss this contact here is 1) its proximity, 2) apparent time-transgressive nature, and 3) possible correlations of upper Tertiary rocks in the Furnace Creek quadrangle with time equivalents in the northern and southern regions of our field trip. For example, Jeff Knott maps coarse fanglomerate derived from the Black Mountains (Stop C3) as within the lower part of his Funeral Formation, but it contains the tuffs of Mesquite Spring. If these tuffs are the same as ones seen at our next stop (B5.3), then there must be a significant age difference in the Funeral Formation as mapped in each area. Jeff argues that the Funeral/ Furnace Creek formational boundary should be at the base of McAllister's (1970) unit Tfu, based on the presence of the tuffs of Mesquite Spring near the base of "Funeral-like" basin-filling sedimentary sections in several other parts of Death Valley.

Similarly, coarse, well-cemented fanglomerates along State Highway 190 southeast of here (upper Furnace Creek Wash) are interbedded with basalts that have been K/Ar dated at about 4 Ma (McAllister, 1970). Clearly, the base of the Funeral Formation as mapped on the basis of coarse clastic debris has a significantly different age near the Funeral Mountains (>4 Ma) than it does in the Furnace Creek basin (probably <3.1 Ma).

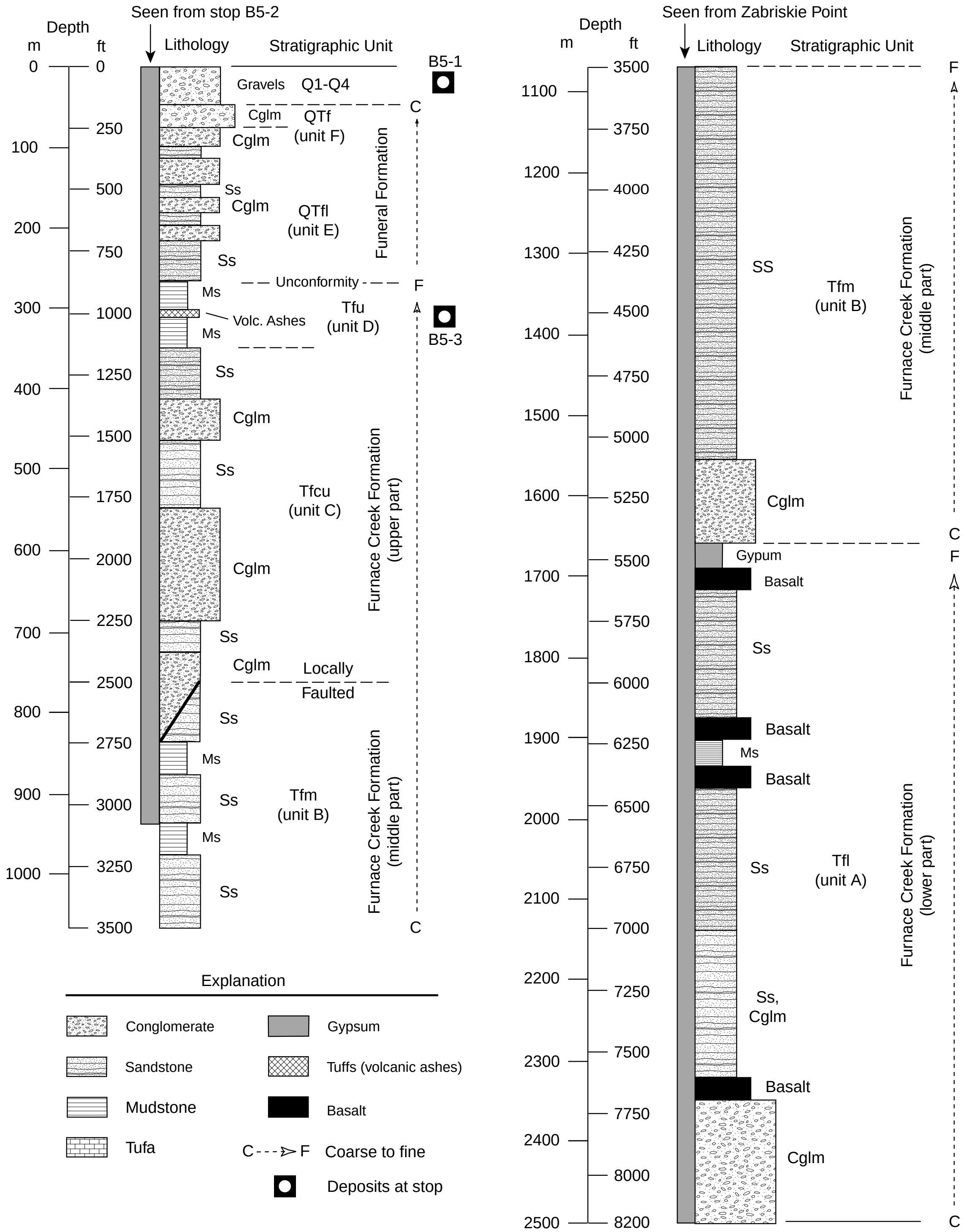


*Figure B5-4 Schematic stratigraphic column of geologic units and strata of upper part of Furnace Creek Formation and Funeral Formation near Stop B5. Section derived from mapping of McAllister, 1970 (modified from Machette and others, 2000).*

# Stop B5.3

# Volcanic-tuff marker beds in the Furnace Creek Formation

Loc. A: UTM 11S $^{40}31^{250}$ mN, $^{5}17^{430}$ mE
Elevation 186 m (610 ft) ASL
Loc. B: UTM 11S $^{40}31^{520}$ mN, $^{5}17^{070}$ mE
Elevation 177 m (580 ft) ASL

Volcanic-tuff beds are well-exposed along Zabriskie Wash and in the drainage basin of Double Ash Wash (fig. B5-2), a kilometer to the north. At this stop, we have two opportunities (loc. A and B) to look at closely coupled tuff beds (i.e., the "Double Ashes"). These tuffs can be traced not only throughout the Double Ash Wash area, but several kilometers farther to the northwest and southeast. We suspect that there are actually six separate volcanic tuffs (see Sarna and others, Chapter E in this volume), although minor faulting to the east of this stop (loc. A) makes it difficult to determine the exact stratigraphic position of each tuff. Nevertheless, all of these tuffs are within the upper part of the Furnace Creek Formation (unit Tfu) as mapped by McAllister (1970) (see fig. B5-3B).

The small ridge before us is held up by a thick bed of pumiceous tuff (see description in table B5-1). On weathering, the tuff becomes hard and forms blocks that have a characteristic orangish cast. This tuff is the upper of two exposed here, the lower one cropping out discontinuously along the base of the ridge. The two tuffs are separated by about 8 m of fine grained tufaceous sandstone and siltstone, including a characteristic green claystone (fig. B5-5) near the base of the upper tuff.

The two tuff beds were sampled for tephrochologic characterization by Andrei Sarna-Wojcicki's lab in Menlo Park. Correlations are based on mineralogy, state of preservation of the glass, shard shape, and chemistry (volatile-free oxides, see paper by Sarna-Wojcicki and others, Chapter E in this volume). A computer correlation program suggests possible matches with existing samples.

Both tuffs have close chemical matches with the Mesquite Spring group of tuffs, which are in the range of 3.1 to 3.5 Ma. The lower tuff (MNM-DV-11-FC) is almost an exact match with sample JT-NOVA-1, a tuff collected by John Tinsley and Andrei Sarna-Wojcicki from the Nova Formation on the west side of Death Valley, and with Jeff Knott's sample JRK-DV-80, a coarse approximately 3-m-thick tephra layer from the Emigrant Wash Road on the west side of Death Valley.

The upper tuff (MNM-DV-8-FC) is almost an exact match with Ralph Klinger's sample RKSC-3, which is a 15- to 20-m-thick massive, reworked pumiceous tuff that is exposed in the northern part of Death Valley (see Stop A2).

The upper tuff is quite similar to Ralph Klinger's sample RKDVW-5, which is from the same general area (Stop A2) and is also one of the tuffs of Mesquite Spring. Bob Fleck (USGS-Menlo Park) recently obtained a $^{39}Ar/^{40}Ar$ date of 3.27±0.02 Ma (1-sigma) from sanidine in Klinger's tuff of Mesquite Spring (see paper by Sarna-Wojcicki and others, Chapter E in this volume).

Thus, if we accept the mineralogical and chemical correlation of the two (double) tuffs, which are well exposed at Stops B5.3A and B5.3B, with the Mesquite Spring tuffs from elsewhere in Death Valley, then one can assume that this uppermost member of the Furnace Creek Formation (unit Tfu, fig. B5.3) is between about 3.30 and 3.25 Ma at this locality, and slightly younger (perhaps 3.0 Ma) in the 100 m of strata higher in the formation. Thus, unless there is a marked time unconformity at the upper formational boundary (of McAllister), the overlying Funeral Formation must be late Pliocene and Pleistocene in age. The upper limit of the Funeral Formation (as mapped by McAllister, 1970) is not well established, but Machette believes that it may well extend in to the early (?) Quaternary.

Both of the tuffs at stops B5.3A and B5.3B are pumiceous, and some exposures to the north or south are even more so. The presence of pumice suggests local sources, inasmuch as pumice of >1 cm diameter can probably not be transported more than 50-60 kilometers through the air (see Chapter E in this volume). Suspect source areas such the Long Valley calderas north of Bishop are at least 200 km distant. Without the presence of a fluvial (river) system linked to the eastern Sierra Nevada, it appears that the Mesquite Spring tuff beds within Death Valley must have a source within its Pliocene drainage basin. Recent discovery of very coarse (>5-10 cm diameter) pumice deposits beneath late Pliocene (2-3? Ma) basalt east of Grapevine Junction (M. Machette, Nov. 2000) and conversations with Chris Fridich (USGS-Denver) suggest that the Mesquite Spring group of tuffs may have been erupted from unknown sources from this area, which remains poorly mapped for the most part. Careful geologic mapping in the Grapevine Mountains of northern Death Valley will help solve the mystery about the source of the Mesquite Spring tuff beds.

### Table B5.1 Data on volcanic tuffs (ash beds) at FOP Stops B5-3A and B5-3B

DV-8, UPPER TUFF; Machette's Station 79, sample MNM-DV-8-FC. Collected 4/12/99 at Stop B5.4A

Location: From low ridge on north side of Double Ash Wash, about 1.0 km north of Zabriskie Wash and 0.6 km east of State Highway 190. Prominent tuff bed through region, traced both northwest and southeast for several kilometers. More variable in thickness than DV-11. See GPS coordinates for Stop B5.3A

Field Description: Upper tuff at Double Ash locality. Pumiceous, white glassy tuff, shards 10-12 mm common, with euhedral biotite. Some glass altered and contains abundant rounded pumice clasts 2-3 cm in diameter. Bed about 0.5 m thick here, but variable (20 cm to 1.5 m locally). Sampled basal 20 cm. Outcrops 8 m above DV-11 at nearby station 83 (Stop B5.3B).

Lab Description: Whitish greenish gray. Splits [-100+200]: This sample contains glass (~80-85%), tectosilicates, and trace biotite and hornblende. A few shards have traces of calcium carbonate on them. Some of the glass shards appear to be altered/altering and have a slight brown color. A few shards are pumiceous, the others are moderately vesicular (irregular, tubular, and spindled vesicles) or bubble wall/bubble wall junctions; many are elongate.

Chemistry (hydrated):

| Oxide | $Na_2O$ | MgO | $A1_2O_3$ | $SiO_2$ | $K_2O$ | CaO | $TiO_2$ | MnO | FeO | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| Mean | 3.430 | 0.042 | 12.447 | 72.950 | 5.510 | 0.439 | 0.046 | 0.083 | 0.622 | 95.569 |
| Std. dev. | 0.182 | 0.010 | 0.195 | 0.630 | 0.270 | 0.028 | 0.032 | 0.026 | 0.076 | 0.758 |

Chemical Correlations (volatile free):

| Sample No. | $SiO_2$ | $A1_2O_3$ | $Fe_2O_3$ | MgO | MnO | CaO | $TiO_2$ | $Na_2O$ | $K_2O$ | Total | †S.C. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| MNM-DV-8-FC | 76.28 | 13.01 | 0.72 | 0.04 | 0.09 | 0.46 | 0.05 | 3.59 | 5.76 | 100.00 | 1.0000 |
| RKDVW-5-Tt | 77.30 | 12.73 | 0.72 | 0.04 | 0.09 | 0.48 | 0.06 | 3.73 | 4.84 | 99.99 | 0.9847 |
| RKSC-3-Tt | 76.99 | 12.82 | 0.71 | 0.03 | 0.09 | 0.48 | 0.06 | 3.70 | 5.13 | 100.01 | 0.9841 |

Note: †S.C., similarity coefficient

Correlation: Matches with the Mesquite Spring group of tuffs.
This group of tuffs is in the range of 3.1 to 3.5 Ma and is often closely associated with the Putah Tuff (stratigraphically below) and the Nomlaki Tuff (stratigraphically above), or sandwiched in between the two Nomlaki-type tuffs. In Death Valley, the best match is with sample RKSC-3, which comes from Ralph Klinger's locality at the base of "Slot Canyon," where it meets Death Valley Wash (Stop A2). Sample RKSC-3 is a 15-20-m-thick massive, reworked pumiceous tuff, which is considered to be Mesquite Spring tuff according to Jeff Knott and Andrei Sarna-Wojcicki (see Sarna-Wojcicki and others, Chapter E in this volume). Sample RKDVW-5 is from the same general area, but is farther up Death Valley Wash in a side canyon to the west; it is the same tuff unit. Recent Ar-Ar dating of sanidine from RKDVW-5 by Bob Fleck yielded an age of 3.27±0.02 Ma (1-sigma). (For more information, see Sarna-Wojcicki and others, Chapter E in this volume).

DV-11. LOWER TUFF; Machette's Station 79, sample MNM-DV-11FC. Collected 4/14/99 at Stop B5.4A

Location: From low ridge on north side of Double Ash Wash, about 1.0 north of Zabriskie Wash. Prominent through the region, traced both northwest and southeast. See GPS coordinates for Stop B5.3A.

Field Description: Lower tuff at Double Ash locality. Clean, glassy fine-grained tuff. Lower meter of bed is clean, upper part is reworked. Sandy (glassy?) for 6-8 m higher in section. Dark-brown thin sandstone at base, green clay above. First exposed at station 75 to southeast (2 m thick, clean glassy).

Lab Description: Whitish grey (N8). Split [-100+200]: sample contains glass (~85-90%), tectosilicates, biotite, and trace opaques, possibly hornblende? Small percentage of shards are altering and have a slight brown coloration. Most shards are bubble wall/bubble wall junctions, a few are moderately vesicular with irregular and spindled vesicles. Possibly hydrated.

Chemistry (hydrated):

| Oxide | $Na_2O$ | MgO | $A1_2O_3$ | $SiO_2$ | $K_2O$ | CaO | $TiO_2$ | MnO | FeO | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| Mean | 3.010 | 0.039 | 12.045 | 70.973 | 5.499 | 0.445 | 0.049 | 0.071 | 0.628 | 92.758 |
| Std. dev. | 0.076 | 0.011 | 0.096 | 0.483 | 0.088 | 0.020 | 0.031 | 0.025 | 0.058 | 0.585 |

Chemical Correlations (volatile free):

| Sample No. | $SiO_2$ | $A1_2O_3$ | $Fe_2O_3$ | MgO | MnO | CaO | $TiO_2$ | $Na_2O$ | $K_2O$ | Total | †S.C. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| MNM-DV-11-FC | 76.46 | 12.98 | 0.75 | 0.04 | 0.08 | 0.048 | 0.05 | 3.24 | 5.92 | 100.00 | 1.0000 |
| JT-NOVA-1 | 77.01 | 13.15 | 0.75 | 0.04 | 0.08 | 0.48 | 0.05 | 3.31 | 5.14 | 100.01 | 0.9960 |
| JRK-DV-80 | 76.82 | 12.72 | 0.75 | 0.04 | 0.08 | 0.48 | 0.06 | 2.84 | 6.21 | 100.00 | 0.9951 |

Note: †S.C., similarity coefficient

Correlation: Matches with the Mesquite Spring group of tuffs, including sample JT-NOVA-1, a tuff collected by John Tinsley, III, and Andrei Sarna-Wojcicki from the Nova Formation on the west side of Death Valley, and Jeff Knott's samples JRK-DV-80 and DV-71. Sample JRK-DV-80 is a coarse-grained approximately 3-m-thick tephra layer from the Emigrant Wash Road on the west side of Death Valley. (For more information, see Sarna-Wojcicki and others, Chapter E in this volume).

*NOTE: Chemistry was analyzed by Charles Meyer (USGS-Menlo Park) using electron-microprobe analysis.*

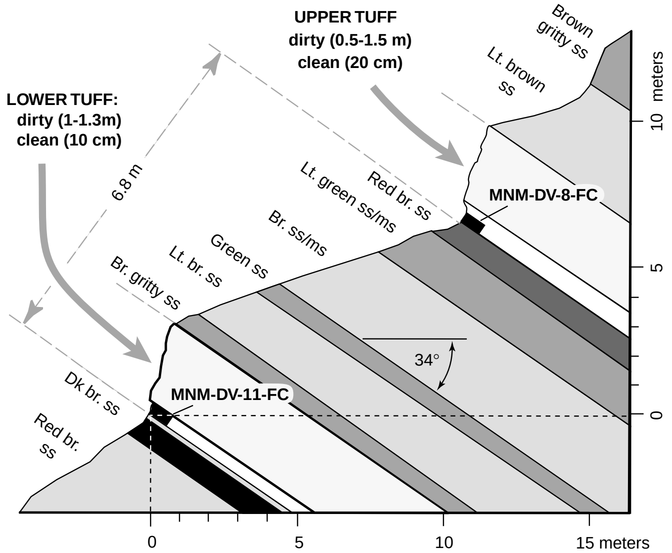


*Figure B5-5. Schematic section of two volcanic tuff beds seen at stops B5-3A and B5.3B.*

*Figure B5-6. Photograph of upper of two tuff beds exposed in Double Ash Wash at Stop B5.3A (eastern of two localities to be visited, see figure B5-2. Base of tuff bed is at end of pick handle. Pick is about 50 cm long. (Photograph by M. Machette, Nov. 2000).*

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# Field trip guide for Day C, Central Death Valley

*Jeffrey R. Knott, Andrei M. Sarna-Wojcicki, John C. Tinsley, III, Stephen G. Wells, and Michael N. Machette*

## OVERVIEW

Day C focuses on the Quaternary geology, geomorphology, and tectonics of the western piedmont of the Black Mountains in the central part of Death Valley. The Black Mountains piedmont offers some of the most spectacular Quaternary geology and tectonic geomorphology in the world and informative field trip stops could be made almost anywhere along the 80-km-long front of the Black Mountains. Our four planned stops (fig. C-1) are designed to achieve the broadest possible perspective on Quaternary geology, tectonic geomorphology, pluvial lakes, low-angle normal faulting, and tephrostratigraphy.

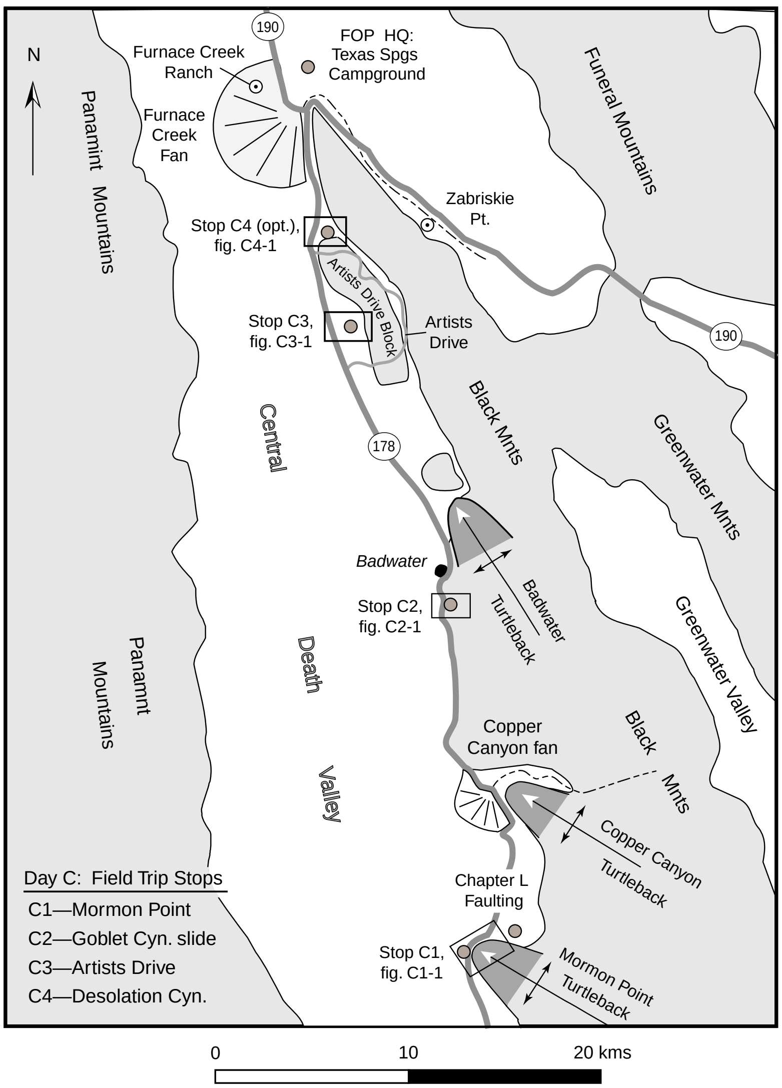


*Figure C-1. Location map showing field trip stops for Day C.*

From Furnace Creek we will drive about 52 km (32.4 miles) south to Mormon Point (Stop C1) where we will spend a majority of our day and take our longest hike. Along the way, we'll stop at places that present special perspectives or features for discussion (Stops C1.1-1.10). Mormon Point (fig. C-2) is an appropriate place to start since this is where the 1986 Southern Death Valley FOP trip ended. Here, we will examine sediments of the early to middle Pleistocene Mormon Point formation, which overlies the Mormon Point turtleback fault and contains pluvial lake and alluvial-fan facies. The newly named Mormon Point formation (Knott and others, 1999) provides valuable insights into the late Quaternary tectonics and paleoclimate of Death Valley. Emerging from the narrow slot canyons that are cut into Mormon Point, we will walk across the relatively flat ground of the 0.12-0.18 Ma (marine oxygen-isotope stage VI, hereafter OIS6) lake abrasion platform. The abrasion platform provides several excellent overlooks of Death Valley from which we can discuss Quaternary stratigraphy, faulting (both low- and high-angle), and pluvial lakes.

From Mormon Point, we will retrace our morning drive north to the rock avalanche (Stop C2) just south of Badwater. The 28-m-high scarp across the avalanche is the highest Quaternary fault scarp on the Black Mountains fault zone (fig. C-3). Here we will see and discuss recent mapping of the avalanche complex and slip rates for the Black Mountains fault zone.

Stop C3 is just north of the Artists Drive entrance road. Here, we will hike across the broad alluvial fans that emanate from the Artists Drive block to look at tuffs exposed in sediments near the base of the

*Figure C-2. Oblique aerial photograph looking southeast at Mormon Point area. Photograph by J.R. Knott.*

*Figure C-3. Vertical low-sun angle photograph of rock avalanche complex near Goblet Canyon. Photograph from University of Nevada, Reno collection.*

*Figure C-4. View to east of Hunt Canyon, west side of Artists Drive showing upper Pliocene tuffs. Photograph by J.R. Knott.*

Funeral Formation (fig. C-4). These tuffs have proven to be important marker beds in the Death Valley area (see Chapters A, B and E, this volume) and provide a minimum age for the Funeral Formation at Artists Drive. The section exposed here clarifies a number of tephrostratigraphic problems uncovered in other regions as well. We will also discuss the implications of this section with respect to the geomorphic development of the Artists Drive block.

This last, short stop (C4; optional) is in Desolation Canyon at the north end of the Artists Drive block. Here, we will see steeply south-dipping gravels related to a spit formed by the OIS 6(?) lake. This spit is at the north end of the broadest, wave-cut terraces related to this lake, which are appropriately called the "Manly Terraces."

From Desolation Canyon, our route returns to State Highway 190 at the Furnace Creek Inn. Along the way, notice the prominent fault scarps along the Black Mountains, which the highway parallels for the remainder of our trip. Also, at Gower Gulch (fig. C-5), notice the large alluvial fan that debouches from the mountain front. This fan is fed by the middle and upper reaches of Furnace Creek, which was been diverted into the Gower Gulch drainage basin (see Stop B4 in this volume).

## ACKNOWLEDGEMENTS

The authors would like to thank the many colleagues that provided stimulating conversations and assistance throughout this project. We would especially like to thank Lauren Wright, Bennie Troxel, Clark Burchfiel, Diane Clemens-Knott, Charlie Meyer, and Elmira Wan. John Geissman collected and analyzed the paleomagnetics samples. This work was supported by grants from the National Science Foundation EAR-94-06029 (to SGW), Sigma Xi, The National Honor Society the Geological Society of America (to Knott) and by the U.S. Geological Survey (Sarna-Wojcicki, Tinsley, and Machette).

*Figure C-5. Aerial view to east of western front of Black Mountains. Notice prominent scarps are along Black Mountains fault zone. Deeply incised channel is Gower Gulch, which is modern outlet of Furnace Creek through its diversion at Zabriskie Point. Photograph by M.N. Machette, Nov. 2000.*

# Road log for Day C

# Central Death Valley

*J.R. Knott*

Furnace Creek 7.5' quadrangle
GPS: NAD 27, UTM Zone 11
$^{40}33^{510}$mN $^{5}13^{260}$mE
Elevation: 1 m (3 ft) ASL

Road log from State Highway 190 south to Stop C1 (miles in parenthesis are for reverse trip, from Stop C1 north to State Highway 190).

| Miles | Description |
|---|---|
| 0.0 (32.4) | Intersection with State Highways 190 and 178 (at Furnace Creek Inn). |
| 0.1 (32.3) | Canyon walls to left (east) are composed of Pliocene Furnace Creek Formation with capping Qg2 gravels; across Death Valley the dark elongate volcanic hill is called the Sleeping Dinosaur (or Dinosaur Hill). |
| 0.5 (31.9) | To left, Breakfast Canyon fault scarps of the Black Mountains fault zone. |
| 1.1 (31.3) | Straight ahead, north side of Village Canyon alluvial fan. Notice the stone circles built by early Shoshone tribes that are just along the fault scarp above the road. |
| 2.5 (29.9) | Golden Canyon. Conglomerate on south wall is the base of the Furnace Creek Formation. To the south, the Black Mountains are composed of volcanic and sedimentary rocks of the Miocene Artists Drive Formation. |
| 2.6 (29.8) | Gower Gulch. Incised alluvial fan whose captured drainage is at Zabriskie Point (Stop B4; fig. C1-5). |
| 2.8 (29.6) | Miocene Artists Drive Formation rocks form the Black Mountains escarpment on left; straight ahead (south), the bedrock salient is the Artists Drive block. The horizontal surfaces on the west side of the Artists Drive block are called the Manly Terraces, the product of a marine oxygen isotope stage VI(?) (OIS 6?) lake. |
| 3.6 (28.8) | Desolation Canyon Road; black rocks at the base of the wineglass canyon cut into the Black Mountains are Ordovician Ely Springs Dolomite. |
| 4.3 (28.1) | Mushroom Rock on left (famous photo stop for tourists). |
| 4.6 (27.8) | To the left (east) up the small drainage, the bright white rock is Ordovician Eureka Quartzite. |
| 4.7 (27.7) | Exit for Artists Drive road. |
| 5.1 (27.3) | Abrasion platforms from OIS 6 lake can be seen at the base of the Artists Drive block to the left (east). |
| 5.9 (26.5) | West Side Road. This road traverses the salt pan that occupies the floor of Death valley; road leads to the west side of the valley and the enormous alluvial fans (Hanaupah, Trail, Death Valley, etc.) that emanate from the Panamint Mountains. |
| 6.5 (25.9) | Hunt Canyon (Stop C3) is to the left (east) on the Artists Drive block (fig. C1-4) |
| 7.9 (24.5) | Hillocks (large mounds) to the right are composed of Pliocene- to lower Pleistocene Funeral Formation sedimentary rocks. The origin of the mounds is unknown. |
| 8.5 (23.9) | Artists Drive entrance road. |
| 9.6 (22.8) | Trail Canyon fan, on the opposite side of Death Valley, emanates from the Panamint Mountains |
| 10.8 (21.6) | Road to Devil's Golf Course (bring lots of balls). |
| 11.7 (20.7) | To the left (east), a shoreline of OIS 6 lake is at the break in slope on the Artists Drive block. |
| 13.4 (19.0) | Natural Bridge Canyon, which marks the northern end of the Badwater turtleback, is up the road to the left (east). The turtleback is marked by the broad sloping bedrock-cored surface that forms the mountain escarpment here. The light-colored rocks covering the northern end of the turtleback are Quaternary in age and contain the 0.758 Ma Bishop ash bed. |
| 14.1 (18.3) | The canyon going up the turtleback is called Straight Canyon. At the mouth of Straight Canyon, near the valley floor, are flat-lying carbonate-cemented conglomerates from the OIS 6 lake. |
| 15.6 (16.8) | To the left, you will get a close view of the OIS 6 lake gravels. |
| 16.1 (16.3) | Good view of the fault scarps on bedrock above Badwater. |

16.3 (16.1) Badwater, at -86 m (-282 ft) is the lowest point in the Western Hemisphere.

17.1 (15.3) Bad Canyon and Bad Canyon fan to the left. Liquefaction-induced lateral spreads are present along the road, here on the north side of the Bad Canyon fan (Chapter O in this volume).

20.0 (12.4) Rock-avalanche complex offset by Black Mountains fault zone (Stop C2; fig. C1-3).

20.1 (12.3) To the left (east) is Goblet Canyon, an excellent example of a wineglass canyon.

22.1 (10.3) Coffin Canyon alluvial fan is straight ahead (south).

27.1 (5.3) Copper Canyon alluvial fan is straight ahead (south); volcanic rocks in the lower part of the Copper Canyon Formation form the Black Mountains here.

27.7 (4.7) Copper Canyon turtleback with OIS 6 lake gravels form the mountain front to the left (east).

29.5 (2.9) Sheep Canyon alluvial fan to the left (east) with Hooke's (1972) Gold Valley strandline on the south side. For scale, the two large white boulders in the channel near the fan's apex are 4 m (13 ft) in diameter.

30.4 (1.7) Good view of the Mormon Point area straight ahead. The large canyon emanating from the left (east) is Willow Wash.

30.7 (1.7) Prominent fault scarps at the mouth of Willow Wash (see Klinger and Piety, Chapter L in this volume).

31.6 (0.8) Mormon Point Canyon to the left (southeast); notice the fault scarps at the mouth of the canyon (fig. C1-2).

32.0 (0.4) Crossing Black Mountains fault zone, which shows as en-echelon cracks in the roadway (tectonic or settlement?).

32.4 (0.0) Stop C1.

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# Stop C1 Late Quaternary tectonic-geomorphic development and pluvial lakes at Mormon Point

*Jeffrey R. Knott, Andrei M. Sarna-Wojcicki, John C. Tinsley, III, and Stephen G. Wells*

Mormon Point and Gold Valley 7.5' quadrangles
GPS: 27 NAD, UTM Zone 11S
UTM $^{39}89^{770}$ mN, $^{5}21^{200}$ mE
Elevation -71 m (-232 ft) MSL

## INTRODUCTION

At Mormon Point, park along the main road west of Mormon Point, near the sign "Mormon Point—Sea Level" (seen by northbound traffic). On the Mormon Point 7.5' quadrangle, this is where a provisional elevation of -232 ft msl (mean sea level) is shown with an "x" symbol on the road. The hike for C1 is a long loop to the east, and this is where we will rejoin the road. We will be gone several hours, so a snack and plenty of water are required.

Here at Mormon Point (Stop C1), we will spend the majority of our day, pausing at 10 places (Stops C1.1-1.10) that present special perspectives or features for discussion. We will examine sediments of the early to middle Pleistocene Mormon Point formation, which overlies the Mormon Point turtleback fault, and contains pluvial lake and alluvial-fan facies.

For most of its 80-km length, the Black Mountains fault zone (BMFZ) separates latest Pleistocene to Holocene (?) alluvial fans and Tertiary and older bedrock (Noble and Wright, 1954), except at Mormon Point in south-central Death Valley (fig. C-1). Here, geologic mapping has consistently shown that:

1. The BMFZ separates latest Pleistocene-Holocene alluvial fans and uplifted Quaternary sedimentary rocks (Noble and Wright, 1954; Drewes, 1963; Hunt and Mabey, 1966; Burchfiel and others, 1995).

2. The base of these uplifted Quaternary sedimentary rocks is a fault contact with the low-angle (<30°) normal Mormon Point turtleback fault (Troxel, 1986; Burchfiel and others, 1995). Although examples of Tertiary low-angle normal faulting and normal faults that have been active at low angles are found in western North America (Wernicke, 1995; Axen and others, 1999), clear evidence of low-angle normal faulting of well dated Quaternary rocks is not documented.

3. The uplifted Quaternary sedimentary rocks are overlain by the most extensive exposures of Late Pleistocene Lake Manly deposits (Hunt and Mabey, 1966) in Death Valley. In addition, shorelines correlative with marine oxygen-isotope stages (OIS) 2 and 5-6 lakes have been reported at Mormon Point (Dorn, 1988; Dorn and others, 1989, 1990).

Thus, Mormon Point is a key location for understanding the Quaternary structural geology, stratigraphy and pluvial lake history of Death Valley and low-angle normal faults in general. As such, it has been the focus of our work over the past several years. The key observations and conclusions that will be presented and discussed at Mormon Point are:

- Uplifted sedimentary rocks at Mormon Point contain the 0.8-1.2 Ma Upper Glass Mountain, 0.758 Ma Bishop, 0.665 Ma Lava Creek B, and ~0.51 Ma Dibekulewe tephra layers. These rocks are within the newly named Mormon Point formation (Knott, 1998; Knott and others, 1999).
- Facies of the Mormon Point formation show that shallow perennial to playa lakes were present at Mormon Point during OIS 20 (~1 Ma) and 16 (before 660,000 years ago) (Knott, 1997; Knott and others, 1999).
- The Mormon Point formation is in fault contact with the low-angle Mormon Point turtleback fault. Lacustrine beds within the Mormon Point formation show that Quaternary slip occurred at a low angle (Knott and others, 1999). Thus Mormon Point is one of the few places that Quaternary low-angle faulting has been documented.
- The OIS 6 lake cut an extensive abrasion platform and formed a strandline at about +92 m elevation at Mormon Point. Risers cut into the abrasion platform at lower elevations are considered to be fault scarps rather than shorelines (Knott and others, in press), including the OIS 2 strandlines reported by Dorn (1988) and Dorn and others (1989, 1990).
- Uplifted alluvial-fan sediments at the mouth of Mormon Point Canyon are equivalent to the Qg2 gravel of Hunt and Mabey (1966). The amount of post-OIS 6 incision provides a minimum slip rate of 0.16-0.25 mm/yr for the BMFZ (Knott, 1998).
- Using the fault relations at Mormon Point, the rate of along strike growth of the north-south-trending western section of the BMFZ is about 1.6 mm/yr (Knott, 1998). Fault growth has been postulated as a mechanism affecting mountain front morphology, but had not been previously quantified in the western U.S. (Leeder and Jackson, 1993).

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# Stop C1.1

UTM $^{39}89^{200}$ mN $^{5}21^{600}$ mE; Elevation -25 m (-83 ft) MSL

From the parking spot for C1, walk south along the road to the larger alluvial fan and canyon where the road bows out around the fan. The escarpment to the east is composed of conglomerates, mudstones and a prominent carbonate bed, all within the lower mudstone member of the Mormon Point formation. The 0.51 Ma Dibekulewe ash bed is found below the carbonate bed and just above the light-colored mudstones. The alluvial fan at the base of the escarpment is offset about 8 m by the BMFZ, which trends north-south here. We will head up Cairn Canyon, which Knott (1998) informally named for a large cairn farther up the canyon.

Walking up the fan, Cairn Canyon leads to a dry fall composed of orange to light brown highly metamorphosed rocks of the Precambrian Noonday Formation. Above the Noonday are moderately cemented conglomerates of the Mormon Point formation. The sharp contact between these two formations is the Mormon Point turtleback fault, which is marked by a 20-cm-thick gouge zone that dips about 20° W.

This is one of three turtleback faults along the Black Mountains front, the other two being at Copper Canyon and Badwater (see fig. C1-1). The turtlebacks were named by Curry (1938) for their resemblance to the carapace of a turtle. They are complex antiformal structures exhibiting an older ductile fabric overprinted by a later brittle fabric, they are considered to be part of the “active” BMFZ (Wright and others, 1991). The origin of these and other low-angle normal faults has been the subject of numerous studies (e.g., Wernicke, 1995). Because focal mechanisms showing low-angle slip are rare, some models have proposed that the turtleback faults began as high-angle faults (~65°), tilted to a lower dip (~30°) at which point they become inactive and are cut off by a new basinward, high-angle fault (e.g., Miller, 1991; Wernicke, 1995). Many of these models were either proposed or tested on the Death Valley turtlebacks, thus the age of rocks offset by the turtleback faults is critical in these models.

The purpose of this stop is to become familiar with the structural relations at Mormon Point. This stop is similar to one about ¼ mile to the south that was visited on the 1986 FOP trip (Troxel, 1986). From the outcrop at Stop C1.1, three important observations can be made:

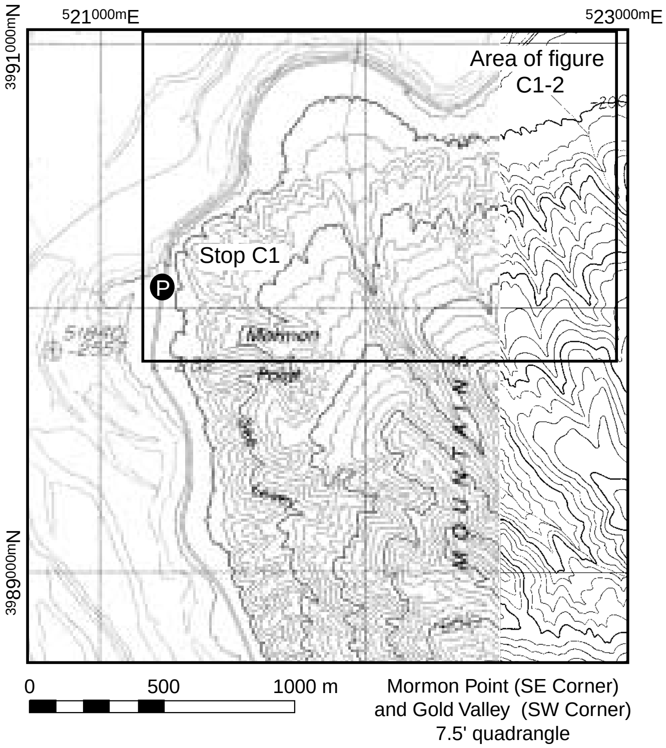


*Figure C1-1. Topographic map of Mormon Point area showing stop C1. Location "P" indicates parking place. Area of figure C1-2 is shown by rectangle.*

1. The overlying headwall conglomerates are in fault contact with underlying Precambrian rock.
2. The turtleback fault is not offset by any of the higher angle faults that are in the headwall-block conglomerates.
3. The dip of the turtleback fault is such that the basin sediments buttress the headwall conglomerates. Down-dip movement of the headwall conglomerates could not be solely related to gravational forces or landsliding, and therefore, the driving forces for this structure must be tectonic (Wernicke, 1981).

The next stop (C1.2) is up Cairn Canyon. Rather than attempt scaling the dry fall, you should scramble up the canyon wall to the north. The small channels offer the best footing. Where the canyon widens and forks, go up the north (left) fork about 20-30 m. Along the way, the channel above the dry fall has incised into Precambrian bedrock, exposing the turtleback fault in the walls above. At several locations along the way, there are folds (ductile fabric) in the Precambrian rock.

## Stop C1.2

UTM $^{39}89^{210}$ mN $^{5}21^{770}$ mE; Elevation +26 m (+85 ft) MSL

As we walk the 20-30 m along the north fork of Cairn Canyon, the channel crossed the turtleback fault and went back into headwall sediments. Here, the sediments are interbedded conglomerates, sandstones and rare carbonates and shales. Just left (north) of the channel thalweg at 20-30 m is a white, biotite-phenocryst tephra bed. The tephra's glass-shard composition and normal polarity indicates that this is the 0.758 Ma Bishop ash, which erupted from the Long Valley volcanic field about 200 km to the northwest. The Bishop ash bed is exposed here in the south canyon wall and for about 30 m to the south, where it dies out against the turtleback fault. Exposure at the contact between the Bishop and turtleback fault is poor.

The important points at this stop are:

1. Identification of the Bishop ash indicates that these sediments are middle Pleistocene in age.
2. Subsequently, the age of faulting on the Mormon Point turtleback fault is post-middle Pleistocene (<0.665 ma) and clearly Quaternary.
3. The facies above and below the Bishop ash bed are mostly conglomerates, which we interpret as having been deposited in a proximal alluvial-fan environment. However, there are green and light-brown colored fine sands and silts, which are indicative of perennial lake and playa sedimentation, respectively.
4. Looking back down the canyon from here (to the west), and at the walls all along during the hike up and in the canyon fork to the south, the turtleback fault shows no evidence of being offset by other faults. The importance of this observation will become obvious later.

To get to the next stop (C1.3), continue up the north fork. This channel narrows, with conglomerates on both sides, then turns to the east and widens slightly. The stop is near the top of the broad areas of the canyon. Along the way, the section is best exposed on the south wall and does not appear to be significantly faulted. Once the canyon turns east, notice that the facies become much finer grained and finer bedded, and the sediments have mostly green to brown hues.

# Stop C1.3

UTM $^{39}89^{400}$ mN $^{5}22^{060}$ mE; Elevation +96 m (+320 ft) MSL

Near the top of the fine-grained section, look at the south wall for a gray bed of silt to fine-sand size material, which is the Lava Creek B ash bed. Lava Creek B erupted ~665,000 years ago from Yellowstone caldera, which is located about 1,100 km to the northeast of Death Valley. Together, the Lava Creek B and Bishop ash beds form a distinct couplet in middle Pleistocene deposits throughout the western U.S. (see Chapter E in this volume). The Lava Creek B ash bed is identified here at Mormon Point by its stratigraphic position above the Bishop ash bed, its chemical composition of glass shards, and its normal polarity.

Key aspects of this stop are:

1. Identification of the Lava Creek B ash bed makes the correlation of the underlying Bishop ash bed below more reliable. Both the Lava Creek B and the Bishop are easily distinguished in outcrop by color and grain size, and therefore, make excellent marker beds in the Mormon Point area (fig. C1-2) and throughout Death Valley.

2. The fine-grained facies are interpreted as a playa to playa-lake depositional environment. In this particular outcrop, carbonate beds are not as common as in others; however, the presence of carbonates in these sections is interpreted as indicating that the water quickly became saline. This is interpreted to indicate that the water body was of limited surface area. Such rapid changes from clastic to carbonate lithologies are more representative of a shallow playa lake as opposed to a deep fresh-water lake as proposed by Dorn (1988). These fine-grained sediments are called the middle mudstone member of the Mormon Point formation (fig. C1-3).

3. The presence of Lava Creek B ash (0.665 Ma) allows correlation of these playa-lake sediments to OIS 16. The absence of fine-grained sediments just above Lava Creek B suggests that the playa lakes dried up permanently soon after 0.665 Ma, which is similar to observations at Searles Lake to the west (Smith, 1984) and Lakes Lahontan and Bonneville to the north and northeast, respectively (Morrison, 1991). However, this observation is inconsistent with the record from Lake Tecopa, just to the east, which shows a rising lake surface about 0.665 Ma and desiccation about 0.56 Ma (Morrison, 1991).

To get to the next stop (C1.4), retrace your route to near the base of the fine-grained sediments and look for a rill/channel incised into the north wall. Climb up this channel, out of the canyon and onto the relatively flat ground above. It's a steep, but short climb.

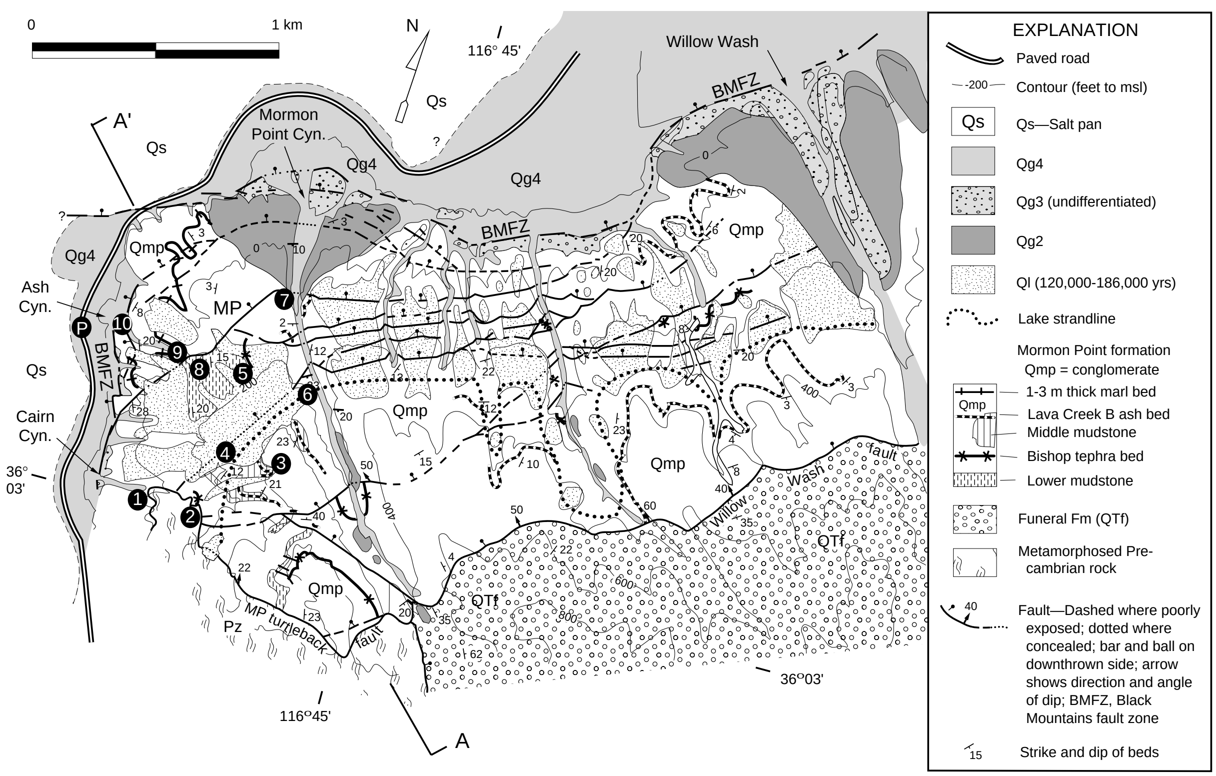


*Figure C1-2. Geologic map of the Mormon Point area showing canyons discussed in text as well as locations of field trip stops (numbered black circles). Location "P" indicates parking place.*

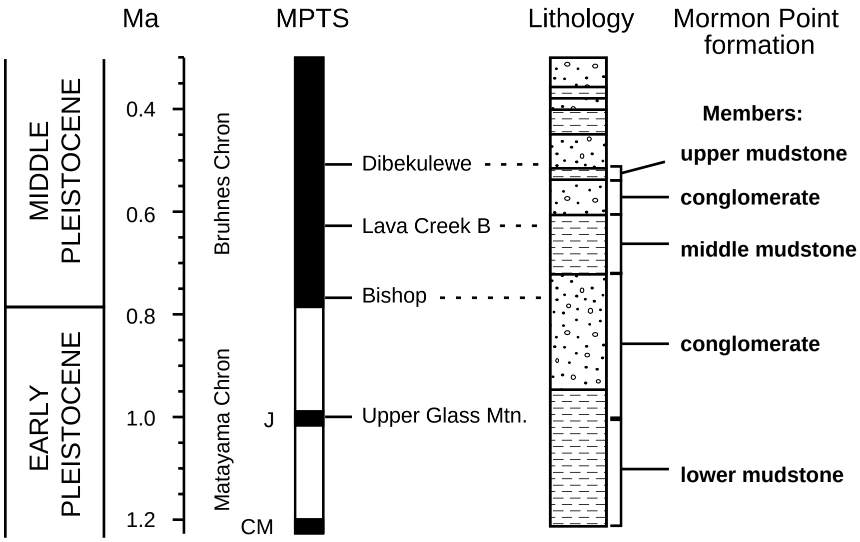


*Figure C1-3. Composite stratigraphic section of the Mormon Point formation at its type area—Mormon Point. Mudstone members are composed of interbedded mudstones and carbonates. Conglomerate members also include sandstone beds. Correlation to Magnetic Polarity Time Scale (MPTS) is based on unpublished paleomagnetic data (Knott, 1998); the Jaramillo (J) and Cobb Mountain (cm) subchrons are based on work of Berggren and others (1995).*

# Stop C1.4

UTM $^{39}89^{609}$ mN $^{5}21^{856}$ mE; Elevation +90 m (+297 ft) MSL

The low-relief surface that we are standing on is an abrasion platform formed by the 0.12-0.18 Ma lake, which is often referred to as "Lake Manly" (see Chapter G in this volume). The 0.12-0.18 Ma age (OIS 6) is based on numerous uranium-disequilibrium analyses on tufa by Ku and others (1998) and their correlation to lake deposits obtained from a core near Badwater (Lowenstein and others, 1999). Hunt and Mabey (1966) noted that the Mormon Point area contains the most extensive lacustrine deposits in Death Valley. The paleo-lake elevation (strandline) is near the change in slope above and to the east of our stop. This abrasion platform will be discussed further at later stops.

The purpose of this stop is to provide an overview of the tectonic complexities within the Mormon Point formation and to introduce the OIS 6 Lake Manly. Looking to the southeast and referring to fig. C1-4 you will see:

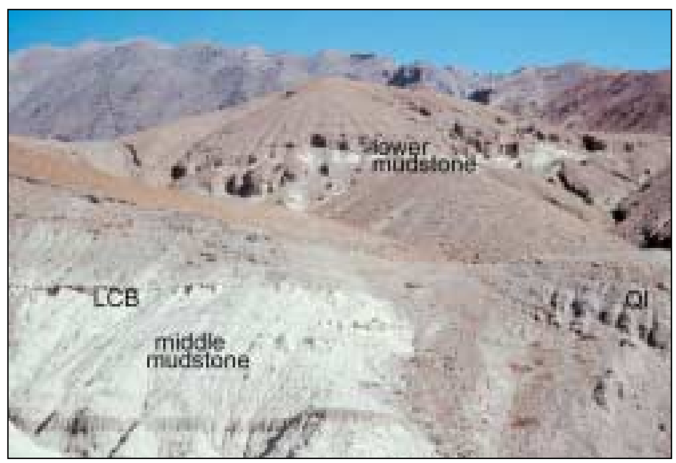


*Figure C1-4. View to southeast from Stop C1.4 showing upper and lower mudstones. See figures C1-2 and C1-3 for explanation of units.*

1. In the north fork of Cairn Canyon (just below us) there are the fine-grained sediments of OIS 16 with the Lava Creek B ash bed near the top.
2. On the ridge to the right of the fine-grained sediments are well-sorted, coarse, rounded gravels of OIS 6. These gravels are cross-bedded with both foreset and backsets beds; they are 20 m in thickness at some exposures in this area and overlie the Mormon Point formation in a slight (0°-20°) angular unconformity.
3. On the next ridge, which is the north-facing canyon wall of the south fork of Cairn Canyon are more light-colored, fine-grained sediments (elevation +160 m). These sediments comprise the lower mudstone of the Mormon Point formation, which contain several reverse-polarity beds of the 0.8-1.2 Ma Upper Glass Mountain ashes (OIS 20).
4. Above the light-colored sediments, interbedded with the brown conglomerates near the top of the ridge (not visible from this point), is the Bishop ash bed (+200 m elevation). Our interpretation is that the Bishop ash bed is repeated by faulting (fig. C1-5) along a high-angle (>65°) fault that trends nearly down the center of Cairn Canyon and is exposed in the canyon walls (fig. C1-2). The throw on the high-angle fault is about 200 m as measured in cross section

A-A'; however, the Mormon Point turtleback fault and the footwall Precambrian rocks are not offset by this high-angle fault.

5. Because the high-angle fault does not offset the turtleback fault, the turtleback fault is interpreted to be the principal structure at Mormon Point. Heave along the turtleback fault is estimated to be about 438 m. This interpretation is consistent with interpretations of structural (Burchfiel and others, 1995) and geophysical data (Keener and others, 1991).

6. Using the 0.758-Ma Bishop ash bed as a piercing plane, the vertical displacement of about 200 m yields a vertical slip rate of 0.26 mm/yr on the high-angle fault. If slip on the fault were assumed to be solely vertical, this would also be the slip rate for this fault. However, the 438 m heave yields a dip-slip of 0.58 mm/yr for the turtleback fault. Both of these values are minimum rates because this particular part of the turtleback fault may no longer be active.

7. Looking to the south, the OIS 6 gravels nonconformably overlie the turtleback fault but are not tilted (fig. C1-2), indicating this part of the turtleback fault has been inactive over the past 0.12-0.18 m.y.

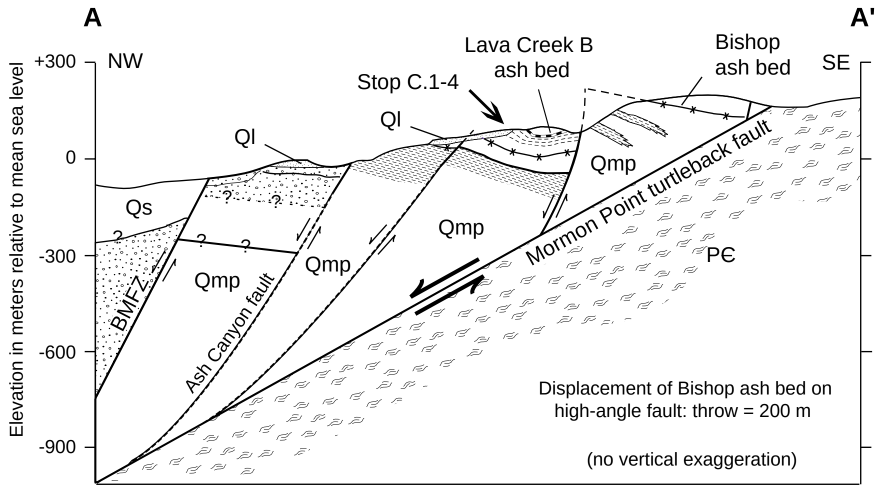


*Figure C1-5. Structural cross section A-A' showing relationship between Mormon Point turtleback fault and higher angle normal faults. See figure C1-2 for explanation of units and location of cross section.*

With the exception of those beds nearest the faults, beds in the Mormon Point formation dip gently (0°-20°). This lack of general tilting indicates that the Mormon Point turtleback fault was active at its present low angle dip (i.e., it has not been subsequently tilted). The lack of tilting of these beds is inconsistent with models that propose that low-angle normal faults initiate at high angles, tilt and then become inactive at a low angle (Knott and others, 1999).

The question then is "how did the Death Valley turtlebacks form?" Holm and others (1994) proposed that the turtlebacks are Miocene folds related to crustal extension. Knott and others (1999) proposed that the mechanism was related to thermal warping of the brittle-ductile transition during intrusion of the 11 Ma Willow Spring gabbro, followed by exhumation through continued extension.

The next stop (C1.5) is about 400 m north at the head of the north side of Ash Canyon. The abrasion platform makes for easy walking. Along the way, boulders from the Willow Spring gabbro are found as debris on the abrasion platform.

# Stop C1.5

UTM $^{39}90^{006}$ mN $^{5}21^{797}$ mE; Elevation +40 m (+131 ft) MSL

This is an overview stop (for now), looking west down into the badlands topography of Ash Canyon. We can see several key features from this location, which allow some interpretation:

1. In the north wall near the head of Ash Canyon are light brown, poorly cemented sands having a total thickness of 3 m. These sands are composed primarily of glass shards that correlate well with the 0.78 Ma Bishop ash (fig. C1-6). There is another exposure of the Bishop ash bed interbedded with conglomerates near the top of the section exposed in Ash Canyon.

2. The repetition of the Bishop ash bed indicates that a fault offsetting the Mormon Point formation must be buried beneath the abrasion platform between Ash Canyon and Cairn Canyon.

3. Most of Ash Canyon is composed of the Mormon Point lower mudstone. The 0.8-1.2 Ma Upper Glass Mountain ash beds are also found in this section, as they are in Cairn Canyon to the south. In contrast to the Cairn Canyon section, the lower mudstone in Ash Canyon is thicker and contains more green hued, fine-grained sediments. These facies are interpreted to indicate significant periods of perennial

water, but ripple marks and carbonate beds suggest that the water was still relatively shallow and the lake small enough to rapidly become saline. This shallow saline lake contrasts greatly with the deep, overflowing lake in Searles Valley at the same time and implies lower effective precipitation in Death Valley during OIS 20.

4. Stop C1.5 also offers a view of the Ash Canyon fault, which separates fine- and coarse-grained sediments on the north canyon wall (fig. C1-7). At this location, the Ash Canyon fault has a trend of N. 30° E. and dips 50° NW. (fig. C1-2). The Ash Canyon fault changes trend 90° over about a 2.5-km distance, and the dip is 15° steeper to the southwest and east than at C1.5. Essentially, the trend of the Ash Canyon fault mimics the Mormon Point turtleback (fig. C1-2), implying a structural relationship (i.e., the Ash Canyon fault soles into the turtleback fault).

*Figure C1-6. Photograph showing Bishop ash bed in headwaters of Ash Canyon.View from Stop C1.5. Photograph by J.R. Knott.*

The path down Ash Canyon is described later. The next stop (C1.6) is to the southeast at the edge of Mormon Point Canyon where we will get a more detailed look at the lower mudstone member of the Mormon Point formation.

*Figure C1-7. View looking west from Stop C1.5 down into Ash Canyon. Linear feature on canyon wall (right side of photograph) is Ash Canyon fault, which separates ~1.0 Ma lower mudstone (below) from ~0.5 Ma conglomerates (above). Photograph by J.R. Knott.*

# Stop C1.6

UTM $^{39}89^{853}$ mN $^{5}22^{079}$ mE; Elevation +87 m (+287 ft) MSL

The walls of Mormon Point Canyon offer a cross section through the OIS 6 gravels, the underlying Mormon Point formation and the OIS 6 abrasion platform. The GPS coordinates (above) are for what is probably the best observation point for the highest prominent linear feature visible on the low-sun angle photograph (fig. C1-8).

*Figure C1-8. Low-sun-angle vertical aerial photograph of Mormon Point area. North is approximately toward top of the photograph. Canyon in shadow from lower right to about center of photograph is Mormon Point Canyon. Photograph from University of Nevada-Reno collection (01-07-1969, DVF-20-7).*

Since Noble (1926) first noticed them 75 years ago, the numerous linear features visible on the low-sun angle photograph (fig. C1-8) have been interpreted as lake strandlines left by a receding Lake Manly. Both rock varnish (Dorn, 1988; Dorn and others, 1989, 1990) and cosmogenic isotopes (Trull and others, 1995) have been used to date these inferred "shoreline features." These features have published ages ranging from 0.13 Ma (OIS 5-6) for the upper shoreline at ~92 m elevation to 12 ka (OIS 2) for the shoreline near sea level (Dorn and others, 1990). Because a lake's surface elevation is often taken as proxy for effective precipitation, the presence of dated OIS 5-6 and OIS 2 strandlines well above the valley floor implies that the effective precipitation of these two pluvial climatic periods were fairly similar in the Death Valley region. However, we believe that the outcrop data shows that these risers are not lacustrine features, but are fault scarps, which invalidates any climatic inferences about an OIS 2 Lake Manly.

The following observations can be made from this position using the illustrations:

1. At about the same elevation just south on the west wall of Mormon Point Canyon are about 3 m of light-colored, fine-grained sediments containing the 0.665-Ma Lava Creek B ash bed. This is the same ash bed found at the top of a much thicker section of fine-grained sediments in Cairn Canyon. The rapid thinning of fine-grained sediments implies that the playa lake existed for a longer time period to the west of here, and while not quite at the shoreline, this location is very near the 0.665-Ma lake shore. Only alluvial-fan conglomerates are found on the east wall of Mormon Point Canyon.

2. To the southeast are prominent, north-facing facets that are cut into concordant ridges of the Mormon Point formation. Hooke (1972) described these as wave-cut facets. Although mantled in places with colluvium, exposures of sedimentary rocks in the walls of Mormon Point Canyon beneath these facets dip gently to the south and are uninterrupted by faults.

3. Figure C1-8 shows the east wall directly across Mormon Point Canyon. The sedimentary rocks that form the lower two-thirds of the vertical canyon wall are Mormon Point formation. Above the Mormon Point formation are OIS 6 gravels, which are less resistant and have a mantle of colluvium. The basal contact of the OIS 6 gravel dips gently to the north and is distinguished by a change in its slope character. Also prominent is a steep, north-dipping fault. Using the change in slope as a piercing line, the fault in the canyon wall appears to offset the base of the OIS 6 gravels and project up to the riser (scarp) on the abrasion platform surface.

Gilbert (1890) noted that it may be difficult to distinguish horizontal fault scarps from lake strandlines; however, strandlines often have clastic deposits associated with them (e.g., spits) and are independent of underlying structure. At Mormon Point, only the base of the wave-cut facets is associated with spits that extend into the north-facing canyons (fig. C1-2) and is independent of underlying structure. The remaining risers are similar to the one shown in figure C1-9 in that none are found above faults or are associated with clastic shoreline deposits (Knott and others, in press). The faults themselves have been mapped in previous studies (Drewes, 1963; Burchfiel and others, 1995); however, the correlation between the faults and the overlying risers is a new observation. Our interpretation that the lower risers are formed by faulting rather than wave action, which is also consistent with observations by Hooke (1972) that the upper bench (at the base of the facets) has the best geomorphic expression.

Stop C1-7 is reached by walking north along the edge of Mormon Point Canyon. Along the way, note that risers in the abrasion platform correspond to faults in the canyon wall. Also, the light-colored beds exposed in the canyon wall, near the channel, contain the Lava Creek B ash. Thus, Lava Creek B ash bed is repeated by high-angle normal faulting.

*Figure C1-9: Photograph of eastern wall of Mormon Point Canyon showing fault in canyon wall and scarp on overlying OIS 6 abrasion platform.*

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## Stop C1.7

UTM $^{39}90^{25}2$ mN $^{5}21^{880}$ mE; Elevation -12 m (+144 ft) MSL

At this stop nearly horizontal conglomerates are seen on the opposite wall, rather than south-dipping Mormon Point formation (fig. C1-2). Also, the Lava Creek B ash bed is on the opposite canyon wall in a small reentrant canyon. The important points at this stop are:

1. To the north, toward the mouth of Mormon Point Canyon, the sediments are part of an uplifted alluvial fan whose surface gradient is visibly lower than that of the abrasion platform. The triangular shape of this fan is visible on the low-sun angle photograph (fig. C1-8).

2. The age of the alluvial fan at the mouth of Mormon Point Canyon must postdate the 0.12-0.18 Ma abrasion platform based on its geomorphic position (i.e., closer to the active channel than the abrasion platform). This <0.12-0.18 Ma alluvial fan is correlated with the Qg2 unit of Hunt and Mabey (1966) on the basis of its the well-developed desert pavement and varnished clasts.

The differentiation of sediments of unit Qg2 and the Mormon Point formation may seem unremarkable; however, it resolves one of the significant (and few) unanswered questions of Hunt and Mabey (1966). They noted that lake gravel overlies the Qg2 (No. 2 gravel) at both Mormon Point and the North Side Borax Camp (Hunt and Mabey, 1966, p. A71). This left them to ponder, why lake deposits were not apparent on the extensive Qg2 deposits found along the Panamint and Black Mountain piedmonts. This was particularly troubling in light of the fact that Mormon

Point is the most extensive deposit of OIS 6 gravels in Death Valley.

From the relationships found at this stop, it is apparent that older sediments (Mormon Point formation) underlie the OIS 6 lake deposits, not Qg2 gravels, and that the Qg2 gravels are inset below and thus younger than the lake deposits. This is the same relationship—Qg2 younger than the lake deposits—that is found at virtually every other location in Death Valley. However, one should note that there is a large range to the Q2g gravels as mapped by Hunt and Mabey (1996), as discussed elsewhere in this volume.

3. The apex of the alluvial fan is bounded by the Ash Canyon fault, which has an orientation of N. 90° W., 85° N. and here separates middle Pleistocene sediments of the Mormon Point formation from <0.12-0.18 Ma Qg2 alluvial-fan deposits (fig. C1-2).

4. Directly across, at the apex of the Qg2 deposits and along the Ash Canyon fault is the near sea level ~12,000-year-old shoreline of Dorn and others (1990). Based on its coincidence with the Ash Canyon fault and the apex of the Qg2 alluvial fan, Knott and others (in press) have reinterpreted this purported shoreline as a fault scarp.

5. Most significantly, the lacustrine deposits overlying the Mormon Point formation all appear to be related to an OIS 6 Lake Manly. There is no stratigraphic evidence of OIS 2 lakes on the footwall at Mormon Point. This would indicate that the climate during OIS 2 was significantly drier or had a lower effective precipitation than during OIS 6. The interpretation of a markedly smaller OIS 2 lake is also consistent with data from cores in the salt pan, which shows that the lacustrine deposition was occurring below -84 m elevation about 17,000 years ago (Hooke, 1972; Anderson and Wells, 1997).

6. The gradient of the Qg2 alluvial fan implies that local base level was at this location after recession of the OIS 6 lake and the position of the fan apex suggests that the Ash Canyon fault was active after OIS 6, most likely at the mountain front. If these assumptions are correct, then the ~30 m of incision of the active channel has occurred over the past 0.12-0.18 m.y. These data yield a minimum slip rate of 0.16-0.25 mm/yr for this strand of the BMFZ.

The assumption that the abandoned Qg2 fan and Ash Canyon fault were formerly at the mountain front illustrates the process of basinward-propagation of normal faults in the Black Mountains fault zone that has been ongoing since the Pliocene at Mormon Point. During the Pliocene(?), the mountain front was located 1.5 km south of its present position, with the Mormon Point turtleback fault as the basin-bounding structure (fig. C1-2). In the Pleistocene(?), the Willow Wash and turtleback faults marked the basin edge (fig. C1-2). During the middle to late Pleistocene, the Ash Canyon fault was the basin-bounding structure. Finally, sometime in the late Pleistocene, the present BMFZ stepped 0.5 km northward to its present position (see Chapter L in this volume for a discussion of the present BMFZ).

The mechanism for this basinward stepping is inferred to be along-strike growth of the BMFZ to the west of Mormon Point (Knott, 1998). Leeder and Jackson (1993) applied this same mechanism to mountain fronts in Nevada and Greece; however, they lacked suitable age control to describe the timing of fault evolution. Based on the data at Mormon Point, the BMFZ has grown northward at about 1.6 mm/yr from the Mormon Point turtleback fault, which was the mountain front ~600,000 years ago. The intact nature of the Qg2 fan (i.e., largely unfaulted) shows that these steps are not gradational, but episodic, jumping hundreds of meters at a time. This evolutionary pattern suggests that ground-rupture hazard along normal faults may wider than previously thought.

From here, proceed back to Stop C1.5 at the head of Ash Canyon. Ash Canyon has several relatively steep areas that require some scrambling over rocks and down slopes. A gentler but yet geologically less spectacular route is to return to the cars via the canyon just north of Ash Canyon. Returning via Ash Canyon provides a down section walk through the Mormon Point lower mudstone. The fine bedding and grain size of the green-hued sediment is interpreted as indicating a perennial lake environment.

## Stop C1.8

UTM $^{39}$89$^{780}$ mN $^{5}$21$^{700}$ mE; Elevation -6 m (-20 ft) MSL

This stop is at the point where the canyon narrows, after climbing over (around) boulders that block the channel. From here we will see:

1. In the north canyon wall, several 4- to 5-cm-thick ash beds are interbedded in the green to brown mudstones and sandstones. The composition of glass shards in these ash beds indicates they are part of the Upper Glass Mountain family of tephra beds. The paleomagnetic declination of these ash beds is reversed, indicating a minimum age of 0.78 Ma (age of the top of the Matayama chron).

   At this stop at Mormon Point and Stop A2 in Lake Rogers are the only locations in Death Valley where the Upper Glass Mountain ash beds have been reliably identified (see Chapter E in this volume). Based on the green hue of the mudstones and sandstones and their fine bedding, Knott (1997) interpreted that these sediments are part of a perennial lake that was present at Mormon Point around 0.8-1.2 Ma (or OIS 20).

2. These facies are consistent with those described by Smith (1991) for perennial lake deposits at Searles Lake and other areas of the western U.S. The timing of the perennial lake at Mormon Point overlaps with the 1-1.25 Ma wet climatic period interpreted from the Searles Lake core (Smith, 1984), as well as high stands in pluvial Lakes Lahontan and Bonneville (Morrison, 1991).

The limited number of outcrops here prevents interpretation of the area of the OIS 20 lake, however, ripple marks and sparse carbonates imply that the water depth at Mormon Point was shallow and that the lake rapidly turned saline. Both of these implications suggest an aerially limited lake surface. This is consistent with observations at Lake Tecopa, just east of Death Valley, where no high lake levels, only playa intervals, were described by Morrison (1991). Such limited lakes and playas suggest a slightly drier climate in the Death Valley/Tecopa region compared to other, northerly or glacially influenced areas. Thus, the tephrochronology and facies indicate that the OIS 20 lake at Mormon Point was perennial, but of limited extent. To reach Stop C1.9, continue down Ash Canyon, until the canyon widens and the lithology changes from mudstone/sandstone/conglomerate to conglomerate.

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## Stop C1.9

UTM 3989760 mN 521640 mE; Elev. -18 m (-60 feet) msl

1. Downstream, Ash Canyon is wide and the walls are composed predominantly of conglomerates with the exception of a several-meter thick carbonate bed that is best displayed on the north wall, where it forms a resistant ridge. This same carbonate marker bed is mostly flat lying, found just above the 0.51 Ma Dibekulewe ash bed, and is the uppermost part of the upper mudstone member of the Mormon Point formation.

2. The contact between the upper and middle members of the Mormon Point formation is a ~0.7-m thick gouge zone (N15°E, 83° NW) of the Ash Canyon fault, as seen before. The change in the morphology of Ash Canyon is clearly related to lithology, with less resistant rocks downstream and more resistant rocks upstream.

Continue downstream to the mouth of Ash Canyon. Along the way, note the relatively flat-lying OIS 6 gravels that mantle the tops of the ridges. A normal fault that places Mormon Point formation mudstones against conglomerates can be seen on the south (left) wall near the mouth of the canyon.

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## Stop C1.10

UTM $^{39}89^{820}$ mN $^{5}21^{320}$ mE; Elevation -55 m (-180 ft) MSL

At the mouth of Ash Canyon and the apex of its alluvial fan, look back at the fault on the south wall of the canyon. From this view, one can see that the fault has a clear listric geometry, offsets the overlying OIS 6 lake gravels, and forms a scarp in the ridge above (fig. C1-10). Listric normal faults are rare, but often inferred to be present in Quaternary rocks (Wernicke, 1995; Axen and others, 1999). Thus, the OIS 6 gravels in the south wall of Ash Canyon are an important structural locality. Based on only this one outcrop, the listric fault could be interpreted as the slip surface of a landslide. However, the fault extends in a rather straight trend another 250 m south, subparallel to the BMFZ, and exhibits none of the morphological features of a landslide (curvate head scarp, back rotation of beds, etc.). In addition, if this were a landslide, the toe would be buttressed, and therefore slip is mechanically unlikely.

Return to cars.

*Figure C1-10: View looking south at mouth of Ash Canyon showing listric normal fault offset of Mormon Point formation in southern wall of canyon (lower part) and OIS 6 gravels near ridge line. Photograph by J.R. Knott.*

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## Stop C2

# Late Pleistocene slip rate of the Black Mountains fault zone

*Jeffrey R. Knott and Stephen G. Wells*

Badwater 7.5' quadrangle
GPS: 27 NAD, UTM Zone 11S
UTM $^{40}04^{780}$ mN, $^{5}20^{820}$ mE
Elevation -79 m (-260 ft) MSL

### INTRODUCTION

Stop C2 is intended to be a relatively short stop along the main road, just south of Badwater. The main reason for stopping along the road is that the features to be discussed are most visible from a distance. If time allows, a short hike across to the mountain front can be made to examine the rock-avalanche debris.

Just south of Badwater, a large lobe of rock-avalanche debris has been shed from the Black Mountains onto the piedmont (fig. C2-1). Here the debris is offset about 28 m by the Black Mountains fault zone (BMFZ) as first recognized by Hunt (1975). Jibson (1996) suggested that if one could determine the age of the avalanche debris, a minimum slip rate for the BMFZ could be calculated. Knott (1998) mapped the rock avalanche area (fig. C2-2) and found that there were actually two discrete avalanche deposits (older and younger) rather than one. The older avalanche moved from the northeast to southwest, while the younger avalanche moved from southeast to northwest. The older avalanche deposit has a smoother appearing surface and is overlain by the younger avalanche deposit. Hunt (1975) claimed that horizontally bedded tufa-encrusted lake gravel mantles the ridges to the north and south, but are not present in the avalanche area.

However, Knott (1998) found sparse outcrops of tufa on the older avalanche debris, suggesting that the older avalanche debris is younger than the lake deposits. The steep, unweathered character of the scarp face implies that the scarp has formed after retreat of the lake. Ku and others (1998) have dated the tufa from the lake deposits by U-series, suggesting a preferred age of 120,000-186,000 years (roughly marine oxygen-isotope stage VI [OIS6]), which is correlative with the timing of lacustrine deposition in a nearby core (Lowenstein and others, 1999). If one uses 120,000-186,000 years as a maximum age for the fault scarp and the 28-m scarp height as the offset, the minimum calculated slip rate for the BMFZ is 0.15-0.2 mm/yr.

This slip rate compares favorably with the 0.16-0.25 mm/yr post-OIS 6 slip rate estimated at Mormon Point by Knott (Stop C1.7), but is significantly less than the 3-5 mm/yr Holocene slip rate measured by Klinger and Piety (1994, Chapter L in this volume). These rates are also less than the 3-5 mm/yr slip rate for the Northern Death Valley fault zone (Klinger and Piety, 1994; Chapter A in this volume). Thus, there appears to be a slip deficit between the Northern Death Valley fault zone and the BMFZ, suggesting that slip is either missing along the BMFZ or is being accommodated on other structures in central Death Valley.


