Proceedings of Conference on Status of Geologic Research and Mapping in Death Valley National Park, Las Vegas, Nevada, April 9-11, 1999

U.S. GEOLOGICAL SURVEY
Open-File Report 99-153

Front cover:
View to west from Zabriskie Point. Photo by Michael N. Machette.

Inside back cover:
A, Generalized geologic map of the Death Valley region, modified from Faunt and others (1997). Faults in California are from Lienkaemper (1985), in Nevada from Dohrenwend and Moring (1993). *B*, Isostatic residual gravity anomalies. NDV, northern Death Valley; CDV, central Death Valley; SDV, southern Death Valley; GM, Grapevine Mountains; FM, Funeral Mountains; BM, Black Mountains; CM, Cottonwood Mountains; TM, Tucki Mountain; AD, Amargosa Desert; AM, Avawatz Mountains; OM, Owlshead Mountains; PV, Panamint Valley; PR, Panamint Range; VC, southwest Nevada volcanic complex; FF, Furnace Creek fault; DF, Death Valley fault zone; GF, Garlock fault.

Back cover:
A, Topography of the Death Valley region. Green areas indicate exposures of pre-Tertiary basement. *B*, Basement surface, where colors indicate depth below sea level. *C*, Basement surface, where colors indicate basement gravity anomaly. Contour interval 5 mGal.

Proceedings of Conference on Status of Geologic Research and Mapping, Death Valley National Park

Janet L. Slate, Editor

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Denver, Colorado
1999

U.S. DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

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Charles G. Groat, Director

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PROLOGUE

H. Donald "The Kid" Curry, Death Valley's First Ranger-Geologist (1908–1999)

Vincent L. Santucci[1] and Torrey Nyborg[2]

[1]National Park Service, P.O. Box 592, Kemmerer, WY 83101 <vincent_santucci@nps.gov>

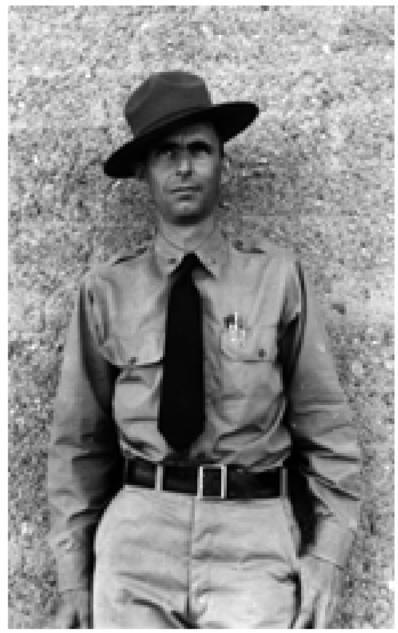
[2]Death Valley National Park, Death Valley, CA 92328 <torrey_nyborg@hotmail.com>

Most geologists working in Death Valley National Park recognize the contributions that H. Donald Curry has made to the understanding of the regional geology. In 1999, original unpublished Death Valley maps produced by Curry during the 1930's were donated to the National Park Service (NPS).

Donald Curry attended the State University of Iowa between 1925 and 1932, receiving B.A. and M.S. degrees in geology. He was also enrolled in the graduate geology program at the California Institute of Technology between 1932 and 1934. As a student intern, Curry honed his skills in geologic mapping with the U.S. Geological Survey, where he acquired the nickname "The Kid."

On February 11, 1933, President Herbert Hoover proclaimed Death Valley as a national monument. A year later, in 1934, Don Curry was hired as the first Ranger Naturalist at Death Valley National Monument. Curry is possibly the first professional geologist to wear the ranger uniform. He conducted geologic research during the day and presented interpretive programs to the public in the evenings.

Curry made many contributions to the understanding of Death Valley's geology. He produced numerous contour and cross-section maps using the classic "plane table" techniques, some of which remain unpublished but available through the NPS Museum in Death Valley. He was the first to describe and name the "Turtleback" structures in the Black Mountains, and he pioneered the recognition of the rich paleontological resources in Death Valley. Curry is credited with the discovery of titanothere remains in Titus Canyon, fossil plant material from the Furnace Creek Formation, several new Tertiary fish fossils, and three fossil vertebrate track localities, most notably at the Copper Canyon tracksite. In his honor, two fossil species have been designated *curryi*.



Donald's career with the National Park Service was interrupted by his participation in World War II. However, he was considered as an NPS staff member until his departure to work for the oil industry. In 1941, Curry joined Shell Oil Company as a geologist, where he rose to the position of Senior Geologist. Curry retired in the mid 1960's after several decades with the oil industry, but maintained a long-term interest in Death Valley geology and in Tertiary fossil tracks, publishing numerous articles on these subjects. H. Don Curry passed away at the age of 90 on January 7, 1999, leaving a rich legacy as a ranger and geologist with the National Park Service.

INTRODUCTION

Welcome to this conference on the "Status of Geologic Research and Mapping in Death Valley National Park." We organized this conference in an effort to foster communication and increase awareness among parties conducting geologic research in and around the park. Additionally, we hope to assess the status of geologic mapping efforts within the park boundaries in an effort to provide a framework for future discussions regarding the impact and merits of the development of a park-wide geologic map.

The topics presented at this meeting reflect the breadth of recent and ongoing geologic research in and near Death Valley National Park. Sessions include (1) regional structure, tectonics, and bedrock geology; (2) Neogene basin stratigraphy, geophysics, and hydrology; (3) posters on mapping in the Death Valley region and topical ones on Death Valley National Park; (4) imagery, Quaternary stratigraphy and geomorphology, and Quaternary geochronology; and (5) paleoclimate and active tectonics. On a one-day field trip to Death Valley, we will visit areas of "type locality" status as well as areas of new research.

The meeting has three goals:

- Compile up-to-date information on the status of geologic research and mapping in Death Valley National Park and surrounding areas. We hope you agree that this volume and the accompanying diskette, which contains citations of geologic references for the area, meet this goal.
- Establish a network of active researchers to create synergy for cooperative research endeavors. Geologic complexities observed in the Death Valley region require interdisciplinary approaches.
- Present recent and current research results in an informal setting, thus encouraging dialogue. Much of the meeting time will be dedicated to poster sessions and field trip discussions.

The academic, government, and private-sector earth scientists assembled at this conference are a veritable Who's Who of geologists who have worked in Death Valley National Park, many over several decades. We look forward to your input and participation, and we hope you renew or make acquaintances that further your research and understanding of Death Valley geology.

We would like to acknowledge those agencies and individuals who have helped to make this conference a success. The support of the U.S. Geological Survey, National Park Service, Department of Energy, and Death Valley Natural History Association made this conference possible. We appreciate the services of Lorna M. Carter and Gayle M. Dumonceaux, of the USGS-Geologic Division, Central Region, Publications Group. Lee-Ann Bradley and Christopher M. Menges, both USGS, provided logistical support. Angela S. Jayko, Melanie Moreno, and Bonnie Murchey-Setnicker, all USGS, developed the conference web site.

Signed,
The Organizing Committee
Janet L. Slate, Michael N. Machette, Ren A. Thompson, and Bruce Heise

DEATH VALLEY NATIONAL PARK

Geologic Highlights of Death Valley National Park

Michael N. Machette,[1] Ren A. Thompson,[2] and Mel Essington[3]

[1] U.S. Geological Survey, Box 25046, Denver Federal Center, M.S. 966, Denver, CO 80225-0046 <machette@usgs.gov>

[2] U.S. Geological Survey, Box 25046, Denver Federal Center, M.S. 913, Denver, CO 80225-0046 <rathomps@usgs.gov>

[3] National Park Service, Resource Management Division, P.O. Box 759, Death Valley, CA 92328 <mel_essington@nps.gov>

Of the more than 365 national parks and monuments in the United States, Death Valley National Park is perhaps the most spectacular from a geologic perspective. Certainly Yosemite and Yellowstone have their special qualities, but Death Valley never fails to capture the hearts and minds of geologists.

Since the area's discovery by Euro-American emigrants on Christmas Day in 1849 (150 years ago), the barren landscapes, arid and often hot climate, and lack of water have shaped visitors' and inhabitants' regard for the area. On average, about 1.65 inches (42 mm) of rain falls in the valley; summertime temperatures commonly exceed 120˚F (49˚C), and there is little or no vegetation at the lower elevations of the park. These factors combine to create a geologically fascinating landscape where virtually all the bedrock and younger sediment are exposed to the elements.

The park, which now includes portions of the Panamint, Saline, and Eureka Valleys to the north and west, contains geologically important or fascinating features that are either unique or so spectacular that they draw the geologist's attention immediately. Many geologists have been entranced by the park: four of note are Levi Noble, Donald Curry, Lauren Wright, and Bennie Troxel. These "Desert Rats," as they are fondly known, spent the better part of their lives pursuing the geology of Death Valley and the surrounding mountains. Levi Noble and Donald Curry (see prologue, this volume) have passed away, but their legacy is embodied by terms such as "Amargosa Chaos" and "Turtlebacks" that are still the subject of spirited debate. Features such as these, coupled with the severe climate and landscape, endear the park to the international geologic community.

In our opinion, the following features represent the more interesting geologic aspects of the park (many of these are discussed in more detail in this volume). Those shown in bold are either found only in Death Valley National Park, or are of "type locality" status in the park. However, many other notable geologic features of the park provide "textbook" examples of geology for both the student and visitor.

Spectacularly sculpted landscapes, such as at Zabriskie Point, Manly Beacon, Golden Arch, Titus Canyon, and Artist Palette, show the dramatic effects of fluvial erosion, which is an occasional but catastrophic agent of change in Death Valley.

Racetrack Playa. This playa in the remote northwestern part of the park displays fascinating curvilinear tracks, caused most likely by ice-rafted rocks that are occasionally pushed across the playa during winter windstorms (See Messina and Stoffer, this volume.)

The desert landscape. Ancient land surfaces are characterized by vesicular A horizons, desert varnish, and desert pavements. Although by some considered erosional, the pavements are actually aggradational surfaces. The resulting smooth dark-colored (varnished) stone pavements are underlain by several to tens of centimeters of calcareous silt—the result of a slow but insidious influx of desert dust. These fragile surfaces can preserve vehicle or animal trails for hundreds of years.

Rapid rates of active tectonics. Strike-slip movement on the Furnace Creek fault zone may approach 10 mm/yr (1 m/century). These rates are the highest in the Basin and Range province, and are only exceeded by the plate-boundary faults of the San Andreas system farther west in California.

Greatest relief in conterminous U.S. The topographic relief between Telescope Peak and Badwater is 11,331 ft (3,455 m), the combined result of ongoing rapid uplift and subsidence.

Lowest ground in U.S. and Western Hemisphere. Badwater at -282 ft, (-86 m), and the associated below sea-level-basins (Cotton Ball and Middle Basin) are maintained by high slip on the Death Valley fault zone. At rates of perhaps 4 mm/yr, the vertical slip is higher here than on Utah's Wasatch fault zone or any other predominantly normal fault in the U.S.

Spectacular alluvial fans with tectonic control. The low basin-margin landscape is characterized by alluvial fans. The asymmetry of the valley is demonstrated by the contrast in relative size between long, gentle fans on the more stable western margin of the valley and small, steep fans on the rapidly subsiding eastern margin as noted by G.K. Gilbert almost 125 years ago.

Lake Manly in Death Valley and Panamint Lake in Panamint Valley. These are the last two lakes in a long string of lacustrine pearls strung along the Owens and Mojave river systems. Some of these lakes were at least 500 ft (150 m) deep in the past, filling intermittently during the late Pleistocene and earlier times. Although the lake deposits are mostly covered, isolated remnants of the eroded shorelines, tufa deposits, and constructional bars and spits are preserved in the valleys.

Recorder of ancient volcanic eruptions. Death Valley is a closed basin and, as such, is a sump for airborne volcanic ashes. Recently discovered volcanic-ash deposits range from about 500,000 years to 3.4 million years in age. These rhyolitic ashes are mainly from distant sources such as the Yellowstone and Long Valley calderas and the Cascades, and provide critical time-lines for interpreting the late Cenozoic history of Death Valley.

Ubehebe Volcanic Crater. Eruptions from this young phreatic (explosion) crater spewed basaltic ash across northern Death Valley. One deposit, which is perhaps only 300 years old, is offset by the Furnace Creek fault zone near the Grapevine Ranger Station.

Devils Hole. Calcite-rich speleothems (spring deposits) from this deep cavern in the Amargosa Valley record a 500,000-year-long paleoclimatic record. The ^{18}O-isotope content of uranium-series dated bands in the speleothems track changing air temperatures through the geochemistry of ancient rainfall.

The Salt Pan. The Death Valley hydrologic basin covers about 8,700 square miles, of which about 500 square miles are below sea level. The bottom of the basin—the salt pan of Death Valley, which is one of the world's greatest salt pans—covers more than 200 square miles and its sediments are thousands of feet thick. Cores from the salt pan provide a long though discontinuous record of the region's Quaternary paleoclimate.

Tertiary basin-fill deposits. Ancient sub-basins related to Death Valley have been active extensional depressions for at least the past 14 million years. The associated basin-fill deposits of the Furnace Creek and Funeral Formations record the uplift, unroofing, and erosion of adjacent mountains and are the main aquifers for Death Valley's sparse water supply, in conjunction with the regional carbonate aquifer.

The discovery of borates and other evaporite deposits, in addition to gold and silver, led to the early development of the valley. The Harmony Borax Works, located about 5 km north of Furnace Creek Ranch, is one of the few vestiges of this valley's early mining history. Interestingly, Borax was recently found to be an effective agent at reducing Mediterranean fruit-fly reproduction.

The Turtlebacks. First recognized and named by H. Donald Curry, these fascinating folded, upwarped, or exhumed detachment faults have their type locality in the Black Mountains, specifically near Badwater and Mormon Point. The turtlebacks are the subject of several papers in this volume and our first field trip stop.

Central Death Valley Volcanic Field. Tertiary volcanic rocks exposed on the eastern margin of Death Valley record a 12-million-year-long eruptive history from volcanic highlands on the margins of actively subsiding basins. Deformation of these time-stratigraphic units constrains the timing and extent of regional extension.

Greatly extended terrains. Rocks previously astride or atop the Black Mountains of eastern Death Valley now form the Panamint Mountains, some 20 km to the west. The Grapevine Mountains are the allochthonous (upper) plate that has slid tens of kilometers to the northwest, off the Funeral Mountains.

Precambrian and Paleozoic rocks of Death Valley represent a composite crustal section that was formerly at 10–15 km depth. Now exposed as uplifted blocks in the footwall of active frontal faults or along low-angle normal faults, these bedrock exposures are the grandest representation of "Basin and Range geology."

We believe the abbreviated list of geologic features mentioned herein, in part depicted by associated photographs (see poster), illustrate well the unique attributes that make Death Valley "America's premier geologic national park."

Status of Geologic Mapping in Death Valley National Park—A Database

A.S. Jayko,[1] M. Essington,[2] Bruce Heise,[3] H.E. Johnson,[4] P.W. McGrath,[4] D.W. Prichett,[4]
G. Saucedo,[5] R. Thompson,[6] and D. Wagner[5]

[1]U.S. Geological Survey, 345 Middlefield Rd., M.S. 975, Menlo Park, CA 94025

[2]Death Valley National Park, Death Valley, CA 92328

[3]National Park Service, Box 25287, Denver, CO 80225

[4]University of California, White Mountain Research Station, 3000 East Line St, Bishop, CA 93514

[5]California Division of Mines and Geology, 801K St., M.S. 12-31, Sacramento, CA 95814

[6]U.S. Geological Survey, Box 25046, Denver Federal Center, M.S. 913, Denver, CO 80225

The geology of Death Valley National Park records more than one billion years of Earth history in rocks that range in age from Precambrian to Holocene (Recent). The park lies predominantly within the eastern part of Inyo County, Calif., but includes parts of Nye and Esmeralda Counties, Nev., encompassing an area of more than 13,500 km^2 (3,336,000 acres). The entire area of Death Valley National Park has been mapped at a scale of 1:250,000 (Trona, Death Valley, and Mariposa 1°×2° sheets) and much of the area at a more detailed scale. About half of the area has been mapped at 1:96,000 scale or larger scales and published as various U.S. Geological Survey (USGS) or California Division of Mines and Geology (CDMG) maps, but much detailed mapping remains unpublished and availability is therefore limited. The poster presented at this meeting is an initial attempt to summarize the status of geologic mapping in Death Valley National Park. It also provides an opportunity for workshop participants to contribute information regarding the status of geologic map data not currently in the database being compiled cooperatively by the USGS, NPS, CDMG, and the University of California–White Mountain Research Station. To date, database entries derive largely from references in Schilling and Thompson (1993), Wright and others (in review), a catalog of thesis work maintained by the CDMG, and the reference bibliography maintained by Death Valley National Park. We are combining data from all the sources in an ARC/INFO database that includes searchable fields for author, date, title, source, and map scale. The database is available in ARC/INFO export format from our server at <sierra.wr.usgs.gov> via anonymous FTP. Note that we are currently updating the database; the associated README file indicates the date of the most recent entry.

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Schilling, S.P., and Thompson, R.A., 1993, Geologic mapping index to the Death Valley National Monument Area, California and Nevada: U.S. Geologic Survey Open File Report 93-506, 51 p.

Wright, L.A., Thompson, R.A., Workman, J.B., in review, Tectonic-geologic map of the Death Valley region, California and Nevada: U.S. Geological Survey Miscellaneous Investigation Series Map, 1:250,000 scale.

How to Get a Research Permit from Death Valley National Park

Richard L. Anderson, Environmental Specialist, Death Valley National Park
Death Valley, CA 92328 (760) 786-3251 < Richard_L_ Anderson@nps.gov>

As the Death Valley National Park (DVNP) employee responsible for processing research permit requests, I present general information, common problems, tips for success, and common misconceptions about the National Park Service's research permitting process. Three subjects are covered: (1) the permit application process; (2) the park's evaluation process; and (3) a review of wilderness considerations.

Permit Application Process. A generic packet is sent to researchers when an initial request for a permit is made. The researcher reviews the information and responds with a brief research proposal to the park. The park evaluates the proposal and responds with (1) an early approval, or (2) questions for clarification, requests for changes to the proposal, requests for more information on specific aspects of the project, or (3) an early denial. The ultimate goal, of course, is project approval. Park resources must be protected; project information needs to flow back to the park; and National Park Service policies must be observed. Park employees and official park volunteers performing their jobs usually do not need to obtain a research permit. All other researchers need permits, even if they are not collecting specimens.

DVNP's Evaluation Process. All project proposals are evaluated through a formal process directed by the National Environmental Policy Act (NEPA). Also called NEPA compliance, the proposal-review process includes an interdisciplinary critique to identify possible impacts, alternatives, and mitigation. The management team of the park (the superintendent and division chiefs) reviews the proposal and makes a tentative decision. Then a team of subject specialists from every park division (resource management, protection, administration, interpretation, and maintenance) reviews the proposal and recommends the level of NEPA compliance required—either a categorical exclusion, an environmental assessment, or an environmental impact statement. Depending on the project, a researcher may need to plan on many months for NEPA review. Common issues that can delay the permitting process are concerns about safety, cultural resources, wilderness, aquifers, wetlands, floodplains, ecologically significant areas, National Register of Natural Landmarks, controversy, uncertain effects, precedence, cumulative effects, National Register of Historic Places, listed or rare species or habitat, tribal consultation, archeology, and ground disturbance. Except for categorical exclusions, NEPA is a public-disclosure law, and some projects may require time for public review as well. Following successful NEPA compliance and management approval, the project is approved.

Wilderness Considerations. The Wilderness Act of 1964 bars certain uses in the park's wilderness area. About 95 percent of the park is wilderness. Roads open to vehicular traffic are not wilderness. Generally, motorized equipment, motor vehicles, structures, and installations are not allowed in wilderness. Certain exceptions are permitted; for example, a shaver is allowed even though it is considered motorized equipment. An emergency involving the health and safety of a person or persons within the wilderness area is another exception. Wilderness areas are not closed to entry, to research, or to sampling. In fact, their isolation makes them some of the best areas in which to conduct research of natural conditions.

National Park Service Geologic Resources Inventory

Joe Gregson, I&M Program, and Bruce Heise, Geologic Resources Division,
National Park Service, Box 25287, Denver, CO 80225

Bedrock and surficial geologic maps and unit descriptions provide a critical basis for ground-water, geomorphic, soils, vegetation, and environmental-hazard studies. Geologic maps describe the underlying "physical habitat" of natural systems and are an integral component of the geophysical inventories collected by the National Park Service Inventory and Monitoring (I&M) Program. The NPS Geologic Resources Division and I&M Program (Natural Resource Information Division) are cooperating with USGS and State geologists to compile digital geologic maps and other data for NPS units with significant natural resources. Each park inventory consists of four components:

1. a bibliography of geologic literature and maps
2. an evaluation of resources and issues
3. an assessment of geologic map coverage and production of digital products, and
4. a compilation of a geologic report with basic geologic information, hazards and issues, and existing data and research.

The inventory was initiated during the past year through a series of scoping meetings in national park units in Colorado. This year the project will focus on park units in Utah. Examples of products generated by the program for the Colorado parks will be displayed. Input on available geologic map coverage and literature for Death Valley National Park and Mojave National Preserve will be sought from conference attendees.

Inventorying Paleontological Resources at Death Valley National Park

Torrey G. Nyborg[1] <torrey_nyborg@hotmail.com>, and Vincent L. Santucci[2] <vincent_santucci@nps.gov>

[1]Death Valley National Park, Death Valley, CA 92328 (current address: 4400 SW 179th, Aloha, OR 97007)

[2]Fossil Butte National Monument, P.O. Box 592, Kemmerer, WY 83101

We initiated the first comprehensive paleontological resources inventory of Death Valley National Park in 1998. Death Valley preserves an extensive geologic record ranging from Precambrian through Holocene. More than a dozen fossiliferous stratigraphic units have been identified at Death Valley National Park. These formations contain a rich and scientifically significant diversity of fossil plants, invertebrates, vertebrates, and trace fossils.

Notable resources include (1) a possible *"Ediacara"* fauna equivalent; (2) Precambrian/Cambrian trilobite faunas; (3) the type section of the Lower Cambrian Waucoba Series; (4) Devonian fishes; (5) titanothere in Eocene sediments; and (6) mammal and bird tracks in Miocene and Pliocene lacustrine sediments.

As a part of the Death Valley Paleontological Survey, we searched biological, geological, paleontological and government bibliographic databases to locate any published information related to paleontological resources at Death Valley. This information, along with the input of current and past paleontological researchers, was synthesized into this new park management document.

Along with paleontological resource recommendations, we compiled bibliographic data, a faunal inventory list, fossil locality maps, and a park-wide stratigraphic column in an effort to provide a baseline for park paleontological resource management.

As this survey demonstrates, Death Valley contains significant and diverse paleontological resources. Communication with research geologists and paleontologists indicates a wealth of unpublished paleontological resource data from Death Valley. We hope that this document helps to increase the awareness and status of Death Valley's paleontological resources and provides a baseline from which future projects can be planned. We believe that the information contained in this report can both enhance management decision-making relative to paleontological resource issues and perhaps facilitate future discoveries in Death Valley.

Accessing Death Valley National Park's Museum Collection for Geological and Paleontological Research

Blair Davenport
Death Valley National Park, P.O. Box 579, Death Valley, CA 92328
(760)786-3287 (Phone), (760)786-3283 (FAX), <blair_davenport@nps.gov>

INTRODUCTION

The mission of Death Valley National Park ("the park") is to maintain, preserve, interpret, and perpetuate the aesthetic, natural, and cultural resources of the Mojave and Great Basin deserts of California and Nevada. The management philosophy for the park is to provide visitors and researchers the opportunity to discover, explore, and understand these varied resources, while also ensuring their preservation.

Death Valley National Park's museum collection and archives contribute directly to the understanding and interpretation of the park's mission, purpose, themes and resources. These collections are considered resources in and of themselves, and therefore must be preserved by Federal mandate. Specimens and records derived from geological and paleontological research and interpretation within the park are a major component of our large collection.

Park personnel accession and catalog geological and paleontological specimens collected within the park that are not consumed in analysis and are appropriate for long-term preservation. Many of these specimens and records are in the park's library, archives, and museum collection; many are in outside repositories of other Federal agencies, universities, and public or private museums.

GEOLOGICAL AND PALEONTOLOGICAL COLLECTIONS

The park's collection of geological and paleontological specimens and associated records that are located at our Furnace Creek and Cow Creek facilities began as a collection of "unique" or "unusual" objects "collected" by Park Naturalists beginning in the early 1930's. These early specimens generally included rock and mineral samples that were collected to answer geological questions, or paleontological specimens of newly discovered fossil remains. The whole collection, which includes smaller reference collections, synoptic collections, and voucher and type collections, continues to grow and is systematically accessioned and cataloged.

Most of these collections and associated records are derived from authorized scientific research based on needs identified in the park's approved *Resource Management Plan*. Scientific research may be conducted by either National Park Service (NPS) or non-NPS staff and must comply with all applicable Federal and State laws and regulations regarding collection, research, museum cataloging, and associated activities.

The park museum collection has approximately 750 geological and 1,250 paleontological specimens. Most have been cataloged and can be accessed by a computer database. These specimens include:

- *Rocks and Minerals:* Rock hand specimens and mineral samples that illustrate the mineral forms and varieties required to document rock types, formations, and mineral varieties found in the park.
- *Economic Minerals and Ores:* Specimens that document the mineral forms and varieties currently or formerly mined in the park.
- *Vertebrate and Invertebrate Fossils:* Actual fossilized faunal remains are rare in Death Valley. Existing examples were excavated under permit and removed to other museums in the 1930's. Most notably, due in part to the discovery of *Titanothere*, the park's boundaries were expanded to include the region near where these fossilized remains were located. Fossilized fish imprints have also been found in two separate areas within the park. (See recent paleontological resources inventory, Santucci and Nyborg, this volume.)
- *Paleobotany:* Isolated finds include leaf imprints, relict lakeside vegetation imprints, and fossilized wood. (See recent paleontological resources inventory, Santucci and Nyborg, this volume.)
- *Trace Fossils:* Tracks of various birds and animals mainly from the Copper Canyon Formation. (See recent paleontological resources inventory, Santucci and Nyborg, this volume.)
- *Associated Records:* There are approximately 1,500 references to the records, original manuscripts, dissertations, photographic images, oral histories, and maps that pertain to the geological and paleontological record of the park. These records are located in the park library, museum archives, and offices of Park Resource Management staff. Various aids and databases are available to access these records.

USE OF THE COLLECTION

The park's collection of geological and paleontological specimens and associated records is used for exhibits, interpretive programs, research, and other interpretive media (such as publication, film, television, and web pages). As the museum curator, I encourage researchers and other specialists to visit the collections and library to examine specimens and records. Objects may be loaned to qualified institutions for approved purposes (such as exhibition, storage, or research). Institutions must meet NPS museum standards for security, handling, and exhibition of museum material. To request access to the museum collections, archives, and library, please contact the Furnace Creek museum curator either by writing, by telephone, or by e-mail as above.

REGIONAL STRUCTURE, TECTONICS, AND BEDROCK GEOLOGY

Tectonic Evolution of the Death Valley Region

Brian Wernicke, Division of Geological and Planetary Sciences, Mail Stop 100-23
California Institute of Technology, Pasadena, CA 91125 (626) 395-6192 <brian@gps.caltech.edu>

INTRODUCTION

Progress in understanding the evolution of continents hinges on seamlessly applying techniques of modern structural geology to the largest possible regions of the crust. In most areas, meaningful practice of regional structural geology is limited by a lack of correspondence between highly strained crust and well-defined regional strain markers, that is, large-scale geologic features whose initial geometry can be reasonably inferred, and their kinematic evolution constrained, through structural, stratigraphic, isotopic, paleomagnetic, and geodetic study.

A ~100,000-km^2 segment of the U.S. Cordilleran orogen, encompassing the celebrated landscapes of Death Valley National Park and five nearby parks that are among the most visited in the U.S., was severely deformed in late Cenozoic time. In addition to spectacular geologic exposures, the region harbors a rare endowment of regional structural markers, developed before and during late Cenozoic deformation. The markers are defined by isopachs and facies boundaries in the west-thickening Neoproterozoic-Paleozoic Cordilleran miogeocline, by pre-Cenozoic thrust faults that disrupt the miogeoclinal wedge, and by proximal Tertiary terrigenous detrital strata and their source regions. The region is still tectonically active, providing an opportunity to compare deformation patterns of the last decade, constrained by geodetic studies, with late Cenozoic deformation patterns spanning 15–20 m.y.

These scientific assets have attracted the attention of significant numbers of structural geologists over the last three decades, and distinguished the region as the birthplace of, and testing ground for, an impressive number of fundamental tectonic ideas. Oroclinal bending of mountain ranges, continental transform faulting and "pull-apart" basins, low-angle normal faulting, the influence of plate motions on intracontinental deformation, the "rolling hinge" model of progressive extensional deformation, the fluid crustal layer or "crustal asthenosphere" concept, and Pratt isostatic compensation of mountain ranges were all originally discovered or have their best known expressions in the region. This remarkable history of geologic investigation and innovation continues unabated as growing numbers of scientists recognize it as a unique place on Earth to ponder the nature and origin of large-scale continental deformation.

METHODS AND SCOPE OF RESEARCH

The author's research program in this region began with his doctoral research in 1979 at MIT, mapping in the Mormon Mountains of southern Nevada under the supervision of B.C. Burchfiel. After joining the professoriate in 1982, my research program expanded to include most of the area from the Sierra to the Colorado Plateau, funded primarily by the Tectonics and Continental Dynamics programs in the Earth Sciences Division of the National Science Foundation, with important contributions from the Department of Energy, Nuclear Regulatory Commission, a consortium of energy companies, and university funds. It has included geologic mapping and structural analysis, stratigraphic studies, isotopic studies, paleomagnetic studies, geodetic studies, and participation in two major seismic experiments, the Southern Sierra Continental Dynamics (SSCD) Project and the Basin and Range Geoscientific Experiment (BARGE). A bibliography of the group's work relating to Basin and Range tectonics, including 53 published research papers, 4 abstracts of papers in preparation, 8 discussion papers, 6 field trip guidebooks and 8 theses, is presented at the close of this paper.

Mapping and structural analysis. Bedrock geologic mapping by the group totals some 3,300 km^2 at field scales ranging from 1:10,000 to 1:24,000 (fig. 1). It includes 2,000 km^2 between the Spring Mountains and Sierra Nevada (Death Valley extensional domain) and another 1,300 km^2 east of the Spring Mountains (Lake Mead extensional domain). In the Death Valley domain, the group has mapped (1) the Panamint Range from Stovepipe Wells to Harrisburg Flats (Hodges and others, 1987; Wernicke and others, 1993); (2) the central Resting Spring Range (Niemi and others, in press; Wernicke, unpublished); (3) the Cottonwood Mountains north of Hunter Mountain (Snow, 1990 and unpublished); (4) the central Black Mountains (Holm, 1992); (5) the northwestern Spring Mountains (Abolins, 1998); and (6) the Grapevine Mountains between Scotty's Castle and Titus Canyon (N. Niemi, Ph. D. thesis in progress). In the Lake Mead domain, mapping has included (1) most of the South

INDEX TO GEOLOGICAL MAPS, WERNICKE RESEARCH GROUP, 1979-1999

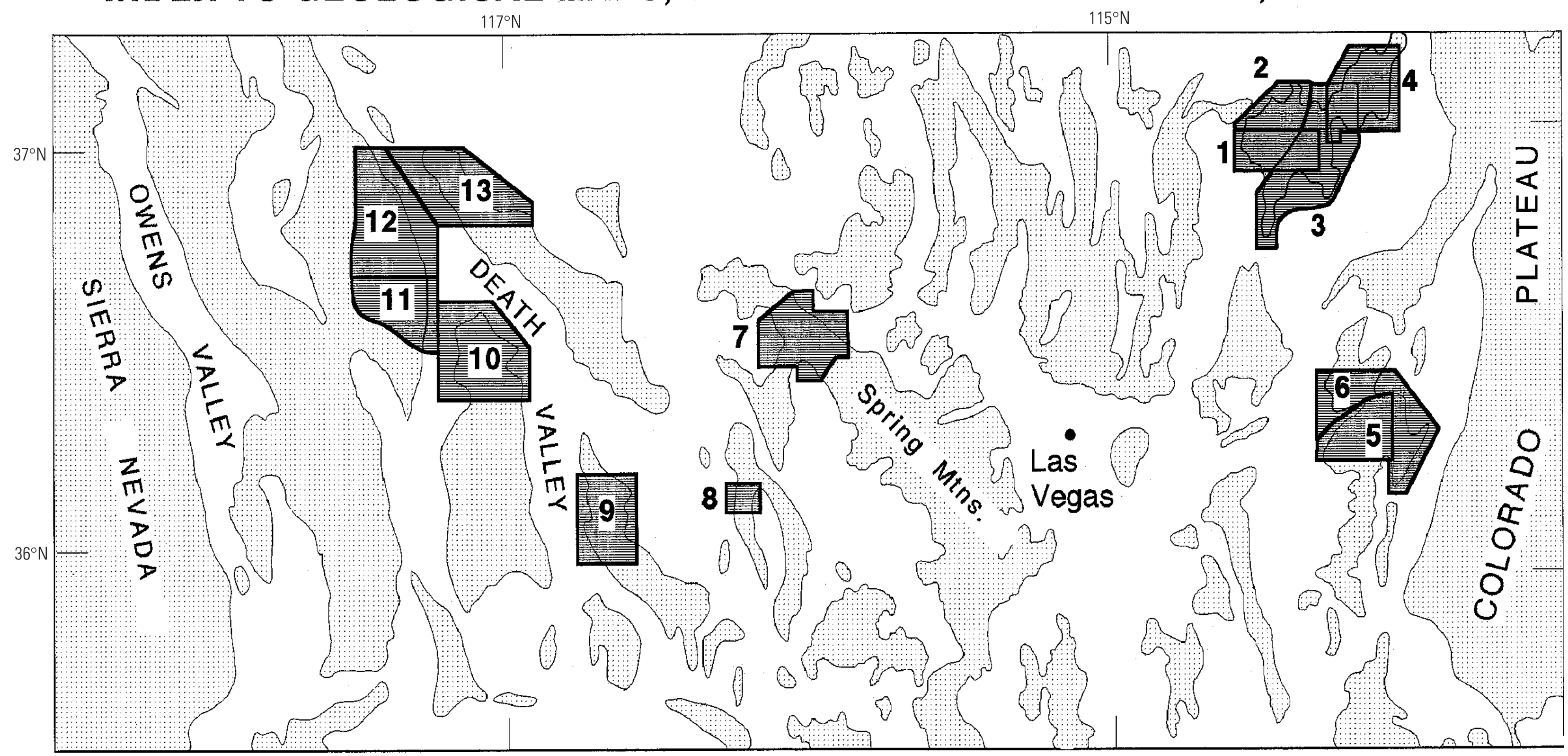

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Figure 1. Geologic mapping of the Wernicke research group, full references in bibliography at close of paper.