*Figure C2-1. Vertical low-sun angle photograph of rock avalanche area. Arrow points to older avalanche debris, which is offset by Black Mountains fault zone. Box shows portion of area mapped on figure C2-2.*

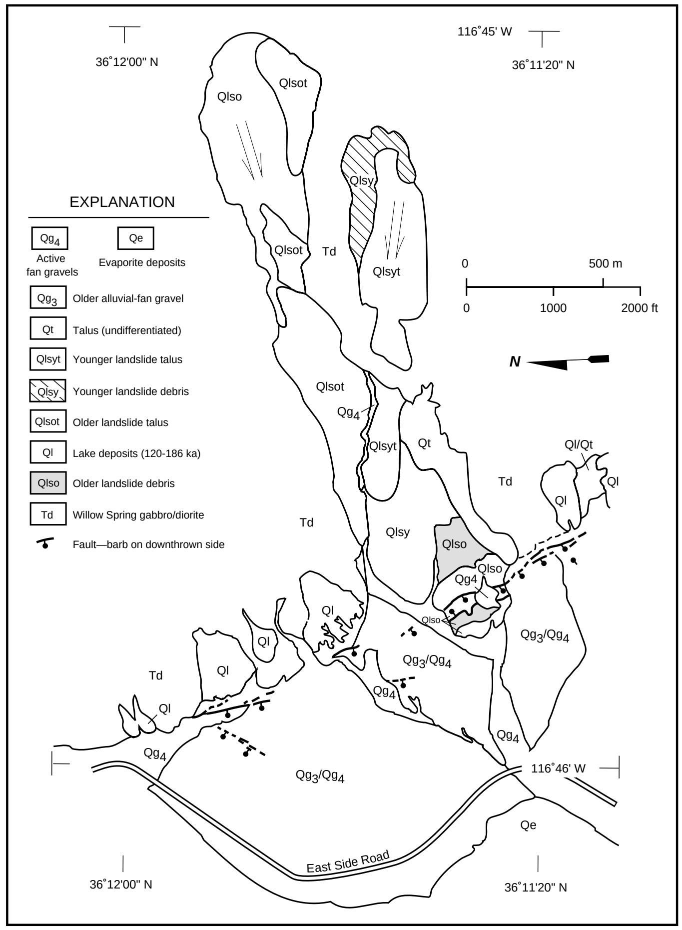


*Figure C2-2. Geologic map of rock avalanche complex south of Badwater.*

# Stop C3

# Late Pliocene tephrostratigraphy and geomorphic development of the Artists Drive structural block

*Jeffrey R. Knott and Andrei M. Sarna-Wojcicki*

Devils Golf Course 7.5' quadrangle
GPS: 27 NAD, UTM Zone 11S
UTM $^{40}23^{650}$ mN $^{5}14^{200}$ mE
Elevation -30m (-100 ft) MSL

## INTRODUCTION

This stop will consist of a short hike east across the alluvial fan to the west side of the Artists Drive block to see various tephra beds within the Furnace Creek Formation. We will park along the main road about 2 mi north of the Artists Drive Entrance Road (fig. C3-1). Along the way, notice that the alluvial fan here is over 3 km in radius, much broader than the small alluvial fans to the south. In addition, to the north and south along the Artists Drive block are remnant abrasion platforms, presumably from the marine oxygen-isotope stage VI (OIS 6) lake.

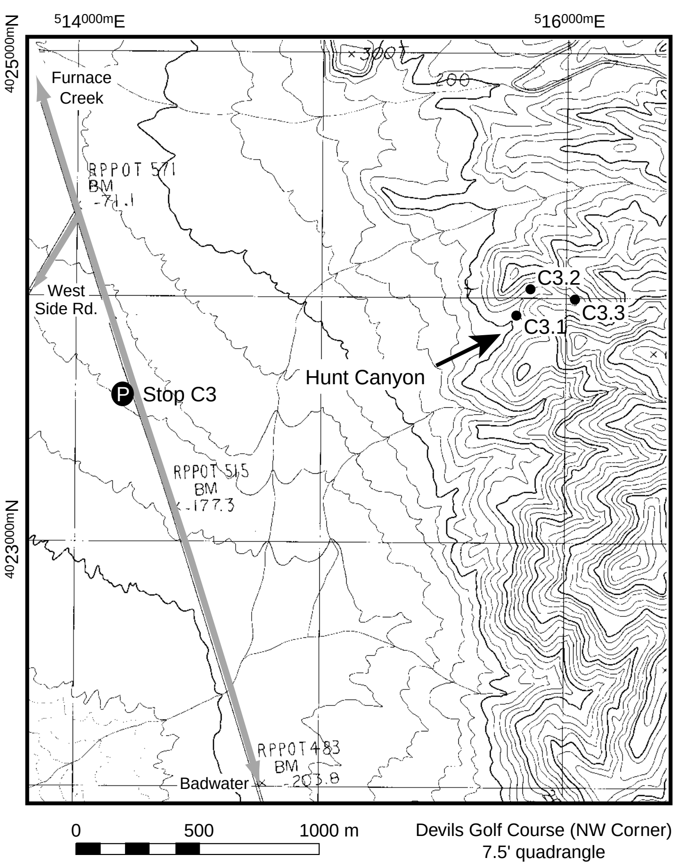


*Figure C3-1. Portion of topographic map showing location of Hunt Canyon.*

The 80-km long western piedmont of the Black Mountains is often characterized as a linear, steep west-side-down mountain front bounded by the Black Mountains fault zone (BMFZ). This is true except for Artists Drive where a 20-km long portion of the piedmont consists of bedrock salients surrounded by alluvial-fan deposits (fig. C3-2). Hunt and Mabey (1966) named this area the Artists Drive structural block and speculated that its origin was possibly related to the subsurface NNW projection of the Badwater turtleback. Brogan and others' (1991) map of the Death Valley fault zone shows that the east side of the central Artists Drive block is bordered by an east-side-down normal fault, thus forming a graben structure with the west-side-down main fault trace at the mountain front.

Early geologic mapping showed that the Artists Drive salients are composed of volcanic and sedimentary rocks of the Miocene Artists Drive Formation, which are unconformably overlain by alluvial fan conglomerates, breccias, intercalated basalts and tephra beds of the Pliocene to early Pleistocene(?) Funeral Formation (Noble and Wright, 1954; Hunt and Mabey, 1966). We hypothesized that if the age of the Funeral Formation alluvial-fan deposits at the Artists Drive could be determined, then we could resolve when the Artists Drive area became a depocenter relative to the Black Mountains upland and when the Artists Drive graben formed. These two events represent significant changes in the mountain front morphology and consequently, the behavior of the BMFZ as well.

At this stop we will see the alluvial-fan facies in the lower part of the Funeral Formation that is exposed in "Hunt Canyon" (informal name). We present tephrochronologic and paleomagnetic data that identify four separate tephra beds that range from >3.58 to <3.1 Ma age at this location. From oldest to youngest, these tephra beds are the lower Nomlaki tuff, lower Mesquite Spring tuff, Nomlaki Tuff, and upper Mesquite Spring tuff. We discuss the importance of differentiating these Pliocene tuffs from middle Pleistocene tephra beds of similar composition, and the tuffs significance to tephrochronologic studies and as marker beds in the western U.S. The correlation of these tuffs and others (Knott and others, 1999; Chapter E in this volume) in the alluvial-fan complex at Artists Drive allows us to interpret the behavior of the BMFZ and relate these changes in the BMFZ to the tectonic history in other faults in the Death Valley area

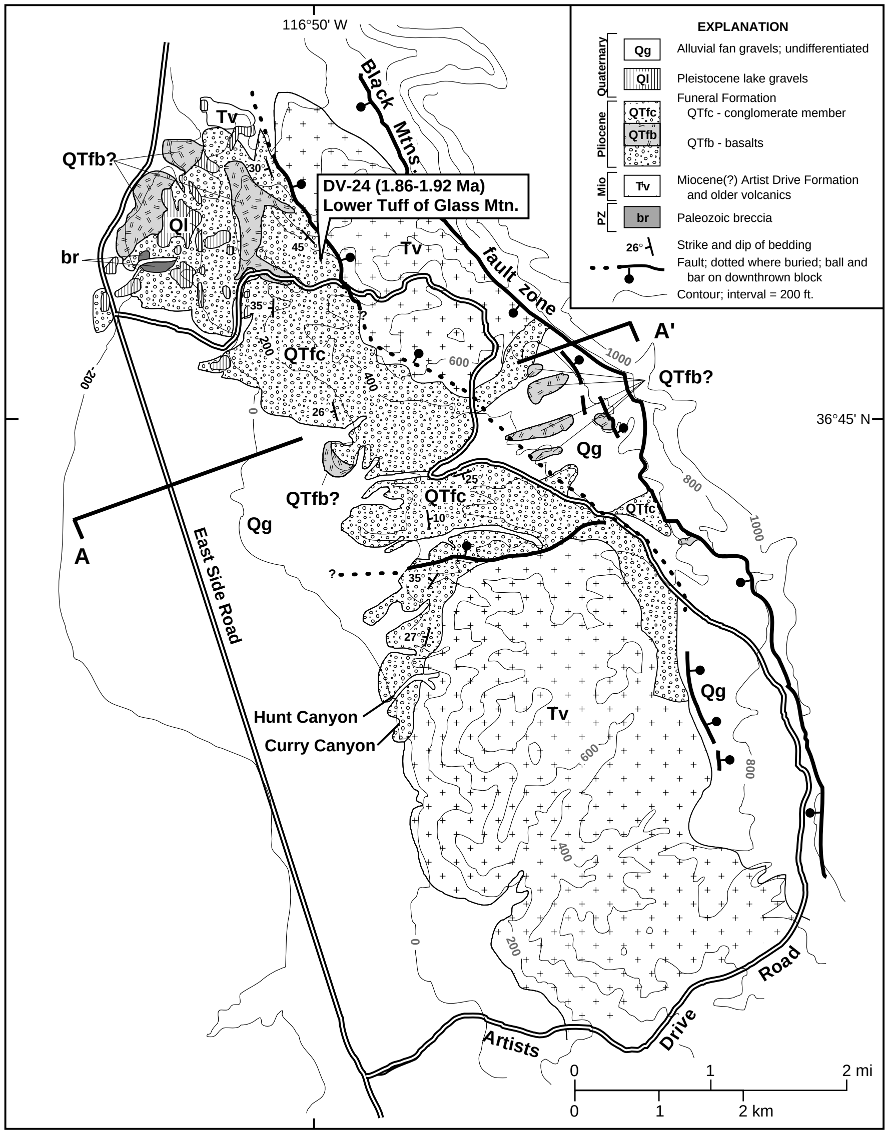


*Figure C3-2. Geologic map of the central Artists Drive area showing location of Hunt and Curry Canyons where sections on figure C3-3 were measured and location of cross section A-A on figure C-5 (modified from Knott and others, 1999).*

## Stop C3-1

$^{40}23^{950}$ mN $^{5}15^{800}$ mE +73 m (+240 ft) MSL

This stop in Hunt Canyon is at an exposure of a 60-cm-thick tephra bed on the north canyon wall, about 3 m above the active channel. Hunt Canyon is near the southern extent of the Funeral Formation at Artists Drive. Here, tephra beds are interbedded with conglomerates that uncomformably overlie volcanic rocks of the Artists Drive Formation. Hunt Canyon trends east-northeast in its lower reaches and nearly east-west upstream, where it enters the Artists Drive Formation.

The alluvium with intercalated tephra beds dip consistently to the west at about 30°-35°, but only evidence of only minor faulting has been noted. Stratigraphic sections were measured at various locations on the west wall of the canyon and samples were collected for tephrochronologic and paleomagnetic analysis.

The tephra bed exposed at Stop C3-1 is the lower Nomlaki tuff (fig. C3-3), which is exposed both here and upstream near the sharp east bend in the channel. The name “lower Nomlaki tuff” is used because this tuff has a major-element composition very similar to the 3.27 Ma Nomlaki Tuff (table C3-1). The lower Nomlaki tuff is as much as 60 cm thick and has a reverse paleomagnetic declination (fig. C3-3). Without reference to other datums, the lower Nomlaki tuff is most easily distinguished from the Nomlaki Tuff by a greater abundance of heavy

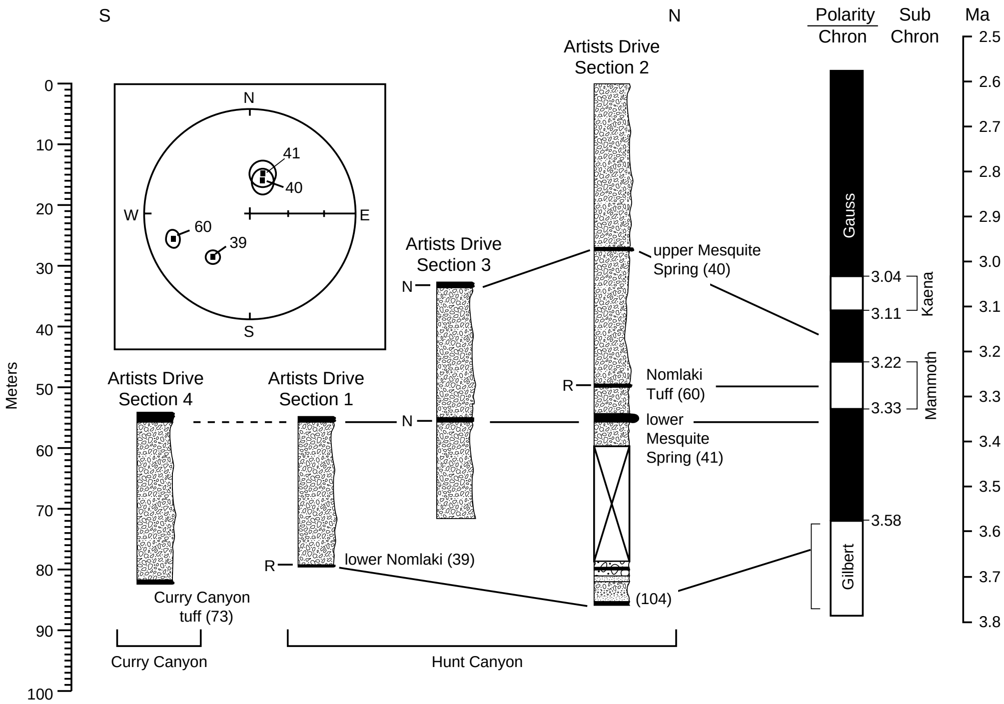


*Figure C3-3.Measured stratigraphic sections from western parts of Hunt and Curry Canyons. Speckled pattern indicates conglomerate; tuffs shown in black. Sample numbers [e.g., JRK-DV-60 = (60)] refer to table C3-1. Solid lines between tuff beds indicate continuous exposure between section or high tephrochronologic similarity coefficient. Dashed lines between tuffs indicate inferred correlation. Paleomagnetic declinations for tuffs are shown as N (normal) or R (reversed). Magnetic Polarity Time Scale (MPTS) is shown with chrons, subchrons and boundary ages from Berggren and others (1995). Inset shows in situ site mean directions.*

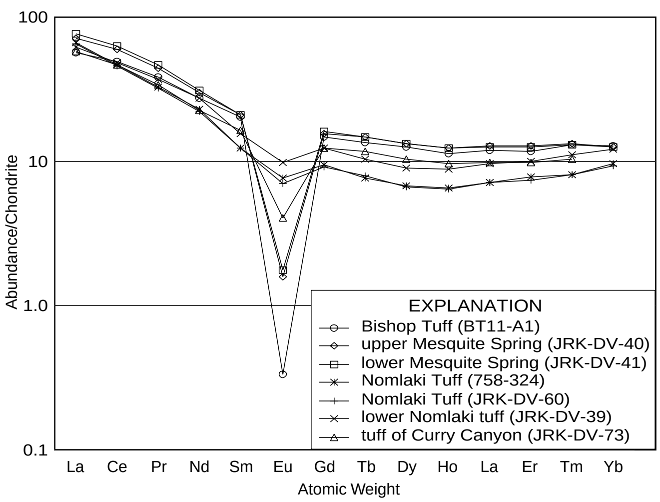


*Figure C3-4. Rare-earth element diagram of tuffs from Artists Drive, the Bishop Tuff from the Tablelands near Bishop, California, and the Nomlaki Tuff from the Tuscan Formation of northern California.*

rare-earth elements (fig. C3-4). The lower Nomlaki tuff is estimated to be between 3.58 and 3.9 Ma on the basis of its reverse polarity and stratigraphic position below the 3.35-Ma lower Mesquite Spring tuff.

The eruptive source of the lower Nomlaki tuff is still unknown, but the compositional similarity to the Nomlaki Tuff suggests a source in the southern Cascade Range of north-central California. Intuitively, one would expect the lower Nomlaki tuff and Nomlaki Tuff to have the same source; however, there are no tuff beds exposed below the Nomlaki Tuff at its type locality.(If these two tuffs are from the same source, evidence of the older, lower Nomlaki tuff is not preserved at the source.)

By stepping a few meters more up the channel, we get a wider view of Hunt Canyon. Here, the lower Mesquite Spring tuff is exposed nearly continuously, low on the west wall of the canyon. The name is informal at this time and is derived from the similarity in composition to the Mesquite Spring tuff of Snow (1990), which is found in the Cottonwood Mountains that bound the northwest part of Death Valley. The lower Mesquite Spring tuff is nearly 1 m thick and has a normal paleomagnetic declination (fig. C-3). The major element composition of the lower Mesquite Spring tuff is very similar to the Upper Glass Mountain family of tephra beds, including the Bishop ash bed.

The lower Mesquite Spring tuff has been assigned an age of 3.35 Ma based on $^{40}Ar/^{39}Ar$ dating by Snow and Lux (1999), which is supported by its stratigraphic position below the 3.27-Ma Nomlaki Tuff. This age is consistent with a normal paleomagnetic declination, which is correlative with the lower Gauss chron (3.33-3.58 Ma).

The other tuff that is visible higher on the west wall of Hunt Canyon is the upper Mesquite Spring tuff. This tuff is found near the western ridgeline of Hunt Canyon about 22 m above the Nomlaki Tuff (see below). Like the lower Mesquite Spring tuff, the informal name refers to the compositional and petrographic similarities to the Mesquite Spring tuff of Snow (1990).

Table C3-1. Electron-microprobe analyses of volcanic glass shards from upper Pliocene tephra layers, Artists Drive, Death Valley, California, and comparative compositions

| Sample* | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MgO | MnO | CaO | $TiO_2$ | $Na_2O$ | $K_2O$ |
|---|---|---|---|---|---|---|---|---|---|
| Tuffs of Mesquite Spring and related tuffs (~3.1 - ~3.3 Ma) | | | | | | | | | |
| 1. JRK-DV-71 | 77.3 | 12.7 | 0.73 | 0.04 | 0.08 | 0.48 | 0.05 | 3.48 | 5.21 |
| 2. JRK-DV-80 | 76.8 | 12.7 | 0.75 | 0.04 | 0.08 | 0.48 | 0.06 | 2.84 | 6.21 |
| 3. JRK-DV-40 | 77.1 | 13.2 | 0.76 | 0.04 | 0.09 | 0.48 | 0.06 | 4.54 | 3.77 |
| 4. JRK-DV-41 | 77.2 | 13.2 | 0.75 | 0.04 | 0.07 | 0.48 | 0.07 | 4.60 | 3.57 |
| 5. JRK-DV-44 | 77.8 | 12.9 | 0.71 | 0.04 | 0.07 | 0.49 | 0.07 | 4.33 | 3.61 |
| 6. FLV-19-WW | 77.3 | 13.2 | 0.72 | 0.04 | 0.08 | 0.48 | 0.06 | 3.76 | 4.31 |
| 7. M94FI-143 | 76.9 | 13.1 | 0.73 | 0.04 | 0.08 | 0.48 | 0.07 | 4.02 | 4.55 |
| Nomlaki Tuff (3.27 Ma) | | | | | | | | | |
| 8. JRK-DV-60 | 76.9 | 12.8 | 1.21 | 0.24 | 0.04 | 1.13 | 0.21 | 3.99 | 3.52 |
| 9. TSN-1 | 76.5 | 13.5 | 1.19 | 0.20 | 0.05 | 1.07 | 0.22 | 3.82 | 3.40 |
| 10. MLG-1 | 76.6 | 13.1 | 1.17 | 0.21 | 0.05 | 0.98 | 0.21 | 4.37 | 3.23 |
| 11. MLG-2 | 76.0 | 13.7 | 1.14 | 0.22 | 0.06 | 0.91 | 0.21 | 4.51 | 3.23 |
| Curry Canyon Tuff (>3.35 Ma) | | | | | | | | | |
| 12. JRK-DV-73 | 77.5 | 13.0 | 0.60 | 0.07 | 0.06 | 0.57 | 0.07 | 4.18 | 3.92 |
| Lower Nomlaki tuff (>3.58 Ma) | | | | | | | | | |
| 13. JRK-DV-39 | 75.4 | 13.8 | 1.20 | 0.24 | 0.06 | 0.93 | 0.22 | 4.55 | 3.56 |
| 14. JRK-DV-104 | 76.9 | 13.4 | 1.12 | 0.22 | 0.06 | 0.88 | 0.20 | 3.76 | 3.53 |
| 15. FLV-119-WW | 76.6 | 13.1 | 1.14 | 0.17 | 0.02 | 0.92 | 0.21 | 3.30 | 4.47 |
| 16. TSN-1 | 76.5 | 13.5 | 1.19 | 0.20 | 0.05 | 1.07 | 0.22 | 3.82 | 3.40 |
| 17. MLG-1 | 76.6 | 13.1 | 1.17 | 0.21 | 0.05 | 0.98 | 0.21 | 4.37 | 3.23 |
| 18. MLG-2 | 76.0 | 13.7 | 1.14 | 0.22 | 0.06 | 0.91 | 0.21 | 4.51 | 3.23 |
| Natural glass standard used as monitor in analysis (electron-microprobe analysis)§§ | | | | | | | | | |
| RLS 132 (n=18) | 75.4 | 11.3 | 2.12 | 0.06 | 0.16 | 0.11 | 0.19 | 4.9 | 4.4 |
| ± 1 s: | 0.1 | 0.2 | 0.04 | 0.01 | 0.01 | 0.01 | 0.01 | 0.1 | 0.1 |
| % s: | 0.2 | 1.4 | 1.9 | 17 | 6.3 | 9 | 5.3 | 2.7 | 1.4 |
| RLS 132 | 75.7 | 11.4 | 2.12 | 0.06 | 0.16 | 0.11 | 0.19 | 4.9 | 4.4 |
| Natural glass standard used as monitor in analysis (wet-chemical analysis) | | | | | | | | | |
| RLS 132 | 75.7 | 11.4 | 2.12## | 0.05 | 0.15 | 0.12 | 0.21 | 5.3 | 4.5 |

Note: Values given are in weight-percent oxide, recalculated to 100% fluid-free basis. C.E. Meyer, Analyst, USGS., Menlo Park, Calif.

* Samples are grouped according to best matches (inferred correlations).

† Total—Original oxide totals before recalculation are given to indicate the approximate degree of hydration of the volcanic glass.

§ SC—Similarity coefficent (Borchardt and others, 1972) used in quantitative comparisons of the tephra samples, where 1.000 represents a perfect match.

\# Comparison based on Si, Al, Fe, Ca, and Ti.

** Based on Si, Al, Fe, Ca, Na, and K.

†† Data from correlative samples.
FLV-47-WW and FLV-48-WW: lower tuffs of Glass Mountain, Fish Lake Valley, Calif. (1.78 to 1.96 Ma; Reheis and others, 1991).
TTC-23: lower tuffs of Glass Mountain, Blind Springs Valley, Calif. (1.92 ±0.02 Ma; Sarna-Wojcicki and others, unpubl. data, 1996).
JRK-DV-71: 3.35 ±0.13 Ma (Snow, 1990); White Top Road, Cottonwood Mts., Death Valley, Calif.
JRK-DV-80: 3.35 ±0.07 Ma (Snow, 1990); Nova Fm., Emigrant Canyon, Death Valley, Calif.
FLV-19-WW: Ash Butte section, Willow Wash, Fish Lake Valley, Calif.
M94FI-143: upper Pliocene alluvium, Fort Irwin, Calif. (about 3.4 Ma; Nakata, written comm., 1994).
FLV-119-WW: Black Hole section, Willow Wash, Fish Lake Valley, Calif.
TSN-1: Nomlaki Tuff, Tuscan Fm., Tuscan Springs, Calif.
MLG-1 and MLG-2: Repetto beds, Malaga Cove, Los Angeles County, Calif.

§§ Analytical values for replicate analyses of a homogenous natural glass used as an internal standard are given to provide an estimate of analytical precision.

\## Iron reported as FeO for the standard.

This ½-m-thick tuff has a normal paleomagnetic declination (fig. C3-3). The lower and upper Mesquite Spring tuffs are compositionally indistinguishable from each other (table C3-1; fig. C3-4); however, they may be identified by their position relative to the Nomlaki Tuff—lower Mesquite Spring tuff below the Nomlaki Tuff and upper Mesquite Spring above the Nomlaki Tuff.

The identical composition of the upper and lower Mesquite Spring tuffs suggests that they have the same source. Holm and others (1994) determined an age of 3.1 ± 0.1 Ma ($^{40}Ar/^{39}Ar$ on biotite) for a Mesquite Spring tuff in Copper Canyon of the Black Mountains. Also, Snow and Lux (1999) determined an age of 3.17 ± 0.09 Ma ($^{40}Ar/^{39}Ar$ on sanidine) for a Mesquite Spring tuff in the Cottonwood Mountains (see also Chapter E, in this volume). Thus, an age of about 3.1 Ma is suggested for the upper Mesquite Spring tuff, which is consistent with its normal paleomagnetic declination (fig. C3-3).

The source of the Mesquite Spring tuffs is not known. A source to the north or northwest is consistent with an increased thickness in those directions. Although similar to other tephra from the Long Valley volcanic field some 200 km to the northwest, no evidence of silicic volcanism greater than 3 Ma is found at Long Valley (Metz and Mahood, 1985). The source of the tuff may be much closer, perhaps within Death Valley, as suggested by the tuffs relatively coarse pumice size (see Stop B4).

### TEPHROSTRATIGRAPHY

The 1.9 to 2.6 m.y. age difference between the 3.1-3.35 Ma Mesquite Spring group of tuffs and the 0.758-1.2 Ma Upper Glass Mountain family of tephra beds is significant for paleoclimatic, tectonic and paleogeographic reconstructions of the late Cenozoic. And so, the unequivocal differentiation of the Mesquite Spring tuffs from the Upper Glass Mountain family of tephra beds should be done with care because their glass shard compositions are very similar. However, even without stratigraphic relations or direct dating, the normal-polarity Mesquite Spring tuffs are discernible from the reverse-polarity Upper Glass Mountain D, G, T and U by paleomagnetism. Distinguishing the Mesquite Spring tuffs from the Bishop ash bed is more difficult because they both are normally magnetized. However, the Mesquite Spring tuffs have consistently higher concentrations of Mn and Eu (Knott and others, 1997). In combination with other trace and minor elements, similarity coefficients may be used to reliably separate the Mesquite Spring tuffs from the Bishop ash bed (see Chapter E in this volume). As a result, the Mesquite Spring tuffs have been identified in a number of places in Death Valley, Fish Lake Valley, the Amargosa Valley (in Nevada, east of Death Valley), and near the base of a core from Searles Lake (Knott and others, 1997).

Proceed up Hunt Canyon to where the canyon turns abruptly to the east. Notice that the lower Mesquite Spring tuff is, for all intents, continuously exposed along the canyon wall.

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## Stop C3.2

$^{40}24^{030}$ mN $^{5}15^{850}$ mE +79 m (260 ft) MSL

At this point, we can see a 25-cm-thick whitish tuff about 4 m above the lower Mesquite Spring tuff. This thin tuff—the 3.27-Ma Nomlaki Tuff—is the most reliably correlated tuff in the Artists Drive block. Exposure of the Nomlaki Tuff in Hunt Canyon is limited to the face of a small drainage channel, just before the channel turns east. Major-, minor- and trace-element composition of samples of this tuff correlate well with samples from other well-known Nomlaki Tuffs (fig. C3-4).

The Nomlaki Tuff, which is a widespread stratigraphic marker bed in the western U.S., was erupted from the southern Cascade Range (Sarna-Wojcicki and others, 1984). Its 3.27 Ma age (personal communication, A. Deino) is consistent with the 3.22-3.33 Ma reverse-polarity Mammoth subchron (fig. C3-3).

Under most circumstances, discriminating between the lower Nomlaki tuff and Nomlaki Tuff may not be important because the age difference is only about 0.3 m.y. However, identification is significant for determining the volume and aerial distribution of these two large eruptive events. At this time, multiple "Nomlaki-like" tuffs have been described at Artists Drive and in Fish Lake Valley (Reheis and others, 1991). Absent stratigraphic relations or direct dating, the lower Nomlaki and Nomlaki Tuff may be distinguished by their heavy rare-earth element composition.

The composition of the Mesquite Spring and lower Nomlaki tuff suggest that they have the same eruptive source as the Upper Glass Mountain family and Nomlaki Tuff, respectively. However, neither is found at Long Valley or in the southern Cascades, respectively. This suggests that either (1) earlier eruptives are not preserved proximal to the source or (2) there are two sources that are able to produce compositionally similar eruptives. The answer to this problem is not known, but may be resolved by further tephrostratigraphic studies.

Continuing to walk upstream, on the right is another exposure of the lower Nomlaki tuff. In about 100 m at Stop C3.3, the Funeral Formation conglomerates give way to the Artists Drive Formation volcanic rocks.

# Stop C3.3

$^{40}24^{000}$ mN $^{5}16^{020}$ mE +7109 m (+360 ft) MSL

At this location, the contact between sedimentary rocks of the Funeral and Artists Drive Formations is depositional, which has implications toward the tectonic-geomorphic development of the Artists Drive block. Our interpretation of the geologic relations at Artists Drive is described below.

If coarse-grained alluvial-fan deposits such as these are assumed to be filling accommodation space created in basins adjoining tectonically active mountain fronts, then the spatial and temporal distribution of the Funeral Formation alluvial-fan deposits may be used to describe the geomorphic development of a mountain-front piedmont. Such is the case at Artists Drive where alluvial-fan deposition may be divided into three separate groups by time and space: (1) late Pliocene atop the Artists Drive block, (2) early to middle Pleistocene within the graben, and (3) late Pleistocene to Holocene of the western piedmont (fig. C3-5).

The Funeral Formation at Artists Drive has an age between >3.58 Ma (lower Nomlaki tuff) and 1.86-1.92 Ma (lower Glass Mountain tuff; Knott and others, 1999). The distribution of the Funeral Formation indicates that the BMFZ was near its present location at the foot of the Black Mountains and that a large part of the Artists Drive block was buried by the Funeral Formation (fig. C3-2). Thus, from about 3.5-1.9 Ma, the Artists Drive block was being downdropped along the BMFZ.

Knott and others (1999) inferred that cessation of Funeral alluvial-fan deposition was most likely caused by initiation of the antithetic fault that bounds the east side of the Artists Drive block. This antithetic fault resulted in uplift of the Artists Drive block and formation of the graben morphology that is present today. Another consequence of formation of the antithetic fault is creation of a drainage divide in what had previously been a contiguous alluvial-fan piedmont resulting in deposition in both the graben and west of the Artists Drive block.

This hypothesis is supported by the morphology of the incised and abandoned alluvial fan surfaces found in the graben. Alluvial fans in the graben between the Artists Drive block and the Black Mountains have surfaces that are composed of well-varnished clasts incorporated into a well-developed desert pavement. On the Avawatz Mountains in southern Death Valley, this surface morphology indicates a minimum age of late Pleistocene (McFadden and others, 1989). We interpret these relations to indicate that the alluvial fans deposition was occurring in the graben up to the Late Pleistocene. During the Late Pleistocene, these fans were captured by headward erosion of Artists Drive drainage basins.

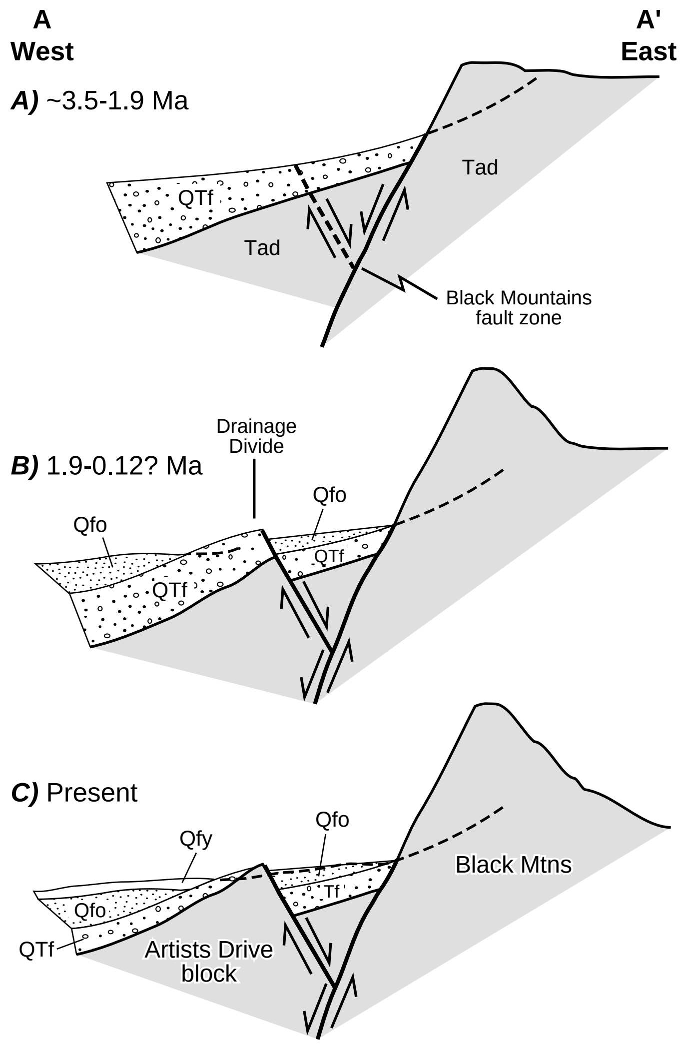


*Figure C3-5. Schematic cross section showing interpretation of tectonic-geomorphic development of the Artists Drive block. Tad, Artists Drive Formation; QTf, Funeral Formation; Qfo, Pleistocene alluvial fans; and Qfy, Holocene alluvial fans. Dashed lines show drainage channel profiles. A) Normal fault front from about 3.5 to 1.9 Ma; antithetic fault (dashed) develops about 1.9 Ma on contiguous basin/fan system. B) Post-1.9 Ma slip on antithetic fault results in drainage divide within the Artists Drive block. C) Post middle Pleistocene headward erosion of Artists Drive drainages has progressed faster than uplift of Artists Drive block resulting in capture of graben fans and resumption of contiguous drainage system.*

Headward capture of the graben drainages resulted in a nearly 300 m drop in base level with the locus of deposition of Black Mountain drainage basins shifting to the west of Artists Drive. Subsequently, drainages within the graben fans have incised as much as 10 m below the late Pleistocene surface in the Holocene (fig. C3-6) and alluvial-fan deposition is only occurring now west of the Artists Drive block preserving the Late Pleistocene fan surfaces in the graben (fig. C3-6).

Hunt and Mabey (1966) inferred a fault on the west side of the Artists Drive block. However, there is no surface expression of faulting preserved in the alluvial fans west of Artists Drive. In addition, gravity data shows no evidence of a structure in this area, but rather a gentle mountain front (Hunt and Mabey, 1966; Blakely and others, 1999). Thus, a fault may be present in the subsurface west of Artists Drive; however, this fault shows no evidence of Quaternary offset and is significantly less active than the BMFZ.

As an alternative to our tectonic-geomorphic interpretation, Blair and McPherson (1994) proposed that Artist's Point [*sic*] is a large rock mass that has been transported by imperceptible rotation along listric faults. Since the >3.58-1.9 Ma Funeral Formation does not appear to be dismembered or otherwise deformed by landsliding, it implies that the landsliding occurred pre-3.58 Ma. However, the Miocene-Pliocene Furnace Creek basin was dominated by northwest-southeast fluvial systems into the Pliocene (Hunt and Mabey, 1966). This could only have occurred if the entire southern side of the Furnace Creek basin was bounded by uplands; thus, there was no pre-3.58 Ma relief for landslide translation.

## SUMMARY

These four tuffs in the Funeral Formation at Artists Drive lead to the following conclusions and interpretations:

Earlier tephrochronologic studies in eastern California that found tephra beds with chemical composition similar to the 0.8-1.2 Ma Upper Glass Mountain family of tephra beds in clearly Pliocene sediments (Sarna-Wojcicki and others, 1984; Reheis and others, 1991) and multiple “Nomlaki-like” tephra bed (Reheis and others, 1991) are herein verified. As a result, these tephra beds, especially the Mesquite Spring group of tuffs, are considered to be prominent marker beds in Pliocene deposits throughout Death Valley (Knott and others, 1999; see also Chapters A, B, and E in this volume).

The Artists Drive area was a simple, west-side-down mountain front in the Pliocene, from about 3.6 to 1.9 Ma (Knott and others, 1999).

Development of the Artists Drive graben about 1.9 Ma created a drainage divide in the Artists Drive block with alluvial-fan deposition occurring both in the graben and west of Artists Drive. In the late Pleistocene, headward-eroding streams in the Artists Drive block captured the graben streams, causing about 10 m of incision through the graben fans, thereby shifting active deposition to the large alluvial fans west of the Artists Drive block.

Return to cars by retracing our route down Hunt Canyon.

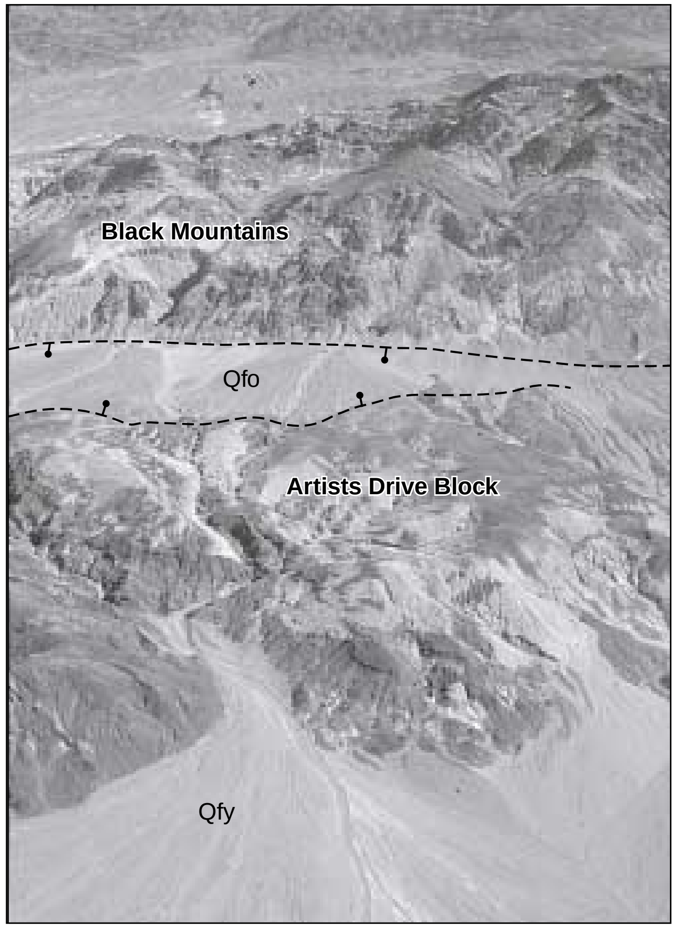


*Figure C3-6. Oblique aerial photograph of central Artists Drive looking east. Black Mountains are in the near background and Artists Drive block comprises the variable colored rocks in center. Incised late Pleistocene alluvial fans (Qfo) are found in the graben, whereas the active Holocene fans are in the foreground (Qfy). Dashed lines show main trace of the Black Mountains fault zone and the antithetic fault; bar and ball on the downthrown side.*

# Stop C4 — Lacustrine gravel in Desolation Canyon

*Jeffrey R. Knott and Michael N. Machette*

FurnaceCreek 7.5' quadrangle
GPS: 27 NAD, UTM Zone 11S
UTM $^{40}27^{760}$mN, $^{5}13^{755}$ mE
Elevation -56 m (-185 ft) MSL

## INTRODUCTION

Stop C4 is intended to be an optional stop along the gravel road that leads to Desolation Canyon (fig. C4-1). The main reason for stopping here is to discuss well-exposed lacustrine gravel that forms the remnant of a spit that extends eastward into Desolation Canyon. Stop C4 is located at the intersection of the highway and Desolation Canyon road; however, we will turn east and proceed about ½ mi (0.8 km). At this point, the road forks: the east fork leads to an unnamed canyon and a spectacular view of the Black Mountains fault zone. The south fork, which we take for about 200 m, leads to Desolation Canyon in the northern end of the Artists Drive block. If time allows, we will visit this natural exposure (Stop C4.1) and walk 100 m west to the top of the spit (Stop C4.2).

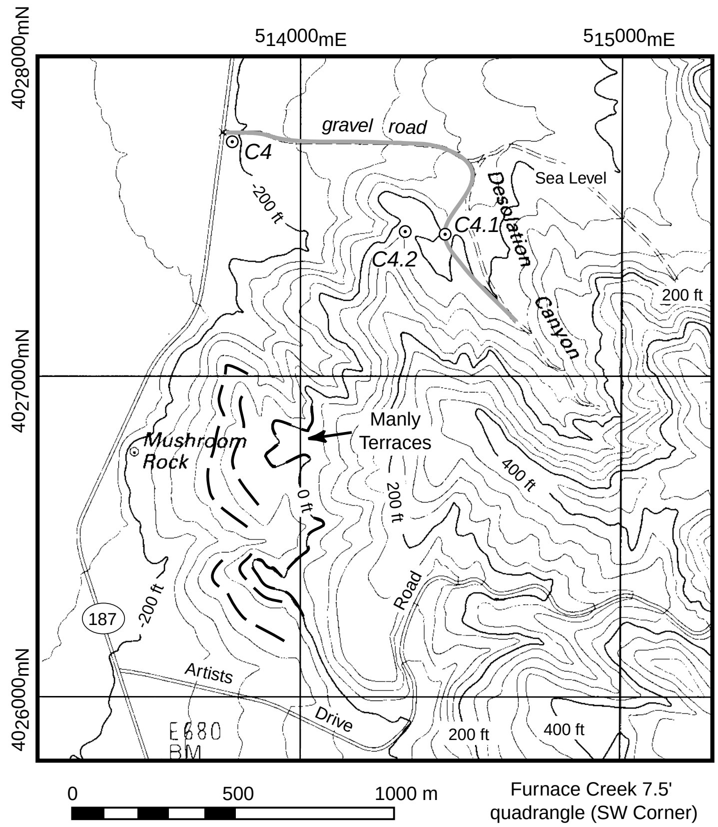


*Figure C4-1. Topographic map of area around Stop C4.*

# Stop C4.1

# Lacustrine gravel

UTM $^{40}27^{440}$ mN, $^{5}14^{450}$ mE
Elevation (approximate) 0 m (0 ft) MSL

The northern end of the Artists Drive block is deeply embayed by two major canyons that cut south into the block. The western, smaller canyon—Desolation—has a drainage that heads in the block about 1 km south of this stop. The east wall of this canyon is composed of highly brecciated volcanic rocks, presumably of the Miocene Artists Drive Formation. The western and south walls are composed of Funeral Formation basalts and conglomerates that are about 1.9 Ma based on the presence of a lower Glass Mountain tuff in the south wall (Knott and others, 1999).

The basin of the eastern, larger unnamed canyon is eroding along the Black Mountains fault zone (BMFZ) (fig. C4-2). The linear trend and scarps in the eastern canyon indicates rapid, recent uplift and incision along the fault. Here, the BMFZ places strata of the Miocene Artists Drive Formation against Quaternary alluvium that is impounded behind the Artists Drive block, much the same situation as described for the graben mentioned at Stop C3. The bedrock cored fault scarp is so steep (essentially vertical) in some places along the canyon that talus has cascaded off uplifted block and deposited free-standing cones of debris.


*Figure C4-2. Aerial view to east showing northern end of Artists Drive block, lacustrine spit (Stop C4.2), and Black Mountains (in background). Photograph by M.N. Machette, Nov. 2000.*

The lacustrine gravel in Desolation Canyon is exposed in a natural cut on the west side of the access road (see fig. C4-1). The gravel dips about 25°-30° to the southeast (fig. C4-3) and is composed primarily volcanic and volcano-clastic debris, which is derived from the late Pliocence Funeral Formation that forms the west side of the Artists Drive block to the south. The thick to thin beds are composed of well rounded, well-sorted pebble to small cobble gravels, and sparse pebbly sands. Based on the morphology and facies, we interpret this deposit to be a remnant of a spit that was possibly formed by northeast- and east-flowing longshore currents. The clast types indicate that transport is generally less than a kilometer.

*Figure C4-3. West view of south-dipping lacustrine gravel. Natural outcrop is about 10-15 m high. Photograph by M.N. Machette, April 2000.*

# Stop C4.2 The spit and relation to Manly Terraces

UTM $^{40}27^{460}$ mN, $^{5}14^{330}$ mE
Elevation -4 m (-13 ft) MSL

About 120 m to the west of Stop C4.1 (at the natural exposure), the lacustrine gravel fills a narrow canyon between the Artists Drive block (to the south) and a formerly isolated knob of volcanic rocks. By filling this canyon, the gravel connected the two bedrock areas, thus forming a baymouth bar (fig. C4-4). This bar has a slightly convex shape, both in plan view and in elevation. The bar falls to the north-east (in the direction of transport). The southwest end is at about -1 m (-3 ft) elevation, as measured with a laser theodolite from the -185 ft (-56 m) benchmark at Stop C4. The low point in this 60-70 m long spit is at about -4 m (-13 ft) elevation. From here the gravel extends more eastward, falling in elevation (to sea level) as lake deposited repeated foreset beds into the deeper landscape Desolation Canyon.

*Figure C4-4. Southwest view of crest of spit. Elevation of swale in crest is -4 m (-13 m ft msl); elevation of southwest end, which laps onto bedrock, is -1 m (-3 ft msl).Photograph by M.N. Machette, April 2000.*

One kilometer to the south from the spit-and-bar complex are the Manly Terraces of Clements and Clements (1953) (fig. C4-5). Hunt and Mabey (1966, p. A70) reported that the Manly Terraces are at about sea level, and this would appear to be correct based on the topographic maps, but we have not surveyed them to confirm either their elevation (or range in elevations). However, the Manly Terraces are only the most prominent expression of lacustrine gravel along the west side of the Artists Drive block at this location. Outcrops of lacustrine gravel may be found in the area of the Manly Terraces at elevations as high as +17 m and to the south along the Artists Drive block as high as +71 m (Knott, unpublished mapping). The spit and bar complex of Desolation Canyon was deposited by Lake Manly and although we believe that it was a marine oxygen-isotope stage VI (OIS 6) of the lake (i.e., 128-180 ka), we lack numeric age control at this location to prove this suspicion.Machette and Chris Menges sampled a fine-grained bed from a point about 2 m below the crest of the spit for luminescence dating, but the results were still pending at the time this guidebook was assembled. It is possible that the gravel is related to a relatively high stand of an OIS 2 Lake Manly (latest Pleistocene) as Klinger has dated by radiocarbon at Stop A4 in the Mesquite Flats area of northern Death Valley.

Whatever the age of the causative lake stand, this spit is most likely temporally and certainly spatially related to the Manly Terraces. One should remember that both of these features, the spit and shorelines, are located on the downdropped Artists Drive block of the Black Mountains fault zone, whereas the dated lacustrine tufas at Badwater (at as much as +90 m elevation) and at Mormon Point (at as much as +92 m elevation) are on the upthrown fault block. These structural relations make it extremely difficult to determine true elevations (and water depths) for any or all of the deep-water stages of Lake Manly (see also Chapter G in this volume). One thing that is certain is that many of the canyons along the Black Mountains Artists Drive block were deeply incised prior to inundation by the lake, otherwise the spit could not have draped into Desolation Canyon, nor would we find spits forming in canyons at Mormon Point and other areas of Artists Drive.


*Figure C4-5. Aerial view of Manly Terrace on northern end of western face of Artists Drive block. View to the northeast (photograph by J.R. Knott).*

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# Satellite image map of Death Valley

*John Dohrenwend*

CHAPTER D

## THE IMAGE MAP

The satellite image map shown in figure D-1 was produced from data acquired by the Landsat 7 satellite on the morning of 15 October 1999. The Landsat 7 satellite has a near-polar orbit with an average altitude of almost 440 miles. This orbit is sun-synchronous and is timed so that the satellite passes over this area of southeastern California once every 16 days at about 9:50 a.m. mean local sun time. As the satellite moves along the daylight part of its orbit, its Thematic Mapper scanner collects image data along a 185-km (115-mile) wide path on the earth's surface. Measurements are collected from seven broad bands of the electromagnetic (light) spectrum: three nearly contiguous bands spanning most of the visible range (Bands 1, 2 and 3) and four more widely-spaced bands covering critical portions of the infrared (Bands 4 through 7).

## INTERPRETATION OF THE IMAGE MAP

This satellite image map of Death Valley (fig. D-1) is a computer-generated composite of infrared and visible light. Although infrared light lies beyond the range of human eyesight, the combination of infrared and visible light selected for this image produces a somewhat intuitive result wherein vegetation appears as shades of green to yellow green and most human-made features appear as shades of gray. However, the conspicuous light blue areas in the center of Death Valley do not indicate water. Rather, these features are deposits of salt formed by the evaporation of ancient lakes and modern flood waters that occasionally reach the valley floor.

Making the image look much like a geologic map, the wide variety of colors reflects the great diversity of rock types and soils exposed in the Death Valley area. For example, the eroded 4-5 Ma (million year old) cinder cones of basaltic volcanoes (southeast of Furnace Creek in the northern part of the Greenwater Range) show up as conspicuous blotches of bright orange-red, whereas the surrounding basaltic lavas appear as much more natural looking grays and gray browns. The orange-red color of these ancient volcanic vents indicates alteration of the basaltic cinders by water vapor and other hot gases during and after the eruptions that formed them. In contrast, the somewhat older (5-12 Ma), more silica-rich volcanic rocks (rhyolite and rhyodacite) on the north end of the Black Mountains (just west of the basaltic rocks) appear as intricately mottled areas of red, orange, yellow, brown, green, and blue. Paleozoic (250 to 590 Ma) carbonate rocks (mostly limestone and dolomite) on the lower east flank of the Panamint Range and at the south end of the Funeral Mountains appear as shades of light to medium brown and blue-gray. Higher up in the Panamint Range west of Furnace Creek and in the central part of the Funeral Mountains, Precambrian (greater than 590 Ma) metasedimentary rocks (interbedded quartzite, argillite, shale and metaconglomerate) are conspicuous as intricately-folded, multicolored bands. In the Black Mountains southeast of Badwater, Precambrian metadiorite appears as large areas of reddish-purple. These varied rocks record the long and complex geologic history of Death Valley

## THE NATURAL LANDSCAPE

Death Valley is is one of the largest basins in the Basin and Range province of western North America, a region extending from the Sierra Nevada to the Colorado Plateau. The Basin and Range is dominated by elongate, northwest-trending mountain ranges and intervening basins that were formed during the last 30 to 35 million years (m.y.) by extensional faulting. The southern part of the valley (that portion shown on the image map) is more than 100 km (60 miles) long and 6 to 20 km (4 to 12.5 miles) wide. Death Valley is also one of the youngest, most tectonically active areas in this region. During the last 12 m.y., extension of this area has formed the high ranges and deep basins that dominate the present day landscape. The ranges are tall, steeply sloping, and deeply dissected. The basins between the ranges are very deep and are fringed by coalescing, steeply sloping alluvial fans that grade to broad, undissected basin floors. In the southern part of the valley, the asymmetric development of these alluvial fans testifies to continuing tectonic activity. Large, low gradient fans along the relatively stable western side of the valley contrast sharply with the small, steep fans of the rapidly subsiding eastern margin. Also indicative of tectonic activity is the 3,454 m (11,332 ft) relief between Badwater (-86 m/-282 ft, the lowest point in the Western Hemisphere) and Telescope Peak (3,368 m /11,050 ft, the highest point in Death Valley National Park): this is the largest local elevation difference in the southwestern United States. Add to this the total depth of the valley, which is equal to about twice surface relief. The structural basin beneath the modern valley floor averages about 3,000 m (almost 10,000 ft) deep, and in the central part of the valley just north of Stovepipe Wells, it reaches a depth of nearly 5,000 m (16,400 ft). This subsurface basin is filled mainly with sediments that have been eroded from the surrounding mountains. Uplifted and dissected basin-fill sediment (appearing as mottled blue-grays and tans on the image map) is distributed throughout the valley (including locations along Furnace Creek and Artists Drive, at Mormon Point, and in the Confidence Hills). These older basin-fill deposits range from >5 Ma to approximately 0.5 Ma in age and record a long and continuing history of basin formation.

## THE HUMAN LANDSCAPE

Evidence of human activity in this sparsely populated region is very limited. Visible indications of intensive agricultural activity are restricted to the Amargosa Valley (northeastern corner of the map) where numerous bright-green fields contrast sharply with the grays and browns of the surrounding desert landscape. This agriculture is dependent on 'fossil' water that accumulated thousands to tens of thousands of years ago in underground aquifers. Other man-made features include the bright-green oasis of Furnace Creek Ranch, the broad gray path of the adjacent airstrip, the narrow, dark-gray paths of the principal access roads within the Park, and the lighter-colored pathways of the area's unpaved roads (mostly in the Amargosa Valley).

*Figure D-1 (facing page). Satellite image map of central and southern Death Valley. This false color image is based on Landsat 7 Thematic Mapper (TM) images using a composite of shortwave infrared data (Band 7, displayed in red), near infrared data (Band 4, displayed in green), and visible green data (Band 2, displayed in blue). Image colors have been enhanced by custom processing in Hue-Saturation-Intensity color space. Acquisition date was 15 October 1999. (A poster-size version of this map is available for purchase from the author; see list of contributors to this volume for address information.)*

# Weaving a temporal and spatial framework for the late Neogene of Death Valley—Correlation and dating of Pliocene and Quaternary units using tephrochronology, $^{40}Ar/^{39}Ar$ dating, and other dating methods

*A.M. Sarna-Wojcicki, M.N. Machette, J.R. Knott, R.E. Klinger, R.J. Fleck, J.C. Tinsley, III, Bennie Troxel, J.R. Budahn, and J.P. Walker*

CHAPTER E

## INTRODUCTION

New data derived from tephrochronologyy, isotopic and other dating and correlation techniques provides age calibration for the study of previously undated upper Neogene (upper Pliocene and Quaternary; Berggren and others, 1995) sediments and sedimentary rocks in Death Valley. Sediments, sedimentary rocks, and associated structural features (faults, folds, and unconformities) are used to decipher geologic history and to determine the nature and rates of geologic processes in the past. Numerical age control is a critical component of these studies. Despite their relative youth, upper Neogene sedimentary units in Death Valley have been among the most poorly dated and least understood. The study of upper Neogene sedimentary deposits in Death Valley has been hampered by their discontinuous distribution, rapid facies changes, tectonic dismemberment, and by a lack of reliable methodologies or materials for precise age control.

A major goal of a regional chronostratigraphy for Death Valley is to determine the development, abandonment, and destruction of these upper Neogene basins in space and time, as a consequence of both tectonic and surficial processes. The application of tephrochronologic correlation and $^{40}Ar/^{39}Ar$ dating of volcanic flows and tephra layers during the past ~15 years have made it possible to develop a working chronostratigraphic framework that allows correlation among the upper Neogene deposits within Death Valley, to other upper Neogene deposits in the western U.S., and to the more complete deep-ocean stratigraphic record. The new age control in turn paves the way for a new round of studies of the temporal and spatial succession of environmental conditions and surficial and crustal processes that have shaped Death Valley.

The sediments and sedimentary rocks that are the object of the present study range from the middle part of the Pliocene (~4.2 Ma) to latest Holocene in age. They have been found in a diverse collection of deposits, ranging from debris flows, fan and stream alluvium to lacustrine, playa, and eolian sand. We refer to these sediments and rocks as *upper Neogene deposits*.

Systematic development of a tephrochronological database for the upper Neogene deposits in Death Valley began only about 15 years ago (~1985). Earlier investigators had noted the presence of tephra layers (Drewes, 1963; Hunt and Mabey, 1966), but the technology had not yet been developed to exploit these observations. As a result, only a few scattered K-Ar ages on several volcanic flow rocks had been obtained (e.g., McAllister, 1973). The development of chemical-fingerprinting techniques of volcanic glass from tephra layers enabled correlation of tephra layers in Death Valley to sites long distances away and to "import" age data by means of correlation. Moreover, the continued improvement of $^{40}Ar/^{39}Ar$ dating, permits direct dating of uncorrelated or questionably identified tephra layers and testing of the reliability of other numerical ages or chemical correlations by multiple independent criteria.

Sites with late Pliocene and Quaternary tephrochronologic age control in Death Valley are unevenly distributed across the area, coinciding with exposed remnants of former upper Neogene depositional basins. These remnants are commonly at higher elevations than modern depositional basins, situated either along the foothill margins of mountain ranges adjoining the modern playas (for example, at Furnace Creek, Artists Drive, Mormon Point, Kit Fox Hills, and Lake Rogers; see fold-in Plate 1), or as uplifted, lower lying areas within the ranges (for example, at Nova basin, Ubehebe basin, Titus Canyon, and Copper Canyon) where they are surrounded by older, higher, more resistant bedrock. Most frequently, these ancient basins have been abandoned as depositional sites by tectonic lowering of regional base level and abandonment by headward erosion and breaching. Specifically, the changes in loci of sediment deposition have often resulted from progressive changes in fault geometry (for example, along-strike fault growth or migration of normal faults away from range fronts) that have shifted depositional sites from one block to another. The dominant regional mechanism for this is the tectonic northeast-southwest extension of the western Great Basin. The late Neogene range-margin remnants are often offset by normal, dextral, or oblique-slip, range-bounding faults, and tilted or warped into broad, gentle folds (Klinger, Machette, and Knott articles in this volume). At some sites, the late Neogene basins may be affected by broader, regional igneous underplating (Sass and others, 1980).

Remnants of former late Neogene depositional basins are also exposed at low elevations in or near the margins of modern basins, where evidence of localized compressive deformation is present, as in the Confidence Hills, the Lake Rogers basin, the Salt Creek Hills, and within the Furnace Creek drainage basin. At the Confidence Hills, upper Neogene alluvial and lacustrine sediments have been uplifted and deformed as a result of localized compression between adjacent strands of the dextral Southern Death Valley fault zone (Dooley and McClay, 1996). Similarly, upper Neogene sediments in the Furnace Creek Basin east of Furnace Creek Ranch appear to be compressively deformed within the Texas Springs syncline into a broad fold positioned between the southern dextral Furnace Creek fault zone and the uplifted northern end of the Black Mountains and Central Death Valley fault zone (Wright and others, 1991; see Stop B5). In northern Death Valley, upper Neogene deposits in the Kit Fox Hills and on the western flank of the Grapevine Mountains are tilted eastward at steep to moderate dips along the dextral Northern Death Valley fault zone. Thus, in addition to effects of broad, regional east-west crustal spreading, we also see the imprint of broad, northwest-southeast dextral shearing, which may affect much of the region west and north of Death Valley, to the boundary between the North American and Pacific plates.

Undoubtedly, some or maybe an even greater volume of deposits coeval with the remnants of these ancient late Neogene basins remnants are present at depth beneath the playa surfaces of modern depositional basins in Death Valley (see review in Smith, 1991). But, with the exception of borate exploration (Hunt and Mabey, 1966) and the recent core by Lowenstein and others (1999, and numerous references cited within), few deep (>30 m) cores have been drilled in Death Valley to determine thickness and age. Most recently, geophysical studies have hinted at the depth and structure of some of the basins formed within Death Valley (Blakely and others, 1999). Where deep cores have been taken, as for example in Owens Lake to the west and at Bristol Lake to the southeast (fig. E-1), sediments coeval with some of the dismembered basinal and basin-margin sediments have been demonstrated (Rosen, 1989; Sarna-Wojcicki and others, 1997; Smith and Bischoff, 1997).

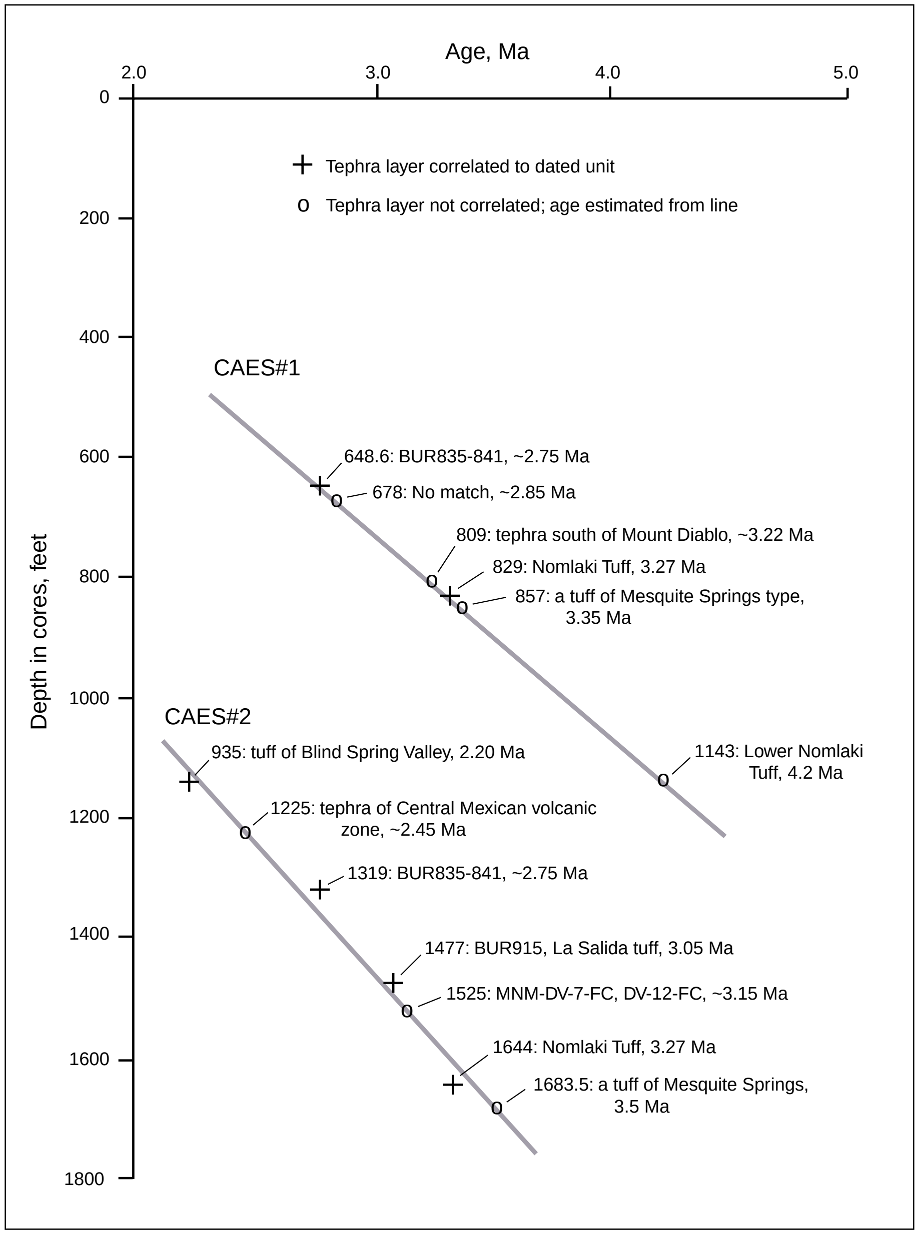


*Figure E-1. Age versus depth curves for two cores drilled in Bristol (dry) Lake, southeastern Mojave Desert, California. Core and sample depths from Rosen (pers. commun., 1983; Rosen, 1989). Cores are Southern California Edison—CAES Exploratory Holes No. 1 and No. 2.*

## CHRONOSTRATIGRAPHIC METHODS

### Tephrochronology

We provide tephrochronologic age control in two ways: The first is by chemical analysis of the volcanic glass fraction separated from the tephra layers (volcanic ash beds and tuffs), and matching the compositions of these layers to those of known age at other sites (Sarna-Wojcicki and Davis, 1991; Sarna-Wojcicki, 2000; also see Izett, 1981; Izett and others, 1988). The second method is by direct $^{40}Ar/^{39}Ar$ dating of minerals separated from the tephra layers (LoBello, 1987; Dalrymple, 1989). The first method is by far the most commonly used in this study because it is an easier, faster, and cheaper way of obtaining age control. Verifiable and reliable isotopic ages on tephra are often best determined on proximal coarse pumice clasts containing large mineral phenocrysts that are easy to separate and for which the problem of detrital contamination is eliminated. Fine-grained, water-deposited tephra often contains detrital contaminants that result in spurious age determinations. Most of the upper Neogene tephra layers found in Death Valley are fine-grained, water-lain, and exotic; that is, their eruptive sources are outside the Death Valley region. For example, the Lava Creek B ash bed, found in the informally named Mormon Point Formation (Knott and others, 1999) (Plates 1, 2) was erupted from the Yellowstone area of northwestern Wyoming, about 1,100 km to the northeast, and the Nomlaki Tuff (member of the Tuscan and Tehama Formations) and its older relative, were erupted from the southern Cascade Range in northern California, about 700 km to the northwest. The identification of these reliably dated, diagnostic distal tephra layers (“ringers”) in stratigraphic sections also provides a method of evaluating the consistency of other numerical or relative-age techniques, given good stratigraphic control.

### Chemical methods

Among chemical methods that we use for “fingerprinting” volcanic glass shards, the real workhorse is electron-microprobe analysis (EMA). Once we have determined that volcanic glass shards are present in a sample and that they are relatively unaltered (i.e., still mostly isotropic), we separate and clean the glass shards, and analyze internally polished surfaces to determine their major- and minor-oxide composition (Sarna-Wojcicki and others, 1984; Sarna-Wojcicki, 2000). By this technique, we can determine whether a shard population is homogeneous or heterogeneous, and if the latter, what the nature of the heterogeneity is. In other words, is the sample a collection of many different shard compositions—an ambient level of reworked tephra within the particular drainage basin that we are studying? Or conversely, is there a single differentiation trend expressed in the spread of data; is there a dominant compositional mode; or is the sample polymodal with two or more major modes?

The abundance and homogeneity of shards in the sample are important in evaluating the chemical data, matching of the sample with known tephra layers, and the final interpretation of age. Sedimentary processes may have elutriated the low-density glass and pumiceous shards in detrital sediment and concentrated them in a layer or interval that could be erroneously interpreted as the products of a single eruption, diluted or disseminated during transport and deposition. The abundance of shards and the nature of their compositional spread give us clues as to the origin of the tephra and the enclosing sediments. In elutriated concentrates of shards, the percentage of shards will be low relative to the amount of detrital clastic material present, and the shard population will tend to be heterogeneous. The value of such a sample for chronostratigraphy is diminished, but not useless. The presence of the youngest identifiable mode in such a sample provides a minimum age for the enclosing sediment. Similarly in soil studies, the oldest identifiable tephra present in the soil profile, combined with the youngest identifiable tephra in the parent sediment, provides a bracketing age range for the soil. Such studies tend to be laborious, expensive, and often inconclusive—consequently, we engage in them rarely, and with caution.

Electron-microprobe analysis (EMA) allows for accurate determination of only the six major oxides ($SiO_2$, $Al_2O_3$, $Fe_2O_3$, CaO, $Na_2O$ and $K_2O$), and occasional precise analysis of several minor oxides and elements (MgO, MnO, $TiO_2$, BaO, P, and Cl) provided they are present in sufficient concentration. Chemical compositions of volcanic glasses determined by electron probe, particularly for those tephra from the same eruptive province, can be very similar and may fail to distinguish between the layers on this basis. In such cases, for unimodal shard populations, we may employ other chemical techniques that have greater sensitivity for minor and trace elements, such as instrumental neutron-activation analysis (INAA), X-ray fluorescence (XRF), or inductively coupled plasma mass spectroscopy (ICP-MS) (see, for example, Knott, 1998). Analyzing polymodal shard populations by the more sensitive techniques is pointless because we have no guarantee that the proportions of the modes remain the same from site to site, and can be correlated on this basis—particularly because the latter techniques tend to be more laborious and expensive. Until recently, we have been hampered in developing reliable criteria for distinguishing between very similar tephra samples—such as those erupted from Glass Mountain, or from the Mono Craters, of eastern California—using single shard analysis alone. Development of ion-probe technology, however, may provide a breakthrough in single-shard analysis for minor and trace elements of tephra.

In addition to chemical characterization of the volcanic glass, supplementary analyses include mineralogy and shard morphology. Characteristic stratigraphic sequences (invariate homotaxial successions), and relative- and numerical-age data provide additional evidence that is weighed in assessing the validity of correlated ages, imported on the basis of chemical composition of glass shards. Magnetostratigraphic studies often complement the tephra studies, and help to provide a more definitive chronostratigraphy. The presence of well-dated tephra layers within sections helps, in turn, to calibrate paleomagnetic reversal sequences in time. The resulting magnetostratigraphy, in turn, provides age brackets to undated tephra layers in studied sections, or confirmation of their ages and, consequently, their identities. See, for example, Liddicoat (this volume), who has determined the magnetostratigraphic record for the upper part of the Furnace Creek Formation; our work in Double Ash Wash of the same area (stop B5) has resulted in identification of six tephra layers.

### Other dating methods

Methods other than tephrochronology that have been employed in Death Valley include the direct dating of volcanic flow rocks by K-Ar or the newer $^{40}Ar/^{39}Ar$ techniques. For example, dating of basalts in the Furnace Creek, Nova, Copper Canyon and Ubehebe basins provides limiting ages for overlying or intercalated tephra-bearing sediments (Wright and others, 1991; Hodges and others, 1989, Drewes, 1963; Snow and Lux, 1999, respectively). The ages of these basalts (5.2 to 3.7 Ma) are generally older than most of the tephra layers we are dealing with in this study. Other techniques currently employed in developing age control for studies in Death Valley are luminescence and $^{14}C$ dating (Anderson, 1998; Klinger, 2001), $^{230}Th/^{234}U$ dating (Hooke, 1972; Ku and others, 1998), cosmogenic exposure dating (Knott, 1998; Phillips and Zreda, 1999), relative-age dating techniques (Klinger and Piety, 1996), soils (Knott, 1998; KIinger, 2001), and magnetostratigraphy (Pluhar and others, 1992; Liddicoat, this volume).

## CORRELATION OF UPPER NEOGENE DEPOSITS IN THE DEATH VALLEY REGION—SOME GENERAL OBSERVATIONS

Major research sampling sites for chronostratigraphy and other age control in the Death Valley region are shown in Plate 1 (Shaded Relief Map of the Death Valley region, 11" x 17", fold-in with field trip guide). Accompanying this map is a tephra correlation chart, Plate 2 (also separate), for the Death Valley area. In general, tephra correlations and ages fall into three main age groups within the upper Neogene deposits of Death Valley: middle and late Pliocene (~4.2 to ~3.1 Ma), late Pliocene and early Pleistocene (~2 to ~1.8 Ma), and middle Pleistocene to late Holocene (>1.2 Ma).

More than 20 tephra layers and groups of closely related tephra layers have been identified in the Death Valley area (table E-1). The individual tephra layers are distinguished on the basis of their chemical and petrographic characteristics, and have been dated or their ages bracketed within relatively narrow age ranges, at various sites in the western U.S., and a few, within the Death Valley area. Groups of chemically and petrographically similar tephra layers that are also close in stratigraphic position are also correlated, but somewhat more loosely constrained in terms of age ranges. Tephra layers in these groups are difficult to distinguish on an individual basis by EMA alone, and usually require analysis by more sensitive techniques to identify them to a unique “species” level (that is, to individual layers). The latter type of analysis (for example, by INAA or ICP-MS) has been done on only a few samples.

### Middle to Upper Pliocene tephra layers

Overlying the 5.9- to 3.7-Ma basalts in Copper Canyon, Furnace Creek, Nova, and Ubehebe basins (Drewes, 1963; Hodges and others, 1989; Wright and others, 1991; Knott and others, 1999, Snow and Lux, 1999), is a group of middle and upper Pliocene tuffs that range from ~<4.2 to ~2.8 Ma in age. To date, at least eight tuffs within this age range have been found in the Death Valley area. These tuffs include the lower Nomaki (Nomlaki-like) tuff (~4.2 to >3.58 Ma), tuff of Curry Canyon (>3.35 Ma), lower (3.35 Ma) and upper (~3.3 to 3.1 Ma) tuffs of Mesquite Spring, Nomlaki Tuff Member (~3.3 Ma), an unnamed tuff in “Double Ash Wash” of Cascadian provenance in Furnace Creek (~3.15 Ma), an unnamed tephra layer in Furnace Creek derived from the Coso volcanic field to the west of Death Valley (~3.09 Ma), and the tuff of Benton Hot Springs (2.81-2.87 Ma). Three or more of these tuffs are found in all of the major late Neogene basins of Death Valley including Furnace Creek, Nova, Copper Canyon, northern Death Valley, and central Death Valley basins. Two families of tuffs (Mesquite Spring and Nomlaki) are important marker beds in Death Valley.

### Tuffs of Mesquite Spring

Several of the tephra layers found throughout Death Valley area are quite thick and coarse, contain large pumice lapilli (2-5 cm), and are thick (up to 8 m); as such we think they must be derived from a nearby source (<60-100 km). These tuffs are chemically similar to each other, and are part of a chemical “family” of tephra layers erupted from sources in the western Great Basin. Because of their importance to the late Neogene stratigraphy of the Death Valley region, we (e.g., Knott and others, 1999; Machette and others, this volume; and this paper) and others (e.g., Holm and others, 1994; Snow and Lux, 1999) have dated these layers directly or by other means and have obtained consistent ages between 3.5 to ~3.1 Ma, mostly about 3.3 Ma. We refer to this group of tuffs collectively as the *tuffs of Mesquite Spring*.

Previously, the tuffs of Mesquite Spring group were tentatively correlated with either the Bishop ash bed (~0.76 Ma), or the upper Glass Mountain D ash bed (~1.2 Ma to ~0.90 Ma; Izett, 1981; Sarna-Wojcicki and others, 1984; Izett and others, 1988; Sarna-Wojcicki, 2000), which they strongly resemble in composition, mineralogy, and shard morphology. Slightly higher concentrations of Mn and Ca, as measured by EMA, however, prevented conclusive correlation with the latter units. Tephrochronologic studies south of Fish Lake Valley, at Willow Wash (Reheis and others, 1991), and in the Amargosa Desert (A. Sarna-Wojcicki and J. Yount, unpublished data, 1983), in Searles Valley, and the Searles Lake core (Smith and others, 1983; Sarna-Wojcicki and others, 1984; and Sarna-Wojcicki, unpublished data, 1984) revealed that some tephra of this chemical type was stratigraphically close to, or underlay the

*Table E-1. Characteristics of tephra layers found in the Death Valley area*

| Name of Tephra Unit | Age | Eruptive Source | Chemical Type | Diagnostic Mineralogy | Shard characteristics |
|---|---|---|---|---|---|
| Ubehebe cinders and ash | <300 yr B.P. | Ubehebe Crater, Death Valley, Calif. | Basaltic, low Si, K; very high Fe, Mg, Ca, Ti. | NA | cinders, ash |
| Mono Craters, Panum Crater(?) ash bed | 1200 yr B.P. | Mono Craters, Calif. | Rhyol., low Fe, Mg, Ti; high K, Na | qtz, san, biotite | pum, b-wall, chunks |
| Mono Craters, Wilson Creek Bed 10-19(?) | 25 to 34 ka | Mono Craters, Calif. | Rhyol., low Fe, Mg; Ti; high K, Na | qtz, san, biotite | pum, b-wall, chunks |
| Orange ash beds (1 at Lake Tecopa) | ~170 to 220 ka | Newberry, Oregon area | Rhyo-dac., high Fe, Ca, Mg, Ti, Na; low K | plag, (hblde, biotite: detrital?) | pum, b-wall, b-wall junct. |
| Dibekulewe | 0.51 Ma (?) | Unknown; S. Cascade (?) | Rhyol., low Fe, Ca, Mg, Ti; high K, Na | plag. | pum, b-wall, b-wall junct. |
| Lava Creek B ash bed | 0.67 or 0.64 Ma | Yellowstone National Park area | Rhyol., interm. Fe, low Ca, Mg, Mn; high K | qtz, san, cpx, zir, chev | b-wall, b-wall junct. |
| Bishop ash bed | 0.76 Ma | Long Valley, Calif. | Rhyol., low Fe, Ca, Mg, Ti; high K, Na | qtz, san, biotite, opx, zir, alan | pum, b-wall, b-wall junct. |
| Upper Glass Mountain ash beds (2 or more) | ~0.80 to ~1.2 Ma | | Ti; high K, Na | qtz, san, biotite, px, zir, hblde? | pum, b-wall junct. |
| Middle Glass Mountain (?) ash bed | ~1.5 Ma | Glass Mountain, Calif. | Rhyol., low Fe, Ca, Mg, Ti; high K, Na | qtz, san, biotite, px, zir, hblde? | pum, b-wall junct. |
| Lower Glass Mountain ash beds (13 or more) | ~1.80 to ~1.95 Ma | Glass Mountain, Calif. | Rhyol., low Fe, Ca, Mg, Ti; high K, Na | qtz, san, biotite, px, zir, hblde? | pum, b-wall junct. |
| Tuffs of Emigrant Pass (Fish Lake Valley) (3) | <2.09 to >1.95 Ma | Glass Mountain, Calif. (?) | Rhyol., low Fe, Ca, Mg, Ti; high K, Na | qtz, san, biotite, px, zir, hblde? | pum, b-wall junct. |
| Tuff of Confidence Hills | <2.09 to >1.95 Ma | Cascade Range (?) | Rhyo-dac., high Fe, Ca, Mg, Ti, Na, low K | plag | pum, b-wall junct. |
| Huckleberry Ridge ash bed | 2.09 Ma | Yellowstone National Park area | Rhyol., interm. Fe, low Ca, Mg, Mn; high K | qtz, san, cpx, zir, chev | b-wall, b-wall junct. |

Nomlaki and Putah Tuffs (Tuff Members of the Tehama and Tuscan Formations in Sacramento Valley, Calif.). The latter tuffs are ~3.3 and ~3.4 Ma, respectively (Sarna-Wojcicki and others, 1991). Thus, the compositionally “Bishop-like” tephra at Willow Wash in upper Neogene sediments at several sites in the Death Valley region could not be either the Bishop or Glass Mountain ash beds, but had to be older. Subsequent analyses of these tephra layers by INAA and ICP-MS support the correlations to the older age range, as do independent $^{40}Ar/^{39}Ar$ dates on the tuffs of Mesquite Spring (Snow, 1990; Holm and others, 1994; Snow and Lux, 1999; and this paper).

A good example of the close similarity of the Mesquite Spring and Upper Glass Mountain families of tuffs is from Six Springs Canyon in southern Death Valley. Izett and others (1988) correlated a tuff at Six Springs Canyon, in the southern Panamint Range, with the Glass Mountain D ash bed (~0.9 Ma). The tuff of Six Springs Canyon, however, is most similar chemically to the tuffs of Mesquite Spring (Knott and others, 1997, 2000).

The similarity of the chemical composition of the tuffs of Mesquite Spring to the Bishop and Glass Mountain tephra layers suggests that they were both erupted from the Long Valley-Glass Mountain volcanic field ~100 to 150 km to the northwest (Sarna-Wojcicki and others, 1984; Izett and others, 1988). The tuffs of Mesquite Spring, however, are older than any silicic volcanics at Long Valley (Metz and Mahood, 1985). Additionally, more precise analysis of volcanic glass for minor- and trace-elements of the tuffs of Mesquite Spring and the Bishop and Glass Mountain tephra layers by ICP-MS and INAA shows consistent and significant differences between these two groups in glass chemical composition that allow us to distinguish between them (Knott and others, 1997; Sarna-Wojcicki and Budahn, unpublished data, 2000).

Where found in Death Valley, including Six Springs Canyon, the tuffs of Mesquite Spring are relatively thick (0.5-7 m), thin to the southeast, and are generally coarse grained (pumice clasts ranging from sand-size up to 2-3 cm in diameter). In contrast, the Bishop ash bed at Mormon Point, which is at the same latitude as Six Springs Canyon, has a cumulative thickness of 3 m with a maximum grain-size diameter of 0.5 mm. These characteristics suggest that the source of the tuffs of Mesquite Spring is to the northwest of central Death Valley, probably closer than the Long Valley volcanic field, but the exact source of the tuffs of Mesquite Spring is as yet unknown.

### Nomlaki and related tuffs

The ~3.3-Ma Nomlaki Tuff (Member of the Tehama and Tuscan Formations in northern California; Sarna-Wojcicki and others, 1991), and the older, lower Nomlaki (“Nomlaki-like”) tuff that underlies the tuffs of Mesquite Spring, has also been identified in the Death Valley region (Knott and others, 1999; Knott and others, this volume). The Nomlaki Tuff is a widespread marker bed in the western U.S., frequently found with the underlying ~3.4-Ma Putah Tuff. The Putah Tuff is derived from the Sonoma volcanic field north of San Francisco Bay, California. The Nomlaki Tuff, and the lower Nomlaki tuff are derived from the southern Cascade Range, in northeastern California. At Willow Wash in Fish Lake Valley, a Mesquite Spring tuff and the lower Nomlaki tuff underlie the Nomlaki and Putah Tuffs.

We derive a crude age estimate for the lower Nomlaki tuff based on its exposure in Hunt Canyon, and at Bristol Lake, south of Death Valley. Magnetostratigraphy indicated that the lower Nomlaki tuff has a reverse paleomagnetic declination. Thus, its minimum age must be 3.58 Ma, equivalent to the top of the Gilbert Reversed-Polarity Chron that has an age range of 3.58 to 4.18 Ma (Berggren and others, 1995). At Bristol Lake, ~150-200 km to the southeast of Death Valley, in core CAES#1 (Rosen, 1989), a tuff of Mesquite Spring is underlain (87 m lower down) by the lower Nomlaki tuff, similar to that in Hunt Canyon. The Nomlaki Tuff (~3.3 Ma), and a tuff correlated to the Burmeister core (BUR840.1; ~2.75 Ma), are present higher in the core (fig. E-1). Extrapolating from the correlated age data higher in the Bristol Lake core, we get an age estimate of ~4.2 Ma for the lower Nomlaki tuff. This estimate is consistent with the >3.58 Ma age estimated at Hunt Canyon, but probably is a maximum age.

### Upper Pliocene to Lower Pleistocene tephra layers

A second set of tephra layers, representing a younger time frame (~2.2 to ~1.8 Ma) is found in Death Valley. These tephra layers include the tuffs of Blind Springs (formerly called the tuff of Taylor Canyon; 2.22 Ma), the Huckleberry Ridge ash bed (2.09 Ma), the tuff of Confidence Hills (<2.09, >1.95 Ma), the tuffs of Emigrant Pass (<2.09, >1.95 Ma), and the lower tuffs of Glass Mountain (<1.95, > 1.79 Ma). These tuffs are found predominantly in the Confidence Hills of southern Death Valley (Troxel and others, 1986; Sarna-Wojcicki and others, in review). But they are also found at Artists Drive (Knott and others, 1999), Furnace Creek (Machette and others, this volume), and northern Death Valley (Klinger and others, this volume).

### Middle Pleistocene to Holocene tephra layers

A third set, representing a time range from between about 1.2 to ~0.01 Ma, includes the upper ashes and tuffs of Glass Mountain (~1.2 to 0.8 Ma), the Bishop ash bed (0.76 Ma), the Lava Creek B ash bed (~0.67 to 0.64 Ma), the Dibekulewe bed (~0.51 Ma) of Davis (1978), a tephra layer of Mono Craters, and the locally derived Ubehebe (cinder) bed. The middle Pleistocene tephra beds are found at Mormon Point (Knott and others, 1999), and possibly at the Kit Fox Hills (Klinger, this volume), whereas the latest Pleistocene tephra beds are found in northern Death Valley.

The three middle Pleistocene tephra layers (Bishop ash bed, Lava Creek B ash bed, and Dibekulewe bed) form a characteristic and important set of middle Quaternary chronostratigraphic marker beds in the western Great Basin, and are particularly useful for studies of middle Quaternary climatic fluctuations, as well as tectonic reconstructions. The tripartite sequence of Bishop ash bed, overlain by the Lava Creek B ash bed, and in turn by the Dibekulewe, is distinctive and identifies the layers and the intercalated sediments as middle Pleistocene in age.

The upper tephra layers of Glass Mountain that underlie the Bishop ash bed are chemically very similar to the Bishop. When found in isolated outcrops without other stratigraphic context, we often cannot distinguish them from the Bishop ash bed on the basis of EMA analysis alone. In these instances, in addition to more precise analyses using INAA and ICP-MS, paleomagnetic orientation is a valuable aid because the Bishop ash bed lies within the Brunhes Normal-Polarity Chron, while most of the upper Glass Mountain ash beds lie within the later part of the Matuyama Reversed-Polarity Chron (Sarna-Wojcicki and others, 2000). When multiple ash beds of the Bishop ash-Upper Glass Mountain chemical types are superposed in stratigraphic sections in the western Great Basin, the uppermost layer is usually the Bishop ash bed, particularly if it is the thickest and/or the coarsest. Nonetheless, precise chemical and paleomagnetic data are useful to confirm the identities of tephra layers in such sequences.

### Late Pleistocene and Holocene Tephra Layers

In addition to these three upper Neogene sets of ash beds, three very young tephra units (latest Pleistocene and Holocene) are also present in northern Death Valley. One of these ash beds is found in ancient “cienega” (marshy-spring) deposits in the uppermost part of the “Lake Rogers” beds. This unit is tentatively correlated with a late Pleistocene (34-25 ka) tephra layer of the Mono Craters near Mono Lake, Calif. In addition, a late Holocene Mono Craters tephra layer (<1200 yr) is found at two separate sites, in ponded sediments behind a shutter ridge along the Northern Death Valley fault east of the Lake Rogers beds, and interbedded with dune sand in Mesquite Flat. The third and youngest unit is the basaltic ash erupted from Ubehebe Crater in northern Death Valley, which is distributed locally. Charcoal from just below this unit has been dated at 300 $^{14}$C yr B.P. This ash is commonly seen on the surface or beneath a thin cover of eolian or alluvial sediments. The names, ages, summary chemical and petrographic characteristics, and sources of these tephra layers (where known or inferred) are summarized in table E-1.

Note that although the $^{40}$Ar/$^{39}$Ar ages cited here might have an analytical precision of as high as ±0.2 percent, they have been obtained by different laboratories using different monitors in analysis, or different values for the same monitors. These differences are as high as 2 percent. Other analytical and sampling errors—for example, the presence of excess radiogenic argon, or its loss after emplacement of the tephra—may equal or exceed the monitor errors. The evaluation and coherence of isotopic ages here, as elsewhere, is tested by agreement of ages with stratigraphic positions of multiple units, and agreement of multiple dates determined on the same units, from either the same or correlated sites.

In summary, recent geologic mapping and chemical fingerprinting of tephra layers in the Death Valley area have resulted in identification of ~40 tephra layers, spanning an age range of about 4 Ma to the late Holocene. Of these, about half are diagnostic with respect to their ages and compositions, so that they can provide correlated ages to sediments within this time frame, even at isolated exposures. With additional, precise chemical analysis for minor and trace elements, the remaining ~20 tephra layers, may also be uniquely identified by their compositions and/or dated directly, providing refined age control to upper Neogene deposits in Death Valley.

## DISTRIBUTION OF TEPHRA THROUGH TIME, AS CONTRASTED WITH TEPHRA PRESERVATION IN STRATIGRAPHIC SECTIONS—SOME GENERAL OBSERVATIONS

As we can infer from the above discussions, the presence of tephra layers in upper Neogene deposits in Death Valley is spatially sporadic, coinciding with the distribution of sediments of this age, as well as temporally episodic. The latter effect may be a consequence of either the episodic nature of volcanic eruptions that have produced these layers, or of the episodic nature of tephra preservation. Although both factors probably play a role in the record that is preserved in Death Valley, we know from other studies that there are many more tephra units within the interval of time considered here (~4 Ma to Holocene) in the western U.S. than what has been found in Death Valley. Preservation of tephra layers is enhanced in low-energy aqueous environments, such as perennial lakes and marshes (“cienegas”). Tephra layers are also better preserved at sites where they are rapidly buried after deposition. From this, we may conclude that tephra layers in general are more likely to be preserved in depositional environments during wet/cold (i.e., glacial) periods, and that the tephra groups mentioned above were deposited during generally wetter, cooler periods in the past. Correlations of tephra layers to other sites in the greater Death Valley region, for example, to Lake Tecopa to the southeast and to ancient Searles Lake to the southwest, support the general observation that tephra layers tend to be better preserved during cool/wet periods. At Lake Tecopa and in Searles Lake, multiple tephra layers are preserved in basinal lacustrine deposits, where at present only dry playas exist. At Lake Tecopa, the Huckleberry Ridge ash bed, several of the older and younger Glass Mountain tephra layers, the Bishop and the Lava Creek B ash beds, were all deposited during periods that were relatively cooler/wetter than the present, as indicated by their presence within lake beds. Probably the best preserved records of tephra layers are in long-lived lake basins, where the tephra is deposited into standing water and rapidly covered by sediments. In basin-margin deposits such as alluvial fans and debris flows, some of the same tephra layers are also preserved, presumably because they were quickly covered by younger deposits, again suggesting that storm frequencies may have been higher at these times.

During drier and warmer periods, tephra deposited on the land surface tends to be quickly reworked by flash floods and by wind, and redeposited, but the absence of perennial, standing water bodies makes the tephra deposits on playa surfaces vulnerable to eolian and fluvial reworking, and dilution with clastic sediments brought down to the playas.

A final factor that relates to the tephra record available in Death Valley is the long-term opportunity for tephra layers to become *exposed* at the surface by tectonic uplift and exhumation of basinal sediments, as a function of rates of sedimentation and tectonic uplift. For example, multiple tephra layers correlative with deep-ocean oxygen-isotope stage 6 (~180-127 ka), and stage 2 (~30-14 ka) have been found at many sites within the tectonically unstable western margin of the Great Basin. Death Valley, however, has been the depositional sump during pluvial periods for both the east Sierran and the Amargosa Desert drainage systems (Plate 1), and sedimentation may be too rapid relative to tectonic uplift, to have exposed the younger tephra layers.

## SAMPLE/STUDY SITES IN DEATH VALLEY

Several sites in Death Valley have been studied intensively to provide age control. These sites contain multiple tephra layers within relatively thick stratigraphic sections; some contain fine-grained sediments, which are conducive to tephra preservation. Presence of multiple layers increases the probability of identifying diagnostic tephra of known age ("ringers"), whereas the fine-grained nature of the containing sediments enhances preservation of tephra layers, both during and after deposition, and also provides good materials for paleomagnetic studies.

### Lake Rogers basin, northern Death Valley

Several tephra layers are exposed on the northeast side of Lake Rogers basin, in and near Death Valley Wash, just west of the Northern Death Valley fault zone that bounds the eastern side of northern Death Valley (Klinger, this volume). The stratigraphically lowest layers are exposed in playa and debris-flow deposits that are overlain by coarser alluvial fan deposits (see Stop A2, this volume). Starting from the bottom of Death Valley Wash, the lowermost exposed tephra is a thick, reworked, coarse, pumiceous layer as much as 15 to 20 m thick; this unit (REK-DV-3) correlates chemically with the tuffs of Mesquite Spring. The same unit, as correlated by chemistry and petrographic characteristics, is found up a small tributary canyon just to the northwest of the latter locality and Death Valley Wash (REK-DV-5), where it appears to be air-fall ash. The two sites are separated by the Death Valley Wash fault, a steep northeasterly-dipping, reverse fault that parallels the Northern Death Valley fault, and the late Pliocene section appears to be repeated here by faulting (see Stop A2, Chapter A, this volume). We have determined a date of 3.27 ± 0.03 Ma on sanidine separated from coarse pumice lapilli obtained at the latter exposure. Both the composition and age of this unit are within the same ranges as the tuffs of Mesquite Spring, thus confirming its identification. The tuffs of Mesquite Spring here in Death Valley Wash were previously confused with, or even putatively assigned to, the younger Bishop and Glass Mountain group of tephra layers (see above).

About 1-2 km to the northwest of Death Valley Wash and the locality at which REK-DV-5 was collected are muddy playa beds overlying light-colored pink, sandy silty lake(?) beds. The playa beds contain a tephra layer ~30 cm thick (REK-DV-13), which chemically matches the middle tephra layer in "Slot Canyon" (REK-DV-2), on the basis of EMA and INAA. This tephra layer also correlates on the basis of chemical composition with one of the tuffs of Mesquite Spring (tephra layer at White Top Mountain [JRK-DV-71], in the Six Springs area in the Panamint Mountains [JRK-DV-SIX-SP], and in the Furnace Creek Formation along Furnace Creek [MNM-DV-8-FC]). Thus, these deposits are ~3.3 Ma in age, and the underlying pink lake beds must be older.

Reworked tephra similar to the Bishop ash and tephra of Glass Mountain (REK-DV-12) is present higher in a landslide deposit within the cienega deposits that overlies the basal tephra layer (REK-DV-13), but no definitive match can presently be made. The sediments containing REK-DV-12 and 13 dip to the east, and are unconformably overlain by much younger "cienega" deposits (see below).

Stratigraphically above the thick tuffs of Mesquite Spring in Death Valley Wash is a tephra layer (REK-DV-4A, 4B) that has not been previously identified in Death Valley. This tuff contains two compositional modes, a dominant and a subordinate mode. There is no particularly good match of this tuff to other tephra layers we have analyzed, although there is a similar tephra layer in the Burmeister core, estimated to be ~3.22 Ma in age, that is compositionally close (Bur 958.0; Williams, 1993; similarity coefficient of 0. 94). The age of this unit is compatible with the age and the stratigraphically lower position of the tuffs of Mesquite Spring.

To the east of Death Valley Wash, within a narrow tributary canyon referred to informally as "Slot Canyon" (Klinger, 2001), two tephra layers are present higher in the section above the massive reworked tuff of Mesquite Spring that is correlated to the Nova Formation as defined by Snow and Lux (1999). The lower of the two tuffs (REK-DV-2), present within pink muddy playa beds, is ~30 cm thick, and matches best with an unnamed tuff (CAES#1 857; Plate 2) present in cores from Bristol (dry) Lake in the southeastern Mojave Desert, where it underlies the Nomlaki Tuff and overlies the lower "Nomlaki-like" tuff (fig. E-1). We estimate that the age of REK-DV-2 is ~3.35 Ma, based on its position in the Bristol Lake core, and its position relative to correlated-age, overlying tephra layers (fig. E-1). Sample REK-DV-2 is also similar to the lower and upper Glass Mountain tephra layers, but the match is not as good. We tentatively correlate REK-DV-2 to the ~3.35-Ma tephra layer at Bristol Lake on the basis of close age and stratigraphic proximity to the Nomlaki Tuff (above), and on its close stratigraphic proximity above another tuff of Mesquite Spring at Death Valley Wash. Note, however, that the estimated age of REK-DV-2 at ~3.35 Ma is somewhat older than the 3.27-Ma correlated age of REK-DV-3 that lies stratigraphically below it. The ages are close, however, and the older age estimate for the upper tephra layer is likely to have a higher error associated with it.

Within coarse fan gravels about 25-35 m above REK-DV-2 in Slot Canyon, is a lenticular tephra bed (REK-DV-1) as much as 30 cm thick. This unit matches best with Upper Glass Mountain tephra layers: for example, with a Glass Mountain tephra layer in the Mormon Point area (JRK-DV-36), both on the basis of EMA and INAA analysis. If this correlation is correct, then this tephra layer (REK-DV-1) is probably between 1.2 and 0.8 Ma in age. These coarse fan gravels are included by Klinger (2001) in his unit Q1b, but would be correlative to the Panamint Valley sequence of Snow and Lux (1999) and the Mormon Point Formation of Knott and others (1999).

A few kilometers to the north of Slot Canyon, is another narrow canyon that we informally refer to as “Lake Rogers Canyon” (see Stop A2, Chapter A, this volume) that enters Death Valley Wash from the east. Three tephra layers have been identified in this canyon, all stratigraphically higher than REK-DV-4. The lower two of these three layers (REK-DV-8 and REK-DV-7), are stratigraphically close (1.5 m apart) and about 53 m above REK-DV-4. They are present within a part of the section consisting of silty sand and silty mudstone. On the basis of EMA and INAA analysis, they match most closely with the lower tuffs of Glass Mountain, for example, with the tuffs exposed in the upper part of the Confidence Hills section, ~1.95 to 1.80 Ma (see below). If our correlations are correct, the age data imply the presence of a significant unconformity in Lake Rogers Canyon, between samples REK-DV-4 and REK-DV-8. This unconformity is apparent in the difference in the dip of the beds as one goes up the section (REK-DV-4 is steeply dipping at ~70° to the northeast whereas REK-DV-8 is dipping at ~50° to the northeast). Sample REK-DV-7 also matches well with the lenticular tephra layer MNM-DV-1-FC beneath “capping” travertine-cemented gravel of the Furnace Creek Formation near Texas Springs (see below). At the latter locality, there is good evidence of an unconformity between the underlying finer-grained upper part of the Furnace Creek Formation, and the capping gravels of the Funeral Formation.

Stratigraphically highest in Lake Rogers Canyon, at about 112 m in the section above REK-DV-4, is a ~20-cm-thick tephra layer that resembles the Glass Mountain group of tephra layers in general chemical composition and in petrographic characteristics, but it does not match any of them well. It also has a unique composition in terms of its scandium content (determined by INAA), which is much lower than any of the other Glass Mountain tephra layers we have analyzed. Based on its position above the lower Glass Mountain ash beds, and its unique chemical signature, we believe that this unit may be a previously unknown, rare middle Glass Mountain tephra, erupted during the more generally quiescent period of the Glass Mountain source, roughly between 1.8 and 1.2 Ma.

### Lake Rogers beds (Field Trip Stop A2)

To the northwest of the sites just discussed, on the west side of Death Valley Wash and north of Ubehebe Crater (Stop A1), is an extensive area (about 8 $km^2$) of light-colored upper Neogene beds that have been previously interpreted to be lake beds (Clements, 1952; Moring, 1986). These beds appear to be “cienega” deposits (marsh or wet meadow deposits formed by seepages of ground water from springs during past wet periods; see Quade and others, 1995). The ancient “lake” basin may have formed by a blockage of the northern Death Valley Wash with upper Neogene basalts that crop out to the south of the lake beds, thus pounding water, or the basin may have been downdropped to the north, along the Tin Mountain and Death Valley Wash faults. These marshy deposits unconformably overlie upper Pliocene playa and lake(?) beds that contain one of the tuffs of Mesquite Spring (REK-DV-13, see above).

Within the young cienega deposit that unconformably overlies the unit containing a tuff of Mesquite Spring (REK-DV-13) is a 3-cm-thick tephra layer (REK-DV-11) that closely resembles late Pleistocene tephra erupted from the Mono Craters east of the central Sierra Nevada, based on EMA analysis. The closest matches are to Wilson Creek ash beds 9 through 19, in the age range of ~25 to ~40 ka, situated in pluvial lake beds on the north side of Mono Lake. At present, we are not able to make a definitive correlation with a specific bed of the Mono Craters ash beds based on the data we’ve obtained for REK-DV-11, but if this layer turns out to indeed be late Pleistocene, it would indicate that the cienega deposits in northern Death Valley are very young and correlate in part with deep-ocean oxygen isotope stage 3 and/or 2.

The cienega beds, unlike the underlying older playa deposits that contain the tuff of Mesquite Spring, appear to slope from the northwest toward the southeast, and this attitude may reflect their original depositional orientation. These deposits probably form during wetter periods, when the springs were active and gave rise to marsh vegetation that acted as sediment traps. During dry times, such as the present, when the springs are inactive and the marshes dry out, little or no sediment accumulates, and more than likely, erosion of the deposits takes place.

Similar but older cienega deposits are also present at the appropriately named Ash Meadows, in the Amargosa Desert to the east of Death Valley, and throughout the southern Great Basin (Quade and others, 1995). In Ash Meadows, James Yount and Sarna-Wojcicki (unpublished data, 1983) found one of the tuffs of Mesquite Spring, and a Nomlaki-like tuff (either the

Nomlaki Tuff or the lower Nomlaki tuff) within these deposits (not in continuous exposure). Such cienegas may contain long records of climatic variability and environmental change, but by their very nature, the succession of accumulation and deflation, and the concomitant complexity in the changing loci of both, suggest that the interpretation of such records may be difficult.

In addition to the Mono Craters tephra bed interbedded with the Lake Rogers beds, there are also two sites within northern Death Valley where upper Holocene Mono Craters tephra beds were identified. The ash at these two sites may be the same tephra layer.At a site in Mesquite Flat, a 2- to 3-cm-thick ash bed is exposed in a low, east-facing scarp along the Northern Death Valley fault, interbedded with eolian sand near the base of a nabkhas dune (south of Stop A4). A comparison of the major element oxide composition of the volcanic glass by EMA indicates that the ash bed is similar (SC=0.963) to a number of the Mono Craters ashes erupted from the Mono-Inyo Craters volcanic field. Based on aerial distribution patterns and comparisons of the trace-element composition, the ash bed is tentatively correlated to the “tephra 2” ash bed of Wood (1977) that erupted from Panum Crater at about 1190 ± 80 $^{14}C$ yr B.P. (950 and 1270 cal yr B.P.). The presence of an upper Holocene Mono Craters ash bed near the base of the dunes and the age of the Panum Crater ash is consistent with the age interpretation of the dunes by Hunt and Mabey (1966) based on archaeological correlations. The same, or a very similar, ash is also present in sediments ponded by a shutter ridge of the Northern Death Valley fault zone, in Lake Rogers basin. There, the ash is about 0.5 m below a $^{14}C$ AMS date on charcoal of 300 yr B.P. (Klinger, 2001). At this site, a cindery, basaltic ash layer is present just above the level of the dated charcoal (see Stop A1, Chapter A, this volume). This coarse, basaltic ash (REK-DV-10) is present at or near the surface throughout the Lake Rogers basin in northern Death Valley (Plates 1, 2), and was erupted from Ubehebe Crater in northern Death Valley. This tephra is readily identified by its composition, dark color, and stratigraphic position at the top of the section. The tephra record in Death Valley thus extends to the historic period of human occupation in the western U.S.

### Furnace Creek; Field Trip Stop B5

Fine-grained tuffaceous sediments in the east-central part of Death Valley, to the southeast of Texas Springs along Furnace Creek, and north and northeast of the campground and springs, have been mapped by Michael Machette as part of quadrangle mapping by Machette, Chris Fridrich, Janet Slate, and Ren Thompson (all USGS). Much of this area has also been mapped previously by McAllister (1970) at 1:24,000. The upper Neogene sediments exposed in this area are part of the Furnace Creek Formation (McAllister, 1970), which is composed of mudstones and fine- to coarse-grained alluvium that is gently folded into the broad, northwest-trending, southeast-plunging Texas Springs syncline (see stops B4 and B5, this volume, and Machette and others, 2000). The syncline also involves folded, coarse-grained deposits overlying the Furnace Creek Formation and early- to late-Quaternary stream gravels that are incised into this structure. Although McAllister assigned an age of Miocene and Pliocene(?) to the Furnace Creek Formation, our correlated ages indicate that this formation is as young as upper Pliocene.

Recent results of our joint mapping and tephrochronologic studies in this area provide new age calibration to these sediments (fig. B5; Plate 2). Proceeding from the southwestern limb of the syncline, within the uppermost part of the Furnace Creek Formation, we find the following tephra units:

1) The tuff of Curry Canyon (MNM-DV-5-FC; >3.5 Ma; also found by Knott in Curry Canyon and in the Funeral Formation, in the Artists Drive area; see below).

2) Above this basal unit are two tuffs of the Mesquite Spring group (Lower Ash MNM-DV-11-FC and no, 2b, Upper Ash MNM-DV-8-FC) separated by about 8m of strata.

3) Another 20-30(?) m upsection, there is a newly identified, compositionally distinct tuff that contains high concentrations of iron, calcium, and the minor elements magnesium, manganese, and titanium (MNM-DV-7 and -12). This tephra layer has a strong provincial resemblance to tephra layers erupted from the southern Cascade Range, and is thus probably derived from that area. We informally refer to this tuff as the unnamed tuff of Double Ash Wash (fig. B5; Plate 2). The age of this tuff has not been determined directly, but can be estimated by a process of successive correlations to several key sedimentary sections in the western U.S., and interpolations between layers of known age. The only other locality where this tuff has been found previously is in a core, from Bristol Lake, a dry playa about 150 km southeast of Death Valley (Rosen, 1989). There, the tuff is present at a depth of ~465 m in the core. Lower in this core, at a depth of ~501 m, we previously identified the Nomlaki Tuff (~3.3 Ma). Above the tuff, at a depth of ~450 m, we have also identified the La Salida tuff. The latter tuff has not been dated directly, but its age is estimated to be ~3.05 Ma from tephrochronology and magnetostratigraphy in the Burmeister core, which is from the Great Salt Lake (Williams, 1993). Using these age data and the position of the tuff in the Bristol Lake core relative to the correlated-dated tephra layers, we estimate the age of the unnamed tuff of Double Ash Wash to be ~3.15 Ma.

4) Stratigraphically above the latter tuff in the Furnace Creek area, we identify yet another rather rare tephra layer (MNM-DV-6-FC, -9-FC, and -10FC, fig. B5), that bears a very strong similarity in terms of its chemical composition to an ash-flow tuff erupted from the Coso volcanic field, ~90 km to the west of Furnace Creek (9-85-2A, pyroclastic flow between Cactus Flat and Haiwee Reservoir; 3.09 ± 0.09 Ma on sanidine.[1] Despite some difference in calcium, the over-

all similarity of the air-fall tuff to the ash flow in the Coso Hills, and concordant age with the stratigraphic sequence in the Furnace Creek Formation, support the correlation. This tuff is informally referred to as the unnamed tuff from Coso eruptive field.

5) The uppermost tephra layer found to date in the uppermost Furnace Creek Formation matches the tuff of Benton Hot Springs (MNM-DV-13-FC; 2.81 ± 0. 02 Ma; Sarna-Wojcicki and others, in review); equivalent to the Rimrock ash bed of Reheis and others (1991; 2.87 ± 0.03 Ma, Sarna-Wojcicki and others, in review; R.J. Fleck, written communication, 1997).

Unconformably overlying this section are upper Pliocene to lower Pleistocene gravels of McAllister's (1970) Funeral Formation that contain somewhat younger tephra. These are found near and northeast of the Texas Springs Campground. This tephra bed, which crops out near Texas Springs Campground (MNM-DV-3-FC), best matches lower to middle tephra layers of Glass Mountain, ~1.95-1.5 Ma. The two ash beds farther to the northeast (MNM-DV-1-FC, ~1.87 Ma; MNNM-DV-2-FC) best match the lower tephra layers of Glass Mountain,~1.97-1.90 Ma. These are tentative correlations and age assignments, and the actual stratigraphic positions of layers DV-2 and DV-3 are not well known. Paleomagnetic work in this area, together with additional minor- and trace-element characterization of the volcanic glasses of these units, may help to pin down the ages and identities of these units more precisely.

### Mormon Point (Field Trip Stop C1)

J.R. Knott studied the section at Mormon Point in detail (Knott, 1998; Knott and others, 1999). The section consists of faulted and gently folded alluvial fan and lacustrine sediments that form the hanging wall block of a shallow-dipping "turtle-back" fault. Earlier studies had broadly stated that these sediments were Quaternary, based on their youthful appearance (Noble and Wright, 1954; Drewes, 1963; Hunt and Mabey, 1966; Troxel, 1986); however, reliable age control has only recently become available (Knott and others, 1999). Identification of tephra layers present in the sediments as the middle Quaternary upper Glass Mountain, Bishop, Lava Creek B, and Dibekulewe ash beds in this section indicates that the sediments are younger than the Funeral Formation. Knott (1998) and Knott and others (1999) named these sediments the Mormon Point formation (informal name).

[1]Footnote: A K-Ar date of 3.75 ± 0.32 Ma was obtained on biotite, by Bacon and others (1982). The weighted age of both dates is 3.14 ± 0.15 Ma; we prefer the younger age, however, because of the age and stratigraphic constraints that we obtain in the Furnace Creek area.

### Copper Canyon and Artists Drive sections, east-central Death Valley (Field Trip Stop C3)

In Copper Canyon, a conglomerate mapped as the Funeral Formation by Drewes (1963) contains a tephra layer that has been dated by the $^{40}Ar/^{39}Ar$ (on biotite) at 3.1 ± 0.2 Ma (Holm and others, 1994) (Plate 1). This layer matches well in terms of its chemical composition and petrographic characteristics with one of several of the tuffs of Mesquite Spring, found within the Death Valley region, and to the north at Willow Wash (Reheis and others, 1991).

At Artists Drive in Hunt Canyon (Stop C3), two tuffs of the Mesquite Spring chemical type have been found in superposition, within the Funeral Formation, both overlying the lower Nomlaki tuff and straddling the Nomlaki Tuff (Knott and others, 1999; Knott and others, this volume). Most of the available correlated and direct age control suggests an age within the range 3.1 to 3.5 Ma for the tuffs of Mesquite Spring (Holm and others, 1994; Snow and Lux, 1999; Knott and others, this volume). The lower Mesquite Spring tuff is assigned an age of 3.35 Ma (Knott and others, this volume) based on (1) age determinations of 3.35 ± 0.5 Ma ($^{40}Ar/^{39}Ar$ on sanidine) on chemically identical tuffs (Snow, 1990; Snow and Lux; 1999); (2) its stratigraphic position below the ~3.3-Ma Nomlaki Tuff; and (3) its normal paleomagnetic orientation (corresponding to the lower part of the Gauss Normal-Polarity Chron, 3.33-3.58 Ma). The age of the upper tuff of Mesquite Spring is estimated to be ~3.1 Ma (Knott and others, this volume) based on (1) ~3.1-Ma age determinations on chemically identical tuff (Holm and others, 1994; Snow and Lux, 1999); (2) its stratigraphic position above the Nomlaki Tuff; and (3) its normal paleomagnetic declination (<3.22 Ma).

In Curry Canyon, about 1 km south of Hunt Canyon, the 3.35-Ma lower tuff of Mesquite Spring is exposed again. Here, the lower tuff of Mesquite Spring is stratigraphically underlain by another tuff, referred to as the tuff of Curry Canyon (Knott, 1998). Because of its stratigraphic position, the latter tuff must be older than about 3.35 Ma. This tuff is broadly similar in chemistry to the tuffs of Mesquite Spring, but chemically distinguishable from the latter. This tuff is also present in the upper part of the Funeral Formation near Zabriskie Point (MNM-DV-5-FC; see above, and Machette, this volume).

### Nova basin

Although not part of this field trip, the Nova basin is the most extensive and intact of the late Pliocene basins within the Death Valley area and therefore deserves mention here. This basin is situated in the west-central part of Death Valley at the northwestern end of the Panamint Mountains, south of Stovepipe Wells (Plate 1). The sediments are composed of basin-margin alluvial gravels and mudflows, intercalated basalt flows, and rare, lenticular tephra layers.

At least two tephra layers have been found within the Nova Formation (J. Tinsley, written communication, 1987; Hodges and others, 1989; Knott, 1998). We identify these layers as one or more of the tuffs of Mesquite Spring (JT-NOVA-1 and JT-NOVA-1600, and JRK-DV-80), and one of the Nomlaki-like tuffs (JT-WALL ASH and JT-BPT-1). The first two samples of the tuffs of Mesquite Spring are found west of Tucki Mountain, near Black Point; the third sample (JRK-DV-80) is further to the south, near Emigrant Wash Road. The tephra layer at Emigrant Wash has been dated at 3.35 ± 0.07 Ma ($^{40}Ar/^{39}Ar$ on sanidine; Snow, 1990). Due to local faulting, the exact relationship between the Nomlaki-like tuff and the tuffs of Mesquite Spring in the Nova basin is unclear. Therefore, without more precise chemical data, it is not clear which of the two Nomlaki tuffs this one is.

### Confidence Hills

The Confidence Hills are a linear range of low hills that crop out within the southern part of Death Valley. These were visited during the 1986 FOP trip (Troxel and others, 1986), and are an important tephrostratigraphic area (CH, Plate 1). The Confidence Hills are parallel to the trend of the dextral Southern Death Valley fault zone. These hills represent uplifted (possibly diapiric in part) older, late Neogene basin sediments that are now well above the present playa surface (Dooley and McClay, 1996). Several stream valleys that drain the Owlshead Mountains to the west of the Confidence Hills are antecedent to the uplift of the Confidence Hills, and cut eastward across the hills, more-or-less at right angles to their northerly trend. The bedding of the sediments exposed in these valleys is steep to vertical. The beds are composed of clays, silts, and fine sands, with lenses of coarser sand and gravel, some halite, and anhydrite. These sediments represent generally quiet-water depositional environments that would be encountered in the central and marginal parts of a depositional basin. The tephrochronology (Troxel and others, 1986; Sarna-Wojcicki and others, in review), sedimentology (Beratan and Murray, 1992), and magnetostratigraphy (Pluhar and others, 1992) of these beds have been well described. The section contains multiple tephra layers of latest Pliocene and early Pleistocene age, as described below.

Starting in the lower part of the section and proceeding upward, the tephra layers are (1) the tuffs of Blind Spring Valley (2.135-2.224 Ma; formerly referred to as the tuff of Taylor Canyon, Izett and others, 1988); (2) the Huckleberry Ridge ash bed (2.09 Ma); (3) the tuff of Confidence Hills (a previously unknown ash bed of Cascadian provenance, <2.09, > 1.95 Ma); (4) the tuffs of Emigrant Pass (<2.09, > 1.95 Ma); and (5) the lower tuffs of Glass Mountain (<1.95, >~1.80 Ma) (Plate 2). Magnetostratigraphic studies by Pluhar and others (1992), and chronostratigraphy provided by tephra correlations (Sarna-Wojcicki and others, in review) document the presence of two and possibly three Reunion Normal-Polarity Subchrons of the Matuyama Reversed-Polarity Chron (at ~2.225, ~2.175, and 2.145 Ma), the base of the Olduvai Normal-Polarity Subchron of the Matuyama Reversed-Polarity Chron (1.96 Ma), and the top of the Olduvai Subchron (1.79 Ma).

Several of these tephra layers are completely altered. Alteration probably occurred during drier periods, when alkaline conditions prevailed in the intermittent playas. Silica becomes readily soluble at higher pH's, thus the dissolution and alteration of volcanic glass are enhanced under these conditions. Loss of tephra and other fine sediments in the section may have also occurred during the drier periods by wind erosion, as mentioned above.

### Other sites in Death Valley

Within the Death Valley area, there are several sites not mentioned above, where tephra layers have been found. For example, scattered exposures of the tuffs of Mesquite Spring are found in the eastern foothills of the northern Cottonwood Mountains, near Mesquite Campground (from which the name of this group of tuffs is derived). Further to the southwest, tuffs of this same group are present along the White Top Mountain Road, and across Death Valley west of Mormon Point, in Six Springs Canyon of the Panamint Range.

### Other sites within the region

As mentioned above, development of the present tephrochronologic framework for Death Valley would not have been possible without the presence of several key "Rosetta stone" sections that are present within the greater Death Valley region, and from which we can import chronostratigraphic information, both sequence and age, to Death Valley. The closest reference sites to Death Valley are at Lake Tecopa, where an intermittent tephra record extends from 2.09 Ma to ~200 ka (Sarna-Wojcicki, and others, 1984; and Sarna-Wojcicki, unpublished data; Morrison, 1999). The Willow Wash section south of Fish Lake Valley contains one of the most complete, though structurally complicated, upper Neogene sections in the region (Reheis and others, 1991). The section represents a time span from ~5 Ma to ~1.7 Ma. The Bristol Lake section (Rosen, 1989), about 150 km to the southeast of Death Valley, provides a record of multiple tephra layers, from ~4.2 to 2.22 Ma, based on two cores recovered from depths of up to ~520 m. Simple interpolation and extrapolation of correlated-age tephra layers in these cores provide some new age control to tephra layers in Death Valley (Plate 2).

The stratigraphy and structure of Bristol Lake basin provides a glimpse into the subsurface that can serve as models for interpreting the subsurface stratigraphy and structure of other modern basins in the western Great Basin, such as Death Valley, and may shed light on some long-standing questions that relate to the late Neogene history of Death Valley and its extensive tributary fluvial/pluvial system. Among these is the long-standing hypothesis first posed by Blackwelder (1954)—that the southwestern Great Basin once drained via a southerly route, such as the Bristol Lake basin, to the Colorado River.

### ACKNOWLEDGEMENTS

We thank Drew Erikson, Regina Boussard, Michelle Richardson, and Elmira Wan for sample preparation and petro-

graphic descriptions of the tephra samples; Charles Meyer for assistance in EMA probe analysis; and Janet L. Slate and Scott W. Starratt for assistance in bringing this manuscript to completion and for improving the manuscript.

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# Paleomagnetism of the upper part of the Furnace Creek Formation, Death Valley, California

*Joseph C. Liddicoat*

CHAPTER F


## ABSTRACT

The upper part of the Pliocene Furnace Creek Formation exposed near its type area about 12 km east of the Furnace Creek Inn in Death Valley records two short reversals of the paleomagnetic field that might correlate with the Mammoth (3.33-3.22 Ma) and Kaena (3.11-3.04 Ma) Reverse Subchrons in the Gauss Normal Chron (3.58- 2.58 Ma). This interpretation is supported by volcanic tuffs found in a similar part of the section several kilometers to the northwest at FOP Stop B5; northeasts of Zabriskie Point. An alternate correlation is with two unnamed short reversals in the upper Gauss Normal Chron that place an age of about 2.8 Ma on the studied part of the formation. Either correlation is consistent with the Pliocene age assigned to the Furnace Creek Formation from paleontology investigations (Axelrod, 1940; Hunt and Mabey, 1966).


## INTRODUCTION

Death Valley is one of a series of valleys that generally trend north to south in the Great Basin of the western United States and that contained pluvial lakes in the Pleistocene. Rocks in Death Valley span much of the geologic time scale (Noble, 1934, 1941; Hunt and Mabey, 1966), but the Tertiary strata are mainly exposed along the margins of the modern pull-apart basins. Pliocene strata on the eastern margin of the valley include the Furnace Creek Formation composed of conglomerate and about 2,500 m of playa and lacustrine deposits exposed in fault blocks surrounding the central part of Death Valley (fig. F-1) and in the Texas Springs syncline within the Furnace Creek basin (fig. F-2). Overlying these strata are mainly fanglomerates of the Funeral Formation and Quaternary alluvial sediment. All of these deposits can be viewed from Zabriskie Point, near FOP Stop B4.

I sampled a section of the playa and lacustrine deposits for paleomagnetic investigation to try to narrow the age of the Furnace Creek Formation and to study a polarity

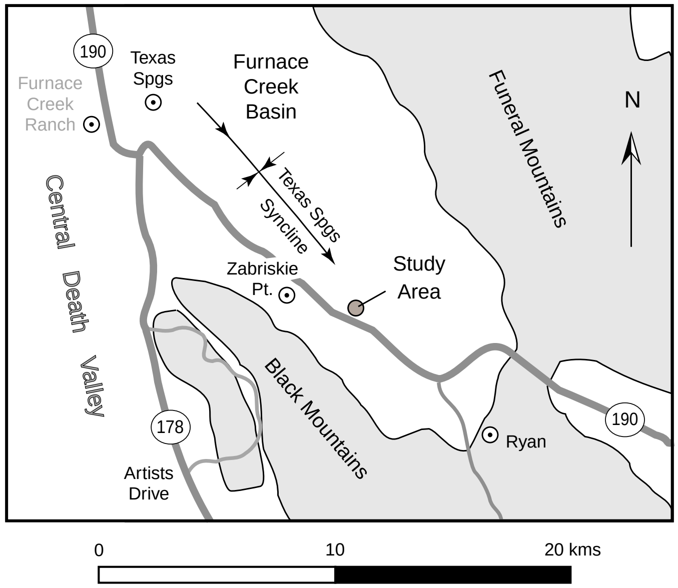


*Figure F-1. Map of Furnace Creek basin in Central Death Valley showing structural position of study area.*

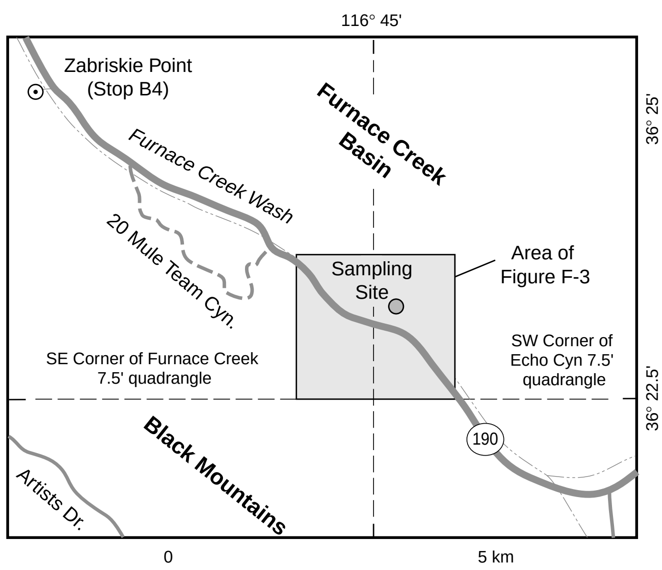


*Figure F-2. Map of paleomagnetic-sampling site on north side of California Highway 190 about 12 km east of Furnace Creek Inn in Death Valley, California.*

transition that occurs in this section. This report describes the results of the magnetostratigraphic investigation. The study of the polarity transition is still in progress.

## LOCALITY AND STRATIGRAPHY

About 200 m north of California Highway 190 in the southwest corner of the Echo Canyon 7.5' quadrangle, the fine grained upper part of the Furnace Creek Formation is exposed beneath a mantle of alluvial gravel on the north bank of Furnace Creek Wash (36.4° N, 116.7° W) (fig. F-3). The fine-grained basin-fill strata dip 30° to the northeast and continue laterally for about 130 m (45 m of section). About 30 m to the east across a tributary of the wash, the formation is exposed for another 40 m (15 m of section). Overall, the formation is about 3,000 m thick and consists of fine-grained playa deposits separated by a several conglomerates that thickens toward the center of the Furnace Creek basin (McAllister, 1970). Other conglomerates define the top and bottom of the formation, and some basalt is interbedded with the playa deposits west of the sampled section (Hunt and Mabey, 1966).

The provenance of the playa deposits is upper Tertiary volcanic rocks and Precambrian and Paleozoic rocks from the Funeral Mountains and Black Mountains that border Furnace Creek Wash on the northeast and southwest, respectively (fig. F-1). On the basis of lateral changes in thickness and geochemistry of the playa beds, it is believed the central part of the playa has moved progressively northwest, from this location to the center of Cottonball basin, where the modern playa beds are highly saline (see FOP Stop B2). Elsewhere, the playa beds contain sulfates, borates, and veins of gypsum. Magnetite is present in micrographs of thin sections of the playa beds (Hunt and Mabey, 1966). Diatoms collected from the top and base of the formation (Hunt and Mabey, 1966) and other plants (Axelrod, 1940) indicate a Pliocene age for the Furnace Creek Formation. Also, recent tephochronologic investigations by Sarna and others (Chapter E, this volume) reveal an age range of about 3.5-3.0 Ma for the upper part of the Furnace Creek Formation (see also FOP Stop B5).

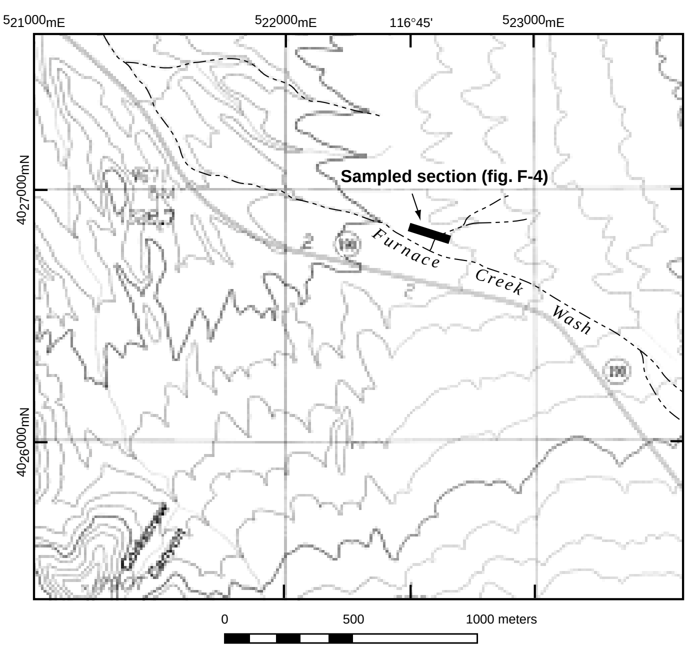


*Figure F-3. Topographic map showing location of sampled section shown in figure F-4.*

## FIELD AND LABORATORY PROCEDURES

Although indurated, the playa deposits are not hard enough to core with a portable water-cooled drill. Instead, oriented hand samples were collected and cut into subsamples (cubes 2.54 cm on a side) on a lapidary saw cooled with kerosene to avoid dissolution of the sediment. Individual beds in the playa deposits are a few to more than 10 cm thick, enabling repeated measurement of strike and dip on well defined bedding planes (fig. F-4). As many as six subsamples were prepared for each measured horizon. The combined error during the collection of hand samples and preparation of subsamples is estimated to be ±5° in the horizontal and vertical planes.

Alternating field and thermal demagnetization were used to demagnetize pilot subsamples spaced about 10 m apart in the section. The paleomagnetic measurements were done in a shielded room using a 2-G, 3-axis cryogenic magnetometer, and demagnetization was done using Schonstedt equipment. On the basis of those measurements, thermal demagnetization was chosen to demagnetize all other subsamples. The subsamples contain an overprint of normal polarity, which is removed at about 350 °C, and an unblocking temperature of about 650 °C (fig. F-5) reveals the presence of hematite.

## DISCUSSION

The section of the Furnace Creek Formation sampled for paleomagnetic investigation contains two short intervals of reverse polarity (fig. F-6). Without direct dating of the strata, there are two possible correlations. The first correlation (fig. F-6A) is with two reversals (Mammoth and Kaena; age 3.33-3.22 Ma and 3.11-3.04 Ma, respectively) recorded in lacustrine sediment in Searles Valley, California, about 80 km southwest of Death Valley. The paleomagnetic polarity time scale of Cande and Kent (1995), indicates that the maximum age of the lacustrine sediment in Searles Valley, recovered in the 930-m, rotary-drilled called KM-3 core (Smith, and others, 1983), is about 3.4 Ma (Liddicoat, Opdyke, and Smith, 1980).

However, the reversals in the Furnace Creek Formation match equally well with two younger but unnamed short reversals (R1 and R2) in the Gauss Normal Chron in KM-3 (fig. F-6B). Thus, a second correlation with those reversals is also possible. The ages of these younger reversals are about 2.7 and 2.8 Ma when extrapolated from the Gauss/Matuyama boundary (2.58 Ma; Cande and Kent, 1995) if it is assumed that the sedimentation rate in Searles Valley was about 2.5 cm/100 yrs.

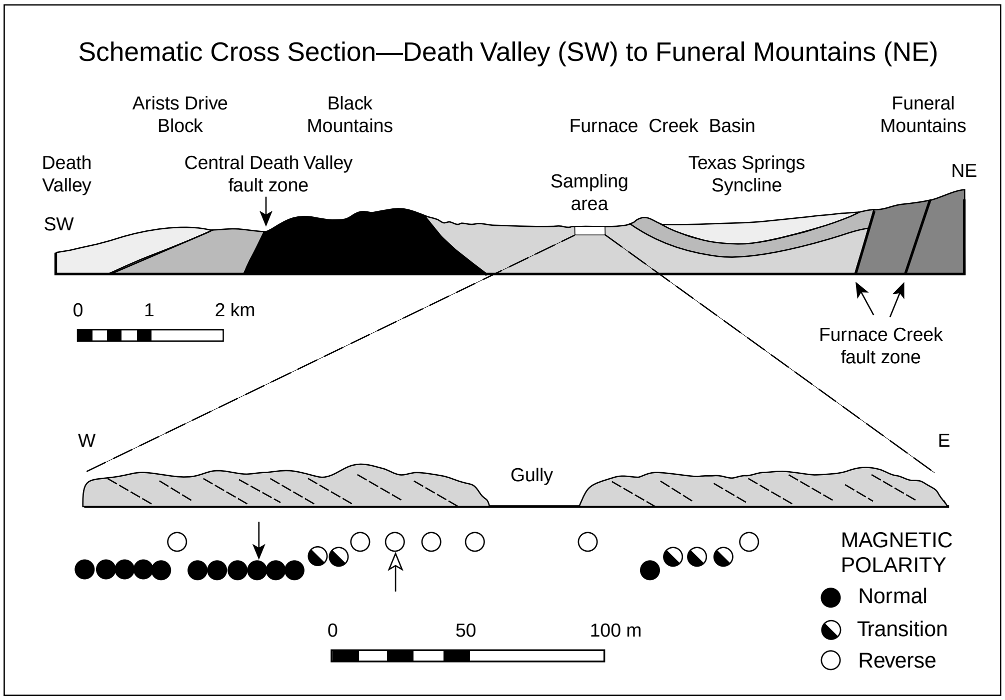


*Figure F-4. Above—Simplified geologic cross section across upper part of Furnace Creek basin near the locality sampled for the paleomagnetic investigation (after Hunt and Mabey, 1966, fig. 79). Below—Upper part of Furnace Creek Formation sampled for paleomagnetic investigation. Beds dip about 30° to northeast. Arrows identify sites for subsamples shown in figure F-5.*

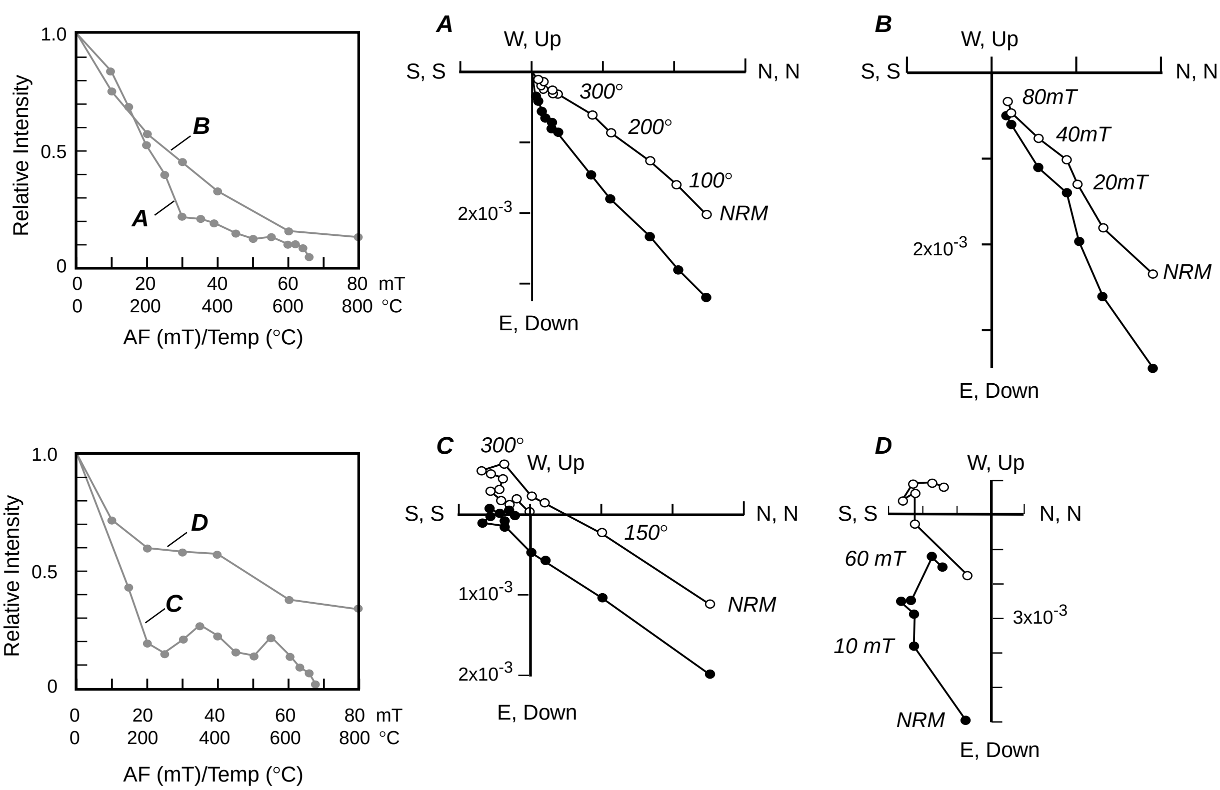


*Figure F-5. Relative intensity and vector end-point diagrams for subsamples progressively treated by thermal (A and C) and alternating-field (B and D) demagnetization. In vector plots, solid circles are projections on NS-EW plane and open circles are projections on EW-vertical plane. Divisions on axes are in Am$^{-1}$.*

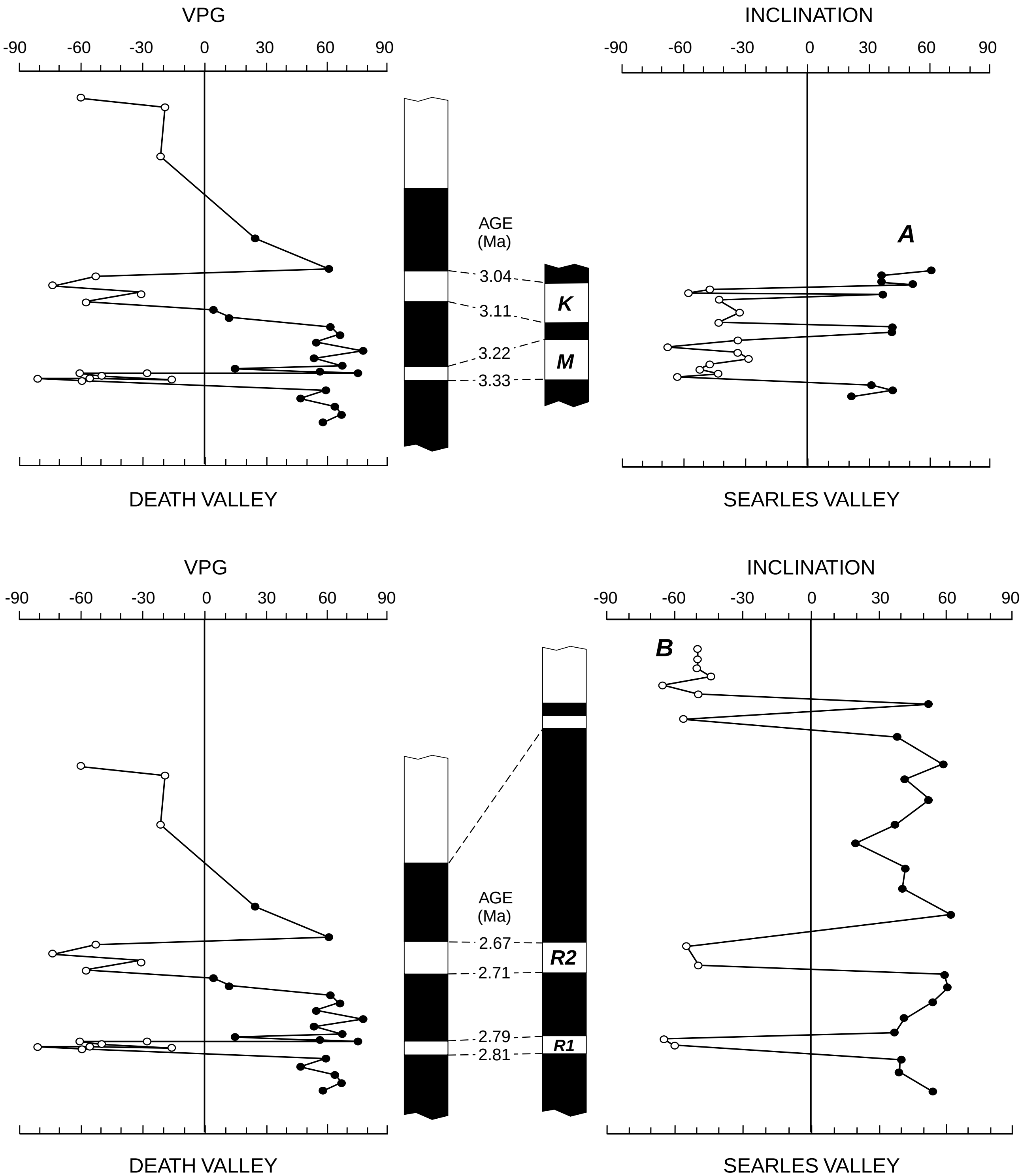


*Figure F-6. Virtual Geomagnetic Poles (VGP) for upper part of Furnace Creek Formation in Death Valley (left columns) and Inclination in Searles Valley core KM-3 (right columns). The large number of poles determined for lower reversal is for polarity transition study. VGPs for samples in KM-3 are not calculated because core is not oriented in horizontal plane. A) Upper-right column shows correlations with Mammoth (M) and Kaena (K) Reverse Subchrons, which are assigned ages of 3.33-3.22 Ma and 3.11-3.04 Ma, respectively (Cande and Kent, 1995). Negative VGPs indicate south latitude. B) Lower-right column shows correlations with two unnamed reversals (R1 and R2) in upper Gauss Normal Chron. Ages assigned to R1 and R2 are 2.81-2.79 Ma and 2.71-2.67 Ma, respectively. For Cande and Kent (1995) time scale, age for each reversal would be about 0.1 Ma older.*

The northeast declination for normal polarity and southwest declination for reverse polarity that are shown in the vector end-point diagrams in figure F-5 are not present in subsamples from most of the entire section. Thus, on the basis of all the paleomagnetic data, there is no indication of horizontal rotation about a vertical axis for strata of the Furnace Creek Formation that are exposed in the study area.

## SUMMARY


1. Two short reversals of paleomagnetic polarity in the upper part of the Furnace Creek Formation in Death Valley might correlate with either of two pairs of reversals of polarity in lacustrine sediment in Searles Valley, California. The possible match of the reversals to the Kaena (K) and Mammoth (M) Reverse Subchrons in the Gauss Normal Chron would make the sampled part of the Furnace Creek Formation about 3.2 Ma old. The other possible match of reversals to two unnamed reversals (R1 and R2) in the upper Gauss Normal Subchron would make the sampled part about 2.8 Ma.

2. The mean inclination in the Furnace Creek Formation is about 20° shallower than the inclination of an axial dipole field.

3. The mean declination in the Furnace Creek Formation does not reveal horizontal rotation where the formation was sampled.


## ACKNOWLEDGEMENTS


I thank Ed Rothfuss, former Superintendent of Death Valley National Monument, for permission to sample in the park, and Richard Reynolds of the U.S. Geological Survey for a critical review of the manuscript. National Science Foundation Grant 86-10050 provided funding for this investigation.


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# Questions about Lake Manly's age, extent, and source

*Michael N. Machette, Ralph E. Klinger, and Jeffrey R. Knott*

## ABSTRACT

In this paper, we grapple with the timing of Lake Manly, an ancient lake that inundated Death Valley in the Pleistocene epoch. The pluvial lake(s) of Death Valley are known collectively as Lake Manly (Hooke, 1999), just as the term Lake Bonneville is used for the recurring deep-water Pleistocene lake in northern Utah. As with other closed basins in the western U.S., Death Valley may have been occupied by a shallow to deep lake during marine oxygen-isotope stages II (Tioga glaciation), IV (Tenaya glaciation), and/or VI (Tahoe glaciation), as well as other times earlier in the Quaternary. Geomorphic arguments and uranium-series disequilibrium dating of lacustrine tufas suggest that most prominent high-level features of Lake Manly, such as shorelines, strandlines, spits, bars, and tufa deposits, are related to marine oxygen-isotope stage VI (OIS6, 128-180 ka), whereas other geomorphic arguments and limited radiocarbon and luminescence age determinations suggest a younger lake phase (OIS 2 or 4). In addition, the extent of constructional lacustrine features is poorly mapped, and the relationships between the lake deposits and alluvial stratigraphic units are poorly documented. Problems discussed in this paper tie directly to stratigraphic relations and possible ages for lacustrine gravel that we visit on our trip, specifically at the Beatty Junction bar complex (Stop A5), the Tea House above Furnance Creek Inn (Stop B1), and at Mormon Point (Stop C1).

As with many geologic controversies, Lake Manly's history is more unsettled than resolved. And like Lake Bonneville, which saw its purported history go from a relatively simple rise and fall to complicated oscillations based on complex interpretations, the history of Lake Manly has suffered from broad interpretations based on limited data. In this paper, we assess the merits and flaws of the various time histories proposed for Lake Manly.

## INTRODUCTION

Late 19th-century surveys of the Great Basin indicated widespread lacustrine deposits related to ancient Pleistocene lakes. Benchmark papers by Russell (1885, 1889) and Gilbert (1890) established the basic framework for Lake Lahontan in northern Nevada and Lake Bonneville in northern Utah. Both of these lakes occupied large closed basins, themselves the products of Pliocene to Pleistocene basin-and-Range extension (see Gilbert, 1928). Both Russell and Gilbert referred to a former lake in Death Valley, but Gale (1902) was the first to apply a name—Death Valley Lake. Gale, however, failed to recognize the immensity and importance of this lake, stating:

> *"In spite of the immense drainage territory [that is] tributary to Death Valley there is no evidence that the waters from these streams ever accumulated in it to sufficient extent to form more than a shallow inconstant lake. A search for traces of any upper lines [shorelines] around the slopes leading into Death Valley has failed to reveal evidence that any considerable lake has ever existed there." (Gale, 1914, p. 401, as cited in Hunt and Mabey, 1966, p. A69.)*

So, almost 20 years after Russell's inference of a lake in Death Valley, the pot was just starting to simmer.

## RECOGNITION AND NAMING OF LAKE MANLY

In 1924, Levi Noble—who would go on to have a long and distinguished career in Death Valley—discovered the first evidence for a large lake with his companions W.M. Davis and H.E. Gregory. Noble (1926) identified strandlines on a prominent basalt hill at the south end of Death Valley, which would later become known as Shoreline [*sic* Shore Line] Butte. By 1925, he found strandlines in the north-facing embayment east of Mormon Point (Noble, 1926, p. 69) that would later become a cornerstone of the lake's geomorphology and stratigraphy (Chapter C, Stop C1 in this volume). Soon thereafter, Means (1932) named the lake "Lake Manly," in honor of William Manly, one of the two men who lead the first pioneers out of the valley. Blackwelder (1933, 1954) conducted the first systematic studies of the lake's surficial deposits and geomorphology and used the term widely in his work. On the basis of mostly observational geology, Blackwelder (1933) speculated on the existence of Lake Manly, as well as its source areas, age, and predecessors. In one of the first papers documenting archaeological evidence for early man in Death Valley, Clements and Clements (1953) outlined the history of Lake Manly as it was then understood and described the locations of many newly recognized constructional landforms associated with the lake.

In 1966, Charlie Hunt and Don Mabey published the first comprehensive geologic map (1:96,000 scale) of the Death Valley area (Hunt and Mabey, 1966, plate 1). Hunt's mapping of the Quaternary deposits established a four-fold division of alluvial units, and related lacustrine deposits of Lake Manly to his alluvial stratigraphy (see discussions of Quaternary stratigraphy in Chapter H in this volume).

Most of the early studies of Lake Manly (see table G-1) involved comparative geomorphology, relative stratigraphic positions, and correlations of lake deposits (and history) to other well-studied lakes in the Basin and Range, such as Lakes Bonneville and Lahontan.

## THE AGE OF LAKE MANLY

With the advent of numerical dating techniques, chronologic studies sought to determine the age of Lake Manly—a few of which we summarize here (see table G-1).

In 1972, Roger Hooke reported ages between 11 and 26 ka based on the radiocarbon analysis of lake deposits from several cores near Badwater. He also mapped lacustrine deposits at several locations in central Death Valley (table G-1) and hypothesized that the prominent lacustrine deposits that extend to about +90 m elevation were related to the 11->26 ka sediments. He named this the Blackwelder stand of Lake Manly.

Subsequently, Hooke and Lively (1979; as cited in Hooke and Dorn, 1992) determined an age range of 60 to 225 ka using uranium-series disequilibrium dating; however, they recognized inconsistencies in their ages caused by open-system migration of daughter products of uranium. Consequently, Hooke and Dorn (1992) redefined the Blackwelder stand of Lake Manly as the one that left tufa at +90 m on the Black Mountains. These tufa deposits are now considered to have formed during marine oxygen-isotope stage VI (OIS6) (Ku and others, 1998).

Based on results from a series of shallow (up to 26 m deep) cores south of Badwater, Anderson and Wells (1996, 1997) proposed that numerous lakes occupied Death Valley in the latest Pleistocene (10-35 ka) and that they were relatively small, shallow, and separate from each other. Soon thereafter, Lowenstein and others (1999) analyzed a 126-m-long core from near Badwater and recognized two major lacustrine periods—an older lake at 120-186 ka (OIS6) and a younger lake at 10-35 ka (OIS2). A parallel study by Ku and others (1998) determined ages ranging from 18 to 216 ka on tufa along the Black Mountains from Badwater to Mormon Point. Both of these latter studies used uranium-series disequilibrium dating methods.

A selection of the chronologic studies on Lake Manly (table G-1) provides a broad context on the state and evolution of knowledge of the lake, with an emphasis on age and elevation of deposits. This compilation shows a significant range in the age estimates of Lake Manly deposits and that the dates of some shoreline features have also changed significantly over the last several years. Additionally, most of the data suggests that the +90 m shoreline is associated with an OIS6 highstand, but there also is a wide range in ages (18 to 216 ka) for the +90 m shoreline deposits. Dates coupled with careful stratigraphic studies and detailed mapping are needed to refine our understanding of the lake history and location of shoreline deposits.

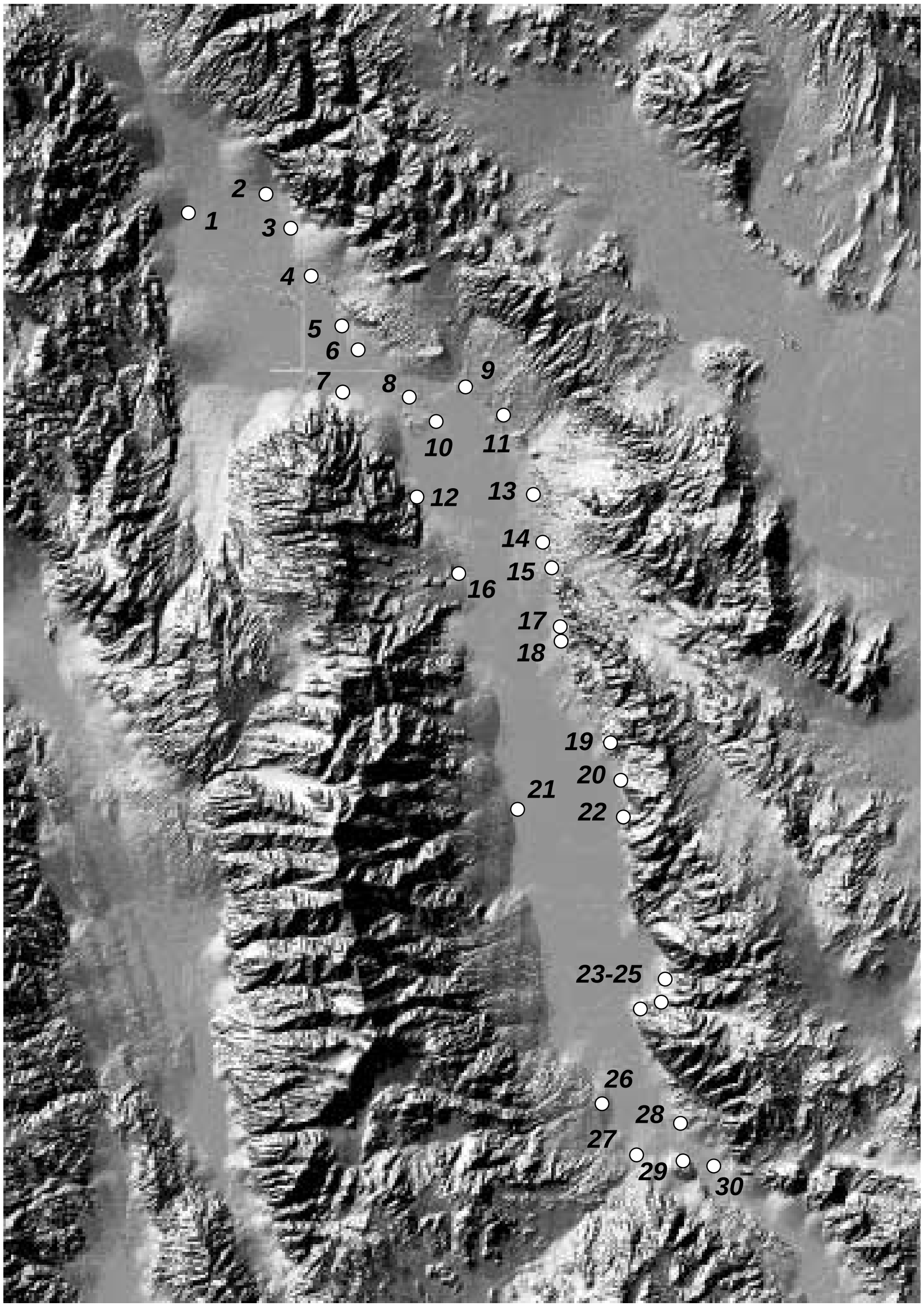
In the past 30 years, most geologic research on Lake Manly has involved local mapping, topical studies, and numerical dating, first using radiocarbon techniques and then uranium-series disequilibrium analyses (table G-1). More recently, researchers have attempted to date near-shore lake sediment by thermoluminescence techniques (TL, table G-1) and gravelly shoreline deposits by cosmogenic dating techniques (primarily $^{10}$Be and $^{36}$Cl, table G-1). No new systematic effort, however, has been undertaken to map the surficial deposits related to Lake Manly in a modern context and tie these deposits, their stratigraphic relations, and positions relative to the Death Valley fault system to the ever-increasing catalog of numerical ages. Therefore, we have initiated several separate studies to examine the age and distribution of Lake Manly deposits using cosmogenic- and luminescence-dating techniques coupled with geologic mapping. In addition, the continued compilation and updating of a catalog of all such significant deposits related to Lake Manly will provide a spatial and temporal framework for assessing existing and new age determinations.