Virgin Mountains (Fryxell and others, 1992; Brady and others, in press); (2) the Mormon Mountains (Wernicke and others, 1985; Axen and others, 1990; Wernicke and others, 1984, unpublished); and (3) the Tule Springs Hills (Axen, 1993).

Stratigraphy. Detailed stratigraphic studies have been focused primarily on Oligocene and younger strata deposited prior to and during major Cenozoic deformation, and on key portions of the pre-Cenozoic miogeoclinal prism. From oldest strata to youngest, these studies have included (1) sequence analysis of the Neoproterozoic Johnnie Formation (Charlton and others, 1997; Abolins, 1998); (2) paleoflow directions in Eocambrian strata (Snow and Prave, 1994); (3) studies of the orientation of facies boundaries and isopachs in Paleozoic strata (Snow, 1992); and (4) measured sections, facies analyses, and paleoflow directions for Tertiary strata in the Cottonwood, Grapevine, and Funeral Mountains (Snow and White, 1990; Snow and Lux, in press), Black Mountains (Holm and others, 1994), and Resting Spring Range (Niemi and others, in press).

Geochronology, thermochronology and thermobarometry. Isotopic and petrologic studies, in collaboration with S. Bowring and K. Hodges (MIT), D. DePaolo (Berkeley), R. Dokka (LSU), P. Fitzgerald (Arizona), K. Farley and J. Saleeby (Caltech), S. Jacobsen (Harvard), D. Lux (Maine), and J. Selverstone (New Mexico) have included (1) cooling history and paleobarometric studies of the South Virgin Mountains (Fitzgerald and others, 1991; Brady, 1998; P. Reiners, unpublished data), Spring Mountains and Panamint Mountains (Wernicke and

Dokka, unpublished data), Nopah Range (Wernicke and Farley, work in progress), Funeral Mountains (Holm and Dokka, 1991), Black Mountains (Holm and Wernicke, 1990; Holm and others, 1992; Holm and Dokka, 1993), northern Snake Range (Lewis and others, 1999), Skagit River area (Wernicke and Getty, 1997) and central Sierra Nevada (House and others, 1997, 1998); (2) intrusive and eruptive age determinations of igneous rocks in the South Virgin Mountains (Brady, 1998), Black Mountains (Asmerom and others, 1990; Holm and others, 1994), Resting Spring Range (Niemi and others, in press) and Cottonwood Mountains (Snow and others, 1991; Snow and Lux, in press; Niemi and others, in press); and (3) tracer studies targeted at understanding the evolution of source regions of magmas in the central Death Valley volcanic field (Asmerom and others, 1990, 1994). These studies include isotopic and nuclear-track age determinations on a total of 237 mineral separates, using the $^{40}Ar/^{39}Ar$ (68 separates), (U-Th)/He (85 separates), fission-track (61 separates), U/Pb (16 separates) and Sm/Nd (7 separates) systems.

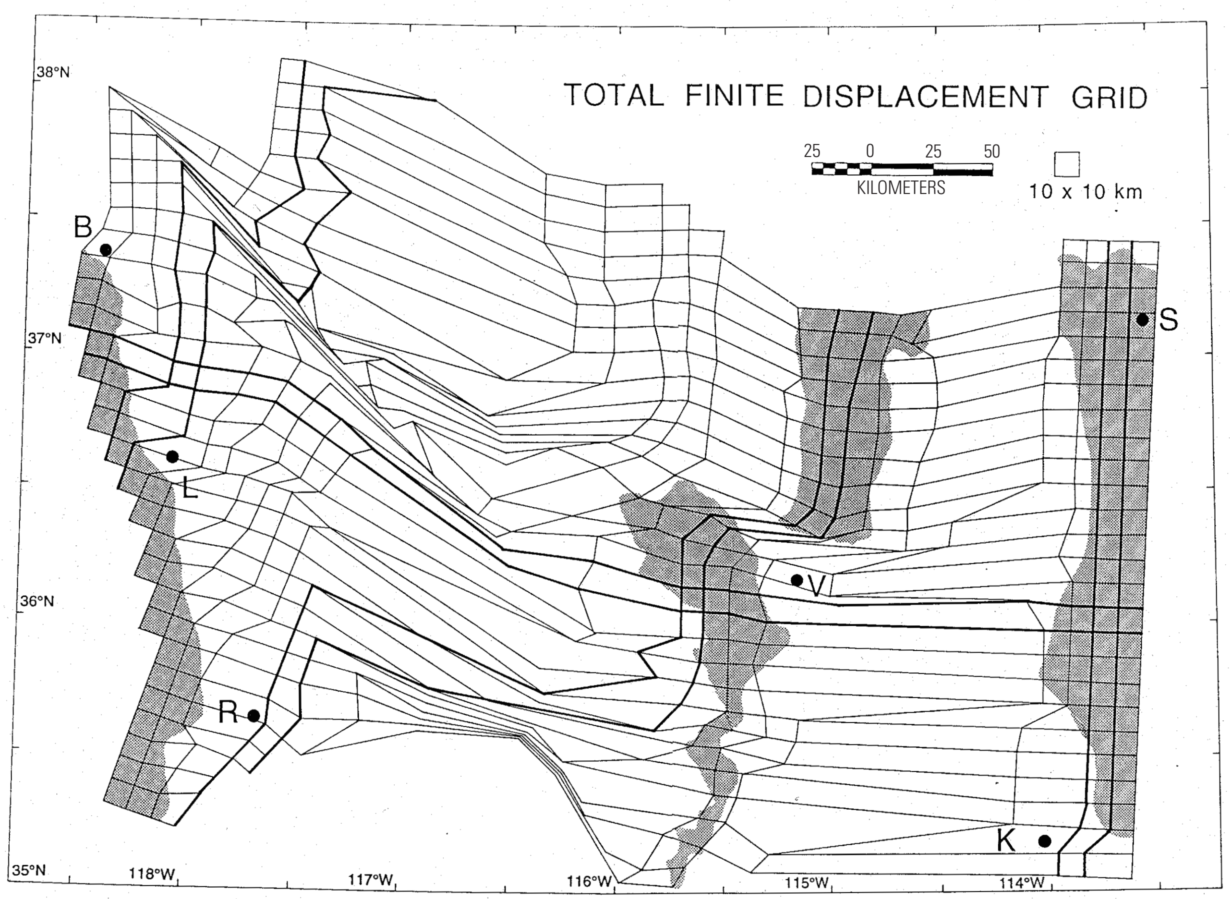
Paleomagnetism. Paleomagnetic studies in collaboration with J. Geissman (New Mexico) have been aimed at unraveling the complex vertical-axis rotation histories of critical range blocks. To date, we have sampled and analyzed more than 250 sites (about 2,300 sample cores), including (1) 75 sites in the South Virgin Mountains (Proterozoic and Mesozoic crystalline rocks; J. Geissman and others, unpublished data); (2) 54 sites in the Black Mountains (Miocene intrusions and mafic lavas; Holm and others, 1993; Petronis and others, 1997); (3) 47 sites in the Funeral and Grapevine Mountains (mainly Paleozoic carbonate and Tertiary volcanic strata; Snow and others, 1993); (4) 30 sites in the Panamint Mountains (Miocene intrusives, mafic lavas, and Paleozoic carbonates; Petronis and others, 1997); and (5) 50 sites in the Greenwater Range (Miocene intrusions and Miocene and younger volcanic strata; Petronis and others, 1997).

Geodesy and geophysics. In collaboration with J.L. Davis (Smithsonian Astrophysical Observatory), we have conducted annual campaign-style GPS geodetic surveys of a 15-site network in Death Valley National Park and the adjacent Yucca Mountain area since 1991 (Bennett and others, 1997; Wernicke and others, 1998a). Since 1996, we have been building a 50-site network of continuously operating GPS stations covering the entire Great Basin and adjacent portions of the Colorado Plateau and Sierra Nevada. The first 18 of these sites, primarily in the northern Great Basin, became operational in 1996 (Bennett and others, 1998; in press). The remaining 32 sites became operational in early 1999 (Wernicke and others, 1998b). Continuous sites include one site each in the Argus Range, Panamints, Funerals, Greenwaters, Dublin Hills, Bullfrog Hills, and Las Vegas Range; two each in the Sierra Nevada, Spring Mountains, and Grand Canyon area; and an additional 15 sites deployed across the southern part of the Nevada Test Site, centered on Yucca Mountain.

In September 1993, in collaboration with a large number of institutions, the group participated in the SSCD, which involved deploying 700 seismometers along an east-west seismic refraction line extending from Visalia to Death Valley Junction, and 2 days later reinstalling the same 700 seismometers along a north-south line from Bishop to the Ridgecrest area.

SUMMARY OF RESULTS

The results of our latest reconstruction (fig. 2, Snow and Wernicke, in press), which modifies an earlier reconstruction (Wernicke and others, 1988) by accounting for new stratigraphic, paleomagnetic and isotopic data, indicate ~250–300 km of west-northwest motion of the Sierra away from the Colorado Plateau since 20 Ma. Extension is balanced by both crustal thinning and north-south shortening of the intervening continental crust. Tertiary intermontane basin deposits and mineral cooling ages of deeply exhumed rocks constrain the overall kinematics, permitting the construction of a strain-compatible “movie” of range-block positions in 2-m.y. increments. This exercise revealed a strong component of westward migration of intense deformation with time,



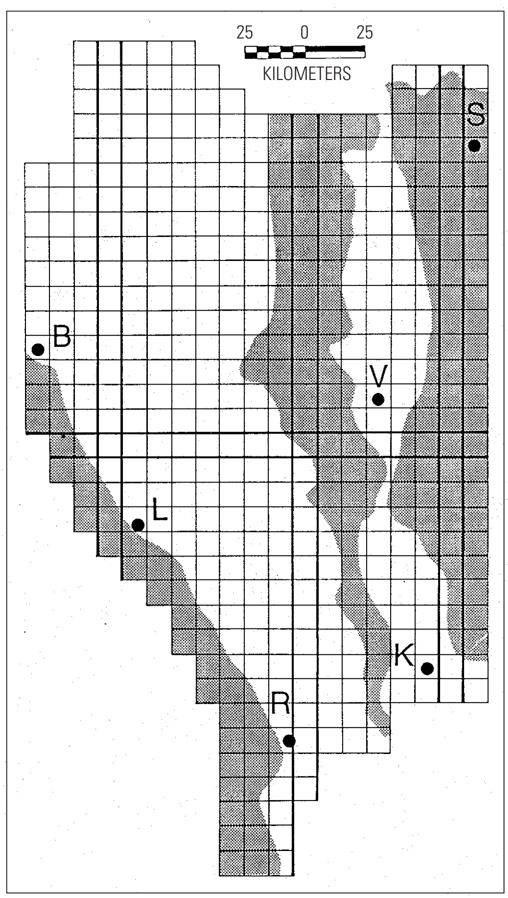


Figure 2 (above and left). Reconstruction of deformation, southern Great Basin region, modified from Snow and Wernicke (1999). Left, configuration at 36 Ma; above, present day configuration. B, Bishop; L, Lone Pine; R, Ridgecrest; V, Las Vegas; S, St. George; K, Kingman.

consistent with the "rolling hinge" model of extensional deformation (Wernicke and Axen, 1988; Wernicke, 1992; Holm and others, 1992; Holm and Dokka, 1993; see also Hoisch and others, 1997).

Kinematic interpretations of local subareas at significant variance with the Wernicke and others and Snow-Wernicke reconstructions include those of Anderson and others (1994) for the Lake Mead area, Caskey and Schweickert (1992) for the Nevada Test Site area, and Cemen and others (1985) and Serpa and Pavlis (1996) for the central Death Valley area. All kinematic models agree that significant extension has affected the crust, but they differ in the restored positions of range blocks and in the amounts of map-view shear, crustal shortening, and crustal thinning so derived. In the author's opinion, these models lack balanced consideration of the entire system of traceable strain markers, each realizing small gains in local simplicity in the face of huge losses in regional coherence, especially in regard to strain-compatible incremental restorations.

The restored positions of range blocks are not specified in the Anderson and others model for comparison with the

Snow-Wernicke model. However, their previously published cross sections through the Mormon Mountains–Tule Springs Hills area that attempt to minimize extension are grossly out-of-balance. Their conservative pre-Cenozoic positioning of the Spring Mountains relative to the Colorado Plateau fails to account for proximal fan breccias on the west side of the region derived from the South Virgin Mountains on the east side. Although we agree with their overall premise that the deformation pattern is complex, it is difficult to identify specific elements in their interpretations that preclude our model, and we therefore find their claims of variance with our model somewhat exaggerated and dificult to evaluate.

The Caskey-Schweickert model of thrust geometry in the Test Site area turns on sparsely exposed, relatively ambiguous structural relations in the Mine Mountain–CP Hills area. Alternative interpretations of this area lead to major differences in the geometry of pre-Cenozoic thrusts, and hence in how one correlates them with thrust to the south and west. Their preferred geometry and correlations do not significantly compromise the Snow-Wernicke reconstruction, which is based primarily on relations in the central Death Valley area. However, they do introduce improbable along-strike complexities in the pre-Cenozoic geometry of both the thrust belt and miogeoclinal stratigraphic trends.

The Cemen and others model calls for relatively modest extension across the central Death Valley region, based primarily on the distribution of middle and upper Miocene strata between the Panamints and the Resting Spring Range. In contrast, the Snow-Wernicke model (essentially the same as that of Stewart (1983) in this area) juxtaposes the Panamint and Resting Spring Ranges in order to align various pre-Cenozoic markers. As with the Caskey-Schweickert model, both the Cemen and others and Serpa-Pavlis models require a complex and improbable initial configuration of these markers. Even if such complexity is granted, both restorations leave proximal middle Miocene conglomerates in the Resting Spring Range stranded many tens of kilometers southeast of their source area in the southern Cottonwood Mountains. These conglomerates record multiple flooding events carrying detritus up to a meter in diameter that is derived entirely from rock types in the modern Marble Canyon drainage, now 105 km to the north-northwest (Niemi and others, 1999). These considerations and paleoflow data suggest that the conglomerates were deposited no more than 10–20 km north-northeast of their source, precluding both models. The comparative tectonic stasis of the central Death Valley area throughout the middle and late Miocene indicated by the Cemen-Wright model also precludes any reasonable explanation for the exhumation of the Black Mountains crystalline terrain from depths in excess of 10 km during the same interval (Asmerom and others, 1990; Holm and others, 1992; Holm and Dokka, 1993).

The principal feature of the Serpa-Pavlis model is a net clockwise rotation of the Panamints relative to the Funerals during deformation, such that the east side of the Panamints lay against the southwest margin of the Funerals, restoring the southern Panamints adjacent to the northern Resting Spring Range. The Serpa-Pavlis model does not take into account major range-parallel distension of the Funerals relative to the Panamints, which precludes their map-view reconstruction geometry and proposed correlations of pre-Cenozoic thrust faults. Further, the proposed relative range block rotations conflict with both paleomagnetic and paleoflow orientations measured in the Panamints and Funerals (Snow and Prave, 1994; Petronis and others, 1997). However, aspects of the Serpa-Pavlis model may provide a more plausible explanation than the Snow-Wernicke model for complex relations in the southern Death Valley area, where in any event regional strain markers are not well defined.

Based on our reconstruction (fig. 2), the motion of the Sierran block with respect to the Colorado Plateau was mainly westerly at more than 20 mm/yr from 16 to 10 Ma, changing to northwest or north-northwest since 8–10 Ma, at an average rate of 15 mm/yr (Wernicke and Snow, 1998). This overall kinematic reconstruction is consistent with two other independent methods of determining the position of the Sierran block since 20 Ma. These include (1) reconstructions based on paleomagnetic data from range blocks that bound the Basin and Range on the west (see L. Frei, 1986, *Geological Society of America Bulletin*); and (2) a revised history of Pacific-North America plate motion based on a global plate circuit (see T. Atwater and J. Stock, 1998, *International Geological Review*). The plate tectonic reconstruction shows a change to more northerly motion between the Pacific and North American plates at about 8 Ma, in concert with the motion of the Sierran–Great Valley block. Moreover, the northeast limit of extant oceanic crust (as indicated by the reconstruction of the continental geology) tracks closely with the southwest limit of extant continental crust (as indicated by the positions of oceanic plates) since 20 Ma. The coordination between plate motions and the intraplate geology implies that we have not grossly overestimated the amount of deformation in the Death Valley and Lake Mead regions; rather it strongly suggests that evolving plate boundary forces were a major influence on deformation within the continent.

The Snow-Wernicke reconstruction makes it possible to quantify the partitioning of strain between vertical crustal thinning (via normal faults), map-view plane strain (via conjugate strike-slip faults), and crustal shortening (via folds and thrust faults). Placing a grid of 10 km×10 km square elements on a retrodeformed map of the region, and measuring the increase in area of grid elements between the undeformed and present-day (Snow and Wernicke, in press), we obtain a maximum finite elongation of the Basin and Range at lat 36°–37° N. of 3.4, oriented N. 73° W. (fig. 2).

Map-view area balance shows that 20 percent of this elongation is accommodated by map-view plane strain, and 80 percent by crustal thinning. This yields an average thinning factor for the upper crust of 2.7 between the Sierra and Plateau, consistent with values suggested previously (Wernicke and others, 1988) and precluding the hypothesis that overall Neogene deformation in the central Basin and Range is predominantly dextral shear plane strain.

The contemporary strain field, however, as revealed by GPS studies, is clearly dominated by regional right shear (Bennett and others, 1997; in press). The extreme localized thinning of the upper crust, in concert with seismic data showing that the southern Sierra Nevada has similar crustal thickness to the central Basin and Range (Wernicke and others, 1996), supports the hypothesis of large-scale eastward flow of Sierran deep crust during extension, as a fluid layer or crustal asthenosphere (Wernicke, 1990, 1992; Wernicke and Getty, 1997).

ROLE OF THE NATIONAL PARK SERVICE IN RESEARCH

During the last 20 years, support for geologic research in the region by the National Park Service and other agencies has generally been strong. Recently, however, in Death Valley National Park in particular, relations between scientists and park managers and patrol rangers have deteriorated significantly. The root of the problem may lie in intensifying demands on the Park Service by Congress, various public interest groups (assuming you're part of their particular public), and possibly even the public itself, without commensurate increases in Federal support. These changes may have promoted misunderstanding on the part of both park managers and researchers as to one another's objectives and concerns.

Researchers perceive a heightened bureaucratic workload unilaterally imposed on them by park managers, and are skeptical that these efforts are of significant benefit to either science or protection of park resources. Based on a formal poll of scientists working in the park, newly instituted permitting and reporting requirements (outlined in *Information for Researchers*, 1995) are variously regarded as unrealistic, excessively bureaucratic, obstructive, out-of-step with the needs of the research community, or all of the above. Despite the official encouragement of research by the park, in practice most researchers complain of an unwelcoming atmosphere and distrust from resource managers and outright hostility from patrol rangers, and believe that substantial damage to the park's scientific mission is being done. Accordingly, these procedures require careful reevaluation by the park. A local task force, perhaps including both researchers and park managers, should be formed to air concerns and establish a new set of permitting and reporting procedures, perhaps more along the lines of those in place prior to 1995.

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[T] Tectonic analysis
[S] Stratigraphy
[C] Geochemistry (geochronology, thermochronology, thermobarometry)
[G] Geophysics (paleomagnetism and seismology)
[N] Neotectonics (geodesy)

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Tectonics of the Southwestern Death Valley Region—A Progress Report

Terry L. Pavlis and Laura Serpa, Dept. of Geology and Geophysics,
University of New Orleans, New Orleans, LA 70143

Tectonic models for the Death Valley region vary widely in the predicted magnitude of extensional versus strike-slip displacements in the major fault systems within the greater Death Valley system. Our group has concentrated on this problem from the perspective of southern Death Valley and northeastern Mojave geology, and because strike-slip deformation dominates within this region we have naturally emphasized this process. Nonetheless, it is clear that the Greater Death Valley system has been characterized by a complex combination of strike-slip and extensional deformation (transtension in the strict sense) throughout the late Cenozoic history of the system.

One of the most unusual tectonic features of the Death Valley region is the extreme contrast in structural style between the northeastern Mojave Desert and central Death Valley region. Specifically, central Death Valley has long been recognized for its extreme crustal extension along systems of low-angle normal faults coeval with strike-slip fault systems (transtension). Just to the south, in the northeastern Mojave Desert, late Cenozoic deformation is dominated by strike-slip fault systems coeval with contractional structures (transpression). Burchfiel and Davis (1981) used this observation to interpet the general boundary between these domains—the Garlock fault—as an intracontinental transform separating the actively extending Death Valley system from the older Mojave Desert system. Although this generalization serves as a good template for general interpretations, the model requires significant modification in detail. Specifically, our work suggests several key modifications.

First, our recent work in Ft. Irwin to the southwest of the eastern termination of the Garlock fault strongly supports the transrotation model for latest Cenozoic left-lateral motion on the Garlock fault (general model of Garfunkel, 1974, with modifications of Dokka and Travis, 1990). Latest Cenozoic deformation at Ft. Irwin is characterized by a combination of north-northwest-trending folds and thrust faults that developed simultaneously with a system of east-west-striking, left-lateral faults, the northernmost of which is the Garlock fault itself (Schermer and others, 1996). Following the general models of Garfunkel (1974) and Dokka and Travis (1990), we infer that the east-west-trending sinistral faults bound a set of transrotational crustal panels within a predominantly dextral shear system. This interpretation is important because offset piercing lines along one of the faults in the array provide clear evidence for ~10 km of sinistral slip on the array, a conclusion suggestive of ~45° of latest Cenozoic clockwise rotation within the array. Applying this slip estimate to a transrotational model indicates that ~55 km of dextral shear have been transferred into the Death Valley region during Pliocene-Pleistocene times; such a shear magnitude is adequate to account for nearly all the apparent Pliocene-Pleistocene dextral shear along both the Panamint and Death Valley fault systems. Thus, by inference, we conclude that for the latest Cenozoic, the east end of the Garlock system did not serve as an intracontinental transform but instead was only one of an array of left-lateral faults that transferred dextral shear into the Death Valley region.

Second, given the evidence for a significant component of transrotation of the Garlock fault itself, the model begs the question of how this vertical axis rotation was transferred into the Death Valley transtensional system. Holm and others (1993) presented paleomagnetic evidence for large-magnitude vertical axis rotations in the Black Mountains, and Serpa and Pavlis (1996) used these data to infer that both the Panamint Mountains and Black Mountains were involved in this rotation. This conclusion predicts significant left-lateral slip at the south end of the Panamint Range in what is now Wingate Wash. Indeed, assuming the transrotational model for the latest Cenozoic history of the eastern Garlock, restoration of this motion allows for a paleo-Garlock fault system near what is now Wingate Wash. We are presently attempting to test this hypothesis through detailed studies in Wingate Wash. As of this writing, results from this study are incomplete, and preliminary conclusions may change as field and geochronological studies progress during spring 1999. Nonetheless, our work to date indicates several important new results within this region:

1. Wingate Wash is neither a simple zone of extension nor a simple strike-slip system. Active deformational features indicated by deformed Quaternary deposits indicate that at least the west half of Wingate Wash is undergoing north-south contraction recognized primarily as young thrust faults and folds. These dip-slip structures are apparently synchronous with northwest-striking dextral faults associated with the Panamint Valley fault system and northeast-striking oblique-sinistral faults that are subparallel to the axis of the wash. We are evaluating the hypothesis that the present topographic expression of the wash may largely be controlled by active thrust systems depressing the crust along the axis of the wash versus a more complex transpressional mechanism. In any case, the topographic expression is clearly not extensional.

2. Latest Miocene or Pliocene sediments in lower (eastern one-third) Wingate Wash lie unconformably on an older geologic framework, and this overlap assemblage obscures much of the older history. Nonetheless, significant structures predate this assemblage because newly recognized exposures of Proterozoic Crystal Springs Formation are faulted against volcanic rocks just north of Wingate Wash but are overlapped by the youngest strata of this sedimentary overlap assemblage. These Miocene-Pliocene strata may represent syntectonic growth strata along fault systems subparallel to the wash. Overlap by the youngest part of the section, however, leaves this conclusion speculative. We are presently attempting to date these sediments using interbedded volcanic flows and ash beds. No active structures have been recognized in lower Wingate Wash, but the youngest structures are a series of west-dipping normal faults that contrast markedly with the contractional structures in the west half of the wash. These sediments possess a complex stratigraphy, but facies distributions clearly indicate the axis of the basin was toward the present site of Death Valley.

3. Below the Miocene-Pliocene unconformity in lower Wingate Wash, the axis of Wingate Wash separates rocks with a very different volcanic stratigraphy. South of Wingate Wash the rocks are dominated by basalt with several distinctive scoria cone centers and surrounding flows with a distinctive rhyolite-tuff marker near the middle of the section. In contrast, rocks north of the wash are dominated by rhyolitic flows, andesites, and basaltic andesites with a preponderance of coarse pyroclastic deposits. Our work on these volcanic rocks north of the wash supports previous conclusions that a large volcanic edifice was present in this region during the Miocene and probably represents a dissected stratovolcano. The absence of these deposits south of the wash is consistent with significant faulting across the axis of the wash, but we have not yet found convincing piercing lines to quantify this offset.

4. Geochemical studies of the Miocene volcanic rocks in the north-central part of Wingate Wash are consistent with the hypothesis that these rocks are the volcanic equivalents of Miocene plutonic assemblages exposed to the east in the Black Mountains. This hypothesis is being further tested by geochronological studies of the volcanic rocks to clarify their absolute age.

Together these observations suggest that the neotectonics of Wingate Wash are primarily driven by a clockwise rotation of the Owlshead domain that is an extension of the transrotation of the Garlock system. As the Owlshead system rotates, the west edge of the system is in contraction against the Panamint block as it moves westward relative to the Owlshead domain. To the east, however, the systems is extensional as the Panamint Mountains pull away from the rotating Owlshead domain. During older (late Miocene?) periods Wingate Wash apparently was a major strike-slip domain, although the exact magnitude of the slip remains poorly constrained.

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Architecture and Miocene Evolution of the Northeast Death Valley Detachment Fault System, Nevada and California

Chris Fridrich, U.S. Geological Survey, Box 25046, Denver Federal Center,
M.S. 913, Denver, CO 80225 <fridrich@usgs.gov>

INTRODUCTION

This paper provides a summary of data and interpretations developed by the author during ~18 months of field work, conducted from 1992 to 1998, in the region extending from the Nevada Test Site southwestward to the floor of Death Valley, Calif. (fig. 3). This region is an excellent subject for a structural geology study because (1) it provides a superb desert-mountain exposure of a complex detachment fault system, as originally described by Hamilton (1989); (2) the development of this system was coeval with the local eruption of numerous widespread tuffs of the southwest Nevada volcanic field, which provide detailed constraints on the timing of evolution of this structural system; and (3) this system differs from most well-studied detachment fault systems in that it accommodated approximately as much strike-slip strain as extension.

ARCHITECTURE OF THE DETACHMENT FAULT SYSTEM

The northeast Death Valley detachment fault system extends over a region that has basin-range topography which formed during the middle to late Miocene evolution of the detachment fault system and reflects its internal architecture, which is a regular arrangement of five partially overlapping, but fundamentally different types of structural domains: (1) areas of tectonic denudation along the main detachment fault, (2) other areas of denudation, (3) extended upper-plate rocks, (4) trailing-edge basins, and (5) transverse basins (fig. 3). Domain type (1) consists mainly of turtlebacks, uplifts formed where the movement along the regional detachment fault has totally removed the upper plate of the detachment exposing the lower plate, which is thus "tectonically denuded" in these areas. Domain type (2) consists of upper-plate areas where the Tertiary cover over Paleozoic and Precambrian rocks has been denuded by other processes including movement along structures other than the main detachment fault, as well as erosion. Whereas strongly metamorphosed rocks are exposed within the northwesternmost parts of the turtlebacks, no metamorphic rocks are exposed in domain (2) areas, indicating a fundamental difference in the processes responsible for the denudation. In the largely Miocene-age basin fills, progressively higher metamorphic grade clasts are found as one progresses upsection, showing that the basins of this region were forming throughout the unroofing of the metamorphic core complex turtlebacks in the adjacent ranges.

The easternmost part of the structural system is an alignment of deep half- or full-graben basins that formed at the "trailing-edge" of the system, defined here as the limit of the system where the detachment fault originally reached the surface. The trailing-edge basins (domain type (4)) thus formed in an area that is mostly beyond the area of detachment faulting; however, areas of relatively minor (~3 km, in most cases, of) tectonic denudation probably are present at least in the westernmost parts of these basins where the detachment fault originally daylighted (figs. 3*B* and 4). The range-front-like master faults (the trailing-edge faults) at the west boundaries of these basins facilitated the abrupt onset of multiple-kilometer footwall uplift in the area of major tectonic denudation that begins immediately to the west of the trailing-edge basins. Hence, the trailing-edge basins, although not evidently underlain by a detachment fault, are nonetheless considered an integral part of the detachment fault system.

The four turtlebacks in this system (fig. 3*B*) are uplifts with smoothly curved upper surfaces. The anticlinal forms of these turtlebacks are either giant mullions or antiformal upwarps of the detachment fault surface, probably a combination of the two. Three of the turtlebacks are metamorphic core complexes, namely, Bare Mountain, the core of the Funeral Mountains, and the small metamorphic turtleback in the south-central part of the Bullfrog Hills (fig. 3). In at least the first two of these features, metamorphic grade increases to the west-northwest, reflecting that the detachment fault originally dipped to the west-northwest and that the magnitude of tectonic denudation increases to the west-northwest in these exposures of the tectonically denuded lower plate of the detachment system. The detachment fault in this system has thus been rotated to a shallower angle as the upper plate was transported to the west-northwest (Hoisch and Simpson, 1993; Hoisch and others, 1997), exposing dip sections through the predetachment upper crust. In all three core complexes, the maximum metamorphic grade is amphibolite, and the age of prograde metamorphism is Mesozoic. Metamorphism associated with the detachment faulting is all retrograde in character, and is associated with the denudation and uplift of the core complexes. Cooling ages for the metamorphic rocks in the core complexes reflect the time of uplift (delayed by the cooling process) and are middle to late Miocene in age (Hoisch and others 1993; 1997), just slightly (~0.5 m.y.) younger than the timing of peak tectonism in the immediately adjacent upper-plate rocks.