## DISTRIBUTION OF CONSTRUCTIONAL DEPOSITS OF LAKE MANLY

Clearly recognizable lacustrine deposits are sparse but present throughout Death Valley, mainly at elevations below +90 m (<300 ft), although Hunt and Mabey (1966) suggested even higher deposits at several locations such as Shoreline Butte (fig. G-1, no. 29). and Dinosaur Ridge (fig. G-1, no. 16). Lake Manly deposits extend from Shoreline Butte, on the south, to as far north as the Mesquite Flat basin (fig. G-1, no. 2). At a hypothetical level of +30 m (+100 ft msl), Lake Manly would have been about 140 km long from north to south and 10-15 km at its widest.

The majority of the deposits are preserved along the eastern margin of the valley, mainly as a result of their preferential formation of the prevailing wind (west to east); this places the shoreline deposits close to the majority of active faults in the valley. Figure G-1 shows the approximate location of these deposits, and the associated table (table G-2) lists their attributes.

Notwithstanding the lake's long (north to south) fetch, the rather limited preservation of the deposits on the west side of the valley is somewhat surprising. This side of the valley is marked by very large alluvial fans, many of which are old enough (unit Qg2 of Hunt and Mabey, 1966) to have preserved shorelines and deposits of an OIS 2 or 4 lake. In fact, Blackwelder recognized this anomaly and said that the shorelines of Lake Bonneville and the expanded (deeper) stage of Mono Lake are *"…much more continuous and distinct than those of Lake Manly—an indication that they are younger"* (Blackwelder, 1933, p. 469). Blackwelder suspected, as we now know, that the prominent shoreline features of Lakes Bonneville




**Localities shown above:**
1. Niter beds
2. Titus Canyon (Stop A4)
3. Eastern Mesquite Flat
4. Triangle Springs
5. Mud Canyon
6. NPS Route5 at Hwy 190
7. Stovepipe Wells
8. Salt Creek Hills Anticline
9. Beatty Junction (Stop A5)
10. Salt Creek
11. Three Bare Hills
12. North of Salt Spring
13. Park Village Ridge
14. Road to NPS landfill
15. Tea House (Stop B1)
16. Unnamed ridge
17. Desolation Canyon (Stop C4)
18. Manly Terraces/Artists Drive
19. Natural Bridge
20. Nose Canyon
21. Tule Springs, Hanaupah Canyon
22. Badwater
23. Sheep Canyon
24. Willow Wash
25. Mormon Point (Stop C1)
26. Warm Springs Canyon
27. Wingate Delta (?)
28. East of Cinder Hill
29. Shoreline Butte
30. East of Ashford Mill

*Figure G-1 Index map of Death Valley showing selected locations of Lake Manly deposits. Information for localities are shown in table G-2. Base map modified from figure M-1 in this volume. North-south banding is an artifact of processing the DEM data.*

Table G-1. Selected compilation of Lake Manly chronologic studies

[Abbreviations: NA, not applicable; ka, thousands of years ago; msl, mean sea level, $^{14}C$, radiocarbon analysis; U-series, uranium-series disequilibrium analysis of calcium carbonate; TL, thermoluminescence; OSL, optically stimulated luminescence]

| Study | Observations/Contributions (no. is location on figure G-1) | Age and Elevation (msl) | Basis for Age |
|---|---|---|---|
| Noble (1926) | Recognized lake strandlines at Shoreline Butte (**29**) and Mormon Pt. (**25**). | NA | NA |
| Blackwelder (1933) | Described lake deposits at seven locations, Panamint Valley overflow at Wingate Pass | Tahoe glaciation (late Pleistocene) | Morphology |
| Clements and Clements (1953) | Described lake deposits at a number of locations throughout Death Valley | Tioga glaciation (latest Pleistocene) | Archaeology |
| Drewes (1963) | Mapped lake deposits at Mormon Point (**25)** | NA | NA |
| Hunt and Mabey (1966) | Mapped and described lake deposits at numerous locations throughout Death Valley | Late Pleistocene, older than Qg2 | Superposition of deposits |
| Hooke (1972) | Mapped and described lake deposits in central Death Valley and deltaic deposits of Wingate Wash (2**7**); dated sediment at 11-26 ka from core; named +90 m shoreline Blackwelder stand (**25**) | 11-26 ka at +90 m | $^{14}C$ |
| Hooke and Lively (1979) | Dated tufa at Goblet Canyon | 60-225 ka | U-series |
| Dorn (1988) | Dated rock varnish on shoreline features and deposits near sea level (**25**); speculated on deep lake during middle Pleistocene (oxygen-isotope stage 16) | 12 ka at 0 m; 665 ka | $^{14}C$ |
| Dorn and others (1989) | Dated rock varnish on shoreline features | 12 ka at +3 m | $^{14}C$ |
| Dorn and others (1990) | Dated rock varnish on shoreline features | 12 ka at 0 m; 120-130 ka at +90 m | $^{14}C$ and cation ratios |
| Hooke and Dorn (1992) | Dated rock vanish on shoreline features on Hanaupah fan (**21)** | 180 ka at +90 m | Cation ratios |
| Trull and others (1995) | Dated clasts from shoreline(?) deposits at Mormon Point (**25**), new locality near Tule Springs | 40 ka at 0 m; 135 ka at 158 m | Cosmogenic $^{10}Be$ |
| Anderson and Wells (1996, 1997) | Dated organic sediment from cores | 10-26 ka at -70 m | $^{14}C$ |
| Knott, cited in Anderson (1998) | Dated silt from fine-grained deposit behind Beatty Junction bar complex (**9**; Stop A5 in this volume) | 24.0±2.5 ka at +45 m | TL |
| Knott (unpubl. data, 1998) | Dated silt from fine-grained deposit behind Beatty Junction bar complex (**9**; Stop A5 in this volume) | 68 ka @ +45 m | OSL |
| Ku and others (1998) | Dated tufa along the Black Mountains (**22-25**) | 185±15 ka at 90 m | U-series |
| Lowenstein and others (1999) | Dated deposits in core 3.2 km northwest of Badwater Springs | 10-35 ka at 10-18 m; 120-186 ka at 110-160 m | U-series |
| Hooke (1999) | Describes observations of deposits in the region | 180 ka at +90 m | NA |
| Phillips and Zreda (cited in Orme and Orme, 1991) | Dated lacustrine gravel clasts from crest of Beatty Junction bar complex (**9**; Stop A5 in this volume) | 154±13 ka at +46 m | Cosmogenic $^{36}Cl$ |
| Phillips and Zreda (1999) | Dated lacustrine gravel profile from crest of Beatty Junction bar complex (**9**; Stop A5 in this volume) | 20-85 ka at +46 m | Cosmogenic $^{36}Cl$ |
| Klinger (Chapter A, this volume) | Dated tufa deposit along shoreline, north edge of Mesquite Flats (**2**) | ~16 ka at +37 m | $^{14}C$ |

**Table G-2.** List of selected locations of Lake Manly deposits

[Abbreviations: Elev., elevation relative to sea level; Position relative to Death Valley fault system: U, upthrown side; D, downdropped side; H, above Hanaupah fault scarp; F, on the limb of fold; W, west side of valley]

| No. | Name of locality (informal) | Features/deposits | Position: Elev. in m (ft) | Primary reference (* means not previously reported) |
|---|---|---|---|---|
| 1. | Niter beds | Lacustrine and playa sediment | W: 34 (110) | Blackwelder, 1933 |
| 2. | Titus Canyon (Stop A4) | Tufa, limestone | D: 37 (120) | Chapter A, this volume* |
| 3. | Eastern Mesquite Flat | Beach shore | D: 34-37 (110-120) | Chapter A, this volume* |
| 4. | Triangle Springs | Back bar deposit | U: 30 (100) | Machette, unpubl. data* |
| 5. | Mud Canyon | Beach ridge | D: 50 (160) | Chapter A, this volume* |
| 6. | NPS Route 5 at Highway 190 | Spit, deltaic beds | D: 25 (80) | Machette, unpubl. data* |
| 7. | Stovepipe Wells | Terraces | W: 0-50 (0-160) | Blackwelder, 1933; Clements and Clements, 1953 |
| 8. | Salt Creek Hills Anticline | Terraces, shoreline gravel | F: Sea Level | Chapter A, this volume* |
| 9. | Beatty Junction (Stop A5) | Spit and bar complex | U: 46 (150) | Clements and Clements, 1953; Blackwelder, 1954 |
| 10. | Salt Creek | Shoreline gravel | F: -48 (-160) | Klinger, unpubl. data* |
| 11. | Three Bare Hills | Deltaic gravel | U: 36 (120) | Hunt and Mabey, 1966 |
| 12. | North of Salt Spring | Shoreline gravel | W: Sea Level | Klinger, unpubl. data* |
| 13. | Park Village Ridge | Shoreline gravel | U: 0-46 (0-150) | Hunt and Mabey, 1966 |
| 14. | Road to NPS landfill | Deltaic | U: -3 (-10) | Machette, unpubl. data* |
| 15. | Tea House (Stop B1) | Shoreline gravel, foreset beds | U: 24-32 (80-105) | Chapter B, this volume* |
| 16. | Unnamed ridge | Shoreline gravel, tufa | W: 48 (160) | Clements and Clements, 1953; Hunt and Mabey, 1966, Reheis, unpubl. data* |
| 17. | Desolation Canyon (Stop C4) | Spit | D: Sea Level | Chapter C, this volume* |
| 18. | Manly Terraces | Shoreline gravel | D: 30 (100) | Clements and Clements, 1953; Hunt and Mabey, 1966 |
| | Artists Drive | Cross-bedded gravel | D: 8 (25) | Chapter C, this volume* |
| 19. | Natural Bridge | Lacustrine sand | U: 73 (240) | Knott, unpublished data* |
| 20. | Nose Canyon | Lacustrine gravel, foreset beds | U: 90 (295) | Hunt and Mabey, 1966; Knott, unpubl. data* |
| 21. | Tule Springs | Eroded bar, deltaic gravel | W, H: 27 (90) | Hunt, 1975, fig. 155; Trull, et al., 1995; Meek, 1997, Machette,, unpubl. data* |
| | Hanaupah Canyon | Shorelines | W, H: 39-58 (128-190) | Hooke, 1972 |
| 22. | Badwater | Tufa-encrusted shorelines | U: 90 (295) | Hooke, 1972; Ku and others, 1998 (U/Th ages) |
| 23. | Sheep Canyon | Spit and shoreline | U: 60 (200) | Klinger, unpubl. data* |
| 24. | Willow Wash | Platform, bars, back bar | U: 0-92 (0-300) | Knott, unpubl. data* |
| 25. | Mormon Point | Lacustrine gravel, platform, spit | U: 0-60 (0-200) | Chapter C, this volume |
| 26. | Warm Springs Canyon | Lacustrine sand and gravel | U: 35-55 (115-180) | Blair, 1999, sta. 32; Machette, unpubl. data* |
| 27. | Wingate Delta | Deltaic beds, shorelines | U: 50±15 (16050) | Hooke, 1972 |
| 28. | East of Cinder Hill | Lacustrine gravel, terraces | U: 0, 24-35 (0, 80-115) | Troxel and Butler, 1986; Knott, unpubl. data* |
| 29. | Shoreline Butte | Shorelines (12), gravel | W: 15-125 (50-380) | Blackwelder, 1933 |
| 30. | East of Ashford Mill | Deltaic gravel | U: 50 (160) | Klinger, unpubl. data* |

and Mono are related to the last major pluvial (OIS2), which is recorded by lacustrine sediment of 35-10 ka age.

## TECTONICS

Considerable controversy exists regarding the timing, depth, and extent of the many phases of Lake Manly that have occupied Death Valley in the Quaternary. Different dating techniques suggest that the youngest highstand is from OIS 2, 4, or 6, yet the geomorphology and limited preservation of these features suggest (at least to us) an OIS6 lake. We briefly discuss additional and important complications in terms of tectonics and paleolake hydrology below.

Hunt and Mabey (1966) suggested that the lake basin has tilted eastward about 6 m (20 ft) in the past 2,000 years (as dated by archaeology), which implies a 3 mm/yr slip rate on the Black Mountains fault zone (BMFZ) since 2,000 years ago. This rate, although indirectly derived, suggests that the BMFZ is a very active structure (see Chapter J and L in this volume). This bears on the issue of lake depths in tectonic areas. If a long-term slip rate of 1-3 mm/yr is reasonable for the BMFZ (see Chapter L in this volume), then in 186 k.y. the fault could generate 186 m to 558 m of tectonic displacement. Lowenstein and others' (1999) 120-186 ka sediments were reached at 130-160 m below the surface. Their drill rig started at about -85 m (-280 ft) elevation; so the OIS6 deposits are at about -215 m to -245 m elevation (msl) beneath Badwater, whereas Ku and others (1998) 186-ka tufas are at +90 m msl at Badwater (table G-1; fig. G-1, no. 22). Thus, the net relief between these two areas, which are only about 3 km apart but on different sides of the BMFZ, is 305-335 m. Therefore, one half to more than all the net relief may be accounted for by 1-3 mm/yr of slip on the BMFZ, so it's anyone's guess as to the depth of the OIS6 Lake Manly. Similar tectonic problems exist all along the eastern margin of Death Valley. Many of the most important deposits straddle the Death Valley fault system, or are close to its modern trace. Table G-2 lists many of these deposits and shows their relation to the fault system, specifically whether they exist on the upthown (U) or downdropped (D) block.

Considering the long history of searching for lacustrine deposits by very capable geologists (such as Noble, Blackwelder, Hunt, Hooke, and others), our recent discoveries are surprising (see table G-2). One of the most important new localities of Lake Manly deposits that we have found is on the upthrown side of the Hanaupah Canyon fault (fig. G-1, no. 21) about 12 km west of Badwater. These deposits form an elongate east-west bluff that is composed of a series of climbing bars, from about -15 m (-50 ft) elevation to about +27 m (+90 ft) elevation as determined from the Hanaupah Canyon 7.5' topographic map. On the north side of the bluff (away from the Hanaupah Canyon road), pebble- to small cobble-size gravelly foreset beds are clearly visible. The lacustrine bar(s) have been extensively eroded, with Q2-like gravels (probably units Q2c and Q2b, see Chapter H in this volume) inset at lower elevations to the south and Q3 and Q4 gravel inset at lower elevations to the north. Cosmogenic and luminescence dating is underway, but the results are still pending at the time of our FOP trip. Gravel from the highest of the Hanaupah Canyon bars has been sampled for cosmogenic $^{36}$Cl dating and a fine-grained lacustrine sand from this same bar has been sampled for luminescence dating. These age determinations may prove piviotal in answering the question of the age of Lake Manly, inasmuch as this is one of the few well-exposed lacustrine deposits on the west side of Death Valley, well away from the Death Valley fault system.

## PALEOHYDROLOGY

Some main concerns in terms of paleolake hydrology are the source(s), flow-paths, and volumes of water for the lakes and southward closure of the lake basin. Many authors including Blackwelder (1933) suggested that the major water source for the lake was distant flow from the Sierra Nevada, ultimately entering the valley via Wingate Pass from southern Panamint Valley. Few researchers, however, have been able to find, or looked for stratigraphic records for this overflow, with the exception of Hooke's (1972) reported deltaic deposits in Anvil Spring Canyon. Similarly, the Mojave River drainage has been considered a possible southern source, but it probably was not intregrated into the Death Valley system until the latest Pleistocene. Li and others (1997) examined the geochemistry of the source waters feeding Death Valley and compared it to the evaporite mineralogy from Badwater basin. They concluded that over the past 100 k.y. the brines and evaporite minerals were produced by the mixing of meteoric water primarily from the Amargosa system and local spring water. Ancient overflow from Lake Manly may have reached the Colorado River as suggested by Blackwelder (1933). This hypothesis seemed to be supported by faunal evidence in the classic paper by Hubbs and Miller (1948) where they used fossil cyprinodonts (pupfish) to reconstruct the past hydrography of the region. Hooke (1999) speculated that Lake Manly may have extended south into the Mojave. This hypothesis is based on high-level lacustrine deposits in the northern Mojave that he believes could correlate with the Blackwelder stand of Lake Manly. This connection, however, requires several hundred meters of vertical movement related to transpression along the Southern Death Valley and Garlock fault zones.

## CONCLUSIONS

Much remains to be discovered and resolved concerning Lake Manly. Continued dating by conventional, experimental, and yet-to-be discovered techniques will help to resolve the age of individual deposits, but further reconnaissance, geologic mapping, and a basinwide inventory of constructional lacustrine deposits will be needed to determine when, where, and how Lake Manly was created.

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# Regional surficial-deposit mapping in the Death Valley area of California and Nevada in support of ground-water modeling

*Christopher M. Menges, Emily M. Taylor, Jeremiah B. Workman, and A.S. Jayko*

## ABSTRACT

We have been mapping upper Tertiary to Quaternary surficial deposits at 1:250,000-scale as part of a regional geologic map and digital data base that will provide the basis for a detailed hydrogeologic framework for the Death Valley Regional Flow System (DVRFS) ground-water model. This model is being developed by the U.S. Geological Survey in collaboration with the U.S. Department of Energy to assess regional ground-water flow near the Nevada Test Site (NTS) and the potential radioactive waste repository at Yucca Mountain. The map area is defined to circumscribe the entire regional ground-water basin that includes and discharges into Death Valley. The model's 57,000 square-km area, enclosed within a 3° x 3° region centered on the NTS, includes a diverse range of climatic, physiographic, geologic, and tectonic conditions that affect the characteristics of the surficial deposits.

Surficial units were identified and compiled on Landsat 5 Thematic Mapping (TM) data that were geographically rectified and plotted at 1:100,000 scale. The TM data in these image maps are specially processed to maximize the spectral discrimination of surficial deposits in arid to semiarid basins. Unit identification on the image maps is supported by (a) stereographic photointerpretation of black/white high-altitude aerial photography, (b) calibration from field data, collected at more than 620 GPS-located stations within the model area that are being compiled into relational and GIS-referenced databases, and (c) variations in geomorphic characteristics that can be derived from 30-m DEMs. The surficial mapping is classified into hydrologically significant units containing both (a) generalized time-stratigraphic alluvial subdivisions that reflect pavement and soil development, induration, and internal dissection, and (b) additional units of potential hydrologic importance (for example, sediments in active playas and major channels, eolian deposits, paleo- and modern spring-discharge deposits, and fine-grained alluvial facies on distal alluvial fans and plains). Several tables were developed to correlate these units with surficial deposits portrayed in a number of previous and ongoing regional- and local-scale mapping studies within and adjacent to the model area. These correlations were used both to aid map compilation and interpretation and to formally incorporate age control developed in some of these studies into the DVRFS surficial mapping program.

A direct by-product of this project is a comprehensive map of surficial deposits for most of Death Valley National Park, including all of Death Valley, Greenwater Valley, and the Amargosa River drainage, as well as parts of the basins to the west. Also, the characteristics of surficial deposits throughout this area, including spectral attributes on the satellite data, geomorphic surface patterns, dissection and geomorphic setting, texture and lithology, and associated soil development, are being tabulated from the regional mapping, supportive field data, and eventually from the DEM data. Preliminary evaluation of these data indicates that a general regionally consistent suite of units can be recognized across this very large and diverse area, which suggests a regional control such as climate change. There are significant variations in both unit sequences and deposit characteristics within and among individual basins that appear to reflect the localized influence of specific combinations of other factors such as lithology, drainage pattern and geomorphic setting, altitude (local climate), and tectonic activity.

## INTRODUCTION

Regional mapping of upper Tertiary to Quaternary surficial deposits is being conducted as hydrogeologic input to the Death Valley regional flow system (DVRFS) model (Menges and others, 1999, 2000). This regional ground-water model is under development by staff from the Water Resources and Geologic Divisions of the U.S. Geological Survey under the primary sponsorship of the Department of Energy (DOE) (D'Agnese, 2000; D'Agnese and Faunt, 1999; Faunt and others, 1999; O'Brian and others, 1999). Current work consists primarily of hydrologic and hydrogeologic revision of the preliminary DVRFS model developed by the USGS for Yucca Mountain site characterization studies (D'Agnese and others, 1997; Faunt and others, 1997) and the hydrogeologic and ground-water models developed for the Underground Testing Areas (UGTA) program of the NTS (IT Corp., 1996). A significant component of this phase of model refinement focuses on development of an upgraded hydrogeologic framework model for the DVRFS model. This includes preparation of comprehensive regional geologic and tectonic maps and digital GIS databases at 1:250,000 scale (Rowley and others, 1999; Workman and others, 2000).

The area of these products lies within a 3.25° x 3° region (35.00° to 38.25° North; 115.0° to 118.0° West) centered on the Death Valley hydrogeologic ground-water basin as defined for the DVRFS model (fig. H-1). Preparation of the bedrock part of the maps primarily involves compilation and synthesis of existing geologic maps from published and unpublished sources. This type of literature compilation is not feasible, however, for most of the upper Tertiary and Quaternary surficial deposits in the basins because of generally limited definition of these units, inconsistency in mapping scale and approach, and (or) restricted arial coverage of available maps that do adequately portray surficial units. Thus we were tasked to produce comprehensive regional coverage of surficial deposits across the entire map area based primarily on new photointerpretive mapping with limited reconnaissance-scale field support (Menges and others, 1999, 2000).

The map and model area is defined to enclose the entire regional ground-water basin that provides the water source for the springs and salt-pan within Death Valley, which represent the ultimate sump and discharge zone for the regional ground-water flow (fig. H-1; D'Agnese and others, 1997; Faunt and others, 1997). This area includes most of Death Valley National Park, including the entire length of Death Valley proper, as well as Greenwater Valley and the Amargosa drainage to the east. To the west, the map incorporates the eastern parts of Panamint, Saline, and Eureka Valleys and the numerous intramontane valleys and sub-basins in the intervening ranges. The physiography, geology, and tectonics of the 57,000-km$^2$-area included in the DVRFS regional maps is extremely diverse and complex (e.g., Hunt and Mabey, 1966; Stewart, 1980; Jennings, 1994; Slate and others, 1999; Slate, 1999; Wright and Thompson, 1999; Wright and Troxel, 1999). For example, the physiography of the DVRFS includes (a) typical Basin-and-Range topography in the north and east; (b) diverse irregular sets of ranges, plateaus, basins, and alluvial flats (e.g., NTS volcanic highlands and Amargosa Valley) in the center; and (c) the extremely rugged ranges and basins of the Death Valley area of eastern California along the western border. Basin altitude and local climate ranges from more than 1,750 m in the semiarid basin margins north of the NTS to -86 m in the hyperarid basin floor of Death Valley. The bedrock lithologies exposed in the ranges includes varying proportions of Precambrian, Mesozoic, and Tertiary crystalline rocks; Proterozoic, Paleozoic, and Mesozoic clastic and carbonate rocks; and Tertiary volcanic and sedimentary rocks. The map spans numerous tectonic and neotectonic subdivisions of the Great Basin. Deformation includes several generations of upper Paleozoic to upper Tertiary thrust fault systems that have been dismembered by extensive regional extension in the Tertiary and Quaternary characterized by intermixed normal and strike-slip faulting. Much of this latter extensional and translational deformation is active today, with rates and amounts that vary from low to moderate in the central, eastern, and northern portions of the model area in Nevada to very high in the southwestern and western parts in California.

The purpose of this paper is two-fold. First, the methodology developed and implemented during this project for regional

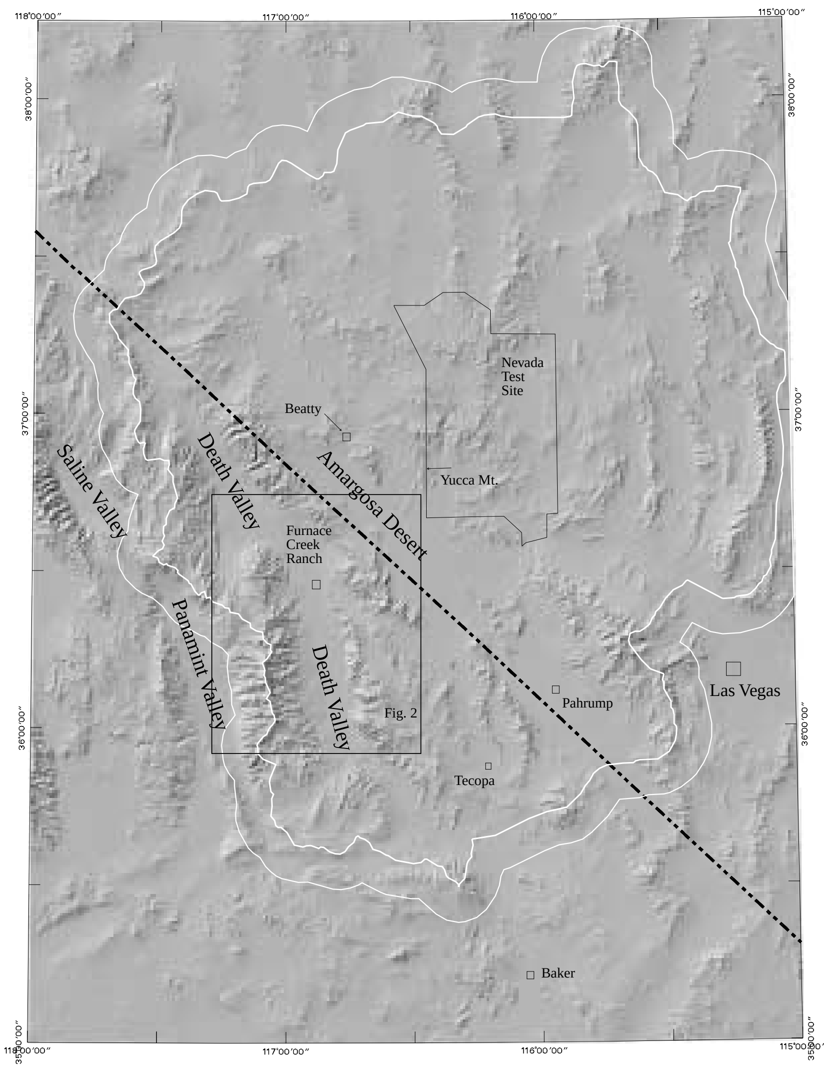


*Figure H-1. Shaded relief map showing Death Valley regional ground-water flow system (DVRFS) model area (inner boundary) and slightly larger area of regional geologic and tectonic map and database that supports the model (outer boundary). Box in left center of map shows location of geologic map (fig. H-2). Dashed diagonal lines is border between Nevada (upper right) and California (lower left).*

mapping of surficial deposits are described, emphasizing the use of suitably processed satellite imagery integrated with DEM data and more conventional mapping tools such as aerial photography and field traverses. Secondly, an example of the resulting surficial map is presented and the characteristics of the major units are summarized, particularly with reference to field attributes and their appearance on satellite imagery

## METHODS

### General Strategy

A number of factors related to this project, including the very large area of coverage, severe time and schedule constraints, and the level of mapping detail compatible with map scale precluded use of standard techniques for surficial mapping. These techniques typically consist photointerpretation from conventional vertical aerial photography that is precisely transferred and compiled onto base maps with an analog or digital plotter. A more effective approach for this project consisted of direct mapping of surficial units on suitably processed and projected Landsat Thematic Mapping (TM) satellite imagery and incorporating this mapping as layer coverage in the digital GIS map and database. This method allows relatively rapid and regionally consistent interpretation and compilation of map units across the very large map area.

### Landsat Image Base Maps

The image base maps used for compilation are derived from a series of six Landsat 5 Thematic Mapper scenes acquired in April 1996 that cover the entire regional map and model area. These data were processed digitally by combining either spectral bands 7, 4 and 2 or 7, 4, and 1, and then applying to the composite image an iterative series of high contrast, hue-saturation-intensity processing techniques. This digital processing is specifically designed to enhance the differentiation of surface characteristics such as pavement-varnish development, soils, dissection, and texture that are particular important for regional mapping of surficial units. The processed data were then rectified and projected onto a series of 1:100,000-scale images that are geo-referenced to the 21 1:100,000-scale topographic sheets that are entirely or partially enclosed within the area. This technique provides a regionally consistent set of images at a scale suitable to serve as primary base maps for unit identification and compilation.

### Map Interpretation and Compilation

The basic procedures for map compilation consist of the following steps. Conventional high-altitude black-and-white vertical aerial photography (nominal scale of 1:80,000) that provides stereographic coverage of the entire area was used both during field-calibration traverses (see later section) and for the preliminary photointerpretation of surficial units. This initial photointerpretation was transferred and compiled on the satellite image maps in two ways. One consisted of an analog procedure wherein the photointerpreted units were identified and traced with ink directly on scale-stable clear mylar sheets overlain on 1:100,000-scale laminated prints of the processed satellite-image maps. This process was guided by the interpreted aerial photography, available published geologic maps, and an intermediate layer of screened topographic contours and selected cultural features printed on clear mylar. The line work on the mylar containing the surficial-deposit boundaries for each image map were digitized and then imported as a single digital layer into the regional GIS geologic-map coverages.

An alternative digital procedure was developed later during the interpretation and compilation phase and applied to part of the map area. An original geo-referenced and processed digital image was imported as a layer into a CAD mapping program. The surficial units were then identified and the boundaries traced on screen in another digital layer. Additional layers containing scanned geologic maps or topography could be added as required. The layer with the final interpreted unit boundaries and labels was then exported in an appropriate format for direct importation into the existing GIS map coverages.

Digital layers with surficial units compiled by either of the two processes outlined above were then merged and incorporated within a GIS program into the existing map coverages containing other information such as bedrock, structures, labels and culture. Figure H-2 shows a part of the central Death Valley area converted from color into black and white.

### Field Calibration and Data Collection

The interpretation of surficial units during map compilation was supported by field work specifically designed to both (a) provide field calibration for surficial units identified on image maps and aerial photography and (b) collect basic field data on these units suitable for development of relational and GIS data bases.

Field data were collected along road traverses in order to maximize coverage within the restricted amount of field time. So far, data have been collected at least 618 field stations. A given road traverse for each day consisted of a series of stops or stations selected primarily to identify those units along the route that appear to need calibration on the appropriate image map. Additional stops were added as warranted by observations in the field. At each station, a military-issue GPS unit was used to locate the precision position and approximate elevation of each station, and the resulting coordinates were used to plot the station on 7.5' topographic maps. The surficial units at and near to the site then were identified and labeled on the quadrangle map and the appropriate aerial photography. Other more distant units visible from the station also were identified and labeled on the maps and photography, to the extent possible. Finally supportive field observations of the surficial deposit(s) at or near the station were recorded and referenced to the station identifier.

Field data collected at each station consisted of mostly qualitative to semi-quantitative observations due to the reconnaissance nature of the traverses. These observations included some or all

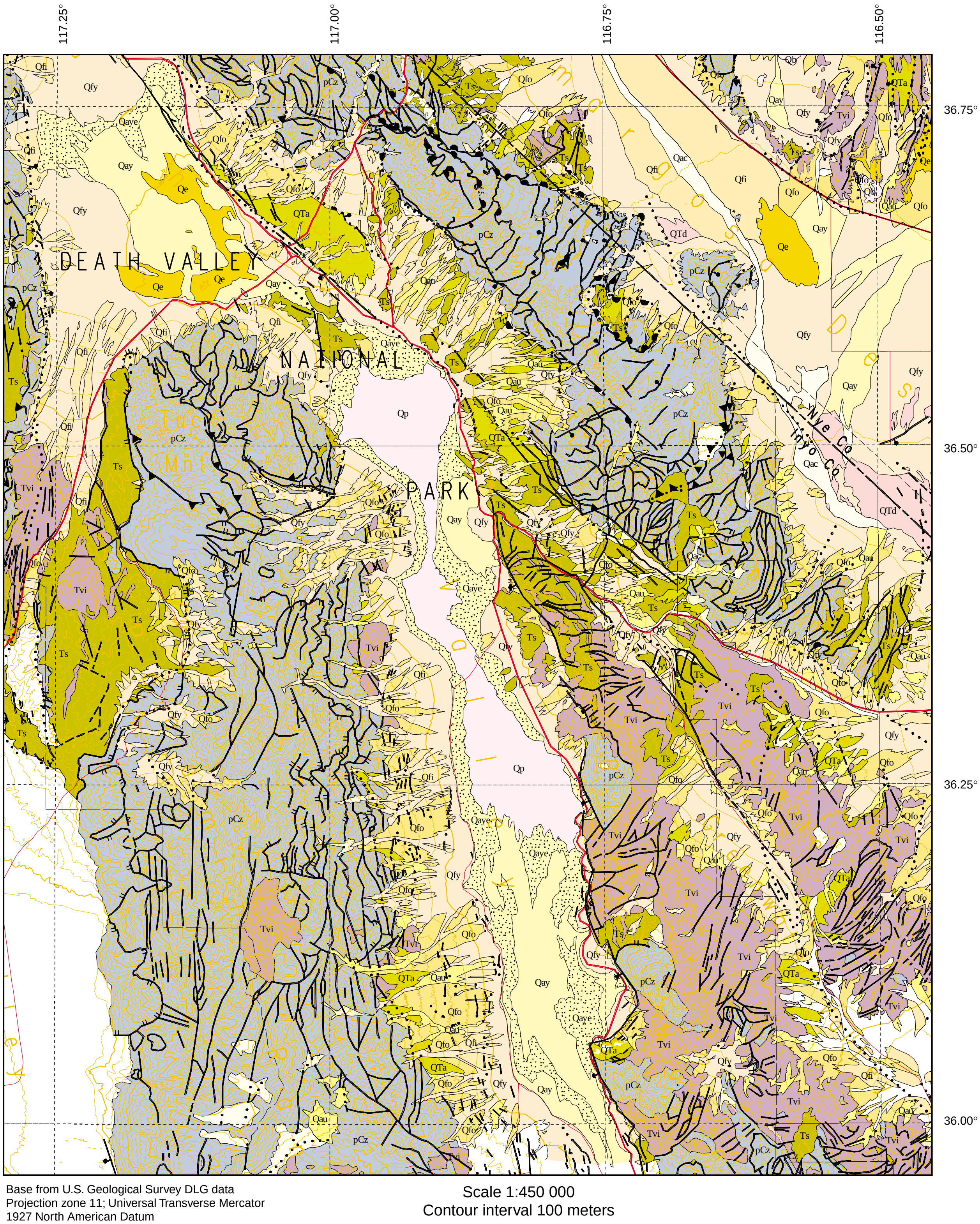


*Figure H-2. Part of preliminary regional geologic map centered on central Death Valley, shown at reduced scale of 1:450,000 (from 1:250,000-scale of map of Workman and others, 2000). The full suite of surficial deposits is shown, as listed in correlation chart of figure H-3, summarized in table H-1, and described in text. In this rendition the bedrock geology has been simplified into three units: pCz—pre- Cenozoic rocks (mixed sedimentary, metamorphic, plutonic, and volcanic); Tvi—Tertiary plutonic and volcanic rocks; Ts—Tertiary strata with inferred or documented age ranges that predate most QTa deposits. Unpatterned (or uncolored) areas are unmapped.*

of the following as appropriate: (a) general setting, including relationship to previous stations; (b) physiographic setting, including general drainage patterns in area; (c) characteristics of unit on image maps and aerial photography (e.g., gray tones, color, and texture); (d) parent material lithology and degree of induration; (e) general size range of gravel clasts and (or) fine fraction; (f) surface characteristics, including pavement development, preservation of depositional bar-swale topography, and (or) surface weathering (fracturing, disaggregation, etching or pitting); (g) strength of varnish development on tops and bottoms of clasts; (h) where exposed adequately, soil characteristics, including overall strength and depth range of profile development and the type, characteristics, and thickness/depths of diagnostic horizons (mainly argillic, cambic, and calcic horizons); (i) dissection of unit (degree, depth range, original surface preservation); and (j) unit labels from both the generalized DVRFS system (see below and table H-1) and the more detailed regional chronosequence of Bull (1991). These field observations form the basis for most of the unit characteristics summarized in table H-1 (table H-1 placed at end of Chapter H).

## SURFICIAL UNIT DEFINITIONS AND CORRELATIONS

### Hydrogeologic Surficial Units

We have defined a set of surficial map units that include some modifications from the standard types of surficial-deposit units encountered in most geologic mapping programs. These modifications are designed to emphasize factors of potential importance to the hydrogeologic framework model, as well as infiltration-recharge and discharge elements of the model. This includes not only differentiation of specific units (such as modern channels, discharge deposits, and playas) that directly impact these factors, but also identification of generalized textural variations in deposits of potential hydrologic significance. Thus, variation in grain size was approximated by differentiating where possible (a) fine-grained deposits on distal alluvial fans and alluvial plains from coarse-grained alluvial deposits in proximal or medial piedmont positions, and (b) in older Quaternary-Tertiary units, fine-grained exposed basin fill from coarse-grained fanglomerates, mostly within old dissected fans. Alluvial units are further subdivided according to more standard age categories that reflect other potentially important hydrologic characteristics such as degree of soil and pavement development, cementation, and amount of internal dissection.

The surficial units for the DVRFS geologic map are summarized below and in figure H-3. The key characteristics of the most common units are presented in table H-1. Unit Qfy is the basic unit for young medium- to coarse-grained alluvium that is mostly Recent (modern) or Holocene in age, but may locally include uppermost Pleistocene deposits. This unit is characterized by sandy gravel to gravelly sand deposits that are common in alluvial fans on the flanking piedmonts so prominent throughout Death Valley, as well as gravelly axial drainages (e.g., the axial channel fans of north-central Death Valley that drain to Mesquite Flat). Unit Qay is a fine-grained unit equivalent in age to Unit Qfy, but that consists of mostly of sand and silt with some scattered fine pebbles. This unit is mapped primarily along low-gradient alluvial plains and fine-grained axial drainages in basin interiors (e.g., the lower Amargosa River in Death Valley south of Badwater), but locally may include the fine grained distal margins of some adjacent alluvial fans. (Note: Unit Qay is a variant of this unit that denotes areas where the surface of this deposit is encrusted with a thin layer of calcium carbonate or salt suggestive of potentially high evaporation and transpiration). Unit Qac is another alluvial facies that is mapped along active (Recent to latest Holocene) channel or well defined distributary channel systems sufficiently large to depict at map scale. Unit Qfi specifically identifies older elements of unit Qfy that typically range in age from middle to early Holocene, but may locally include the latest Pleistocene as well. This unit is only differentiated from unit Qfy (a) where deposits of this age range are identified on existing maps, (b) where these units are identified in the field based on soil and geomorphic-surface characteristics, and (or) where sufficiently large areas of these types of deposits are particularly well defined on aerial photography or satellite imagery near these types of calibration. Unit Qfo is the basic unit for Pleistocene alluvium (including mostly upper to middle, but locally lower Pleistocene as well) that consists mainly of variably dissected medium- to coarse-grained gravel and sand in similar geomorphic and depositional settings to unit Qfy. Fine-grained deposits of this age are rarely exposed or preserved in most areas of the map. Unit QTa is the oldest medium- to coarse-grained alluvial deposit included as a surficial deposit in the map. This unit generally has a poorly constrained age range of mostly early Pleistocene to Pliocene and mostly is associated with highly dissected older fans with no remnants of original depositional surfaces or pavements. The composite Qau and QTau units are used to identify areas with intermixed deposits with Quaternary (units Qfy-Qfo equivalents) or Pliocene-Quaternary (units QTa/af-Qfo-Qfy equivalents) age ranges, respectively, that are too small or too complexly intermingled to differentiate at map scale.

The map also identifies a number of non-alluvial deposits, including (a) unit Qp, fine grained sand-silt-clay sediments and (or) carbonate or salt precipitates in active playas or salt pans in basin interiors; (b) unit Qlc, medium- to fine-grained lacustrine gravel and sand deposits, mostly in Death Valley, that are similar in many characteristics to unit Qfo, but generally are better sorted and stratified and commonly are associated with lacustrine landforms (e.g., gravel bars, beach ridges, or deltas); (c) unit QTaf, fine-grained sediments (silt, clay, and sand) of mostly lacustrine to inactive playa origin, with local gravelly interbeds, that are exposed in the interiors of a few basins (e.g., Rogers Lake sediments in northern Death Valley, local basin interior deposits in north-central Death Valley, and the Tecopa beds near Shoshone); (d) unit QTp, paludal sediments and (or) precipitates (sand, silt, diatomite, ground-water carbonates, travertines) that have accumulated at springs or seepage areas associated with active or past (Recent to Pliocene age) ground-water discharge; (e) unit Qe, undifferentiated eolian deposits associated with landforms ranging from active dunes or sand mantles to stabilized middle Pleistocene sand ramps; and (f) unit QTls, bedrock landslide blocks, commonly composed of recemented breccia that overly or are interstratified with uppermost basin-fill deposits near range fronts.

### Correlations to Existing Maps and Studies

These hydrogeologic surficial units have been provisionally correlated with upper Tertiary to Quaternary units mapped in other studies within and adjacent to the DVRFS area (tables H-2 and H-3; tables placed at end of Chapter H). Only alluvial deposits are included in these correlation tables because there is much less consistency in whether and how other types of surficial deposits are portrayed in the various studies referenced in the tables. Many of these studies are in the DVRFS area, including a number in Death Valley and adjoining parts of the National Park (table H-2). Most of these are local studies that produced detailed large-scale maps with little or no independent age control on map units (see for example, Stop B3, table B3-1 and fig. B3-3). Nonetheless they are useful as reference when interpreting and compiling units in that specific subarea of the regional map. Many of these studies were specifically calibrated to DVRFS units during field traverses as well. A few studies of appropriate regional scale within the map area were adapted and incorporated into the map as well (e.g., Slate and others, 1999). Studies with geochronologic control located within the model area, as well as a selected number of investigations with good age control adjoining or surrounding the model area, were also correlated in order to estimate general age ranges for the DVRFS surficial units (table H-3).

## RESULTS AND CONCLUSIONS

A surficial deposit map has been generated at 1:250,000-scale for the model area, including all of Death Valley, using the techniques outlined above. This surficial map is integrated in GIS digital format with coverages for bedrock lithology and structural features in both bedrock and surficial deposits (Rowley and others, 1999; Workman and others, 2000). This product will be released as a part of composite digital or hard copy geologic map and database. Integration of the new surficial mapping into the upgraded geohydrologic framework will further constrain modeling of the shallow aquifer in the regional ground-water model and provides additional constraints to infiltration and (or) discharge components of the model.

An important byproduct of this project is the production of a consistent and comprehensive regional surficial geologic map for most of Death Valley National Park, a large area that currently lacks this type of coverage (e.g., fig. H-2). Although many topical studies of Quaternary geology, geomorphology and neotectonics, and some large-scale local mapping programs have been conducted in Death Valley over the years (table H-2), a consistent map of surficial deposits has not been produced for a significant section of the park since the early 1960's mapping of central Death Valley by Hunt and Mabey (1966, 1:96,000 scale). The types of units and level of detail of the DVRFS surfi-

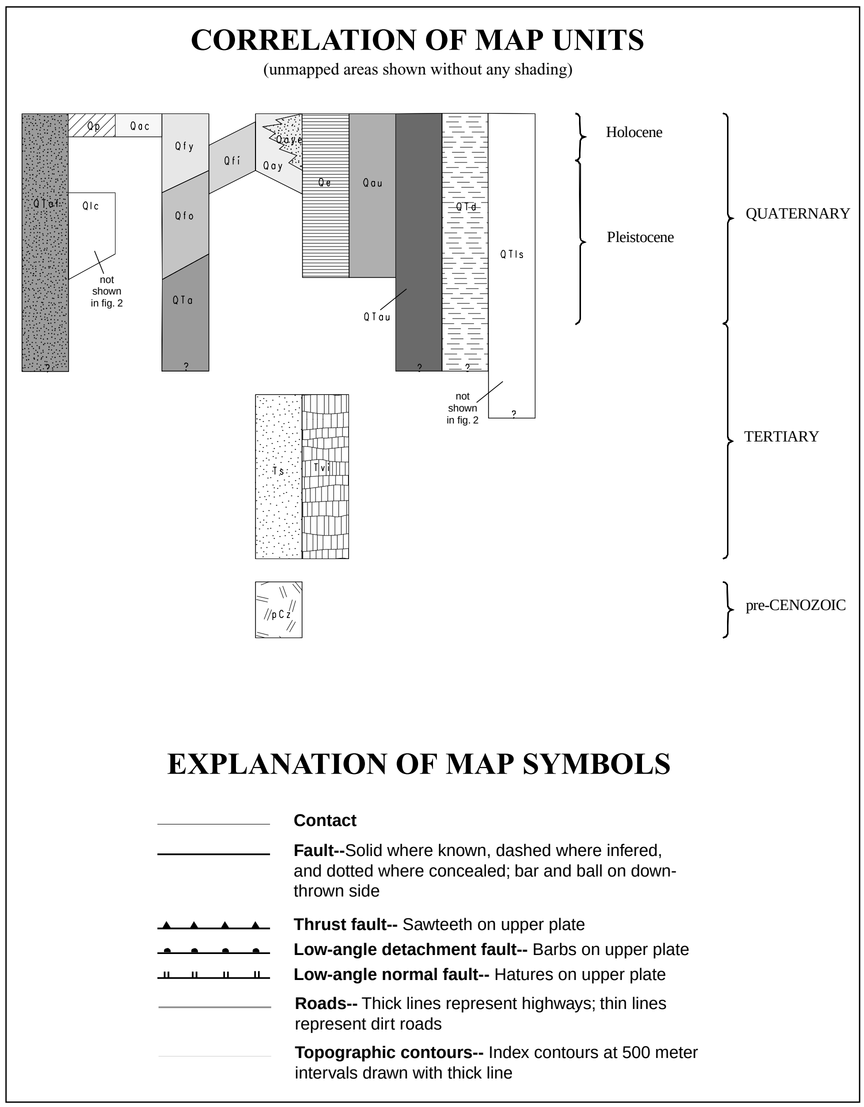


*Figure H-3. Correlation diagram for part of surficial units defined and portrayed in DVRFS geologic map. Age ranges are estimated from correlations to regional and local studies with geochronologic control on surficial deposits (see tables H-2 and H-3). Note that labels are preliminary and may be modified somewhat in final map.*

cial mapping is necessarily generalized due to limitations of map scale, large area of coverage, and overall project schedule constraints, although as much detail has been preserved as possible. However, the mapping is consistent and uniform across the entire area and is supported by reconnaissance field observations; thus, the map potentially provides a useful regional context and valuable starting point for more detailed mapping projects in the region.

Formal integration of the surficial mapping with DEM topographic data is another interesting and potentially very informative element of this project. The DVRFS surficial units mapped using procedures described earlier are being merged with the 30-m DEM data generated as part of the complementary surficial mapping program outlined in Jayko and Menges (Chapter Q in this volume). The DEM data are being used to generate additional quantitative topographic characteristics (e.g., dissection depth and density, slope gradients), with statistical parameters, for each surficial unit. Further, the DVRFS map and the supportive field data will be used as calibration for and eventually integrated with another surficial map produced independently via a different mapping technique which digitally integrates satellite imagery with DEM topographic data (see Jayko and Menges, Chapter Q in this volume). A composite version of these surficial maps will also be combined with a compilation of bedrock units (Tertiary and older) and structures in the general Death Valley region being prepared for release at 1:250,000-scale as described by Wright and others (1999).

Another potentially useful product from the DVRFS project is the correlations of alluvial surficial units defined in regional- to local-scale studies within and adjacent to the model area (see above; tables H-2 and H-3). These correlations demonstrate an impressive degree of consistency in not only generalized units, such as defined for the DVRFS program, but also in more detailed subdivisions of units within the Holocene and Pleistocene, despite the highly variable scales, objectives, and age control in the component studies. This consistency suggests a general similarity in mappable characteristics of a basic suite of surficial deposits that can be recognized throughout the region. This inference is also supported by a comparison of the available age control for these surficial units in studies having geochronologic control (tables H-2 and H-3). In particular, commonly two to three sequences having general age ranges of late (0-2 ka), middle (2-5 ka) and (or) early (7-12 ka) can be identified in the Holocene in most areas. Similarly, most studies define at least two and commonly three dominant pre-Holocene units with general ranges of late Pleistocene (20-70 ka), early-late to late-middle Pleistocene (70-250 ka), and early-middle to early Pleistocene (400->600 ka). Most studies also identify one or more older alluvial deposits with poorly constrained age estimates of early Pleistocene to Pliocene (500 to >1500 ka), although generally the age control for these old deposits is too sparse or lacks sufficient resolution to establish more refined unit subdivisions or precise correlations.

Systematic analyses of map and field data, although planned, are presently only in their initial stages. However some preliminary generalized observations are offered on the map patterns of various deposits in the Death Valley area, particularly regarding the interplay of field attributes with spectral characteristics on the satellite imagery and field attributes (table H-1; compare fig. H-2 with the satellite image of central Death Valley in Dohrenwend, Chapter D, this volume). For example, differentiation of Holocene (unit Qfy) and Pleistocene (unit Qfo) alluvial deposits is generally relative straightforward throughout the area, and especially within the flanking alluvial fans of closed basins such as Death Valley. The Holocene units typically appear on the processed image maps as rough- to medium-textured (speckled) surfaces with dark-toned shades of light to medium brown or reddish brown, in contrast to the smooth texture and bright shades of brown to brownish red associated with unit Qfo. These contrasts are related to the greater degree of varnish development and degradation of bar-swale topography to smoother pavements in the latter. Commonly, dark streaks corresponding to incised channels are also evident within unit Qfo units. The biggest problem encountered in mapping these units was discriminating older lower Holocene parts of Qfy units (unit Qfi equivalents) from upper Pleistocene parts of unit Qfo deposits on the satellite images. The reddish-brown and bright brown colors are similar in many places, such as the low-altitude basins of the Death Valley area, due to moderate to strong varnish development on both of these units. However, the young Qfo deposits generally appear smoother textured with well-defined drainages on the imagery relative to the rougher textured Qfy/Qfi deposits. This reflects the distinctly greater pavement development and increased dissection associated with these surfaces, in contrast to the less incised relict bar-swale topography on older elements of Qfy/Qfi units. The typical distinguishing characteristics between units Qfy and Qfo described above do break down in condition that tend to inhibit the development of varnish and smooth pavements, as for example on piedmonts derived from limestone/dolomite or granitic source terrains. Unit QTa can usually be distinguished on the basis of either (a) strong dissection into ridge-ravine terrain (also known as ballinas) with no preservation of original depositional surfaces or well-developed pavements and (or) (b) whitish or pale colors that reflect an abundance of calcium carbonate chips that litter the surface from the erosion of subjacent petrocalcic soils.

Other types of units have variably distinct signatures on the satellite imagery that can be related to certain physical characteristics. Eolian deposits generally may be distinguished by a diffuse “fuzzy” texture that lacks internal detail and a distinctive pink or pinkish gray color, especially where derived from granitic source rocks that produce quartz- and feldspar-rich grussy detritus (e.g., southern Death Valley adjacent to the Owlshead Mountains). The fine-grained alluvial plains of central and southern Death Valley typically display light toned, commonly variegated pastel colors, depending on the degree of salt encrustation and diffuse drainage development. In the interiors of other basins to the east (e.g., the Amargosa Desert), unit Qay alluvial plains may be darker toned and similar in appearance to distal Qfy deposits, especially where thinly mantled by eolian sand and silt under a thin capping layer of weakly to moderately varnished pebbles. Active playas (unit Qp) are commonly smooth textured and light colored, in contrast to the more variable textures and variegated white to pale brown colors of the salt pans in central Death Valley. The characteristics of unit QTd discharge deposits vary from the dark brown colors of travertines in Death Valley to highly variable whites and pastel colors of the fine-grained paludal deposits in Ash Meadows and similar paleodischarge sites (see Hay and others, 1986, and Quade and others, 1995). Distinct bluish colors that reflect near surface moisture at the time of acquisition of the satellite imagery (April) are commonly associated with deposits that have recently been affected by either recent surface runoff and (or) near-surface evaporative discharge. These include some reaches of well-defined channels (unit Qac), diffuse distributary drainages on low-gradient alluvial plains (unit Qay), the fine-grained fringes of some alluvial fans (unit Qay), playa or salt pans (unit Qp), and sites of active spring discharge or seepage (unit QTd). QTaf units may resemble the fine-grained discharge sites on both satellite imagery and in some cases superficially in the field, but the former generally are not associated with the vegetation and moisture patterns of active spring seepage and (or) lack diagnostic fauna, flora, and stratigraphy associated with past ground-water discharge sites (Quade and others, 1995).

Several additional preliminary interpretations can be drawn from the maps and field data produced by this project. The widespread distribution and general similarity in surficial-deposit sequences across the map region described above suggests a dominant first-order regional factor (such as major climate change) as the fundamental control on the basic regional set of time-stratigraphic units. However, the satellite imagery and field data from study, as well as detailed correlations of specific studies, all indicate significant local variation within the broadly defined regional units across the entire model area. This is evident in both the details of the local stratigraphy and physical characteristics at various sites within and among individual basins. Much of this second-order variation can be attributed to differences in other more localized and spatially diverse external factors, such as types of soil parent material, neotectonic activity, local relief, altitude (mainly as a proxy for local climate), proximity to local dust sources, basin geomorphology, and drainage-dissection patterns. The regional map provides a context for further systematic analyses of the relative influences of these secondary features on the overall regional stratigraphy by using the field data collected during this study supplemented with additional detailed mapping and field work in selected areas specifically targeted to address this problem.

## ACKNOWLEDGEMENTS

This mapping program is primarily sponsored by several projects within the Department of Energy (DOE), including the Underground Testing Areas (UGTA) and Hydrology Resources Management Programs within the DOE Nevada Test Site (NTS) and the Yucca Mountain Project (YMP). Additional technical interaction and feedback is provided by several county (including Nye, Lincoln, and Clark Counties in Nevada and Inyo County in California) and federal agencies (National Park Service, Fish and Wildlife Service, and Bureau of Land Management). Frank d'Agnese and Claudia Faunt (USGS) developed and administered the overall modeling program that supported this mapping and Claudia provided oversight specifically on development of the hydrogeologic framework model. We appreciate the logistical support provided by Death Valley National Park staff during field work in the area. John Dohrenwend (consulting geologist) developed the processing techniques, applied them to the satellite data, and produced the image maps that proved so effective in mapping surficial deposits. William (Rick) Page, Gary Dixon, and Pete Rowley (all USGS) directed various stages in the development of the regional geologic and tectonic maps and databases that provide the context for this surficial mapping. Paul Denning and Carma San Juan (USGS) provided many of the materials used in map compilation and assisted with many aspects of the digital preparation of various sections of the map. Ren Thompson and Janet Slate (USGS) assisted in various field and map compilation endeavors in the Death Valley area. We would also like to thank the many workers who have shared unpublished or partially completed data and mapping that have been used in compiling the map, as listed in tables H-2 and H-3, and in particular, Michael Machette (USGS), Jeff Knott (Unocal) and Ralph Klinger (USBR) in Death Valley, and Scott Lundstrom, James Yount, Dave Miller, Chris Fridrich, and Janet Slate (all USGS) in adjoining areas.

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Wright, L.A., and Troxel, B.W., 1993, Geologic map of the central and northern Funeral Mountains and adjacent areas, southern California: U.S. Geological Survey Miscellaneous Investigations Map I-2305, scale 1:48,000.

Wright, L.A., and Troxel, B.W., 1999, eds., Cenozoic basins of the Death Valley region: Geological Society of America Special Paper 333, 381 p.

Table H-1. Summary of selected surficial deposit units mapped in DVRFS area.

[Table summarizes characteristics of the most common and distinctive surficial-deposit units in DVRFS mapping program subdivided into primarily alluvial units and other types of deposits. Mixed undifferentiated units (Qau and QTau) are not included because they consist of various proportions of other units listed below and thus lack a consistent set of characteristics. QTls, the bedrock landslide unit, is not included, because it resembles bedrock on the images and aerial photography and in the field consists of brecciated bedrock outcrop. Unit Qaye is not listed separately, as it is a variant of unit Qay distinguished only by a thin crust of carbonate or salt on the surface of the deposit (see text). The first three columns list map nomenclature, general character, and age range estimated from correlations in tables H-2 and H-3. The next two columns list characteristics of units observed in the satellite image maps and black-white aerial photography used to interpret and compile units for map. The remainder of the columns list characteristics of deposits and related geomorphic surfaces that are primarily based on observations from field traverses. Characteristics are summarized from full area of DVRFS model and map area, and thus vary significantly reflecting the wide range of geologic, tectonic, and local climatic conditions across the region. Note: unit label nomenclature is preliminary and will be modified somewhat in final map. Abbreviations: mod., moderate; N/A, not applicable; Pleist., Pleistocene, stage, stg.]

| Units[1] | Type[2] | Age[3] | Image/Photo Characteristics[4] | | Physiographic Position[5] | Internal Dissection[6] | Surface Characteristics[7] | | Varnish[8] | General Soil Characteristics[9] | Typical Grain Size[10] | Cementation[11] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Image Maps | B/W Aerial Photography | | | Pavement | Bar and Swale | | | | |
| Alluvial | | | | | | | | | | | | |
| Qac | Channel alluvium | Recent | Variable, light colored to white; light blue where moist | White to light gray | Intra-range valleys, piedmonts, and axial basin drainages | None to minor thalweg incision | None | Unmodified primary | None (only inherited) | None | Variable, from mixed gravel to fine sand | None (except local gully bed) |
| Qfy | Medium- to coarse-grained alluvium | Recent to Holocene | Light to dark colors, including browns; rough to medium textures | Light to medium gray | Proximal to distal piedmonts, terraces, coarse axial drainages | None to minor (mostly primary) | None to weak | Unmodified to faint (but discern-able) | None to moderate | None to weak (cambic and stg. I calcic horizons) | Coarse to fine gravel and sand | None |
| Qfi | Medium- to coarse-grained alluvium | Middle to early Holocene | Medium to dark colors, including browns; medium textures | Medium to dark grays | Proximal to distal piedmonts, terraces | None to minor | Weak | Faint, but discernable | Weak to moderate | Weak (cambic and stg. I calcic horizons) | Coarse to fine gravel and sand | None |
| Qay | Fine-grained alluvium | Recent to Holocene | Light to medium colors, including brown; light blue where moist; medium to smooth textures | White and light to medium grays | Mostly fine-grained axial drainages and interior alluvial plains, some distal piedmonts | None to very minor | None to weak | None to faint | None to moderate | None to weak (cambic and stg. I carbonate horizons) | Sand, silt, minor fine gravel | None |
| Qfo | Medium- to coarse-grained alluvium | Pleist. | Light to dark colors, including brown to reddish brown; smooth to medium textures | Light to medium grays | Proximal to medial, and locally distal, pied-monts; terraces in intrarange valleys | Commonly mod. to strong; lo-cally minor | Strong to mod., present on interfluves where dissected | None | Strong to moderate | Strong to mod.; includes argillic and (or) stg. II-IV calcic to petrocalcic horizons) | Coarse to fine gravel and sand | Poor to moderate |
| QTa | Medium- to coarse-grained alluvium | Early-middle Pleist. to Pliocene | Light to medium colors, possible light brown tint; smooth to medium textures | Light to medium grays | Proximal to locally medial piedmonts; range-front embayments; intra-range valleys | Commonly strong and deep (ballena topography) | None to weak, commonly with carbonate chips | None | None to weakly preserved | Strong to mod.; stripped stg. III-V petrocalcic where preserved | Coarse to fine gravel and sand | Moderate to strong |
| Other | | | | | | | | | | | | |
| Qlc | Medium- to coarse-grained lacustrine | Late to middle Pleist. | Light to dark colors, including brown to reddish brown; smooth to medium textures | Light to medium grays | Mostly medial to distal piedmonts | Commonly mod. to strong; locally minor | Strong to mod., but present on interfluves where dissected | None | Strong to moderate | Strong to mod.; includes argillic and (or) stg. II-IV calcic to petrocalcic horizons) | Medium- to fine gravel and sand (mod.-ly to well sorted) | Poor to moderate |

Table H-1 Continued. Summary of selected surficial deposit units mapped in DVRFS area.

| Units | Type | Age | Image/Photo Characteristics | | Physiographic Position | Internal Dissection | Surface Characteristics | | Varnish | General Soil Characteristics | Typical Grain Size | Cementation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Image Maps | B/W Aerial Photography | | | Pavement | Bar and Swale | | | | |
| QTaf | Fine-grained lacustrine, inactive playa, and alluvial deposits | Pleist. to Pliocene | White to light colors; medium to smooth textures | White to light grays | Variable, including proximal to distal fans and basin interiors | Mod. to strong, in dissected basins; locally none | N/A | N/A | N/A | Local buried paleosols, variable weak to strong development | Silt, clay, fine sand; local gravel interbeds | Poor to moderate |
| Qp | Active playa and salt flat deposits | Recent to late Holocene | White to variegated light and pastel colors; light blue where moist; smooth textures | White to light grays | Basin interiors | None | None | None | None | None; local near-surface encrusta-tions on salt pans | Clay and silt; local fine sand | None to mod. (on salt pans) |
| QTd | Inactive and active discharge deposits | Recent to Pliocene | White to variegated light and pastel colors; light blue where moist; smooth to medium textures; local green vegeta-tion | White to light grays | Mostly distal piedmonts and basin interiors; locally proximal to medial piedmonts | None to moderate | None; locally weak to mod. on alluvial caps | N/A; none to weak on alluvial caps) | None to weak (on alluvial caps) | None to mod. (may include stg. I-II calcic horizons) | Clay, silt, fine sand; local fine gravels and organic mats | None to mod.; locally strong where crystalline precipitate |
| Qe | Eolian deposits | Holocene to middle Pleist. | Light brown, pinkish gray to pink; medium textures | Light grays | Mostly basin interiors; locally variable piedmont | None | None | N/A | None | None | Fine to medium sand; silt | None |

[1] Labels used to identify surficial units for DVRFS geologic (preliminary, may be changed in final map). Units are subdivided into alluvial and other (e.g., lacustrine, playa/salt flat, eolian, ground-water discharge). Excluded from table are composite or mixed age-range alluvial units (Qau and QTau) and the bedrock landslide unit (Qtls) for reasons explained in table header.

[2] General type or classification of deposit, including general size range of coarse fraction, such that medium- to coarse-grained refers to gravel and sand and fine-grained refers to sand, silt and clay.

[3] Age range of deposits, based on correlations to local or regional studies with geochronologic control listed in tables H-2 and H-3.

[4] Typical characteristics of unit observed in satellite image maps and aerial photography used to interpret and compile maps. Satellite image refers to the specially processed Landsat 5 Thematic Mapper image projected onto 1:100,000-scale maps for compilation of units and B & W aerial photography refers to high-altitude black-white aerial photography that were used as aid to interpretive mapping and for field observations, as described in text.

[5] Typical physiographic positions of unit within landscape, commonly given in reference to alluvial basins and (or) bedrock ranges.

[6] Relative amount of local dissection or incision of drainages within or along margins of given mapped area of deposit. Common depth ranges include 0-2 m (minor), 2-5 m (moderate) and >5 m (strong).

[7] Characteristics of geomorphic surface associated with a given unit deposit. Subcategories listed are qualitative strength of pavement development, including smoothness and degree of interlocking clasts, and the preservation of original depositional form, given in reference to bar and swale morphology (i.e., original channel bars and distributary channels, respective-ly).

[8] Degree of desert varnish observed at surface, given qualitatively in reference to darkening of tops and (or) reddening of undersides of surface clasts.

[9] General strength of maximum soil development associated with upper surface of deposits, typically as observed in natural outcrops (gullies) or road cuts, or as exposed in shallow pits. Soil pits exposing the full depth range of deep profiles could not be excavated during the reconnaissance field traverses required for this project. Observations focused on relative degree of development of horizons of secondary accumulation of carbonate, after Machette (1985) and locally salt or silica, and presence or absence of cambic or argillic horizons. In some cases, generalized soil characteristics were inferred less reliably where soil were not exposed on undissected surfaces from features on surface, including carbonate chips, carbonate rinds on clasts, and fine-grained materials brought up from burrowing insects or rodents.

[10] Typical textural size range of deposits, given for gravel in terms of coarse (cobble to boulder) or fine (pebble to cobble) grained.

[11] Degree of internal cementation or induration throughout deposits, below surface zone of soil development. Bonding agent varies from fines (silt, clay) in uncemented to poorly cemented deposits to secondary carbonate, salt, or silica cement in moderately to strongly cemented materials.

Table H-2. Correlation table of alluvial surficial-deposit units in DVRFS map with surficial-deposit stratigraphic sequences in local to regional studies that are either within Death Valley itself or are adjacent to Death Valley and lack independent age control.

[First column from left includes selected surficial units for DVRFS mapping program at regional (1:250,000) scale. Only alluvial units are shown because there is little or no consistency in whether or how other non-alluvial deposits are mapped in the studies included in the correlation. Numbers in parentheses refer to minimum and maximum age estimates (in ka); number after range is preferred age estimate where given. Some correlations adapted from Klinger and Piety (1996).]

| DVRFS Study[1] | | | | Hanaupah fan, Death Valley, CA[2] | Central Death Valley, CA[3] | Valjean and central Greenwater Valley, CA[4] | Northern Death Valley CA[5] | Northernmost Death Valley, CA[6] | Southern Death Valley, CA[7] | Ash Meadows area, CA-NV[8] | Nevada Test Site (Revsion 4 Map), NV[9] | Resting Spring and Nopah Ranges, CA-NV[10] | Tecopa Basin, CA[11] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Qtau (0->758) | Qau | Qac (0-2) | Qfy, Qay (0-18) | Modern | Qg4 (0-1) | Qyw,Qyw$_1$, Qya$_1$ | Q4b | Qf4 | Qf | Qrg, Qal | Qay | Qf4 | Qa$_1$ |
| | | | | Q4c (0.5-2.5) | | | Q4a | Qf4 | | | | | |
| | | | | Q4b (2-4.5) | | Qw$_2$, Qya$_2$ | Q3c | Qf3 | | Qal | Qay | Qf4 | Qa$_1$ |
| | | | | | Qg3 (2-10) | | | | Qg3 | | | | |
| | | Qfi (4-18) | | Q4a (6-11) | | Qw$_3$, Qya$_3$ | Q3b | | | | | | |
| | | | | | | | Q3a | | | | | Qf3 | |
| | | Qfo (18-758) | | Q3 (13-50) | | Qia$_1$, Qia$_2$ | Q2c | | | | | | |
| | | | | | Qg2 (>20-<185) | | | Qf2 | Qg2 | | | | |
| | | | | Q2a/Q2b (110-190) | | Qia$_3$ | Q2b | | | | Qai | Qf2 | |
| | | | | | Qg1 | | | | | | | | |
| | | | | | | | | | | Qgs, Qgv | | | Qa$_2$ |
| | QTa, QTaf (500->758) | | | Q1a/Q1b (>500->800) | QTg1/Qmpc (>500-1200) | Qoa | Q2a | Qf1 | Qg1 | | QTa | Qf1 | |
| | | | | Q1a/Q1b (>500->800) | QTg1/QTfc (>1900-5000) | Qao, QToa | Q1 | Tc, Tg (758->3500) | QTfc (1700-2200) | | QTa | QTf, Qla | Qtc, Qtlm |

**Footnotes for Table H-2 are on following page.**

### Footnotes for Table H-2

1 Surficial units from DVRFS study are summarized in text and in table H-1. Only alluvial units, with the exception of the lacustrine-alluvial unit QTaf, are included in this table because other types of deposit are not included or are not consistently identified in many of the local studies referenced in this table.

2 Dorn and others, 1987. Age estimates are uncertain due to use of C14 varnish-dating method, which is considered to be unreliable by some researchers.

3 Hunt and Mabey, 1966 (original definition and mapping of Qg units); Wright and Troxel, 1993 (application of stratigraphy of this stratigraphy to map of Beatty Junction area); Knott, 1998, 1999 (general use of this stratigraphy, with redefinition of some units and development of age control for older units).

4 D.M. Miller and J.C. Yount, mapping in progress. Stratigraphic units provided for correlation by Miller, written and oral communications, 2000.

5 Klinger and Piety, 1996; Klinger (2001); Machette and Crone (Stop B-3 in this volume). Alluvial stratigraphy defined after and correlated with Bull, 1991 (Lower Colorado Rive area, in column 5 and footnote 5 of table H-3) with minor refinements in age ranges based on some new data. Mapping by Machette in progress in central Death Valley uses this same stratigraphy, but he is in process of developing independent age control in Death Valley proper in collaboration with S. Mahan, F. Phillips, B. Harrison, R. Klinger, J. Slate, and J. Knott.

6 Moring, 1986.

7 Wright and Troxel, 1984. Mapping in area of Confidence Hills 7.5-minute quadrangle uses basic stratigraphy of Hunt and Mabey, 1966 (Central Death Valley column to left, footnote 2 above). Their oldest map unit (QTfc), originally mapped mainly in the Confidence Hills and correlated with the Funeral Formation to the north, has been redefined as the Confidence Hills formation and assigned the indicated age range by Knott (1999).

8 Denny and Drewes, 1965. Note: these correlations are approximate as there is no unique correspondence to units in the DVRFS study or most of the other studies.

9 Slate and others, 1999. From geologic map of Nevada Test Site (Revision 4, at 1:100,000 scale). Surficial units mapped by J. Slate, M. Berry, and V. Williams, based primarily on photointerpretation on Beatty 1:100,000-scale topographic quadrangle and the westernmost part of the Pahranagat Range and Indian Springs 1:100,000-scale quadrangles. Surficial deposits on the Pahute Mesa 1:100,000-scale quadrangle adapted from surficial mapping (mostly unpublished) by W. Swadley, with some modifications based on photointerpretation.

10 McKittrick, 1988.

11 Hillhouse, 1987.

Table H-3. Correlations of alluvial surficial-deposit units in DVRFS map with surficial-deposit stratigraphic sequences in local to regional studies adjacent to the Death Valley area with some independent age control.

[First column from left includes selected surficial units for DVRFS mapping program at regional (1:250,000) scale. Only alluvial units are shown because there is little or no consistency in mapping of other non-alluvial deposits among many of the studies included, and most of the age control cited refers to alluvial chronosequences. Numbers in parentheses refer to minimum and maximum age estimates (in ka); number after range is preferred age estimate where given. Some correlations adapted from Klinger and Piety (1996)]

| DVRFS 1:250 k[1] | | | | Yucca Mtn., NV (post 1992)[2] | | Yucca Mtn - NTS, NV (pre 1992)[3] | Crater Flat, NV[4] | Lower Colorado River, CA[5] | Silver Lake, CA[6] | Providence Mtns., CA[7] | Fish Lake Valley, CA[8] | Pahrump-Las Vegas area (Las Vegas 1:100K sheet)[9] | Kyle Canyon, NV[10] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Whitney and Taylor | Lundstrom and others | | | | | | | | |
| Qtau (0->758) | Qau | Qac (0-2) | Qfy, Qay (0-18) | Q7 (<0.2) | Qayy, Qfyy (0) | Q1a (0) | Modern (0) | Q4b (0) | Qf5/6 (0-0.7) | Qf8 (0-2, <0.1) | Late Marble Creek (0-0.75) | Qayy (0-3) | Q4 (0) |
| | | | | Q6 (<1) | Qayy, Qfyy (<1?) | | Crater Flat (0.4-1.5) | Q4a (0.1-2) | | Qf7 (0-4, ~1) | Middle Marble Creek (1-1.6) | Qayy (0-3) | |
| | | | | | | | | Q3c (2-4) | Qf4 (2.5-3.4) | Qf6 (3-8, ~4) | Upper Marble Creek (1.9-5.3) | Qay (0-14) | |
| | | | | | | | | Q3b (4-8) | Qf3 (<8) | | | | |
| | | Qfi (4-18) | | Q5 (2-17 | Qfy, Qayo (3-15) | Q1c (3-30, ~10) | Little Cones (7-11) | Q3a (8-12) | | Qf5 (8-18, ~10) | Leidy Creek (6.4-10) | Qayo | Q3-upper (4-80, 15) |
| | | Qfo (18-758) | | Q4 (30-100) | Qaiy, Qfiy (20-50) | Q2b (140-160) | Late Black Cone (>17-30) | Q2c (12-70) | Qf2 (10-40) | Qf4 (17-75, ~50) | Indian Creek (50-130?) | Qaiy (25-50) | Q3-lower (4-80, 50) |
| | | | | Q3 (100-250) | Qai, Qfi (50-130) | Q2c (270-500) | Early Black Cone (>159-200) | Q2b (70-200) | Qfo | Qf3 (29-758, ~150) | | Qai (50-130) | Q2 (18-750, 130) |
| | | | | Q2 (~400) | Qao (>300-1000) | | Yucca? (>343-375) | Q2a (400-758) | | | | Qao (≥300-600) | |
| | QTa, Qtaf (500->758) | | | Q1 (500->758) | | Qta (900-2000) | Solitario (>433-<758) | | | Qf2 (29-758, ~600) | McAfee Creek (600?-758) | | Q1 (750-800, 800) |
| | | | | Q0 (>758) | Qao, Qta (>300->1000) | Qta (900-2000) | | Q1 (>1200) | Tg | Qf1 (758-4000, ~1500) | Perry Aiken Creek (>758) | QTa | |

**Footnotes for Table H-3 are on following page**

**Footnotes for Table H-3**

[1] Units from DVRFS are summarized in text and in Table 1. Only alluvial units, with the exception of the lacustrine-alluvial unit QTaf, are included in this table because other types of deposit are not consistently identified in the local studies referenced in this table.

[2] Surficial mapping conducted as part of site characterization at Yucca Mountain. Two studies are referenced, including (a) E. Taylor and J. Whitney, in review, Surficial Geology Chapter of the Site Description of Yucca Mountain, which summarizes a number of other post-1992 Quaternary mapping programs at Yucca Mountain such as Wesling and others, 1992; and (b) Lundstrom and others, in review, a detailed map and discussion of surficial deposits at Yucca Mountain and adjoining areas.