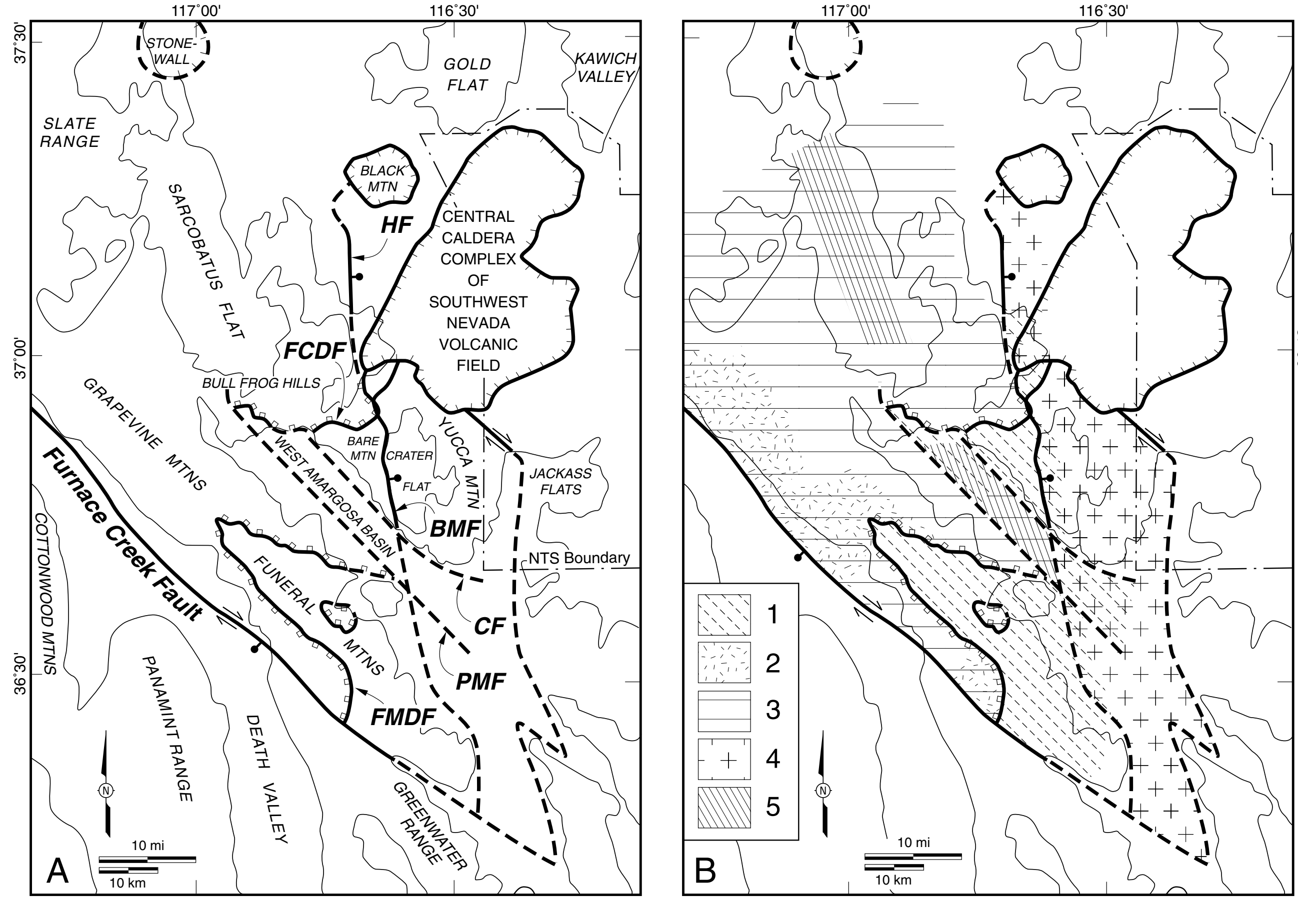

Figure 3*A*. Location map of the northeast Death Valley detachment fault system showing bedrock-alluvium contacts (thin lines), western boundary of the Nevada Test Site (dot-dash line), major faults (thick lines) including caldera margins (thick lines with ticks), exposures of the regional detachment fault of this system (thick lines with square teeth), trailing-edge faults (thick lines with ball and bar), and buried faults (dashed lines). From north to south, major faults shown include the Hogback fault (HF), Fluorspar Canyon–Bullfrog Hills detachment fault (FCDF), Carrara fault (CF), Porter Mine fault (PMF), and Funeral Mountains detachment fault (FMDF).

Figure 3*B*. Same area as figure 3*A*, showing the partially overlapping structural domains of the northeast Death Valley detachment fault system, which are numbered: 1, areas of tectonic denudation along the main detachment fault; 2, other areas of denudation; 3, extended upper-plate rocks; 4, trailing-edge basins; 5, transverse basins.

The three metamorphic core complex turtlebacks are elongate in the west-northwest direction of extensional transport of the upper plate relative to the lower plate. The fourth turtleback is located at the northeast limit of the system (fig. 3), where only the upper part of the Tertiary section has been tectonically removed. Hence, this last turtleback alone is not a metamorphic core complex. To the west-northwest of the turtlebacks, and locally on their flanks, are the large areas of strongly extended upper-plate rocks (domain type (3)) underlain by the same shallowly dipping detachment fault that forms the locally preserved tops of the turtleback surfaces (figs. 3 and 4). The structure in these upper-plate exposures is typically one of closely spaced normal faults with stratal tilts into the faults (“tilted-domino” structure). Structures formed by strike-slip strain are also ubiquitous in the upper plate as well as in the limited exposures within the trailing-edge basins.

Features of the extended upper plate (and of the trailing-edge basins) that formed by strike-slip strain change character laterally across the detachment fault system. Near the northeast limit of the system, in the Crater Flat basin and on the north side of Bare Mountain (fig. 3), the dominant strike-slip feature is a strong southwestward increase in the magnitude of extension, reflected as a chinese-fan pattern of extensional faulting (Fridrich, in press; Fridrich and others, in press) and an associated southwestward increase in stratal tilting and steep-axis rotation (Hudson and others, 1994). Near the southwestern limit of the system, in the Funeral and Grapevine Mountains, the Tertiary strata of the upper plate are shredded by large (~10-km-long) northwest-striking right-oblique-slip faults, the largest of which are predominantly strike slip faults. In the middle of the system, in the southern Bullfrog Hills, the typical structure is intermediate between these two

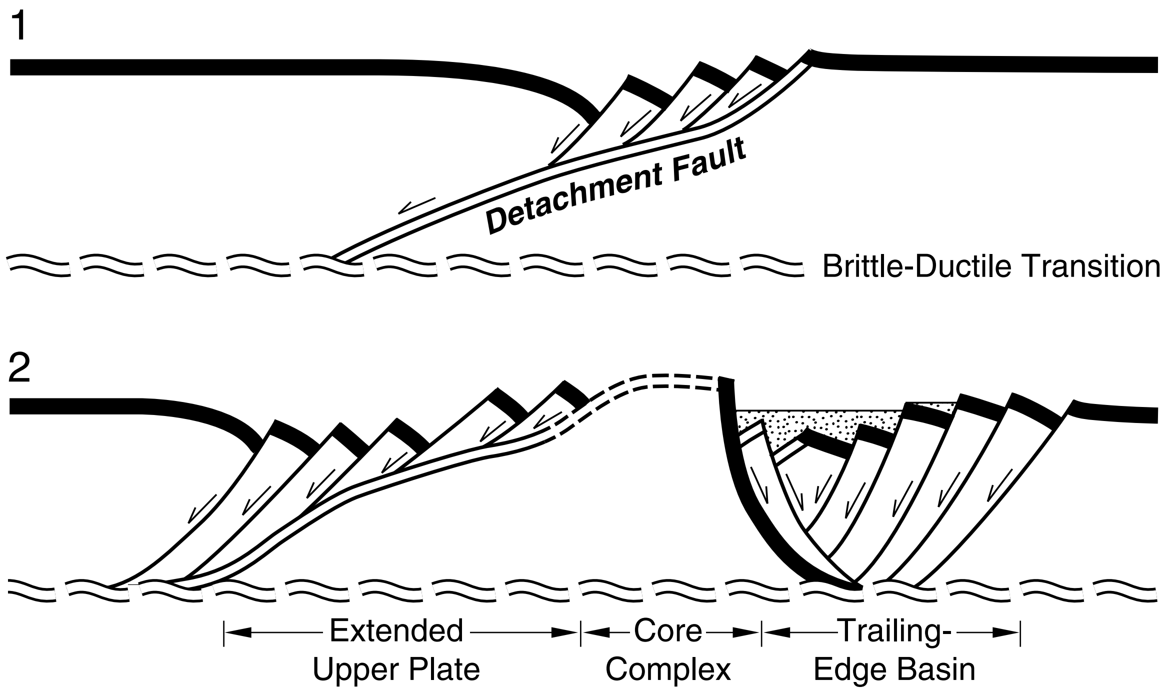

Figure 4. Schematic cross sections drawn in the major direction of extension, showing two stages in the evolution of the detachment fault system: **1**, initiation of detachment faulting; **2**, exposure of a tectonically denuded metamorphic core complex turtleback and development of a trailing-edge basin, at the eastern limit of the core complex, in the area where the detachment fault system originally daylighted.

extremes; it is largely a mosaic of small chinese-fan domains separated by relatively short (typically 3- to 6-km-long) oblique-slip faults, including both northwest-striking right-slip faults and northeast-striking left-slip faults.

The vast majority of the denudation not associated with the main detachment fault is found in the Grapevine and Funeral Mountains, in close proximity to the Furnace Creek fault (fig. 3). In this area Tertiary rocks, along with some underlying Paleozoic rocks, have been shredded by the system of oblique-slip faults described above. Some and probably most of these northeast-dipping faults are strongly listric; they appear to penetrate only shallowly into the pre-Tertiary rocks before flattening out. Additional mapping remains to be done in this area; however, existing data suggest the denudation resulted from strong transtensional deformation of the upper plates of these oblique-slip listric faults as well as extensive erosion of the tectonically shredded upper-plate rocks in the vicinity of the steep scarp along the northeast flank of Death Valley (along the scarp of the Furnace Creek fault).

The final category of structural domains is represented by two transverse basins, the west Amargosa and Sarcobatus Flat basins, extending across and overlapping two of the other four types of structural domains. These two northwest-trending en echelon basins are separated by the Bullfrog Hills (fig. 3). The west Amargosa basin is better understood owing to the availability of high-quality geologic maps and geophysical data. Detailed gravity and magnetic surveys in this basin show two subtle northwest-trending lineaments, interpreted as faults. The Carrara fault extends along the southwest flank of Bare Mountain (Stamatakos and others, 1997; Slemmons, 1997), apparently continuing to the southeast across the southern limit of the Crater Flat basin (fig. 3). The Porter Mine fault extends through the southwest part of the basin and along the west side of the small core complex in the Bullfrog Hills (fig. 3).

The Carrara and Porter Mine faults are interpreted as strike-slip faults based on several lines of evidence, all of which are circumstantial since these faults are nowhere exposed. This evidence includes (1) abrupt large changes in magnitude of vertical-axis rotations across these structures (Hudson and others, 1994; and see data by Hudson published in Fridrich and others, in press), (2) juxtaposition of distal and proximal facies of some volcanic formations at these faults, and (3) large offset of a 13–17 Ma north-northeast-striking growth fault that is interpreted as a piercing point. The preliminary interpretation is that there is about 10 km of right-lateral offset across the Carrara fault and about 25 km of right-lateral offset across the western Amargosa basin as a whole, indicating about 15 km of right-lateral offset across the Porter Mine fault (fig. 3). Mapping on both sides of the Sarcobatus Flat basin is not sufficient to evaluate whether there is strike-slip offset across this basin; however, the large strike-slip offset across the western

Amargosa basin is inferred to continue to the northwest through the Sarcobatus Flat basin.

An apparent problem with the interpretation of strike-slip offset in the western Amargosa basin is that the two strike-slip faults interpreted in this basin evidently do not significantly offset the main trailing-edge fault that extends from Bare Mountain down to the Furnace Creek fault (fig. 3). A likely explanation is that the strike-slip component of the offset across these faults is largely if not entirely limited to the upper plate of the detachment fault system precluding lateral offset of the trailing-edge fault, which is strictly a lower-plate fault. Existing gravity data indicate, however, that the two transverse faults in the west Amargosa basin offset the lower plate in a dip-slip sense or, at least, that the elevation of the regional detachment fault changes abruptly across these transverse structures. Either way, these structures are transverse ramps in the detachment fault.

Several lines of evidence indicate that the northeast Death Valley detachment fault system as a whole is a triangular pull-apart structure. First, Tertiary rocks near the northeast limit of the system show the least extensional faulting and tilting and the least evidence of strike-slip strain (Fridrich, in press; Fridrich and others, in press). Moreover, this deformation terminates completely in the outer margins of the central caldera complex of the southwest Nevada volcanic field. As the southwest limit of the system is approached, strike-slip faults in the upper plate become progressively closer spaced and larger in both length and offset, reflecting the lateral change in the character of strike-slip deformation discussed above. Based on the lateral changes, the system can be divided into several subdomains. Within these subdomains, the magnitude of extensional faulting and related tilting increases strongly to the west or southwest; however, the pattern of variation in magnitude of extensional deformation in the Tertiary rocks across the whole system is highly variable and difficult to generalize. Nonetheless, an overall increase in the magnitude of extension across the whole system is indicated by the strong southwestward increase in the average length of the tectonically denuded turtlebacks in the direction of extensional transport (fig. 3). The abundance of "other areas of denudation" near the southwest limit of the system is also taken as evidence of a southwestward increase in the magnitude of extension because the denudation in this area is associated with transtensional shredding of the Tertiary rocks.

TIMING OF EVOLUTION OF THE DETACHMENT FAULT SYSTEM

The history of Tertiary tectonism in the region of the northeast Death Valley detachment fault system is recorded in the Miocene rocks by features such as angular unconformities, fanning dips (decreasing upsection reflecting tilting concurrent with deposition), upsection burial of faults, stratigraphic thickening across faults, and tectonic (mostly rock avalanche) breccias (Fridrich, in press; Fridrich and others, in press). Owing to the abundance of widespread volcanic units, mainly tuffs, that were locally emplaced during the evolution of this structural system, the ages of these features can frequently be bracketed within about 1–2 million years. Although these constraints are only partly developed in the poorly mapped northwest half of this system at this time, enough is known from the well-mapped southeast half of the system, and from reconnaissance in the rest of the system, to present a tentative picture of how this detachment fault system evolved. However, some details of the timing constraints (fig. 5) are expected to change as additional data are collected.

The first stage of deformation that can be documented in the evolution of the northeast Death Valley detachment fault system extends from 12.7 to 11.6 Ma, the interval between the eruptions of the Tiva Canyon and Rainier Mesa Tuffs. Significant Tertiary extension occurred in this region before 12.7 Ma; however, all existing evidence indicates that the detachment fault system described above did not exist before 12.7 Ma. For example, the structures formed at ~12.7 Ma cut across preexisting extensional structures, and the core complex uplifts of this system, such as Bare Mountain, did not exist until shortly after 12.7 Ma based on the Tertiary stratigraphy in the vicinity of these uplifts (Fridrich, in press) as well as uplift (cooling) ages of the core complexes (Hoisch and Simpson, 1993; Hoisch and others, 1997).

The main area of the 12.7–11.6-Ma tectonic episode is roughly triangular in shape (fig. 5). The dogleg along the northwest boundary of this area is interpreted as a consequence of right-lateral offset of the upper-plate rocks across the Porter Mine fault after 11.6 Ma. In addition, a smaller area of tectonism associated with this interval lies off to the northwest. It may be connected to the main area, as the intervening area is covered by younger (post-11.6 Ma) rocks. Areas of strong tectonism of three additional intervals can be bracketed by younger volcanic units. In sum, these data show a pattern of progressive migration of the area of strong tectonism to the west-northwest during the evolution of this system, from 12.7 to ~7 Ma (fig. 5). The tectonism that has occurred in the region on the northeast of the Furnace Creek fault since ~7 Ma is minor, and in most areas trivial, compared with that of the 12.7–7-Ma interval. In all four intervals discussed here, the magnitudes of both extension and strike-slip deformation increase to the south and west, as is true for the system as a whole throughout its evolution. Tectonism in this region in fact continues to have this fanning-open transtensional style based on the pattern of feeble Quaternary-age faulting (USGS, 1996; and see Fridrich and others, in press, for a comparison of Miocene and Quaternary patterns).

Detailed mapping of subdomains of the study region that are temporally well constrained show relations that bear on the mechanism of detachment faulting. For example, in

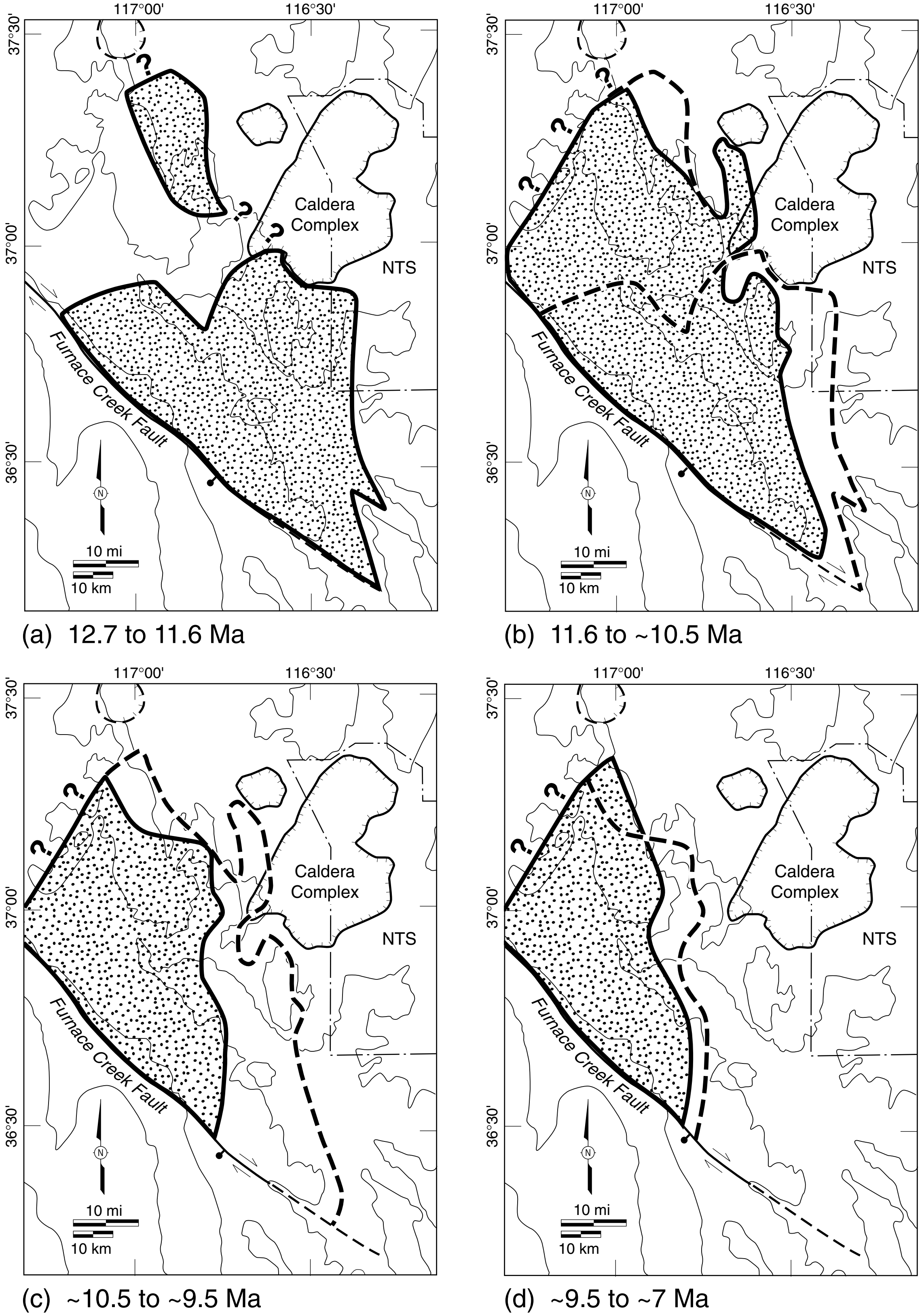

Figure 5 . Areas of strong transtensional tectonism pattern, as evidenced by stratal tilting, faulting, angular unconformities and other features in four intervals in the evolution of the northeast Death Valley detachment fault system: (a) 12.7–11.6 Ma; (b) 11.6– ~10.7 Ma; (c) ~10.7 Ma– ~9.5 Ma; (d) ~9.5– ~7Ma. On panels B, C, and D, the northeastern limit of the area of strong tectonism in the previous stage is shown for comparison. Tectonism in the areas beyond the limits of the northeast Death Valley detachment fault system in these intervals is not shown.

any one place, the record of tectonism is typically one of abrupt onset of a strong pulse of faulting and tilting, followed by a roughly exponential decline in activity over the next 1 to 4 m.y. (Fridrich, in press; Fridrich and others, in press). From the east side of the Crater Flat basin across to the western Bullfrog Hills, there is a regular westward progression in the age of angular unconformities indicating that the tectonism migrated like a wave advancing through the rocks. Relations in the vicinity of the Bare Mountain and Hogback faults show that these trailing-edge faults formed immediately after the local initiation of tectonic denudation and upper-plate thinning associated with movement of the regional detachment fault to the west. The tectonism that formed this detachment fault system thus began with a large pulse of activity at the trailing edge of the system, and, with time, tectonism migrated to the west-northwest away from the trailing edge; hence the name trailing edge.

DISCUSSION

Reasons for defining the region described above as a single structural system are that (1) the whole area appears to be a single megadomain characterized by both large-scale west-northwest-directed extension and coeval strong dextral strike-slip strain, both of which evidently increase to the southwest such that this system is a triangular pull-apart structure, with the caldera complex as the pivot point and the Furnace Creek fault as the line of maximum transport of the upper plate relative to the lower plate; (2) tectonism in this region evolved in a systematic manner over a distinct, relatively short period of time, from 12.7 to ~7 Ma; and (3) it appears that a single regional-scale detachment fault encompasses this area. Although a distinct domain, the region described here does not exist in isolation; it lies in the southern part of the Walker Lane belt, a northwest-trending zone of irregular topography and structure between the Sierra Nevada and the northern Basin and Range (Stewart, 1988). The distributed style of strike-slip strain in the northeast Death Valley detachment fault system is in fact typical of the Walker Lane belt as a whole. In many parts of the world, a 60-km-wide zone of transtensional deformation like that of the study region would not be found along a major strike-slip fault, except in a large releasing bend. The region of this study as well as several other large domains within the Walker Lane belt has this type of deformation in the absence of releasing bends, suggesting that this structural style reflects something else, such as thermal weakening of continental crust by high temperatures at the base of the crust combined with a great preextensional crustal thickness owing to Mesozoic compression.

The Furnace Creek fault has been estimated as having several tens of kilometers of offset northwest of northern Death Valley (McKee, 1968), just beyond the northwest end of the northeast Death Valley detachment fault system, but offset dies out about 140 km to the southeast, at the southwest limit of this structural system. The triangular transtensional pull-apart structure between the central caldera complex of the southwest Nevada volcanic field and the Furnace Creek fault played a major role in accommodating the termination of this major strike-slip fault, but it is only half of the story. The other half of the story lies on the other side of the Furnace Creek fault (Stewart, 1983). The geometric relation of the structure of the northeast Death Valley detachment fault system to the Furnace Creek fault makes it appear that the upper plate of the system was dragged along with the structural block on the southwest side of the Furnace Creek fault, and that the caldera complex, 60 km to the northwest, somehow acted like a nail through the crust, about which the system pivoted. In fact, rocks do not have enough tensile strength for this to be a reasonable actualistic interpretation. It appears more probable that the distributed transtensional deformation of this system reflects the pattern of deformation that was occurring in the lower crust (and upper mantle?) under this region in the Miocene, when the crust was thermally weakened.

The regular west-northwestward migration of tectonism within the northeast Death Valley detachment fault system during its evolution supports one major concept of the rolling-hinge model for detachment faults (Hamilton, 1988; Wernicke and Axen, 1988), which is that detachment faults are rotated to shallower angles as the lower plates are tectonically unloaded and uplifted, and that strongly rotated parts of the fault are abandoned, such that the zone of activity advances in the down-dip direction (away from the trailing edge of the detachment). However, other data from this system do not support the other major concept of the rolling-hinge model, which is that detachment faults start out as high-angle faults. The triangular pull-apart geometry of the northeast Death Valley detachment fault system suggests that this detachment fault was shallower in original dip close to the Furnace Creek fault, steepening progressively to the northeast across the system toward the pivot point. From the halfway point across the north side of Bare Mountain to the northeast (fig. 3), all exposures of the detachment fault today dip 40° or steeper. West of that halfway point, the exposed dips decrease to ~20° at the northwest tip of Bare Mountain, and average ~10° to the south and west of there. Original dip angles can only be calculated at two points in the system, and only with considerable uncertainty; however, they support the same pattern. Using the known extension direction and current geometry of the detachment fault, along with an assumed geothermal gradient of ~30°C/km in the Miocene (in thick pre-12.7-Ma crust), the original angles of formation of the detachment can be estimated from uplift data (DeWitt and others, 1988; Hoisch and Simpson, 1993; Hoisch and others, 1997). The estimated original angles are ~30° for the Fluorspar Canyon detachment at the northwest tip of Bare Mountain and ~15° for the Funeral Mountains detachment. A problem with these estimates is that it appears likely that the middle Miocene geothermal gradient increased toward the caldera complex; hence, the estimate for the Fluorspar Canyon detachment is too high, both in an absolute sense and relative to the estimate for the Funeral Mountains detachment.

Within the last-mentioned trend in the angle of the detachment fault, however, there are some significant deviations. For example, the scarp along the southwest flank of Bare Mountain, which corresponds to the upper-plate Carrara strike-slip fault, is much steeper than both the original and current dip of the detachment fault on either side of this feature. The current dip of the detachment fault flattens abruptly to the west across the line where this feature projects to the northwest, into the Bullfrog Hills, and a significant change in structural geometry of upper-plate faulting, described above (from one big fan domain to a mosaic of small domains), also occurs across this line of projection. Similar changes are found across the Porter Mine fault as well as the Keane Wonder fault, a name given to that part of the detachment fault that forms the southwestern boundary of the Funeral Mountains core complex (Wright and Troxel, 1993; fig. 3). These features are interpreted as transverse ramps in the detachment fault system that separate parts of the regional-scale detachment fault that differed in their original dips. Why these ramps are present in this system is unclear, but they may reflect the effect of preexisting crustal weaknesses on the pattern of original breaking of the detachment fault. Conversely, the lateral change in original dip angle of the detachment fault, necessitated by the triangular pull-apart geometry of this system, may favor the formation of transverse ramps separating segments of the detachment fault that differ in original dip, rather than formation of a detachment having a smooth lateral change in original dip angle.

One feature of this system that is difficult to understand is why the extensional transport direction of the upper plate, relative to the lower plate, is not parallel either to the Furnace Creek fault or to the transverse structures within this system. The best measure of the extensional transport direction is the lineations of mylonites in the metamorphic core complexes, which trend from N. 60° W. to N. 80° W. and average roughly N. 65° W., which is the same as the trend of the long axes of the core-complex turtlebacks. In contrast, the Furnace Creek fault as well as the transverse strike-slip structures in the west Amargosa basin appears, on a large scale, to strike N. 45° W., and the Sarcobatus Flat basin trends N. 25° W. If the greatest principal stress was oriented at about N. 25° E., as the mylonitic lineations suggest, then the resolved stress on the N. 45° W. structures was right-oblique with almost twice as much strike-slip as dip-slip, whereas on the N. 25° W.-trending Sarcobatus Flat basin, the resolved stress was right-oblique with subequal dip-slip and strike-slip. On the one hand, this is consistent with the fact that these transverse structures are in basins, presumably extensional features at least in part, and that the N. 45° W.-striking Furnace Creek fault has a significant component of dip-slip offset. But that still does not explain why these features would form that way.

For an explanation to the above question, I see at least two possible alternatives, which are not mutually exclusive. One is that the transverse structures as well as the Furnace Creek fault were preexisting faults, which, at least for the latter, is supported by the study by Cemen and others (1985) at the southeastern tip of the Funeral Mountains. The other is that the lower crust and upper mantle under this system were extending in more than one direction at once, wherein the primary extension direction was N. 65° W. and a secondary component of extension was roughly perpendicular to the transverse structures. If this second alternative is true, then the regional detachment fault accommodated the primary component of extension and the transverse structures formed as extensional faults cutting the lower plate of the detachment fault system, accommodating the secondary component of extension. Because the Furnace Creek fault is roughly straight rather than strongly arcuate, extension in more than one direction at once is, in fact, an inherent geometric requirement of the triangular pull-apart geometry of this system.

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Temporal, Spatial, and Compositional Constraints on Extension-Related Volcanism in Central Death Valley, California

R.A. Thompson,[1] L.A. Wright,[2] C.M. Johnson,[3] and R.J. Fleck[4]

[1] U.S. Geological Survey, Box 25046, Denver Federal Center, M.S. 913, Denver, CO 80225

[2] Department of Geoscience, Pennsylvania State University, University Park, PA 16802

[3] Department of Geology and Geophysics, University of Wisconsin, Madison, WI 53706

[4] U.S. Geological Survey, 345 Middlefield Rd., Menlo Park, CA 94025

Neogene volcanism in central Death Valley (12–0.7 Ma) was accompanied by large-scale regional extension accommodated in part by regional low-angle faulting, extensive footwall uplift, and significant displacement along northwest-trending strike-slip faults. In excess of 700 km^3 of lava flows, domes, and pyroclastic deposits were emplaced from numerous centers mainly in the upper plate of a northwestward-migrating detachment system. We defined four stages of volcanism based on whole-rock K-Ar geochronology, geologic mapping, petrology, and geochemistry. Stage I eruptions (12–8.5 Ma), associated with the onset of extension, include minor basaltic andesite lava flows but are dominated by calc-alkalic dacite to rhyolite lavas erupted from presently unrecognized centers. This sequence includes the Rhodes Tuff (9.6 Ma), the only regional rhyolite ash-flow sheet in the volcanic field. The deposits were highly attenuated along both low-angle and high-angle faults and, in places, intruded by late Miocene silicic, hypabyssal plutons, stocks and dikes. Stage II eruptions (8.5–7.5 Ma) are coincident with and in places postdate a period of rapid unroofing of the Black Mountains. This sequence includes basaltic lavas (>8 wt.% MgO; <50 wt.% SiO_2) but consists largely of dacite to rhyolite lava flows and minor pyroclastic deposits erupted in the south-central and southeastern part of the field. The third stage of volcanism (7.0–5.5 Ma) postdated major tectonic denudation, was restricted to the central part of the field, and consisted of basaltic to rhyolitic lava flows and small-volume, weakly welded ash-flow tuffs and associated ash-fall deposits. Volcanism between 5.0 and 0.7 Ma (Stage IV) was wholly basaltic to andesitic; deposits are little deformed and restricted to the northern part of the volcanic field with the exception of low-volume eruptions from Quaternary centers on the floor of southern Death Valley. Pre-Quaternary eruptive activity migrated northwestward, paralleling the dominant regional extension direction.

Basaltic lavas are dated at approximately 9.4, 8.5, 8.3, 7.7, 7.5, 7.0, 5.8, 5.0, 4.0, 1.6, and 0.7 Ma, increasing in volumetric proportion with decreasing age. Early basaltic lavas (>8 Ma) in part record contributions from ocean island basalt (OIB)-type mantle, reflected in low LREE to HFSE ratios (La/Ta=12; La/Nb=1), low light- to middle-REE ratios (La(n)/Sm(n)<3) and high epsilon Nd values (ε_{Nd}=+7). Basalts younger than 4 Ma exhibit high LREE to HFSE ratios (La/Ta >50) and low light- to middle-REE ratios (La/Nb >3 and La(n)/Sm(n) >4), giving rise to characteristic Ta and Nb

troughs on chondrite-normalized element plots. These depletions are accompanied by low epsilon Nd values (ε_{Nd}= -7), and thus the sources apparently derive from subduction-modified lithospheric mantle. Coincident eruption of basalts that exhibit trace-element and isotopic characteristics of multiple mantle sources reflects melting of heterogeneous subcontinental mantle during large-scale crustal extension. Major- and trace-element compositions of primitive lavas (<8 Ma) rule out contamination of melts derived from OIB-type mantle solely by assimilation and fractional crystallization processes involving continental crust.

Basaltic rocks exhibit a wide range of isotopic compositions with ε_{Nd}=+7 to –11, I_{Sr}= 0.7045 to 0.7085 and $^{206}Pb/^{204}Pb$=18.0 to 19.0. Primitive compositions [low Th (2 ppm), Rb (11 to 16 ppm) and SiO_2 (<48 wt.%) and high Cr (150 to 260 ppm) and MgO (>7.5 wt.%)] are believed to be derived from three distinct mantle sources: (1) Mantle A, interpreted as ancient LREE-enriched lithospheric mantle, with ε_{Nd}= -6, I_{Sr}=0.7065 and $^{206}Pb/^{204}Pb$=19.0; (2) Mantle C, interpreted as depleted asthenospheric mantle with ε_{Nd}=+7, I_{Sr}=0.7045, and $^{206}Pb/^{204}Pb$=19.0; and (3) Mantle B, possibly a mixture of Mantle A and Mantle C with ε_{Nd}=+2, I_{Sr}=0.7050, and $^{206}Pb/^{204}Pb$ =19.0.

Trends of decreasing $^{206}Pb/^{204}Pb$ ratios with decreasing ε_{Nd} values and increasing I_{Sr} ratios and Th, Rb, and SiO_2 concentrations indicate interaction of primitive melts with an ancient U-depleted crustal component. Samples from chemically defined suites of lavas either increase or decrease in $^{208}Pb/^{204}Pb$ with increasing I_{Sr} and decreasing ε_{Nd}. This suggests that individual suites interacted with one of two types of crust: (1) lower crust with an ancient U and Th depletion similar to Proterozoic granulite basement exposed in the region; or (2) crust with an ancient U-depletion only.

Trends of ε_{Nd} versus time suggest that there was no simple progression in magmatic source regions from lithospheric mantle- to asthenospheric mantle-dominated melts as the magnitude of extension increased, as has been suggested by other studies in the Basin and Range province. Early magmatic input to the crust (12–10 Ma) was dominated by Mantle B, followed in time by input (8.5–5 Ma) from three components: Mantle A, Mantle B, and a reasonable estimate of asthenospheric-type mantle component represented by Mantle C. This later period of magmatic activity coincides with a peak in eruptive volume, partly coincident with latter stages of extension and unroofing of the Black Mountain crustal block (Holm and others, 1992; Holm and Dokka, 1993; Wright and others, 1991; Serpa and Pavlis, 1996).

Combined Pb isotope data (this study and the Nova basalts of the northern Panamint Mountains (Coleman and Walker, 1991) suggest that the lithospheric mantle beneath the Death Valley region has highly variable $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$. The geographic distribution of these rocks suggests that a major structural and (or) geochemical boundary separates the subcontinental mantle beneath the eastern and western extremes of the region.

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Fluid Flow during Metamorphism and Deformation in the Panamint Mountains

Theodore C. Labotka, Department of Geological Sciences, University of Tennessee,
Knoxville, TN 37996-1410 <tlabotka@utk.edu>

Regional metamorphism of the Precambrian sedimentary rocks in the Panamint Mountains, Calif., occurred during the middle and late Mesozoic Era in association with emplacement of granitic rocks in the Sierran arc and folding along north-northwest-trending axes. The rocks show development of low-pressure, high-temperature assemblages, which preserve Jurassic ages, followed by generally retrograde assemblages, which have a Late Cretaceous age, similar to the age of muscovite-bearing granite found throughout the central and northern Panamint Mountains. The metamorphic rocks were displaced by Tertiary normal faults associated with the widespread extension throughout the Death Valley region.

Low-pressure, high-temperature metamorphism required an enhanced flow of heat through the upper part of the crust, a process that can be heightened by the flow of aqueous fluids through the magmatic arc. Study of the extent of fluid flow during metamorphism in the Panamint Mountains indicates that fluids were largely stratabound, although there is evidence for fluid mixing across stratigraphic boundaries in some places. There is evidence for much more extensive fluid flow along faults and shear zones during Cretaceous metamorphism and Tertiary extension.

The rock types in the Panamint Mountains include pelitic schist, calcsilicate marble, and calcareous schist. In general, assemblages in the calcsilicate marble formed in equilibrium with a CO_2-rich fluid, calcareous schists equilibrated with H_2O-rich fluid, and an intermediate-composition fluid permeated pelitic schists during prograde metamorphism. Retrograde metamorphism occurred in the presence of a uniformly H_2O rich fluid.

The stable-isotope composition of carbonate rocks from the Noonday Dolomite clearly records the fluid-rock interaction. Rocks from the upper reaches of Wildrose Canyon contain the assemblage dolomite + quartz + calcite + talc, indicating a relatively low fluid:rock ratio for which the fluid composition was capably buffered to CO_2-rich compositions. The fluid composition and temperature of metamorphism of these rocks are related (fig. 6). Small amounts of reaction drove the fluid composition to the invariant point near 450˚C and $x_{CO_2} = 0.6$, at which tremolite replaced talc.

The dolomite is faulted in many places, and the marble was retrograded. Fine-grained calcite and dolomite mostly replaced tremolite. The isotopic composition of calcite and dolomite is shown in figure 7, which also shows the fractionation between calcite and dolomite at two temperatures. Grains of calcite and dolomite extracted from relatively unaltered matrix preserve the prograde fractionation with a $\Delta^{18}O$ dol-cc = 0.5; grains from the altered tremolite have much greater fractionations, with a $\Delta^{18}O = 4.0$. The pattern of alteration indicates that calcite exchanged with an isotopically light fluid before dolomite during retrogradation. The Noonday Dolomite was extensively infiltrated by an exotic fluid only during retrograde metamorphism. The compositions of calcite and dolomite in the unaltered rocks are essentially those of the sedimentary rock before metamorphism. The fluids during prograde metamorphism were the local pore fluids.

The source of the retrograde fluid is not yet known. The compositions of C and O isotopes in the underlying Kingston Peak Formation do not show evidence for massive infiltration of exotic fluid, despite the petrologic evidence that the rocks equilibrated with a large volume of H_2O, an amount necessary to dilute the large volume of CO_2 released during the recrystallization of the calcareous rocks. In fact, the C-isotope composition was controlled by reequilibration between calcite and graphite and shows no influence of external fluids at all. The metamorphic fluid in the Kingston Peak Formation may still be the source of the retrograde fluid that infiltrated the overlying Noonday Dolomite.

The Johnnie Formation, lying above the Noonday Dolomite, also contains evidence that the metamorphic fluid was local, although the textures indicate that the Johnnie Formation was infiltrated by an H_2O-rich fluid. The rocks contain porphyroblasts of andalusite that enclose relict porphyroblasts of cordierite. The pelitic schist appears to have buffered the fluid composition in the presence of graphite by the reaction, chlorite + muscovite + quartz = cordierite = andalusite + biotite + H_2O (fig. 8). Infiltration of H_2O, probably from the underlying Noonday Dolomite, resulted in the consumption of graphite, an increase in x_{H_2O}, and conversion of the earlier cordierite porphyroblasts to chlorite + muscovite + quartz.

This study indicates that the low-pressure, high-temperature metamorphic terrain in the Panamint Mountains formed in the absence of large-scale heat advection. The high geothermal gradient must have resulted from the enhanced heat flow associated with the Jurassic magmatic arc.

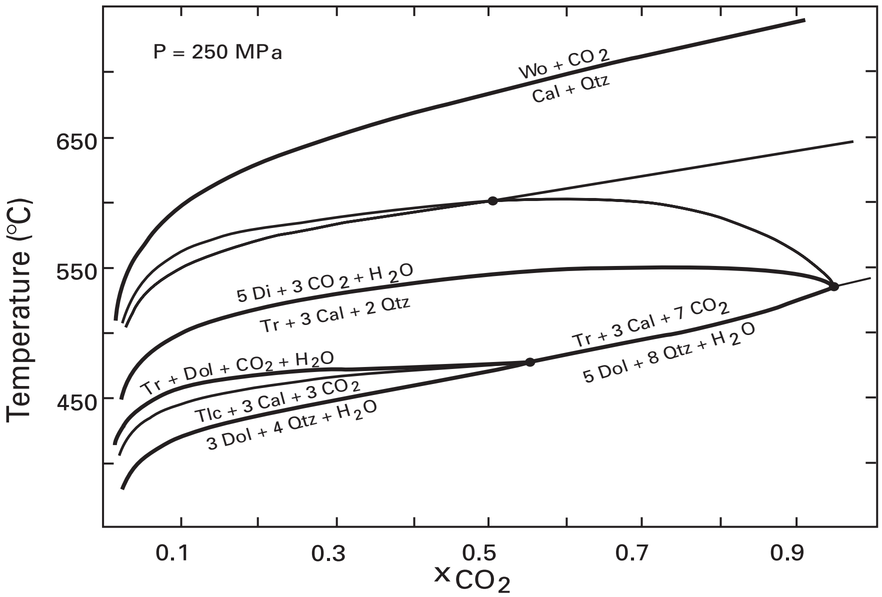

Figure 6. Relation of fluid composition and temperature of metamorphism in samples from Wildrose Canyon.

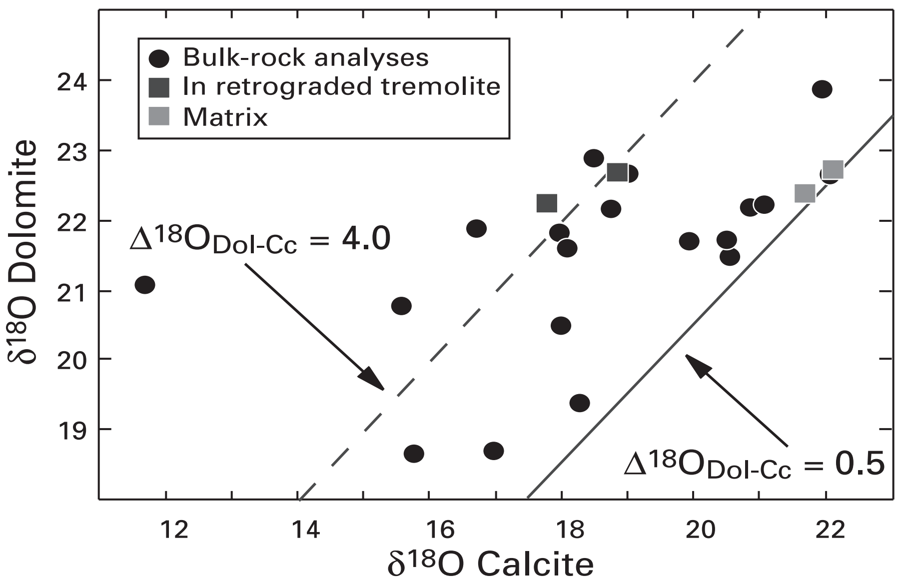

Figure 7. Isotopic composition of calcite versus dolomite, Wildrose Canyon samples.

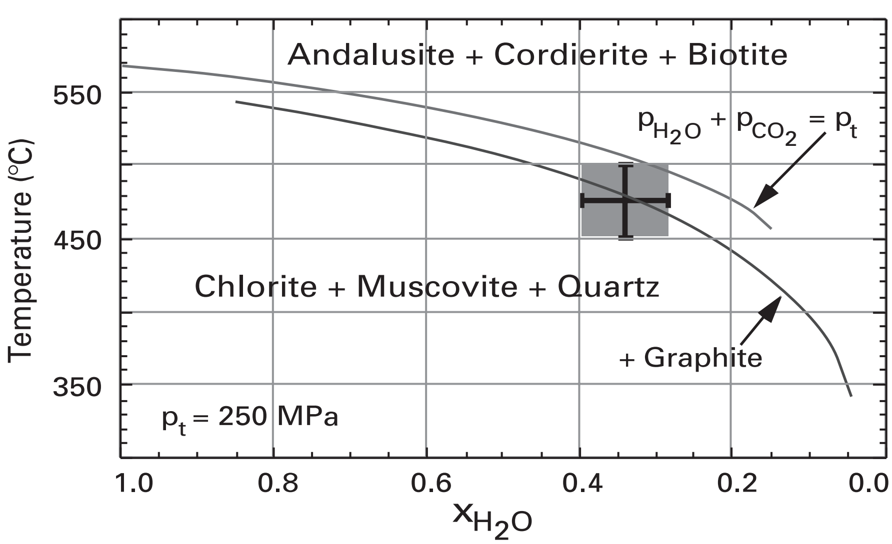

Figure 8. Metamorphic fluid versus temperature in samples from the Johnnie Formation.

Preliminary Results of Detailed Structural Investigation and Large-Scale Mapping in the Southern Panamint Range, California.

Joseph E. Andrew, Geology Dept., Room 120, Lindley Hall, University of Kansas, Lawrence, KS 66045
<joejoe@eagle.cc.ukans.edu>

Detailed structural data collected from the southern and western Panamint Range during summer 1998 delimit a complex, multiple-event tectonic history. At least six distinct deformation events are noted, building and expanding on previous authors' results and interpretations. The oldest event is manifested as east-vergent thrusts, duplexes, and abundant microfolds in carbonate rocks. This deformation is older than a 148-Ma quartz diorite (recalculated from Armstrong and Suppe, 1973) and may coincide with high-grade metamorphism along the western Panamint Range at 170–150 Ma (Labotka and others, 1985). West-vergent deformation overprints earlier east-vergent structures. The Big Horn Canyon fault (BHCF) (McKenna and others, 1993) is a west-vergent structure interpreted to be extensional based on stratal omission and antipodal reactivation of thrust faults. This deformation affects the 148-Ma quartz diorite, and is cut by the 140-Ma (recalculated from Armstrong and Suppe, 1973) Manly Peak pluton (McKenna and others, 1993; Andrew, unpub. mapping, 1998). East-vergent, north-trending reverse faults of the South Park Canyon fault system (SPCF) (Johnson, 1957; McKenna and others, 1993) cut the BHCF (Johnson, 1957; McKenna and others, 1993; Cichanski, 1995), and the Manly Peak pluton, and deform the east edge of the South Park Canyon pluton. The maximum age of the SPCF is 107 Ma (Cichanski, 1995), and the minimum age is constrained by the Skidoo and Hall Canyon plutons, 100–83 Ma (Lanphere and Dalrymple, 1967; Hodges and others, 1990) and ~70 Ma (Crossland, 1995; Mahood and others, 1996), respectively. These two Late Cretaceous plutons intrude country rocks with strong top-east fabrics, but these plutons have no top-east fabrics. The next deformational event is best preserved in the northern Panamint Range as the Harrisburg fault (HF) (Hodges and others, 1990). The HF has stratal omission, cuts the Skidoo pluton, and is cut by the 11-Ma Little Chief stock (Hodges and others, 1990). The Hall Canyon pluton was originally interpreted by Crossland (1995) to have intruded passsively, but there is evidence for syn-intrusive west-vergent shear. This deformation may correlate to extensional deformation of a same-age pluton in the nearby Funeral Mountains (Applegate and others, 1992). Local, north-striking dextral shear zones occur along the western range flank (Cichanski, 1995; Crossland, 1995), locally reactivating reverse faults. The age of dextral shear is interpreted to be about 55 Ma (Cichanski, 1995), based on $^{40}Ar/^{39}Ar$ ages (Labotka and others, 1985). Lastly, Tertiary top-west extension created the present western flank of the range via top-to-the-west removal of hanging-wall rocks to expose the footwall rocks, which compose the Panamint Range. Tertiary extension reactivated many of the Mesozoic structures, but this extension resulted in a strong brittle fabric which can be contrasted with the more ductile fabric of the Mesozoic events.

Mapping also addressed the Butte Valley fault (BVF) (Wrucke and others, 1995) and its relation to other structures in the Panamint Range. To the south, the BVF is composed of at least three, near-vertical, north-northeast-trending faults that have east-side-down offset (Johnson, 1957; Miller, 1983; Cole, 1986; Andrew, unpub. mapping). These faults cut Tertiary volcanic rocks probably related to 14–12-Ma volcanic rocks in the Owlshead Mountains (Davis and Fleck, 1977). These faults cut Proterozoic to Tertiary rocks; farther north these faults cut the BHCF (Johnson, 1957; Cichanski, 1995; Andrew, unpub. data) and are then cut by the Little Chief stock in the central Panamint Range (Albee and others, 1981). These faults may be related to the emplacement of the Little Chief stock, synchronous with Tertiary extension (Hodges and others, 1990).

The previously interpreted continuation of the BVF in Warm Spring Canyon (Wrucke and others, 1995) shows a much different history than the BVF in Butte Valley. In Warm Spring Canyon this fault is a west-northwest-trending fault overlain by Tertiary volcanic rocks, and it thus must be either synchronous with lava-field development at 14–12 Ma or must be older than the BVF in Butte Valley. This fault is herein termed the Warm Spring Canyon fault (WSCF). The WSCF separates upper Paleozoic sedimentary rocks on the south from Proterozoic metasedimentary rocks on the north (Wrucke and others, 1995). Subhorizontal slickenlines with sinistral offset are found along the fault. The fault appears to cut 154-Ma (recalculated K-Ar, Stevens and others, 1974) quartz diorite. The Proterozoic strata on the north side of the fault are deformed into a large fold with a fold trace parallel to the fault. The north limb of this fold is subhorizontal, whereas the south limb is subvertical and very attenuated from a normal stratigraphic thickness of ~2,000 m (Hunt and Mabey, 1966) to ~270 m. Microfolds in the north limb indicate top-to-the-south shear. This fold is intruded by the 154-Ma intrusion along the southern portion of the southern limb. An older kinematic story is preserved as abundant small to large blocks of L-tectonite porphyritic granite within the quartz diorite. The present-day average orientation of these lineations is west-northwest trends and subhorizontal plunges. The quartz diorite and the large fold appear to be cut by the west-vergent extensional faults, but the quartz diorite also cuts several faults. The sinistral WSCF may be related to the top-west extensional faults as accommodation or transform faults. The age of this extensional faulting is Late Jurassic, Late Cretaceous, or Tertiary, if comparable to other deformations in the central portion of the Panamint Range. These observations elucidate separation of the WSCF from the BVF but don't resolve the controversy as to the major deformation that folded and thinned the Late Proterozoic rocks.

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Magnitude and Timing of Extreme Continental Extension, Central Death Valley Region, California

N.A. Niemi,[1] B.P. Wernicke,[1] R.J. Brady,[2] J.B. Saleeby,[1] and G.C. Dunne[3]
[1]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125
<niemi@gps.caltech.edu>; <brian@gps.caltech.edu>; <jason@gps.caltech.edu>
[2]Northstar Energy Corp., 3000, 400 – 3rd Avenue SW, Calgary, Alberta, Canada T2P4H2
<robbr@northsnrg.com>
[3]Department of Geological Sciences, California State University, Northridge, CA 91330
<george.dunne@csun.edu>

New geochronologic, stratigraphic, and sedimentologic data indicate extreme late Cenozoic extension across the central Death Valley region (fig. 9). $^{40}Ar/^{39}Ar$ geochronology of sanidine from tuffs intercalated with steeply tilted sediments along the eastern margin of the central Death Valley region, including sections near Chicago Pass and at Eagle Mountain, indicates deposition from approximately 15 to 11.7 Ma (fig. 10). Clasts of marble, orthoquartzite, fusilinid limestone, and leucogabbro are prominent at both locations. The only known source in the Death Valley region for this clast assemblage is in the southern Cottonwood Mountains, more than 100 km away on the western flank of the Death Valley region. U/Pb geochronology of baddeleyite confirms that leucogabbro clasts from both sections have the same igneous crystallization age (~180 Ma) as the leucogabbroic phase of the Hunter Mountain batholith, in the southern Cottonwood Mountains. The sediments include debris flows, flood deposits, and monolithic boulder beds of large leucogabbro clasts (>1 m), suggesting deposition in an alluvial fan setting. Sedimentary transport of these deposits is unlikely to have exceeded 20 km. Restoration of the Eagle Mountain and Chicago Valley

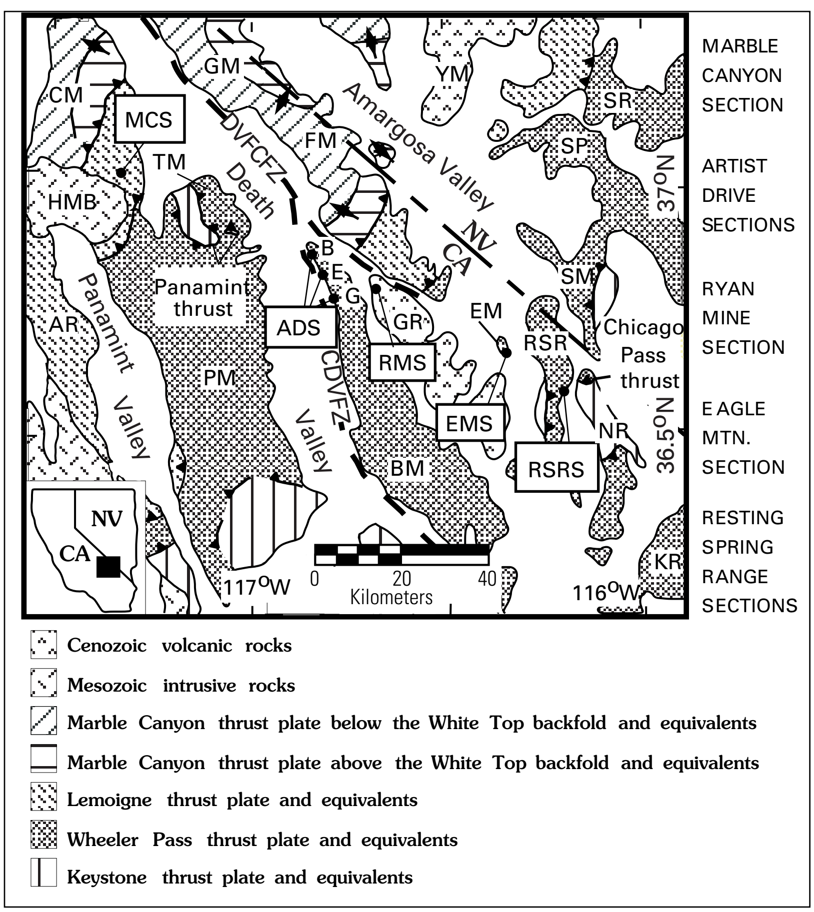

Figure 9. Map showing major ranges and basins in the Death Valley region, distribution of thrust faults and folds offset along Cenozoic normal and strike-slip faults, Hunter Mountain batholith, and locations of selected middle and upper Miocene stratigraphic sections discussed in text. Patterns on range blocks indicate thrust sheets as defined by Snow (1992). AR, Argus Range; BM, Black Mountains; CDVFZ, Central Death Valley Fault Zone; CM, Cottonwood Mountains; DVFCFZ, Death Valley–Furnace Creek Fault Zone; EM, Eagle Mountain; FM, Funeral Mountains; GM, Grapevine Mountains; GR, Greenwater Range; KR, Kingston Range; PM, Panamint Mountains; RSR, Resting Spring Range; SM, Spring Mountains; SP, Specter Range; SR, Spotted Range; TM, Tucki Mountain; YM, Yucca Mountain.

deposits to a position just east of the southern Cottonwood Mountains results in approximate net translations of 80 km and 104 km, respectively, at an azimuth of N. 67° W. (fig. 11). This suggests overall extension magnitudes of at least 500 percent across the Death Valley region since 12 Ma, with strain rates that approached 10^{-14}/s during maximum extension. These results support previous reconstructions based on isopachs and Mesozoic structural features. (See, for example, Wernicke and others, 1988.)

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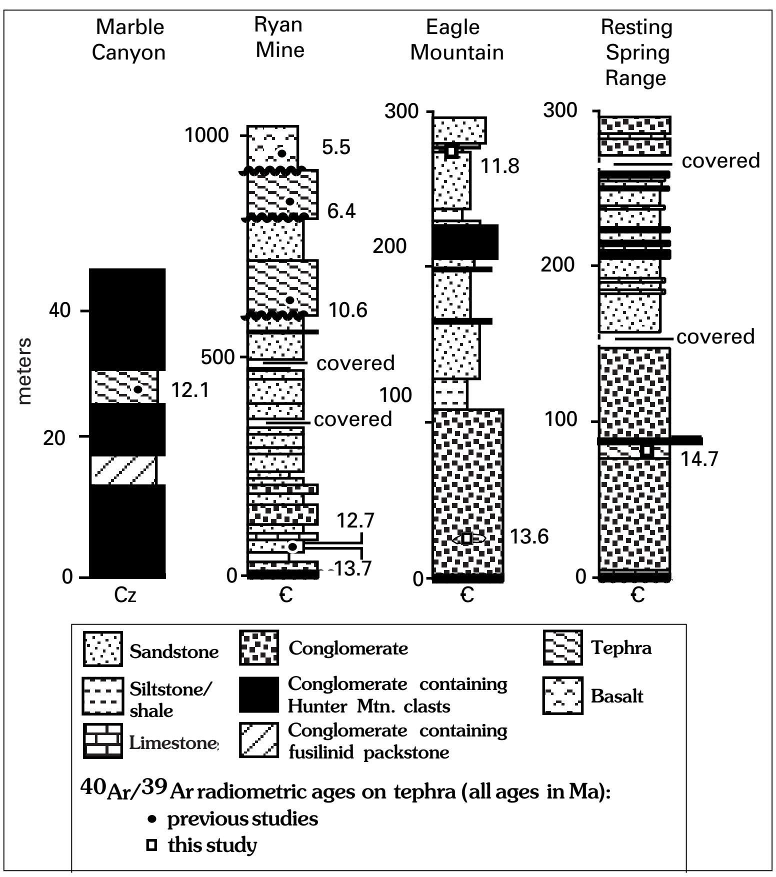
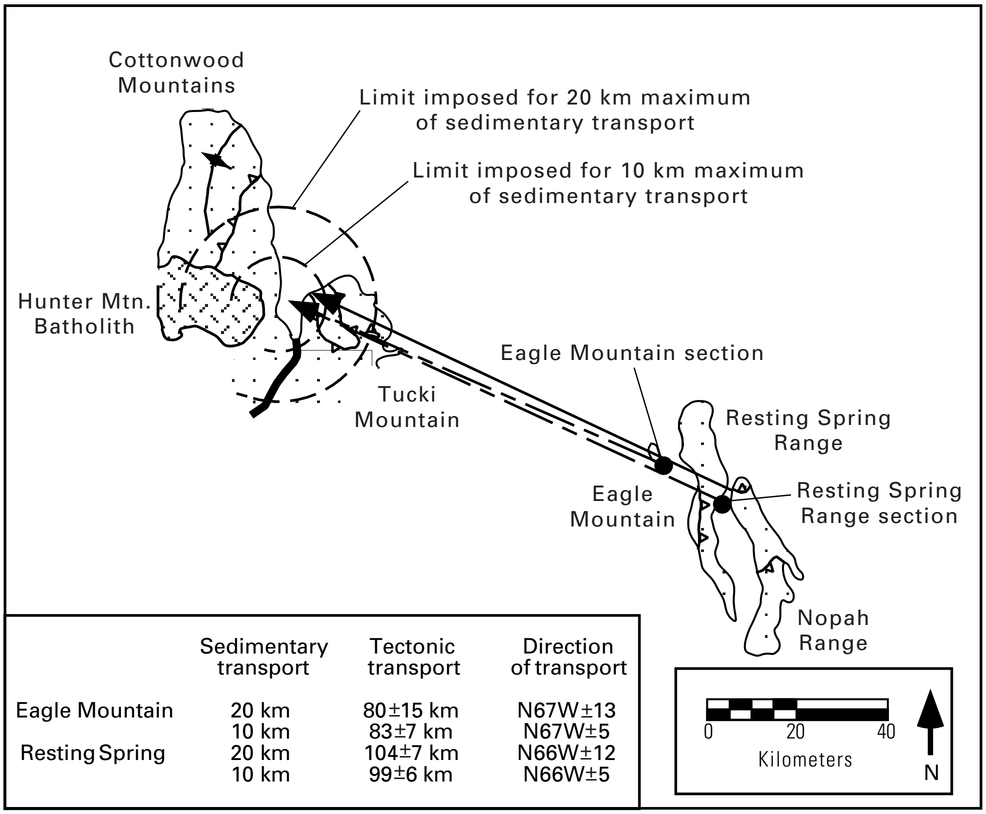


Figure 10. Columnar sections of middle and upper Miocene strata located on figure 9, except the Artist Drive sections. Marble Canyon section from Snow and Lux (in press). Ryan Mine section from Cemen and others (1985) and Greene and Fleck (1997). Radiometric ages for Ryan from Cemen and others (1985) and Greene and Fleck (1997), for Marble Canyon from Snow and Lux (in press) and this study. Note scale differences between sections.



	Sedimentary transport	Tectonic transport	Direction of transport
Eagle Mountain	20 km	80±15 km	N67W±13
	10 km	83±7 km	N67W±5
Resting Spring	20 km	104±7 km	N66W±12
	10 km	99±6 km	N66W±5

Figure 11. Map showing probable original limits of the Eagle Mountain Formation with respect to the southern Cottonwood Mountains for 10-km and 20-km maximum sedimentary transport from easternmost exposures of Hunter Mountain batholith.

Field and Laboratory Studies of Fault Rocks from Detachment Faults, Western Black Mountains, Death Valley

Darrel Cowan,[1] Trenton Cladouhos,[1,2] Nicholas Hayman,[1] Julia Morgan,[3] and Peter Vrolijk[4]
[1]Dept. of Geological Sciences, University of Washington, Seattle, WA 98195-1310
[2]Golder and Associates, Redmond, WA 98052
[3]Dept. of Geology and Geophysics, University of Hawaii, Honolulu, HI 96822
[4]Exxon Production Research Co., Houston, TX 77252-2189

We are investigating the origin and history of fault rocks developed along late Cenozoic and Quaternary low-angle normal faults at the western front of the Black Mountains. Using photo bases, we mapped fault rocks at scales of 1:10 along the segments of the Badwater Turtleback, Mormon Point, and Copper Canyon detachments. Fault rocks typically are disposed in regular zones beneath a sharp, striated fault plane. Fine-grained, locally flow banded gouge is present immediately beneath the fault plane. Next below is crudely foliated, coarser grained cataclastic breccia, which overlies a fractured, or damaged, footwall. We infer that this zonation reflects particle paths and a gradient in total shear strain analogous to those recorded in mylonitic shear zones.

Studies of microfabric in gouges indicate that a very strong shape-preferred orientation exists, parallel to the boundaries of the shear zones. We infer the shape-preferred orientation to have resulted from rotations in a matrix deformed to high shear strains. Our analysis of particle-size distributions in rocks affected or created by faulting shows that the 3-D power-law exponent, or fractal dimension, increases from 2.6 in the damaged footwalls to 3.5 in gouges. These data conflict with models hypothesizing a universal fractal dimension of ~2.6 in fault rocks and indicate that particle-size distributions reflect diverse micro-scale mechanisms of deformation and grain-size reduction.

Based on observations to date, we hypothesize that cataclasis and fluid-driven authigenesis proceeded contemporaneously during slip on these faults. We consider the fault rocks to be an analog for a certain type of fault seal. Petrographic, X-ray diffraction analyses, and bulk chemical analyses indicate that although the fault rocks were not completely open systems with regard to fluids, authigenic minerals such as mixed-layer clays grew during deformation. In a current phase of our study, we are characterizing the evidence for coupled cataclasis and authigenesis, and evaluating different models for the conditions of authigenesis and the nature of fluid-rock interactions in the fault zones.

Evidence for Pre–55 Ma Phanerozoic Fabrics in the Black Mountains, Death Valley, California

Martin G. Miller <millerm@darkwing.uoregon.edu>,[1] Henry Turner,[1] and Richard M. Friedman[2]
[1]Dept. of Geological Sciences, University of Oregon, Eugene, OR 97403
[2]Dept. of Earth and Ocean Sciences, University of British Columbia, Vancouver, BC V6T 1Z4 Canada

Structures within the footwalls of the three turtlebacks of the Black Mountains are generally considered to reflect late Tertiary extension. Pegmatite with a known early Tertiary age, however, cuts some mylonitic and nonmylonitic foliations at the Badwater Turtleback, indicating an earlier period of metamorphism and deformation. Similar but presently undated pegmatite also intrudes the footwalls of the Copper Canyon and Mormon Point Turtlebacks; it locally cuts fabrics there as well. We are determining ages on additional pegmatite bodies and examining pre-pegmatite fabrics in the Black Mountains to (1) determine the extent of early Tertiary magmatism, and (2) understand the style and kinematics of early Tertiary or older deformation.

The pegmatite yields two U-Pb zircon ages of 54.7 ± 0.6 Ma and 56 ± 3 Ma (Miller and Friedman, 1999) at the Badwater Turtleback. This age is unique for southeastern California, because it greatly postdates Sierran magmatism but predates late Tertiary extension-related magmatism. The nearest known similar-aged magmatism occurred in Arizona as part of the Laramide event (Dickinson, 1989). In Death Valley, the closest magmatic ages come from a 70–72-Ma pegmatite in the Funeral Range (Applegate and others, 1992).

Generally, at shallow structural levels of the turtlebacks, pegmatite is deformed with the surrounding country rock. Where surrounded by mylonitic carbonate, it forms lens-shaped, locally mylonitized outcrops interpreted by Miller (1992) and Miller and Friedman (1999) as boudins (figs. 12*A*, *B*). Where surrounded by gneiss or schist, the pegmatite forms mylonitized sills (fig. 12*C*). Therefore, fabrics at shallow levels, because they involve the pegmatite, reflect the well-documented, top-to-the-northwest late Tertiary extension.

At deeper structural levels (>50 m), the pegmatite locally forms dikes that cut mylonitic and nonmylonitic foliations in all rock types (fig. 13*A*). These dikes are well documented at the Badwater Turtleback (Miller and Friedman, 1999) but also exist at the Mormon Point and Copper Canyon Turtlebacks. Some dikes, which become sill-like at either end where they are deformed by later foliation, enable the distinction between pre- and post-pegmatite foliations (fig. 13*B*).

Pre-pegmatite foliations appear to exist as rafts within and concordant to the post-pegmatite foliations (figs. 13*B*, 14). They also typically display northwest-trending mineral lineations, subparallel to the late Tertiary direction. In contrast to post-pegmatite foliations, which are dominantly mylonitic, most pre-pegmatite fabrics we have observed are nonmylonitic. They may, however, display evidence for limited shear strain in the form of micro-scale asymmetries and mineral lineations. In conjunction with the mylonites that do exist, they likely represent a broad zone of

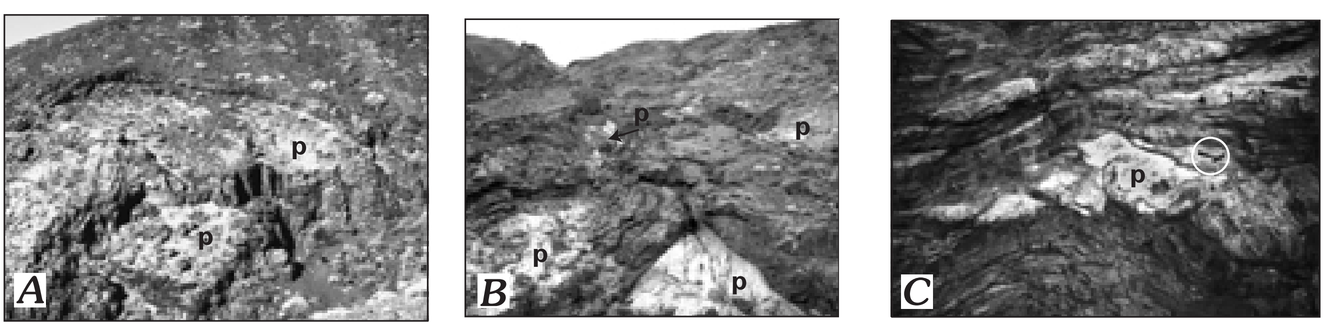


Figure 12. Photographs of deformed pegmatite (p) at high structural levels of the turtlebacks. *A*, Boudin-shaped bodies in carbonate of the Badwater Turtleback. Image is approximately 30 m high. *B*, Boudin-shaped bodies in carbonate of the Mormon Point Turtleback. Outcrop at lower right is fault-bounded. *C*, Sill-like body in mylonitic gneiss at Badwater Turtleback. Handle of rockhammer (circled) is parallel to northwest-trending stretching lineation.