[3] Hoover, 1989; Swadley and others, 1984; Taylor, 1986. This is the Quaternary stratigraphy used in pre-1992 NTS and Yucca Mountain mapping programs. Age estimates for post-Q1, and particularly Q2, units are unreliable because of reliance on uranium-trend method, which is not considered a valid method by most practitioners of uranium dating methods, including U-series..

[4] Peterson, 1988; Peterson and others, 1995. Age estimates are uncertain for some units due to use of C14 varnish-dating method which is currently considered unreliable.

[5] Bull and Ku, 1975; Ku and others, 1979; Bull, 1991.

[6] Wells and others, 1990.

[7] McDonald and McFadden, 1994; Wang and others, 1996.

[8] Slate, 1991; Reheis and Sawyer, 1997.

[9] R. Page, S.C. Lundstrom, and others, in review, Geologic map of the Las Vegas 30 x 60-minute quadrangle, Clark and Nye Counties, Nevada, and Inyo County, California. Surficial mapping by S. Lundstrom. Contains a number of new age determinations (TL and U-series) on surficial deposits, including many on paleodischarge deposits not included in the correlations of this table.

[10] Reheis and others, 1992.

# A short note on developing digital methods for regional mapping of surficial basin deposits in arid regions using remote sensing and DEM data—Example from central Death Valley, California

*A.S. Jayko and Christopher M. Menges*


## ABSTRACT

Derivative maps generated from DEM's and remote sensing data can be used to characterize surficial basin deposits in the Death Valley region. Preliminary work indicates the technique could be useful for rapid digital mapping of surficial deposits in the Basin and Range province or similar arid regions where a first-order, systematic subdivision of alluvial fans, active washes, and playas is unavailable at regional scales. Digital mapping can provide information about relative age and material properties of units that are related to the position of the units within the basin system. Such mapping combined with detailed field studies in selected parts of basins can provide useful constraints until more field-intensive studies are done. In addition, the digital mapping can be useful to indicate anomalous areas where more detailed field or air-photo work is warranted. The main features that can be mapped digitally with some consistency in the Death Valley basin are bedrock-basin contacts, alluvial fans (generally multiple fan units), active washes, playas, playa-rimming marshes and seeps.


## INTRODUCTION

There is an important need for providing regional scale maps that show the distribution of surficial units in alluvial basins from arid regions (especially at 1:1,000,000 to 1:250,000 scales, but extending usefully to 1:100,000 scale). Until systematic field and air-photo interpretation can be completed, interpretation of remote sensing and digital terrain data can provide a preliminary framework. The ability to digitally characterize basin deposits and geomorphic features related to past pluvial and interpluvial periods has broad application to groundwater, ecological and climate models. We've experimented with generating preliminary maps digitally by combining reclassified imagery (monochromatic 15-m SPOT data) with morphologically defined areas derived from 30-m Digital Elevation Models (DEM's). These maps are systematically compared for purposes of verification, consistency and error assessment with (a) published geologic maps where appropriate surficial deposits have been mapped from air-photo interpretation and field studies (e.g., Hunt and Mabey, 1966; 1:96,000 scale), and (b) preliminary regional surficial-deposit maps that have been independently developed from more conventional interpretative mapping of Landsat 5 TM satellite imagery plotted at 1:100,000 with reconnaissance field observations (see Menges and others, Chapter H in this volume; Menges and others, 1999). Previous work combining remote sensing data with DEM's has primarily been directed towards describing relative tectonic activity along active range fronts (Farr, 1996) and local examination of alluvial fans (Thiessen and Farr, 1996).

This paper provides information about the basic procedure developed for the Death Valley area, preliminary results, and suggestions for future directions. We are investigating some additional potential uses of digital mapping and derivative products. For example, we can quantify morphological properties of units including amount of dissection, smoothness, slope variation and curvature that can supplement the traditional lithologic descriptions. In addition, we can enhance escarpments that have resulted from active faulting, incision of alluvial fans, and locally, paleoshorelines.

## METHODS

The objective of this digital processing effort is to develop tools to utilize new sources of terrain data (remote sensing and DEM) to produce regionally consistent surficial deposit maps that differentiate surfaces underlain by active playa, marsh and seepage areas, active stream channels, alluvial fans, and where possible, to subdivide the fan units based on the intensity of varnish development, surface smoothness, and degree of dissection (Jayko and Pritchett, 1999). To do this digitally, we have used 15-m SPOT panchromatic imagery to infer information from the tone of deposits: (1) varnish development on fan deposits helps to indicate relative age of units using variations in low reflectivity; and (2) clay and silt characteristic of playa and active stream-channel deposits are expressed in high reflectance. The 15-m SPOT data have similar information content to about 1:80,000-scale black and white air photos (fig. I-1). A single 30' x 30' scene covers the central

Death Valley study area, thus complications introduced by edge matching scenes is locally avoided. In addition, the 30-m DEM can be used to delineate three units—two ages of alluvial fan deposits and playa deposits. Alluvial fan deposits can be subdivided into at least two units using curvature, and the playa can be differentiated using slope properties. The combination of SPOT and DEM data can help to indicate the location of seep and marsh deposits where extremely low reflectance coincides with extremely low slopes. These areas commonly occur at the interface between the distal fan and playa deposits.

The study area is an arid, high-relief tectonically active region where bedrock is exposed principally in the rough, steeply sloping ranges, and surficial deposits accumulate in the broad smooth, gently sloping basins. This contrast in morphology provides a basis for digitally differentiating domains. The first step is to derive masks from the DEM's for three regions—those primarily underlain by bedrock, alluvial fan plus stream channels, and playas. The SPOT data that correspond to these areas can then be independently reclassified, rather than applying a single reclassification scheme uniformly to the entire image. Reclassification is the process of combining a range of spectral values to represent a surface characteristic. Most of the bedrock can be digitally isolated from the basinal deposits by making a derivative map that excludes topography with slopes in excess of about 20°; in some areas, topography with slopes in excess of about 15° is sufficient. The playa and lacustrine areas are generally flat with slopes ranging from 0° to 1°; these flat areas can be manipulated independently of the rest of the image in order to enhance and discriminate floodplains, seeps, marshes, salt crusts, and silts. All of the area underlain by alluvial fan deposits, and some areas that may include gently sloping bedrock features (generally slightly inclined volcanic units in this area), can be extracted from the SPOT image using just the DEM slope mask (2°-20° in this region).

The active stream channels generally have high reflectance, due to the presence of light-colored clays deposited by recent flash floods and debris flows (fig. I-2). After the playa and lacustrine deposits, these are the second most straightforward feature to extract from the SPOT imagery. A spectral range for the unit is not widely applicable, however, because reflectance varies from scene to scene, even for similar units, and the correction factor between SPOT images is nonlinear. Active channels selected spectrally from the SPOT image can be cross-checked and verified by a number of means including: published geologic maps, hydrologic DLG (digital line graph) base layers, stream channels generated from DEM's, overlays on low-angle shaded relief bases, and contour maps. The composite map (fig. I-3) is a shaded relief and stream-network map showing the stream order in shades of gray, both generated from the DEM. The unit boundaries were made by vectorizing the digitally generated map of surficial units.

Active marsh and seep deposits commonly occur where the distal fan deposits reach the playa surface forming wet vegetated areas that have very low reflectivity. These areas can be classified on the subset of the SPOT imagery that has been selected using the 0-1° DEM slope mask. Such areas cannot be automatically reclassified from the complete SPOT image because the reflectance values overlap with the heavily varnished surfaces on the older alluvial fan pavements.

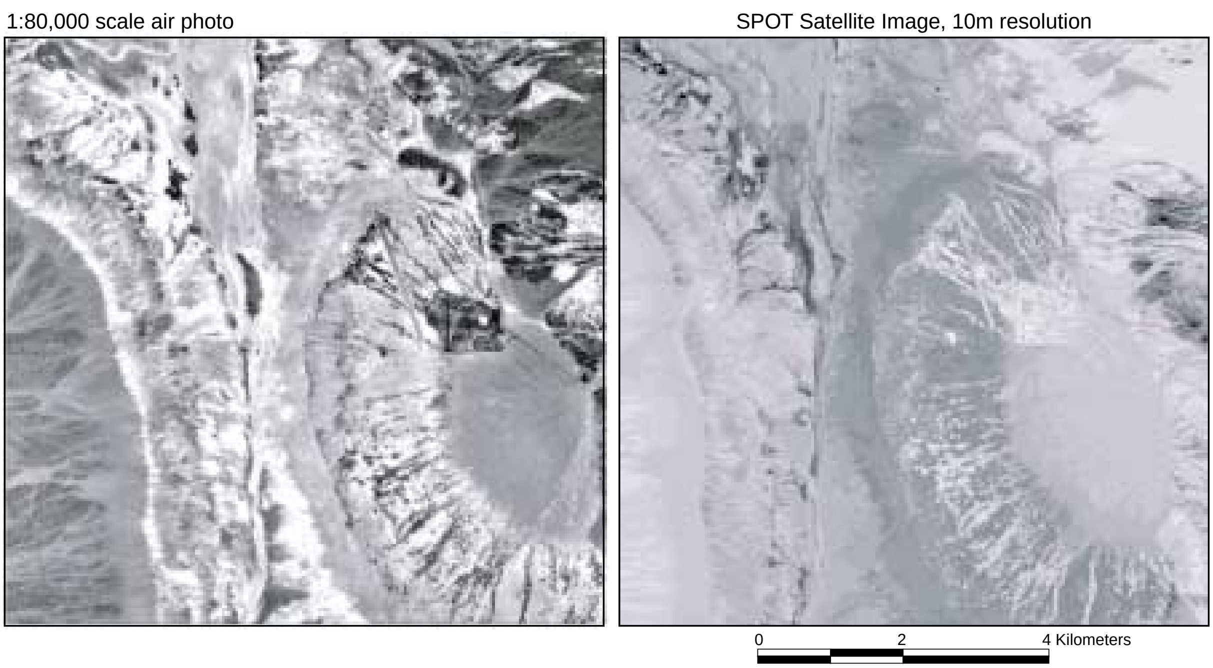


*Figure I-1. Comparison of 1:80,000-scale air photo with SPOT image near outwash fan, Furnace Creek.*


*Figure I-2. A) Aerial view showing outwash from July 1999 flash floods and light-colored new deposits. Although material of varied grain size—up to small boulders—has been transported, the tone of the deposits is controlled by the 'unoxidized' silt and clay fraction, which tends to coat the clasts. B) Edge of depositional lobe and fluid escape path at Artist Drive. C) Ground view of flooding at south gate. D) Ground view of flooding of Gower Canyon (Gulch).*

In the Death Valley area, fans are divided into four units—the active wash or 'Holocene' surface (Qg4), an intermediate-age surface defined primarily by the degree of rock-varnish development (Qg3), and deeply dissected, heavily varnished surfaces (Qg2). These map units approximately correlate with units defined and mapped by Hunt and Mabey (1966). The middle(?) and late(?) Quaternary alluvial fan deposits can be differentiated in the imagery based primarily on reflectance, which is generally controlled by varnish development. The degree to which the dominant lithology of the surface clasts can varnish, however, complicates mapping on this basis. For example, mafic or intermediate volcanic rocks and quartz-rich sedimentary rocks develop strong varnish, but carbonate and granitic rocks do not readily varnish. We examined spectral histograms to determine the appropriate range for each fan unit. Ranges for units were also adjusted such that the resultant map would match published maps. The fit to published maps can be quantified by creating a derivative map that shows areas of greatest similarity or difference to the published map.

The older, early(?) Quaternary and/or late Pliocene alluvial units cannot be readily differentiated from the intermediate-age surfaces using only spectral data, because these surfaces all have similar reflectance. But the deep dissection of these older units enables us to isolate them using the curvature values (second derivative = change of slope) of the DEM, which enhance the edges of the unit. To derive the curvature map (fig. I-4), the DEM was passed through a slope mask of 35° to capture as much of the highly dissected part of the basin surface as possible and limit the amount of bedrock processed. Slopes in excess of 35° are shown in black. Dark shades depict edges, where curvature is either strongly positive (convex upward) or negative (concave upward); light shades represent flat areas where curvature is near zero (relatively constant slope). The Qg2 unit then is digitally selected as the area that includes and lies within the areas of high curvature, which reflects fan dissection. This derivative map enhances the edge of any kind of escarpment including features such as stream terrace edges, active fault scarps and paleoshorelines, as well as mismatches along the DEM quadrangle boundaries. On figure I-4 the abrupt, quasi-linear termination of the areas of extreme curvature are northwesterly and northeasterly trending Quaternary faults. The east-west and north-south straight lines in the middle of figure I-4 are data gaps between DEM quadrangle boundaries.

## RESULTS

A preliminary basin-deposits map of the Central Death Valley area generated from digital processing (fig. I-5a) shows a decent correlation with field observations (Chapter H, this volume) and Hunt and Mabey's (1966) 1:96,000-scale mapping (fig. I-5). There is generally good correspondence in much of the alluvial fan areas, especially between Qfy of Menges and others (Chapter H, this volume) and the digitally mapped Qg4, as well as between Qfo (Chapter H, this volume) and Qg3. Digital processing at this stage of the work captures a large part of Qg2 (older dissected fans) but under-represents the distribution. The playa areas can be readily differentiated but the materials on the playas (salt vs. silt and clay) require other multispectral information (Crowley, 1993). Hunt and Mabey's (1966) mapping of the salt deposits was based on systematic sampling and field traverses in addition to standard air-photo interpretation. Thus, they are able to show salt units that were not differentiated by the monochromatic imagery, but which can be mapped from the increased spectral content of the TM data as demonstrated by Crowley and Hook (1996).

Preliminary work suggests the technique shows promise as a tool for rapid objective mapping of large regions at a regional scale (i.e., 1:250,000). Future activities will include: (1) additional evaluation, verification and modification to improve reliability and accuracy; (2) application of the technique to Landsat TM 7 data; and (3) detailed comparisons with existing maps (e.g., surficial maps of Menges and others, Chapter H in this volume) and field data.

## ACKNOWLEDGEMENTS

We thank our USGS colleagues—Ren Thompson for support during the project's initiation and whose review comments significantly improved the manuscript; Janet Slate for slogging through the paper, editing and making important clarifications; Lee-Ann Bradley for making vast improvements to the figures; and Emily Taylor and Chris Fridrich who's brainstorming and fuming on a field trip to the Amargosa during the autumn of 1998 lead to the development of this effort.


*Figure I-3. Map showing edges of basin-fill units derived from SPOT image and 30-m DEM's overlain on shaded-relief base map. Gray lines are ordered stream network generated from the DEM.*


*Figure I-4. Map showing enhancement of deeply dissected parts of alluvial fans using curvature. Dark areas on fan surface are edges and light areas are constant slope surfaces. Location of the figure is west side of Death Valley near Galena Canyon. Northerly trending breaks are fault controlled. Some of faults show west-side down displacement.*

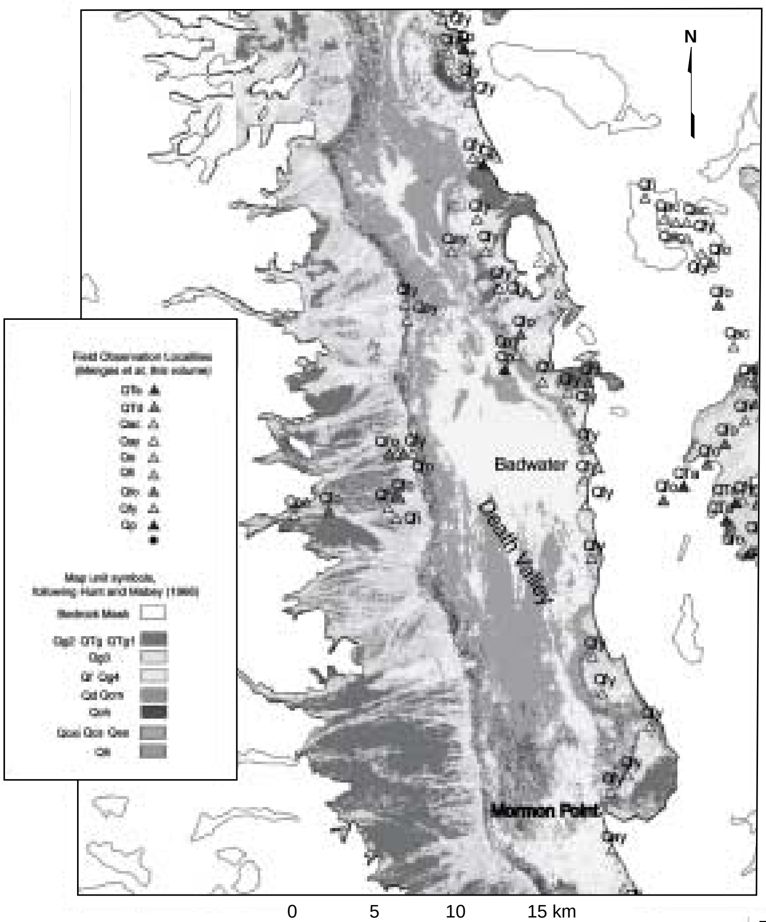


*Figure I-5a. Reclassified SPOT image showing distribution of surficial basin deposits selected from imagery using DEM mask; with field observation localities (see Menges and others, Chapter H, this volume).*

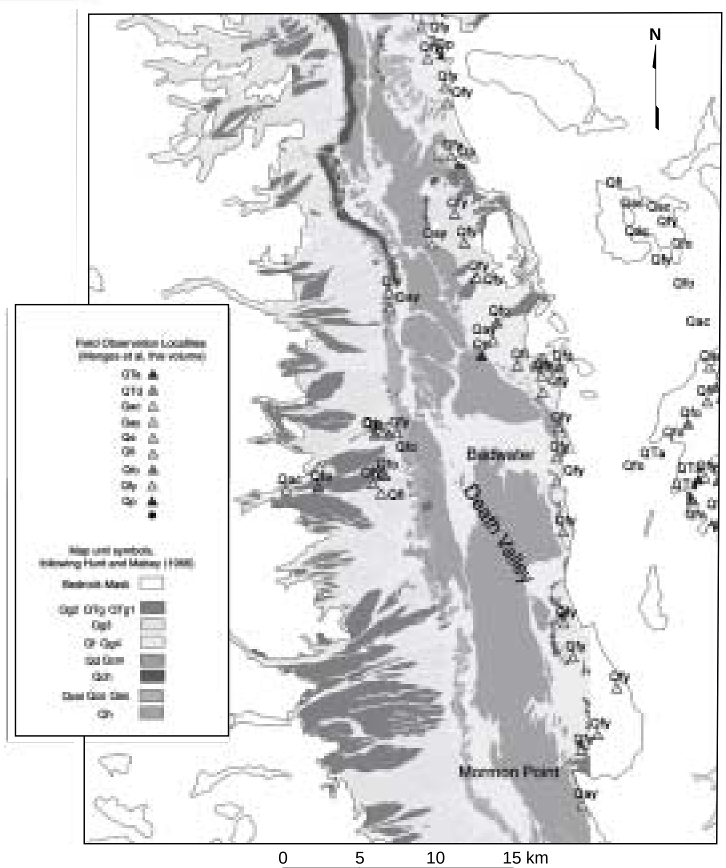


*Figure I-5b. Digitized map of surficial basin deposits from Hunt and Mabey (1966) with field observation localities (see Menges and others, Chapter H, this volume).*

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# A proposed nomenclature for the Death Valley fault system

*Michael N. Machette, Ralph E. Klinger, Jeffrey R. Knott, Chris J. Wills, William A. Bryant, and Marith C. Reheis*

CHAPTER J

## INTRODUCTION

The Death Valley fault system is confined to a relatively narrow zone of nearly continuous Holocene surface ruptures from the northern end of Fish Lake Valley (Nevada), south along the entire eastern margin of Death Valley to at least the Garlock fault zone (California), a distance of 310 km. Abundant right-laterally deflected drainages, offset of young alluvial deposits, fresh fault scarps, closed depressions, and other geomorphic expressions of Holocene activity exist along nearly the entire system. Right lateral (dextral) offset is dominant north of Salt Springs (8 km north of Furnace Creek Ranch) and south of Shoreline Butte (also known as Shore Line Butte on the USGS 7.5-minute quadrangle). In the region between, the pull-apart Death Valley basin is dominated by normal dip-slip displacement with a component of dextral offset. The fault system has been evolving over the past 14 m.y. as the Death Valley region reached its modern configuration; as a result, some older faults are no longer active. Our main interest in this article is Quaternary through Holocene movement on the fault system. Recent mapping studies have extended our knowledge of the amounts and possible times of offset, although much still remains to be discovered about the system in terms of its ability to generate surface ruptures during large, potentially devastating earthquakes.

Many names have been applied to parts of this fault system: Death Valley, Furnace Creek, Northern Death Valley-Furnace Creek, Black Mountains, Fish Lake Valley, Southern Death Valley, Confidence Hills, and others. To some, this proliferation of names has tended to obscure the importance, size, and lateral continuity of the fault system, which is one of the longest and fastest moving in the Basin and Range Province. In addition, major structures, such as the Furnace Creek fault zone, have evolved since the middle Miocene, and modern earthquake rupture paths are different now than they have been in the past. Please note that the nomenclature we propose herein applies to the Quaternary Death Valley fault system, and some usage of terms differs with that still used and favored by Wright and Troxel (written commun., 2001).

In the past decade, the fault system has been subdivided into various fault zones, faults, and fault segments (or fault sections), largely on a geometric basis. Almost all authors have recognized that significant changes in fault trend (azimuth), uplift amounts, slip directions, or continuity exist in the area north of Furnace Creek and south of Shoreline Butte (fig. J-1). However, these areas may or may not represent persistent structural boundaries that control the lateral propagation of surface-rupturing faults, and thus may or may not define the boundaries of fault segments.

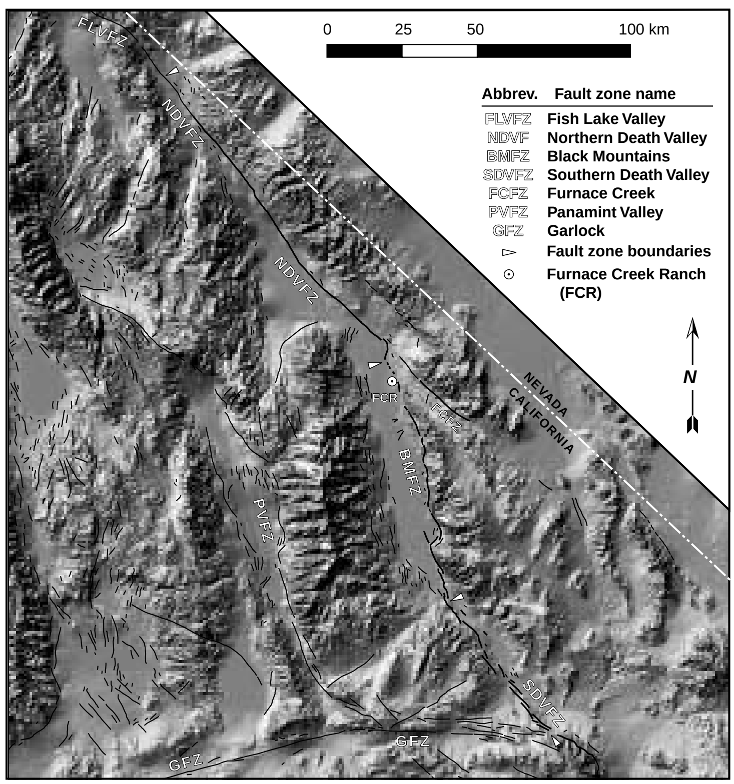


*Figure J-1. Shaded relief map showing major Quaternary faults of Death Valley region. Full extent of Fish Lake Valley and Southern Death Valley fault zones are not shown. Furnace Creek Ranch (FCR), in the central part of Death Valley, is shown for orientation. Modified from figure M-1 of Frankel and others (Chapter M in this volume); faults based on mapping by Reheis and Noller, 1996.*

Segmentation schemes for the Wasatch and San Andreas fault zones, two of the best studied faults in the United States, are based on tens of detailed investigations and, even these schemes continue to be the topic of debate.

Documentation of Quaternary segmentation along the Death Valley fault system or its individual fault zones requires detailed knowledge of the most recent times of faulting and the timing of earlier faulting events. However, no historic ground ruptures have been documented on the Death Valley fault system, and no paleoseismic studies have been conducted within the bounds of Death Valley National Park. With these facts in mind, there are four main points of this short paper.

1) We propose that the entire Quaternary zone of faulting that extends through and along the eastern margin of Death Valley be called the “Death Valley fault system.”

2) We suggest that the basic subdivisions of the fault system be referred to as fault zones, and that even finer subdivisions be termed fault sections. We avoid the popular, but often overused term “fault segment” because of its seismological implications of independent rupture entities. The fault sections reported herein are based on non-genetic criteria; verification to fault segments will have to wait pending paleoseismic information on temporal and behavioral characteristics of the fault system.

3) We suggest that the Death Valley fault system be subdivided into the following fault zones (from north to south): Fish Lake Valley, Northern Death Valley, Black Mountains (Death Valley *senso stricto*), and Southern Death Valley.

4) Finally, we suggest that many of the names applied to the Death Valley fault system and its fault zones (e.g., Artists Drive fault, Confidence Hills fault) be abandoned. Most importantly, we redefine the Furnace Creek fault zone to be the largely pre-Quaternary range-bounding, strike-slip fault that lies near the western base of the Funeral Mountains along the upper reaches of Furnace Creek, and which extends southeast into the Amargosa Valley. We propose that reference to the Northern Death Valley fault zone should be reserved for the Quaternary zone of deformation northwest of the Black Mountains. Thus, our Death Valley fault system does not include the older Furnace Creek fault zone (fig. J-2). Conversely, Wright and Troxel (written commun., 2001) prefer to use the term Furnace Creek fault zone for the nearly continuous zone of Miocene to Quaternary faults that extends from Fish Lake Valley to Amargosa Valley (Fish Lake Valley, Northern Death Valley, and Furnace Creek fault zones of our usage) that apparently evolved though at least 16 m.y. We agree to disagree on this point of nomenclature, our differences being flavored mainly by our differing perspectives on Death Valley (Quaternary geology and seismic hazards versus late Cenozoic geology and structural evolution).

Although these points may seem largely semantic, problems in nomenclature create confusion, misunderstanding, and undermine the importance of this long-lived, world-class fault system. The nomenclature proposed herein helps highlight the spatial and temporal evolution of the Death Valley fault system and focuses on its most recent, potentially active structures.

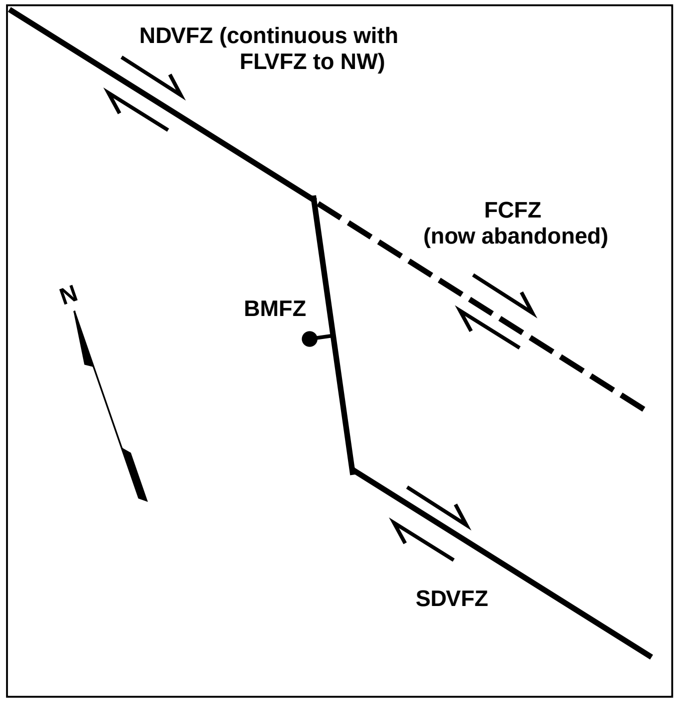


*Figure J-2. Simple diagram showing geometric relations between major fault zones of Quaternary Death Valley fault system and the Furnace Creek fault zone. Abbreviations: FLVFZ, Fish Lake Valley fault zone; NDVFZ, Northern Death Valley fault zone; FCFZ, Furnace Creek fault zone; BMFZ, Black Mountains fault zone; and SDVFZ, Southern Death Valley fault zone. FCFZ is now inactive, whereas NDVFZ and SDVFZ have dextral slip and BMFZ has oblique (dextral<normal). (Based on drawing of K.S. Kellogg, written commun., 2001).*

## A BRIEF HISTORY OF FAULT STUDIES

Lawson (1908) was the first geologist to recognize the importance of faults within Death Valley. He showed a fault at the base of the Funeral and Grapevine Mountains and another fault on the west side of Death Valley at the base of the Panamint Mountains (Lawson, 1908, map no. 1); however, he did not name these faults.

Levi Noble (1926; see also 1927) first named the normal fault at the base of the Black Mountains escarpment the “Death Valley fault,” but did not mention other faults or faulted areas. Thus, on the basis of first usage, the fault along the front of the Black Mountains should be known as the “Death Valley fault zone” (*senso stricto*). Noble (1941) later mapped many of the

Quaternary (post-Funeral Formation) strike-slip faults that continue north and south from the Black Mountains without naming them.

Noble and Wright (1954) and Curry (1954) continued to use the term Death Valley fault zone, but designated parts of the fault zone as the "Black Mountains frontal fault" and the "Artists Drive fault." The frontal-fault term is still used by some today (e.g., Wright and others, 1999). Noble and Wright (1954) used the term "Furnace Creek" in reference to the northwest-trending dextral fault zone that extends beyond their map and more than 50 miles into northern Death Valley. They also described the fault along the western base of the Funeral Mountains as the "Keane Wonder fault" and noted similarities between it and the Black Mountains frontal fault near Badwater, although the Keane Wonder is largely a pre-Quaternary fault. They showed the Death Valley fault zone along the Black Mountains, but extended it through the Confidence Hills and south all the way to the Garlock fault zone.

Hunt and Mabey (1966) recognized three individual zones for the Death Valley fault system. They used the following terms:

1) Furnace Creek fault zone for the strike-slip fault that extends from northern Death Valley south into the Furnace Creek basin;

2) Death Valley fault zone for the normal fault at the base of the Black Mountains (between Furnace Creek Ranch and Shoreline Butte); and

3) Confidence Hills fault zone for the southern strike-slip fault beginning at Shoreline Butte and extending south to the Garlock fault zone (well beyond the limits of their mapping).

Burchfiel and Stewart (1966) and Hill and Troxel (1966) continued usage of "Death Valley-Furnace Creek fault zone." They considered the Furnace Creek fault to be north and east of the Black Mountains, but noted that it lacked Quaternary motion near the Funeral Mountains. They grouped the normal fault along the Black Mountains and the dextral fault to the south together under the original Death Valley fault name. This usage is consistent with the nomenclature of Noble and Wright (1954). Troxel (1986) and Butler and others (1988) continued the use of "Confidence Hills fault zone" for the dextral-slip fault traces in the northern part of the Southern Death Valley fault zone, south of Shoreline Butte.

Wesnousky (1986, table A1, p. 12,607) divided the system into two faults [zones], calling the northern part the "Furnace Creek." For the southern portion, he used the term "Death Valley fault," but he further subdivided it into West, East, and South faults (zones). Thus, the Death Valley East fault is for all purposes the same as the Black Mountains fault zone and the Death Valley South fault is the Southern Death Valley fault zone (of our usage). We recommend abandoning Wesnousky's (1986) use of Death Valley (West, East, and South) faults. By now, you must be appreciating the ever-growing and confusing taxonomy for the Death Valley fault system.

Other than Wesnousky's (1986) reference to the Death Valley West fault, the late Pleistocene(?) to Holocene(?) fault scarps on the west side of Death Valley have been largely excluded from, or maybe spared, separate names. However, Hunt and Mabey (1966) called the scarp near the toe of the Hanaupah alluvial fan on the piedmont east of the Panamint Mountains the "Hanaupah Escarpment." For the most part, the faults on the eastern piedmont of the Panamint Mountains constitute a long, broad, but discontinuous zone of distributed normal faulting, most of which have not been studied in any detail. These latter faults are not considered to be part of the Death Valley fault system.

The Death Valley fault system was evaluated by Bryant (1988) and Wills (1989a) of the California Division of Mines and Geology for zoning under the Alquist-Priolo Earthquake Fault Zoning Act of 1972. This act requires the State Geologist to delineate regulatory zones encompassing those faults that are "sufficiently active and well defined as to constitute a potential hazard to structures from surface faulting or fault creep" (Hart and Bryant, 1997). Death Valley was included in an ambitious program to map the principal active faults statewide (Hart and Bryant, 1997). In their evaluation, Bryant (1988) and Wills (1989a) used the terms "Northern Death Valley-Furnace Creek fault zone" and "Death Valley fault zone," respectively.

Bryant (1988) mapped the Death Valley fault system in the Fish Lake Valley and Northern Death Valley area, whereas Wills (1989a) mapped the system from Furnace Creek south to the Garlock fault zone. Both found evidence for major northwest-trending, predominantly right-lateral strike-slip faults with abundant evidence of Holocene surface rupture, except for the rapidly eroding Willow Wash and Cucomongo Canyon areas (see mapping by Reheis, 1991; Reheis and others, 1993, 1995). Their overall conclusion was that the Death Valley fault system constituted a single, nearly continuous zone that has mainly right-lateral movement, with a probable compressional component in the Willow Wash area and a clear normal component in central Death Valley (Black Mountains front).

Brogan and others (1991), which is largely a revision of Brogan (1979), used the term "Furnace Creek-Death Valley fault system" to describe the late Quaternary faulting from northern Fish Lake Valley to south of Ashford Mill (near Shoreline Butte). Their compilation relied mainly on interpretation of low-sun-angle aerial photographs and limited field mapping. Brogan (1979) estimated the ages of geomorphic surfaces along the Death Valley fault system, based on surface morphology, varnish covering of clasts, and relative position above the active channel.

Brogan and others (1991) divided the fault system into 12 sections, specifically avoiding the term “segment” due to its ever-growing structural and neotectonic connotations (as suggested by Machette). The subdivision of the fault system into sections was acknowledged as being subjective and based primarily on fault trend, apparent recency of activity, width of the fault zone, continuity of the fault trace, and location of the active trace relative to the range front and bedrock structures. In retrospect, many of the sections are relatively short, clearly shorter than would be expected for a major surface-rupturing earthquake on the fault system.

In the early 1990s, Sawyer and Reheis published a series of detailed studies of the Fish Lake Valley fault zone. Reheis (1992) and Reheis and others (1993, 1995) mapped the trace at 1:24,000 scale, and both Sawyer (1990, 1991) and Reheis (1994) conducted trenching studies on two sections of the fault zone. As such, the Fish Lake Valley fault zone is the best studied part of the entire Death Valley fault system.

Most recently, Knott (1998) and Klinger (1999) used the term Death Valley fault system to describe the three fault zones—Furnace Creek, Death Valley and Southern Death Valley—that accommodate right-lateral extension in the area. Much of their work is reviewed within Chapters A (Klinger) and C (Knott) in this volume.

## PROPOSED NOMENCLATURE FOR THE DEATH VALLEY FAULT SYSTEM

In accord with the usage of Bryant (1988) and Wills (1989a), we propose that the entire length of Quaternary faulting be called the “Death Valley fault system.” This fault system is comprised of four major fault zones: they extend from Fish Lake Valley, south along the entire eastern margin of Death Valley to at least the Garlock fault zone. The Soda-Avawatz fault zone (Grose, 1959) and in-line projections of it farther south to the Bristol and Old Dad Mountains may be an offset continuation of the Southern Death Valley fault zone (Brady, 1988; Skirvin and Wells, 1990; Troxel, written commun., 2001). The Fish Lake Valley fault zone constitutes the northern end of the Death Valley fault system, although it has a different dip (east) and a separate geographic association (the Fish Lake Valley). The Death Valley fault system is part of the larger collection of strike-slip faults (i.e., the Walker Lane belt) that carry most of the northwestward-directed extension in this part of the southern Basin and Range.

As defined, the Death Valley fault system extends at least 310 km in a generally north-south direction (straight-line distance as measured from Jennings' 1994 map). It is comparable in size and activity rate to other major fault systems in the western U.S., such as the Garlock (California), Wasatch (Utah), Sangre de Cristo (New Mexico-Colorado), San Andres-Franklin Mountains (New Mexico-Texas), and Central Nevada Seismic Belt (Pleasant Valley, Dixie Valley, Fairview Peak, and Cedar Mountains faults). However, there appear to be striking changes in the fault system's trend, continuity, slip rate, slip vector, and block uplift direction that suggest a natural basis for subdividing this and other fault systems into multiple fault zones.

Almost all authors have recognized that the most significant changes in the fault system exist at (1) the Cucomongo Canyon area between Fish Lake Valley and northern Death Valley, (2) the Salt Springs/Three Bare Hills area (8-15 km north of Furnace Creek Ranch), and (3) near Shoreline Butte (see location map later in paper). These three areas may or may not represent structural asperities that control the lateral propagation of surface rupturing faults, but they provide logical and geometrically definable limits for our subdivision of the system into four discrete fault zones (from north to south): Fish Lake Valley, Northern Death Valley, Black Mountains (Death Valley *senso stricto*), and Southern Death Valley.

These fault zones may in fact be true seismological segments; that is, portions of the larger fault system that can be expected to rupture independently of one another and over the entire length of each zone in large earthquakes (moment magnitude 6.5-7.5). However, correlation of fault zones to seismic source zones should not be made without paleoseismic verification of each fault zone's (or fault section's) temporal and behavioral characteristics.

The time of the most recent ground-rupturing earthquake along the Death Valley fault system has been the topic of some speculation. Although there is no evidence to suggest that earthquakes on different fault zones of the system are spatially or temporally linked, the morphology along most of the system is certainly suggestive of very young activity (i.e., late Holocene). In the earliest report of youthful faulting, Clements (1954, p. 58-60) suggested, on the basis of newspaper accounts and other turn-of-the-century written records, that the young scarps along the Black Mountains fault zone just south of Furnace Creek were the result of the November 4, 1908, M 6.5 earthquake. Although this is entirely plausible, the records for this particular earthquake are not very good and the location of the event is poorly constrained (Stover and Coffman, 1993, p. 75). Surely, local inhabitants of the valley would have noticed if any substantial ground ruptures occurred in the Furnace Creek area (see Chapter Q for a review of the history of the area). The felt and recorded seismicity in the Central Death Valley area is mainly dominated by M 3-4 earthquakes (see fig. J-3), with only occasional M 5 earthquakes occurring along the northern boundary of the park (near Scotty's Castle) and M 6 earthquakes being well outside the park. The apparent seismic inactivity of the Death Valley fault system is much like many other major faults in the Basin and Range province. For example, the Wasatch fault zone, which marks the eastern margin of the province, has had no M 6 or larger earthquakes since 1847 (see Machette and others, 1991, 1992), the date that Mormon pioneers settled in the Salt Lake City area.

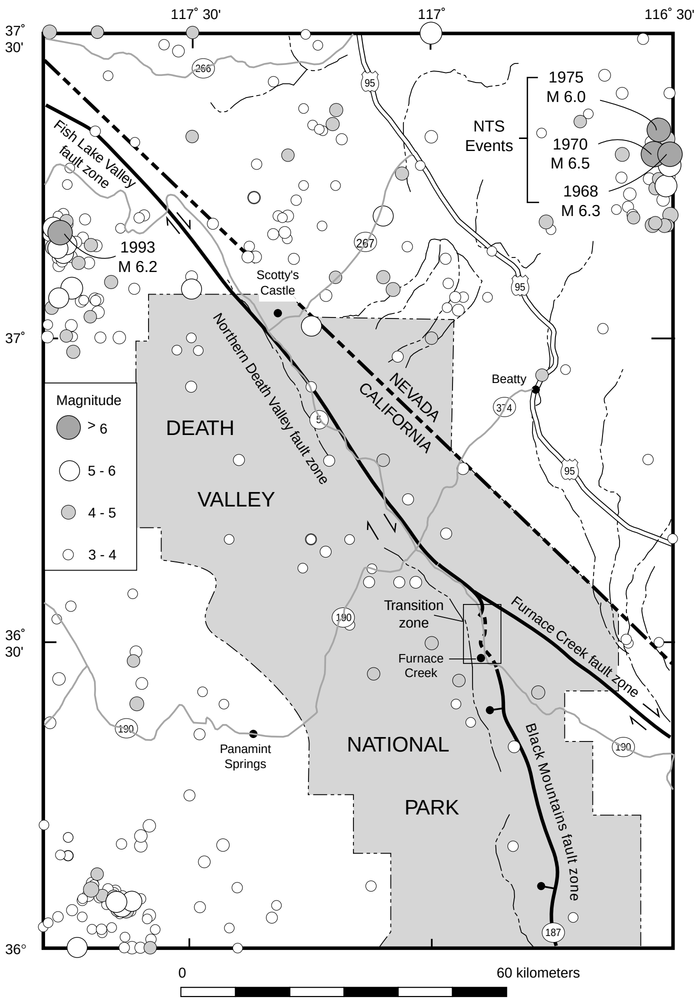


*Figure J-3. Locations of M>3 earthquakes from 1900-1996 in Death Valley region. Earthquake locations from internet search of U.S. Geological Survey seismicity catalog. The four largest historic earthquakes (labeled by date) have occurred in areas of seismic clustering, well away from Death Valley fault system and Furnace Creek fault zone. Furnace Creek Ranch (FCR), in the central part of Death Valley, is shown for orientation.*

Based on the relationship of archaeological sites to the Death Valley fault system, Hunt and Mabey (1966, p. A100) estimated the most recent fault activity south of Furnace Creek (i.e., Black Mountains fault zone) is prehistoric. Brogan and others (1991) also suggested that the youngest ground-rupturing earthquake along the fault occurred sometime within the past several hundred years based on observations from scattered localities along the fault. They also mentioned a 10.8-km-long fissure that formed in 1969, but this interpretation is suspect. In Mesquite Flat, the trace of the Northern Death Valley fault cuts nearly to the ground surface, only being overlain by several centimeters of mud-cracked sediment. Machette and Crone (Stop B3) estimate that the most recent faulting in the transition zone between the Northern Death Valley and Black Mountain fault zones occurred between 500 and 840 years ago.

Along the Fish Lake Valley fault zone, Sawyer and Reheis (1999) summarized evidence from their previous trenching and mapping studies to show that two sections of the fault zone last ruptured between 1,500 and 700 yr B.P., and two other sections prior to 1,700 yr B.P.

## FURNACE CREEK FAULT ZONE

An important point that we want to make is that most previous authors have included the term "Furnace Creek" in naming the active basin margin faults in Death Valley (for example, the Death Valley-Furnace Creek fault zone). This has led to considerable confusion when discussing the Miocene-Pliocene structural features versus the late Quaternary seismogenic features.

Hill and Troxel (1966) and Wright and others (1991) showed the Furnace Creek fault zone extending beyond the Furnace Creek Basin into the Amargosa Valley to the southeast. Offset linear features, such as bedrock contacts or unique lithologies along the southern Funeral Mountains, suggest tens of kilometers of right-lateral displacement that apparently forms the eastern margin of the Amargosa Valley (Wright and others, 1991). The Furnace Creek fault zone was a major player in the evolution of Death Valley in the late Miocene and Pliocene (Wright and others, 1999), but it appears to have been largely inactive in the Quaternary (Burchfiel and Stewart, 1966; Hamilton, 1988; Klinger and Piety, 1996).

Thus, we redefine the largely pre-Quaternary Furnace Creek fault zone to include those largely range-bounding strike-slip faults near the western base of the Funeral Mountains and along the upper reaches of Furnace Creek extending southeasterly into the Amargosa Valley. To the north, the trace of the Furnace Creek fault zone departs from the Funeral Mountains and is poorly located, being mainly concealed by alluvium. Wright and Troxel (1993) showed a trace of the Furnace Creek fault along the southwest margin of the Kit Fox Hills (shown on fig. J-5), which we would suggest is the Northern Death Valley fault zone (see below). We consider the dextral Keane Wonder fault of Wright and Troxel (1993) to be a northern splay of the Furnace Creek fault zone; it too, has been largely inactive in the Quaternary.

## FISH LAKE VALLEY FAULT ZONE

The Fish Lake Valley fault zone is a high-angle, right-oblique, down-to-east fault zone in Fish Lake Valley, bounding the east side of White Mountains and the east side of the Horsethief Hills (informal name, Reheis, 1991) between Eureka and Fish Lake Valleys (fig. J-4). It extends from Chiatovich Creek on the north, through Fish Lake Valley, to south of Cucomongo Canyon, which marks the northern edge of Death Valley. The fault zone was named by Sawyer (1990) and subsequently adopted in maps by Reheis and others (1993, 1995). The fault zone was previously referred to as various iterations of the "northern part of the Furnace Creek fault zone of the Death Valley-Furnace Creek fault system" (see Brogan and others, 1991), but clearly the Fish Lake Valley name is more appropriate in a geographic sense. Four sections (or subzones) were defined on the basis of distinct differences in fault strike and faulting style (Brogan and others, 1991; Sawyer, 1990, 1991); however, these sections were recently revised to incorporate paleoseismic evidence for differences in the timing of the most recent (late Holocene) event along the fault zone (Sawyer and Reheis, 1999). These include, from north to south, the Leidy Creek, Wildhorse Creek, Oasis, and Cucomongo Canyon sections. The Wildhorse Creek and Cucomongo Canyon sections both exhibit apparent reverse-slip components, and appear to have ruptured less recently than the right-oblique normal-slip Leidy and Oasis sections.

There have been a number of paleoseismic investigations of the Fish Lake Valley fault zone, inasmuch as the entire fault zone is outside of Death Valley National Park where use of mechanized equipment in wilderness areas is prohibited. Trenches have been excavated on the Chiatovich Creek (Sawyer, 1990, 1991) and Oasis (Sawyer, 1990; Reheis, 1994) sections of the fault zone, but not on the Dyer and Cucomongo Canyon sections. These investigations document multiple surface-rupturing events in the Holocene, some as recently as late Holocene (Sawyer and Reheis, 1999).

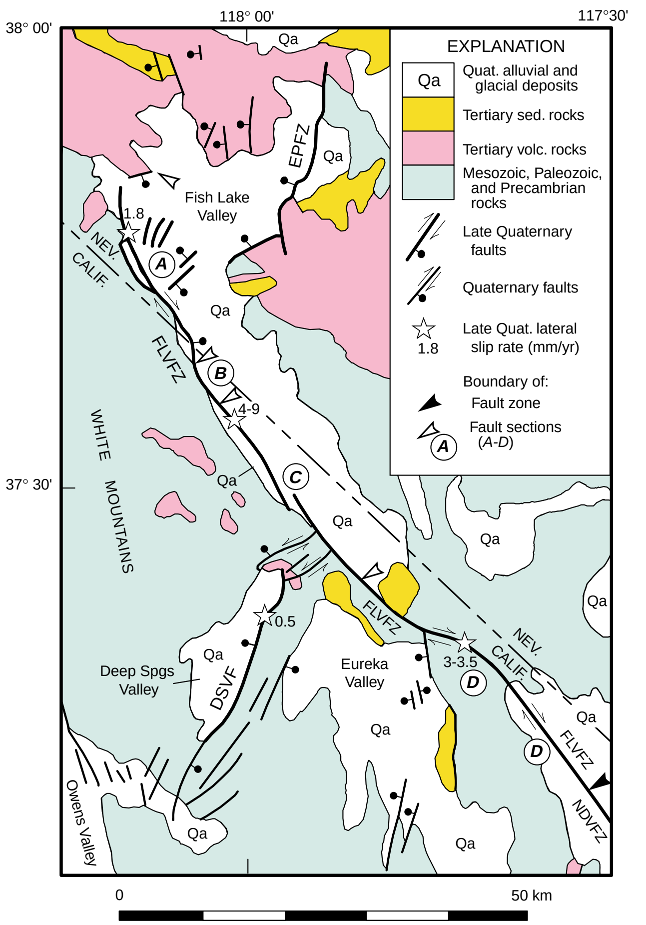


Figure J-4. Index map of Fish Lake Valley fault zone showning fault sections, separated by arrowheads, as described in text. Sections are shown by letters: A) Leidy Creek, B) Wildhorse Creek, C) Oasis, and D, Cucomongo Canyon (from north to south). Abbreviations: DSVFZ—Deep Springs Valley fault zone; EPFZ—Emigrant Peak fault zone; FLVFZ, Fish Lake Valley fault zone; NDVFZ—Northern Death Valley fault zone.

## NORTHERN DEATH VALLEY FAULT ZONE

The Northern Death Valley fault zone is defined as the zone of Quaternary dextral-slip faults more-or-less coincident with the axis of northern Death Valley (Brogan and others, 1991). Klinger (2001) divides the Northern Death Valley fault into three 30- to 35-km-long sections based primarily on the nature of the rocks found along the fault, but also considers the fault's geomorphology, trend, continuity, and location of the fault relative to the range. From south to north, these are defined as the 1) Kit Fox Hills section; 2) Mesquite Flat-Screwbean Spring section; and 3) Grapevine Mountains section (fig. J-5).

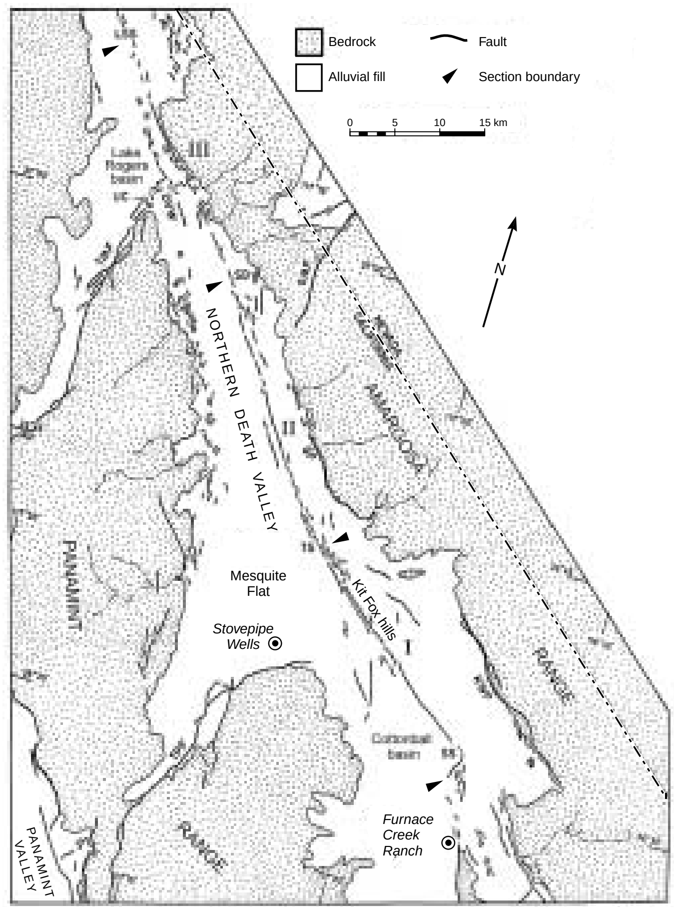


Figure J-5. Northern Death Valley fault zone showing fault sections, separated by arrowheads, as described in text. Section I—Kit Fox Hills; section II—Triangle Spring—Screwbean Springs; and section III—Grapevine Mountain. Other abbreviations: DVW—Death Valley Wash fault; GF—Grapevine fault; GMF—Grapevine Mountain fault; KWF—Keane Wonder fault; LSS—Little Sand Spring; SB—Screwbean Springs; SS—Salt Springs; TMF—Tin Mountain fault; TPF—Towne Pass fault; TS—Triangle Spring; and UC—Ubehebe Crater.

The Kit Fox Hills section extends from the southernmost clear trace of the fault near Salt Spring northwest along the Kit Fox Hills to Triangle Spring (fig. J-5). Along this section of the fault, both structural and geomorphic evidence is suggestive of compression across the fault (see Klinger, 2001). The fault is marked by a very linear trace along the base of uplifted late Pliocene and early Pleistocene rocks in the Kit Fox Hills. The valley floor in this area is distinctly narrower than the valley both to the north and south. In addition, the elevation of the valley floor increases dramatically from less than 73 m (240 ft) below sea level to more than 30 m (100 ft) above sea level and the fault section is marked by associated folding (e.g., Salt Creek Hills anticline northwest of Cottonball basin) and secondary faulting.

The Mesquite Flat-Screwbean Springs section extends from Triangle Spring northward across the floor of Mesquite Flat and along the Grapevine Mountains piedmont to Screwbean Spring (fig. J-5). This section of the fault coincides with the valley axis and is also very linear, but the fault is marked by a low scarp on latest Quaternary deposits. The normal dip-slip Grapevine fault (Reynolds, 1969) is parallel to much of this section of the Northern Death Valley fault.

The Grapevine Mountains section, to the north, is also very linear, but lies mostly at the base of the Grapevine Mountains, as does the Grapevine fault to the south. This section extends from Screwbean Springs north to Little Sand Spring (fig. J-5). Uplifted Tertiary rocks mark the east side of the fault. As in the Kit Fox Hills section, structural and geomorphic evidence along this section is suggestive of compression across the fault. The Death Valley Wash fault, an east-verging reverse fault, parallels much of this section of the fault.

The Northern Death Valley fault zone bisects and uplifts Tertiary basin-fill deposits that occupied a structural basin in the Miocene and Pliocene. This relation suggests that fault was not actively uplifting in the late Tertiary, whereas today it is. Conversely, the Furnace Creek fault zone and associated Keane Wonder bound the eastern margin of the late Tertiary Furnace Creek basin (Wright and others, 1999). Thus, we suspect that the Northern Death Valley fault zone is the Quaternary expression of older Miocene to Pliocene Furnace Creek fault zone, the southern part of which is now inactive. The geometric and temporal separation of the Quaternary Northern Death Valley fault zone from the older Furnace Creek fault zone is consistent with most of the original structural interpretations in the area (see Burchfiel and Stewart, 1966; Hill and Troxel, 1966). The distinction of these two fault zones also further emphasizes the importance of the Furnace Creek and Keane Wonder fault zones as two main Tertiary structures in this part of Death Valley.

The Northern Death Valley fault zone merges with the Black Mountains fault zone over a broad area between Salt Springs and Furnace Creek in an area referred to by Klinger and Piety (1996) as the "Transition Zone" (fig. J-6). This transition zone is marked by short discontinuous faults that trend in varying directions over a wide zone, and is associated with active folding (see Stop B3 and Chapter K, this volume). The transition zone represents a structurally complex area where the Black Mountains fault zone steps over to Northern Death Valley fault zone.

## BLACK MOUNTAINS FAULT ZONE

The Black Mountains fault zone (Death Valley fault zone *senso stricto*) is defined as the zone of Quaternary faulting on the western piedmont of the Black Mountains. Faulting here is predominantly normal with a small dextral component (Wills, 1989a, b; Brogan and others, 1991). By this definition, active portions of the turtleback faults at Badwater and Mormon Point (see Chapter C, fig. C-1), which show evidence of Quaternary slip (Knott, 1999; Knott and others, 1999), are included in the Black Mountains fault zone, as previously suggested by Wright and others (1991).

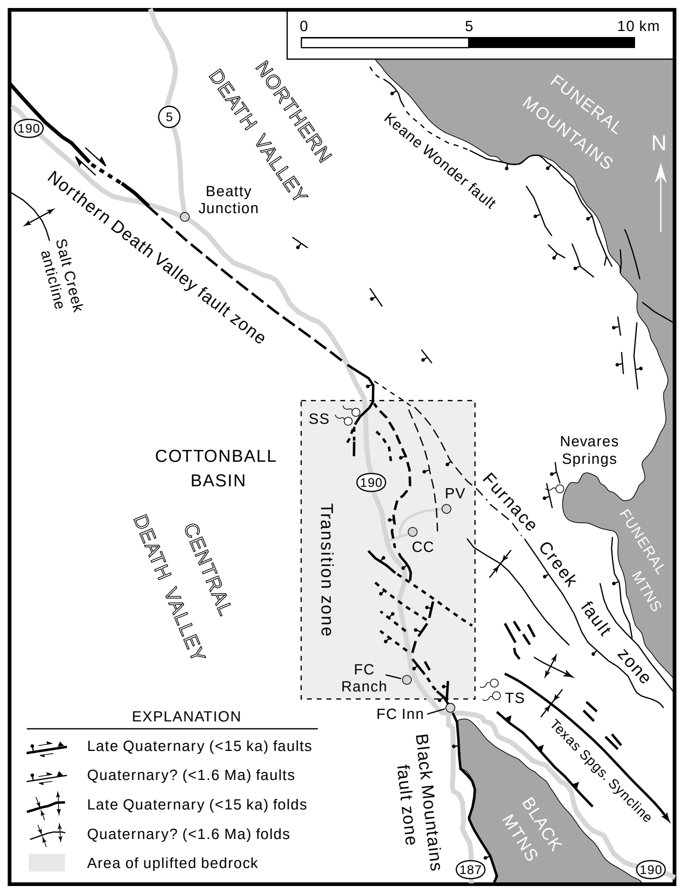


*Figure J-6. Generalized map of transition zone between Northern Death Valley and Black Mountains fault zones. Quaternary faults modified from figure 15 in Klinger and Piety (1996). Abbreviations: CC, Cow Creek facility; FC, Furnace Creek; PV, Park Village; SS, Salt Springs; and TS, Texas Springs.*

Knott (1998) divided the Black Mountains fault zone into six about 20-km-long segments [herein referred to as sections] based on morphological characteristics. Sections defined in this way are, from south to north:

Section 1: Ashford Mill to Shoestring Canyon
Section 2: Shoestring Canyon to Mormon Point
Section 3: Mormon Point to Willow Wash
Section 4: Willow Wash to Natural Bridge
Section 5: Natural Bridge to Desolation Canyon
Section 6: Desolation Canyon to Furnace Creek

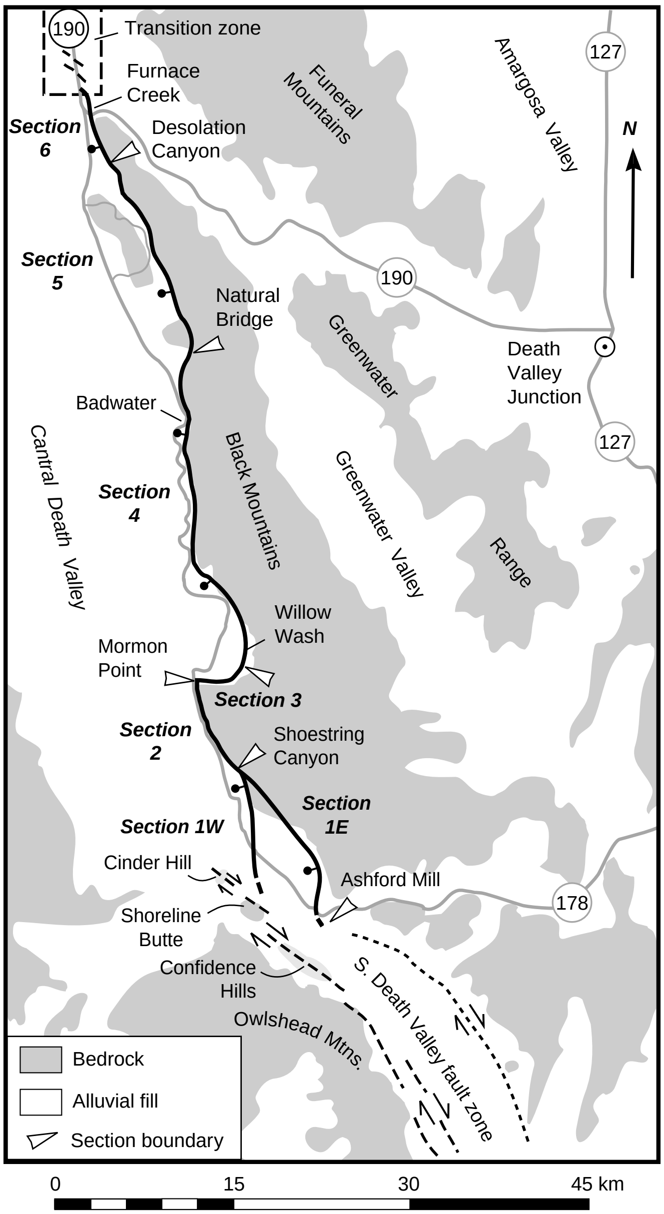


*Figure J-7. Index map of Black Mountains fault zone showning fault sections, separated by arrowheads, as described in text. Sections are numbered from south to north. Traces of the Southern Death Valley fault zone are not accurately depicted or located on this figure.*

For long (>50 km) normal faults, such as the Wasatch fault zone in Utah, section boundaries are commonly found at bedrock salients, cross faults, gaps in faulting, or large en echelon steps (see Machette and others, 1991, 1992). For the Black Mountains fault zone, there is evidence that the Artists Drive block and east-west trending embayment between Willow Wash and Mormon Point and may be barriers to propagation of fault slip. For example, at Mormon Point (fig. J-7), the west-trending fault of Section 3 offsets the Holocene salt pan and crosses north-south-trending fault of Section 2. However, there is evidence that Section 2 has propagated northward along strike during the Quaternary and, as a result, Section 3 has been sequentially abandoned and re-established to the north several times (Knott and others, 1999).

The transition between the oblique-slip Black Mountains fault zone and the strike-slip Northern Death Valley fault zone to the north is characterized by broad zones of very complex normal and dextral faulting and often folding and tilting of beds (fig. J-5). This northern transition zone is described by Klinger and Piety (Chapter K, this volume) and Machette and others (Chapter B, Stop B3, this volume). The transition to the Southern Death Valley fault zone essentially includes all of Section 2 from Mormon Point south and Section 1 (east and west strands). Along this reach, the fault zone makes several 1-2 km right steps away from the front of the Black Mountains. The southern section (1W) of the Black Mountains fault zone, intersects with the right-lateral Southern Death Valley fault zone along the northeast side of Shoreline Butte (see fig. C1-1, Chapter C in this volume).

## SOUTHERN DEATH VALLEY FAULT ZONE

The Southern Death Valley fault zone is defined here as the dextral-slip fault zone that extends southeast from Cinder Hill and Shoreline Butte, both of which show clear evidence of right-lateral offset (fig. J-7; Wright and Troxel, 1984). The Southern Death Valley fault zone is distinguished from the Black Mountains fault zone by its more northwest trend (nearly N. 50° W.) and almost pure dextral sense of slip. The Southern Death Valley fault zone can be traced southeast to the Garlock fault zone (Butler, 1984; Brady, 1986), where it is truncated, bent and has had young reverse slip on it (Troxel and Butler, 1998). An offset continuation of it may extend south to the Bristol and Old Dad Mountains (Brady, 1988; Skirvin and Wells, 1990).

Much of the Southern Death Valley fault zone is characterized by very linear right-lateral fault traces with abundant evidence for Holocene surface rupture. However, strands of the Southern Death Valley fault zone that extend through Shoreline Butte and Cinder Hill, west of the junction of the Southern Death Valley and Black Mountains fault zones, apparently were not active during the most recent movement of the Southern Death Valley fault zone farther south. South of this junction, the Confidence Hills are sandwiched between two strands of the Southern Death Valley fault zone. South of the Confidence

Hills, the Southern Death Valley fault zone begins to splay out into several strands as it approaches the Garlock fault zone (figs. J-1 and J-7) Holocene activity on two main strands appears to die out near the north end of the Noble Hills (Brady, 1986a; Wills, 1989a). Several additional traces with Quaternary displacement extend to within a few kilometers of the Garlock fault zone.

## ACKNOWLEDGEMENTS

The authors thank Lauren Wright and Bennie Troxel who discussed many aspects of this paper with us, provided valuable comments, and corrected some of our misconceptions. We respect their opinions and choice to take a different road in terms of the "Furnace Creek fault zone." Karl Kellogg (USGS), who has close ties to the region (Brogan and others, 1991), provided technical review comments, and the cogent diagram that we used for figure J-3. However, any errors in this quickly assembled paper are those of the authors. Hopefully the paper will provide fodder for discussions on and after the Friends of the Pleistocene trip.

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# Late Quaternary flexural-slip folding and faulting in the Texas Spring syncline, Death Valley

*Ralph E. Klinger and Lucille A. Piety*




## ABSTRACT

The geomorphology and surficial geology in the Texas Spring syncline indicates that strain between the Furnace Creek and Black Mountain fault zone is being accommodated by localized folding and faulting. The northeast-striking, down-to-the-northwest normal dip-slip Cross Valley fault truncates the southeast end of the syncline. Scarps on late Pleistocene alluvium have maximum scarp-slope angles between 9° and 26° with scarp heights of 1.8 and 7.2 m, respectively. The northwest-striking, northeast-verging Echo Canyon thrust fault also displaces alluvium on the southwest limb of the syncline. Scarps on late Pleistocene alluvium have maximum scarp-slope angles between 22° and 25° with a scarp height of 5.4 m. Late Pleistocene, and possibly Holocene geomorphic surfaces formed on alluvium deposited into and across the syncline have also been warped and uplifted at least 10 m on the southwestern limb of the syncline. Displacement along the faults on the southwest limb of the Texas Spring syncline indicates that deformation is continuing and is being accommodated in part by flexural-slip between bedding planes of the Furnace Creek Formation.

The lack of a through-going trace of the Black Mountain fault zone across the northwest projection of the Texas Spring syncline or Quaternary movement on the Furnace Creek fault north of Furnace Creek Wash strongly suggests that the syncline forms a structural boundary between the Northern Death Valley and Black Mountain faults (see also, Chapter B in this volume). Thus, large ground-rupturing earthquakes probably occur as discrete events on each of these faults and do not rupture across the syncline. The style of Quaternary deformation within the Texas Spring syncline also indicates that flexure of the syncline is continuing in response to northeast-southwest directed compression and northwest-southeast extension most likely associated with normal dip slip or normal-dextral slip on the Black Mountain fault zone.


## INTRODUCTION

The Texas Spring syncline is a northwest-trending, southeast-plunging asymmetric fold that is part of the larger structural trough formed between the northern Black Mountains and the southern Funeral Mountains in central Death Valley (fig. K-1). This structural trough is delineated by a sequence of folded and faulted late Cenozoic sedimentary rocks first described by Noble and Wright (1954) as the Furnace Creek basin. Hunt and Mabey (1966; 1:96,000) and McAllister (1970; 1:24,000) later mapped the geology of the basin as part of various borate mineral inventory studies. Other studies of the stratigraphy in the basin (Cemen and others, 1985; Wright and others, 1999) indicate that the basin formed about 12-14 Ma in response to dextral shear along the northwest-striking, right-lateral strike-slip Furnace Creek fault. Currently,

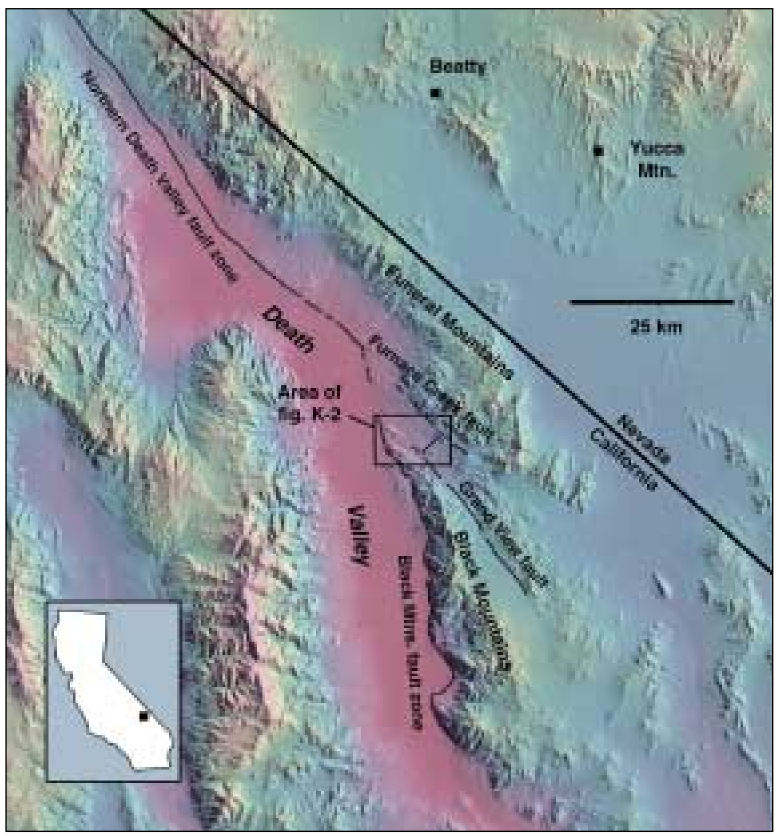


*Figure K-1. Shaded relief map of the area surrounding Death Valley. Outlined area shows location of Texas Spring syncline. YM is site of proposed high-level nuclear waste repository at Yucca Mountain.*

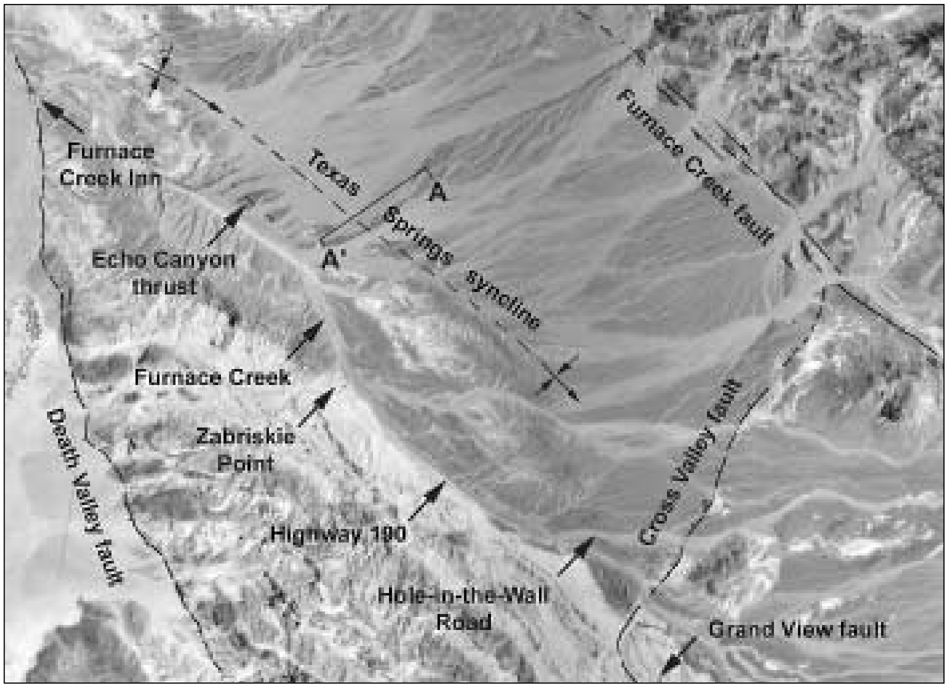


*Figure K-2. Vertical aerial photograph of northwestern end of Furnace Creek Valley showing location of Texas Spring syncline, Cross Valley and Echo Canyon faults relative to Furnace Creek and Black Mountain fault zones.*

the Furnace Creek basin forms the structural trough through which Furnace Creek flows to Death Valley. Furnace Creek presently flows parallel to the axis and against the steeply northeast-dipping strata on the southwest limb of the Texas Spring syncline (fig. K-2).

Much of the previous work in the Furnace Creek basin has focused on the mineral resources and the late Cenozoic structural development of Death Valley (e.g. Noble, 1941; Noble and Wright, 1954; McAllister, 1970; Cemen and others, 1985; Wright and others, 1999). The structural relationship between the Furnace Creek, the Northern Death Valley, and the Black Mountain fault zones has also become a topic of interest, but only of limited studies in site-characterization investigations for the potential high-level nuclear waste repository at Yucca Mountain (Brogan and others, 1991; Reheis and Noller, 1991; Noller and Reheis, 1993; Klinger and Piety, 1996; also see the discussion of fault nomenclature by Machette and others, this volume) (fig. K-1). In an evaluation of the Quaternary movement on the Black Mountain and Northern Death Valley fault zones, Klinger and Piety (1996) recognized that a 19-km-long gap separated the well-defined Holocene traces of the two faults. Fault scarps and folds in this gap are relatively short (<1.5 km) and discontinuous, vary in orientation direction, and display differing styles of deformation (Brogan and others, 1991; Klinger and Piety, 1996). Based primarily on the overall character of deformation and the lack of a distinct, through-going fault trace, the area between the Northern Death Valley and Black Mountain fault zones was viewed as transitional in terms of the dominant style of deformation, thus it was referred to as the transition zone by Klinger and Piety (1996). Most recently, this area has been the focus of studies directed at developing the ground water resources for the national park (Machette and others, 2000).

Recent movement on the faults and folds in this area are likely interrelated. There-fore, the study of the fault scarps, and the uplifted and folded geomorphic surfaces in the Texas Spring syncline are important for discerning how strain is being accommodated between the Northern Death Valley and Black Mountain fault zones. Charac-terizing the late Quaternary deformation is also important to understanding how future tectonic activity may impact an area that contains much of the infrastructure for Death Valley National Park. The focus of this study is on the Texas Spring syncline and the associated structures that show evidence for late Pleistocene and possibly Holocene activity.

## GEOLOGIC SETTING

The stratigraphic and structural relationships between the late Cenozoic sedimentary rocks in the Furnace Creek basin provide important evidence for the formation and development of Death Valley over the last 14 Ma (McAllister, 1970; 1973; Cemen and others, 1985; Wright and others, 1999). The principle lithostratigraphic units that delineate the Furnace Creek basin and the Texas Spring syncline include the Artists Drive, Furnace Creek, and Funeral Formations. The Artists Drive Formation is a late Miocene to early Pliocene volcanic-clastic unit originally designated by Thayer (described in Noble, 1941; p. 955). The age of the Artists Drive Formation is constrained by numerous radiometric ages derived from interbedded volcanic units to 14-6 Ma (Wright and others, 1999). In the Furnace Creek area, the Artists Drive Formation crops out primarily on the northeast flank of the Black Mountains and in fault contact with strata of the Furnace Creek Formation on the southwestern limb of the Texas Spring syncline (cross-section B-B'; McAllister, 1970).

Thayer (described in Noble, 1941; p. 956) originally defined the Furnace Creek Formation. The age of the Furnace Creek Formation was originally estimated to be early to middle Pliocene on the basis of diatoms and a correlation to the Copper Canyon Formation, which contains diagnostic mammalian fauna (McAllister, 1970). A few radiometric ages between 5-6 Ma have been determined for volcanic units in the

Furnace Creek Formation and Sarna-Wojcicki and others (this volume) report probable ages of 3.0-3.3 Ma for air-fall tuffs in the upper part of the Furnace Creek Formation (see also Stop B5). Strata of the Furnace Creek Formation largely delineate the Furnace Creek basin, and certainly the Texas Spring syncline. McAllister (1970; 1973) mapped the Furnace Creek Formation extensively in the region and much of what is currently known about the Furnace Creek Formation is based on his observations, mapping, and cross-sections (Wright and others, 1999).

The Funeral Formation is a late Pliocene fanglomerate that is distinguished from the underlying Furnace Creek Formation in the Furnace Creek basin primarily by a conspicuous angular unconformity (McAllister, 1970; Wright and others, 1999). The age of the Funeral Formation is generally considered to be late Pliocene (Knott and others, 1999; Wright and others, 1999) although the upper part of the formation has been previously reported as being perhaps early Pleistocene (Hunt and Mabey, 1966; Wright and Troxel, 1993). Radiometric ages of 4-5 Ma have been determined on volcanic strata near the base of the formation (Cemen and others, 1985), suggesting that it may be partly coeval with the Furnace Creek Formation. A detailed discussion of each of these formations and a review of the tectonic development of the Furnace Creek basin is included in Wright and others (1999) and in various articles of this guidebook.

The Texas Spring syncline is flanked by the southern Funeral Mountains and the Furnace Creek fault to the northeast and the northern Black Mountains to the southwest (fig. K-1). While the Furnace Creek (Northern Death Valley) fault appears to be one of the most active faults in eastern California (Klinger, 1999), activity on the Furnace Creek fault along the southern Funeral Mountains appears to be pre-Quaternary (Hamilton, 1988; Wright, 1989). The Grand View fault lies along the northeastern flank of the Black Mountains and appears to terminate at the Cross Valley fault (fig. K-1). Quaternary displacement along the Grand View fault can be ruled out because 4-5 Ma basalts in the lower part of the Funeral Formation overlie the fault and are not displaced (Cemen and others, 1985; McAllister, 1970). The Cross Valley fault marks the southeasterly end of the Texas Spring syncline.

## TEXAS SPRING SYNCLINE

Of particular interest to this study are the Quaternary deposits associated with the Texas Spring syncline and the relationship between these deposits and the geomorphology of the fold. Quaternary alluvial fans derived from the Funeral Mountains have been deposited into the basin formed by the Texas Spring syncline (fig. K-2). The Quaternary alluvium is relatively thin at the range front, sloping gently southwest towards the axis of the fold and is typically inset into the Funeral Formation on the northeastern limb (McAllister, 1970). Strata on the steeper southwest limb of the syncline have been uplifted on the northeastern flank of the Black Mountains. In the Texas Spring syncline, the Funeral Formation is separated from the underlying Furnace Creek Formation by a distinct angular unconformity (Hunt and Mabey, 1966; McAllister, 1970). However, southeast of the Cross Valley fault, the relationship is nearly conformable (McAllister, 1970; Cemen and others, 1985). Similarly, the Quaternary alluvium near the axis of the Texas Spring syncline is separated from the older Funeral Formation by an angular unconformity (see McAllister, 1970; cross-section B-B'). Near the axis of the syncline, Holocene alluvial deposits also buries the older Quaternary alluvium. It is difficult to explain the stratigraphic relationships in the Texas Spring syncline by erosion or alluvial deposition without invoking tectonic deformation.

While the Texas Spring syncline is delineated primarily by folded and faulted rocks of the Furnace Creek and Funeral Formations (McAllister, 1970), the surficial expression of the fold is also exhibited by gently folded Quaternary alluvium. Late Pleistocene and possible Holocene deformation across the syncline is indicated by the geomorphic relationships between the alluvial deposits along and near the axis of the syncline (fig. K-3). Holocene alluvial deposits are preserved at the surface and appear to bury older alluvium near the axis of the syncline. These same deposits are inset into Pleistocene deposits on the northeast limb along the southern Funeral Mountains, the source area for many of the tributaries that drain into Furnace Creek. The stable geomorphic surfaces developed on Pleistocene alluvial fans lie several meters above the active channel and Holocene alluvium, often with the Furnace Creek or Funeral Formations exposed beneath them. Similarly, a thin veneer of Quaternary alluvium on this limb of the syncline has been uplifted and currently dips back towards its source in the Funeral Mountains about 3 km (2 mi) to the northeast (fig. K-3B). This relationship is illustrated in topographic profiles measured on a late Pleistocene surface and the adjacent Holocene surfaces across the axis of the syncline (fig. K-3A). Deformation of the late Pleistocene surface, and possibly the early Holocene surfaces, is exhibited in these profiles and the varying heights of correlative surfaces above the active wash (fig. K-3B). Uplift of this late Pleistocene surface may be as much as 10 m. The late Pleistocene surface, which is well above younger surfaces on the northeast limb, is buried by the younger surfaces near the axis of the syncline. It then rises above the younger surfaces on the southwest limb. Well-developed desert pavement, muted bar-and-swale topography, the formation of dark rock varnish, and degree of soil development (Klinger and Piety, 1996) supports a late Pleistocene age for the upper surface.

The axis of the syncline is shown by McAllister (1970) to curve westward and project into Death Valley northeast of the Furnace Creek Inn (fig. K-2, see also field trip Stop B1). Structural relief of the Funeral Formation across the Texas Spring syncline near the hinge of the fold is estimated to be at 230 m and possibly as much as 300 m. Deformation of the late Pleistocene surface mimics the morphology of the syncline and the deformed strata of the underlying Furnace Creek and Funeral Formations (McAllister, 1970). The amount of deformation of the late Pleistocene alluvium is much less than that of the older formations, indicating progressive development of the syncline through the Quaternary. A similar relationship may also exist between the early and middle Holocene and the late Pleistocene alluvium, but stratigraphic correlations and measured topographic profiles are not precise enough to demonstrate this relationship. As would be expected, if these stratigraphic relationships have a tectonic origin, the deformation of the early and middle Holocene surfaces would be noticeably less than that of the late Pleistocene alluvial fan surfaces.

## ECHO CANYON FAULT

Young fault scarps along a northwest-striking, northeast-verging thrust fault on the southwestern limb of the fold provide evidence for late Pleistocene deformation of the Texas Spring syncline (fig. K-4). The fault is referred to as the Echo Canyon thrust based on the excellent exposure of the fault along the Echo Canyon Road (Klinger and Piety, 1996; p. 49). Scarps preserved on late Pleistocene alluvial fans along the Echo Canyon fault indicate that there has been movement on the fault and deformation across the syncline, perhaps as recently as late Holocene. The scarp at the Echo Canyon road is 5.4 m high and has a maximum scarp-slope angle between 22° and 25°, which is fairly indicative of Holocene activity in the western U.S. (see Bucknam and Anderson, 1979). The rock varnish and desert pavement are poorly developed across the scarp slope relative to the adjacent geomorphic surfaces. The desert pavement is disrupted at the scarp and many of the varnished stones in the pavement have been turned over as they are oriented with the darker upper surface down. The sense of slip across the fault is readily apparent in channel exposures and the fault can be seen extending nearly to the ground surface. The soil associated with the late Pleistocene surface (Q2c) on the hangingwall block is clearly disrupted along the scarp and the desert pavement and vesicular A horizon developed on the surface of the footwall is buried by colluvial material

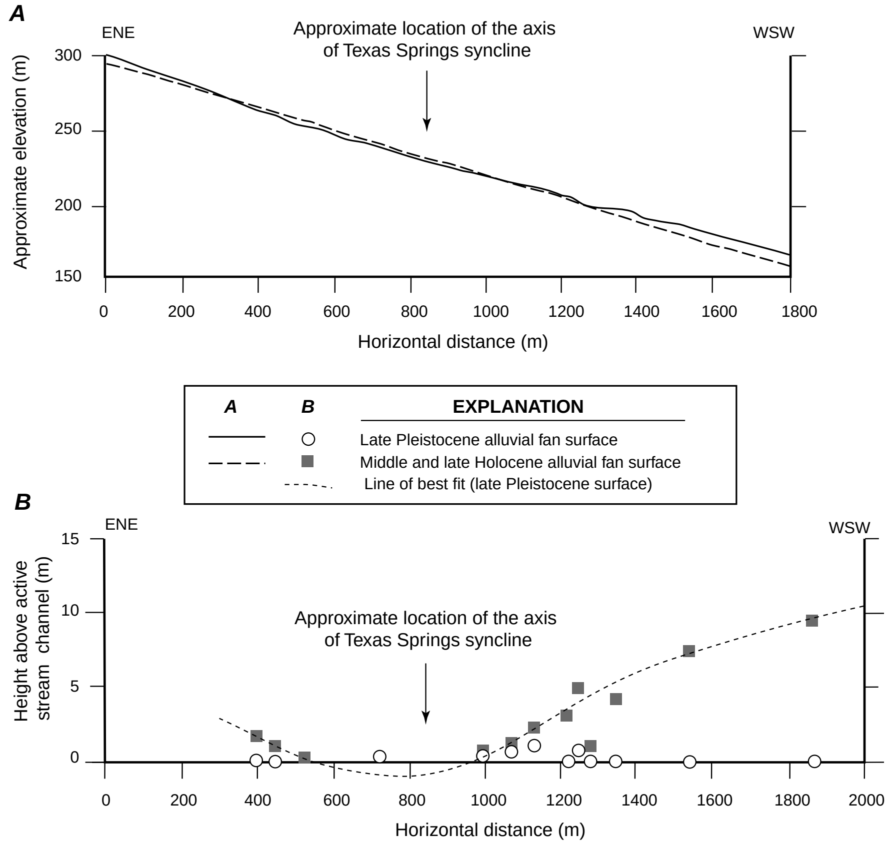


*Figure K-3. A, Topographic profiles of late Pleistocene and Holocene geomorphic surfaces across the axis of Texas Spring syncline near Echo Canyon road (fig. K-2), and B, the height of the surfaces above the active wash. See figure 2 for location of profile A-A'.*

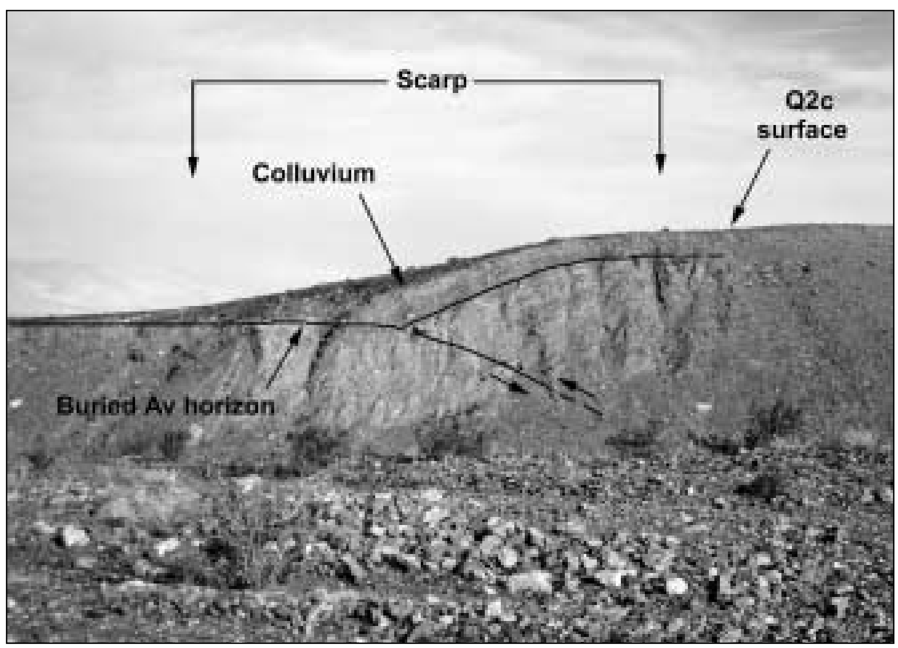


*Figure K-4. Echo Canyon fault exposed below scarp on a late Pleistocene alluvial fan along Echo Canyon Road (fig. K-2). Colluvium from the scarp has buried a vesicular A horizon associated with late Pleistocene surface on footwall block. View is to northwest.*

derived from erosion of the scarp. Exposures of the Echo Canyon fault, its scarps, and evidence for continued deformation of the Texas Springs syncline will be reviewed at field trip stop B4 (Klinger and others, this volume).

Based on the relatively short length (<6 km) of the scarp, the orientation of the fault parallel to the strike and dip of the strata, and the location of the fault on the limb of a fold, the fault is believed to represent a bedding-plane fault associated with folding of the Texas Spring syncline. Coseismic displacement on secondary faults and bedding planes within a fold associated with historical earthquakes has been previously observed (e.g., Keller and others, 1982; Klinger and Rockwell, 1989). The total displacement across the Echo Canyon fault represented by the scarp at this site certainly did not occur during a single ground-rupturing earthquake, but probably represents deformation on the southwest limb of the fold resulting from numerous discrete coseismic events or aseismic creep.

Some constraints can be put on the amount of deformation associated with the Texas Spring syncline. Coseismic deformation of the Willow Creek anticline in the Salton Trough accompanying ground rupture in the 1987 Superstition Hills, Calif. earthquake sequence (Klinger and Rockwell, 1989) ranged between 20-40 percent of the average slip on the main fault. The average displacement per event on the Black Mountain fault zone near Mormon Point is reported to be about 2.5±0.5 m (Klinger, 1999). Assuming that a relationship similar to the Willow Creek anticline exists between the Texas Spring syncline and the Black Mountain fault zone, then the total displacement observed on the Echo Canyon thrust may be the product of 6-8 events since the stabilization of the late Pleistocene surface. This analogy is based on the assumption that movement on the adjacent Black Mountain fault zone drives the flexure of the southwestern limb of the syncline. Deformation of the fold, movement on the thrust fault, and bedding-parallel slip on beds within the syncline may have occurred in response to movement on the Furnace Creek fault, the Black Mountain fault zone, or both. The source of stress driving the continued deformation of the Texas Spring syncline in the late Pleistocene and Holocene is not readily apparent at this point. However, based on the asymmetry of the syncline (steeper southwest limb), uplift associated with the Black Mountain fault zone seems to be the most likely driving mechanism for the continuing deformation of the Texas Spring syncline. This is supported by the apparent lack of late Quaternary activity on the Furnace Creek fault in the Furnace Creek basin.

## CROSS VALLEY FAULT

Late Pleistocene deformation normal to the axis of the Texas Spring syncline is indicated by young fault scarps along a northeast-striking, down-to-the-northwest normal dip-slip fault referred to as the Cross Valley fault (Cemen and others, 1985; p. 136) (fig. K-2). The Cross Valley fault was previously called the Mont Blanco fault by Hunt and Mabey (1966; p. A103) and the "valley-crossing fault" by McAllister (1970; p. 8). Hunt and Mabey (1966) concluded that the fault extended southwestward across the northern end of the Black Mountains into Death Valley. This interpretation was made on the basis of the alignment of faults with four smaller faults (?) represented by linear breaks in the saltpan, a pair of linear hills comprised of Funeral Formation, and a gravity anomaly, all along the axis of Death Valley. Based on these observations, Hunt and Mabey (1966) proposed that the fault might extend to the southwest as far as the fault scarps at the toe of the Hanaupah Canyon alluvial fan. We consider this interpretation to be rather speculative.

In contrast, McAllister (1970) suggested that the Cross Valley fault linked the northwest-striking Furnace Creek fault on the northeast side of the valley with the northwest-striking Grand View fault on the southwest. This interpretation seems more plausible given the tectonic setting and is consistent with stratigraphic relationships exhibited by the late Cenozoic strata in the Furnace Creek basin (Cemen and others, 1985). Hence, the name Cross Valley fault (derived from term valley-crossing fault coined by McAllister, 1970) is given preference over Mont Blanco fault of Hunt and Mabey (1966).

The surficial expression of the Cross Valley fault is delineated by scarps on late Quaternary alluvium (Q2c) that extend at least 4.5 km across the axis of the valley (fig. K-5). The northeastern-most end of the fault appears to be truncated by the Wall fault (part of the Furnace Creek fault zone; fig. K-2) and the southern end of the Cross Valley fault appears to merge with the northwestern end of the Grand View fault (McAllister, 1970). The Funeral Formation is commonly juxtaposed against the Furnace Creek Formation along the fault. This relationship is readily apparent at other locations along the fault where resistant beds in the Funeral Formation form flatirons against easily eroded strata of the Furnace Creek Formation (fig. K-5). The Cross Valley fault also marks the southeasterly extent for the surficial expression of the Texas Spring syncline. McAllister (1970) reported that the total vertical separation of Funeral Formation strata across the fault might be as much as 300 m.

The scarps along the Cross Valley fault are clearly the product of numerous ground-rupturing earthquakes. Evidence for at least two events exists in the larger drainages where two different-aged terraces have been uplifted and truncated by the fault. Measured scarp-slope angles range from 9° on a 1.8-m-high scarp to 26° on a 7.2-m-high scarp and scarp height increases in a northeasterly direction, reaching a maximum of about 12 m (fig. K-6). In addition, there are numerous compound scarps and weakly developed tectonic benches superimposed on the slopes of these higher scarps. Certainly the scarp is the product of multiple faulting events, but it is possible that some of these features are the product of distributed faulting resulting from a single ground-rupturing earthquake. At several locations, the surface trace of the fault is exhibited as a pair of parallel scarps or by a narrow graben (fig. K-7). However, these

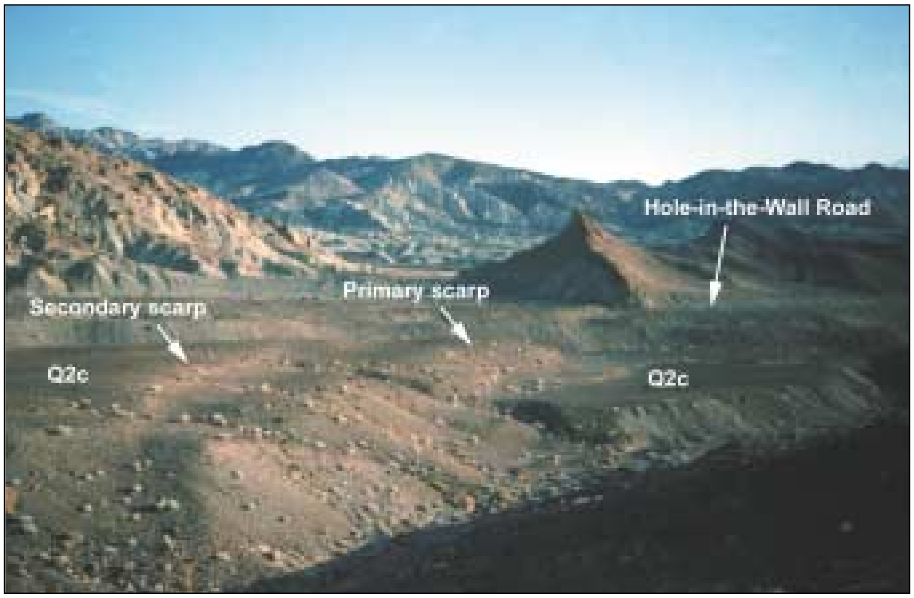


*Figure K-5. Cross Valley fault north of Hole-in-the-Wall road. At this location, height of primary scarp on late Pleistocene Q2c alluvial surface is about 5.4 m. Secondary scarp is about a meter high at this site. View is to the southeast.*

features generally occur at locations where the strike of the fault changes slightly.

Evidence for the youngest movement on the fault is preserved in a small arroyo incised into the older alluvial fan (Q2c) about 300 m northeast of the Hole-in-the-Wall road (fig. K-7). At this location, a 0.5-m-high scarp is formed on a Q4a debris flow whose surface is inset into the Q2c alluvial fan. The age of the debris flow is estimated to be late Holocene on the basis of its topographic position relative to the active channel, its distinct bar-and-swale morphology, weak rock varnish development, and poorly formed desert pavement (Klinger and Piety, 1996). Due to the bouldery nature of the deposit, it is not equivocal that this scarp is of tectonic origin. However, it is along trend with a 1.8-m-high scarp on an older late Pleistocene alluvial fan (Q2c), a scarp that extends to the northeast on the Q2c surface. A second 0.2 m high scarp defines the graben on the Q4a deposits. These are an extension of the scarps that form a graben on the adjacent Q2c surfaces both northeast and southwest of the arroyo (fig. K-7).

## DISCUSSION

Although there has been late Quaternary deformation of the Texas Spring syncline and related structures, the southeast extension of the Furnace Creek fault along the front of the Funeral Mountains does not appear to have experienced significant displacement since at least the early Pleistocene. The surface expression of the fault is limited to several short traces along the range front. It is preserved primarily within the Furnace Creek and Funeral Formations or as the contact between one of these formations and older Paleozoic rocks that make up the southern Funeral Mountains.

Along the Funeral Mountains range front in this area, alluvial fans with strongly developed calcium carbonate soils and desert pavements that include calcium carbonate rubble derived from the underlying soil are being dissected to form ballenas (Peterson, 1981). McAllister (1970) noted that one of these older alluvial fans "… extends across the entire Furnace Creek fault zone, but is not displaced by any of the faults." This conclusion is supported by field observations made during the course of this study. Southeast of the Cross Valley fault, an alluvial fan interpreted to be early to middle Quaternary in age (Q1c; Klinger and Piety, 1996) on the basis of similarities between its desert pavement characteristics and degree of soil development to deposits in northern Death Valley that overlie the 0.76 Ma Bishop Tuff, has not been displaced by the fault. Additionally, near the mouth of Echo Canyon, the Furnace Creek fault is overlain by unfaulted late Pleistocene alluvial fans that when traced downstream are deformed in the Texas Spring syncline. The lack of activity along this part of the fault is in dramatic contrast to the faulting history on the apparent extension of the Furnace Creek fault (the Northern Death Valley fault) to the northwest in northern Death Valley (Klinger, 1999).

The Cross Valley fault clearly displaces Quaternary deposits in the Furnace Creek valley, but the Furnace Creek and Grand View faults only exhibit evidence for vertical and lateral displacement in pre-Quaternary rocks. Cemen and others (1985) suggested that slip on the Furnace Creek fault might have been

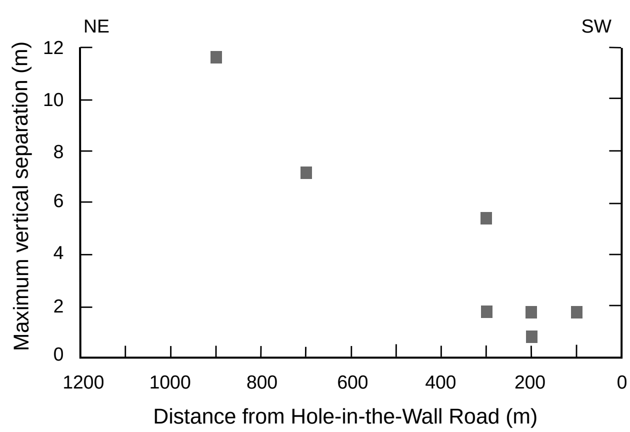


*Figure K-6. Maximum scarp heights measured along the Cross Valley fault northeast of Hole-in-the-Wall Road.*

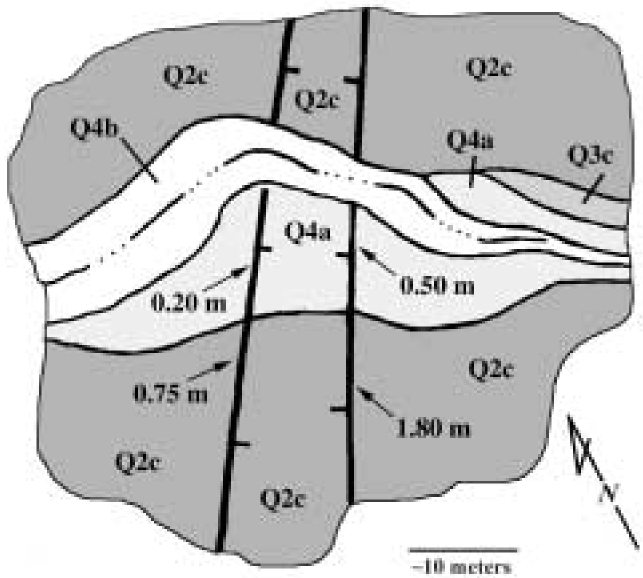


*Figure K-7. Sketch map of scarps that define a graben crossing a small drainage about 300 m north of Hole-in-the-Wall road along Cross Valley fault. Flow in arroyo is from right to left.*

transferred along the northeast-striking Cross Valley fault to the Grand Valley fault during the formation of the Furnace Creek basin. Therefore, the current movement on the Cross Valley and Echo Canyon faults and flexural of the southwestern limb of the Texas Spring syncline represents strain between the active Death Valley and the Furnace Creek faults.

## CONCLUSIONS

Deformation between the late Quaternary traces of the Northern Death Valley and Black Mountain fault zones appears to be accommodated as distributed faulting and localized folding in the Texas Spring syncline and across a transition zone at least 5 km wide. Late Pleistocene, and possible Holocene displacement on the Cross Valley and Echo Canyon faults and flexure of the southwest limb of the Texas Spring syncline indicates that deformation is continuing as the result of northeast-southwest directed shortening and northwest-southeast directed extension. The asymmetry of the fold also suggests that the continued deformation of the Texas Spring syncline is primarily related to displacement on the Black Mountain fault zone. Northwest-southeast directed extension, normal to the strike of the Cross Valley fault and parallel to the axis of the Texas Spring syncline, is consistent with expected deformation in this tectonic setting. The dominate stresses producing the continued deformation of the Texas Spring syncline appear to be driven by uplift of the Black Mountains and normal dip-slip movement on the Black Mountain fault zone to the southwest. Right-lateral shear on the southern part of the Northern Death Valley fault farther to the northwest, has less effect on the formation and continued deformation of the fold. Based on the geomorphology of the Texas Spring syncline and the stratigraphic relationships of the Quaternary alluvium to older rocks, it appears that uplift of the Black Mountains is progressing northward and that activity on the Furnace Creek fault has shifted northwestward on the Northern Death Valley fault zone.

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# Holocene faulting and slip rates along the Black Mountains fault zone near Mormon Point

*by Ralph E. Klinger and Lucille A. Piety*

CHAPTER L

**ABSTRACT**

The influx of air-borne salts and dust derived from the nearby playa and the hyperarid climate in Death Valley enhance the preservation of scarps along the Black Mountains fault zone and inhibit scarp degradation. The lack of precipitation effectively limits the translocation of the salts through the alluvium so they become part of the soil profile. The soil forming the upper parts of the scarps therefore becomes cemented. Soluble salt concentrations in the upper 50 cm of middle Holocene deposits range from 0.5 to 2.0 mmho/cm. The accumulation of dust on equivalent-aged deposits has led to the formation of 3-4 cm-thick vesicular A horizons that effectively seal the surface during typical precipitation events and further hinders the translocation of the salts through the soil profile. In addition to limiting the translocation of air-borne materials, the lack of precipitation in the hyperarid environment also restricts the rate of sediment transport on the scarp.

While these factors may contribute to the preservation of the scarp, they also complicate efforts to estimate the age of the scarp and the time of faulting using the scarp degradation models. However, the well-preserved scarps near Mormon Point along the Black Mountains fault zone has enabled a more extensive analysis of the Holocene behavior of the fault than is typically permitted by an analysis of the scarp morphology alone. An average vertical surface displacement of 2.5±0.5 m is estimated for the Black Mountains fault zone at Mormon Point. This estimate is based on measured scarp heights and preserved bevels and free faces on compound scarps produced by the last four ground-rupturing earthquakes. In addition, an average Holocene slip rate of 1-3 mm/yr and recurrence interval of 1,000-2,000 years is estimated from a 10.5-m-high scarp near Willow Creek. The character of the scarp and associated alluvial fan geomorphology at this site suggests that the scarp was produced by four ground-rupturing events. An estimated age of 4,000 to 8,000 years for the repeatedly displaced alluvial fan surface was made based primarily on degree of soil development and a correlation of other relative age criteria to the regional Quaternary stratigraphy.

## INTRODUCTION

The Black Mountains fault zone is a down-to-the-west dip-slip normal fault that flanks the west side of the Black Mountains in central Death Valley (fig. L-1). Noble (1926) first referred to the fault as the Death Valley fault and Noble and Wright (1954) referred to this same fault zone as the Black Mountains frontal fault, which is a term that still used by some today (e.g., Wright and others, 1999). The nomenclature used in this study follows that suggested by Machette and others (Chapter J in this volume). The effects of young tectonism on the landscape in Death Valley has long been recognized as the active trace of the Black Mountains fault zone is well defined by steep scarps that are preserved almost continuously along more than 60 km of the Black Mountains (fig. L-1). Following reconnaissance in the region in the early 1920's, Noble (1926, p. 425) noted that the scarps along the Black Mountains fault zone were "fresher than any other scarps of similar magnitude in the West" comparing them to scarps he had observed along the Garlock and San Andreas faults. Subsequent work in Death Valley over the next 70 years has located and described most of the major tectonic features associated with latest Quaternary (<15 ka) fault activity (Hunt and Mabey, 1966; Moring, 1986; Bryant, 1988; Wills, 1989; Brogan and others, 1991; Reheis and Noller, 1991). Although the Black Mountains fault zone has been recognized as one of the more prominent range-bounding normal faults in the Basin and Range province, specific details of the fault's behavior (such as surface displacement per event, slip rates, recurrence intervals, and the age of the most recent ground-rupturing event) remained largely unknown (Peterson and others, 1995). This was due in part to the perception that the risk posed by the fault was minor considering the location of the fault relative to large population centers. However, with the potential siting of a high-level nuclear waste repository at Yucca Mountain (fig. L-1), more attention is being focused on understanding the Death Valley fault system and Furnace Creek fault zone (Klinger and Piety, 1994, 1996; Dixon and others, 1995; Bennett and others, 1997; Knott, 1998; Klinger, 1999; Machette and others, 1999; dePolo and Hess, 1999).

While scarps are nearly continuous along the Black Mountains fault zone, evaluating the late Quaternary activity has been difficult. Studies utilizing traditional methodologies

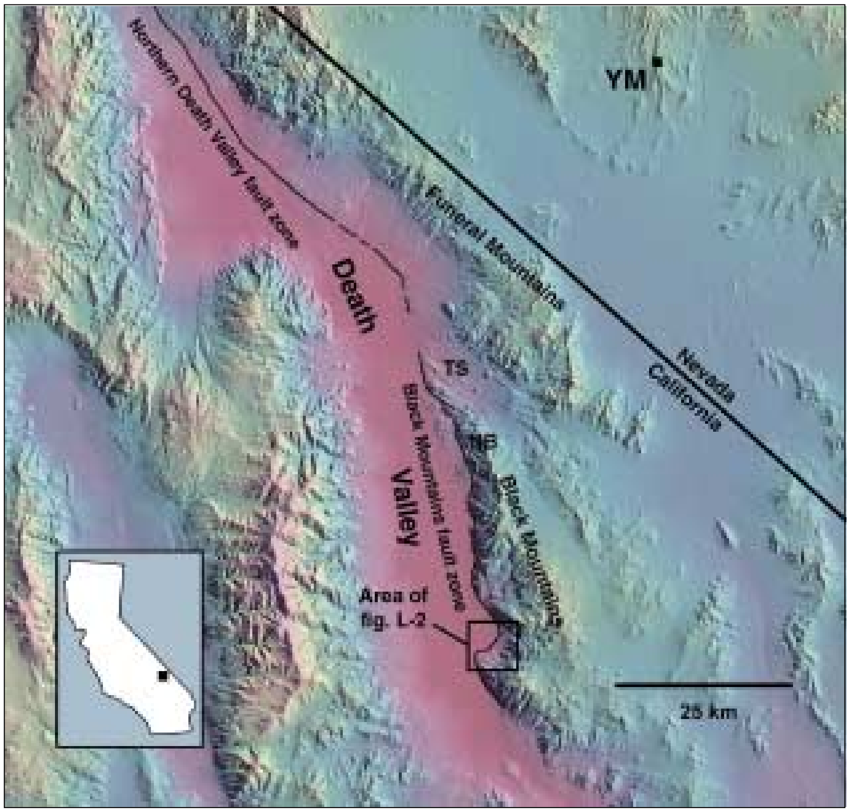


*Figure L-1. Shaded relief map from digital elevation model of area surrounding Death Valley. Outlined area shows area of this study near Mormon Point; YM, Yucca Mountain; TS, Texas Spring syncline; and NB, Natural Bridge.*

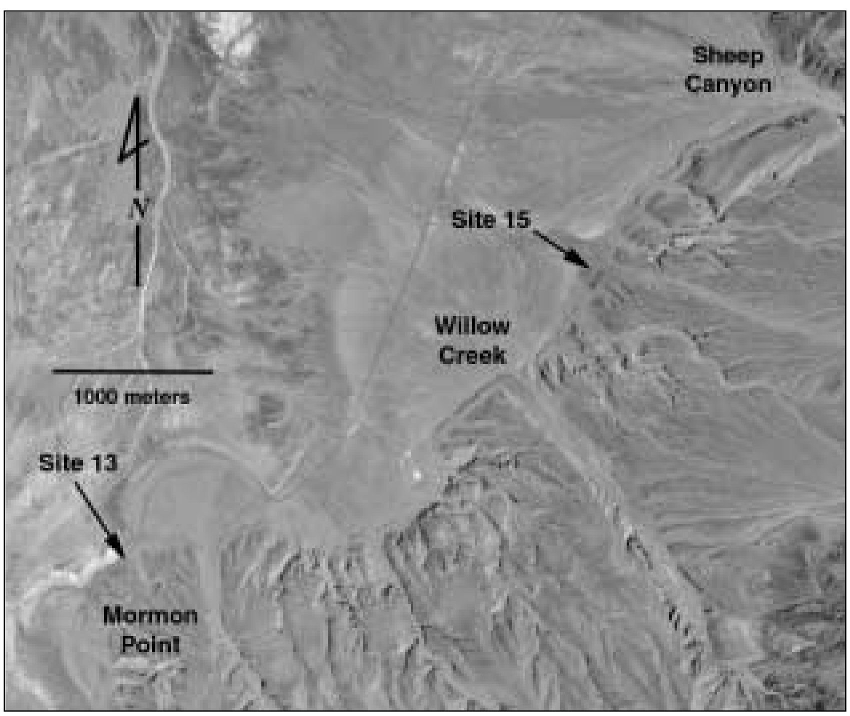


*Figure L-2. A, Vertical aerial photograph of faulted alluvial fans along Black Mountains fault zone near Mormon Point.*

(e.g., trenching) have not been viable options due to the environmental constraints of being wholly contained within Death Valley National Park. Therefore, scarp profiling, a no-impact technique that has been widely used to estimate the age, magnitude, and extent of faulting (Wallace, 1977, 1978; Nash, 1980, 1984, 1986; Hanks and others, 1984; Mayer, 1984; Pierce and Colman, 1986; Machette, 1989; Anderson and Klinger, 1996), was used. Physical characteristics of a scarp of unknown age, primarily the scarp height, scarp width, surface offset, and maximum scarp-slope angle, are commonly related to other scarps of known age (Bucknam and Anderson, 1979; Hanks and Andrews, 1984; Mayer, 1987). However, there are inherent problems involved in this type of analysis (Mayer, 1987). The fundamental assumption in estimating the age of fault scarps with this type of analysis is that the scarp degrades in a systematic and predicable fashion with time. However, there are numerous factors that can influence the rate of scarp degradation including the type of material the scarps are formed on (alluvium versus rock), grain-size, grain-shape, and cohesiveness of the alluvium, fault characteristics such as fault dip and style of deformation (e.g., normal, reverse, or strike-slip), climate (primarily precipitation), type and density of the vegetative cover, surface hydrology, slope, aspect, and other physical characteristics of the site.

The general approach of this study was to map the surficial geology along the fault and focus on those specific areas where there was a single strand of the fault and the parent material was homogenous so that the past behavior of the fault is best developed. The geomorphology of the fault, the character of the scarp, and the stratigraphic relationship of the alluvial fans to the fault north of Mormon Point presented a unique opportunity to better understand the behavior of the Black Mountains fault zone and evaluate the impact of air-borne salt and dust on scarp preservation (fig. L-2).

## GEOLOGIC SETTING

The Black Mountains are formed of a relatively coherent assemblage of Neogene crystalline rocks referred to by Wright and others (1994) as the "Black Mountains block." The western part of this block is comprised of gabbro and younger silicic plutonic rocks. On the flanks of the range, the plutonic rocks are overlaid by a thick sequence of basin-fill deposits that record the uplift of the range and formation of Death Valley between about 2-6 Ma. Quaternary deposits along the range front consist primarily of gravelly alluvial fans that interfinger with fine-grained playa and lacustrine deposits at the margins of the valley. The alluvial fans along the Black Mountains are steep and spatially compact relative to the alluvial fans on the west side of Death Valley (Denny, 1965). This supports the impression of a high rate of uplift along the Black Mountains fault zone. Estimates of the Quaternary uplift rate of the Black Mountains (i.e., slip rate on the Black Mountains fault zone) based on geologic data range from about 0.1 mm/yr to as much as 7 mm/yr (Drewes, 1963; Hooke, 1972; Brogan and others, 1991; Klinger and Piety, 1994, 1996; Knott, 1998). The most recent estimate of the average late Quaternary slip rate is about 1.5±1 mm/yr (Klinger, 1999).

In general, the Black Mountains fault zone strikes north-northwest and shows little evidence for major steps or potential section or segment boundaries (see Chapter J in this volume). The exceptions are a large embayment in the range north of Mormon Point, a 12-13 km-long gap in terms of scarp continuity north of Natural Bridge (Klinger and Piety, 1996), and the Texas Spring syncline area (fig. L-1). The range front along the Black Mountains is notably linear with little embayment and has been described by Bull and McFadden (1977) as a Class I, or active, mountain front. Following an extensive analysis of the tectonic geomorphology, Knott (1998) subdivided the range front into six distinct geometric segments based on variations in the mountain front sinuosity, mountain front-piedmont intersection profiles, range crest profile, the strike of the fault, and several other factors. For purposes of estimating the potential magnitude of future earthquakes on the Black Mountains fault zone, he combined these six segments into three longer segments with lengths similar to the shorter historical ground ruptures reported by Wells and Coppersmith (1994). The most distinct geomorphic boundaries along the range, Mormon Point and Natural Bridge, separate each of these three longer segments (Knott, 1998). This is consistent with a segmentation scheme of the range-front fault based solely on scarp morphology (Klinger and Piety, 1996).

Some part of most scarps observed along the length of the Black Mountains fault zone has scarp-slope angles that range from the angle-of-repose (about 33°) to vertical. On the basis of scarp-slope data alone, the most recent event along the Black Mountains fault zone appears to be very young, perhaps less than 500 years old (fig. L-3). Since Noble (1926) first noted the youthfulness of the fault scarps in Death Valley, subsequent workers have likewise suggested that the scarps may be very young, possibly even historical. Certainly the vertical or near-vertical character of many of the scarps along the fault would lead one to this conclusion. Clements (1954, p. 58-60), on the basis of newspaper accounts and other turn-of-the-century written records, speculated that the young scarps along the Black Mountains fault zone were the result of the November 4, 1908, magnitude 6.5 earthquake reported by Stover and Coffman (1993, p. 75). However, records for this particular earthquake are not very good and the precise location of the event is poorly constrained. Brogan and others (1991, p. 19) also reported that geomorphic features associated with the fault are the product of very young, perhaps historical activity and estimated that the youngest unfaulted deposits may be less than 200 years old.

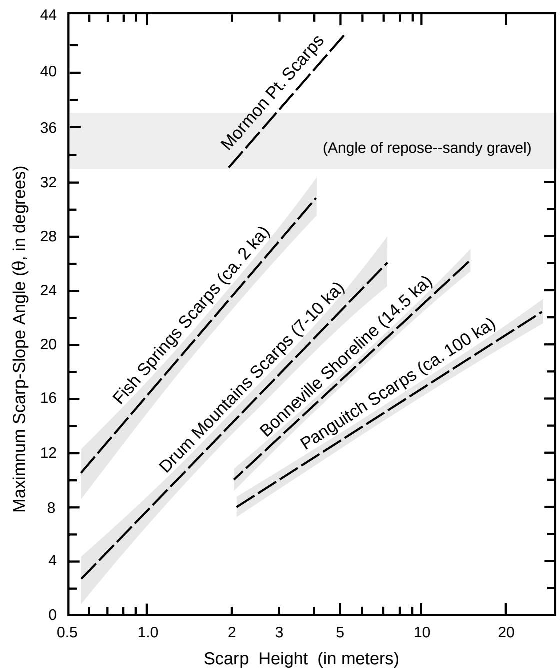


*Figure L-3. Plot of scarp height versus maximum scarp-slope angle showing the Black Mountains fault zone near Mormon Point relative to data for scarps in the Basin and Range (modified from Bucknam and Anderson, 1979).*

Hunt and Mabey (1966, p. A100) inferred that the youngest faulting event on the Black Mountains fault zone may be just prehistoric because the Native Americans of Death Valley constructed mesquite storage pits in colluvium shed from a scarp. Hunt and Mabey (1966) also indicated that the most recent activity along the Black Mountains fault zone was certainly less than 2,000 years old. They noted that the eastern shoreline of a late Holocene lake is 6 m (20 ft.) lower than the western shoreline and suggested that the tilting of the shoreline across the valley occurred as the result of movement on the fault. They estimated an age of 2,000 years for the tilted shorelines on the basis of archaeological artifacts in sand dunes that overlie lake deposits along the west side of Badwater basin (Hunt, 1960; Hunt and Mabey, 1966, p. A82). The age of the artifacts was inferred by Hunt (1960) to be no older than 2,000 years on the basis of a correlation to the regional archaeological chronology and thus provide a minimum age for the underlying lake deposits. However, because the dunes were presumed to immediately post-date the lake high stand that formed the now tilted shorelines, the age of the shorelines was thought by Hunt and

Mabey (1966) to be close to the 2,000 year old age inferred from the artifacts. Thus, the artifacts provide a maximum limiting age for the tectonic activity that tilted the shorelines and presumably formed the youngest scarps along the front of the Black Mountains. Assuming an age of 2 ka for the 6 m of offset yields an apparent late Holocene tilt rate (at the fault) of 3 mm/yr.

Owing to the probable young age of the scarp and the numerous factors influencing scarp degradation in Death Valley, age estimates based on an analysis of the scarp height and scarp-slope angle measurements are less than straightforward. In a study of the effects of soil horizon development on fault-scarp preservation, Prokop (1983) concluded that the impact could be significant. Cementation of the alluvium by soluble salts (primarily calcium carbonate) and a change in the cohesive properties due to the influx of silt and clay increased the resistance of a scarp to erosion. While the steep scarp-slope angles along the Black Mountains fault zone could be viewed as an indicator of scarp youthfulness, soil geomorphic evidence suggests that the scarps are being preferentially preserved due to cementation of the alluvium and translocation of soluble salts into the underlying soils (Klinger, 2000). In Death Valley, these salts are derived from nearby playas (primarily halite and gypsum) and transported to the alluvial fan surfaces by eolian processes (fig. L-2).

Following a typical analysis of scarp morphology or diffusion modeling may lead one to conclude that the fault scarps in this part of Death Valley are younger than their actual age. Therefore, the scarps along the Black Mountains fault zone were not used to estimate the age of the last faulting event, but were instead utilized to develop a measure of displacement per event assuming characteristic fault behavior (i.e. Schwartz and Coppersmith, 1984), to develop a Holocene slip rate, and to evaluate recurrence intervals between large ground-rupturing earthquakes.

## METHODOLOGY

The surficial geology and geomorphology along the Black Mountains fault zone near Mormon Point was mapped on large-scale aerial photographs (e.g., fig. L-2). Surficial alluvial units were delineated on the basis of their tonal and textural differences and relative topographic position, properties that are easily distinguished on aerial photography. To date, age control for latest Quaternary deposits and geomorphic surfaces in Death Valley has been very difficult to obtain primarily due to the hyperarid environment. Therefore, detailed descriptions of alluvial-fan surface characteristics including bar-and-swale morphology, desert pavement formation, rock varnish color, and degree of soil development were made in order to refine the criteria by which the surficial units were categorized and ages estimated (Klinger and Piety, 1996). Of these relative age indicators, McFadden and others (1989) have shown that the degree of soil development is one of the most useful criteria for delineating and differentiating late Pleistocene and Holocene deposits.

In this study soils were described in the field following the guidelines outlined by the Soil Survey Staff (1993) and by Birkeland (1999). Laboratory analyses of the soils included particle size, bulk density, and calcium carbonate content following the methodology outlined by Singer and Janitzky (1986) and Black and others (1965). Other soluble salts in the soils were determined by IC/ICP analysis and the content was calculated using electrical conductivity measurements (Noller, 1993). An estimate of the relative degree of soil development was made using a soil development index calculated following the methodology of Harden and Taylor (1983). The soil development indices for the soils in Death Valley were determined on the basis of the five soil properties: texture, rubification, profile lightening, dry consistence, and soluble salt accumulation (table L-1).

Most stratigraphic sequences developed in the region are based on relative-age criteria (e.g., Hunt and Mabey, 1966; Moring, 1986; Dorn and others, 1987, 1990; Wells and others, 1990; Bull, 1991; Peterson and others, 1995; Klinger, 2000). The nomenclature used for the surficial units described in this study (table L-1) follows the regional framework for the alluvial stratigraphy in the southwestern United States established by Bull (1991, p. 86) on the basis of relative-age properties. Age assignments for the surficial units in this study were adjusted from those of Bull (1991) based on the stratigraphic relationships of the alluvial stratigraphy to the late Pleistocene lacustrine deposits and late Holocene ash beds found in Death Valley, and correlations to dated soil sequences in the region (Reheis and others, 1989; McFadden and others, 1992; Peterson and others, 1995). Menges and Taylor (this volume) provide an updated regional correlation of Quaternary geologic units for the desert Southwest.

Scarp profiling is a technique commonly used to characterize a topographic scarp (Wallace, 1977; Bucknam and Anderson, 1979; Mayer, 1984; Nash, 1986). All scarp profiles described in this study were measured in the field following procedures outlined in USGS-YMP Technical Procedure GP-52. Scarp heights and maximum scarp-slope angles were derived from computer-generated plots of the field data. Because the dip of the fault is needed to measure throw and actual surface displacement and because exposures of the actual fault plane are rare, the correlative surfaces preserved on opposite sides of the scarp were used to approximate the vertical separation of the ground surface. Although the vertical separation is a minimum estimate of the throw, and thus for fault surface displacement, the relatively gentle far-field slopes adjacent to most scarps and the steep fault dip make the measured vertical separation a very close approximation of the throw. Measurement error introduced to the analysis due to (1) the overall height of the scarp, and (2) the extent of the bar-and-swale development is believed to be about 5 percent of the total scarp height based on repeat measurements. It should be noted that the uncertainties inherent in the measurement of morphologic features on coarse-grained alluvial deposits has less of an impact on the slip-rate estimates than results from the uncertainties in the age estimates.

## WILLOW CREEK SCARP

The location of the Black Mountains fault zone is evident along most of the Black Mountain range-front due to the well-preserved triangular facets on bedrock and fault-line scarps on alluvium (Drewes, 1963). North of Mormon Point, the strike of the fault changes from north-northwest to the east-northeast and forms an embayment in the range (fig. L-1). Young fault scarps are nearly continuous on Holocene alluvial fans in this area and are missing only where they cross active stream channels (fig. L-4). These young scarps mark the active trace of the Black Mountains fault zone and parallel the older triangular facets and fault-line scarps (fig. L-2). The scarp heights in this area are also among the highest reported along the entire length of the fault (Brogan and others, 1991; Klinger and Piety, 1996).


*Figure L-4. Compound scarp along Black Mountains fault zone near Willow Creek. Note coarse-grained nature of Q3b alluvium and well-defined bar-and-swale morphology on alluvial fan surface at this location.*

Table L-1. Generalized descriptions of late Quaternary stratigraphic units in Death Valley

| Unit | Age (ka) | Desert Pavement[1] | Bar/Swale Morphology[2] | Rock Varnish Color[3] | Soil Profile Development[4] | Profile Thickness (cm) | Maximum Profile Color[5] | Soil Development Index[6] |
|---|---|---|---|---|---|---|---|---|
| Q4b | <0.2 | None | Prominent | None | None | None | 10YR6/3 | 0 |
| Q4a | 0.2-2 | None | Prominent | None | Thin Av/2C | 4 | 10YR7/2 | 0.5 |
| Q3c | 2-4 | PP | Distinct | 5YR6/6 | Avk/2Bkz/2C | 20 | 10YR7/3 | 5.2 |
| Q3b | 4-8 | MP | Subdued | 5YR5/8 | Avk/2Bkz/2C | 50 | 10YR7/3 | 12.8 |
| Q3a | 8-12 | MP-WP | Subdued | 5YR5/8 to 2.5YR4/8 | Avk/Bkz/2C | 72 | 10YR6/4 | 30.4 |
| Q2c | 35-60 | WP | None | 2.5YR4/8 | Avkz/Btkz/2Bkz | 100 | 7.5YR5/6 | 45.0 |

[1]Desert pavement development is rated on the basis of stone packing on the pavement surface and is dependent upon particle size and clast shape of the original deposit; PP, poorly-packed; MP, moderately packed; WP, well-packed.

[2]Bar-and-swale morphology as a relative measure of the original depositional topography and its degree of preservation.

[3]Maximum rubification color on the bottom of clasts in the pavement using Munsell color notation (Munsell Color, 1975).

[4]Typical profile development; described in the field as outlined by the Soil Survey Staff (1993) and by Birkeland (1999).

[5]Maximum profile thickness observed.

[6]Dry color on <2 mm soil fraction using Munsell color notation (Munsell Color 1975).

[7]Profile development index was calculated following the methodology of Harden (1982) and Harden and Taylor (1983). The five best developed properties averaged from profiles described in Death Valley; texture, rubification, profile lightening, dry consistence, and soluble salt accumulation (as measured by electrical conductivity) were used.

A compound scarp north of the mouth of Willow Creek, hereafter referred to as the Willow Creek scarp, reaches a height of 10.5 m (site 15 on fig. L-2).

In addition to the overall scarp height, an equivalent-aged alluvial fan surface displaced by the fault is preserved on both sides of the Willow Creek scarp (fig. L-4). Commonly, alluvial fan surfaces on the hangingwall (down-dropped) side of the Black Mountains fault zone have been modified by either erosion or deposition resulting in surfaces of different ages being juxtaposed across the fault (fig. L-2). Thus, the scarp near Willow Creek was chosen as a site for more detailed study because it is one of the few places where a correlative surface is preserved on both sides of the fault. The relative age characteristics of the alluvial fan deposits along the scarp were examined to better estimate the age of the displaced surface and develop the history of faulting during the Holocene.

The Holocene alluvial fan surface adjacent to the Willow Creek scarp displays distinct bar-and-swale morphology with the top of the bars being up to 0.5 m higher than the bottom of the swales. The desert pavement is poorly developed, but this is not unexpected due to the very coarse grain size of the deposit (fig. L-4). The surface is dominated by diorite cobbles and boulders mixed with a variety of metamorphic rocks. Rock varnish formation on the surface is limited to the tops of the clasts and has a maximum color of light reddish brown (5YR6/4). The distinct morphology of the bar-and-swale topography and the lack of desert pavement formation led to the previously reported age estimate of about 2,000-4,000 years for the faulted surface near Willow Creek (Klinger and Piety, 1994, 1996). These relative age characteristics are consistent with Q3c deposits at other locations in Death Valley (Q3c; table L-1). However, based on the coarse-grained nature of the alluvial-fan surface and degree of soil development, for this study the deposits are correlated with Q3b deposits and are estimated to be between 4,000 and 8,000 years (table L-1), or about twice the age previously estimated.

Soils found on Holocene deposits along the Black Mountains fault zone are, in general, weakly developed (table L-1). This is believed to be the direct result of the very coarse-grained nature of the deposits found along much of the fault and the hyperarid environment. The mean annual precipitation in Death Valley is less than 50 mm/yr and the mean annual temperature is about 26° C. (i.e., extremely arid moisture and hyperthermic temperature regimes). The combination of low precipitation and high temperature has resulted in the presence of highly soluble salts in the soils and an extremely low density of vegetation. Typically, the organic carbon content in aridisols similar to those found in Death Valley is less than 0.5 percent (Soil Survey Staff, 1999). Overall, the environment along the Black Mountains fault zone is not very conducive to the preservation of either the stratigraphic evidence needed to evaluate past faulting activity or the organic material needed for radiocarbon age control.

The soil related to the middle Holocene Q3b surface adjacent to the Willow Creek scarp is formed primarily on the eolian material trapped by the gravelly alluvium. The influx of silt- and clay-sized material is a significant change from the textural characteristics of the parent material; a silt loam versus a gravelly sand, respectively. This abrupt change in texture with depth limits the translocation of material through the profile. Vesicular A horizons reach a maximum thickness of about 3-4 cm and the total profile thickness on the Q3b deposits is more than twice as thick as soils developed on the younger Q3c deposits. This increase in thickness is directly attributable to a greater accumulation of silt and clay in the A and B horizons and a broader distribution of salt in the B horizon (fig. L-5).

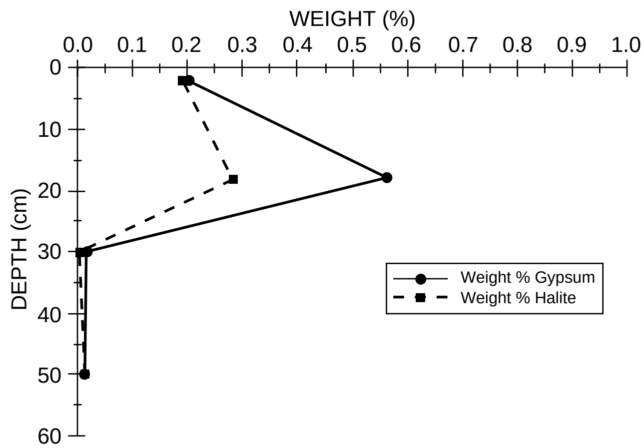


*Figure L-5. Distribution of soluble salts (gypsum and halite) with depth in a soil on unit Q3b.*

The B horizon development is generally limited to the accumulation of soluble salts (gypsum and halite) in gravelly parent material, although minor accumulations of calcium carbonate are found in other locations. Salt accumulation is concentrated in the uppermost 30 cm of the profile (fig. L-5) and displays up to stage II morphology (stages after Bockheim, 1981). Salt coatings on stone bottoms are thin and discontinuous; flecks as much as 1-2 mm in diameter are common. The measured electrical conductivity in the B horizon from unit Q3b ranges from about 0.5 to 2.0 mmhos/cm. The concentration of salt is visibly greater on vertical exposures and scarp faces than was observed in freshly exposed soil pits. This is a commonly observed phenomena associated with calcium carbonate cementation described as case hardening by Lattman and Simonberg (1971). However, because the translocation of soluble salts in the profile appears to be limited by the extreme aridity at this site (fig. L-5), the greater concentration of salts on natural exposures is believed the result of direct deposition, particularly on exposures with west aspects (facing the playa).

Gravel shattering observed on alluvial-fan surfaces and in the A and B horizons of Q3b deposits were limited to clasts with narrow cracks, similar to stage C morphology (stages after Amit and others, 1993). While the range of the measured salinity values 0.5 to 2.0 mmhos/cm is consistent with stage B morphology, the mean percentage of silt and clay in the A and B horizons is between 30-50 percent. The appearance of shattered gravel and the amount of silt and clay is consistent with the properties reported on alluvial-fan surfaces in the Israeli desert dated between 2000-7000 years old (Amit and others, 1993). Despite the abundance of soluble salts in the environment, the lack of moisture (i.e., low average precipitation) appears to be hindering the translocation of soluble salt and clay through the profile (Machette, 1985).

A topographic profile was measured across the Willow Creek scarp in order to better characterize the total scarp height, maximum scarp-slope angles, surface offsets, and estimate the per event slip exhibited by the compound scarp (fig. L-6). Due to the degree of bar-and-swale topography preserved on the faulted alluvial fan surface adjacent to the scarp, some uncertainty in the measurement of the total scarp height was introduced. However, based on the results of repeated measurements and considering any erosion of the scarp that may have occurred since the stabilization of the surface, the total scarp height of 10.5 m measured from a computer-generated plot of the profile (fig. L-6) is believed to accurately estimate the net displacement of the surface to within ±0.5 m. The scarp is 10.9 m wide measured from the toe of the colluvial slope to the crest of the scarp and the scarp's slopes range from the angle of repose (33°) at the toe to a maximum of 90° at the crest. The scarp has two vertical sections near the crest that are separated by a narrow step. The lower 5.8 m of the scarp is buried by colluvium that currently rests at or slightly higher than the angle of repose.

In many areas north of Mormon Point, the scarp crosses the alluvial fans at a high angle to the slope of the fan. Thus, the swales developed on the fan surface and subsequently displaced by the fault often give the illusion of being laterally offset across the fault. Several investigators have reported evidence for a component of right-lateral slip along the Death Valley (Hooke, 1972; Wills, 1989; Slemmons and Brogan, 1999). Based on the apparent northwest-southeast extension direction across Death Valley (Burchfiel and Stewart, 1966) and the overall northerly strike of the fault, a measurable component of right-lateral slip should be present along parts of the Black Mountains fault zone (Slemmons and Brogan, 1999). However, no clear evidence for lateral displacement was recognized along the fault in the area between Mormon Point and Sheep Canyon (fig. L-2).

Given the height and compound nature of the Willow Creek scarp, the scarp is certainly the product of more than one event and may be the product of as many as four discrete events. A compound scarp near Mormon Point helps support this interpretation (site 13; fig. L-2). The measured heights of the two bevels on this scarp (2.2 and 2.7 m; fig. L-7) are similar to the measured heights of the two vertical sections near the crest of the Willow Creek scarp (2.1 and 2.6 m; fig. L-6). It follows that the lower 5.8 m of the Willow Creek scarp that is covered by colluvium could represent the surface displacement from two additional events (average of 2.9 m per event). If this interpretation is valid, then the two vertical sections of the scarp would represent preserved free-faces from discrete events and the youngest ground-rupturing earthquakes that formed the scarp.

Fluvial stream terraces that are preserved on the uplifted footwall of the fault provide additional evidence supporting the hypothesis that the Willow Creek scarp represents at least the last four ground-rupturing earthquakes in the area (fig. L-8). At several locations near Willow Creek, as many as three terrace surfaces related to small drainages are inset into the faulted

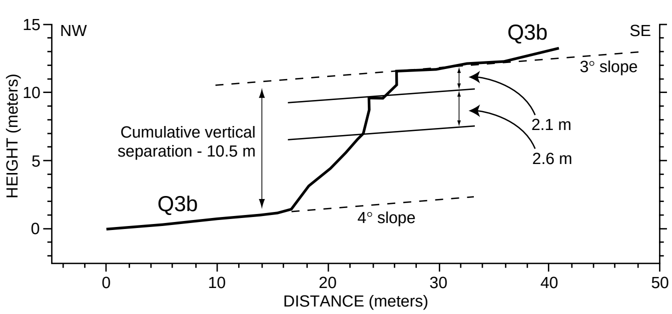


*Figure L-6. Topographic profile of the Willow Creek scarp. A total scarp height of 10.5 m and a maximum scarp-slope angle of 90° were measured at this site. Two near-vertical sections near the crest of the scarp (2.1 and 2.6 m) are interpreted as preserve free faces.*

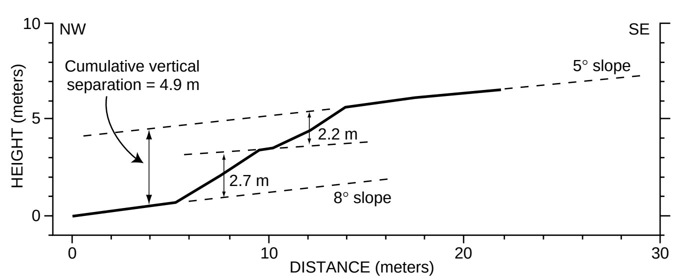


*Figure L-7. Topographic profile of scarp at site 13 near Mormon Point (see fig. L-2). A total scarp height of 4.9 m and a maximum scarp-slope angle of 34° were measured at this site. Two distinct scarp slopes (2.2 and 2.7 m) separated by a small break near the center of scarp are interpreted to be product of last two ground-rupturing earthquakes.*

alluvial-fan deposits. Two of these surfaces can be traced laterally to the base of the vertical segments of the fault scarp (B and C in fig. L-8). It is also apparent that each of these terrace surfaces is related to separate faulting events because they vary in age. The alluvial-fan surface forms highest and oldest “terrace” surface and exhibits relative age characteristics associated with Q3b deposits; a moderately developed desert pavement, more subdued bar-and-swale topography, and darker rock varnish. These characteristics become progressively less developed on each lower and younger terrace to the point where the youngest terrace (C in fig. L-8) displays none of these properties. On the basis of the measurements derived from bevels and free faces preserved on compound scarps and the uplifted stream terraces between Mormon Point and Willow Creek, the average displacement per event is estimated to be 2.5±0.5 m in this area. This is consistent with scarp heights measured at 101 locations along the length of the Black Mountains fault zone (fig. L-9).

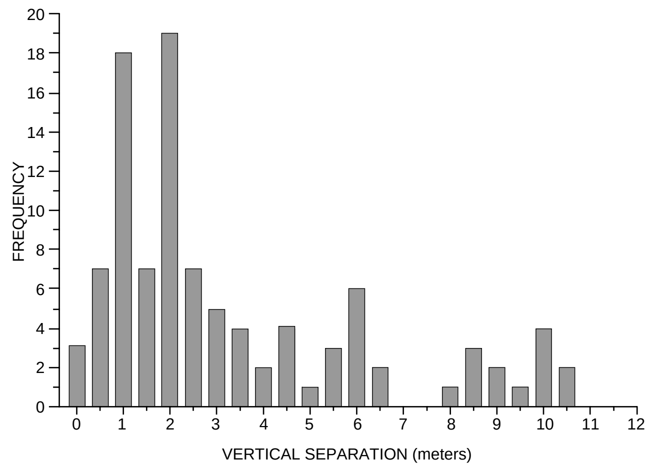


*Figure L-9. Frequency plot of scarp heights measured along Black Mountains fault zone (n=101).*

Based on the presence of bevels and free faces on compound scarps, terraces inset into uplifted alluvial fans, and the overall character of the Willow Creek scarp, it is apparent that scarps along the Black Mountains fault zone are being preferentially preserved. Brogan and others (1991, p. 17) reported that overhanging scarps were observed in the Willow Creek area (their Willow Creek section). They implied that the overhanging scarps might provide evidence for local reverse faulting. However, given the overall tectonic setting, with extension directed to the northwest-southeast (Burchfiel and Stewart, 1966) and the northeasterly strike of the fault in the area, this hypothesis seems unlikely and no structural evidence was found to support it. However, soil geomorphic evidence in the area suggests that the overhanging, and the more common vertical and near-vertical scarps are actually preserved scarps. Due to the hyperarid climate, the infiltration of these salts, silt, and clay into the alluvium and the development of soil are limited to the uppermost 30 cm (fig. L-5). The overhanging scarps noted by Brogan and others (1991) along the Black Mountains fault zone seem to reflect the more resistant, salt-cemented alluvium that overlies more easily erodible, poorly cemented alluvium at the base of the scarp. The underlying more weakly cemented alluvium appears to have collapsed away in areas from the overlying more resistant “cap rock” formed by the accumulation of salts in the soil profile.

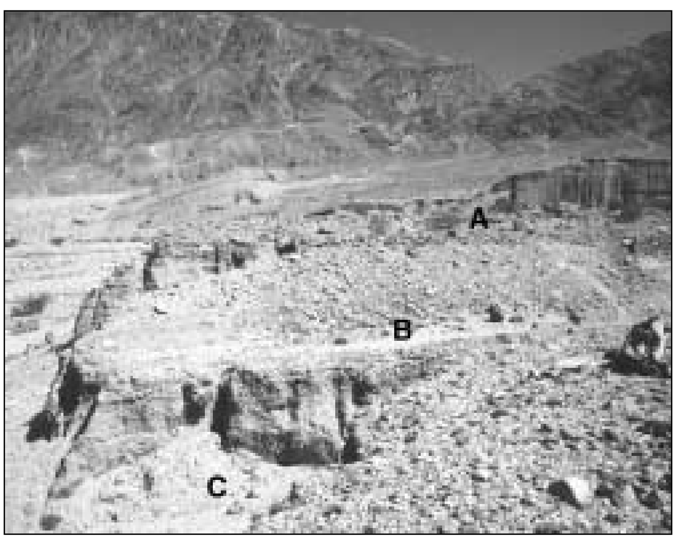


*Figure L-8. Uplifted fluvial terraces inset into a middle Holocene alluvial fan surface (A) near the mouth of Willow Creek. Terrace tread (B) can be traced laterally to base of uppermost vertical section of scarp. A second terrace in incised gully (C) can be traced to base of lower vertical section of scarp and top of debris slope (see fig. L-6).*

## DISCUSSION AND CONCLUSIONS

The preservation of fault scarps along the Black Mountains fault zone near Mormon Point illustrates the importance of soluble salts and dust derived from the adjacent playa. The influx of air-borne salts and dust in combination with the hyperarid climate, specifically the lack of moisture, has played an important role in preserving fault scarps. Soils developed on the faulted alluvial fans are formed primarily in eolian material. The leaching and precipitation of air-borne material has formed a 3 to 4 cm-thick vesicular A horizon overlying a 25-cm-thick Bzy horizon. Salt in middle-to-late Holocene soils has accumulated in the upper 30 cm of the profile, exhibits stage I-II morphology with maximum concentrations of about 2.0 mmho/cm. The presence of silt loam A horizons and the lack of precipitation helps restrict the translocation of salt and clay through the soil profile. This eventually results in salt cementation of the soil, which in turn inhibits scarp degradation. Close examination of these scarps near Mormon Point indicates that the original scarp morphology is being preserved by the cementation of the alluvium by soluble salts (primarily halite and gypsum).

Study of the well-preserved scarps along the Black Mountains fault zone permits a more extensive analysis of the Holocene faulting than is typically permitted from scarp profiling. Assuming that ground-rupturing events on the Black Mountains fault zone follow characteristic fault behavior model (Schwartz and Coppersmith, 1984), the history of faulting near Willow Creek can be developed. It is apparent from the geomorphology along the fault that about 4,000-8,000 years ago, deposition of alluvium on the surface of the fan near Willow Creek ceased due either to abandonment by an avulsion of the main stem drainage or by the formation of a scarp that isolated this part of the fan surface. The abandonment and subsequent stabilization of this part of the fan would have led to the accumulation of salts and dust and allowed the formation of rock varnish on the surface to begin. Following the first ground-rupturing earthquake, the fault scarp on the surface would have been between 2-3 m in height with a vertical scarp-slope. At that point in time, there would be little or no accumulation of salt and dust on the alluvial-fan surface. The degradation of the scarp over the next 1,000 to 2,000 years would have been substantial, scarp angles in the unconsolidated alluvial would have decreased to the angle of repose, and a colluvial wedge would have formed at the toe of the scarp.

Following the second earthquake, the scarp would have doubled in height. While the abandonment of the alluvial-fan surface for 1,000-2,000 years would have allowed rock varnish formation and soil development to progress, the cementation of the alluvium would not be extensive enough to significantly alter the degradation rate of the scarp relative to the previous 1,000-2,000 years. The scarp-slope would again degrade to the angle-of-repose and the accumulation of a thick colluvial wedge at the base of the scarp would continue. By the time the third and fourth ground-rupturing events occurred, the accumulation of salt and dust would have reached a stage that would have dramatically slowed the degradation of the scarp. At this point, the degradation of the scarp would no longer follow a slope diffusion model with the scarp-slope angles decreasing at a predictable rate through time. Due to the cementation of the alluvium by salts, the scarps would now follow a parallel retreat form of degradation, thus retaining their vertical character.

On the basis of measured scarp heights along this part of fault and from preserved bevels and free faces, the average surface displacement for the last four ground-rupturing earthquakes at Willow Creek is about 2.5±0.5 m. Age estimates of 4,000 to 8,000 years were made on the basis of relative age criteria developed on repeatedly displaced alluvial deposits (Q3b) between Mormon Point and Sheep Canyon. These age estimates combined with a total surface displacement of 10.5 m across the Willow Creek scarp yield an average Holocene slip rate of 1-3 mm/yr. In addition, based on the faulting history developed from characteristics of the scarp and associated stratigraphic relationships, it was determined that evidence for the last four ground-rupturing is preserved in the area near Willow Creek. Given the age of the alluvial deposits displaced by the fault and evidence for four events yields a recurrence interval for large earthquakes of about 1,000-2,000 years. Our estimate of 2.5±0.5 m of displacement per event is supportive of characteristic fault behavior for ground-rupturing earthquakes at this site. No additional evidence was discovered during this study that would more precisely constrain the timing of the last surface-rupturing event.

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# Characteristics of Holocene fault scarp morphology, southern part of the Black Mountains fault zone, Death Valley

*Kurt L. Frankel, A.S. Jayko, and Allen F. Glazner*

CHAPTER M


## ABSTRACT

The 76-km-long Black Mountains fault zone (BMFZ) bounds the western margin of the Black Mountains in the central part of Death Valley. The BMFZ is but one of four active fault zones in the 310-km-long Death Valley fault system (see Chapter J in this volume). Previous workers found evidence for three Holocene events with predominantly normal displacement and 0.3 to 9.4 m of vertical separation on various sections of the fault zone (see Chapter L in this volume). We measured 21 scarp profiles at 11 locations along a 46-km portion on the BMFZ to characterize the relative ages of fault scarps and to determine if scarps of different relative ages could be correlated along the fault. Such information may provide constraints for future delineation of rupture segments. Results of the profiling indicate that at least three different scarp morphologies are present; two of these can be spatially correlated along part of the fault zone. These three morphologies are provisionally interpreted as being related to late, middle, and early Holocene faulting events, and referred to in the text as young, medium and old scarps. The young scarps are recognized mainly near, and south of Badwater (from about 0.5 km north of Badwater to about 17 km south of Badwater). The middle (?) Holocene age scarps are more extensive: they are found between Ashford Mills and about 0.5 km north of Badwater. Heights of the medium age scarps increases progressively from about 0.6 m in the south to about 6 m just north of Badwater, near the northern extent of the study area. The heights of the young scarps do not vary noticeably along the short distance they were measured. These results suggest that the only a portion of the length of the Black Mountains fault zone has ruptured during events in the Holocene.

These results are consistent with previous work and indicate that the scarps are young and that there were at least three rupture events during the Holocene. These results also indicate that surface rupture occurred along at least two spatially different rupture sections. The morphology of the youngest scarps compares favorably with that of the 1872 Owens Valley fault scarp, near Lone Pine, California. All scarps in the study area must be younger than marine oxygen-isotope stage II Lake Manly, the relatively shallow perennial lake that occupied central Death Valley during the latest Pleistocene (>10 ka).


## INTRODUCTION

The Black Mountains fault zone (BMFZ) forms an extensional stepover that connects the Northern Death Valley fault zone (see Chapter J in this volume for fault nomenclature) with the Southern Death Valley fault zone (Burchfiel and Stewart, 1966), locally creating a pull-apart basin and one of the longest fault zones (>310 km) in California (Brogan and others, 1991) (fig. M-1). Displacement on the BMFZ over the past 1 m.y. is characterized by oblique-slip, with horizontal motion comprising only a few hundred meters of offset and dip-slip dominating along the front of the Black Mountains (Butler and others, 1988). Fault scarps on alluvial fans at the base of the Black Mountains show evidence of late Holocene activity (Brogan and others, 1991; Klinger and Piety, 1996), but no major surface-rupturing earthquakes have been recorded in historic time (since 1849).

Brogan and others (1991) divided the BMFZ into 11 fault sections based on the trend of faults, recency expressed by geomorphic features, width of rupture zones, consistency of fault patterns, and proximity of active traces to the range front and bedrock features. In this volume (Chapter C), Knott and others suggest that the BMFZ has five sections. Brogan and others (1991) measured scarp-slope angles at 20 localities and they noted evidence for young faulting events, such as steep free faces and lack of varnish development. In addition, they measured the vertical surface offset of scarps as much as 15 m in height and found evidence for widespread ground rupture within the mapped Q1B unit (late Holocene surface), indicating three or more surface faulting events in the Holocene. Faults mapped along the Golden Canyon area of the fault zone (fig. M-2) were inferred to be almost historic, but no specific dates were assigned to these scarps (Brogan and others, 1991). Brogan and others (1991) study did not include measurement of scarp profiles or reporting of characteristics of offset fan surfaces.