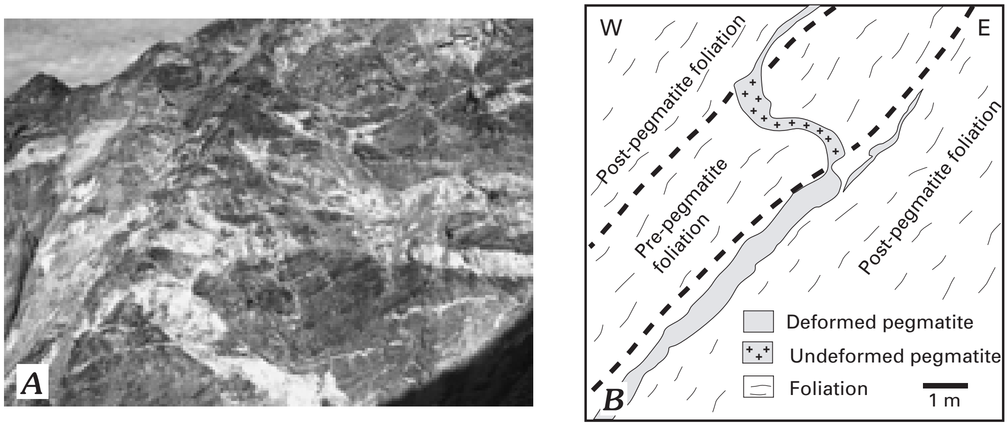


Figure 13. Photograph and field sketch of relations at deep structural levels. *A*, Pegmatite dikes cutting foliation at Badwater Turtleback. *B*, Pegmatite dike/sill and relations with foliation at Copper Canyon Turtleback.

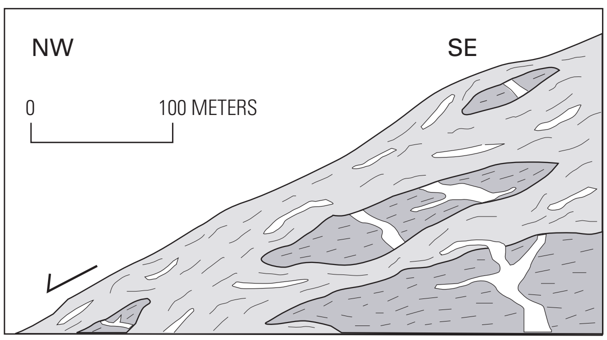


Figure 14. Schematic cross section to illustrate relation between pre-pegmatite and post-pegmatite fabrics. Post-pegmatite fabrics are light gray; pre-pegmatite fabrics are medium gray. From Miller and Friedman (1999).

deformation. Our preliminary determination of shear sense is inconclusive.

These fabrics involve, and therefore postdate, Late Proterozoic metasedimentary rocks. As they are also asociated with probable contractional structures, they are likely Mesozoic in age, related to deep-seated deformation of the fold-thrust belt. We cannot yet rule out, however, a Permian or earliest Tertiary age. The contractional structures include a thrust fault near the top of the Mormon Point Turtleback (Holm, 1992), repetition of the Noonday Dolomite between the Mormon Point Turtleback and Gold Valley (L.A. Wright, written commun., 1997), and the presence of Precambrian basement rock structurally above Late Proterozoic metasedimentary rocks at the Badwater Turtleback.

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Structural Features of the Amargosa Fault near Virgin Spring Canyon

Charles Rogers <crogers@darkwing.oregon.edu> and Martin G. Miller,
Dept. of Geological Sciences, University of Oregon, Eugene, OR 97403

The Amargosa fault, as defined by Noble (1941) and mapped by Wright and Troxel (1984), is the fault contact in the southern Black Mountains between Precambrian crystalline basement and overlying Proterozoic and younger sedimentary and volcanic rock. This contact typically plays a central role in tectonic reconstructions of Death Valley, but detailed structural description is generally lacking. Near Virgin Spring Canyon, Wright and Troxel (1984) showed that the contact consists of three distinct geometrical segments: a south-dipping, a north-dipping, and an east-dipping segment (fig. 15). Many workers interpret these segments as parts of a single folded fault surface. We are beginning a project to test this interpretation by determining the detailed geometries and kinematics of the three segments.

Our preliminary field work shows that each segment is markedly nonplanar in that each displays abrupt changes in dip angle (fig. 15). These changes do not appear to indicate originally listric geometries, because many of the shallow angles exist at higher elevations than do the steep angles. Instead, the segments locally coincide with orientations of footwall foliation and so may reflect basement control. Along steep portions of the south-dipping segment, however, abrupt changes in strike suggest that several distinct, smaller fault surfaces, rather than one master surface, define the contact.

Outstanding exposures of the contact near Virgin Spring Canyon contain a host of fault rocks and brittle deformation features. Unlike the turtlebacks of the Black Mountains, these exposures do not show a single, well-defined sliding surface. Instead, they tend to be diffuse zones of high strain with several prominent surfaces. Fault gouge and cataclasite, which varies in thickness from approximately 10 cm to 10 m, tend to be thicker on the north-dipping segment. This zone generally displays color banding, small-scale folding and faulting, and abundant inclusions of both the hanging wall and footwall. Minor faults within the zone, combined with striated surfaces, can yield slip directions.

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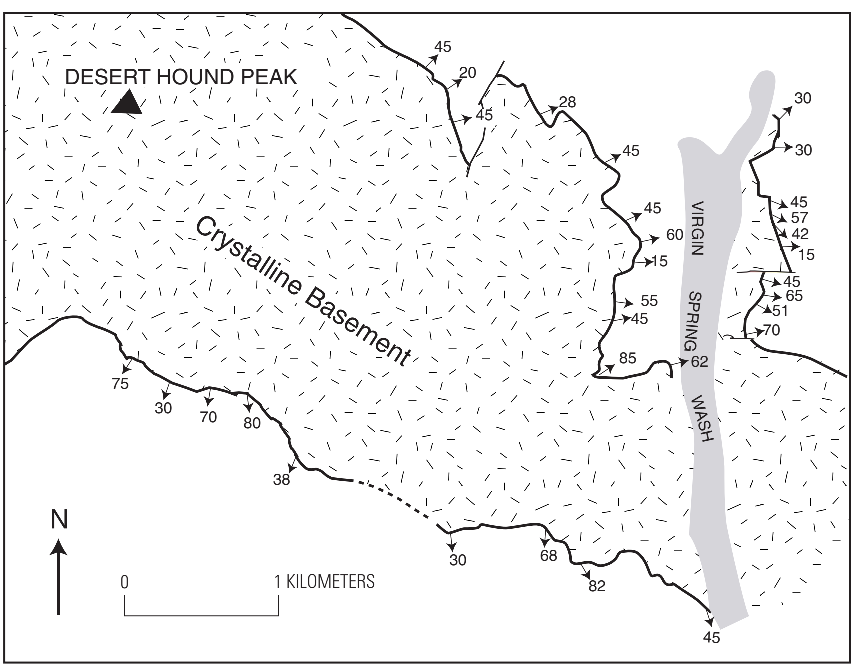

Figure 15. Simplified map of the Amargosa fault. Basement rock patterned; blank, Late Proterozoic and younger rock.

NEOGENE BASIN STRATIGRAPHY, GEOPHYSICS, AND HYDROLOGY

Cenozoic Basins of the Central Death Valley Region, Eastern California

L.A. Wright, Department of Geosciences, Pennsylvania State University, University Park, PA 16802
(Present address: 500 E. Marilyn Ave., State College, PA 16801)

INTRODUCTION

The Cenozoic basins of the central Death Valley region tend to be distributed around the periphery of the Central Death Valley volcanic field (fig. 16). The fill of most basins has been exposed by headward erosion related to the ongoing collapse of central Death Valley. The fill typically consists of mixed volcanic and sedimentary rock, ranging in age from middle Miocene to Quaternary, and is broadly coeval with the units of the igneous terrane. The generally excellent exposures, together with the presence of tuff beds and lava flows at various levels in the individual basins, permit the construction of a closely constrained chronology, as yet only partially achieved.

The basins and the igneous field share a tectonic framework containing abundant evidence of severe crustal extension related to large-scale right-lateral movement on long-recognized northwest-striking faults and to related movement on master normal faults and thrust faults. Each kind of movement has figured in the evolution of individual basins of the central Death Valley region. This report is aimed at emphasizing evidence in the basin record that should be included in future tectonic models for the Cenozoic development of the Death Valley region. Among these are the evidence for (1) the nearly contemporaneous initiation, about 14 Ma, of most of the basins east of the igneous field; (2) extreme pre-14-Ma crustal extension in at least parts of the crust in the area now occupied by the Furnace Creek basin and the Black Mountains; (3) the maintenance from 14 to 6 Ma of a drainage system along the northeast margin of the igneous field; (4) the extrusion of mantle-related volcanic rocks contemporaneous with the tilting of the southern Resting Spring Range block; and (5) the presence of a late Miocene rollover and breakaway along the length of the Tecopa Valley.

TYPES OF BASINS IN THE CENTRAL DEATH VALLEY REGION

The Furnace Creek basin (McAllister, 1970; Wright and others, in press), by far the largest of the basins east of Death Valley, is bordered on the northeast by the Furnace Creek strike-slip fault and has evolved during contemporaneous movement on the fault. It thus qualifies as a *strike-slip basin.* It also differs from the other basins in that the fill intertongues southwestward with extrusive units of the igneous field. Along and near the Black Mountain front, however, it is bounded on the south by the Badwater normal fault.

The fill of the central Death Valley basin, beneath the exposed alluvial fans and salt pan, has been long recognized as a west-pointing wedge between two east-tilting ranges (Serpa and others, 1988), and thus broadly defines a *half-graben.* It is also divisible into sub-basins, apparently fault controlled. In addition, it is a *pull-apart basin*, indeed, the type pull-apart as defined by Burchfiel and Stewart (1966). It is so named because it has been pulled apart between the right-stepping, en echelon terminations of two right-lateral faults, specifically the active part of the Furnace Creek fault zone on the north and the Southern Death Valley fault zone on the south. The Copper Canyon basin (Drewes, 1963), occupying a reentrant in the western part of the Black Mountains, was once a part of the fill of the larger basin. It now can be viewed as a *hanging basin*, as the two have been separated by major dip-slip displacement on the frontal fault of the Black Mountains.

The Northern Chicago Valley and Southern Chicago Valley basins, between the east-tilted Resting Spring Range and Nopah Range, also occupy *half-grabens.* But the Southern Chicago basin differs from its northern counterpart in that it (1) has been *preferentially extended* south of a northwest-trending right-lateral fault that cuts across the Resting Spring Range, and (2) contains abundant mafic to intermediate volcanic flows contemporaneous with the tilting of the range.

The Tecopa basin functioned as a *rollover* during part of its Miocene history. This feature, here termed the “Tecopa Valley rollover” is discussed briefly herein. The fill also includes a flat-lying Pliocene and Quaternary upper part (Morrison, in press) which was *tectonically dammed* behind a natural barrier formed slightly earlier by uplift of the China Ranch beds to the south (McMackin, 1997).

The fill of the Shadow Valley basin, immediately east of the southeast corner of the area of figure 16, overlies and is largely coeval with a major detachment fault, thus qualifying as a *supradetachment basin* (Friedmann and others, 1996; Friedmann, in press). By definition, such a

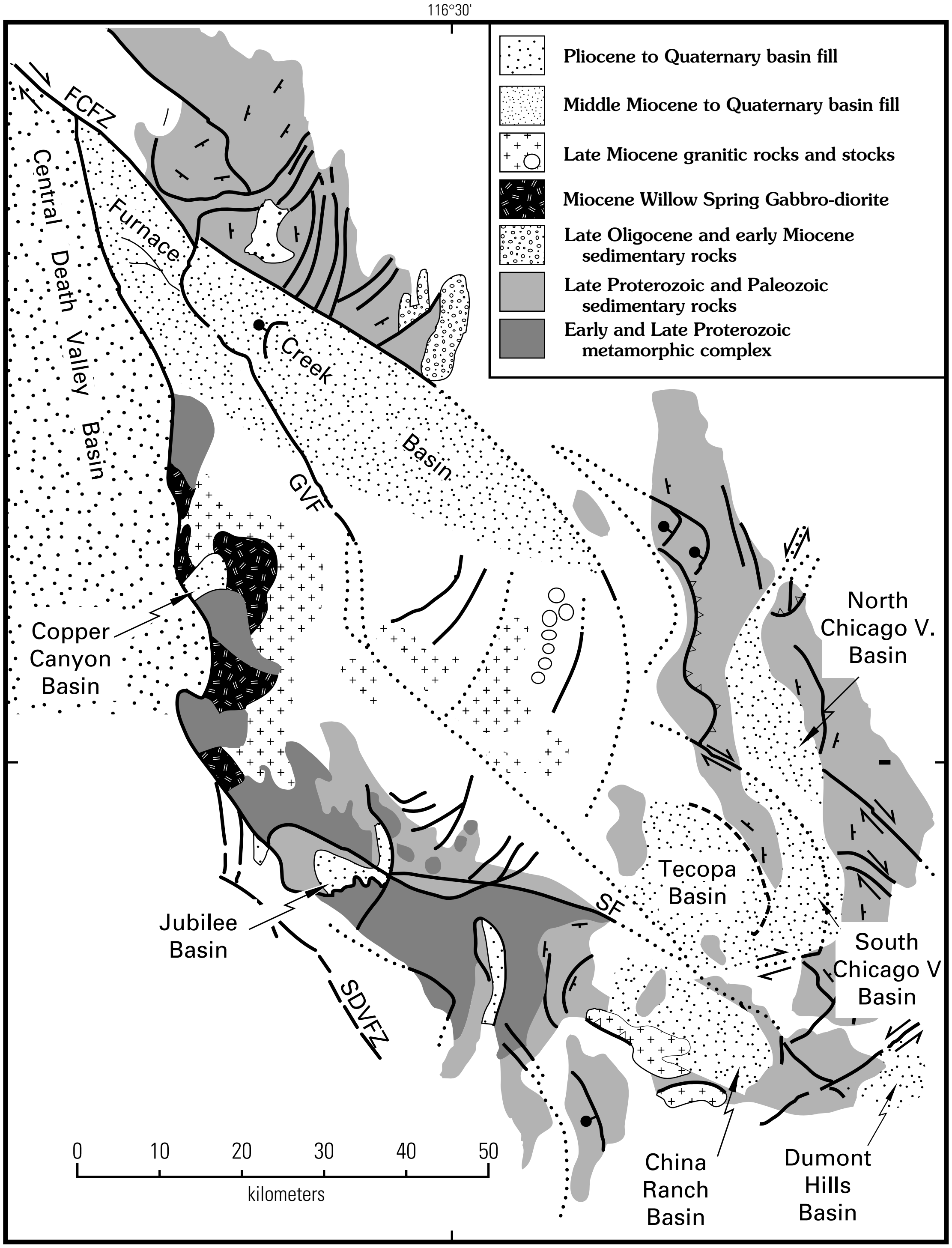

Figure 16. Generalized geology of the central Death Valley region showing distribution of the Cenozoic basins about the Central Death Valley plutonic-volcanic field and within the regional tectonic framework. FCFZ, Furnace Creek fault zone; SDFZ, Southern Death Valley fault zone; SF, Sheephead fault zone.

basin contains fill eroded from the isostatically uplifted lower plate. This fault is pinned by the Kingston Peak granite pluton dated at ~12.4 Ma.

Part of the fill of the Miocene China Ranch basin was eroded from blocks of granitic rock, temporally correlated with the ~12.4-Ma Kingston Peak pluton of the Kingston

Range to the east, and contemporaneously uplifted along thrust faults (Scott and others, 1988). The faults may be ascribed to contraction related to regional northwest-directed dextral shear. If so, the China Ranch basin has evolved, in part, as a *transpressional* feature.

The Miocene fill of the Dumont Hills basin, between the Shadow Valley and China Ranch basins (Prave and McMackin, 1999), consists of two large coalescing fans, one derived from the east, the other from the west. These provide symmetry unshared by the other basins, and thus define a *symmetrical coalescing fan* basin.

The small Jubilee basin, also termed the "Amargosa Chaos basin" by Topping (1993), lies at the south end of the Black Mountains (Wright and Troxel, 1984). Topping viewed this feature as a *supradetachment basin* because the fill overlies an occurrence of the upper plate of the Amargosa detachment fault. This basin and the implications of its fill are treated briefly following.

BASIN CHRONOLOGY

Layered volcanic bodies in the fill of the basins of central Death Valley have yielded scores of radiometric dates during the past 25 years. The basic analytical data for most of these dates are contained in the references herein. Because the chronology of some basins has been more completely determined than others and the accuracy of some of the dates is questionable, the history of basin development in this region remains incompletely constrained.

Dates within the range of 13.5 to 14.5 Ma, however, have been obtained from volcanic units low in the fill of the Furnace Creek basin (Cemen and others, 1985), Northern Chicago Valley (Brian Wernicke, personal commun., 1999), Shadow Valley (Friedmann, in press), and Jubilee basin (Topping, 1993). Thus, the initiation of these basins, and probably the less completely dated Tecopa and Southern Chicago Valley basins, began nearly contemporaneously, regardless of their distance from the centers of igneous activity. This apparently pervasive initiation of normal faulting also predates by 2 to 3 million years the cooling, at ~11.6 Ma, of the oldest of the plutons, specifically the Willow Spring gabbro-diorite pluton of the Black Mountains (Asmerom and others, 1990). These observations strongly suggest that the pluton was intruded into crust already under extensional strain and that the tectonic denudation of the area now occupied by the igneous field had already begun.

A younger age for the initiation of the China Ranch basin is indicated by the ~10.3-Ma dacite flow near the base of the China Ranch beds (Scott and others, 1988). The fill of the nearby Dumont Hills basin, although undated, appears to be largely contemporaneous with that of the China Ranch basin (Prave and McMackin, in press).

That major movement on the basin-bounding normal faults ceased progressively from east to west has been long recognized (Wright and others, 1984). In brief, the principal evidence lies in (1) the ~12.4-Ma age of Kingston Peak pluton that pins the Shadow Valley detachment fault; (2) the ~9.6-Ma whole-rock age of the gently dipping Resting Spring Pass ash-flow tuff that buttresses the west side of the Resting Spring Range, combined with an ~11.7-Ma biotite K/Ar age of a lava flow that dips moderately eastward on the east side; (3) the much steeper dip of the Resting Spring Pass tuff on the west side of the Tecopa basin compared to that of the east side; and (4) Pliocene and Quaternary strata that are flat lying in the Tecopa Valley but are strongly displaced by movement on the frontal fault of the Black Mountains.

FEATURES OF SPECIAL SIGNIFICANCE

HIGHLY ATTENUATED CRUST BENEATH THE FURNACE CREEK BASIN DEPOSITS

The basement rocks that underlie the Furnace Creek basin fill, south of the Furnace Creek fault, are exposed at two localities, one at the the Billie borate mine in upper Furnace Creek Wash and the other near Desolation Canyon, close to the west face of the Black Mountains. At each, the middle and late Miocene Artist Drive Formation depositionally overlies thoroughly shattered Paleozoic units. The underground workings and exploratory drill holes at the Billie mine penetrate a Cambrian section composed of the upper part of the Wood Canyon Formation, the Zabriskie Quartzite, the Carrara Formation, and the lower part of the Bonanza King Formation. All are thoroughly brecciated and pervasively broken by gently to steeply dipping normal faults oriented orthogonally to the Furnace Creek fault (Wright and others, in press). In this state, the Carrara and Zabriskie are only a third to a fifth as thick as they are in the intact sections in the adjacent Funeral Mountains and at Eagle Mountain 20 km to the southeast. A pre-14-Ma timing of the attenuation is indicated by a K/Ar biotite date of ~13.7 Ma from a tuff about 30 m above the base of the Artist Drive Formation (Cemen and others, 1985). This date, the degree of attenuation, and intact state of the Cambrian formations north of the Furnace Creek fault provide evidence for pre-14-Ma movement on the Furnace Creek fault and, at least locally, severe pre-14-Ma extension of the crust to the southwest.

Because only the Ordovician Ely Spring Dolomite is exposed in the shattered basement at Desolation Canyon, estimates of attenuation are precluded; but this occurrence does indicate that the shattering extended well beyond the Billie mine area. Evidence that the pre-14-Ma Cenozoic extension involved a still larger area and involved deeper crustal levels has been detected by Miller (in press) in the ductile fabrics of the Badwater metamorphic complex, which borders the Furnace Creek basin on the south.

MESOZOIC GRANITOID CLASTS IN THE ARTIST DRIVE AND CHICAGO VALLEY FORMATIONS

Clasts of granitoid and metamorphosed upper Paleozoic rocks have long been known to exist in the conglomerates of the 14- to 6-Ma Artist Drive Formation of the Furnace Creek basin and the apparently correlative Chicago Valley Formation in northern Chicago Valley. In recent years the provenance of these clasts has been traced to the Jurassic Hunter Mountain batholith and vicinity about 100 km northwest of the Chicago Valley location (Wernicke, 1993; Niemi and others, 1997). The conglomerate bodies have been interpreted by Wernicke, Niemi, and their coworkers as segments of an alluvial fan with a theoretical slope length of no more than 20 km. Others (Wright and others, in press) view the conglomerates as fluvial in origin. The latter interpretation is supported by recent observations that the conglomerate bodies occur throughout the 2 km thickness of the Artist Drive. They are ordinarily enclosed in much finer grained feldspathic lithic-sandstones and siltstones; some of the bodies are lenses only meters thick and tens of meters in maximum exposed dimension (A.R. Prave, personal commun., 1999).

Whichever interpretation is correct, these conglomerates and the enclosing finer clastics indicate a southeast-directed drainage of low relief, recurring over an interval of 8 m.y., and contemporaneous with all but the latest of the igneous events in the adjacent plutonic-volcanic field (fig. 16). This temporal and spatial relationship between the two suggests that the crustal extension in the area of igneous activity was of a lower magnitude than previously assumed.

THE TILTING HISTORY OF THE SOUTHERN RESTING SPRING RANGE AS RECORDED IN THE LARGELY VOLCANIC FILL OF THE SOUTHERN CHICAGO VALLEY BASIN

The down-dip geometry of the faults that border the east-tilted ranges east of the central Death Valley igneous field has been interpreted variously as a relatively shallow rooting at about 7 km (Wright and Troxel, 1973), a deeper rooting at mid-crustal levels (Serpa and others, 1988), and a very shallow termination against an essentially horizontal detachment fault (Wernicke, 1992). Less attention has been paid to the relationship of the basinal deposits to the tilting of the bordering blocks. A pile of dominantly volcanic rocks on the east side of the southern part of the Resting Spring Range (Heydari, 1981) provides clues that this block is, indeed, deeply rooted. The succession overlies moderately east tilted Cambrian formations. Exposed thickness is at least 1.5 km. The lower part, about 600 m thick, consists of mafic flows and pyroclastic units interlayered with very subordinate limestone and sandstone. An upper part of intermediate flows with abundant mafic inclusions issued from one or more extrusive centers east of the present crest. The mafic flows yielded a K/Ar biotite date of ~11.7 Ma and the overlying intermediate flows a K/Ar biotite date of ~9.5 Ma. The units dip progressively steeper eastward with age, but less steep than the underlying Cambrian strata. In addition, the southern part of the Resting Spring Range and the associated volcanic pile lie south of a northwest-trending fault with a strike-slip component of several kilometers. The overall configuration of the fault indicates that the southern part of the range has moved preferentially westward with respect to the northern part.

These observations provide evidence that the tilting of the range began prior to 11.7 Ma and continued through 9.5 Ma, and that the tilting was accompanied by the intrusion and extrusion of mantle-related volcanic bodies on the east side of the block. They also theoretically show that westward movement of the southern block relative to the northern block would provide the space for the rising magma.

THE TECOPA VALLEY ROLLOVER, THE RESTING SPRING PASS TUFF, AND THEIR TESTIMONY TO THE LATER HISTORY OF THE TECOPA BASIN

The Tecopa basin, lying on the west side of the southern Resting Spring Range and thus opposite the Southern Chicago Valley basin, has an early history related to the pre-11.7-Ma to 9.5-Ma tilting of the southern Resting Spring block. The contemporaneous deposits on the west side of the tilted block are only locally exposed, however, and are assumed to be downfaulted in the central part of Tecopa Valley and thus hidden beneath the flat-lying Pliocene and Pleistocene beds that form the upper part of the Tecopa Valley basin fill. But an ash-flow tuff that postdates most of the tilting of the Resting Spring Range and later was involved in the Tecopa basin rollover is discontinuously exposed on both the east and west sides of Tecopa Valley. Its unexposed, intervening part must underlie the Pliocene and Pleistocene beds. This tuff, the Resting Spring Pass tuff of Heydari (1986), has a K/Ar whole-rock glass date of ~9.7 Ma and thus postdates much of the volcanic pile on the east side of the range.

The tuff displays a maximum exposed thickness of about 200 m in the northeast corner of the basin. In this area, the tuff is extensively exposed and dips gently eastward and overlies the borate-bearing Gerstley lake beds. Most of this occurrence is densely welded, but its upper part is partly welded lapilli tuff. From there, the body thins eastward and westward, thus recording the existence of a contemporary Tecopa Valley. On the east side of the present valley, the tuff dips gently eastward and buttresses against moderately to steeply dipping Cambrian strata of the Resting Spring Range.

On the west side of the valley, only the upper lapilli-bearing unit is exposed. There, at several localities, it wedges out against Cambrian strata of the Dublin Hills and, most importantly, dips 30°–60° eastward in the manner of a classic rollover. The Dublin Hills are thus predictably underlain by a low-angle detachment fault that postdated most of the tilting of the Resting Spring Range. Less steeply dipping basalt flows, which overlie the tuff and which have yielded a whole-rock K/Ar date of 9.4 Ma, indicate that movement on the detachment fault continued until at least that time. It had ceased, however, with the deposition of the still flat-lying Pliocene-Pleistocene basin fill.

THE JUBILEE BASIN, MEGABRECCIAS, AND BODIES OF MIOCENE GRANITE

The basinal deposits exposed in Jubilee Wash at the southwest corner of the Black Mountains were originally designated as the Jubilee phase of the Amargosa chaos. The name Jubilee basin is here preferred to Topping's (1993) "Amargosa Chaos basin" on the basis of priority, and on the fact that these deposits are not true chaos but overlie the Virgin Spring phase of the Amargosa chaos, which is exposed over a large area of the Black Mountains. These deposits of chaotic appearance consist of Tertiary sedimentary rock associated with brecciated bodies of granite and of various units of Proterozoic and Cambrian age. Noble (1941) originally interpreted these bodies as fault breccias. He later reinterpreted them as monolithologic sedimentary breccias (Noble and Wright, 1954).

Topping (1993), in noting marked lithologic similarities between the granite of the breccias in Jubilee Wash and the granite of the Kingston Range, proposed that the granite breccias of Jubilee Wash originated as a rock-avalanche deposit at the periphery of the pluton of the Kingston Range. These deposits, Topping believed, have been transported 30 km northwestward along the Amargosa detachment fault in post-7.8-Ma time. He also viewed the Jubilee, China Ranch, and Dumont Hills basins (fig. 16) as segments of a single pre-7.8-Ma basin. As supporting evidence, he noted the presence in the now-separate localities of successions much like those of the Jubilee basin, including granite breccia and correlative tuff layers.

Space limitations prevent an adequate commentary on this challenging proposal. Major difficulties apparently exist, however, in (1) previously cited evidence that most or all of the movement on the Amargosa detachment occurred before 10 Ma (Wright and others, 1991); (2) the presence of blocks of thoroughly fractured but unbrecciated granite, as much as 8 km long, in the area between Jubilee Wash and the Kingston Range (Scott and others, 1988); and (3) evidence that these blocks have been mobilized along thrust faults and have shed their own megabreccias into adjacent areas.

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Looking Beneath the Surface, a Three-Dimensional Geophysical View of the Death Valley Region, California and Nevada

Richard J. Blakely,[1] Robert L. Morin,[1] and Claudia C. Faunt[2]

[1] U.S. Geological Survey, 345 Middlefield Road, M.S. 989, Menlo Park, CA 94025
<blakely@usgs.gov>; <morin@usgs.gov>

[2] U.S. Geological Survey, 5735 Kearny Villa Road, San Diego, CA 92123
<ccfaunt@usgs.gov>

INTRODUCTION

Gravity anomalies over the Basin and Range geologic province reflect to first order the sharp contrast in density between pre-Tertiary rocks exposed in the mountain ranges and layered deposits that fill the intervening basins. In the Death Valley region (see inside back cover), for example, the Funeral Mountains, Black Mountains, and Panamint Range are underlain primarily by pre-Tertiary carbonate (limestone and dolomite) and crystalline rocks with densities typically > 2,650 kg m^{-3} and thus are associated with positive gravity anomalies. The Panamint Valley, Amargosa Desert, and Death Valley, on the other hand, are filled with sedimentary and volcanic deposits with densities typically <2,450 kg m^{-3}, and these valleys produce negative gravity anomalies. We can exploit these contrasting densities to calculate the depth at which pre-Tertiary rocks lie beneath basin fill. By applying systematic calculations to the entire area, a three-dimensional model of the *basement surface* can be developed, the topographic surface that would be observed if overlying Cenozoic deposits were removed.

Knowledge of the basement surface has several practical applications. First, it is ultimately a product of the long-term geologic and tectonic evolution of the region; knowledge of its shape provides insights into the geologic history and potential earth hazards of the Death Valley area. Second, the basement surface often corresponds to the top of Paleozoic carbonate rocks, a principal aquifer in this region (Winograd and Thordarson, 1975; Dettinger, 1989; Laczniak and others, 1996). The location of this interface and connectivity of basement rocks influences the flow of water in the Death Valley region.

METHOD

We use the method of Jachens and Moring (1990), modified slightly to incorporate known depths, to estimate the basement surface. In simplest terms, gravity measurements are used to extrapolate pre-Tertiary basement from surface exposures in the mountain ranges to places where these rocks are concealed beneath basin-filling deposits. The method is illustrated in figure 17. Our objective is to separate gravity anomalies into two components: that caused by basement rocks and that caused by younger basin-filling deposits. The density of basement rocks is allowed to vary horizontally, whereas the density of basin-filling deposits is forced to increase with depth according to specified density-depth relationships. Well and seismic information, where available, constrains the calculations.

The method is an iterative approach. A first approximation to basement gravity is derived from gravity stations that lie on exposed pre-Tertiary rocks. This is only a crude approximation to basement gravity because basement stations also include the gravitational effects of all local basins. Subtracting this initial estimation of basement gravity from observed gravity provides a first approximation to the basin gravity field, which is inverted according to prescribed density-depth functions to produce a first approximation for the thickness of basin-filling deposits. The gravitational effect of these deposits is then computed at each basement station, and the basement station is adjusted accordingly. These steps are repeated in an iterative fashion until changes to basement gravity and deposit thickness are negligible.

Two products result from the inversion: (1) a map of gravity anomalies caused by basement rocks, the gravity anomalies that would be observed without the effects of overlying, low-density deposits; and (2) a map reflecting the thickness of basin-filling deposits. Subtracting the latter quantity from topography provides the basement surface relative to sea level.

It is important to understand the limitations of this method and the data on which it is based. Errors can occur because of simplifying assumptions and because of data scarcity in some locations. Although the shapes and relative depths of the basins yielded by this method are generally reliable, the calculated thicknesses of basin-filling deposits depend critically on the density-depth function used in the inversion. Densities of basin-fill deposits below a few kilometers are poorly understood, and the details of the deeper parts of the basins should be viewed accordingly.