Klinger and Piety (1994, 1996) also evaluated Quaternary activity on the BMFZ (along with many parts of the Death Valley fault system) as part of seismotectonic investigations for the Yucca Mountain high-level nuclear

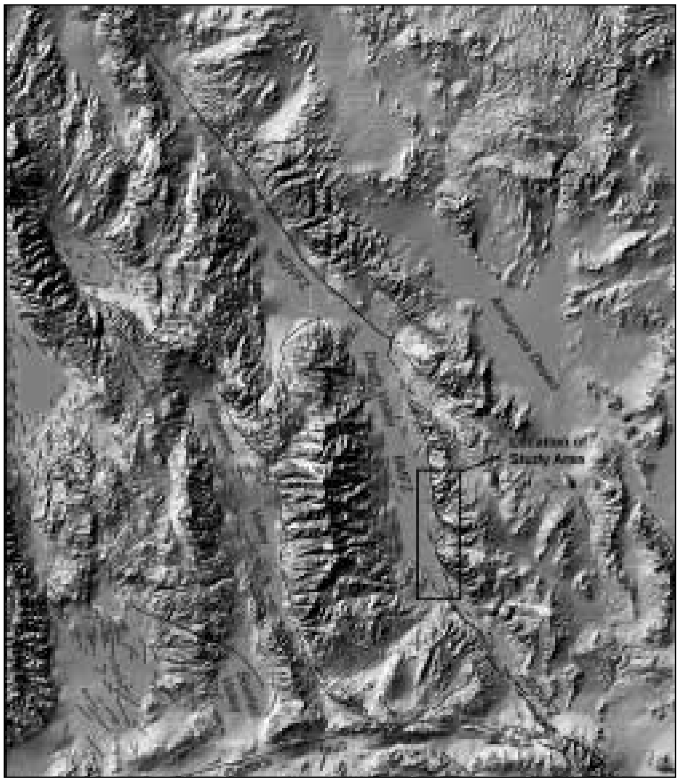

*Figure M-1. Shaded relief map showing location of major faults in the Death Valley area and location of study area shown in figure M-2.*

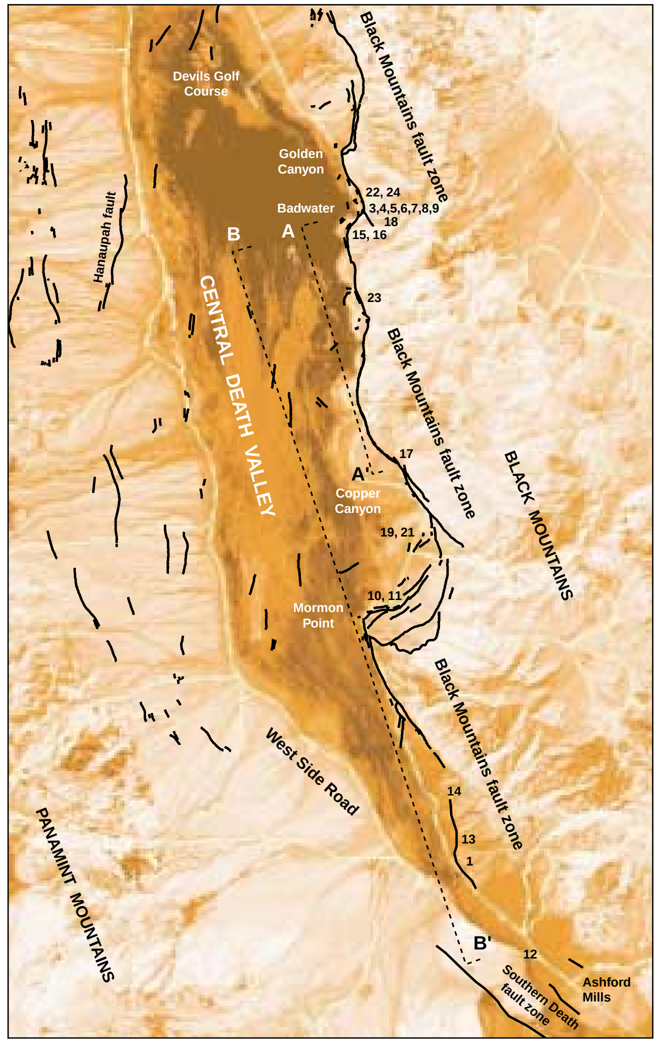


*Figure M-2. Map showing location of study area and numbered scarp profile localities. Faults from Reheis and Noller, 1996. Profile localities in table M-1 and air photo locations are in the Appendix, which follows the references. Lines A-A' and B-B' show extent of young and medium age scarps, respectively.*

waste repository site in Nevada, which is less than 50 km from the fault zone. Klinger and Piety (1994, 1996) found evidence for multiple surface-rupturing events during the late Holocene from a scarp having 10.5 m of displacement on a middle to late Holocene fan near Mormon Point (see Chapter K in this volume). Preserved free faces from the past two ground ruptures and inset tectonic terraces provide evidence for the past three or four events in this area. The average vertical displacement per event at the Mormon Point location was estimated to be 2.6-3.5 m (Klinger and Piety, 1994 and 1996). The age of the displaced fan surface at Mormon Point was estimated to be 2 to 4 ka, yielding an average vertical slip rate along the BMFZ of 3-5 mm/yr (Klinger and Piety, 1994). The most recent event had an average vertical displacement of 2.5 m. Average recurrence intervals for large surface-rupturing earthquakes ranged from 700-1,300 years for three events and 500-1,000 years for four events (Klinger and Piety, 1996).

This study attempts to determine the age and number of faulting events along the central and southern parts of the Black Mountains fault zone through the analysis of tectonic geomorphic features at the base of the Black Mountains. For reference, in the appendix that follows the references, we have included parts of aerial photographs that show the locations of the profiled scarps in a series of illustrations.

## METHODOLOGY

### Relative dating of fault scarps

Fault-scarp morphology is a useful tool in estimating the relative timing of the faulting event that created these young geomorphic features. This approach is especially useful in areas where there are restrictions regarding disturbing the surface or where there is little or no datable material available to determine absolute ages. Scarps younger than a few thousand years may exhibit a steep free face, a debris slope at an angle of at least 33-35° and an abrupt break in slope at the top of the scarp (Wallace, 1977). As scarps increase in age, the slope of the scarp may decrease exponentially through time (Bucknam and Anderson, 1979; Hanks and others, 1984; Andrews and Buchnam, 1987; and Machette, 1989). Early work in the Great

Basin indicated that scarps on the order of 12 ka have maximum slopes of 20-25° (depending on their height). Scarps much older than 12 ka may have slope angles as low as 8-9°, and the break in slope at the top of the scarp becomes progressively more rounded with age (Wallace, 1977).

Many workers have also used a diffusion model in the analysis of scarps (Nash, 1980 and 1984; Colman and Watson, 1983; Pierce and Colman, 1986; Hanks and Andrews, 1989; Jyotsna and Haff, 1997; Hanks, 2000). The diffusion equation estimates ages as well as denudation rates at specific sites. The model requires having morphometric data for a scarp of known age located near the scarps that are being analyzed; unfortunately, no absolute ages have been determined for any of the scarps on the BMFZ, thus limiting application of the technique. However, we used the slope-degradation model of Bucknam and Anderson (1979) ($\theta = -8.5 \log T + 52.5$; where $\theta$ is the scarp angle in degrees and T the time in years) as a first-order approximation of relative scarp age (fig. M-3). This model shows the predicted relationship of scarp angle versus age.

### Relative dating of offset deposits

Rock weathering and soil formation are widely accepted as useful tools in assessing relative ages of surface deposits (Bachman and Machette, 1977; Machette, 1985; McFadden and others, 1989; Bull, 1991). McFadden and others (1989) established that soil profiles, silt accumulation, carbonate cementation and varnish development are useful measures for distinguishing ages of Holocene and Pleistocene deposits in the southwestern U.S. They showed that rock varnish/soil horizon development may

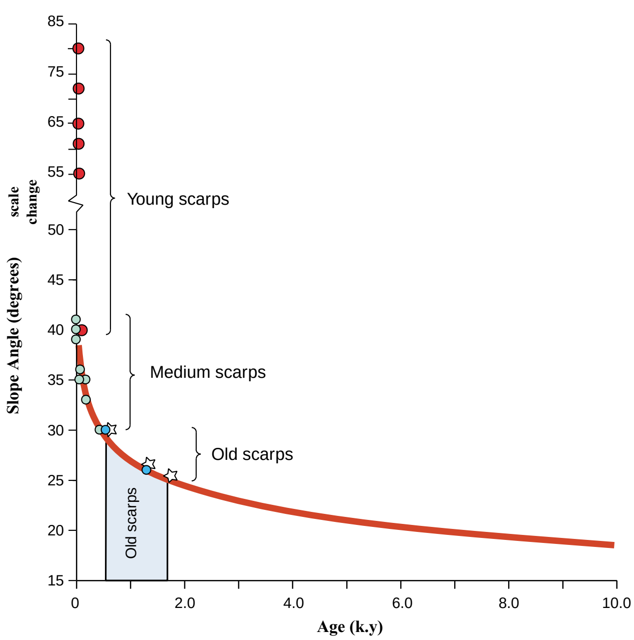


*Figure M-3. Plot showing decrease in scarp height with age from Bucknam and Anderson (1979).*

be directly proportional to age. The degree of rock varnish development can be characterized by color; for example, an alluvial fan having rock varnish with a 7.5YR3/4 color (moderate to dusky yellowish brown) was assigned an age of 4-8 ka, or middle Holocene (Bull, 1991). Others have also used development of bar-and-swale structures (small surficial channels created by drainage on alluvial fans) as an estimation of relative age (McFadden and others, 1989) (also see morphometric and soil criteria of Klinger in Chapter A, this volume).

### Constraints from paleoshorelines

Paleoshorelines, tufa deposits, and lacustrine sediments record evidence for a perennial lake (ancient Lake Manly) that occupied the area between the Black Mountains and the Panamint Range once to several (?) times in the Quaternary (Blackwelder, 1954). A paleoclimate record from a salt core in Death Valley shows variations in lake level relating to climatic changes over the past 200 ka (Lowenstein and others, 1999). The most significant (deepest) of these lakes occupied the basin from 186 ka to 120 ka and from 35 ka to 10 ka (Lowenstein and others, 1999), although the younger lake seems to have been of much less extent (see Chapter C, Stop C1 in this volume). Lakes such as Lahontan, Bonneville, Russell, and Searles also experienced significant variations in their levels during these times. The levels of these lakes dropped significantly between 14,000 and 13,500 years ago in response to deteriorating pluvial conditions (Benson and others, 1990). Lake levels seem to have stabilized or even increased slightly from 11.5 ka until approximately 10 ka, at which time a sudden decline in water levels took place as climate changed and lakes dried up throughout the Great Basin (Benson and others, 1990; Lowenstein and others, 1999). From 10 ka to the present, very shallow lakes have intermittently occupied parts of Death Valley during wet years, but none of these have been of significant size. For example, Hunt and Mabey (1966) report evidence for a shallow lake that extended though central Death Valley about 2,000 years ago. Locally, features like erosion of varnish are evidence for the most recent lake stands. Some of the offset fans profiled in this study are located at the lowest part of the basin (near Badwater), which would have been the final area to be exposed as the last pluvial lake receded. The absence of shoreline features on faulted alluvial fans in these regions supports the Holocene age inferred for the scarps.

### Field Methods

The scarp profiling and field observations were made during 16 days in October-November 1999, and March 2000. Scarp profiles were measured using measuring tapes and vertical rods with standard trigonometric corrections (fig. M-4). National Park Service restrictions regarding digging soil pits prevented subsurface observations of the soil characteristics. However, observations about the character of surface features were noted. The surface color characteristics were described using the GSA Rock Color Chart (1991). Given there is little if any soil development on the small conical Holocene fan surfaces, clasts on the fan surface and on scarps were overturned (and later replaced) to estimate the amount of silt accumulation and development of vesicular texture in the silty A horizon. The surface of the fans along the Black Mountain range front is underlain by a clast-supported matrix (soil parent material).

## RESULTS

Scarp profiles were measured at 11 locations (fig. M-2) along 46 km of the central and southern parts of the BMFZ. All the fault scarps studied are on unconsolidated alluvial fan deposits

*Figure M-4. Scarp profile setup. Steel measuring tape strung across two vertical rods.*

at the western base of the Black Mountains. Information noted on relative ages of the deposits and scarps includes 1) the amount of varnish development on the footwall and hanging wall blocks of the fault, as well as on each scarp, 2) an estimate of silt accumulation beneath large clasts on the fan, and 3) an estimate of the height (relief) of bar and swale structures on each fan (table M-1). Presence or absence of fractured clasts and development of desert pavement were also noted on the fan surfaces. The scarps that were profiled were identified on air photos prior to field studies, concentrating on the youngest accessible scarps. In addition, the 1872 Owens Valley fault scarp near Lone Pine, California (see appendix M-1 for location) was profiled using the same technique for comparison with a historic event in a nearby region. We use this profile to provide additional relative age control for the scarps in Death Valley, acknowledging that the difference in precipitation between the two localities may have a consequence on the morphology and rates of color development.

The scarp faces have little to no varnish development relative to the alluvial fans they are formed on (fig. M-5); however, comparison of the color on scarp faces of different ages is revealing. The youngest scarp faces all have grayish orange pink, grayish orange, or pale brown colors (5YR7/2, 5YR5/2, or 10YR7/4). The medium and old age scarps range in color from grayish orange pink (5YR7/2) to dusky brown (5YR2/2) and generally exhibit slightly more varnish development than the young scarps. It appears that the majority of scarp faces range from grayish orange pink (5YR7/2) to pale brown (5YR5/2), indicating little to no varnish development. Conversely, the colors of the fan surfaces range from very pale orange (10YR8/2) indicating very little varnish development (young fans) to dusky brown (5YR2/2) indicating heavy varnish development, depending on the age and depositional activity on the fans. Hangingwall and footwall surfaces at the same location generally had the same degree of varnish development (table M-1), suggesting that the faulted surfaces are of similar age.

Silt accumulation commonly is weak beneath clasts in the A horizon (uppermost soil horizon). A small percentage of soils have a slight vesicular A horizon beneath larger cobbles and generally correspond to greater varnish development on fan surfaces. No evidence was found for the development of carbonate cement or soils on scarp surfaces, free faces, or in drainages cutting the scarps.

*Figure M-5. Scarp 17 showing a significant difference between varnish development on fan versus scarp face.*

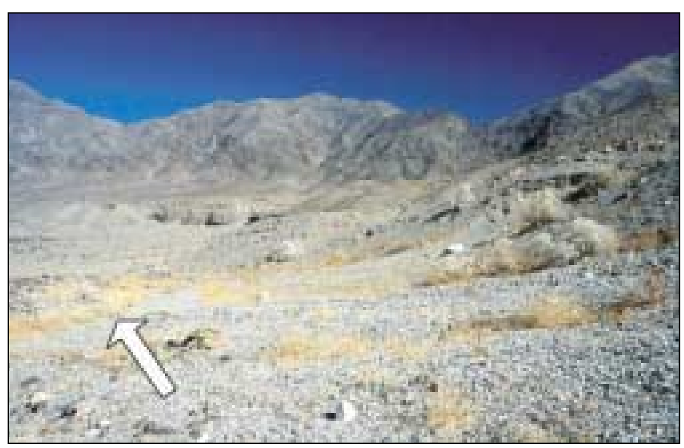

*Figure M-6. Graben defined by line of vegetation (shown by arrow) below scarp 10.*

Table M-1. Information on scarp morphology and data for accessing relative ages of faulted deposits

| Scarp | age | Height | Max. slope angle | Dry color of surface | block | Dry color of hanging-wall block | Comments |
|---|---|---|---|---|---|---|---|
| 3 | Young | 1.6 | 61 | 5YR7/2—5YR5/2 | 10R 6/2-5R 4/2 | 10R 6/2-5R 4/2 | Area of multiple scarps (scarps 3-9) |
| 9 | Young | 2.6 | 72 | 5YR7/2—5YR5/7 | 10R6/2—5R4/7 | 10R6/2—5R4/7 | Area of multiple scarps (scarps 3-9) |
| 15 | Young | 4.2 | 65 | 10YR7/4 | 10YR8/2—5YR5/2 | 10R8/2—10R5/4 | Free face present |
| 17 | Young | 1.6 | 38 | 10YR6/2—5YR2/2 | 10YR6/2—5YR5/2 | 5YR5/2—5YR2/2 | Evidence for strike slip movement |
| 23 | Young | 2.2 | 80 | 5YR7/2 | 5YR7/2—5YR4/4 | 5YR7/2—5R4/6 | Free face present, very young |
| 24 | Young | ? | ? | 10YR6/2 | 10YR8/2—5YR3/2 | 10YR8/2—5YR3/2 | Large graben system visible from Dante's View |
| 25 | Young | 2.9 | 70 | N/A | N/A | N/A | 1872 fault scarp in Owens Valley |
| 1 | Medium | 1.5 | 40 | N/A | N/A | N/A | |
| 5 | Medium | 2.3 | 35 | 5YR7/2—5YR5/3 | 10R6/2—5R4/3 | 10R6/2—5R4/3 | Area of multiple scarps (scarps 3-9) |
| 6 | Medium | 1.15 | 35 | 5YR7/2—5YR5/4 | 10R 6/2—5R4/4 | 10R6/2—5R4/4 | Area of multiple scarps (scarps 3-9) |
| 7 | Medium | 0.75 | 35 | 5YR7/2—5YR5/5 | 10R 6/2—5R4/5 | 10R6/2—5R4/5 | Area of multiple scarps (scarps 3-9) |
| 10 | Medium | 4.1 | 30 | 10YR6/2 | 5YR7/2—5YR3/4 | 5YR5/2—5YR3/2 | |
| 12 | Medium | 0.65 | 25 | 10YR6/2 | 10YR6/2 | 5YR7/2 | Southernmost scarp |
| 13 | Medium | 2.5-3.5 | 30-35 | 5YR7/2 | 5YR7/2—10YR6/2 | 5YR7/2 | |
| 14 | Medium | 1.1 | 40 | 5YR5/2 | 5YR5/2 | 5YR7/2—10YR6/2 | |
| 19 | Medium | 1.2 | 40 | 5YR7/2—5YR4/4 | 5YR5/2 | 10YR6/2—5YR7/2 | |
| 21 | Medium | 1.6 | 40 | 10YR6/2 | 5YR7/2—5R3/4 | 10YR6/2—5YR5/2 | Graben, lower fan has salt fracturing |
| 22 | Medium | 6.0 | 55 | 5YR7/2—10YR4/2 | 5YR7/2—10R3/4 | 10YR6/2—10R3/4 | Steep fan/debris flow |
| 8 | Old | 3.0 | 25 | 5YR7/2—5YR5/6 | 10R6/2—5R4/6 | 10R6/2—5R4/6 | Possible stream modification |
| 11 | Old | 3.4 | 30 | 5YR7/2—10YR6/2 | 5YR5/2—5YR3/2 | 5YR7/2—5YR3/2 | Graben has ~95% fine clasts |
| 18 | Old | 1.1 | 25 | 5YR7/2 | 5YR5/2—5YR4/4 | 5YR7/2 | Scarp in active channel |

Bar-and-swale structures were developed on the majority of fan, indicating youthfulness of their surface. These features were generally small, ranging from about 1.0 to 2.0 m in amplitude (height). Some of the subtle bar-and-swale structures represent mature channels that cut through the scarps, but none of these channels appeared old enough to have developed tectonic terraces.

Approximately 10 percent of the main fault scarps were accompanied by antithetic (mountain-side down) scarps, which create small grabens (fig. M-6). The antithetic scarps were all considerably smaller than the main (valley-side down) scarps. The small graben systems commonly control drainage across the fans, as do many of the scarps in general (see also Stop B3, this volume). Drainages along graben systems often accentuate the steepness of scarp slopes, and locally this created a problem in deciding where to measure the scarp profile. Sediments captured in the grabens are commonly fine-grained silt to pebble-sized.

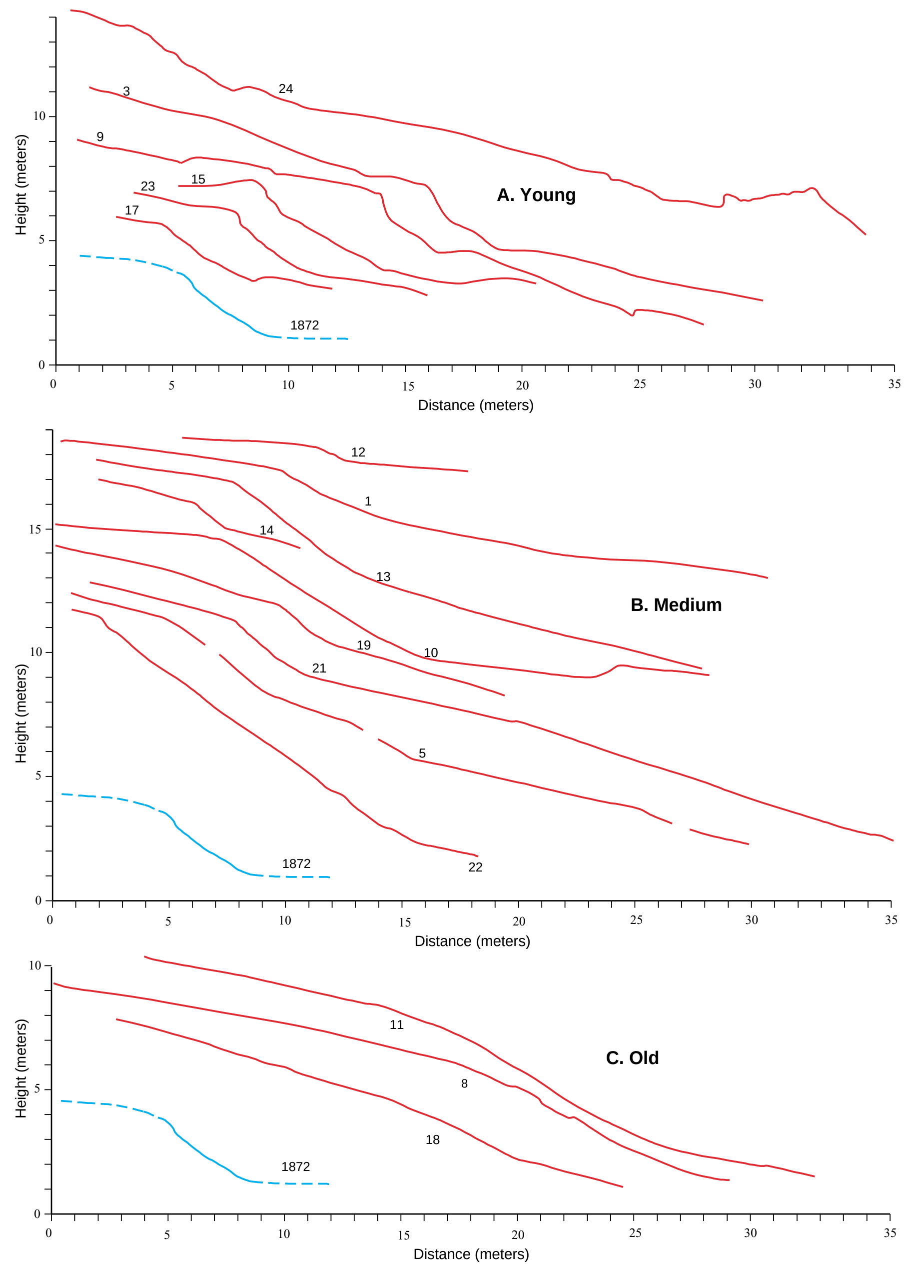


*Figure M-7. Profiles for scarp along Black Mountains fault zone. A) young-scarp morphologies; B) medium-scarp morphologies; and C) old-scarp morphologies. Numbers indicate locations on figure M-1 and table M-1. Lower scarp labeled "1872" is from Owens Valley fault zone in Lone Pine, California. No vertical exaggeration was used on profiles.*

## SCARP MORPHOLOGY

Strong evidence had been demonstrated for multiple Holocene events along the BMFZ (Butler and others, 1988; Brogan and others, 1991; Klinger and Piety, 1994 and 1996). Based on our profiles, the Holocene fault scarps along the central and southern parts of the BMFZ can be divided into three main morphological groups, which we refer to as young, medium and old scarps (figs. M-7A, B, and C, respectively). The scarp degradation equation of Bucknam and Anderson (1979) was used to estimate relative scarp ages (fig. M-3). Because of climatic variations Bucknam and Anderson (1979) cautioned against use of the relation in regions other than their field area (Utah). A scarp in Death Valley with the same maximum slope angle as a scarp in the Utah study site will likely be older than indicated by Bucknam and Anderson's curve, due to the lower mean annual precipitation in Death Valley.

### Young scarps (late Holocene)

The five profiles we measured from the youngest scarps (no. 3, 9, 15, 17, and 23) are located between about 0.5 km north of Badwater to about 17 km south of Badwater (see fig. M-2). These scarps have an average maximum scarp-slope angle of about 65°, with the steepest being about 80°. The young scarps have noticeably irregular, bumpy profiles and angular crests with convex upward profiles (fig. M-7A). Regardless of the large difference in climate between Death Valley and the northern Great Basin, the scarps appear to be extremely young ("zero" age; Wallace, 1977). Wallace (1977) determined that scarps with a steep free face and debris slope greater than 35° (at or above the angle of repose), are less than a few thousand years old. Further constraints on the age of the scarps are gained when data for the young scarps are plotted relative to Bucknam and Anderson's curve; scarps with slopes greater than 35° appear to be only a few hundred years old (see also young scarp data at Stop B3). We estimate that the young scarps are a few hundred to 1,000(?) years old. The lack of young scarps more than 17 km south of the Badwater area suggests that the youngest event may have terminated a short distance south of Badwater. These scarps seem to be morphologically similar to scarps recognized by Klinger and Piety (1996) to the north, at Golden Canyon.

### Medium scarps (middle or late? Holocene)

Most of the scarps profiled in this study are interpreted as being of medium age and have average slope angles of 35-40°. These scarps commonly have a sharp, somewhat angular crest and asymptotic lower slopes (fig. M-7B). The crest is commonly sharper than the toe. Medium-age scarps exhibit notably smoother profiles than the group of young scarps; in addition, the middle parts of the scarp slope are relatively linear. We estimate the age of these scarps to be ~2-6 ka from scarp slope angles (fig. M-3). If all of these scarps represent a single, same-age faulting event, then the rupture would have extended from the West Side Road junction near Ashford Mills (fig. M-2) north to at least Badwater, a distance of about 46 km. This rupture has an apparent vertical displacement that increased from about 0.6 m in the south to about 6 m in the north (fig. M-8).

### Old scarps (early or middle? Holocene)

The scarps in the old category have smooth profiles and somewhat concave middle sections between the toe and crest that distinguish them from the young- and medium-age scarps (Fig. M-7C). The old scarps have an average scarp-slope angle of about 28° with a common range of 25-30°. Although these scarps are still clearly noticeable in the landscape, they lack free faces and steep debris slopes, and have well-rounded crests and toes. They are inferred to be younger than about 10 ka because any significant rise of Lake Manly would have obliterated scarps formed before this time and left evidence of shorelines on faulted alluvial fans of pre-Holocene age. Morphometric comparisons with Bucknam and Anderson's (1979) curves as well as Wallace's (1977) age determinations suggests the scarps could be considerably less than 10,000 years old (i.e., middle or early? Holocene).

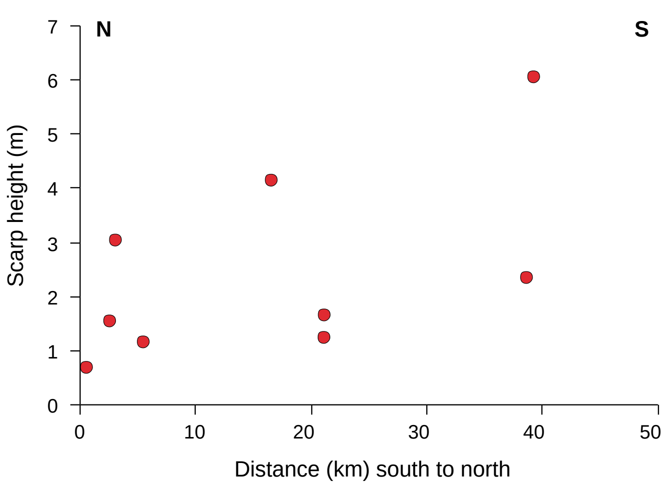


*Figure M-8. Plot showing increase in height for medium age scarps from south to north along the Black Mountains fault zone. Points represent individual scarp heights.*

### 1872 Owens Valley fault scarp, Lone Pine, California

Owens Valley experienced a significant earthquake (M 7.7-8.0) on the Owens Valley fault in 1872. This is the most recent of three Holocene events that formed the composite scarp near Lone Pine, California (Lubetkin and Clark, 1988; Beanland and Clark, 1991). Because its age is known, the Owens Valley scarp was used for calibration in morphologic comparisons with scarps from the Death Valley study area. One uncertainty regarding the diffusion process is that the Lone Pine area receives approximately 2.5 times as much annual precipitation (about 13 cm/yr) as Death Valley (about 5 cm/yr; Hollet and others, 1991). Similarities in profiles from the Black Mountains fault scarps (no. 3, 9, 15, 17, and 23) relative to the 1872 Owens Valley fault scarp are consistent with the other scarp-evolution models and indicate that the most recent faulting at these locations (fig. M-2) along the BMFZ is very recent. Figures 6A and 6B show several scarp profiles that have even more youthful characteristics than the Lone Pine scarp, a relation which is likely a function of the differences in aridity between the two areas (see discussion of scarp-degradation rates at Stop B3 in this volume).

## CONCLUSIONS

Our analyses of scarp profiles and field relations suggest that the BMFZ ruptured in discrete parts (segments?) and that no single Holocene event ruptured the entire 76-km length of the fault zone. However, we recognize the limited scope of this effort and the necessity for more thorough investigations. The scarp morphologies that define the three events seem distinctive and do not grade from one type to the other, suggesting that some time elapsed between events. Preliminary results further suggest the central part of the BMFZ ruptured more recently than the southern part. The young event produced a scarp at least 3-4 m high near Badwater. The middle Holocene event produced a scarp at least 6 m high that may be at least 45 km long. This rupture may have been significantly longer in as much as it is not likely that the rupture terminated at the northern end of our study area where its had its maximum vertical separation. The minimum moment magnitude (M) of the middle Holocene event is approximately 7.0-7.2, an estimate that is based on at least a 45-km rupture length and 6 m of displacement (Wells and Coppersmith, 1994). This estimate is consistent with previous estimates by Brogan and others (1991) and predictions for earthquake magnitudes over the next 10,000 years by Bennett and others (1997).

All of the young scarps are characterized by steep free faces and steep debris slopes. The youngest scarps (no. 3, 9, 15, 17, and 23) are along the central part of the Black Mountains fault zone, within 17 km of Badwater (locations shown in fig. M-2) and are estimated to be about 200-1,000(?) years old. This young time estimate is consistent with morphometric comparisons to the 1872 Owens Valley fault scarp near Lone Pine and scarp-age relations suggested by Bucknam and Anderson (1979) and Wallace (1977). The medium age scarps are estimated to be 500-2,000 years old based on comparison with Bucknam and Anderson's data (1979). Underestimating their age by half still only pushes their time of formation to about 1,000-4,000 years. The old (Holocene) scarps would also be estimated at 500-2,000 years old using Bucknam and Anderson (1979) curves, because the measured scarp slopes are still above 25° on all of the profiles. Thus, the timing of formation of the older scarps remains undetermined, but it appears to be quite recent and clearly postdates the last advance of Lake Manly.

## ACKNOWLEDGEMENTS

This project was part of an undergraduate senior thesis completed by Frankel in August 2000. The project was funded by the University of North Carolina Burch Field Seminar, University of North Carolina-Chapel Hill (UNC-CH) Department of Geological Sciences, and by Charles and Joanne Frankel. Field equipment for scarp profiling and transportation was provided by the U.S. Geological Survey (USGS) and by the University of California White Mountain Research Station (WMRS). Special thanks to Ralph Klinger (U.S. Bureau of Reclamation) and Michael Machette (USGS) who shared time and thoughts in the field. We also thank Michael Rymer USGS) and Michael Machette for thoughtful and constructive reviews, Blair Davenport (NPS) for access to park archive information, and Mel Essington (NPS) who assisted with field logistics. Thanks also go to John Rogers (UNC-CH) and Audrey Huerta for academic guidance, and to Stephanie Briggs (UNC-CH), John Templeton (UNC-CH), and Cecil and Clementine Patrick (WMRS) for assistance with field studies.

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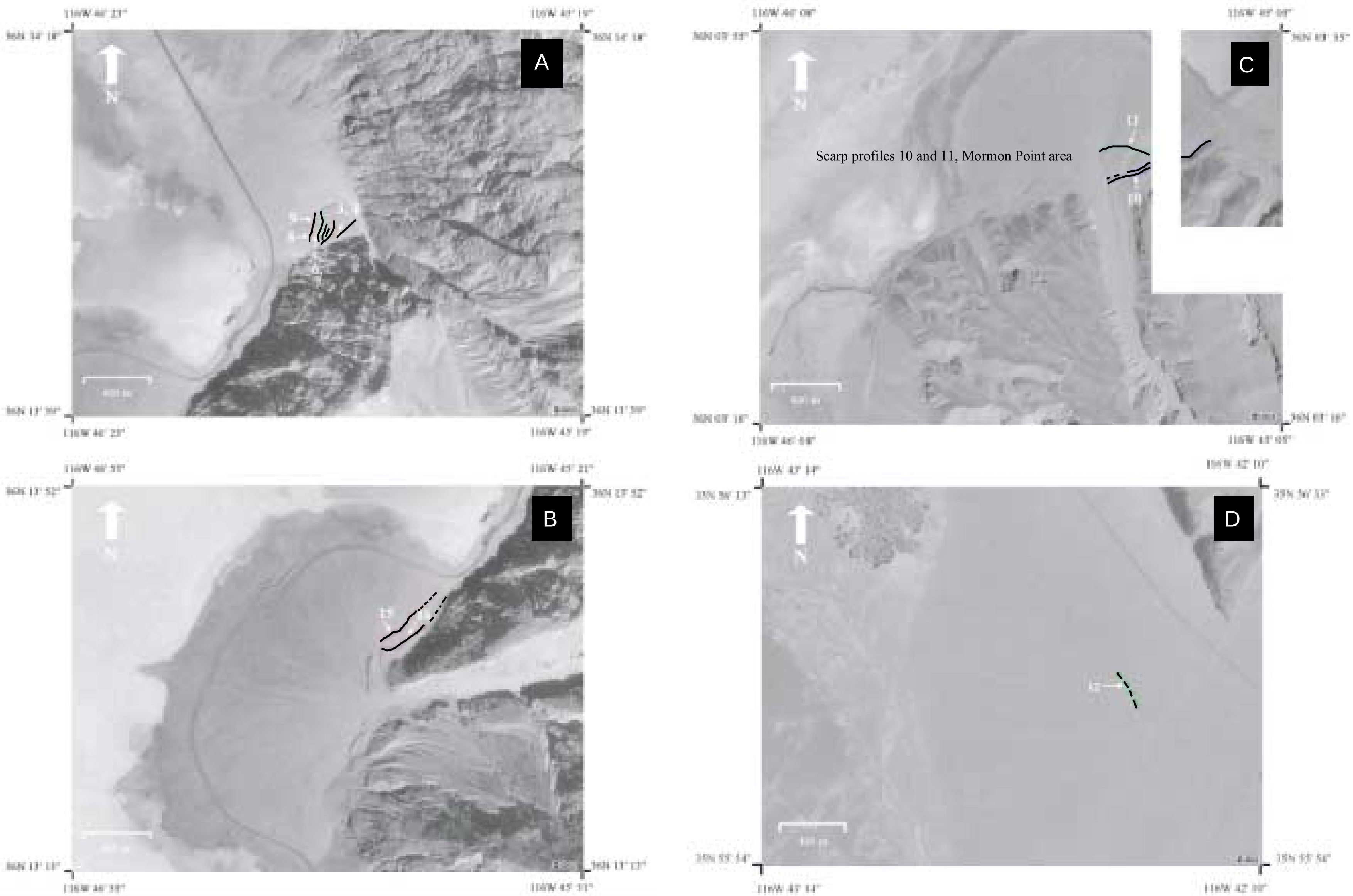
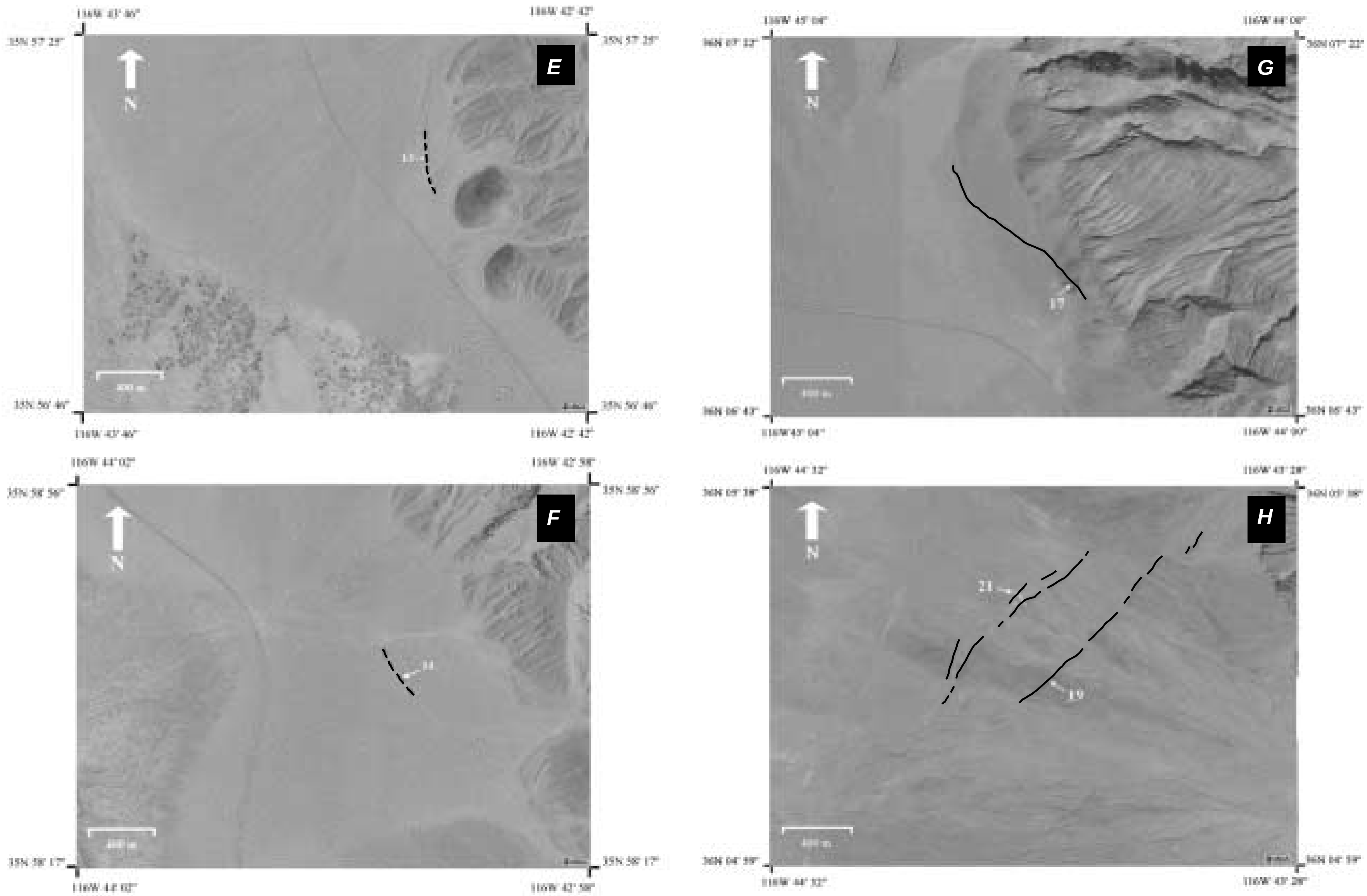



APPENDIX. Air photos showing locations of scarp profiles, Death Valley. Localities also shown on figure M-2 and described in table M-1.




APPENDIX—Continued.  Air photos showing locations of scarp profiles, Death Valley. Localities also shown on figure M-2 and described in table M-1.



1872 Lone Pine Scarp


APPENDIX—Continued.  Air photos showing locations of scarp profiles, Death Valley. Localities also shown on figure M-2 and described in table M-1.

# Search for contemporaneous fault creep in Death Valley, 1970-2000

*Arthur Gibbs Sylvester*


## ABSTRACT

Repeated leveling across four, presumably active faults in Death Valley reveals no unequivocal vertical displacement or strain across them in the period between 1970 and 2000. Marginal evidence for about 1 µrad/yr tilting across the north end of the Artist Drive section of the Black Mountains fault may be related to nontectonic compaction of basin-fill sediment beneath the faulted alluvial fan or to interseismic tectonic warping due to crustal strain accumulation.


## INTRODUCTION

Youthful fault scarps are abundant and prominent in Death Valley and cause one to wonder “when did the earthquakes happen that produced those scarps?” and “are any of the scarps inexorably growing in height now even without earthquakes?” Other investigators have been seeking the answer to the first question and suspect that the causative earthquakes happened several hundred to several thousands of years ago. This study focused on the second question by making repeated, infrequent leveling measurements across the scarps during a 30-year period.

Hundreds, thousands, even tens of thousands of years may elapse between earthquakes on a given part of a fault. In fact, nearly continuous slip, as much as 30 mm/yr and termed “interseismic slip” or simply “fault creep,” has been documented along only a handful of faults in the world. All but one of the creeping faults are strike-slip faults, including and especially the central part of the San Andreas fault near Parkfield (e.g., Schulz and others, 1982; Sylvester, 1995; Behr and others, 1997). The exception is a suspicious case of aseismic normal faulting in the Fish Spring Valley area of western Nevada (Bell and Hoffard, 1990; Bell and Helm, 1998). Whereas fault creep has cogent explanations (e.g., Wesson, 1988), why isn’t it more common? Why does it seem to be restricted to strike-slip faults? And, do any faults in Death Valley slip today by means of creep?

Perhaps other faults do creep but time, diligence, and luck are needed to prove it, because the creep displacements may be so small and episodic at times or places that they are simply missed. The San Andreas fault creep (including creep on the Calaveras and Hayward faults) is noteworthy because it is rapid and consequent damage is clearly evident to engineered structures built on and across the fault (e.g., Steinbrugge, and others, 1960; Rogers and Nason, 1971; Lienkaemper and Galehouse, 1997). Many faults elsewhere in the world pass through vegetated areas, sparsely inhabited areas, or the faults splay into several strands over such a large zone that the measurement of 1-2 mm/yr is simply tedious and difficult, especially if the creep is vertical. Creep has been measured by several methods (Thatcher, 1986; Sylvester, 1986), but unless the fault is unusually active (such as the San Andreas), most methods yield measurement uncertainties that are about as large as the signal. This dilemma compels one to make either extremely precise measurements over short time periods, or make less-precise measurements over a long time period; a period that is usually much longer than that generally afforded by most research grants or by the careers of even the most diligent investigators.

Recent GPS measurements across the southern Basin and Range Province (Smith and others, 1998; Bennett and others, 1999; Thatcher and others, 1999) clearly indicate that right lateral shear strain is occurring across the region at the rate of 12 mm/yr together with 10 mm/yr of E-W extension. Most of this strain is aseismic and concentrated at the west and east margins of the province.

The crustal-strain budget for the region can be balanced only by supposing that some faults slip *interseismically* by creep, at least during the period of the GPS measurements. I commenced a search for a vertical component of missing creep nearly 30 years ago when we placed five arrays of bench marks across oblique-slip faults in Death Valley (fig. N-1) that are regarded as active because of the youthful scarps along their surface traces. Having now resurveyed these arrays six to ten times, the results as reported herein.

## TECTONIC SETTING

Death Valley, at the west edge of the southern Basin and Range, may be subdivided physiographically into three parts (Burchfiel and Stewart, 1966), each of which owes its modern structural grain to youthful faults. The northern and southern parts trend NNW and contain right-lateral strike-slip fault zones, the Northern Death Valley and the Southern Death Valley, respectively. The

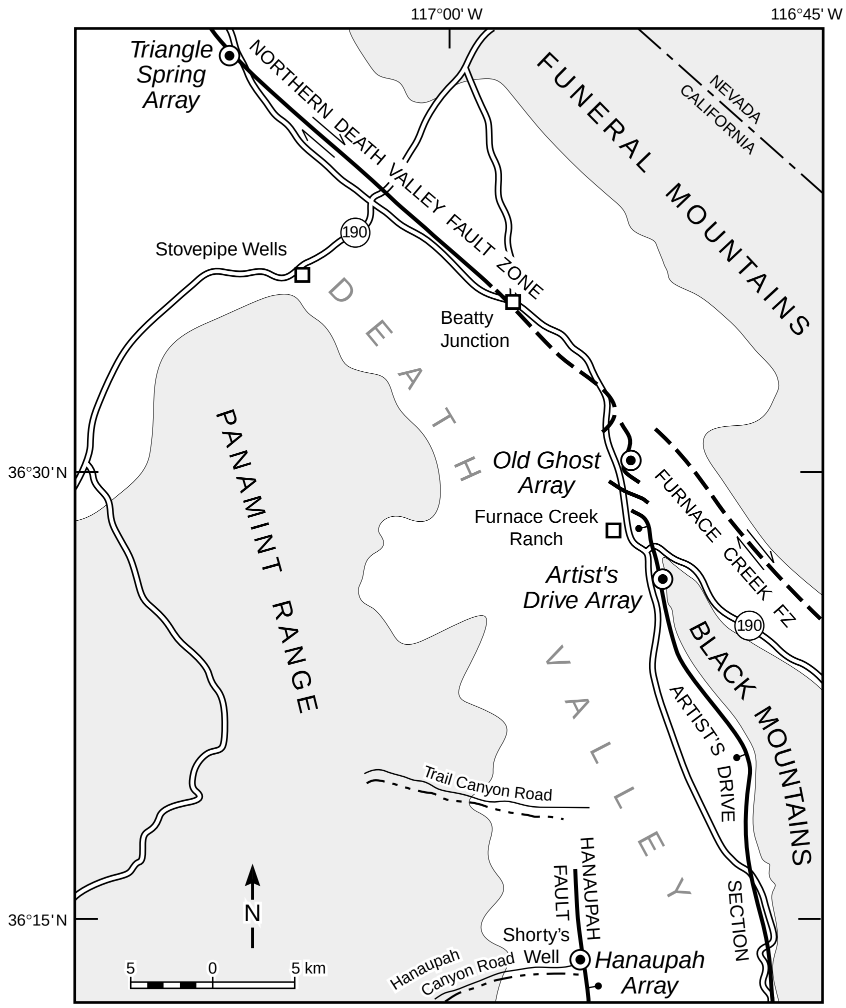



*Figure N-1. Locations of leveling line arrays in Death Valley, excluding Fish Lake array (Nevada).*

central part trends N-S and is bounded on the east by (from south to north) the Mormon Point, Badwater, and Artist Drive sections of the Black Mountains fault zone[1], comprising a zone of right-oblique normal-slip faults at the western base of the Black Mountains (Hunt and Mabey, 1966; Wills, 1989; Brogan and others, 1991; Klinger, 1999).

The central part of Death Valley is a half-graben inclined eastward toward the Black Mountains and the Black Mountains fault zone. This structural geometry is supported by the eastward tilt of the Badwater saltpan, and by the asymmetry of alluvial-fan size and shape from one side of the valley to the other (Hunt and Mabey, 1966). Additional support comes from gravity data (Hunt and Mabey, 1966; Blakely and others, 1999) and from deep seismic-refraction and reflection profiles (Geist and Brocher, 1987; Serpa and others, 1988; Serpa and Pavlis, 1996). The geophysical data indicate that the valley fill consisting of alluvium, lacustrine, and evaporite deposits is about 3,000 m thick, and when combined with geologic data from the Black Mountains, indicate a vertical separation of approximately 5,000 m across the Black Mountains fault zone at Badwater.

The type, timing, and amounts of displacement across the Black Mountains fault zone are quite uncertain. Exposures of mullions and slickensides on fresh fault surfaces (e.g., Noble and Wright, 1954; Hill and Troxel, 1966; Miller, 1999) are evidence that it has a significant component of strike-slip. These estimates range from 2 km to 70 km depending on the investigator, the location, and the age of the geologic marker (Slemmons and Brogan, 1999). Northwest horizontal motion of 2.9 ± 0.6 mm/yr has been measured between 1993 and 1998 by GPS (Williams and others, 1999), but contemporary vertical displacement has not been measured. However, at Goblet Canyon (FOP Stop C2) about 10 km south of our *Artist Drive Array*[2], a vertical displacement rate of 0.9 mm/yr was determined from the 28-m displacement of a rock avalanche that was dated by three cosmogenic exposure ages (Knott, 1998, summarized in Klinger, 1999). Abundant evidence of recent movement on the Black Mountains fault zone is evinced by variably dissected scarps as much as 2  m high on modern alluvium along the Artist Drive section and as high as 10 m along the Badwater and Mormon Point sections (Wills, 1989; Brogan and others, 1991). Klinger and Piety (Chapter L, this volume) and Frankel and others (Chapter M, this volume) present evidence for the timing of movement on these sections of the Black Mountains fault zone.

The Southern and Northern Death Valley fault zones, the Fish Lake Vally falut zone, the (pre-Quatenary) Furnace Creek fault zone, and related fault zones in the area are generally regarded as right-slip faults (e.g., Reheis and Sawyer, 1997), but the timing and amount of displacement on each are still subjects of

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1 Over the years, various names have been given by authors to the zone of faults along the eastern side of central Death Valley, including and especially the Death Valley fault zone (Brogan and others, 1991; Klinger, 1999). This designation is easily confused with the Southern Death Valley fault zone in southern Death Valley (see Chapter J, this volume). The designation of the Artist Drive fault (Hunt and Mabey, 1966) as a separable section of the Black Mountains fault zone is used herein for the purposes of this paper.

2 The *Artist Drive Array* is located in an unnamed canyon between Breakfast and Golden canyons. Because the array spans the Artist Drive section of the Black Mountains fault zone, we called it the *Artist Drive Array*. We are open to suggestions for a more geographically specific name.

investigation. Low, variably dissected, even partially buried scarps, attest to a local component of vertical separation on these faults.

The 7-km-long Hanaupah fault is a relatively short, but impressive fault that is due west of Badwater on the western margin of central Death Valley (Hunt and Mabey, 1966; Brogan and others, 1991). It is marked by a prominent, dissected scarp having a maximum height of about 25 m on older upper Pleistocene (Q2) gravel and 2-3 m in younger upper Pleistocene (Q3) gravel (Hunt and Mabey, 1966, p. A103). Evidence of strike-slip is not apparent on this presumably steep, east-dipping normal fault. The height of the older scarp and the degree of erosion indicate that the fault has had several major earthquakes over tens of thousands rather than hundreds or thousands of years, but conclusive information on the faults slip rate is still lacking.

## METHOD AND PRECISION

In 1969 we placed linear arrays of permanent bench marks (fig. N-1) across the Hanaupah fault (*Hanaupah Array*), the Artist Drive section of the Black Mountains fault zone (*Artist Drive Array*), the transition zone between the Northern Death Valley and Black Mountains fault zones (*Old Ghost Array*) (see FOP Stop B3), and the Northern Death Valley fault zone (*Triangle Springs Array*). Each of these arrays was surveyed in 1970 for the first time. The *Fish Lake Array* crosses the Oasis section of the Fish Lake Valley fault zone (Reheis and Sawyer, 1997; Sawyer and Reheis, 1999) in southern Fish Lake Valley. The Fish Lake Valley fault zone (not shown in fig. N-1) is the northern continuation of the Northern Death Valley fault zone into Nevada.

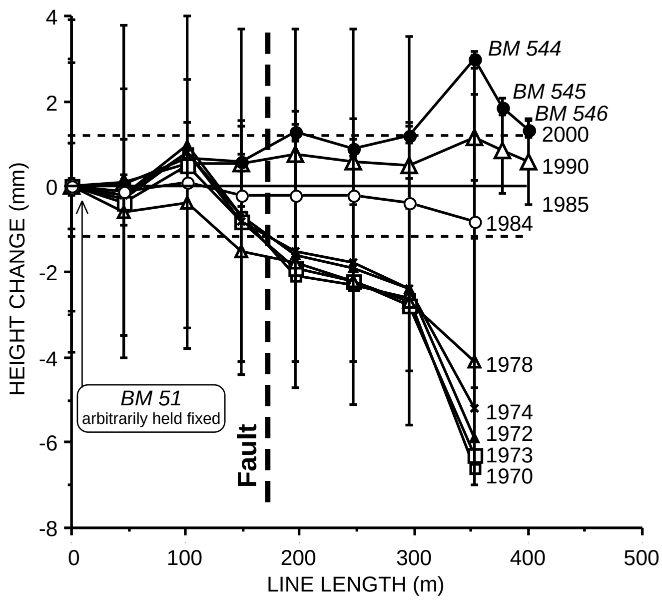


*Figure N-2. Graph of nine levelings in Artist Drive array across Artist Drive section of Black Mountains fault zone, 1970 to 2000 relative to 1985 when array was lengthened. Bench mark 051 was arbitrarily held fixed. One sigma uncertainty in 1985 survey indicated by parallel dashed lines. Greatest uncertainly associated with 1984 survey.*

Most of the bench marks in our arrays are Class B rod marks (Floyd, 1978) that penetrate 2-3 m into the ground. Some of the others are 10-cm-long stubs of copper-jacketed, steel weld rod that have been epoxied into 8 cm-deep holes drilled into large, partially buried boulders. The stability of these marks over time is excellent as indicated by the reproducibility of successive resurveys of them (figs. N-3, N-4, N-5, N-6) and by our experience with them in arrays across faults elsewhere in California, Nevada, and Wyoming (e.g., Sylvester, 1995).

The arrays range from 300 m to 430 m in length, with bench marks spaced no more than 25 m apart. Although the short line lengths and the close bench mark spacing were intentional, some arrays were limited by topography. Initially, we hoped to measure displacement right across the surface trace of the fault, so that if interesting height changes were discovered within the first few years of survey, then we would lengthen the array(s) accordingly and do the necessary work to define the nature and width of the strain zone more completely. We did lengthen the eastern end of the *Artist Drive Array* by 47 m in 1985, because previous surveys indicated that bench mark 544 at the end of the line had risen about 6 mm over 15 years relative to others in the array (Sylvester and Bie, 1986; fig. N-2 this study). We also lengthened the east end of the *Hanaupah Array* in 1974 by 60 m with two additional bench marks. In all our arrays, bench marks were spaced at less than the maximum permitted for first-order leveling in order to minimize refraction errors (Federal Geodetic Commission, 1984).

We seek to achieve an uncertainty less than or equal to 1 mm x $L^{1/2}$ (where L is the one-way length of the line in kilometers), which is designated as "tectonic first order precision," as compared to "first order precision" of 2 mm x $L^{1/2}$ (Federal Geodetic Commission, 1984). Examples of the precision of these orders of leveling data are illustrated in table 1, below:

**Table 1. Examples of precision for leveling data.**

| L (km) | L1/2 (km) | A) Tectonic first order level | B) First order level |
|---|---|---|---|
| 0.100 | 0.32 | 0.32 mm | 0.64 mm |
| 0.500 | 0.71 | 0.71 mm | 1.42 mm |

The majority of the surveys are "tectonic first order." Adverse meteorologic conditions, especially strong wind and heat, are the main factors that generally contributed to surveys having less than "tectonic first order" survey quality. The quality of the March 2000 survey is unusually high, probably because it was done under virtually optimal conditions of gentle breeze and temperatures in the low 80°s F. In addition, *Artist Drive* and

*Old Ghost*, the two longest arrays, were surveyed under lightly overcast skies.

The data presented here are uncorrected, observed data. Leveling over such short array lengths with relatively short, balanced sight lengths should be virtually free of systematic errors due to parallax and refraction and, therefore, should not require synthetic corrections (Castle and others, 1994). The close agreement of surveying results for each Death Valley array from one survey to the next justifies this assumption.

## RESULTS

Changes of bench mark heights are negligible throughout each array, except in the *Artist Drive Array*, both from bench mark to bench mark, as well as from survey to survey, aside from one or two bench marks that behaved somewhat aberrantly relative to the others. Such slight changes logically lead to the conclusions that the bench marks are stable and that surface displacement has not occurred across the faults, whatever the cause, in the past 30 years. The aberrant bench marks are clearly evident by having risen or dropped a millimeter or two relative to adjacent bench marks, and then by retaining that height difference throughout the remainder of the surveys (e.g., bench mark 106, fig. N-3).

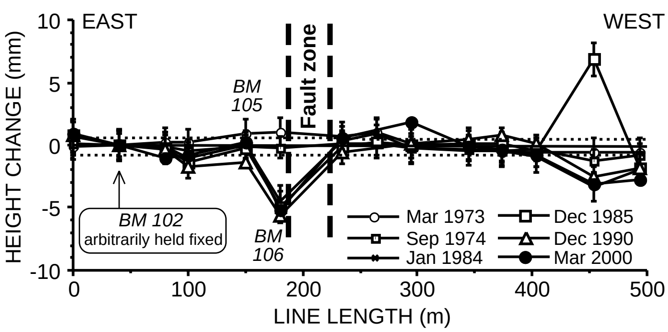


*Figure N-3. Graph of seven levelings in Old Ghost Array across fault scarps in transition zone at Cow Creek, 1971 to 2000. The transition zone is between the Northern Death Valley and Black Mountains fault zones. Bench mark 102 was arbitrarily held fixed. Aberrant bench mark 105 labeled. One sigma uncertainty in 1971 survey indicated by parallel dashed lines.*

Another such aberrant bench mark is 544 in the east end of the *Artist Drive Array* (fig. N-2), which, rose faster than any of the others between 1970 and 1984. We added two class B rod marks (545 and 546) to the east end of the array to see if perhaps 543 and 544 straddled the trace of a fault undergoing displacement. Since 1985, however, 545 and 546 have risen no faster than 541, 542, and 543, whereas 544 continued to rise somewhat faster, indicating that it is relatively unstable (fig. N-2).

The resurveys of the *Artist Drive Array* indicate that height changes among all bench marks were less than 1 mm between 1970 and 1978. Between 1978 and 1984, however, the east end of the line rose 5 mm, and between 1985 and 2000 it rose an additional millimeter (fig. N-2). The pattern of the height changes among all the bench marks indicates that the line tilted about 11 µrad westward, valleydown, over a period of 11 years between 1974 and 1985. Qualitative integration of the bench mark heights from 1978 to 2000 suggests that the tilt was relatively continuous at a rate of 1 µrad/yr. However, the uncertainties attached to several of the relevant surveys are as great as the height changes themselves (fig. N-2), so the signal may be perceived as being not statistically significant, and a conclusion of tilting is only permissive rather than compelling.

Significant height changes among bench marks or across faults are not evident in the *Old Ghost* (fig. N-3), *Triangle* (fig. N-4), or *Fish Lake* (fig. N-5) arrays during the period of study.

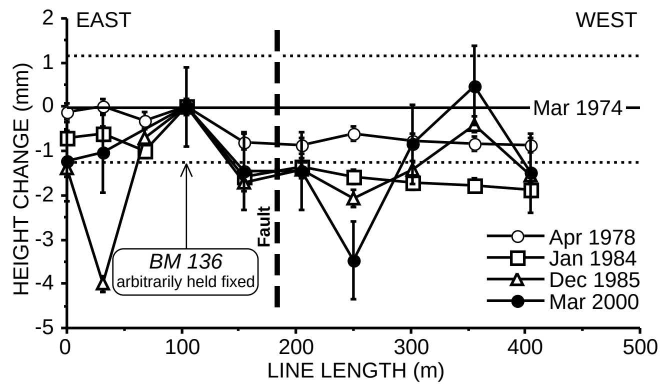


*Figure N-4. Graph of five levelings in Triangle Spring Array across Northern Death Valley fault, 1974 to 2000. Bench mark 136 was arbitrarily held fixed. One sigma uncertainty in 1974 survey indicated by parallel dashed lines.*

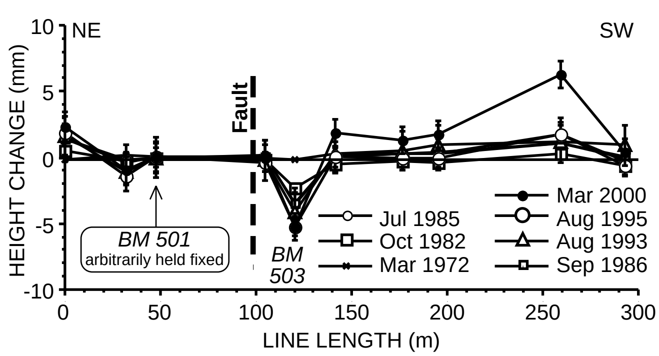


*Figure N-5. Graph of eight levelings in Fish Lake Array across Fish Lake Valley fault near Oasis, 1971 to 2000. Bench mark 501 was arbitrarily held fixed. Aberrant bench mark 503 labeled. One sigma uncertainty of 0.2 mm in 1971 survey is too small to indicate on graph.*

A case can be made for minor displacement across the Hanaupah fault between 1974 and 1990 (fig. N-6B). The first survey of this array was done in 1970, but a comparison with subsequent surveys is not especially revealing (fig. N-6A). The line was lengthened 60 m for the 1974 survey. Only in 1990 and 2000 surveys were the new 1974 bench marks surveyed. A comparison of these surveys (1970, 1990, and 2000) reveals that the footwall block subsided about 1 mm between 1974 and 1990, but the change is within the uncertainty of all three surveys, so the height change across the fault is not statistically meaningful.

## DISCUSSION

Our search for vertical creep was initially directed to only a few of several faults in the western part of the Basin and Range Province that have been recently active, judging from the youthfulness of their scarps. Such faults include those in Owens Valley (Beanland and Clark, 1994), Deep Springs Valley (Bryant, 1989; Lee and others, 1996; Reheis and Sawyer, 1997), Death Valley (Brogan and others, 1991; Klinger and Piety, 1996), Fish Lake Valley (Reheis and Sawyer, 1997), Carson and Eagle valleys (Nevada) (Lawson, 1912), Fish Spring Flat (Nevada) (Bell and Hoffard, 1990; Bell and Helm, 1998), and those associated with historic earthquakes in the Central Nevada Seismic Belt (Pleasant Valley 1915, Cedar Mountain 1934, and Dixie Valley-Fairview Peak, 1954). But if the return frequency of these earthquakes is on the order of thousands to tens of thousands of years in this region as paleoseismic studies suggest (see Chapter L and M, and Stop B3, this volume), then we should have focused on older faults having greatly degraded scarps if we hoped to record their interseismic activity within our lifetime. Because our sampling of interseismic activity is so

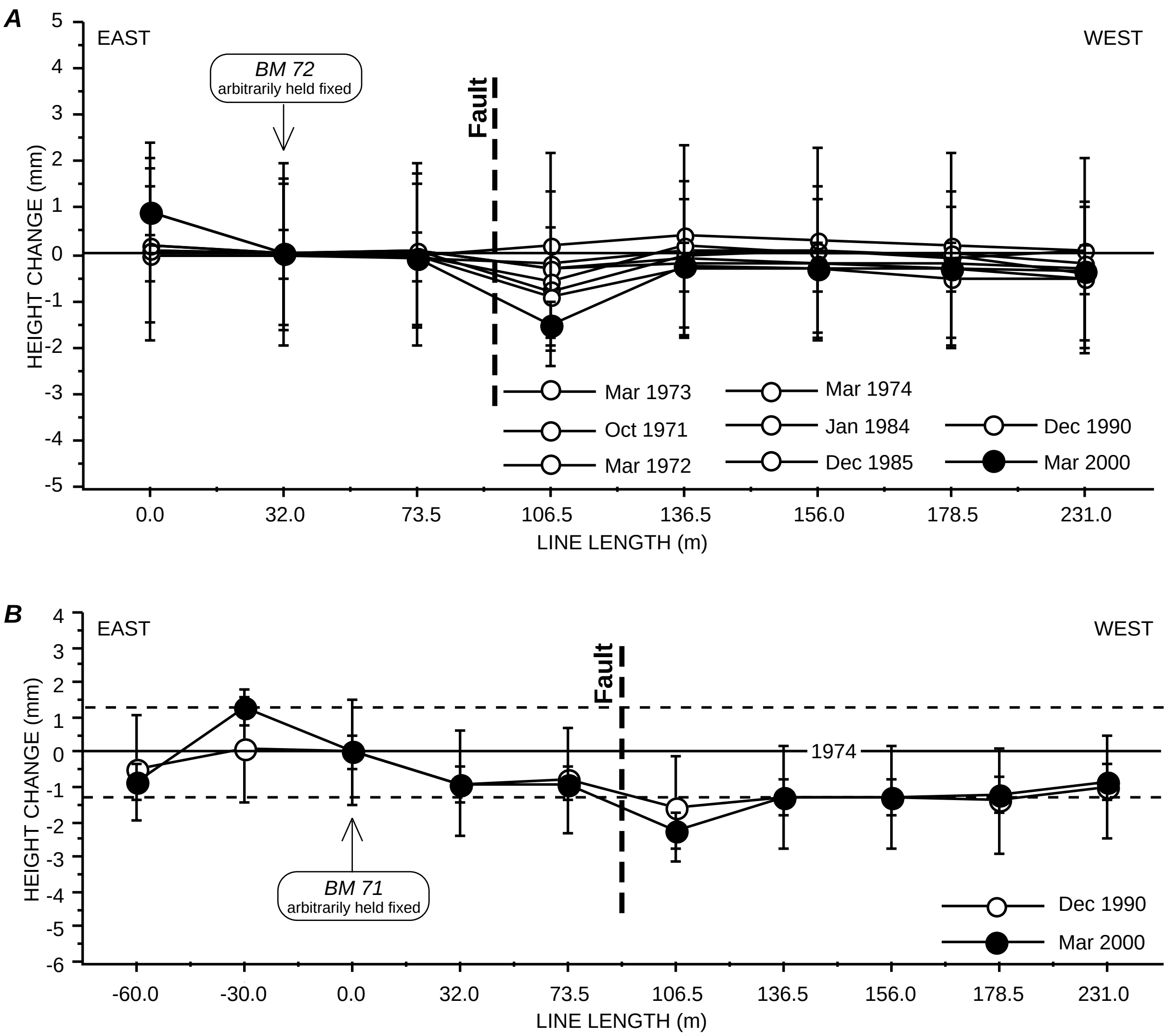


*Figure N-6. Graphs of repeated levelings in Hanaupah Array across the Hanuapah fault. A) Nine surveys, October 1970 to March 2000. Bench mark 72 was arbitrarily held fixed. Solid dots represent 2000 survey. B) Three surveys, 1974, 1990, 2000. Bench mark 71 wzs arbitrarily held fixed. One sigma uncertainty in 1974 survey indicated by parallel dashed lines.*

limited in time and space, it is hazardous to extrapolate the results to the entire Basin and Range, therefore, and the following discussion should be so regarded.

The surveys reported here focus on three faults in Death Valley and one in Fish Lake Valley to the north. The Death Valley faults include one crossing each of the Hanaupah fault, Artist Drive section of the Black Mountains fault zone, and transition zone between the Black Mountains and Northern Death Valley fault zones. We report on two widely spaced crossings of the Northern Death Valley and Fish Lake Valley fault zone. If any one of the surveys had revealed suspicious behavior that could be sensibly linked to tectonic activity, then we would have lengthened the lines, increased the frequency of the surveys, and probably sought NPS permission to establish additional fault crossing arrays. However with the exception of the *Artist Drive Array*, we did not observe any such activity in our 30 years of observation and, thus, conclude from our limited sampling that the surface traces of those faults were inactive in that time.

The *Artist Drive* surveys may evince tilt within a broad zone of tectonic warping across the faults of the Artist Drive section rather than discrete slip along any single fault plane: this warping may be related to tectonism or nontectonic compaction of the basin fill, or to both processes. If it were nontectonic, one might expect the compaction to be a continuous phenomenon rather than episodic. A much longer array and much more time would be required to determine whether the observed tilt is tectonic or nontectonic. A longer line would be difficult to establish, especially across the Badwater playa and up the steep front of the Black Mountains. The postulated tilt is so small that an exceptionally long time will be required for its confirmation by GPS methods, given their current ±5 mm vertical uncertainty.

A primary objective of this project is to reconcile the GPS observations of 12 mm/yr right shear and 10 mm/yr extension in the western Basin and Range with the lack of creep on Death Valley faults. That can be done qualitatively and inconclusively by supposing that Death Valley faults do not creep interseismically and so are not contributors to contemporary regional strain as measured geodetically. However, it is more likely that the shear is so episodic on any given fault that 30 years is an insufficient length of time to measure any consequent creep, or 1) that the shear is purely horizontal and our vertical measurements are insensitive to the regional deformation, or 2) that our arrays are imperfectly located to measure creep in Death Valley, or 3) that the geodetic data provided here may constitute permissive evidence for continuing major elastic strain accumulation in the brittle crust, possibly on one or all of the faults that we have been monitoring. It is also possible that contemporary strain is apportioned across so many faults that the Death Valley faults contribute only a fraction of the total creep which is too small for us to measure in 30 years. Future surveys of the arrays *may* tell the answer and the next earthquake in the region *will* tell.

The lack of significant displacement in our *Artist Drive Array* compared to the observed long-term slip rate of 0.15-0.9 mm/yr at Goblet Canyon (FOP Stop C2; Knott, 1998 in Klinger, 1999) just 10 km south of the *Artist Drive Array*, is perhaps the best reason to argue that displacement on the Black Mountains fault zone probably occurs only at the times of large earthquakes, and that the Black Mountains fault zone—and by extrapolation, all other Basin and Range normal faults—does not creep interseismically, at least at the surface.

## CONCLUSIONS

Repeated leveling across ostensibly active faults in the central part of Death Valley and southern part of Fish Lake Valley over a 30-year period indicates that vertical near-field strain has not taken place across the Hanaupah fault and Northern Death Valley fault zone, but the leveling does provide marginal evidence of about 1 μrad/yr interseismic tilting associated with the Artist Drive section of the Black Mountains fault zone. That conclusion is tenuous because the magnitude of the apparent signal is about the same as that of the noise inherent in the leveling method. The inferred tilt may be related just as easily to nontectonic compaction of basin-fill sediments beneath the faulted alluvial fan as it can be to tectonic warping.


## ACKNOWLEDGEMENTS

The 2000 survey was supported by a grant from the UCSB Academic Senate and with the help of Eric Cline, Jeff Marsh, Brett Wanner, and David Zell. Prior surveys were supported by University of California President's Undergraduate Research Fund grants to UCSB undergraduate students Tom Foster, Rick Keller, John Byrd, Scott Bie, and Gerald Bawden. I am grateful to these intrepid students and their helpers for their work on this project. Pete Sanchez and Richard L. Anderson in the NPS Resources Management Division of Death Valley National Park greased the bureaucratic skids that permitted this long-term project to transpire. Robert O. Castle kindly reviewed and returned the manuscript the same day he received it.


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# Liquefaction in the California desert—An unexpected geologic hazard

*Chris J. Wills*

## INTRODUCTION

Liquefaction has been a significant cause of damage in California earthquakes[1]. It contributed to damage in the Marina District of San Francisco and around Monterey Bay during the 1989 Loma Prieta earthquake. The 1994 Northridge earthquake caused liquefaction damage at King Harbor in Redondo Beach and other scattered areas along the coast. The pattern of damage suggests that coastal and man-made fill areas are the geologic settings most susceptible to liquefaction, but many other settings provide the necessary conditions for liquefaction. Surprisingly, we have found many areas in California's deserts have geologic evidence of liquefaction.

## CONDITIONS FOR LIQUEFACTION

Strong shaking during an earthquake can pressurize the water between grains in loose saturated sand. This rise in pore water pressure can transform a granular material from a solid state into a liquefied state, a phenomena termed liquefaction (Youd, 1973). When liquefaction occurs, a once-firm sand layer can neither support a load nor remain in place, even on a gentle slope.

Loose granular soils and a shallow water table are the two geologic conditions required for liquefaction. If these conditions are met, the soils are susceptible to liquefaction. The most susceptible deposits consist of loose sand having little or no clay or gravel. These well-graded deposits are commonly associated with beaches, coastal dunes, and river point bars and flood plains, all environments of relatively high-energy deposition.

Liquefaction susceptibility is one component of the liquefaction hazard; the other is liquefaction opportunity. Susceptible sediments will not liquefy unless shaken in an earthquake. The opportunity for liquefaction can be shaking from a nearby earthquake as small as magnitude 5.

[1]This article is reprinted from the March-April 1996 issue of California Geology with slight modifications. The descriptions of the liquefaction features in Death Valley have been expanded and I have added maps of liquefaction-induced lateral-spread features between Badwater and Mormon Point.

Extensive liquefaction is usually associated with earthquakes of magnitudes greater than 6.5. Generally, smaller earthquakes will cause liquefaction of especially susceptible deposits in a localized area, while larger earthquakes will cause liquefaction of a broader range of deposits over a wider area (Wills and Manson, 1990).

*Figure O-1: High-angle oblique view of a sand boil at U.S. Geological Survey Wildlife Test Array in Imperial Valley. Calif. Superstition Hills earthquake of November 1987, caused liquefaction of fine sand from a layer about 2 m below surface. Sand erupted through a narrow fissure and flowed over surface, producing a sand boil. Note human and canine footprints for scale. Photograph taken by C.J. Wills, 2/8/1988 from about 1.5 m above surface.*

CHAPTER O

## LIQUEFACTION EFFECTS

Liquefaction can cause serious damage to structures and lifelines. When liquefaction occurs, the most common result is compaction of the liquefied sand with related settlement of the overlying ground surface. Buried structures such as pipelines or tanks may become buoyant because they are less dense than the surrounding liquefied sediment. Heavy buildings or other surface structures may tilt or sink.

If the pressurized pore water finds a conduit through the overlying material, it may erupt onto the surface, carrying sand with it to form a sand boil (figs. O-1, O-2). Sand boils, cracking, and settlement are the most common surface evidence for liquefaction.

If liquefaction occurs on a slope, the liquefied material will flow downhill until excess pore pressure is relieved. Flow of liquefied material takes two forms: 1) a flow failure, where the material extends to the ground surface; and 2) a lateral spread, where the liquefied material is overlain by non-liquefied layers that are broken and carried downslope (fig. O-3).

*Figure O-2. Cross section of sand boil in Imperial Valley. Superstition Hills earthquake of November 1987 caused liquefaction of fine sand from a layer about 2 m. below the surface. Liquefied sand erupted through a narrow fissure and flowed over the surface. Surface crater is approximately 10 cm (4 inches) in diameter. Holzer and others (1989) described this site in detail. Photograph by C.J. Wills, 2/8/1988.*

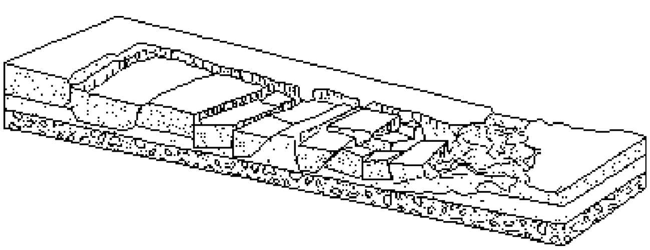

*Figure O-3. Schematic cross section of a lateral spread. Note extensional deformation over much of mass, and compression and thrusting at toe of spread. Modified from O'Rourke and Lane (1989).*

A flow failure requires liquefiable material close to the ground surface, a very shallow water table, and generally a steeper slope than required by lateral spreading. These conditions can be found in relatively small areas on beaches and river banks, as well as in larger areas in submarine environments. Lateral spreads require a liquefiable layer at some level below the water table and a slope on which the mass can move. The conditions for lateral spreading can be found in a wider range of sedimentary environments than flow failures and consequently lateral spreads are more commonly reported.

## LIQUEFACTION IN THE GEOLOGIC RECORD

The surface evidence for liquefaction commonly consists of unconsolidated sand deposits in tectonically active geologic environments. Most sand boils, flow failures, or lateral spreads are rapidly destroyed by erosion. It is not surprising then that sand boils from prehistoric earthquakes have rarely been discovered in California. However, in the Midwestern U.S., sand boils from the 1811 and 1812 New Madrid earthquakes cover hundreds of square miles of the Mississippi River flood plain, but even there sand boils from prehistoric earthquakes are difficult to find (Tuttle and Schweig, 1995). To preserve a sand-boil deposit in the geologic record, the boil must erupt and be rapidly buried without being eroded. Subsequent erosion of overlying deposits may then bring the fossil sand boil back to the surface. This apparently has happened to one fossil sand boil along the Honey Lake fault zone (fig. O-4).

Although sand boils may not be preserved at the surface, evidence for prehistoric liquefaction is sometimes found in the

*Figure O-4. Cross section of fossil sand boil in stream bank adjacent to Honey Lake fault zone. Loose sand that liquefied was forced through fissure in overlying soil and erupted onto ground surface. That surface was then rapidly buried by stream sediments, thereby preserving the sand boil. Sand boil deposit was tilted by deformation related to later earthquakes. White tags are 1 m apart. Photograph by C.J. Wills, 9/20/1990.*

subsurface. Sand boils, contorted bedding, or sand-filled fractures that branch upward from a sand layer have been observed in trenches across fault zones in marsh environments (Sieh, 1978; Rockwell and others, 1986).