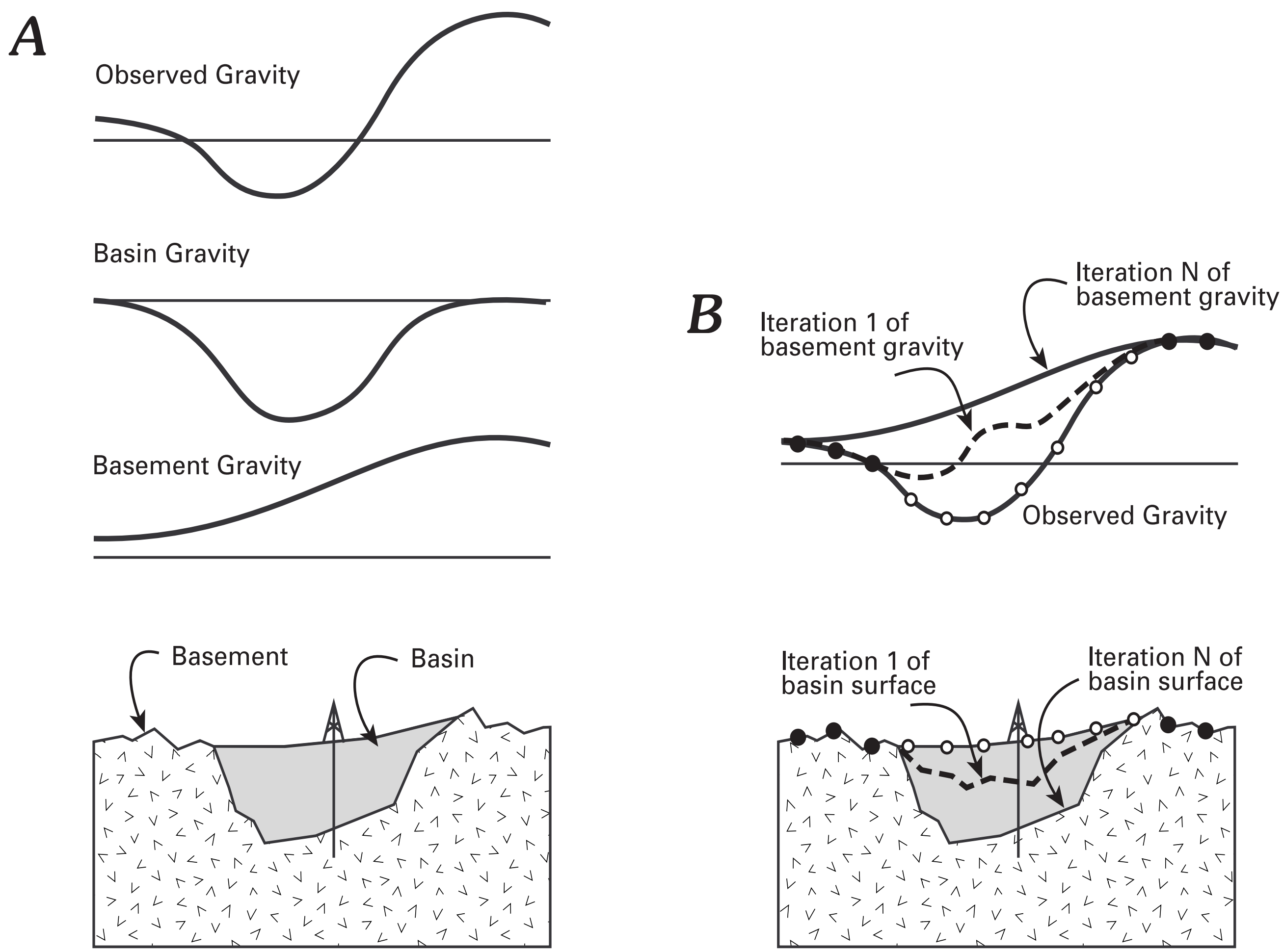

Figure 17. Gravity inversion method (Jachens and Moring, 1990). *A*, Observed gravity is considered to be the sum of the gravitational attraction of basement rock and basin deposits. *B*, The objective is to find both the thickness of basin-filling deposits and the gravity anomaly due to basement through an iterative procedure. See text for details.

REGIONAL IMPLICATIONS

An oblique view of our three-dimensional model for the Death Valley region (back cover, this volume) shows that the relatively flat valley floors of the Death Valley region belie a complex and rugged basement topography. The upper two panels of that figure show the effect of removing Cenozoic deposits from terrain. The lower panel shows basement gravity anomalies “painted” onto the basement surface to indicate the relative density of underlying lithology. Sub-basins of this area have widely variable maximum depths, ranging from less than 1 km to greater than 5 km, and the lateral dimensions of a valley are not good indicators of its depth. Panamint Valley, for example, has a relatively thin veneer of Cenozoic deposits despite its vast topographic expanse.

This aerial view shows that the bounding ranges immediately east and west of Death Valley have, in a regional sense, similar topographic relief and roughly uniform separation along the length of the valley. This uniformity, coupled with the generally flat lying floor of the valley, gives the impression that the ranges have simply moved apart as uniform blocks, leaving behind a relatively continuous and flat-lying detachment surface (Wernicke, 1981, 1985; Hamilton, 1988) beneath the valley. Gravity anomalies, on the other hand, indicate a much more complex basement surface, much of it lying at shallow depth beneath the valley floor, but locally punctuated with exceptionally deep and steep-sided depressions. We believe that this complex basement surface manifests a complex extensional history for Death Valley.

The rugged basement relief beneath Death Valley seems to be characteristic of major basins north of the Garlock fault zone. Pahrump Valley and the Amargosa Desert (Saltus and Jachens, 1995; Blakely and others, 1998), for example, also are characterized by broad expanses of relatively thin (<1 km) Cenozoic deposits surrounding exceptionally deep (>3 km) but areally restricted sub-basins. Indeed, this general characteristic is seen throughout the Basin and Range (Saltus and Jachens, 1995). In Nevada, for example, only 25 percent of Cenozoic deposits are thicker than 1 km (Jachens and Moring, 1990; Blakely and Jachens, 1991), but these deep regions often exceed depths of 3 km.

The linear, flat-bottomed aspect of Death Valley seems to fit a model of simple shear in the manner described by Wernicke (1981, 1985); that is, in east-west section the Panamint Range and Cottonwood Mountains have moved as a coherent block westward with respect to ranges along the east side of Death Valley (the Black, Funeral, and Grapevine Mountains). Detachment surfaces, perhaps regional in scale, may have been important in this episode of extension. The deep and steep-sided sub-basins beneath Death Valley, however, require additional explanations at more local scales. The fact that they are steep on their north and south sides suggests that they are bounded along these sides by relatively steep faults oriented normal or oblique to the axis of Death Valley. Specific examples are provided in the following section. Following ideas presented by Wright (1988) for concealed basins beneath Pahrump Valley and the Amargosa Desert, we suggest that the basins along Death Valley formed as relatively small pull-apart structures along northwest-trending, right-lateral strike-slip structures. Perhaps this localized extension was accommodated by a regional-scale pull-apart system involving strike-slip displacement along the Furnace Creek and Death Valley fault zones, as envisioned by Burchfiel and Stewart (1966), and eastward tilting of pre-Cenozoic basement probably promoted deepening of some of the basins.

The largest basement gravity anomaly in the study area (see illustration, back cover) is a positive anomaly centered over the northern Funeral Mountains. Here a detachment fault has ramped upward to expose lower-plate rocks, described by Hamilton (1988) as metamorphosed siliceous Proterozoic rocks. These rocks, formerly buried to middle crustal depths, are metamorphosed, hydrothermally altered, and typically more dense than upper-plate rocks lying elsewhere beneath the basement surface but above the detachment surface. This surface may underlie a large region from the northern Funeral Mountains to Saratoga Spring. Such lower-plate rocks may figure prominently in directing the flow of water through the region.

DEATH VALLEY SUBSURFACE

A discontinuous gravity minimum extends the entire length of Death Valley, from about lat 37°15′ N. to about lat 35°40′ N., a total distance in excess of 200 km. This gravity low is interpreted in the gravity inversion (illustration, back cover) as a narrow trough in underlying basement rocks extending along this entire 200 km length. Like the gravity anomaly, the trough is by no means of uniform depth; it includes several significant sub-basins, the deepest of which lies beneath Mesquite Flat just north of Tucki Mountain.

The Death Valley trough can be divided into three parts (Burchfiel and Stewart, 1966): a northern segment trending north-northwest from Mesquite Flat to near Sand Spring, a central segment trending nearly north-south from about Mormon Point to Cottonball Basin, and a southern segment trending northwest from near Saratoga Spring to the vicinity of Mormon Point.

The northernmost part of Death Valley is relatively shallow, containing generally less than 300 m of basin-filling deposits. The deepest part of this northernmost region lies beneath Sand Spring, where a small, roughly circular basin approximately 400 m deep underlies the playa.

Southward from Sand Spring, the basement contact beneath Death Valley deepens significantly, reaching its deepest point beneath Mesquite Flat. Hunt and Mabey (1966) estimated from the gravity anomaly over Mesquite Flat that Death Valley is underlain here by 3.2 km of basin-filling deposits. A detailed look at Mesquite Flat (Blakely and others, in press) found 5 km of Cenozoic deposits, one of the deepest basins of the Death Valley extended terrane. In addition, our three-dimensional analysis shows that the Mesquite Flat basin, besides being extraordinarily deep, is also steep on all sides, even at its north end. The average slope along part of the eastern margin of the basin, for example, exceeds 60° between depths of 1 and 4 km. Because this estimated slope is based on a discrete grid, the actual slope may be even greater.

The south end of the northern segment of Death Valley abuts Tucki Mountain. From here Death Valley narrows and turns eastward to Cottonball Basin east of the National Park Headquarters, then turns southward to Badwater Basin. The Cottonball Basin is underlain by a closed depression filled with as much as 3–4 km of deposits. This concealed basin is centered over the eastern margin of the salt pan in this part of Death Valley, east of the central axis of Death Valley.

South of Cottonball Basin, the trough shallows to about 500 m deep, then deepens significantly again beneath Badwater Basin. Here the floor of Death Valley is buried beneath more than 3.5 km of deposits. The basin beneath Badwater is markedly asymmetrical, with a western flank that dips more gently than its eastern flank. Part of the steep eastern flank is virtually continuous with the steep rise of the Black Mountains above the Badwater salt pan. The deepest part of the basin beneath Badwater is located well east of the axis of Death Valley, consistent with the idea that the floor of the basin dips eastward, as proposed earlier on the basis of gravity modeling (Hunt and Mabey, 1966), geologic observations (Wright and Troxel, 1973), and seismic reflection and refraction data (Geist and Brocher, 1987; Serpa and others, 1988).

The abrupt southern margin of Badwater Basin is linear, trends northwest, and is on strike with the steep range front of the Black Mountains south of Mormon Point. Moreover, the Badwater Basin is offset slightly westward from the next basin to the south (Mormon Point basin, discussed following). These observations suggest that the southern margin of the Badwater Basin is a northwest-trending, right-lateral, fault, extending from west of the axis of Death Valley to the range front of the Black Mountains just south of Mormon Point. Deep, multichannel-seismic data acquired in 1982 by the Consortium for Continental Reflection Profiling (COCORP) (Serpa and others, 1988; Geist and Brocher, 1987) provide some support for this bounding basement fault south of Badwater Basin (Blakely and others, in press).

Death Valley south of Badwater Basin is relatively shallow (<1 km) to just north of Mormon Point. Another deep basin lies west and southwest of Mormon Point. Like the basin beneath Badwater, the Mormon Point basin is asymmetrical, with a steep eastern flank, a more gently sloping western flank, and a location well east of the Death Valley axis. Apparently the floor of Death Valley is tilted northeastward beneath the Mormon Point basin. This is consistent with seismic reflection (Serpa and others, 1988; Serpa, 1990) and seismic-refraction interpretations (Geist and Brocher, 1987), both of which indicate eastward-dipping reflectors interpreted to be the basement interface. The east flank of the basin is essentially continuous with the rise of the Black Mountains above the salt pan south of Mormon Point.

Keener and others (1993) used detailed gravity measurements to investigate the subsurface immediately west and northwest of Mormon Point. They described cross sections based on two gravity profiles, one directed east-west, the other northwest-southeast from near Mormon Point. Our results are consistent with their east-west cross section, which predicts that the basin reaches its deepest level, about 3 km deep, at a point about 4 km west of the base of the Black Mountains scarp. Their northwest-southeast cross section, on the other hand, shows depths greater than 1.5 km beneath the salt pan 10 km north-northwest of Mormon Point, whereas we find only about 0.5 km of Cenozoic cover in this location. Keener and others (1993) employed significantly more gravity data in their analysis than used to produce our illustration (back cover), and their model north-northwest of Mormon Point is probably more accurate.

The gravity inversion shows that the Mormon Point basin ends abruptly at its south end, suggestive of a concealed, steeply dipping fault. A Quaternary basaltic cinder cone is located at the south end of Mormon Point basin directly above the steep slope of the basement surface here. The presence of this cinder cone further suggests that the southern margin of the Mormon Point basin is fault-controlled within an extensional setting.

Serpa and others (1988) proposed on the basis of deep-seismic reflection profiles that a zone of faults strikes southwestward into Wingate Wash, where it separates the Panamint Range block from the Owlshead Mountains block. Our three-dimensional basin analysis shows a broad, relatively shallow basin, generally less than 1.5 km deep, north of Wingate Wash and west of the Owlshead Mountains. The southeastern margin of this basin lies along Wingate Wash, trends northeast in a linear fashion, and is on strike with the southern terminus of the Mormon Point basin. Although it is not clear from the gravity inversion if the Wingate Wash basin is connected directly with Death Valley, we agree with Serpa and others (1988) that a major fault zone lies along Wingate Wash and has controlled the evolution of the broad basin to the northwest.

South of Mormon Point, between the Black Mountains and the Owlshead Mountains, the Death Valley trough shallows and remains less than 1 km deep to its southern extremity against the Avawatz Mountains. A broad basin with gently dipping flanks and depths generally less than 500 m is located at this south end, centered about 8 km west of Saratoga Spring.

CONCLUSIONS

Gravity inversions, constrained by geologic mapping and subsurface measurements, help define in three dimensions the subsurface structure beneath basins in the Death Valley region. The vast flat expanse of the valley floors belie a complex basement topography. Steep-sided sub-basins beneath Death Valley and elsewhere in the Basin and Range are areally restricted from one another and together make up a relatively small proportion of the total area of the region. Some of this topographic expression is related to tectonism, active at least as recently as Quaternary time.

Although detachment surfaces, perhaps regional in scale, may have been important in early episodes of extension, the deep and steep-sided sub-basins require local-scale explanations. Relatively small pull-apart structures along northwest-trending, right-lateral, right-stepping, strike-slip faults may have promoted deepening of some of the basins.

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The Death Valley Regional Ground-Water Flow System (DVRFS) Model—Calibration Versus Hydrogeologic Conceptual Model Testing

Frank A. D'Agnese[1] and Claudia C. Faunt[2]
[1]U.S. Geological Survey, Tucson, AZ 85719 <fadagnes@usgs.gov>
[2]U.S. Geological Survey, San Diego, CA 92123 <ccfaunt@usgs.gov>

The Death Valley region lies within the carbonate-rock province of the Great Basin (Prudic and others, 1993). This province is characterized by thick sequences of carbonate rocks that form a generally deep regional flow system that transfers ground water from northern and eastern Nevada toward the south and west. As early as 1909, the deep interbasinal nature of this flow system was recognized (Mendenhall, 1909). Since then, Death Valley has been the focus of many hydrogeologic investigations. Recently, these studies have culminated in the development of several numerical models that simulate the complex flow system in three dimensions (IT Corp., 1996; D'Agnese and others, 1997). Through the cooperation of Federal, State, and local entities, the U.S. Geological Survey has begun a multiyear effort to synthesize these numerical models and other existing hydrogeologic data into a comprehensive three-dimensional conceptual and numerical ground-water flow model of the region.

HYDROGEOLOGIC CONCEPTUAL MODEL

Conceptualization of the geology and ground-water resources of the Death Valley region provides the physical and hydraulic basis for a subsequent numerical analysis of the regional ground-water flow system. The system may be most easily conceptualized as having two main components: a series of relatively shallow and localized flow paths that are superimposed on deeper regional flow paths. Regional flows do not coincide with topographic basins; most flow reflects structural and lithologic conditions that produce variations in permeability. Regional flow paths interact with local flow paths reflecting local geologic and topographic controls on recharge and discharge. In several places, high mountain ranges support local ground-water mounds that may act as boundaries to ground-water flow (Prudic and others, 1993).

The conceptual model used in this study assumes that geologic controls exert considerable influence on the regional ground-water flow system. As a result, a three-dimensional hydrogeologic framework model is being constructed which defines the physical geometry and composition of the subsurface materials in the flow system. It defines the fundamental nature of the ground-water flow system and includes a definition of both the hydrostratigraphy and the hydrogeologic structures of the area. A hydrostratigraphic unit is a geologic unit that has considerable lateral extent and has reasonably distinct hydrologic properties because of its physical (geologic and structural) characteristics (Maxey, 1968). Hydrogeologic structures include faults, fracture zones, and other structural discontinuities that enhance or impede ground-water flow.

The hydrostratigraphic units in the Death Valley region generally include Quaternary playa deposits, Quaternary-Tertiary valley fill, Quaternary-Tertiary volcanic lava flows, welded and nonwelded Tertiary volcanic tuffs, late Tertiary tuffaceous sedimentary rocks, Tertiary-Late Jurassic granitic rocks, Mesozoic sedimentary and metavolcanic rocks, Paleozoic shales and carbonate rocks, Paleozoic-Precambrian clastic rocks, and Precambrian igneous and metamorphic rocks.

Complex, regional-scale geologic structures give rise to hydraulic compartmentalization of ground-water flow paths. Several calderas and resurgent volcanic intrusions forming the Southwest Nevada Volcanic Field may have completely removed or altered the carbonate rocks forming the regional aquifer, thereby disrupting portions of the deeper regional flow system. Most spring and discharge features are associated with faults, and many diffuse discharge areas reflect structural controls. The juxtaposition of permeable and nonpermeable units is one of the major effects that faults (and associated fractures) have in controlling ground-water flow. In addition, fault gouge and associated lower permeability material can act as a barrier to flow across faults. Likewise, fracture zones associated with faults may enhance permeability parallel to and along the feature.

The three-dimensional hydrogeologic framework model in essence is a digital representation of the hydrogeologic conceptual model for the region. This conceptual model helps investigators during the numerical modeling process to (1) determine the most feasible interpretation of the system given the available database; (2) determine the location and type of additional data that will be needed to reduce uncertainty; (3) select potential physical boundaries to the flow system; and (4) evaluate hypotheses about the hydrogeologic framework.

NUMERICAL SIMULATION OF REGIONAL GROUND-WATER FLOW

Until recently (IT Corp., 1996; D'Agnese and others, 1997), numerical ground-water modeling efforts in the

Death Valley region have relied on two-dimensional methods (Waddell, 1982; Czarnecki and Waddell, 1984; Rice, 1984; Sinton, 1987; Prudic and others, 1993). These investigators utilized simplifications to simulate the complex, three-dimensional hydrogeologic system. These simplifications involved considerable abstractions of the natural environment, and became highly dependent on modeling lumped, system parameters. These investigators concluded that their lumped-parameter representations prevented accurate simulation of the three-dimensional nature of the system including the occurrence of vertical flow components (Waddell, 1982, p. 28; Czarnecki and Waddell, 1984, p. 30; Rice, 1984, p. 39), sub-basinal ground-water flux (Waddell, 1982, p. 66; Czarnecki and Waddell, 1984, p. 30), large hydraulic gradients (Czarnecki and Waddell, 1984, p. 30; Sinton, 1987, p. 84), and physical sub-basin boundaries (Waddell, 1982, p. 66; Czarnecki and Waddell, 1984, p. 30). In contrast, the three-dimensional numerical models developed in recent investigations (IT Corp., 1996; D'Agnese and others, 1997) and the ongoing work allow for the examination of the internal, spatial, and process complexities of the hydrogeologic system, thus emphasizing the importance of the three-dimensional digital hydrogeologic framework model.

Because of the numerous hydrologic and geologic factors controlling ground-water flow in the study area, even a relatively coarse gridded, regional ground-water flow model is necessarily large and complex. Calibration of the model by strictly trial-and-error methods would be both ineffective and inefficient (D'Agnese and others, 1997); therefore, the nonlinear-regression methods available in MODFLOWP are used to estimate parameter values that produce a best fit to system observations.

Hill (1992) documented the MODFLOWP computer code, which uses nonlinear regression to estimate parameters of simulated ground-water flow systems, based on the USGS three-dimensional, finite-difference modular model, MODFLOW (McDonald and Harbaugh, 1988). The MODFLOW code simulates an equivalent porous media representation of ground-water flow. Because the Death Valley region dominantly contains rocks bearing numerous, densely spaced fractures, the porous media representation in MODFLOW is assumed to be reasonably representative of these conditions. Where necessary, large fracture zones may be represented explicitly to allow for significant increases or decreases in hydraulic conductivity occurring along or within regional features.

CALIBRATION THROUGH HYDROGEOLOGIC CONCEPTUAL MODEL TESTING

The philosophical approach to numerical model calibration utilizes a series of hydrogeologic conceptual model evaluations of increasing complexity. Using the principle of parsimony, the numerical model is kept as simple as possible while still accounting for the system processes and characteristics evident in the observations (Hill, 1998). In the case of the DVRFS model, observations include ground-water levels and discharge fluxes with carefully assessed degrees of uncertainty. Parameters such as hydraulic conductivity are estimated by MODFLOWP to conform to these observations and user-specified model conditions that are representative of the flow system. Sensitivities calculated as part of the nonlinear regression method reflect how important each observation is to the estimation of each parameter. Therefore, sensitivities can be used to evaluate (1) whether the available data are likely to be sufficient to estimate the parameters of interest, and (2) what additional parameters probably can be estimated. Because the ground-water flow equations are nonlinear with respect to many parameters, sensitivities calculated for different sets of parameter values will be different.

The composite scaled sensitivity (CSS) is a statistic calculated by MODFLOWP that summarizes all the sensitivities for one parameter, and, therefore, indicates the cumulative amount of information that the observations contain toward the estimation of that parameter. Parameters with large CSS values relative to those for other parameters are likely to be easily estimated by the regression; parameters with smaller CSS values may be more difficult or impossible to estimate. For some parameters, the available measurements may not provide enough information for estimation, and the parameter value will need to be set by the modeler—or more observations will need to be added to the model.

Maintaining the required restraint to methodically and progressively increase the required complexities in the ground-water flow model is often difficult for the modeler (Hill, 1998). However, the method of increasing complexity to the hydrogeologic conceptual model based on the resulting CSS values available in MODFLOWP provides a much more defensible numerical simulation.

The required DVRFS model parameter values input to MODFLOWP are supplied by discretization of the three-dimensional hydrogeologic framework model and digital representations of the remaining conceptual model components, including ground-water recharge and discharge, which are the driving forces for ground-water movement.

The hydrogeologic conditions represented in the three-dimensional hydrogeologic framework model vary considerably within the volumes represented by each of the numerical flow model layers; therefore, hydraulic properties for the numerous hydrogeologic framework model layers may be simplified or averaged for a single numerical flow model layer. Initially, the calibration runs may begin with a simplified representation of the flow system describing merely a "bedrock" hydraulic-conductivity parameter and an "alluvium" hydraulic-conductivity parameter. After a parameter-estimation run, the calculated CSS values indicate which of these parameters has enough information provided by model observations to statistically justify additional detail. For example, the "bedrock" parameter could justifiably be subdivided into a "carbonate-rock" and "volcanic-rock" hydraulic-conductivity parameter. With each model-calibration run, additional hydrogeologic detail is added as the model progressively reduces the error in simulating observed ground-water levels and discharge fluxes. The modeler eventually may include numerous hydrogeologic units with varying heterogeneity and anisotropy resulting from degrees of welding in a volcanic unit to grain-size distribution of an alluvial deposit. Also, where necessary, discrete structural entities, such as faults or regional fracture zones, may be added to improve model fit and increase the complexity of the evolving hydrogeologic conceptual model. Ultimately, the calibration process reaches a point where added model complexity does not result in a perceivably better fit to model observations. At this point, there are insufficient observations to justify additional complexity in the numerical model.

CONCLUSIONS

The incorporation of comprehensive geologic interpretations into a three-dimensional hydrogeologic framework model of the Death Valley region provides for a more technically sound ground-water flow model. The complexity of the hydrogeologic conceptual model is added to the numerical model in a manner which is both methodical and statistically defensible. Therefore, the regional ground-water flow model bears fewer simplifications of geologic features that control the complex characteristics of the Death Valley flow system. Once designed and calibrated, such a model may be utilized to better evaluate and illustrate the significance of the hydrogeologic conceptual models of the Death Valley region developed over the last century.

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Preliminary Description of the Subsurface Geologic Units in the Amargosa Desert

Emily M. Taylor,[1] Christopher M. Menges,[2] and Carma San Juan[3]
[1]U.S. Geological Survey, Box 25046, Denver Federal Center, M.S. 425, Denver CO 80225
[2]U.S. Geological Survey, M.S.423, 1261 Town Center Dr., Las Vegas NV 89134
[3]U.S. Geological Survey, Box 25046, Denver Federal Center, M.S. 421, Denver, CO 80225

Description of the subsurface geology is based primarily on the compilation and correlation of subsurface data in the Amargosa Desert. This work supports the geologic investigations of hydrogeologic units and structural controls of the Death Valley Regional Flow System Model, and complements geologic, geomorphic, and geophysical investigations conducted in the Amargosa Valley area at more detailed scales than the regional-scale (1:250,000) geohydrologic investigations. Borehole data are being used to identify Quaternary and Tertiary volcanic and sedimentary rocks in the basin, classify them into hydrogeologic units, and map the subsurface distribution of these units to the extent possible in support of geologic cross sections. This work will be done using GIS layering techniques. Here is a preliminary list of hydrogeologic units we believe can be recognized and correlated in Amargosa Valley, based on an initial inspection of available lithologic logs. These units will be tested against additional borehole data, including additional logs and direct examination of selected cuttings, and revised as required.

AMARGOSA VALLEY SUBSURFACE UNITS

1. Fine-grained alluvium—including playa, mud, mudstone
2. Quaternary and Tertiary coarse-grained alluvium (sand and gravel)—including near-surface unconsolidated gravel and sand and late-stage basin fill
3. Quaternary-Tertiary spring/lacustrine deposits—including an upper limestone aquifer
4. Basalt
5. Silicic volcanic welded tuffs, subdivided when adequate data are available
6. Clastic and volcaniclastic rocks, subdivided when adequate data are available—for example, early basin-formation sediments such as Pavits Spring, Horse Spring, Titus Canyon formations
7. Undivided Paleozoic limestone, dolomite, and quartzite, subdivided into carbonate aquifer and clastic confining units where possible

We initially compiled and analyzed stratigraphy of original lithologic logs from the American Borax boreholes drilled in the southern and central Amargosa region and shallow boreholes in the Amargosa Farms area. Units are defined in generalized lithologic terms, based on characteristics of hydrogeologic importance such as permeability. These generalized hydrogeologic units will be subdivided where more stratigraphic information is available. Direct examination of an adequate sampling of boreholes will serve to ensure accurate stratigraphic and hydrogeologic interpretations of the lithologic logs.

Tectonostratigraphic Relationship between the Cenozoic Sedimentary Successions of the Southern Funeral Mountains, Furnace Creek Basin, Eagle Mountain, and the North End of the Resting Spring Range

Ibrahim Cemen, School of Geology, Oklahoma State University, Stillwater, OK

The area of the southern Funeral Mountains, Furnace Creek basin, Eagle Mountain, and the north end of the Resting Spring Range contains Cenozoic sedimentary rocks that can be divided into two major successions: (1) a succession dated within the interval 25–14 Ma and discontinuously exposed along the southeast end of the southern Funeral Mountains; and (2) a succession dated 14–4 Ma and exposed in the Furnace Creek basin, south end of Eagle Mountain, and the Ash Meadows area of the north end of the Resting Spring Range. Cemen and others (in press) and Wright and others (in press) have discussed the stratigraphy and tectonic implications of the Cenozoic rocks at the south end of the Funeral Mountains and the Furnace Creek basin. The main purpose of this paper is twofold: (1) to briefly discuss the stratigraphy and sedimentary environments of the Cenozoic sedimentary successions of the Eagle Mountain and Ash Meadows areas; and (2) to examine the possible tectonostratigraphic relationship between these two sections and the Cenozoic rocks of the southern Funeral Mountains and the Furnace Creek basin.

THE CENOZOIC ROCKS OF THE EAGLE MOUNTAIN AREA

Exposed at the southeast end of the Eagle Mountain is a 217-m-thick Cenozoic sedimentary rock accumulation, which unconformably overlies the Middle Cambrian Bonanza King Formation. The lowest part of this succession is a 39-m-thick sedimentary breccia deposit. Based on its textural characteristics, the breccia is interpreted here as an alluvial fan deposit. The source area was Eagle Mountain, for it is entirely composed of very angular to angular pebble- to boulder-size clasts of the underlying Bonanza King Formation. The breccia suggests early tilting of Eagle Mountain. Three fining-upward cycles of fluvial deposits overlie the breccia. The cycles total 87 m thick, but thickness of individual cycles varies. They contain fluvial conglomerates at their bases, which contain granodioritic rock fragments of the Mesozoic Hunter Mountain batholith. The conglomerates grade into arkosic sandstones, which in turn grade into siltstones in the upper part of the cycles. This unit includes an approximately 1 m thick rhyolitic air-fall tuff, dated recently at 13.6 Ma (B. Wernicke, personal commun., 1998). This age suggests that the Eagle Mountain section was deposited at the same time as the lower sedimentary member of the Artist Drive Formation (14–11 Ma) of the Furnace Creek basin. The sandstones of both the lower sedimentary member of the Artist Drive Formation and the Eagle Mountain section are arkosic and contain carbonate fragments. This suggests that they were derived from a terrain where carbonate rocks were exposed adjacent to an intrusive rock. A likely source for this clast assemblage is in the northern Panamint Mountains and southern Cottonwood Mountains where the Hunter Mountain pluton intruded the Paleozoic carbonate rocks. The upper part of the Eagle Mountain section is 91 m thick and is composed of fine- to medium-grained yellow sandstone in its lower part and yellowish-brown siliceous sandstone in its upper part. Based on the presence of oscillation ripple marks and other sedimentary structures, the uppermost 91 m of the Eagle Mountain section are interpreted here as having been deposited in a high-energy, shallow lacustrine basin.

The Eagle Mountain section is lithologically very different than the section at the south end of the Funeral Mountains. It is also younger than the 25–14-Ma time interval that was assigned to the Funeral Mountains section. The fluvial to lacustrine nature and similar ages of the Artist Drive and the Eagle Mountain section, however, suggest that the two sections are time equivalent. Their lithology, clast content, and sedimentary environments suggest that during their deposition (1) a fluvial drainage area extended from the northern Panamint Mountains and southern Cottonwood Mountains southeastward, and (2) the northern Panamint Mountains and southern Cottonwood Mountains were adjacent to the northern Black Mountains. Therefore, the Eagle Mountain section may be considered as part of the Furnace Creek basin.

THE CENOZOIC ROCKS OF THE ASH MEADOWS AREA

An approximately 750 m thick Cenozoic sedimentary succession is exposed at the Ash Meadows area of the north end of the Resting Spring Range. The base of the succession is an approximately 250 m thick conglomerate, which is continuously exposed along the north edge of the Resting Spring Range and unconformably overlies the latest Precambrian Stirling Quartzite. The conglomerate consists mostly of pebble- to boulder-size clasts, very poorly to moderately sorted in a grayish-brown to red clay-to-sand matrix. The clasts are consistently angular to very angular in the lower part, but subordinate proportions of rounded clasts are present in the upper part. Clasts 0.5 to 1 m in diameter are common, and a few clasts as large as 2 m were also observed. Within the first 15 m of the conglomerate, the clasts are almost entirely derived from the underlying latest Precambrian Stirling

Quartzite, although some fragments of the late Precambrian Wood Canyon, and Cambrian Carrara, Bonanza King, and Nopah Formations are present. Above the lowest 15 m, the unit consists of about equal proportions of the Wood Canyon, Carrara, Bonanza King, and Nopah Formations.

The clast size gradually decreases upsection to the middle part of the unit. In the middle part is a layer of granule- to pebble-size fragments, about 30 m thick. Still higher, the fragments increase and then gradually decrease in size. The uppermost 60 m of the unit consists of pebbly conglomerate containing lenses of reddish-brown sandstone. A few of the lenses are about 10 m thick, and about 50 m long. They are composed of red, reddish-brown to brown fine-grained sandstone and mudstone. The angularity of the clasts, local derivation, the poor sorting, and the presence of fine-grained matrix indicate that the conglomerate was deposited as an alluvial fan.

Unconformably overlying the lower conglomerate is an approximately 500 m thick unit composed of sedimentary rocks and subordinate volcanic rocks. Cemen (1983) informally combined the sediments and volcanic rocks into one unit. At the base of this unit is a 3-m-thick, light-olive-gray to greenish-gray air-fall tuff. The tuff directly overlies the lower conglomerate and has been radiometrically (K/Ar) dated at 13.2 Ma, which suggests that this succession is time equivalent to the Eagle Mountain section and the lower sedimentary member of the Artist Drive Formation. Overlying the tuff is a 5-m-thick white to very pale orange freshwater limestone unit. Above the limestone, the sedimentary rocks and volcanic unit consist of both fluvial and lacustrine deposits. The fluvial deposits are represented by the fining-upward cycles of red sandstone. The lacustrine deposits are represented by medium- to fine-grained brown sandstone and siltstone. The presence of limestone and gypsum beds indicates that a playa existed in the basin for relatively short time periods. The air-fall tuffs were probably deposited as showers of ash into the basin.

The unit of sedimentary and volcanic rocks includes a mappable subunit composed of red conglomerate to conglomeratic sandstone at the base, fining upward to medium- to fine-grained red sandstone and mudstone. The conglomerate parts are characteristically trough crossbedded, and contain angular to subangular fragments of the Stirling Quartzite and lower Paleozoic carbonate-rock fragments in about equal proportions. The clasts are poorly sorted in a light-brown to moderate-brown silty to sandy matrix. The percentage of matrix is less than that of the lower conglomerate. Most of the sandstone layers of the unit are conglomeratic at the base and fine upward to fine-grained sandstone and mudstone. The sandstones include conglomeratic layers containing granule- to pebble-size quartzite and limestone fragments. The conglomerates contain pebbles of the Stirling Quartzite, Bonanza King, and Nopah Formations. Three- to five-cm-thick gypsum beds locally overlie the siltstone beds of the unit. The cyclic nature of this mappable subunit together with the presence of crossbedded sandstones suggests that the unit was deposited in a fluvial environment. The presence of gypsum beds overlying the siltstones suggests deposition in a lacustrine environment.

The Ash Meadows section is time equivalent to the lower sedimentary member of the Artist Drive Formation and the Eagle Mountain section. The Ash Meadows basin must have been formed at the same time as the Furnace Creek basin. The lower conglomerate of the Ash Meadows area records an alluvial fan whose source was nearby, probably in the present-day Shadow Mountain area. This suggests that the north end of the Resting Spring Range was occupied by a paleotopographic high during the deposition of the conglomerate. This paleotopographic high was probably related to the vertical movements at the southeast end of the Furnace Creek fault zone, in mid-Miocene time when the Furnace Creek basin took form in response to formation of the large pull-apart basin of the Death Valley region. The structural relationship between the Ash Meadows section and the Artist Drive Formation of the Furnace Creek basin remains open to question due to the lack of a systematic dating of the volcanic rocks in the Ash Meadows section.

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Three-Dimensional Model of Pre-Cenozoic Basement beneath Amargosa Desert and Pahrump Valley, California and Nevada—Implications for Tectonic Evolution and Water Resources

Robert L. Morin,[1] Richard J. Blakely,[1] E.H. McKee,[1] Kevin M. Schmidt,[1] Victoria E. Langenheim,[1] and Gary L. Dixon[2]

[1] U.S. Geological Survey, Menlo Park, CA 94025

[2] U.S. Geological Survey, Las Vegas, NV 89119

A three-dimensional inversion of gravity data from the Amargosa Desert and Pahrump Valley reveals a topographically complex pre-Cenozoic basement surface concealed by younger sedimentary and volcanic deposits. The Amargosa Desert is underlain by a deep, steep-sided trough which varies in width from 15 to 20 km. This trough extends from the southwest Nevada volcanic complex, which is centered about 30 km northeast of Beatty, due south to the Nevada-California State line. The linear margins of the Amargosa Desert trough and its internal topography suggest that it formed as a series of transtensional basins. These basins transferred strain between northwest-striking, right-lateral, strike-slip faults arranged in a right-stepping en echelon pattern. Pahrump Valley is underlain by two deep, steep-sided sub-basins separated by a narrow basement ridge aligned parallel to the State line. The Pahrump Valley sub-basins also formed as transtensional pull-apart basins, caused in part by displacement along the northwest-striking State Line fault zone. The State line ridge at Pahrump Valley is on strike with a narrow basement ridge beneath Ash Meadows, also lying along the State line and within the State Line fault zone. Both ridges are associated with late Cenozoic faulting. The ridges may have formed as transpressional structures, caught slightly askew of the northwest-directed strain that formed the sub-basins.

Carbonate rocks probably compose the basement beneath most of the Amargosa Desert and Pahrump Valley. Because carbonate rocks are important aquifers in this region, the three-dimensional aspects of the concealed basement surface strongly influence ground-water flow paths and transport rates. For example, the deeper parts of the Amargosa Desert trough, or faults that bound the western margin of the trough, interrupt the carbonate aquifer and thus may impede the westward flow of ground water. If so, the gravity analysis predicts that water discharging at Ash Meadows originates entirely from the carbonate flow path north and northeast of Ash Meadows, whereas water discharging at Furnace Creek originates from the volcanic flow path north and northwest of Furnace Creek.

This abstract was published in Eos, v. 79, p. F807, 1998, and presented at the 1998 Fall Meeting of the American Geophysical Union, San Francisco, December 1998.

Using Geologic Data for a Three-Dimensional Hydrogeologic Framework Model of the Death Valley Region

Claudia C. Faunt,[1] Wayne R. Belcher,[2] and Frank A. D'Agnese[3]
[1]U.S. Geological Survey, San Diego, CA 92123 <ccfaunt@usgs.gov>
[2]U.S. Geological Survey, Las Vegas, NV 89119 <wbelcher@usgs.gov>
[3]U.S. Geological Survey, Tucson, AZ 85719 <fadagnes@usgs.gov>

In cooperation with the U.S. Department of Energy and other Federal and local agencies, the U.S. Geological Survey is evaluating the geologic and hydrologic characteristics of the Death Valley regional ground-water system. The study area covers approximately 100,000 km^2 (lat 35° to 38° 15' N., long 115° to 118° W.). As part of these studies, we are developing a digital three-dimensional hydrogeologic framework model. Previous digital regional hydrogeologic framework models have been developed (IT Corp., 1996; D'Agnese and others, 1997), which were the basis for regional ground-water flow models. Although these framework models are complex three-dimensional geologic models and have overlapping model domains, the interpretation of the geology and hydrogeology is somewhat different. Our effort represents an ongoing synthesis of these previous models into a single, updated comprehensive hydrogeologic framework model. This work is a multidisciplinary effort being accomplished by USGS Water Resources Division and Geologic Division personnel in Western and Central Regions.

The hydrologic characteristics of the region are a result of both the arid climate and the complex geology. Ground-water flow generally can be described as interbasinal flow and may be conceptualized as a series of relatively shallow and localized flow paths that are superimposed on deeper regional flow paths. Significant components of the regional ground-water flow are through a thick Paleozoic carbonate-rock sequence and a locally thick Tertiary volcanic sequence. Throughout the regional flow system, ground-water flow is probably controlled by extensive and prevalent structural features that result from regional faulting and fracturing.

The construction of the digital three-dimensional hydrogeologic framework model involves the use of data from several sources to define the geometry of the regional hydrogeologic units. The updating of the digital framework model entails the completion of a comprehensive geologic interpretation involving the compilation and production of geologic maps, geologic cross sections, geologic structure analysis, and geophysics. In addition, data from digital elevation models and lithologic well logs are used. This framework model provides a description of the geometry, composition, and hydraulic properties of the material that control the regional ground-water flow system. The framework model also serves as an important information source for the development of the hydraulic properties of the numerical ground-water flow model. Data from these sources will be combined and used to produce gridded surfaces of the hydrogeologic units. These gridded surfaces will then be stacked within geologic modeling software to produce a three-dimensional framework model of the Death Valley region.

Geologic mapping activities include compilation and synthesis of existing geologic data at 1:250,000 scale. Most of the work is based on the synthesizing of published and unpublished geologic maps but necessitates new office compilation and some field work to resolve problem areas. The office and field work includes the resolution of interpretive differences between maps and the development of a consistent stratigraphy for the regional model area. In addition, new geophysical data will be applied to answer geologic questions, especially in approximating buried faults beneath the basins. Because most of the existing mapping lacks definition of Quaternary materials, work is being done to delineate Quaternary units that will affect ground-water flow in the shallow aquifer of the regional flow system; these data will be incorporated into the regional geologic map.

Geologic cross sections for both the Yucca Mountain Project and the Nevada Test Site–Underground Testing Area exist and, in some cases, reflect different interpretations. A new set of cross sections (1:250,000 scale) is being developed that will resolve and document the latest interpretations. A consistent set of hydrogeologic units is also being applied. Alternate geologic interpretations and conflicts between intersecting cross sections are being resolved.

Geologic structural interpretations will be compiled and synthesized for the Death Valley region. This work will involve the identification of significant regional facies and (or) structural changes in aquifers and confining units (degree of welding in tuffs, alteration, faulting/fracturing, folding, grain-size distribution, lithologic gradation), and the synthesis of regional structures that influence flow. The structures include normal faults, strike-slip faults, transverse zones, geophysically identified structural zones beneath basins, thrust sheets, and calderas. The geometry of these structural features (orientation, extent, persistence at depth) will be assessed with regard to their potential to influence ground-water flow.

Geophysical information, in the form of gravity and aeromagnetic data, is being used to define the configuration of the pre-Cenozoic hydrogeologic units in the flow system, particularly the regional carbonate aquifer. Maps of both the estimated thickness of Cenozoic units and the top of the basement rocks will be produced from these data. Within the limits of the data coverage, gravity data will be used to estimate the thickness of Cenozoic basin-fill deposits. Where possible, the lithologic character of the basement rocks will be resolved. Existing geophysical data will be synthesized and supplemented. Supplemental data will be collected and processed from Amargosa Desert, Death Valley, southern Nye County, the Nellis Air Force Range, and Esmeralda and Lincoln Counties.

As a result of the work of a coordinated team of hydrologists, geologists, and geophysicists from Water Resources and Geologic Divisions, a state-of-the-art flow model for an important part of the Desert Southwest will exist for the first time. The techniques, procedures, and teams developed in this work have applications to other parts of the Desert Southwest, as well as other areas.

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Ground-Water Flow Model of Amargosa Valley and Yucca Mountain Site Revisited

Parviz Montazer and Nick Stellavato <metlasvega@aol.com>
Nye County Nuclear Waste Repository Project Office, P.O. Box 1767, Tonopah, NV 89849
Telephone: (702) 794-5547 (voice); (702) 794-5552 (FAX)

A subset of the regional ground-water flow model of the Death Valley Region was set up to evaluate the impact of the new findings from drilling of the Early Warning Drilling Program (EWDP). This subset includes the sub-basins of Amargosa Valley and Yucca Mountain of the USGS-WRD regional ground-water model.

A steady-state model similar to that of the USGS-WRD's was set up and simulations performed to compare with the USGS-WRD model. Hydraulic conductivity values were varied to evaluate the sensitivity of the model to changes in the region for which no data were previously present. Transient runs were also made to evaluate the accuracy of the USGS-WRD regional steady-state model. Hydraulic conductivity values calibrated with the steady-state assumptions are considerably different than those calculated by transient assumptions. In the transient runs, however, storage properties are unknown and play an important role in the response of the aquifers. Further studies underway to refine this model will include simulation of the Pahrump Valley system where more data are available.

Development of a Hydrogeologic Database and Data Analysis Tool for the Death Valley Regional Ground-Water Flow Model

Grady M. O'Brien,[1] Matthew L. Jones,[2] and Claudia C. Faunt[3]
[1]U.S. Geological Survey, 520 North Park Avenue, Suite 221, Tucson, AZ 85719
[2]U.S. Geological Survey, 6770 South Paradise Road, Las Vegas, NV 89119
[3]U.S. Geological Survey, 5735 Kearny Villa Road, Suite O, San Diego, CA 92123

The U.S. Geological Survey is constructing a ground-water flow model of the Death Valley region, which covers approximately 100,000 km^2 between lat 35° N., long 115° W. and lat 38° 25′ N., long 118° W. The purpose of this model is to characterize the Death Valley regional flow system so that important ground-water issues can be quantitatively assessed. A hydrogeologic database and integrated analysis tool are being developed in support of the ground-water flow model.

A relational database structure is being developed and populated with hydrogeologic data obtained from throughout the Death Valley region. Database design utilizes the commonality among all data types so that the structure can be simplified and the performance can be enhanced. The relational structure comprises site information and water level, water chemistry, water use, spring discharge, and borehole interval data. Types of interval data include geology, borehole construction, water level, and aquifer test. In addition, Geographic Information System (GIS) data are linked to the database to simplify access of relational and spatial data.

Many data sources within the Death Valley region are being accessed to populate the Death Valley regional flow system database. The largest contributor in number of sites and data is the U.S. Geological Survey's National Water Information System database. Other major data contributors are the U.S. Department of Energy, the Nevada State Engineer's office, the National Park Service, the Bureau of Land Management, and the U.S. Fish and Wildlife Service. Published data are also being compiled and utilized. Data obtained from these sources must be processed and verified prior to inclusion in the database. To maintain a uniform and defensible platform on which to build the Death Valley regional flow system database, newly acquired data are being entered into the Nevada District National Water Information System database. An automated process was developed to retrieve the data from the National Water Information System and populate the Death Valley regional flow system database. Currently the Death Valley regional flow system database has 7,108 sites and more than 73,000 water-level measurements. Because of the dynamic nature of data integration, the database, although fully functional, continues to be improved and expanded.

An intensive effort is underway to systematically select and analyze data that will be used as flow-model observations. The large number of sites and data available within the Death Valley region necessitated the development of a multifaceted analysis tool. No commercially available software packages, for the necessary types of analyses, could retrieve, compile, annotate, and graphically display relational data as well as utilize spatial Geographic Information System data and techniques. The analysis tool was developed to combine the GIS and graphical display capabilities of ESRI's ArcView software with the relational database capabilities of Microsoft's Access software.

The functionality of the analysis tool allows the investigator to obtain and display many types of data. GIS coverages compiled for the Death Valley region can be used to create complex spatial displays. These coverages become useful tools in assessing the spatial attributes of the data. The measurement and supporting relational data that have been assembled in the Death Valley regional flow system database provide critical information that enhance the quality of the analysis. In addition, data can be annotated in ArcView and automatically saved to the database for future use. The data annotations can be used as restrictive criteria specified in database queries. Model observation data sets are created from the restricted database queries. Data annotated as not representative of regional hydrologic conditions are excluded from the observation data sets.

The relational database provides a means for obtaining and utilizing the most accurate and up-to-date data for the Death Valley regional flow system model. The dynamic nature of the database provides the capability to modify input data sets during the model calibration process, which in turn improves the ground-water flow model.

Correlations of Lithostratigraphic Features with Hydrogeologic Properties, a Facies-Based Approach to Model Development in Volcanic Rocks at Yucca Mountain, Nevada

David C. Buesch[1] and Richard W. Spengler[2]
[1] U.S. Geological Survey, 1180 Town Center Drive, M.S. 423,
Las Vegas, NV 89134 <dbuesch@usgs.gov>
[2] U.S. Geological Survey, Box 25046, Denver Federal Center, M.S. 421,
Denver, CO 80225 <rspengle@usgs.gov>

Volcanic fields in the Death Valley region vary from simple, comprising a cinder cone and a few lava flows, to very complex, made up of a multitude of formations, rock types, and calderas. The challenge in modeling hydrologic characteristics of the saturated or unsaturated zones (SZ and UZ, respectively) is how best to capture critical hydrogeologic parameter variations within the rock mass. Typically, modelers must choose between "formation-based" and "facies-based" or "property-based" model development. The "formation-based" modeling approach commonly relies upon the mapping of depositional boundaries to divide model units even though the rocks contained between depositional boundaries commonly vary significantly in physical and hydrogeologic properties. In contrast, the "facies-based" modeling approach relies on the mapping of vertical and lateral facies variations within formations that have similar hydrogeologic properties to define model units. Formation- and facies-based models use geologic maps and cross sections to determine the three-dimensional geometry of lithostratigraphic and hydrogeologic units. Maps depicting formations and zones in formations can be used for determining the lithostratigraphic and structural evolution of the field, and can be used for formation-based and facies-based hydrogeologic model development, but those depicting only formations restrict the choices of hydrologic modelers.

The site-scale UZ model at Yucca Mountain (Wu and others, 1996) is based on 30 detailed hydrogeologic units based on matrix properties (Flint, 1998). Boundaries between most hydrogeologic units correspond to depositional boundaries, as well as boundaries between zones or subzones defined by welding, crystallization, and cooling-fracture characteristics (Buesch and others, 1996a). Many detailed hydrogeologic unit boundaries are within 1 m of a lithostratigraphic contact. Contacts between vitric and crystalline or vitric and zeolitic tuffs correlate well with hydrogeologic properties, and can be traced laterally based on geophysical log data (Buesch and others, 1996b; Buesch and Spengler, 1998). This close correlation of lithostratigraphic units and contacts with detailed hydrogeologic units and boundaries reinforces the ability to use detailed physical-property-based lithostratigraphic units as a surrogate for hydrogeologic model units.

Because of its proximity to the water table in the Yucca Mountain area, the 13.1 to 13.5 Ma Crater Flat Group (Sawyer and others, 1994; Wahl and others, 1997) is considered important to both UZ and SZ modelers. From youngest to oldest, the Crater Flat Group consists of the Prow Pass, Bullfrog, and Tram Tuffs (Tcp, Tcb, and Tct, respectively). Formations are separated by a bedded tuff (Tcpbt, Tcbbt, Tctbt, respectively). The Prow Pass Tuff is dominantly an ignimbrite that is composed of four depositional units, one of which varies from nonwelded to moderately welded, is dominantly crystallized, and forms a compound cooling unit (Moyer and Geslin, 1995; fig. 18). To provide a context for the hydrogeologic properties and units (Flint, 1998) and to simplify correlation of units between boreholes, the Prow Pass Tuff has been divided into five zones based on welding and crystallization (fig. 18). The lower and upper vitric zones (Tcplv and Tcpuv) consist of vitric nonwelded to partially welded rocks, and these vitric rocks may have been subsequently altered to zeolitic minerals. The crystallized rocks are divided into nonwelded to moderately welded rocks that have undergone pervasive vapor-phase corrosion and mineralization (Tcplc and Tcpuc), and moderately welded rocks with minimal vapor-phase corrosion and mineralization (Tcpm). Similar to the rocks in the Paintbrush Group (Buesch and others, 1996a), cooling joints are best developed in the Tcpm, moderately to poorly developed in the Tcplc and Tcpuc, and poorly developed in the Tcplv and Tcpuv zones. Typically in individual boreholes, the lower vitric zone forms between 30 and 70 percent of the formation, the moderately welded zone constitutes 10–35 percent, and the three crystallized zones comprise 30–70 percent. Depositional, welding, and crystallization characteristics of the Bullfrog and Tram Tuffs are more complex, typically containing one or more compound cooling units. However,a five-zone classification scheme can also be applied to these formations (that is, Tcblv, Tcblc, Tcbm, Tcbuc, Tcbuv, and Tctlv, Tctlc, Tctm, Tctuc, Tctuv). In these formations, the lower vitric-crystallized and lower crystallized-moderately welded contacts are the first occurrence, and the moderately welded-upper crystallized and upper crystallized-vitric contacts are the last occurrence.

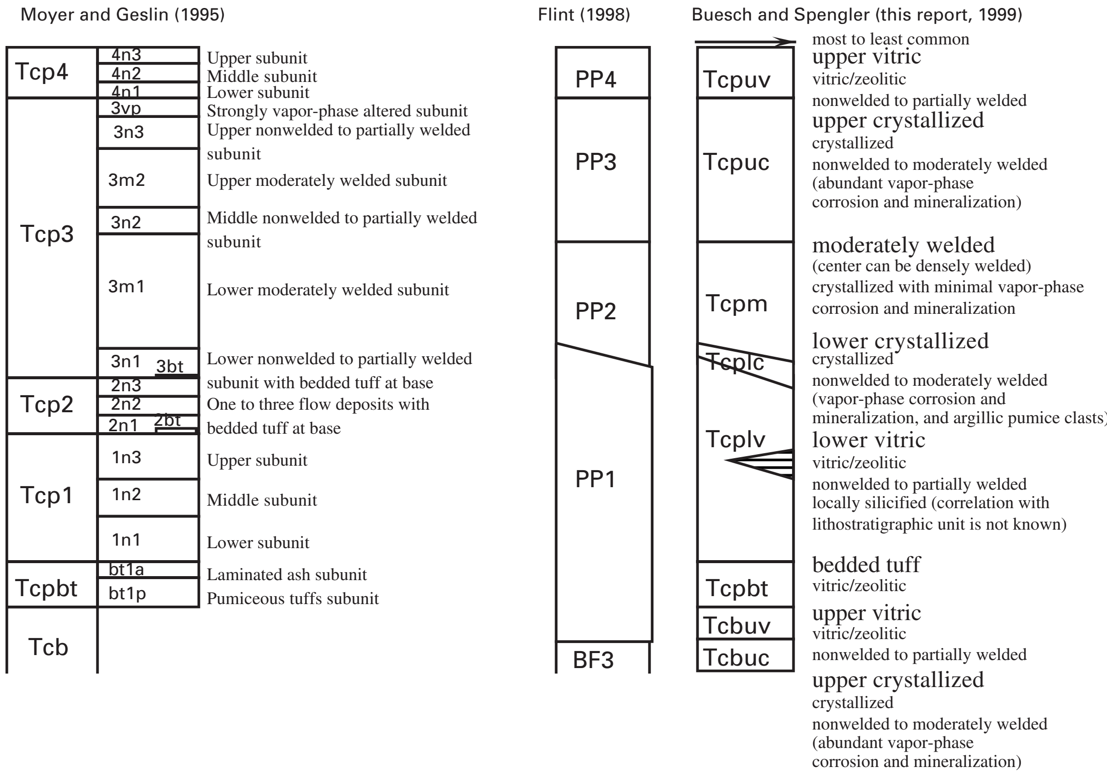

Figure 18. Lithostratigraphic and hydrogeologic units in the Prow Pass Tuff and pre-Prow Pass bedded tuff, Yucca Mountain, Nevada. Depositional units Tcp4, Tcp3, Tcp2, Tcp1, and Tcpbt and subunit descriptions are from Moyer and Geslin (1995); subunit symbols proposed in this paper include bt , bedded tuff, n, nonwelded to partially welded; m, moderately welded; vp, well developed vapor-phase crystallization. Detailed hydrogeologic units PP4, PP3, PP2, PP1, and BF3 are from Flint (1998). Property-based units Tcpuv, Tcpuc, Tcpm, Tcplc, Tcplv are proposed in this paper. Units Tcpuv, Tcplv, and Tcpbt can be zeolitic. Units Tcpbt, Tcbuv, and Tcbuc provide context for the hydrogeologic units (Flint, 1998).

The Crater Flat Group presents a good comparison between formation- and facies-based mapping and modeling because the relative thicknesses of zones vary laterally, which results in conspicuous variations in hydrologic properties that occur within the formation and not at depositional boundaries. Consider how the three formations, each with five zones, and the interstratified bedded tuffs can be hydrogeologically divided. In a formation-based model there are six model units (or three if the bedded tuffs are included in the superjacent formations). A more practical approach to the mapping of these formations is the proposed facies-based five-zone physical-property classification. There are several property-based modeling possibilities: 18 units if each is counted individually, 13 units if the crystallization zones are counted individually and the bedded tuff and subjacent upper vitric and superjacent lower vitric zones are combined (owing to similar properties), or 6 units if the lower crystallized, moderately welded, and upper crystallized zones are combined and the bedded tuff and subjacent upper vitric and superjacent lower vitric zones are combined (maximum generalization of similar properties). With a small additional effort of mapping and modeling of zones within the formations, a flexible, more realistic, geometrically consistent property-based hydrogeologic model can better be developed.

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Using Multivariate Statistical Analysis of Ground-Water Major Cation and Trace-Element Concentrations to Evaluate Ground-Water Flow in South-Central Nevada

Irene M. Farnham,[1] Kevin H. Johannesson,[2] Ashok K. Singh,[3] Klaus J. Stetzenbach,[1] and Xiaoping Zhou[1]

[1]Harry Reid Center for Environmental Studies, University of Nevada, Las Vegas, NV 89154-4009 <Farnham@Nevada.edu >, <Stetzenb@Nevada.edu>, < Xiaopinz@Nevada.edu>

[2]Department of Ocean, Earth, and Atmospheric Sciences, Old Dominion University, Norfolk, VA 23529-0276 <Kjohanne@odu.edu>

[3]Department of Mathematical Science, University of Nevada, Las Vegas, NV 89154-4020 <AKSingh@Nevada.edu>

The ground-water flow system in south-central Nevada has been extensively studied and is generally thought to be of regional extent, encompassing much of eastern and southern Nevada as well as parts of Arizona, California, and Utah (Winograd and Eakin, 1965; Eakin, 1966; Winograd and Friedman, 1972; Winograd and Thordarson, 1975; Dudley and Larson, 1976; Winograd and Pearson, 1976; Claassen, 1985; Thomas and others, 1986; White and Chuma, 1987; Harrill and others, 1988; Thomas, 1988; Peterman and others, 1992; Thomas, 1996; Thomas and others, 1996). These previous investigations have involved many different hydrogeological and hydrogeochemical methods and techniques including head-level studies, flow modeling, major solute analyses, stable oxygen- and hydrogen-isotope analyses of the ground water, and estimates of ground-water ages (using ^{14}C, for example). Although significant progress has been made toward understanding the flow of ground water in southern Nevada, a large uncertainty is still associated with the current ground-water flow models, owing to both the complexity of the ground-water flow system and the overall lack of extensive spatial coverage of hydrologic and hydrochemical data for the region. Because of the high cost of drilling additional wells in this area, new sources of information from the existing wells are continually being sought. Through the integrative interpretation of all available data, a better understanding of the ground-water flow system evolves (Mazor, 1991).

The analysis of multiple trace elements in ground-water samples can provide additional hydrochemical information for a site. Trace elements are the elements that occur in natural waters at concentrations of less than 1 mg/L. In principle, this includes all the elements of the periodic table with the exception of only a few (Drever, 1982). Trace elements, such as oxyanion-forming trace elements (Sb, Se, Mo, W, Re, Cr, Te, V, among others), may behave conservatively in certain ground-water systems (Hodge and others, 1996, among others), whereas others, like the rare earth elements (REEs), will reflect the ground-water-aquifer rock reactions (for example, Smedley, 1991; Johannesson and others, 1997a, b). Trace elements, therefore, may provide additional and more subtle information for evaluating ground-water flow histories, including their sources and mixing, and relationships for ground water with similar bulk (major solute) compositions.

Ground-water samples have been collected from many springs and wells in the southern Nevada area. Sampling locations include Death Valley, Ash Meadows, the Spring Mountains, Oasis Valley, Amargosa Valley, Pahranagat Valley, and the Nevada Test Site. Each sample was analyzed for 55 trace elements, 7 major solutes (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, and HCO_3^{-}), and other parameters including alkalinity, pH, water temperature, and TDS (total dissolved solids). Multivariate statistical methods were required to analyze the large amount of data generated in this project. These techniques (Principal components analysis, correspondence analysis, Hierarchical cluster analysis, and k-means cluster analysis) are powerful statistical tools used to search for patterns within large sets of data. A Geographical Information System (GIS) was used to visualize the results of the various statistical analyses geographically.

Multivariate statistical analyses of the trace-element data, as well as the major solutes, were used to evaluate the possible flow systems within the southern Nevada area. The results of these analyses, with an emphasis on the Death Valley region, will be presented.

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Rare Earth Elements in Ground Water and Aquifer Materials from Southern Nevada and Eastern California

Xiaoping Zhou[1] <xiaopinz@nevada.edu>, Kevin H. Johannesson,[2] Klaus J. Stetzenbach,[1] Caixia Guo,[1] and Irene M. Farnham[1]

[1]Harry Reid Center for Environmental Studies, University of Nevada–Las Vegas, Las Vegas, NV 89154-4009

[2]Department of Ocean, Earth, and Atmospheric Sciences, Old Dominion University, Norfolk, VA 23529-0276

The rare earth elements (REEs), with their unique and chemically coherent behavior, have been used extensively as sensitive tracers of geochemical processes in rocks, seawater, rivers, and estuarine systems. Recently, REE concentrations and behavior have also been studied in several aquifers; these studies demonstrated that ground water can inherit REE signatures from the rocks or aquifer materials (Smedley, 1991; Gosselin and others, 1992; Sholkovitz, 1995; Johannesson and others, 1997a).

In southern Nevada and eastern California, many ground-water samples from springs and wells have been analyzed. Based on REE signatures, we classified these ground-water samples as carbonate ground water and volcanic ground water (Johannesson and others, 1997a). In addition, some of the ground water appears to be mixtures of two or more types of water from different aquifers (Winograd and Thordarson, 1975; Johannesson and others, 1997b). Ground water from the volcanic rock aquifers of the region, such as Tippipah and Topopah springs on the Nevada Test Site, exhibit distinctive LREE enrichments and substantial negative Eu anomalies for their shale-normalized patterns; however, they do not exhibit Ce anomalies. The carbonate ground water has relatively low concentrations of REEs (as much as two orders of magnitude lower than volcanic aquifer ground water) and shows a flat or HREE-enriched pattern after shale normalization. Also, the carbonate ground water, unlike the volcanic ground water, has more diverse shale-normalized REE patterns. Some carbonate ground water, such as from Ash Meadows and Death Valley springs, has no or slightly negative Ce anomalies and possibly minor negative Eu anomalies. The shale-normalized REE profiles of both Ash Meadows and Death Valley springs (excluding Rogers Spring) are fairly flat, although slight enrichments of HREEs are observed. Other carbonate ground water, such as from the Spring Mountains, Pahranagat Valley, and Rogers Spring near Lake Mead, has strong negative Ce anomalies, substantial shale-normalized HREE enrichments, and minor Eu negative anomalies that closely resemble those of seawater (Fleet, 1984).

In order to compare REEs in ground water with those in aquifer materials, and to address the relationship between them, more than 50 rock samples were analyzed for REEs. These rock samples are representative of rock types of aquifers in southern Nevada and eastern California. Tertiary felsic volcanic rocks from the Nevada Test Site show fairly strong shale-normalized LREE enrichments with substantial Eu depletion, and no Ce anomalies. Lower Paleozoic (Cambrian and Ordovician) dolomite and dolomitic limestone from Frenchman Mountain, Mercury, Nev., and Fossil Ridge in the lower Sheep Range have similar shale-normalized REE patterns except for a slight difference in concentrations. None of these lower Paleozoic dolomitic rocks exhibits negative Ce anomalies, and most do not have Eu anomalies. Instead, the shale-normalized REE patterns for these carbonate rocks are quite flat, with only slight LREE or HREE enrichments. However, upper Paleozoic (Permian) limestone exhibits strong shale-normalized HREE enrichments with large Ce depletions. The shale-normalized REE patterns of the upper Paleozoic limestone are essentially identical to shale-normalized patterns for modern seawater. (See, for example, Elderfield and Greaves, 1982; Bertram and Elderfield, 1993.)

In addition to measuring REE concentrations in the rocks and ground water, batch tests were conducted in the laboratory in order to examine how different rock types may affect the concentration of REEs in the solution. Five types of rock samples (shale, sandstone, limestone, dolomite, and pumice) and pure distilled water (pH=7) were chosen for this study. The data show that both individual REE concentrations and total REE concentrations in the leachate solutions are very low, ranging from 5×10^{-3} pmol/kg to 40×10^{-3} pmol/kg, and from 0.26 pmol/kg to 6.75 pmol/kg, respectively. The solution that reacted with pumice has the highest REE concentrations, whereas the solutions that reacted with Ordovician limestone and with Cambrian dolomite have the lowest REE concentrations. Normalized to shale, the REEs for most of the leachate solutions show fairly flat patterns. However, the leachate solution that reacted with pumice exhibits a slight enrichment in HREEs, whereas the solution leached from Cambrian sandstone shows a weak MREE enrichment. These batch studies suggest that different types of rocks can impart REE signatures to ground water that reflect the original rock REE signatures.

Comparisons of the REE concentrations and behaviors in both ground water and aquifer rocks demonstrate that the shale-normalized REE patterns of the carbonate ground water and those of the volcanic rock ground water resemble the shale-normalized REE patterns of the respective rock types through which they flow. Keeping these results in mind, the REE patterns of ground water from Ash Meadows and Death Valley springs suggest that ground water from these areas is from carbonate rocks of chiefly dolomite and dolomitic limestone compositions, whereas ground water from the Spring Mountains and Pahranagat Valley is probably from a carbonate aquifer composed of limestone. The negative Ce and Eu anomalies also correlate between ground water and aquifer rocks. In other words, these anomalies reflect the relative Ce and Eu concentration of the whole-rock samples.

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Estimating Evapotranspiration Rates in Death Valley, California

Guy A. DeMeo <gademeo@usgs.gov>, Randell J. Laczniak <rlaczni@usgs.gov>, and
Walter E. Nylund <wenylund@usgs.gov>
U.S. Geological Survey, 6770 S. Paradise Rd., Las Vegas, NV 89119

In arid regions, the individual components of the ground-water budget often are poorly known. Ground-water recharge occurs intermittently over large areas and can be difficult to measure accurately on a regional scale. Natural ground-water discharge may occur as spring discharge, as underflow to adjacent basins, or as evapotranspiration from open-water surfaces, bare soil, and plants. Of these naturally occurring components, only spring discharge and evapotranspiration can be determined with reasonable accuracy.

The Death Valley regional ground-water flow system covers an area of about 15,800 mi^2 (Laczniak and others, 1996) and is one of the larger regional flow systems within the Great Basin. Ground water originates at principal recharge areas in the high mountains of central Nevada and is conveyed southward, discharging at one of many major areas of ground-water discharge, such as Ash Meadows and Oasis Valley. Because about 500 mi^2 of the valley floor lie below sea level (Hunt and others, 1966), Death Valley serves as the ultimate terminus for the Death Valley regional ground-water flow system. An unknown quantity of ground water is discharged as evapotranspiration across the valley lowland. To help reduce this uncertainty, the USGS is performing intensive field investigations to better quantify evapotranspiration rates throughout the valley.

All environments where evaporative discharge of ground water is believed to be significant are being monitored using equipment that continuously collects micrometeorological weather data. These data are used to estimate evapotranspiration rates from the energy-budget Bowen ratio method. Environments studied thus far include a bare-soil site, a salt-pan site, and two phreatophyte sites: pickleweed (*Allenrolfea occidentalis*) and honey mesquite (*Prosopis glandulosa*).