Surface features related to lateral spreading are preserved more readily than are sand boils. Lateral spreads form scarps, troughs, and irregular topography, just as conventional landslides do on steeper slopes. These landforms will be gradually degraded by erosion, just as landslide and fault scarps become more subtle and difficult to distinguish over time. Depending on local erosion rates, vegetation cover, and other factors, lateral spread features may be preserved at the surface for thousands of years.

The difficulty in interpreting landforms that result from lateral spreading is that these features could also be due to landsliding or faulting. Generally, lateral spreads are present in small areas and its scarps and troughs indicate direct downslope movement similar to landslides. They are distinguished from landslides by the gentle slopes that they typically form on and by the sandy, high shear-strength material (before liquefaction) that they occur in.

### THE IMPERIAL VALLEY— JUST ADD WATER

Before 1905, the Imperial Valley was an inhospitable desert basin. With loose sandy soil and frequent earthquakes on the San Andreas fault system, the valley was predisposed for liquefaction. Water was the only missing ingredient.

When the farmers of the Imperial Valley began importing water from the Colorado River in 1905, they transformed the basin to an agricultural center. The liquefaction hazard, however, rose with the water table. Irrigation and drainage channels built to distribute the water also form free faces toward which the land can slide if liquefaction occurs.

Liquefaction occurred in the Imperial Valley area during earthquakes in 1968, 1979, and 1987 (Castle and Youd, 1972; Youd and Wieczorek, 1982; Holzer and others, 1989). Liquefaction damage has been concentrated along the New and Alamo rivers, which carry runoff from the irrigated fields, and along the many miles of irrigation ditches (Finch, 1987). Lateral spreading of the river banks and the sides of irrigation ditches caused extensive damage to the irrigation system. Sand boils erupted in many of the same areas, commonly along laterally spreading cracks (fig. O-1).

### THE BASIN AND RANGE—IT'S NOT AS DRY AS IT LOOKS

Imported water is not a factor in liquefaction hazard in California's Basin and Range province. Water has been exported from the Owens Valley and Mono basin in the western Basin and Range to Los Angeles. This removal of water may have incidentally reduced the liquefaction hazards in parts of those basins (although there have been other consequences). In other basins, local water tables and liquefaction hazard rise and fall with seasonal rainfall and long-term climatic changes.

Most valleys in the Basin and Range are bordered by steep bedrock mountains, commonly with active faults at the valley margins. Most valleys also have interior drainage, with local streams flowing toward an ephemeral lake or playa in the lowest part of the basin (Death Valley is a classic example of a closed basin). Although these lakes typically hold water for only a few weeks each year, ground water can be near the surface within lakebeds and surrounding alluvium.

#### Deep Springs Valley

Deep Springs Valley, though smaller than most, is typical of Basin and Range valleys in many ways. It is bounded on the southeast by the Deep Springs fault, an active normal fault (Bryant, 1989). Small steep drainages lead to discrete alluvial fans on the fault-bounded side of the valley whereas on the opposite side larger streams drain onto extensive alluvial fans that have merged to form a bajada. An ephemeral lake occupies the lowest part of the basin, much closer to the active fault-bounded side because of tilting of the basin (fig. O-5).

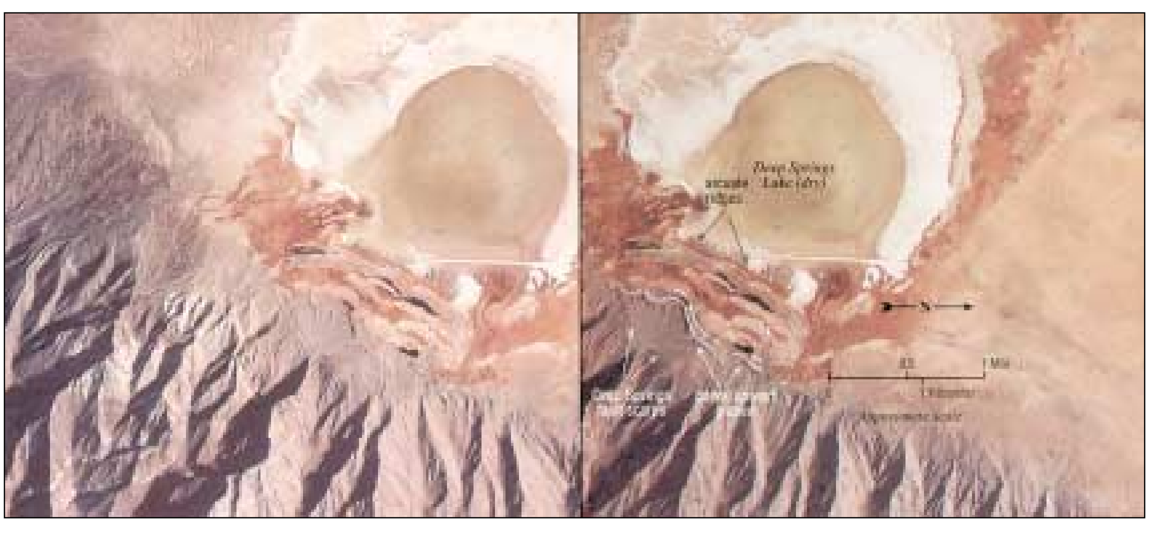


*Figure O-5. Stereoscopic view showing graben around edge of alluvial fan and arcuate ridges, possibly related to extension at head and compression at toe of lateral spread in Deep Springs lakebed. Photograph numbers 2-758 and 2-759, U.S. Bureau of Land Management, 12-3-75.*

Deep Springs Lake (playa) holds no water in most years, and except for some patches of green vegetation at springs along the Deep Springs fault, there is no sign of surface water in the basin. Dirt roads around the northern edge of the playa are deeply rutted and dusty from years of geology students making their way to map adjacent bedrock areas. One year, a truck full of students decided to bypass the dusty, rutted track and drive directly across the hard, smooth bed of Deep Springs playa. They discovered that the hard saline crust on the ancient lakebed is only inches thick and that below the crust, the lake beds are very soft, saturated mud. Water, seemingly the missing ingredient for liquefaction in the desert, can lie just below the surface.

Adjacent to Deep Springs playa, and astride the Deep Springs fault, is a series of ridges and troughs that probably resulted from a liquefaction-induced lateral spread (Bryant, 1989). These features formed on a Holocene alluvial fan composed of gravelly granitic debris from the adjacent mountains. The most prominent trough is as much as 10 m deep and bounded by scarps that slope as much as 39°.

Although the scarps resemble typical normal fault scarps, there are several reasons to believe they are not. The two most prominent scarps face each other across a graben, which has virtually no net vertical displacement (Bryant, 1989). Parallel to the graben are several low arcuate ridges on the lakebed. A lateral spread, like a landslide, has an extensional breakaway scarp at its head and compressional thrust faults or folds at its toe. If the main graben represents the breakaway area of a lateral spread, there should be a corresponding compressional area downslope. These arcuate ridges may represent folding or thrusting at the toe of the lateral spread. Finally, the graben remains at nearly the same elevation around the margins of two alluvial fans, suggesting stratigraphic and lithologic controls. In contrast, the fault in the same area follows the bedrock-alluvium contact, rising in elevation to fan apexes. The near constant elevation of the trough suggests lateral spreads can be distinguished from normal fault features in that lateral spread features commonly follow contour lines on a topographic map. This constant elevation of a trough or scarp might be expected if the scarp forms above the intersection of a dipping layer of soft sandy alluvium and a horizontal water table. However, there is no reason to expect fault scarps or conventional landslide scarps to follow elevation contours in this way.

### Owens Lake

Before construction of the Los Angeles Aqueduct, Owens Lake contained as much as 9 m of water over its 285 square km lakebed. Following completion of the aqueduct, the water level fell rapidly and the lakebed has been mostly dry since the 1920s.

At the time of the 1872 Owens Valley earthquake (M7.8, Toppozada, 1980) the lake was full of water and the water table in the surrounding alluvium was correspondingly high. After the earthquake, cracks in the ground, areas of sunken ground, depressions partly filled with water, and areas of disturbed soils were found from Haiwee Meadows (south of Owens Lake) to Big Pine Creek (about 72 km north of Owens Lake) (Whitney, 1872). Much of this ground disturbance was the result of surface rupture on the Owens Valley fault zone, but some effects, particularly around the edge of the lake, were due to liquefaction-induced lateral spreading.

The problem in this area, and throughout the Basin and Range, lies in distinguishing tectonic fissures and grabens from those due to lateral spreading. Carver (1970) and Bryant (1988), who studied the faults around Owens Lake, both distinguished lake-marginal grabens related to lateral spreads from those of tectonic origin. Lake-marginal grabens are distinguished 1) by always having the basin side displaced downward and toward the center of the basin, 2) by orientation parallel to the lake shore, and 3) by fault planes that dip toward the center of the basin (Carver, 1970). None of these attributes is diagnostic, however, and it may be not be possible to distinguish relatively short normal fault scarps parallel to the lake shore from lateral spread extension in all cases.

### Death Valley

Death Valley would seem to be among the least likely places to look for evidence of past liquefaction. However near Badwater, at the edge of the salt adjacent to the Black Mountains fault zone, a series of deep, narrow grabens show that the alluvial fan has extended by sliding downslope (figs. O-6, O-7, and O-8). The grabens have minimal vertical displacement and are only on the lower parts of the alluvial fan, adjacent to the former lakebed. A rumpled area near the base shows where the sliding blocks of the alluvial fan met part of the playa surface that did not liquefy. The location, type of displacement, and orientation of these features suggest they are not related to the fault zone,

*Figure O-6. Near vertical view of lateral spread at toe of the Bad Canyon alluvial fan, 0.4 km SW of Badwater. Note well-developed graben in center of area, sharper and somewhat arcuate scarps around upslope margin of feature above (south of) the road and smaller ridges at edge of playa, possibly representing compressional deformation. Highway indicates scale). Photograph taken from about 300 m (1,000 ft) altitude by M.N. Machette, Nov. 2000.*

*Figure O-7. Oblique aerial view of Bad Canyon alluvial fan. Traces of Black Mountains fault zone cross head of fan, adjacent to mountain front. Graben at toe of fan (to left) were formed by liquefaction-induced lateral spreading. Photograph by Martin Miller.*

*Figure O-8. Ground view of parallel grabens at toe of Bad Canyon alluvial fan. Photograph by C.J. Wills.*

but formed when liquefaction triggered a lateral spread in the alluvial-fan deposits.

At this locality, the Bad Canyon alluvial fan (Hunt and Mabey, 1966, fig. 38) is comprised of coarse sandy gravel, probably with interbeds of lacustrine sand and silty sand. The adjacent playa lake beds are much finer-grained, typically silt and clay with salt and other mineral precipitates. These playa lake beds may be too fine grained to be susceptible to liquefaction. The alluvial-fan deposits rise steeply from the playa level, so most of the deposits are not saturated. Liquefaction can only occur where the near-surface alluvial-fan deposits are saturated—around the edges of the fans adjacent to the playa.

Alluvial fans typically have layers of varying susceptibility to liquefaction related to grain size, density and sorting of the deposits. Because individual flood or debris-flow events usually affect only part of a fan, liquefaction susceptibility is expected to vary widely across a fan, as well as increasing towards its lower edge. The lateral-spread features, therefore would be expected to be discontinuous around the edges of the fan.

Several alluvial fans south of Badwater have features similar to those mapped at the toe of the Bad Canyon fan (fig. O-6). Liquefaction features can be distinguished from the fault zone along the relatively straight Black Mountain front between Badwater and Copper Canyon. In this area, the fault closely follows the mountain front. Troughs and grabens on the lower parts of the fans are almost certainly due to liquefaction (see fig. O-9).

Along the fault zone from Copper Canyon to Mormon Point, however, it may not be possible to distinguish tectonic faulting from liquefaction-induced lateral spreading. In this area the fault zone has a northeast trend and consequently a larger normal component of movement and a broader zone of faulting (fig. 0-10). Normal fault scarps and grabens are distributed across the alluvial fans. Grabens that are low on the alluvial fan, have little net displacement, and are aligned parallel to contours are likely to be due to liquefaction, but some faults are roughly parallel to these and may even be coincident in places.

The distribution of scarps and grabens on the fans south of Badwater suggest two or more episodes of liquefaction. The freshest appearing scarps are found in young alluvial-fan deposits near the bases of the fans. One fan south of Badwater has two areas of relatively older alluvium, distinguished by darker appearance on aerial photos, which is probably due to their development of desert pavement and desert varnish and slightly higher elevation. These older fan remnants are offset by graben-forming faults that do not appear to extend into the adjacent young fan deposits. (fig. 0-10). If these features are the result of liquefaction, they may be the result of an earthquake that occurred before the younger material was deposited, whereas the lower scarps and grabens in younger deposits may be the result of a separate, later earthquake. Studies of the ages of fan surfaces, coupled with mapping of liquefaction-induced lateral spread features, may provide a way of estimating the timing of past earthquakes in the central part of Death Valley.

Similar troughs can be found along the edges of several of the smaller alluvial fans on the east side of Death Valley and in a broad zone in southern Death Valley. Although these features have been mapped as faults (Brogan and others, 1991), the troughs around the small alluvial fans are almost certainly related to liquefaction and lateral spreading. The broad zone of grabens in southern Death Valley is roughly parallel to faults that have substantial vertical displacement. Many of them, however, follow contour lines across the bajada and indicate downslope extension (Wills, 1989). These and similar features scattered throughout the California deserts tell us that liquefaction (and ground shaking) may be more widespread than one would expect.

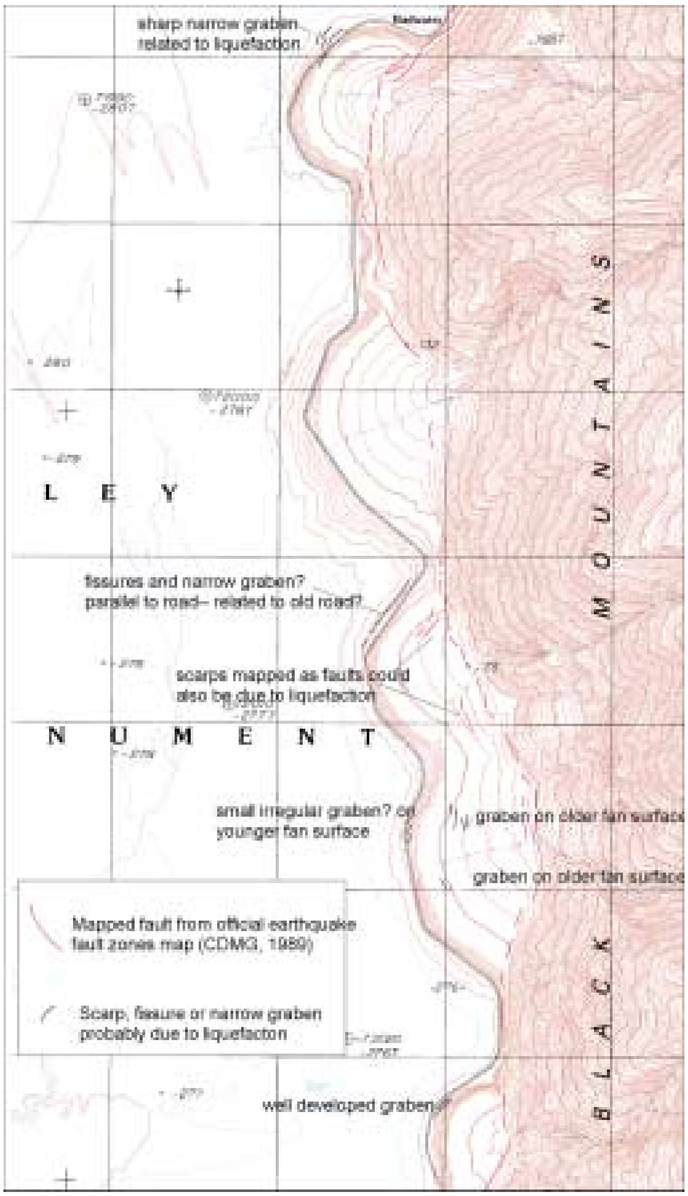


*Figure O-9. Map of faults and liquefaction features on alluvial fans south of Badwater.*

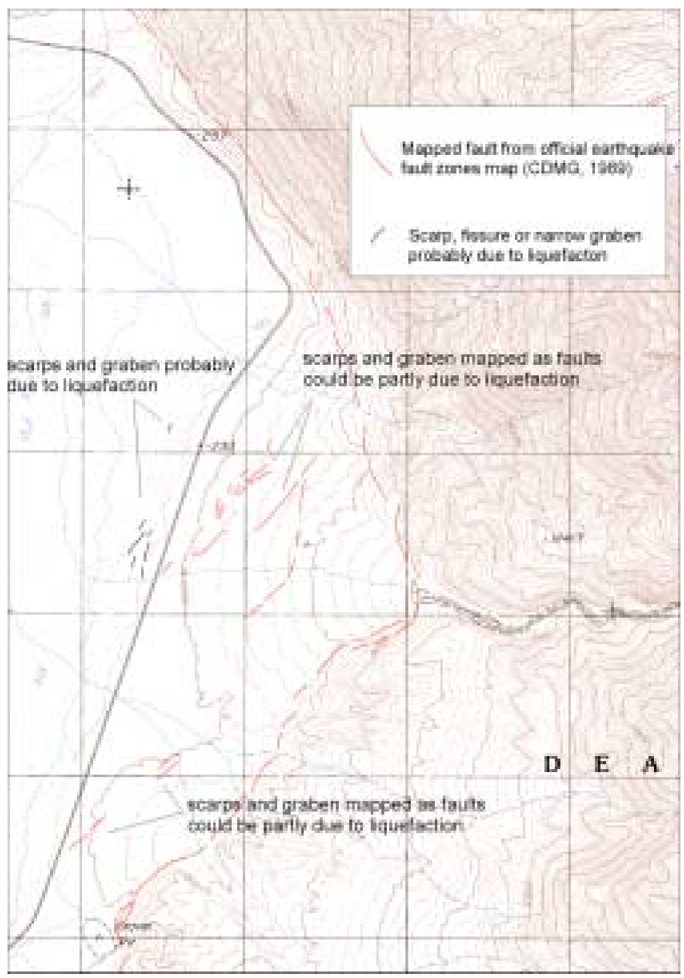


*Figure O-10. Map of faults and liquefaction features on alluvial fans northeast of Mormon Point.*

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# GIS-based terrain analysis of Racetrack Playa, and implications for the sliding rock phenomenon of Death Valley National Park

*Paula Messina and Phil Stoffer*


## ABSTRACT

The Racetrack Playa's unique surface features known as sliding rocks have been subjects of several mapping projects and debates for half a century. Rocks as large as medium-sized boulders (0.5-1 m) have traversed the nearly flat lakebed, leaving recessed trails as the evidence of their activity. The controversy over the causative mechanism persists partly because no one has witnessed the phenomenon, and earlier mapping missions were limited in method and geographic range. In July 1996, we generated the first complete map of all observed sliding rock trails using differential GPS (DGPS) mapping technology. The resulting map shows 132 sliding rocks and associated trails to an accuracy of approximately 30 cm. An inferred wind rose, reconstructed from DGPS trail-segment data, reveals localized wind patterns on the basin floor. Quantitative analysis of the entire trail network reveals no correlation between a rock's physical character and that of its inscribed trail. Terrain analysis of the surrounding topography demonstrates that trail-segment vectors are more closely related to where rocks rested at the onset of motion than to any physical attribute of the rocks themselves. Follow-up surveys in May 1998, May 1999, August 1999, November 1999, and June 2000 revealed little modification of the July 1996 sliding-rock configuration. The magnitude and frequency of sliding rock movement appears to have decreased since annual surveys were conducted in the 1960's and 1970's, when the maximum potential for traction events was attributed to winter storms. The severe El Niño winter of 1997-1998 resulted in the repositioning of only four rocks. Semi-annual visits to the Racetrack subsequent to the 1996 survey may reveal whether sliding rock activity is restricted to winter storms.


## INTRODUCTION

The Racetrack Playa, at an elevation of 1,131 m, is a dry lakebed within the Panamint Range in Death Valley National Park, California (see Chapter A, fig. A-1). The playa's western margin borders the talus slope of Ubehebe Peak, which rises steeply to an elevation of 1,710 m. Whereas the Racetrack was a perennial lake during the Holocene as recently as 2,000-5,000 yr B.P. (Hunt, 1975), today the playa is usually dry. Sharp and Carey (1976) estimated that annual precipitation on the Racetrack averages only 7 to 10 cm, although Stanley (1955) reported water depths as great as 25 cm.

The playa's surface is rather typical of other California desert lake beds: polygons of hard, desiccated sediment (24 percent fine sand; 41 percent silt; 35 percent clay [Sharp and Carey, 1976]) cover the 668-hectare plain (Messina, 1998). Protruding more than 20 m above the dried mud in the northern part of the playa is a weathered knob of quartz monzonite, a feature aptly known as the "Grandstand." The lakebed is *nearly* flat: based on measurements of water depth during wet periods, it is about 5 cm higher in the north than in the south. The Racetrack's major north-south axis length is approximately 4.5 km; it is about 2 km at its widest. Despite its nearly horizontal, planar nature, the playa shows evidence of dynamic traction (sliding) of boulder-sized and smaller rock fragments that tumble onto it from two abutting cliffs of dolomite at its southern margin and surrounding alluvial fans. Rocks likely slide at impressive speeds as inferred by the presence of preserved splash marks and "petrified bow waves" (Messina and Stoffer, 2001), perhaps as fast as 1 to 2 m/s (Sharp and Carey, 1976). The highest concentration of erratics known as the "sliding rocks" are found (fig. P-1) in the playa's southeast quadrant.

## HISTORICAL ACCOUNTS

Scars of sliding rock activity in the form of recessed furrows have been noted since the beginning of the twentieth century, yet to date no one has witnessed the surface process

*Figure P-1. A sliding cobble showing a northeast-heading trail typical of those found on the Racetrack.*

that causes the rocks to slide. As a result, the actual mechanism remains conjectural. Since these events take place in *human* (as opposed to geologic) time frames, the sliding rocks remain titillating puzzles for the casual park tourist and the bewildered Quaternary geologist alike.

The earliest documented account of the sliding rocks was reported by a miner named Joseph Crook in 1915 (Stanley, 1955). Crook's wife, who accompanied the prospector on one of his field excursions, was baffled by the phenomenon so she left a marker in the playa next to one of the rocks; on a later visit, Mrs. Crook was astounded to see that her rock had moved from its marked spot.

Since visits by McAllister and Agnew (1948) who published the USGS geologic map of the area, several researchers have proposed explanations for the phenomenon. Hypotheses may be classified into two groups: those in which wind alone pushes the rocks along (McAllister and Agnew, 1948; Clements, 1952; Kirk, 1952; Bradley, 1963; Sharp and Carey, 1976; Bacon and others, 1996), and those that include the requirement of ice floe activity (Shelton, 1953; Stanley, 1955; Schumm, 1956; Sharp, 1960; Reid and others, 1995). The former camp suspects that wind speeds on the Racetrack may occasionally exceed the threshold necessary for rocks to overcome their coefficients of static friction (specifically when resistance is greatly reduced due to saturated, slick playa-surface conditions). The latter group envisions a cohesive, extensive ice sheet as a more logical mechanism (fig. P-2). Ice blankets up to 10 cm in thickness (Stanley, 1955) have been observed on the Racetrack during winter months. Several researchers contend that if rocks are embedded in a layer of ice it is possible that wind can move the "ice rafts," dragging rocks along which in turn scrape their trails on the sediments below. Highly parallel traces as reported by Stanley (1955), may sometimes be separated by several hundred meters (Reid and others, 1995). Such evidence, coupled with experimental and theoretical modeling (Schumm, 1956;

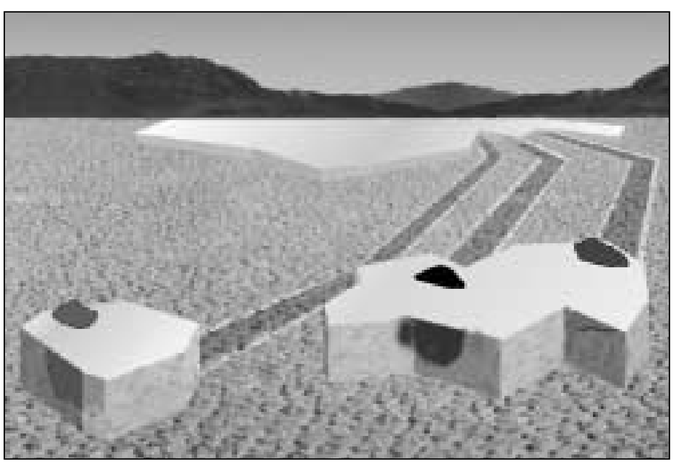

*Figure P-2. If rocks become embedded in ice sheets, rocks may slide as a function of wind-driven ice floes. The 1996 DGPS-based survey showed little evidence of ice-induced activity.*

Sharp, 1960; Reid and others, 1995), has bolstered the ice-raft hypothesis. Each mapping mission prior to ours monitored only a limited number of rocks (N=12 [Kirk, 1952]; N unreported [Stanley, 1955]; N=30 [Sharp and Carey, 1976]; N>23 [Reid and others, 1995]).

An experimental test of the ice-sheet hypothesis was conducted by Sharp and Carey (1976) who monitored the positions of 30 rocks through the late 1960's and early 1970's. On one visit, they built a "corral" of metal stakes surrounding several stones. Surprisingly, they found that *one* of the rocks had moved out of the corral while all others remained in place—an observation difficult to reconcile with their theory that the rocks moved only when embedded in an extensive ice sheet. Had an ice sheet formed, the stakes would have caused the ice to fracture upon any wind-induced motion.

Equally surprising were the observations by Kirk (1952), who noted that neither did the largest (therefore, heaviest) rocks produce the shortest trails nor did the smallest (lightest) rocks produce the longest trails. This fact lends some credibility to the ice hypothesis, since wind is an excellent sorter. Clearly, the entire matrix of sliding rocks needed to be examined and mapped for either of the theories to emerge as the more valid one.

## A NEW SURVEY

Conducting research on the Racetrack is demanding. Summer and winter conditions are extreme, the playa is remote, and the basin's wilderness status prohibits the introduction of permanent data-logging equipment. Standard surveying methods using levels or theodolites would require a team of mappers and a great deal of time.

The Global Positioning System, a constellation of 24 navigation satellites, became fully operational in April 1995; before this time (when other sliding rock mapping missions were conducted), a complete high-resolution map of all sliding rock trails would have been nearly impossible to create. In the summer of 1996, we constructed the first complete, sub-meter map of all sliding rock trails (fig. P-3). We were looking for patterns in the complete trail data set to gain a better understand of when and how rocks slide.

Points (the locations of the rocks), lines (the associated trails), and polygons (the playa's perimeter), were collected using a Trimble Pro-XL GPS receiver. To register rock locations, at least 10 coordinate pairs were logged (one point per second for at least 10 seconds), their precise locations were later averaged during post-processing routines. Rocks were numbered consecutively and named to coincide with a prior survey (Sharp and Carey, 1976). Rock height, horizontal major and orthogonal axes were measured (Messina and Stoffer, 2000). Trails were logged as line features in the direction of inferred inscription (i.e., with the rock's location as the endpoint)—a point collected every 2 seconds as the surveyor walked at a relatively steady pace.

All data were referenced to the WGS84 datum using the UTM (Universal Transverse Mercator) coordinate system. Points, lines, and areas were subject to errors that could result in positional inaccuracies of as much as 100 m. “Selective availability” (in effect until May 2000) was employed to minimize risks to National security by intentionally introducing noise to GPS signals. Hence, raw data were post-processed or differencially corrected to a resolution of ~30 cm using base-station files collected simultaneously in Sacramento. The map (fig. P-3) shows a complex network of trails, with rocks scattered within the south-central section of the playa.


*Figure P-3. The GIS-based sliding rock map, as completed in 1996. Rocks are represented by small gray points; trails are shown as solid black lines. Rising from Racetrack's surface (white) are Grandstand and two smaller “islands” within its northern extent; two small springs (black) near its eastern margin may contribute to geographically controlled differential saturation of the playa sediment.*

All told, two field surveyors walked a combined 100 km to log a total of 161 rocks and create the map. Thirty were omitted from subsequent analyses for a variety of reasons. Ninety-two percent of the rocks observed in the south-central section of the Racetrack were dolomitic (Messina, 1998); 20 undifferentiated intrusive rocks found near the southwestern parking area seem to have been intentionally placed on the playa and were excluded from the data set. Although Ubehebe Peak is composed of quartz monzonite, a ditch dug by the National Park Service to exclude vehicles from the playa has cut off supply from the western talus slope. An additional seven trails with rocks at both ends or no associated rocks were omitted. Without knowing the origin and end points, it was impossible to infer a trail's true heading. Kirk (1952) and Sharp and Carey (1976) attributed such features as the work of vandals. Two trails were omitted due to undetermined technical problems during data collection. All corrected files were imported to ArcView version 3.0; a database containing 50 fields for each of the 132 rocks and trails was exported from the GIS environment to Microsoft Excel for Windows 95, where the data were summarized and tested for numeric correlations.

## QUANTITATIVE ANALYSIS

The “average” sliding rock is a large cobble (13-26 cm) of Cambrian Racetrack Dolomite, with 4.0 corners/0.4 concavities (in the “footprint” plane) and an aspect ratio of 1:1.5. In 1996, mean trail length was 211.7 m, with a range from 1.6 m (“Mary Ann”) to 880.7 m (“Diane”), far longer than any previous survey had reported. The straightness of a trail was calculated as a derived field in which the straight-line distance between start- and end-points was divided by the total distance traveled by the rock. Convoluted trails were found to have straightness values as low as 0.19 (“Claudia”), while only one 6-m trail approached a straight line (1.00, “Agnes”). Average straightness ratio was 0.85 (Messina, 1998).

Although points were collected along trail routes at equal time intervals, node-to-node distances varied inversely to the complexity of the trail: individual segments measured anywhere from a few centimeters to 2 m or more between convoluted and straight-line trail components, respectively. To compensate for these incongruities, trails were simplified into equal 50-cm segments using a C algorithm (Clarke and others, 1993) yielding detailed azimuth data. The headings of trail segments were grouped into eight octants (Octant 0 = 0° to 45° (north to northeast); Octant 1 = 45° to 90° (northeast to east); etc.). A summary of all rocks' cumulative segment headings yield an inferred wind rose for the area (fig. P-4). Octant 0 accounted for more than 50 percent of all summative motion (Messina, 1998), consistent with the area's south-southwesterly prevailing winds (Sharp and Carey, 1976).

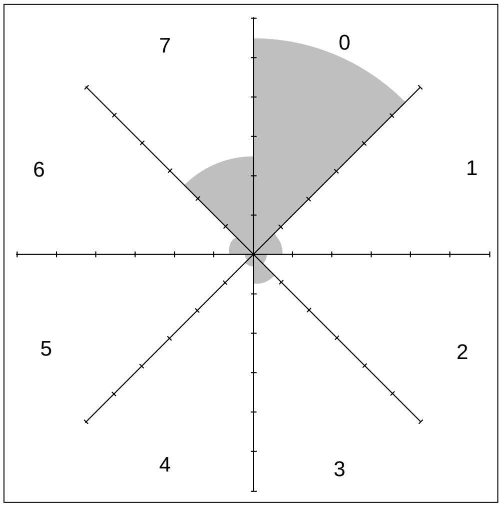


*Figure P-4. An inferred wind rose based on the 1996 survey of over 25,000 m of sliding rock trails, by octant.*

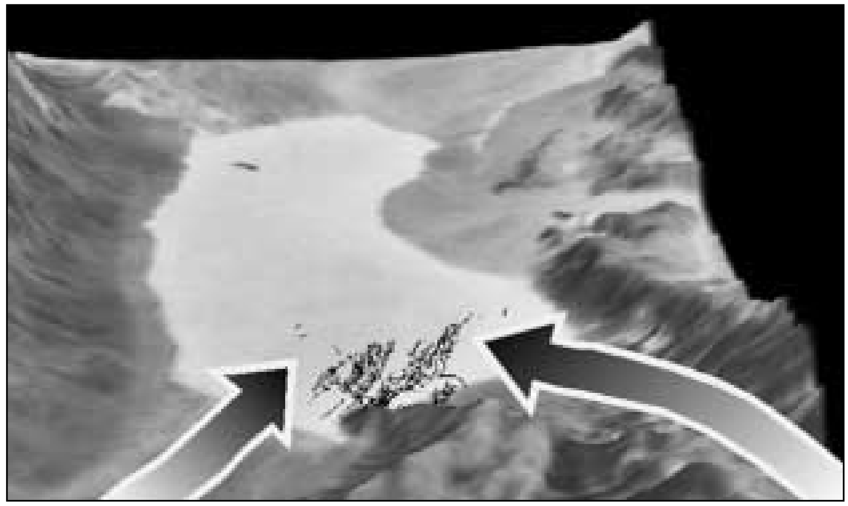

*Figure P-5. Two distinctive topographic corridors focus winds onto playa surface from southwest and southeast. Most trail segments are parallel to these natural wind tunnels.*

Trail straightness, length, and heading were plotted against physical rock characteristics (i.e., major axis length, estimated volume, playa contact area, height, etc.), but yielded remarkably insignificant correlation coefficients. Considering the depth of the database, it would have required more than 6 x $10^{62}$ regression analyses to test the relations between every possible numeric rock descriptor and trail parameter (Messina, 1998). After hundreds of regressions were generated, principal components analysis was used to search for statistically significant, yet unexpected, relations. Even so, $r^2$ values never exceeded 0.6; the sliding rocks moved in ways independent of size or shape.

**Terrain Analysis**

Correlations that yielded the greatest promise of statistical significance were those that compared a trail's character to the coordinates of the rock's starting point. Even cursory examination of the completed map (fig. P-3) reveals that rocks along the eastern playa margin inscribed longer, straighter trails. The Racetrack lies downwind of two natural wind tunnels that direct air from the southwest and, to a lesser degree, the southeast (fig. P-5). Air is channeled up from Saline Valley (the basin just west of Ubehebe Peak), which is more than 500 m lower in elevation. Shelton (1953) surmised that the topography of the southwestern margin of the Racetrack basin favors flowline crowding, which results in amplified wind speeds over the southeast rim of Saline Valley and turbulence around the ends of the barrier ridge (Ubehebe Peak). This topographic configuration may account both for peak gusts of high velocity and the variable direction of the tracks. The landscape's effect on the rocks' movement was also suggested by Bacon et al. (1996), who measured frequent wind gusts up to 40 m/s on Owens Lake; given the lower elevation of Owens Valley, they expected even higher wind speeds on the Racetrack (Messina and Stoffer, 2000).

To statistically test the surrounding topography's influence on rock motion, the 7.5-minute USGS Ubehebe Peak digital elevation model (DEM) was imported into the GIS. Aspects of local terrain elements were examined. The starting point of each rock trail was known; that point represented where force exceeded a rock's coefficient of friction, thereby propelling the rock. The set of regions visible from a single point on the surface is defined as a viewshed (a 360° panorama of the visible terrain around each rock), which is a function of the rock's placement and height above the surface. On perfectly flat terrain, for example, a viewshed would extend to the visible horizon in all directions. Any substantial landform such as a mountain would act as a barrier to the panorama, and also as a shield to air currents of influence. Processing viewsheds for representative rocks could establish the existence of significant variations in the neighboring terrain, and hence, associated airflow potentials. Detailed GIS-based routines are described by Messina (1998) and Messina and Stoffer (2000).

Quantitative geomorphic analyses yielded an inverse relation between a rock's start-point viewshed aspects and trail headings: high pixel aspect values in a quadrant corresponded to low values for trail headings and vice versa (fig. P-6). When percentages for complementing quadrants are summed and compared, the results suggest a significant correlation between trail character and terrain. The trails show a directional preference to the quadrants orthogonal to the majority of the pixel aspects' orientations. In other words, a preponderance of east- or west-facing slopes appears to be correlated with the general north-south plans of the trails. This is particularly evident of north-south, east-west comparisons.

T-tests checked the interdependence of trails to their surrounding orthogonal terrain elements. Tests on whether the paired data support a null hypothesis (i.e., there is *no* relation between

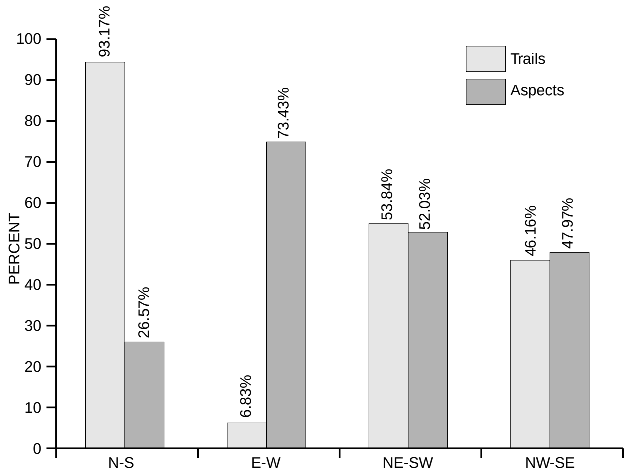


*Figure P-6. Statistical summary of over 25,000 m of trail segment headings and visible terrain aspects of sliding rock start-points (by percent).*

the trails' directions and orientation of the surrounding slopes) allowed the null hypothesis to be rejected at the 95-percent confidence level ($r^2 = 0.05$). The positive relation between the viewshed slope and dissected trail components established that rock movement on the playa correlates with orientation of the flanking corridors. It is likely that these chutes act as natural wind tunnels, directing airflow onto the playa surface.

## INFERRED WIND CLIMATE

Although permanent anemometers are forbidden on the playa, a survey of instantaneous wind velocities was conducted using hand-held anemometers at a fixed height (1 m) along a transect across the Racetrack. The study showed as much as a six-fold variation in wind speed and a 50° direction differential recorded in two locations only 600 m apart (Messina, 1998). Similar erratic wind activity was described by Kirk (1952).

The high density of straight trails in the east and wandering trails near the playa's center implies that more forceful straight winds may be directed onto the lakebed in the vicinity of the longest trails; chaotic winds, perhaps even dust devils (McAllister and Agnew, 1948) may be responsible for the circuitous trails concentrated near the intersection of two inferred air streams. Several trails show both clockwise and counter-clockwise motion; indeed, dust devils may rotate in either direction with similar frequency (Snow and McClelland, 1990).

While dust devils typically develop over dry low-albedo terrain, they are often launched from areas of origin to other localities by prevailing winds. If rocks slide only when the playa surface is saturated, dust devils could still generate along any number of adjacent, dark-colored alluvial fans. A few days after a wetting event, the highly permeable alluvial fans would already be dry, while the playa surface would conceivably be covered by a thin veneer of the finest clay fraction deposited by runoff. Vortices with internal pressures as low as -4 millibars of the surrounding air masses (Greeley and Iversen, 1985) may be generated on the dry areas surrounding the playa, and later directed onto the near-frictionless surface. Dust devils' poor sorting ability and capacity to provide lift provide intriguing possible explanations to the circuitous nature of some of the trails.

Earlier surveys (Sharp and Carey, 1976) suggested that the period of greatest sliding rock potential corresponds to winter storm activity, but prior monitoring expeditions took place no more frequently than once a year. Patrols would need to be conducted bi-annually (in the fall and spring) to determine the season of greatest activity (Messina and Stoffer, 2000). The intense El Niño winter of 1997-1998 enacted little change to the 1996 sliding-rock configuration. Only four of the 132 rocks moved. "Diane" which previously inscribed the longest trail measured (881 m—probably in a single episode as inferred by the uniformity of the trail and lack of indentations or rest spots) showed a mere 6-m extension; other trail additions were even shorter. If, in fact, rocks move more frequently during summer monsoon season, whirlwinds may contribute significantly to this process.

### The Ice Controversy

Careful inspection of several of the most variable trails further suggests that ice sheets may not be essential components of this surface process. Stanley (1955) and Reid et al. (1995) surmised that highly parallel trails suggest rocks must be embedded in ice when they move; each report showed that some trails are parallel, while others show parallelism near their origins but later divergence. This pattern was explained as the eventual fracture

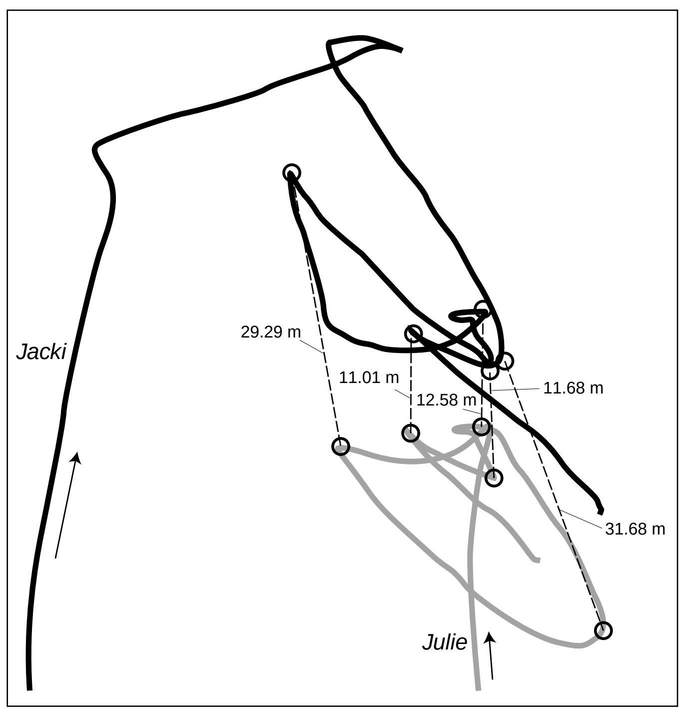


*Figure P-7. Among evidence in conflict with ice-raft hypothesis are these two trails, showing gradual node-to-node convergence.*

of a once-continuous ice sheet (Stanley, 1955; Reid and others, 1995).

Fig. P-7, however, shows two trails with strangely similar end-signatures. Initial examination in the field suggested to us that the rocks must have been directed by a rigid (non-fluid) force, but subsequent examination of the trails revealed that while the inscriptions show a great deal of congruence they continually *converge*. It seems implausible to describe this type of activity within the bounds of an ice-floe theory, unless ice began to break apart and imbricate; there is no indication of surface ice gouging in the area around these rocks. If rocks are subject to nearly identical wind patterns, they may carve nearly identical patterns in the playa mud. Although the same may be true for the ice model, the distance between two or more rocks would either remain the same or increase but could never decrease.

## Conclusions

Although geographically confined, Racetrack Playa may be thought of as having a mosaic of microclimates, each with differing sediment inflow, saturation potential, cyanobacterial presence, and wind climate. Rocks on this playa exhibit seemingly haphazard magnitudes and directions of movement; their mobility is likely related to the highly variable, localized conditions acting on them. Although some show morphologic similarities, the vast majority of trails show almost no parallelism with others; we conclude that ice sheets are not genetic prerequisites for sliding-rock activity. Furthermore, rock-slide events may not be limited to the incidence of winter weather systems; summer storms may promote conditions favorable to this phenomenon as well.

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# A brief history of the Furnace Creek area (1849-1954)

*Genne Nelson*



## IN THE BEGINNING...

Life in Death Valley: it sounds like a contradiction in terms. Once the tree-covered mountains teamed with life around Lake Manly in Death Valley, but following the last ice age, the climate warmed and over the course of time the waters evaporated, leaving behind a valley of salt. Even so, life still existed in the valley, but it was confined and defined by the availability of water. Animals and plants adapted to the arid conditions or were replaced by those that could adapt. Native Americans had lived in the valley for thousands of years before contact with miners, ranchers, and other settlers, but the only record they left of their life here was an assortment of implements and pictures chipped in stone. Nevertheless, we know then as now, they lived where there was water.

Furnace Creek was a living stream of water flowing into Death Valley, created by a collection of springs at the lower end of a long canyon. The canyon runs northwest between the Funeral and Black Mountains along the trace of a major oblique-slip right lateral fault. Below ground just as at the surface, water flows downhill, and with over 200 square miles of Death Valley below sea level, this valley is as downhill as you can get. No one knows for sure how far the water travels underground before rising to the surface in the tan and yellow sedimentary hills of Furnace Creek, but neither the Funeral nor the Black Mountains receive a significant amount of snow in winter—certainly not enough to account for the steady and abundant supply of water flowing from Texas and Travertine Springs. Some evidence suggests that the water flows from Pahrump Valley to the east in Nevada, lying at the foot of the spectacular Spring Mountains west of Las Vegas. The Native American word “Pahrump” means “water beginning” and it is from here that many believe the waters of Travertine Springs originate. Modern researchers suspect that the Furnace Creek fault zone taps the subsurface flow of the Amargosa River, creating a short cut for water flow into the valley. Whatever the source, there was water here, and here lived some of the early residents of Death Valley.

The first Americans to see Furnace Creek were the lost Forty-Niners who stumbled into this forbidding valley. After a long, dry 3-day march from the springs in Ash Meadows east of the valley, they came upon several springs, some hot and some cold, which collected into a small stream of water. They rested, washed and watered their exhausted oxen here on Christmas day of 1849. Later explorers described Furnace Creek as a “bold torrent, which dashes noisily down the rapid descent, and is lined by a fringe of grass and willows.” They estimated that the stream flowed 3 to 4 miles at a volume of 1,100 to 2,200 gallons per minute before disappearing into the sand. Modern measurements indicate Travertine Springs produces 2,000 gallons per minute, or more than 3 million gallons of water per day.

The Forty-Niners noted a shallow cave at the base of a gravel cliff that showed signs of Native American occupation. Later when they explored the mouth of the canyon, near the present site of the Furnace Creek Inn, they discovered a Native American camp, empty save for a lone, blind, crippled old man with skin so weathered that they guessed him to be 150 to 300 years old. Although they gave the old man food and water, they believed he had been left there to die.

A government survey party visited Furnace Creek in 1861 and estimated that over 100 Native Americans lived at the site. Anthropologists report that Furnace Creek was a mixed camp of Shoshone, Paiute, and Kawaiisu, and that they were independent of the neighboring camps to the north. The Native Americans wintered at Furnace Creek and harvested mesquite beans from the numerous trees growing along its drainage. Then they moved up into the Panamint Mountains, to Wildrose, Blackwater, or Ko Springs to escape the searing summer heat. After the Harmony Borax Works and Greenland Ranch were established in the 1880’s, the site became a more permanent home when one of the Shoshone family clans from the Cottonwood Mountains moved their camp to Furnace Creek.

The native inhabitants called their village *Tumbica*, meaning “coyote rock.” The Native Americans living at Furnace Creek today call themselves the Timbisha Shoshone. The land at the mouth of the canyon is sacred ground to them, because their ancestors held a ceremony at the site to give thanks for the gift of the mesquite, the beans that provided a major part of their subsistence. The bedrock mortars used in this ceremony can be seen today in the lower parking lot of the Furnace Creek Inn. Members of other tribes willingly traded with the Timbisha Shoshone for these mesquite beans for the Death Valley beans were noted for their sweetness.

## THE FIRST WHITE PEOPLE

After the Forty-Niners made their fortunate escape from the Valley they named Death, the only men to brave the water-scarce frontier were prospectors searching for gold and silver. They confined their search mainly to the rocky exposed slopes of the desert mountains. Reportedly, one of these early prospectors built a small furnace in the canyon, next to the running stream of water in order to smelt a sample of ore. Upon finding the crude stone furnace during his prospecting trip in July 1860, Dr. Darwin French named the stream "Furnace Creek."

The discovery of silver in Surprise Canyon high in the Panamint Mountains led Kentuckian Andrew Jackson Laswell to establish the first homestead in Death Valley. In partnership with Cal Mowery, Laswell obtained a contract from the Surprise Valley Mill and Water Company in Panamint City to supply hay for their work animals. Late in the summer of 1874, the two men started a hay ranch in southern Death Valley.

Tradition painted Laswell as a loud, outspoken bully of a man known among the locals as "Bellerin Teck." There must have been some truth to the legend, as Laswell shot Mowrey when he argued for his share of the first hay sale, after which Mowrey found it expedient to dissolve the partnership and leave the valley. Despite these personal problems, business must have been good, for Laswell started a second hay ranch at the mouth of Furnace Creek. Unfortunately, the shallowness of the rich silver veins in Surprise Canyon doomed Panamint City to a short life. In the fall of 1875, Laswell abandoned his hay ranches to the desert winds.

## THE ARRIVAL OF THE BORAX MEN

In the fall of 1881, a poor homesteader named Aaron Winters heard about a new mineral that was the latest rage in the mining world. It was white and fluffy, it was called borax, and it lay on the floor of valleys rather than along the rocky spines of mountains. The description brought to mind the white floor of Death Valley, a short distance west of his crude stone cabin in Ash Meadows. Tradition says Winters camped at Furnace Creek when he came to sample and test his theory about borax in the valley. Winters was right, and he was able to turn his white claims into gold—$20,000 worth. Being the wise desert rat, he was able to collect another $2,500 for the water rights he staked on the springs in the nearby hills.

The borates on the valley floor originated in the Furnace Creek Formation. Millions of years ago, volcanic activity caused hot, boron-rich solutions to percolate through the layers of mud in an ancient lake bed. Later faulting upended the beds, exposing them to erosional forces. Water dissolved traces of borax on its way down to the valley floor, then evaporated leaving the white crust of salt, borax and alkalis found by Aaron Winters. Borax is still forming on the valley floor on the marsh northwest of the Harmony Borax plant ruins, and elsewhere in Death Valley. The borax-bearing layers of the Furnace Creek formation can be seen today at Zabriskie Point and in Twenty-Mule Team Canyon.

The man who bought Aaron Winters' claims was William Tell Coleman, a San Francisco businessman with interests in the Nevada borax operations. He sent employee Rudolph Neuschwander, a Swiss immigrant, to set up the necessary facilities at the new Furnace Creek borax marsh. They would need a plant to purify the borax, housing for the employees, and a ranch to provide fresh food for the men and animals in this remote location. The plant site (Harmony Borax Works) was constructed on a low hill close to the borax marsh, and water was piped from a spring in the hills a few miles to the east. A blacksmith shop, storage buildings and probably an office were also constructed here, as well as housing for the approximately 30 Chinese laborers. The plant operated from September to June when they were forced to shut down. They were not so much concerned about the effect of the heat on the laborers; the borax refining process would not work in the scorching Death Valley summers.

About a mile south of the Harmony Borax Works, traditionally placed at the site of Andy Laswell's second hay field, Neuschwander laid out 40 acres for a ranch. Some of the local Shoshone lived at the site with their families, and were able to obtain work from the Harmony plant collecting firewood and at the ranch doing a variety of chores. A mile-long open stone-lined ditch was built from the springs in Furnace Creek canyon to provide water for irrigation. During ditch construction, laborers J.S. Crouch and O. Watkins slept in the cool waters of the ditch, their heads pillowed on rocks to keep their faces above the water. In the winter of 1882-1883, Coleman shipped seeds and seedlings to the ranch that he named Greenland. Although the name sounds incongruous in a desert dominated by white, gray, tan, yellow, and brown colors, once the ranch was completed, it did create a startling green contrast with the stark landscape surrounding it, even as it does today.

Effort was expended to make Greenland Ranch inviting as well as functional. Besides the 30 acres of alfalfa which ultimately produced as many as 9 crops per year, an assortment of shade trees, including cottonwoods, willows, and California palms, native grasses and shrubs were planted and a double pond covering half an acre was constructed at the end of the irrigation ditch. Migratory water fowl, mainly ducks and geese, made the pond a stopping place during their flight through the area, and at some point quail took up residence at the ranch. Also, the ponds were stocked with carp. A vegetable garden provided melons, sweet potatoes, and other vegetables, and a small fruit orchard provided apples, pears, and figs. By 1885, cattle, pigs, and sheep were providing fresh meat for the borax workmen.

Greenland Ranch was the starting point for the famous Twenty-Mule Team route. Two men, the teamster and swamper, were responsible for getting 20 tons of borax to the railhead in Mojave 165 miles to the southwest, picking up supplies and returning to the ranch within 20 days. The teamster's responsibility lay with harnessing, driving, feeding, watering, and caring for the mules, a task requiring skill if not rapport with his charges and for which he earned about $100 per month. The swamper was the responsible for everything else; collecting fuel, cooking and cleaning up, plus helping to brake the rear wagon on downgrades and any other assistance the teamster required. Reportedly, the swamper also kept a box on the lead wagon filled with small rocks, which the teamster could use to get the attention of recalcitrant mules. For such service he received $75 per month.

A sturdy ranch house was built at Greenland with 4-foot-thick adobe walls, a double roof, and an encircling veranda. Later, a 5-foot fan powered by water in a nearby irrigation ditch was installed on that porch. Three men were employed at the ranch, but archaeological evidence at the Harmony plant site suggests that white workmen at Harmony lived at the ranch, along with the swampers, teamsters, engineers, coopers, boiler men, and blacksmiths. Coleman was so pleased with the transformation at Greenland that he considered turning it into an oasis resort, but changing circumstances prevented his pursuit of this idea.

The Harmony Borax Works operated from the fall of 1883 until May 7, 1888 when Coleman's financial empire collapsed. His Death Valley properties, as well as the newly discovered borax deposits in California's Calico Mountains (12 miles north of the Daggett station on the Santa Fe Railroad) were acquired by Francis Marion Smith. Hauling the ore 12 miles was a lot less than 165, so Smith put Death Valley on hold while he developed the Calico deposits. Two men were left at Greenland Ranch to take care of the property, but one of them soon decided to leave and died in his attempt to walk out of the valley. The other, James Dayton, had come to Death Valley in the early 1880's as a swamper for teamster Ed Stiles. He had later been promoted to foreman and he continued to manage the ranch for many years until his own death in the valley in July of 1899.

During the Calico mining years, Greenland Ranch became a haven for the few and scattered Death Valley prospectors seeking fresh food, human conversation, and running water. The borax company sent miners up from Calico each year to perform maintenance work on their borax claim holdings, and they were also able to benefit from the fresh food provided by the ranch during their stay in the area. During the summer heat, activity ceased in the daytime, and necessary ranch chores were done after the sun went down. At night, some of the men rolled themselves in wet blankets to stay cool while they slept, or slept out in the irrigated alfalfa fields to take advantage of the evaporative cooling. Sometime after Smith acquired the ranch in 1889, the name was changed to Furnace Creek Ranch, but for many years the name Greenland continued to be used.

Events following the turn of the century led to increased activity in the Death Valley area. The ore at the Calico mines was running out and Smith's attention turned to the Lila C. Mine in the mountains along the east side of Death Valley. He would have to develop a system of transportation in order to access these deposits and he wanted to avoid the primitive 20-mule teams in preference for a modern mechanical conveyance. Smith opted for a railroad, which took 3 years—from 1904 to 1907—to bring to completion, but mine production had began sooner, so the 20-mule teams were pressed into service again during the summer of 1907 hauling borax to the slowly advancing railhead. Furnace Creek Ranch was back in business providing food for the railroad construction crew, miners, teamsters, and their animals. The ranch maintained 50 head of cattle to provide fresh meat and a total of 30 acres were under cultivation producing fresh vegetables like pumpkins, watermelons, musk melons, corn, and cantaloupes. Poultry were later added to the list of ranch products.

The other major event that affected the valley was the discovery of gold at Bullfrog, Nevada. When Shorty Harris and Ed Cross found a rich vein of gold in the hills east of Death Valley in the summer of 1904, a veritable flood of humanity poured into the remote desert area. When all the good ground around Rhyolite was staked, prospectors fanned out into the neighboring hills and into Death Valley looking for the end of their own rainbows. The new emigrants quickly learned that Furnace Creek Ranch was a reliable source of food, water, and assistance. A traveler in 1907 noted that 50 cents would get you a meal of fresh eggs, lettuce, turnips, carrots, parsnips, cow's milk, and pumpkin pie.

With the completion of the Tonopah and Tidewater Railroad (T&TRR) on August 16, 1907, F.M. Smith toyed with the notion of converting Furnace Creek Ranch into a health resort. He believed the warm, dry climate would exert a curative effect on some diseases. In his mind the railroad could extend a branch line down into the valley, providing transportation for visitors and access to the borax deposits located along Twenty-Mule Team Canyon. The idea of promoting Death Valley as a tourist destination was also carried in an advertisement in Greenwater's monthly magazine, the Death Valley *Chuck=Walla*: "Would you enjoy a trip to Hell? You might enjoy a trip to Death Valley, Now!" The ad promised "all the advantages of hell without the inconveniences…the weird mysticism of Dante's inferno, marvelous scenery, strange romanticism, fabulous wealth and absolute novelty." The primary function of the *Chuck=Walla* was promotion, mainly of the copper properties discovered at Greenwater in January of 1905. The world will never know whether the *Chuck=Walla's* promotion would have created a stampede of sight-seers into the valley since the ads only appeared in the April and May 1907 issues, before the printing office burned to the ground in June. The promotion stopped there, for now.

Like Coleman before him, F.M. Smith's desert resort did not become a reality. Although the T&TRR transported borax to market and provided a critical link between the small desert communities and the outside world, it was not a financial success. In 1913, when the Lila C. Mine approached exhaustion and company officials needed to extend the rail line to the deposits on the west side of the Greenwater Range, the California Railroad Commission refused the financially troubled T&TRR permission to issue stock for the expansion. The company was forced to create the Death Valley Railroad Company (DVRR) in order to construct the 17-mile narrow-gauge spur line to the Biddy McCarthy mine. At the same time, Smith was suffering from personal financial troubles, and in 1914 was forced to sell his borax holdings.

Activity at Furnace Creek Ranch continued relatively unchanged during this period, producing meat and vegetable's for the miners at Ryan and the DVRR construction crews. It is interesting to note that two of the mules from the original Twenty-Mule team days were still living at the ranch in 1914. By 1925, there were 125 miners to feed, and to support a herd of Hereford beef cattle, the ranch was producing 200 tons of hay annually from 40 cultivated acres. A small, hydroelectric plant had been installed that was powered by water flowing in the irrigation ditch. Also a swimming pool had been excavated in the irrigation water's circuit and enclosed next to the screened porch of the old ranch house, a luxury offering a welcome respite from the valley's heat.

Sometime around 1921-1922, Julian Boyd, superintendent of the mines at Ryan, suggested the company should try to cultivate dates at the ranch. Mining men venturing into unknown territory ordered seeds for the *Deglet Noor* (meaning "date of light") date palm and nurtured them into a host of thriving seedlings that were ready for planting within a couple of years. They set out about 4 acres in the young palms which were thriving nicely when they learned to their chagrin that there are two sexes of palm trees, only the female of which bears fruit. It was impossible to tell which of their healthy little seedlings were of which sex. So in 1924-1925, the miner-ranchers purchased 125 seedlings of known sex and hired date authority Bruce Drummond to oversee the date culture. The U.S. Department of Agriculture joined the effort with an acre of experimental varieties of date palms. Traditional date-producing areas around the southern California and Arizona deserts at this time were experiencing a crop-threatening infestation. It was hoped that offshoots from the trees growing in Death Valley could provide insect-free seedling stock. Around 1927-1928, after the date palms had proved their heartiness in the valley climate, a total of 1,500 trees, offshoots of the original seedlings, were set out over 33 acres, ultimately producing an annual harvest of 200 tons of fruit. However, harvesting of the dates never proved profitable, and since the disease problem had been solved during the intervening years, no revenue from the sale of offshoots was ever realized either.

Borax production continued in Death Valley through the teens and twenties, and even today borax resources remain buried in the Greenwater Range. But events 100 miles away changed the future of the valley. In 1913, a man that was drilling a water well in California's Mojave Desert noticed chips of a white mineral churning out of the ground. It turned out to be borax, and although the borax company continued to explore for more indications of the mineral, it was 1926 before geologist Clarence Rasor discovered a veritable lake of borax lay buried beneath the desert. What's more, this marvelous discovery of borax lay within a couple of miles of the main line of the Atchison, Topeka & Santa Fe Railroad. By 1928, Death Valley mining operations were mothballed while production commenced at the new mine site that the company named Boron.

### LUXURY COMES TO THE DESERT

With the announced closure of the borax mines at Ryan, the T&TRR faced the loss of its only significant paying customer and the DVRR its only customer. Over the years, railroad manager Frank Morgan Jenifer had suggested that development of a resort on company property in Death Valley could boost railroad revenues with passenger service. The new borax discovery in 1926 prompted company officials to give Jenifer's suggestion serious consideration. The end result was the creation of the Death Valley Hotel Company, subsidiary of Pacific Coast Borax, with Frank Jenifer as its first president.

At about the same time, Bob Eichbaum had obtained permission from Inyo County (California) to construct a toll road into Death Valley via Towne's Pass, on the northwest side of the Panamint Mountains. He was busily constructing guest bungalows at his road terminus near Stovepipe Wells. The borax people would have to move quickly to prevent Eichbaum from developing a monopoly on tourist trade in the Valley.

Jenifer got suggestions from Nellie Coffman, manager of the Desert Inn at Palm Springs, then selected a tentative site for the hotel. Borax Consolidated president, Richard Baker, flew over from England to give final approval for the location on a low flat-topped prominence at the mouth of Furnace Creek Wash (fig. Q-1). One hundred and sixty acres were set aside for development.

The company retained Los Angeles architect Albert C. Martin to design a mission-style luxury hotel constructed of adobe and native stone and roofed with red Granada tile. The $30,000 projected cost was considered excessive, but Borax executives were persuaded to go along with the plan. Local Shoshone and Paiute laborers began producing adobe bricks at Furnace Creek Ranch in the fall of 1926. Construction began right after Thanksgiving, and a mile-long pipeline was laid from Texas Springs to a reservoir nearby to provide the domestic water supply. Years later an additional 6-inch pipeline was installed below the surface to tap the water from Travertine Springs, increasing

*Figure Q1. Furnace Creek Inn construction, view from Furnace Creek Wash, about 1927. The southern entrance to the Inn was destroyed by a flood in June 1940. Photograph courtesy National Park Service, Death Valley National Park [DEVA #25486].*

the water available for development. Four small Kohler generation units were installed to provide electricity for what would become the Furnace Creek Inn.

Meanwhile, plans were being made to get the tourists into the Valley via the railroads. Union Pacific Railroad (UPRR) officials joined the T&TRR in advertising railroad excursions into the valley. The DVRR purchased a gasoline-powered 30-passenger rail car to shuttle visitors from Death Valley Junction on the T&TRR line to Ryan, in upper Furnace Creek Wash. The UPRR people would bring their touring cars from Zion National Park, where they sat unused during the winter months, to transport tourists from Ryan to Furnace Creek Inn and to points of interest around the valley.

With all the advertising and transportation arrangements in place, the Furnace Creek Inn opened its doors to guests on February 1, 1927, just 3 months behind Eichbaum's Stovepipe Wells Hotel. That first season the inn offered a dozen guest rooms flanking the lobby and dining room complex. The inn would remain open from October through mid-May, when the valley climate was most pleasant. Beulah Brown, manager of the Old Faithful Lodge in Yellowstone National Park during the summer months, brought most of her staff to operate the inn during the first two seasons. Staff members were housed in tent cabins located up the canyon east of the inn.

By the fall of 1927, 10 more guest rooms had been added to the inn, 5 on either side of the parking area. Publicity had improved and black-uniformed attendants were ready to serve guests in first-class European style. All rooms were advertised with a bath and went for the rate of $10 per day including meals. The company's move to Boron, California was completed and the borax mines at Ryan closed indefinitely. The Ryan miner's dormitories were then converted into the Death Valley View Hotel under the management of Julian Boyd (mine superintendent), and when he left in 1928 management was turned over to Pauline Gower. Rooms were available with meals for 5 to 7 dollars or without meals for $2.50 to $4 per day. However, only a sink was available in the rooms; bathrooms were down the hall.

During 1928, an additional 10 guest rooms were added to the Furnace Creek Inn, completing the u-shaped terrace level (fig. Q-2). Mid-season, in January 1929, Miss Katherine Ronan, sister-in-law of Frank Jenifer, assumed management of the inn. This proved to be an expansive, dynamic year for the inn. Water from Travertine Springs was collected and piped via a 12-inch line to a 25 KW Pelton Wheel, thereby increasing both the available electrical and water supplies to the inn. From there, the spring water, which averaged 85 °F, was routed to the new swimming pool, built below the level of the terrace rooms. From the pool, the water flowed via an open ditch to the ranch for irrigation. Tennis courts were also installed at the inn. Finally, substantial employee housing was provided with the construction of the adobe annex building beneath a rocky escarpment east of the inn, replacing the windy, dusty tent cabins that had been used since the opening of the inn.

The year 1930 saw a number of changes in Death Valley. The expected tourist traffic had never materialized for the railroad—people preferred to brave the wilds of Death Valley in their automobiles. So Union Pacific canceled its connecting service to the T&TRR line and withdrew its fleet of touring cars. The hotel company started a subsidiary Death Valley Transport Company to fill the void. This service was later absorbed by the Santa Fe Railroad who provided western-garbed tour guides and drivers to shuttle visitors to points of interest in open-top Cadillacs. However, with little more success than its predecessor, they only operated a couple of seasons. Without connecting passenger rail service, there would be no reason to continue operation of the 17-mile-long DVRR, and without a railroad to bring water to the town of Ryan, the Death Valley View Hotel would be forced to close. The rapid decline in travelers following the stock market crash in the fall of 1929 did not help the situation, and the hotel closed its doors January 1930. Thereafter it would only reopen on busy holidays to accommodate guest overflow from the inn, trucking domestic water up from nearby Navel Spring.

In the spring of 1931, the hotel company opened a nine-hole golf course over the part of the ranch formerly used to raise alfalfa. Supposedly one of the date caretakers, Scotsman Murray Miller, an avid golfer, had set up an informal three-hole course in the pasture around 1927. Borax executives visiting the inn

*Figure Q-2. Starting a trail trip from Furnace Creek Inn, about 1928. Photograph from Union Pacific Historical Collection, courtesy of National Park Service, Death Valley National Park [DEVA #12353].*

were being made at the ranch during this time. Borax officials had been working with U.S. National Park officials since 1927 to try to get Death Valley set aside as a park. Stephen Tyng Mather, founder and then chief of the National Park Service, had worked for the borax company beginning in 1893 and continuing through the early part of the 20th century, developing their "marketing strategy." It was Mather who had come up with the Twenty-Mule Team brand name for the company. Mather appreciated the rugged and unique beauty of Death Valley, but fearing a charge of patronage to a former employer, he was hesitant to lead the effort to have the region designated a national treasure. When his successor Horace M. Albright took over in 1929, he did not share this reluctance. Albright began to study the site and to draw up tentative boundaries. In January 1930, he convinced President Herbert Hoover to issue an executive order withdrawing 2 million acres for potential inclusion in a national park. Public familiarity with the site would aid in the political designation of the park, so in September of 1930, the borax company began airing a radio program called "Death Valley Days." The program's content was drawn from Death Valley's own rich heritage of historical drama and characterization. It is hard to estimate how much this half-hour weekly program advanced the cause to preserve Death Valley, but the show's popularity kept it on the air for 14 years, when it was replaced by a television series of the same name which ran another 18 years. Stanley Andrews, who played the old ranger, originally hosted the series. However, the best-remembered host was his successor, Ronald Reagan, who weekly introduced "Death Valley Days" to television audiences until his election as Governor of California. Finally, after much negotiation and compromise, President Hoover signed Proclamation Number 2028 creating the Death Valley National Monument on February 11, 1933. The monument was later expanded and elevated to national park status by Congress in November of 1994.

apparently liked the idea and expanded upon it, having a nine-hole course developed around the ranch and date orchard. It was the first grass golf course in the California desert region, and the lowest all-grass golf course in the world, averaging 214 feet below sea level. During the summer, when the inn was closed, the course was irrigated and leased to a rancher for grazing of about 150 head of cattle. During the winter golf season a small flock of sheep kept the fairways properly trimmed.

The inn received its share of activity in 1930, too. Twenty-one rooms with private balconies along the second floor and fireplaces in each room were added with the construction of the north wing. The building was joined to the lobby and dining room by an enclosed bridge. Since the inception of the inn, all the kitchen help were Chinese, and a four-room native-stone housing unit was constructed for them directly behind the kitchen, overlooking Furnace Creek Wash. During construction of the inn complex, a great deal of stone work was done for both structural and landscaping purposes. Portuguese stonemasons were brought in for the work under the direction of Spaniard Stephen Esteves. On a little knoll north of Furnace Creek Inn stands a stone monument adorned with an iron Portuguese cross. This is the final resting place of Steve Esteves, a fitting memorial to the man who shaped so much of the buildings and grounds of the Furnace Creek Inn.

After the flurry of expansion from 1929 through 1930, the inn underwent a period of quiescence, possibly due to changes that

In 1934, a lounge and recreation room was constructed at the inn between the terrace rooms and the pool. Later named the Marquez Room in honor of the long-time head chef, the room was built of native stone, massive exposed wood beams, and terra cotta tile floors. Its vaulted windows provided a spectacular panoramic view of the Panamint Mountains. That same year, the inn's gardens were landscaped with grass, flowers, and fan and date palms, and sculptured by flowing streams and pools. Construction of the 4-story tower unit in 1935 added 24 rooms to the inn complex and replaced the covered bridge connecting the north wing to the main building. A roof garden covered half of the tower unit providing a magnificent view of the valley and Panamint Mountains. The lobby, kitchen, and dining rooms were enlarged at the expense of 10 of the original guest rooms. In 1936 the company installed a 225-horsepower diesel generator at the ranch with power transmission lines running up to the inn. Once a fairly dependable and adequate power supply was available, the 25 kW Pelton wheel was only used during emergencies or in the summer when the facilities were closed and only the caretaker lived at the resort.

By the summer of 1937, the architectural vision of the Furnace Creek Inn resort was complete. However, company officials felt additional service facilities were needed. To avoid marring the symmetrical lines of the inn, they employed their mining expertise to excavate a lounge and kitchen facility into the hillside beneath the inn's dining room. Timbers from the trestles of the defunct DVRR provided structural support for the room, and the interior walls were finished with local banded travertine and crystals of the borate colemanite.

In 1942, Katherine Ronan suspended service at the Furnace Creek Inn due to fuel rationing during World War II, ending 13 years of management. When the inn reopened in the fall of 1945, Charles Scholl was the new manager of all the Death Valley properties. The inn continued to operate through the forties and into the fifties with only minor changes. Then in 1956, Pacific Coast Borax underwent corporate reorganization. The company's potash holdings were absorbed by the borax operations and the resultant company was renamed U.S. Borax and Chemical Company. Apparently dissatisfied with the performance of the Death Valley Hotel division, President James Gerstley, acting upon the recommendation of Horace Albright, approached the Fred Harvey Company of Chicago about the Death Valley properties. The result was an agreement for Fred Harvey to lease and operate the hotel division for the Borax Company.

### THE RANCH TRANSFORMS

With the closure of the Death Valley View Hotel in 1930, there was no longer any modestly-priced accommodations in the area. To resolve this shortfall, the Borax Company decided to install rustic tourist housing at Furnace Creek Ranch. Initially 18 tent cabins that were formerly located east of the inn (fig. Q-3) for employee housing were relocated to the ranch. They also moved 21-room miner's cabins and the boarding house from the non-operating Gerstley Borax Mine near Shoshone, California. In Death Valley's climate, these crude wood and corrugated metal cabins (fig. Q-4) were nicknamed "The Sizzlers" for obvious reasons. The ranch opened to guests in 1932 under the management of Edna Boswell and Mary Boswell, wives of the ranch's foreman and mechanic. A couple of years later, Clyde and Bess Erskine took over management of the guest accommodations at the ranch.

In 1932, cabins and cottages of the Boulder Dam Construction crew were relocated from Boulder City, Nevada to the ranch. During 1934 and 1935, an air-conditioned lobby with a comfortable lounge area, a general store, a dining room, and a coffee shop were built in the center of the guest complex. A recreation hall with a seating capacity for 200 people was added in 1936, providing space for daily lectures on the area and movie viewing on the weekends. Today the old recreation hall houses the Ranch General Store. Between 1935 and 1939, additional guest cabins were erected around the property.

*Figure Q-3. Furnace Creek Inn construction, view from ridge south of Furnace Creek Wash showing worker housing in foreground, summer 1927. Photograph courtesy of National Park Service, Death Valley National Park [DEVA #25490].*

*Figure Q-4. Unidentified man and girl in front of a "Sizzler," Furnace Creek Ranch, about 1935. Photograph courtesy National Park Service, Death Valley National Park [DEVA #4808].*

Tourist services were also suspended at the ranch from 1942-45 due to the war. By 1946, there were approximately 150 corrugated iron and stucco buildings at the ranch for the accommodation of visitors. The guesthouses clustered around the central office-store-dining-recreation complex, covered roughly 39 acres, and could handle 300-350 guests. Accommodations at the ranch could not be described as attractive (rustic or primitive would be more appropriate), but following the war, the Borax Company earmarked funds for the construction of some modern additions to the ranch.

The ranch was still operated on a small scale by a foreman and some helpers. Saddle horses were maintained for the benefit of the guests. The 20-acre alfalfa pasture was now fenced and a 15-acre wetland bird sanctuary had been developed. The nine-hole golf course that had been developed in 1930 now covered 44 acres. A 30-acre auto camp was established at the ranch with trailer hook ups for water and power and connections for sewer. During 1951 to 1952, a new office was built at the ranch and a swimming pool was added. The ranch kitchen was also enlarged.

In 1954, the Borax Company decided to set up the Borax Museum for the education and enjoyment of the public. They retained George Ishmael, Ash Meadows native and all around handyman, to move the old borax office from Monte Blanco in Twenty-Mule Team Canyon to the ranch. The building was the oldest existing structure in Death Valley, built by F.M. Smith sometime around 1883-85. Harry P. Gower, long-time resident of Death Valley and collector of historic memorabilia, worked with Ann Rosener, another U.S. Borax employee, to design displays and exhibits for the museum. Artistic and technical assistance was provided by various Disney employees. Gower donated his lifelong mineral collection to the museum as a reflection of the diversity and abundance of mineral wealth in the Death Valley area. A combination of photographs and artifacts tell the story of the Death Valley Forty-Niners, the explorers, the prospectors, the miners, and of course, the role borax played in the valley's history. Outside of the museum building, there is an assortment of mining, logging, and farming tools and machinery and various examples of types of transportation, including one of the engines of the Death Valley Railroad. Harry Gower assembled this collection over the course of many years.

## ACKNOWLEDGEMENTS

The author appreciates the opportunity to have this brief history of Furnace Creek included in this Guidebook for the Friends of the Pleistocene. Blair Davenport (NPS-Death Valley) reviewed that article and provided several photographs from the Park Service's archives. This article is taken from a much longer annotated work in progress. In the interest of space, only a few of the major published sources are listed for those seeking more information about this fascinating area.

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