Preliminary results indicate that the evapotranspiration rates range between 0.11 and 0.25 ft/yr at the bare-soil and salt-pan sites to slightly more than 1 ft/yr at the pickleweed site. Additional sites are planned for salt grass (*Distichlis spicata*) and mixed phreatophyte communities during the next 2 years.

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Ostracodes as Indicators of Present and Past Hydrology in Death Valley

Richard M. Forester, U.S. Geological Survey, Box 25046, Denver Federal Center,
M.S. 980, Denver, CO 80225 <forester@usgs.gov>

INTRODUCTION—OSTRACODES

Ostracodes are microscopic crustaceans having a bivalved shell made of calcite. The life cycles of many ostracode species depend on environmental parameters that link their occurrences to hydrology and climate. They often live in particular hydrologic settings such as springs, streams, lakes, wetlands, or ground water. Within such settings, species are further limited by physical and chemical parameters, including (1) total dissolved solids (TDS), (2) major dissolved-ion composition and especially the total-alkalinity/Ca (alk/Ca) ratio, (3) water temperature, (4) the daily to annual variability of the latter parameters, and (5) the permanence of the environment. Thus the complex sets of environments created by the interchange of water between the atmosphere, surface water, and ground water support particular ostracode species assemblages (Forester, 1987, 1991a).

Lacustrine and wetland taxa typically have biogeographic distributions that can be related to climate, including globally distributed air masses such as the Arctic highs, the Polar lows, or the subtropical highs. Because most ostracodes are easily transported from one place to another, their biogeographic ranges shift with climate-driven change of their environment. Conversely, geologically long lived and environmentally stable settings such as Lake Baikal or large regional, typically fractured aquifers, such as the Paleozoic aquifer in southern Nevada or the Edwards aquifer in central Texas, support endemic species swarms. These endemic species swarms do not survive transport from one place to another (Forester, 1991b).

Ostracode shells are commonly preserved in most sediments and thus provide a means for efficient recognition of both present-day and past environments. Living ostracode baseline data, collected from about 750 localities throughout the United States (Forester and others, unpublished data) and from about 2,500 localities in Canada (Delorme, 1969), provide the basis for understanding the relation between many ostracode species and their environments. The ostracode shell may also be analyzed for stable oxygen and carbon isotopes, radiocarbon, and strontium isotopes as well as environmentally sensitive Mg/Ca and Sr/Ca ratios.

DEATH VALLEY OSTRACODES

Ground-water discharge dominates the modern-day hydrologic setting of Death Valley. Springs, spring pools, scattered wetlands, small streams, and spring-supported, man-made ditches exist throughout the valley. The major dissolved-ion composition of most of these waters is characterized by a low alk/Ca ratio and TDS ranging from fresh to saline water. Most of these waters are warm throughout the year. The warm freshwater springs along the valley margin contain ground-water species that are discharged to the surface with spring flow. Some of these ground-water species are endemic to the regional aquifer, whereas others, such as the darwinulids, are known from many other places. Twenty-five to thirty endemic, largely undescribed species, known mostly from fossils in the Amargosa and Las Vegas Valleys, to the east, are associated with the regional-aquifer discharge. The present-day Death Valley springs do not appear to contain this diverse assemblage of endemic species, but the springs have not been rigorously sampled. Recent ostracode collections made by Doug Threloff (NPS) from Travertine and Nevares Springs contain different ostracode species, possibly reflecting different ground-water flow paths or simply different local environments. Flow from the springs also contains a variety of surface-water cyprid ostracodes including *Chlamydotheca arcuata*, a large tropical ostracode, that lives only in warm springs outside the tropics (Forester, 1991a). The saline spring at Badwater, in contrast to the freshwater springs, contains an estuarine ostracode *Cyprideis beaconensis*, which is common along the west coast of the U.S.A. Saline wetlands are populated by species such as *Limnocythere staplini*, while the ditches usually contain taxa that are tolerant of highly variable, often nutrient-loaded environments.

Lakes existed in the valley during the last two glacial periods based on fossil ostracodes recovered from a 186-m core taken from the Badwater salt pan by Tim Lowenstein and Ron Spencer (Lowenstein and others, 1999). The lakes, at times, received significant stream input and thus indicate a shift away from hydrology dominated by ground-water discharge. During episodes of high stream flow into the valley, the major dissolved-ion composition shifted to a high alk/Ca ratio, reflecting solutes derived from water–volcanic rock reactions; this shift implies source waters from the upper Amargosa and Mojave drainages or even the Owens River drainage. The largest and freshest lakes (< 3 g/L TDS) existed during the penultimate glacial (about 140 to 180 ka) and contained ostracodes such as *Candona caudata* and *Limnocythere ceriotuberosa*. As these lakes evaporated, ostracodes such as the alkalobiotic species *Limnocythere sappaensis* were common. Yet further evaporation and input of low alk/Ca ground water resulted in the appearance of various taxa living in the valley today, such as *Limnocythere staplini*. Lakes during the last glacial were smaller and more ephemeral, often being dominated by the low-alk/Ca-ratio ostracodes. Spring and occasional ground-water ostracodes appear throughout the record, indicating continued and perhaps greater than modern-day spring discharge. One spring discharge dominated episode, during the penultimate glacial, even supported the marine Foraminifera *Elphidium* sp.

The present-day hydrology of Death Valley is a complex mix of natural and man-made hydrological settings, each containing distinctive ostracode species assemblages, as did the glacial lakes that once existed in the valley. Thus identification of modern or fossil ostracode species provides insights into the modern and past hydrology of Death Valley.

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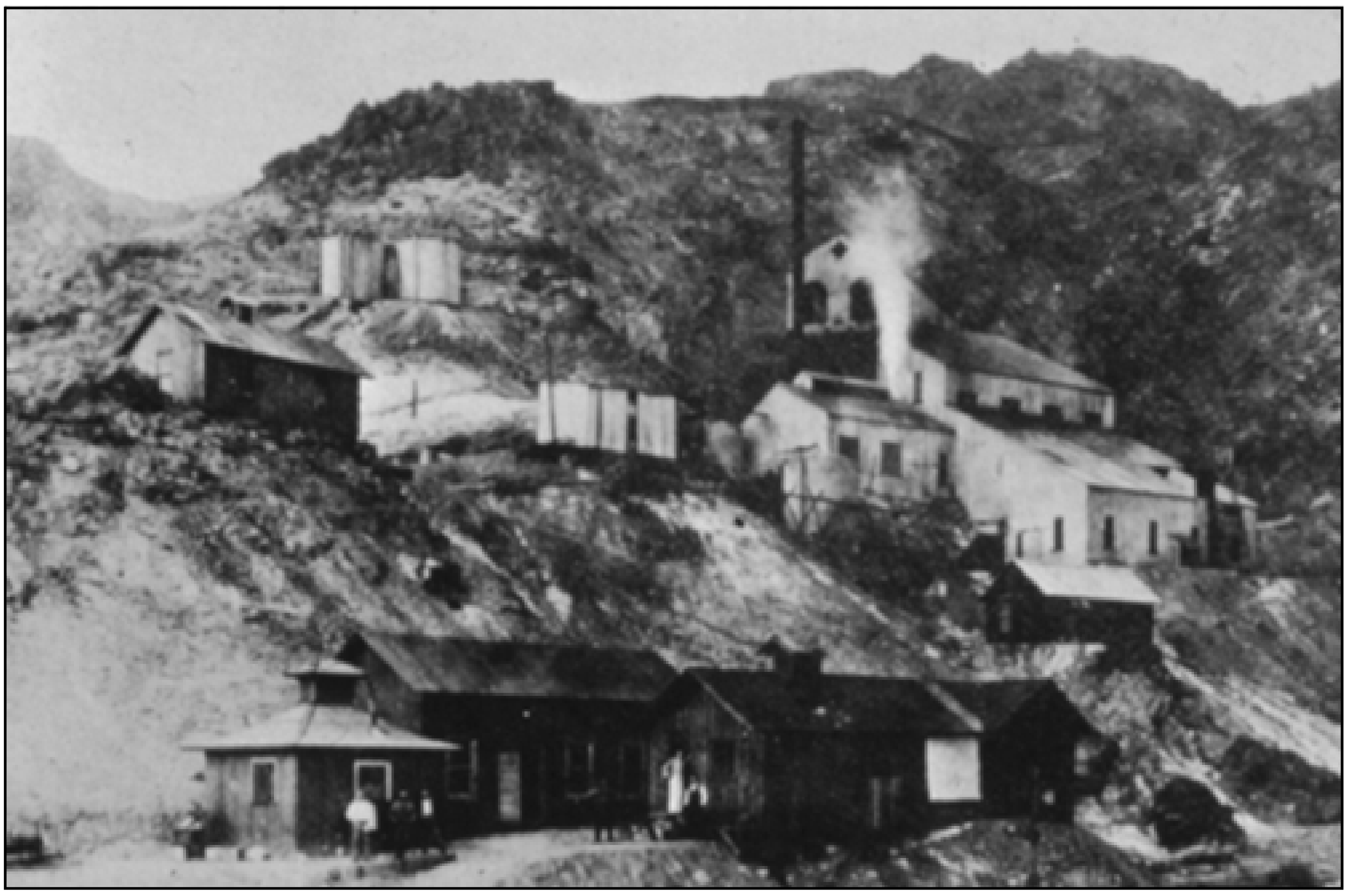

MAPPING IN THE DEATH VALLEY REGION

Regional Geologic Maps of the Nevada Test Site and Death Valley Ground-Water Flow System—The Starting Points for Ground-Water Studies

Peter D. Rowley,[1] Jeremiah B. Workman,[2] Gary L. Dixon,[1] Janet L. Slate,[2] Karen S. Morgan,[2]
E.B. Ekren,[3] David A. Ponce,[4] William R. Page,[2] Mel A. Kuntz,[2]
and Douglas A. Trudeau[1]

<prowley@usgs.gov>; <jworkman@ardneh.cr.usgs.gov>; <gldixon@usgs.gov>;
<jslate@usgs.gov>; <kmorgan@ardneh.cr.usgs.gov>; <ponce@usgs.gov>
<rpage@usgs.gov>; <mkuntz@usgs.gov>; <dtrudeau@usgs.gov>

[1]USGS, Las Vegas, NV 89119
[2]USGS, Denver, CO 80225
[3] Geology Unlimited, 2762 Nottingham Square, Fort Collins, CO 80526
[4] USGS, Menlo Park, CA 94025

The Nevada Test Site (NTS) is a 3,500-km^2 area that is centrally located within the area of the Death Valley regional ground-water flow system of southwestern Nevada and adjacent California. The U.S. Department of Energy (DOE) and its predecessor agencies conducted about 900 underground nuclear tests on the NTS; more than 200 were detonated at or beneath the water table, which commonly is about 600 m below the surface. Because contaminants introduced by these tests may move into water supplies off the NTS, rates and directions of ground-water flow must be determined. Such knowledge also is needed to properly appraise the future effects of the possible nuclear waste repository at Yucca Mountain, adjacent to the NTS. In addition, withdrawal of ground water from upstream parts of the flow system may reduce water levels in springs in downstream areas such as Devils Hole and Death Valley, thereby impacting endangered plant and animal species dependent upon these springs. The NTS project is a closely coordinated effort by the Water Resources and Geologic Divisions of the U.S. Geological Survey to characterize ground-water flow; overall coordination is by the Water Resources Division. Major project funding consists of $4.5 million per year from DOE’s Environmental Restoration and Defense programs. The project works closely with a USGS Water Resources Division team whose DOE funding supports allied work on geologic cross sections, structural analysis, hydrologic studies, and ground-water modeling. Other Federal and State agencies, notably the National Park Service, Fish and Wildlife Service, Nellis Air Force Base, Nye County, Nevada, Lincoln County, Nevada, and Inyo County, California also provide significant support. Project personnel also collaborate with the National Labs; Desert Research Institute; University of Nevada, Reno; University of Nevada, Las Vegas; and DOE contractors.

The cornerstone database and first step in interpreting ground-water flow on and near the NTS are modern digital geologic maps, because the area is geologically complex and lies in the heavily faulted Basin and Range province, within which most ground water travels by fracture flow. Myriad stratigraphic units fracture differently, and aquifers and confining units are in turn displaced and juxtaposed by major faults; the geometry of these rock units and faults determines flow paths. Bedrock mapping identifies faults and other structures that control flow in ranges, and geophysical mapping identifies faults buried in basins. Two geologic maps, accompanied by aeromagnetic and isostatic gravity maps, are being compiled: (1) digital geologic map of the Nevada Test Site and vicinity, Nye, Lincoln, and Clark Counties, Nevada, and Inyo County, California; and (2) digital geologic map of the area of the Death Valley regional ground-water flow system, Nevada and California. The current status of both maps will be shown at the meeting. The completed maps will be made available on the project web page and published as separate USGS Open-File Reports on CD-ROMs.

The geologic map of the Nevada Test Site and vicinity, as well as its accompanying geophysical maps, will be compiled at 1:100,000 scale. The map area encompasses two 1:100,000 quadrangles—the Pahute Mesa quadrangle to the north and the Beatty quadrangle to the south—plus a strip of 7.5-minute quadrangles on the east side. The map area includes not only the NTS but also the rest of the southwest Nevada volcanic field, part of the Walker Lane, most of the Amargosa Desert, part of the Funeral and Grapevine

Mountains, some of Death Valley, and the northern Spring Mountains. The map will be an improvement on the previous digital geologic map of the same area (Wahl and others, 1997) by updating the geology, improving GIS coverages, breaking out contacts for Quaternary units and faults in the south half, supplying geophysical maps, and geophysical interpreting of faults beneath the basins. The map is intended for release at the end of fiscal year 1999.

The geologic and geophysical maps of the area of the Death Valley flow system will be compiled at 1:250,000 scale. The map covers a large area (lat 35° to 38°15′ N., long 115° to 118° W.) in Esmeralda, Nye, Lincoln, and Clark Counties, Nevada, and in Inyo, Kern, and San Bernadino Counties, California. It includes Las Vegas, the area underlain by most of the Las Vegas Valley shear zone, the area underlain by most of the Garlock fault, the Spring Mountains, Amargosa Desert, much of the Walker Lane, Death Valley, Panamint Range, northern Mojave Desert, and easternmost parts of Owens Valley and the Sierra Nevada. A preliminary version of the map will be released in fall 1999.

The two geologic maps will provide the background data from which additional geologic and hydrologic studies will be done by the staff of the Geologic and Water Resources Divisions. These studies will include compiling tectonic maps, from which we will better understand the controls and locations of fractures in the area, and thereby likely flow directions. These studies also will include detailed geologic and geophysical mapping of certain problem areas as well as analysis of structures and placing of drill sites. Inversion of gravity data to determine basin thickness, when combined with geologic cross sections, will provide the third dimension. As part of the mapping, past and ongoing isotopic dating of spring mounds and carbonate dikes in and near the NTS shows that most of these features are Quaternary; this evidence of their youthful age, as well as their close relationship to mapped faults, suggests that these same faults influence present ground-water flow. Hydrologic studies concerning evapotranspiration, isotopic and chemical fingerprinting and dating of ground water, water use, water quality, and spring discharge are ongoing. Future drilling of characterization wells by DOE and Nye County will determine water levels, enable water sampling and monitoring, and provide direct three-dimensional geologic information. The main final product will be a regional ground-water flow model of the flow system. The overall investigation will provide critical background data on the major societal problem of movement of contaminants in ground water in southern Nevada and adjacent California. It also will be one of the first modern multidisciplinary studies of the geologic and hydrologic framework of a large ground-water flow system in the Desert Southwest. This has important ramifications for understanding ground-water flow in many other parts of the world.

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Geologic Map of the Trona-Kingman 1:250,000 Quadrangle, Southeastern California

Eugene Y. Hsu and David L. Wagner <dwagner@consrv.ca.gov>, compilers,
California Division of Mines and Geology, 801 K St.,
M.S. 12-31, Sacramento, CA 95814

The Trona-Kingman quadrangle covers the southwest corner of the Basin and Range province and much of the northern part of the Mojave Desert. The compilation is part of the California Division of Mines and Geology Regional Geologic Map Series, which was intended to supersede the Olaf P. Jenkins Geologic Atlas of California. During planning of the project, which began in 1982, it was decided to combine the Trona and Kingman Sheets of the Geologic Atlas into a single map. Eugene Hsu (now deceased) was responsible for compilation of most of the map. Wagner was responsible for compiling the area north of the Garlock fault and from the Black Mountains westward to the Sierra Nevada. Field mapping of selected areas began in 1982, and the preliminary compilation was completed in late 1985. Some field work continued into 1987 while the map was in the review process. The final product was to include five plates, a colored geologic map, an explanation, a detailed data-source index, a compilation of radiometric dates of rocks, and a fault map classifying faults according to recency of movement. After the review period, revisions were made and the map was submitted for publication. Before the map was completed, severely dwindling revenues throughout State government caused cutbacks, and funds for printing the map were not available.

Many Death Valley researchers contributed to the compilation and are aware of its existence, but many present workers may not be. The Division is evaluating the feasibility of revising the compilation by adding new data as well as digitizing all or part of the compilation. Attendees are invited to inspect the map, provide comments, and indicate where new mapping could be used to revise the map.

Tectonic-Geologic Map of the Death Valley Region, California and Nevada

L.A. Wright,[1] R.A. Thompson,[2] and J.B. Workman [2]
[1]Department of Geoscience, Pennsylvania State University, University Park, PA 16802
[2]U.S. Geological Survey, P.O. Box 25046, Denver Federal
Center, M.S. 913, Denver, CO 80225

This tectonic-geologic map of the Death Valley region has been compiled from scores of geologic maps prepared by numerous geologists working in the region during the past 50 years. The source maps, both published and unpublished, are included in the extensive reference list that accompanies this volume (diskette). The scale of these maps is much larger (that is, more detailed) than the 1:250,000 scale of this map. Thus, in assembling the latter, we have necessarily employed fewer, much more generalized rock units than appear on the original maps. We have also tried to accentuate the major stratigraphic breaks, the volcanic and intrusive rocks associated with Cenozoic extension and major faults, and other structural features that most clearly record and constrain the tectonic history of the region. In this sense, we view the compilation as primarily a tectonic interpretation of the geologic map. At the present scale, and at this point in time, some of the critical structural relations are at the center of controversy as numerous investigators actively pursue the tectonic history represented by the map area. As such, the map portrays a simplified snapshot of the dynamic history of crustal deformation in the Death Valley region spanning more than 1.7 billion years and actively continuing today.

In recent years, many of the geologic features shown on the map area have become especially important in an environmental sense. Yucca Mountain, the site of a proposed repository for high-level radioactive waste, lies in the northeastern part of the map area. The map area is largely downgradient from Yucca Mountain and thus contains the paths of surface and ground waters that originate in the topographically high drainage basins that contain Yucca Mountain and the Nevada Test Site. The map area also contains numerous active faults and two Cenozoic volcanic centers. In evaluating the safety of the radioactive waste site and the long-term sustainability of ground-water resources within Death Valley National Park and neighboring environs, earth scientists are particularly concerned with future dangers related to the movement of contaminated waters, renewed movement on active faults, and potential volcanic activity. These concerns have figured prominently in the rock units we choose to depict and in our representation of faults.

In simplest terms, the pre-Cenozoic bedrock units of the Death Valley region are divisible into (1) an ancient, mostly quartzofeldspathic crystalline complex, (2) a layered, dominantly sedimentary cover composed of Middle Proterozoic to Triassic formations, as much as 10 km in combined thickness, and (3) scattered plutons of Mesozoic age. The crystalline complex records strong metamorphism and deformation, about 1.7 billion years ago (Ga), of a still older terrane of sedimentary and igneous rocks. This complex also contains widely spaced granitic plutons (~1.4 Ga) and numerous dikes (~1.1 Ga). The pre-Cenozoic sedimentary cover rests upon the complex with a profound unconformity that records a protracted interval of erosion at least 200 million years long. The cover rock records a long succession of events that shaped the western margin of the North American plate through Triassic time. We have divided the cover into nine rock units of which eight span Middle Proterozoic to late Paleozoic time. All but one of the eight consists of two or more long-recognized formations.

In one Mesozoic unit, we have grouped various sedimentary and extrusive volcanic units that were emplaced in the Triassic-Jurassic interval in the Death Valley region. These deposits are exposed in the southern and southwestern part of the map area and are the sparse erosional remnants of originally much more extensive deposits. The volcanic component of this assemblage provides the earliest evidence in the Death Valley region of the transition from a passive to an active continental margin—the igneous activity being generated by the subduction of the Pacific plate's oceanic rocks beneath the preexisting continental margin rocks. In the southern and western parts of the map area, there are bodies of Jurassic and Cretaceous plutonic rocks collectively recognized as peripheral to the great Sierra Nevada batholith to the west, but which were crystallized from magmas generated during a continuation of the convergence of the two tectonic plates.

We have divided the Tertiary sedimentary deposits on the map into four basic units by age. The first two units (~35 to 25 Ma) and (~25 to 16 Ma) predate the inception in middle Miocene time (~16 Ma) of major and continuing extension that has shaped the present ranges and topographic basins. These deposits bear evidence of a broad terrain which, in the northern part of the map area, was characterized by distributary streams and lakes. On the other hand, the latter two map units were deposited in intermontane basins during the development of existing topography.

Nearly all the Cenozoic igneous bodies in the map area have proven to be younger than 16 Ma and to have been generated during the extensional tectonic events that produced the existing basin-and-range topography. These consist mostly of plutons and extrusive volcanic rocks, but also include numerous undifferentiated feeder dikes. On the present map they are further subdivided on the basis of composition, geographic distribution, and age. Most of this igneous activity occurs in the southwestern Nevada and Central Death Valley volcanic fields, and in a more southerly belt that extends eastward from the southern Panamint and Owlshead Mountains to the area of the Kingston Range.

The Quaternary and late Pliocene sedimentary deposits in the map area have been divided into seven units that are distinguished from one another by lithic composition, relative age, degree of deformation, and location. We also classify them by environment into (1) alluvial fan, stream and playa deposits, (2) perennial lake deposits, and (3) bodies of sedimentary breccia of debris-flow and avalanche origin. At various localities in Death Valley and Panamint Valley, the late Cenozoic alluvial and playa deposits are divisible into an uplifted and dissected older unit and a flat-lying younger unit. These two units are in fault contact at numerous localities along the west side of the Panamint Mountains and along the full length of Death Valley. In some places, including the Furnace Creek Ranch area, these deposits are moderately to strongly folded. The salt pan of central Death Valley is delineated separately, representing the distal sump for surface and ground-water flow and the site of alternating dissolution and precipitation of saline minerals, most recently in Holocene time. Locally, the salt pan masks evidence for the Quaternary faulting and folding recorded elsewhere in the Death Valley region. Lake-related deposits in the Tecopa and Amargosa Valleys, where exposed, are as old as 3 Ma and probably include strata as old as 5 Ma in the subsurface. They are broadly warped and moderately faulted, but are much less deformed than units of comparable age exposed in Death Valley.

Collectively, about 60 units are required to delineate the simplified geologic and tectonic history of the Death Valley region. We strongly believe that this map represents but a point of departure for future detailed mapping opportunities within this geologically complex and fascinating area.

Regional Hydrogeologic Features from a New Geologic Map of the Yucca Mountain Region

C.J. Potter and D.S. Sweetkind, U.S. Geological Survey, Denver, CO
R.P. Dickerson, Pacific Western Technologies, Ltd., Lakewood, CO

To document the geologic framework that underlies the Yucca Mountain site saturated-zone flow model, we have produced a new geologic map of the Yucca Mountain region at a scale of 1:50,000 covering the area encompassed by the model (fig. 19). The map includes (1) most of the Claim Canyon caldera segment of the Miocene southwest Nevada volcanic field (SWNVF; Sawyer and others, 1994); (2) thick, densely welded to nonwelded ash-flow sheets of the SWNVF exposed in normal-fault-bounded panels at Yucca Mountain; (3) folded and thrust-faulted Devonian and Mississippian strata unconformably overlain by SWNVF tuffs and lavas, cut by complex Tertiary faulting in the Calico Hills; (4) Proterozoic through Devonian strata exposed in the Skeleton Hills, Striped Hills, and in small exposures near Big Dune; (5) late Tertiary and Quaternary basaltic cinder cones and lava flows of Crater Flat and southern Yucca Mountain; and (6) broad basins (Jackass Flats, Crater Flat, and part of the Amargosa Desert) covered by Quaternary surficial deposits.

Several of the geologic and hydrogeologic features portrayed by this map and the accompanying cross sections are significant to the Death Valley regional hydrologic flow model, as well as to the Yucca Mountain site. These features include (1) possible fault-controlled flow channelization in SWNVF tuffs in the highly faulted southern Yucca Mountain area down-gradient of the potential repository; (2) faults inferred in the subsurface beneath the Amargosa Desert south of Yucca Mountain and Crater Flat; (3) the geometry of pre-Tertiary thrust faults; and (4) the subcrop patterns of the principal Paleozoic hydrogeologic units beneath the Tertiary basins and thick volcanic cover.

Extensional faulting at Yucca Mountain is dominated by steeply to moderately west dipping, north- to northeast-striking, block-bounding faults, with dominantly normal displacement and a subordinate component of sinistral slip. Displacement on these faults increases toward the south within Yucca Mountain (Scott, 1990; Day and others, 1998). Although the southern part of Yucca Mountain does not appear to be underlain by extensive tracts of imbricate normal faulting as suggested by Scott (1990), damage zones on the hanging-walls and footwalls of block-bounding faults are commonly tens of meters wide, and locally are more than 100 m wide. These damage zones consist of thoroughly brecciated densely welded tuff, where observed in several places in southern Yucca Mountain. Based on the presence of such zones, we consider the block-bounding faults of southern Yucca Mountain to be possible sites of flow channelization in the saturated zone (for example, Ferrill and others, in press).

Potential-field geophysical anomalies beneath the Amargosa Desert, as well as geologic contrasts across parts of the desert, suggest the presence of several significant buried northwest- to west-striking faults that offset the top of the Paleozoic rocks south of Yucca Mountain and Crater Flat. One of these faults, subparallel to U.S. Route 95, might have experienced dextral displacement that accommodated the paleomagnetically determined vertical-axis rotations of southern Yucca Mountain, as suggested by Fridrich (1998). The presence of such a fault implies that the flow in the volcanic aquifers of southern Yucca Mountain would encounter a steep fault boundary beneath the Amargosa Desert, against the lower carbonate aquifer and lower clastic confining unit (Winograd and Thordarson, 1975; Laczniak and others, 1996) of the Proterozoic and Paleozoic section. A similar juxtaposition is present along a northeast-striking mid-Miocene fault concealed beneath volcanic rocks at Yucca Mountain, originally interpreted by Fridrich and others (1994) from gravity data.

Within the Proterozoic and Paleozoic section in the map area, several thrust faults root in a detachment within the Proterozoic to Lower Cambrian Wood Canyon Formation (Caskey and Schweikert, 1992; Cole and Cashman, in press). As thrust ramps splay upward from this detachment level, contrasting hydrogeologic units (lower carbonate aquifer and lower clastic confining unit; Winograd and Thordarson, 1975; Laczniak and others, 1996) are juxtaposed. Thus, the interpreted presence of the northwest-vergent CP thrust (Cole and Cashman, in press) beneath Jackass Flats, Yucca Mountain, and Crater Flat would require juxtaposition of the lower clastic confining unit and lower carbonate aquifer beneath the pre-Tertiary unconformity. Such a juxtaposition is not incorporated into existing hydrologic models.

We interpret the vertical to overturned strata of the Striped Hills to be the result of successive stacking of south-vergent thrust ramps. The steep dips in the Striped Hills were achieved in pre-Oligocene time, as documented by a prominent angular unconformity between Cambrian and Oligocene rocks in Rock Valley just east of the map area (Sargent and Stewart, 1971). Thus, the steep dips in the Striped Hills cannot be attributed to Neogene movement on

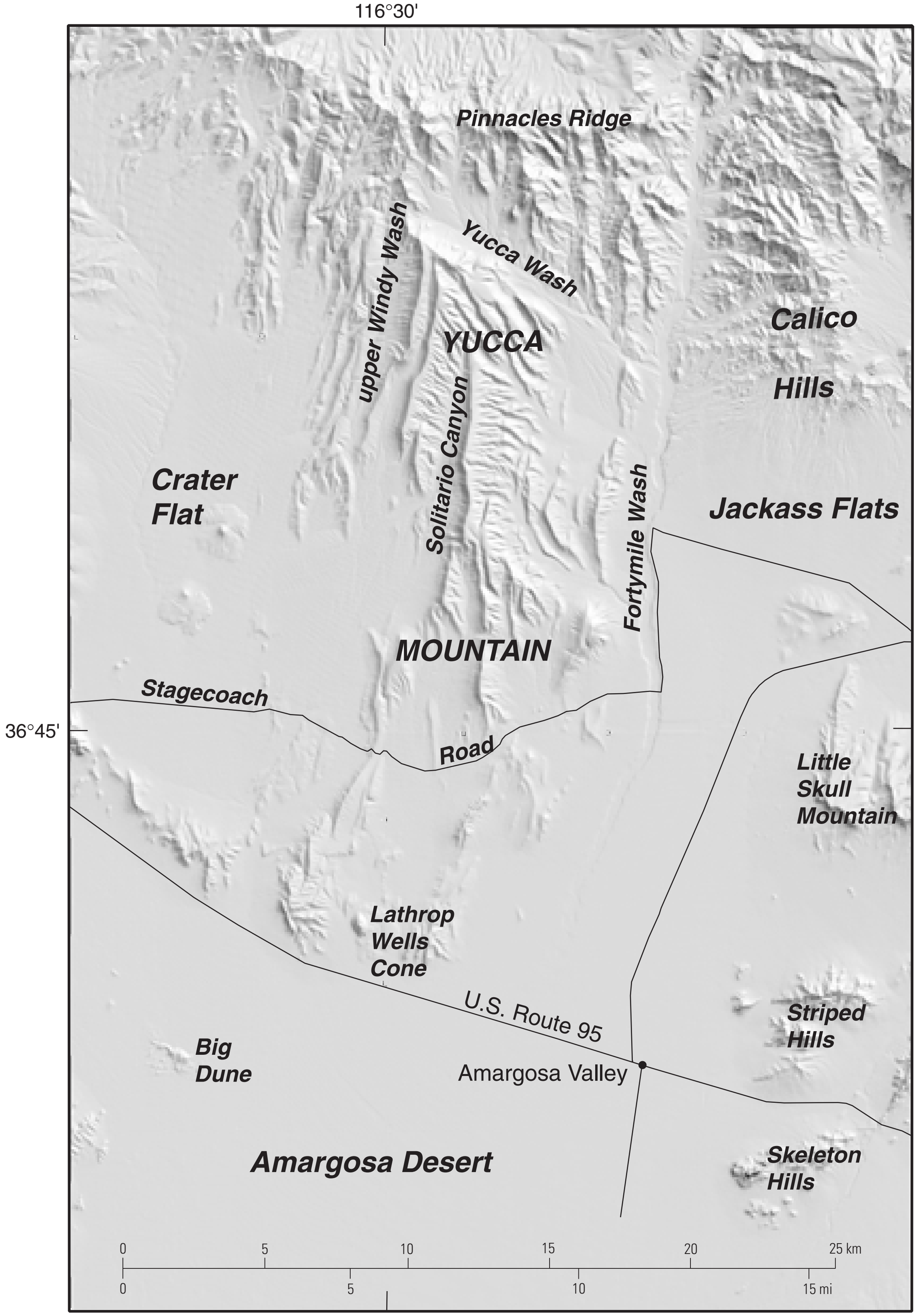

Figure 19. Shaded relief map showing area covered by the 1:50,000 scale Geologic Map of the Yucca Mountain Region, currently in progress.

the Rock Valley fault or similar structures. This steeply dipping to overturned panel, which also contains a juxtaposition of the lower clastic confining unit and lower carbonate aquifer, is interpreted to continue beneath the Amargosa Desert to the west and southwest where it is cut by the Tertiary "gravity fault" of Winograd and Thordarson (1975). This steep panel that includes the lower clastic confining unit is not included in existing hydrologic models.

The 1:50,000-scale Geologic Map of the Yucca Mountain Region introduces several hydrogeologically significant structural features that are currently being incorporated into the Yucca Mountain Project site saturated-zone flow model. The accompanying cross sections form part of the geologic framework being incorporated into the Death Valley regional flow model. Results of this mapping also bear on stratigraphic and structural interpretations of data from Nye County's ongoing Early Warning Drilling Program to the south of Yucca Mountain.

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Preliminary Surficial Geologic Map of the Beatty 30 × 60-minute Quadrangle, Nevada-California

Janet L. Slate <jslate@usgs.gov> and Margaret E. Berry <berryme@csn.net>
U.S. Geological Survey, Box 25046, Denver Federal Center, M.S. 913, Denver, CO 80225-0046

As part of the effort to revise the existing digital geologic map of the Nevada Test Site (NTS) area (Wahl and others, 1997), we mapped and compiled the surficial geology of the Beatty 30 × 60-minute quadrangle, Nevada-California. We took an innovative approach of constructing digital files as we mapped and compiled the geology using photogrammetric methods.

We used digital base materials and previously mapped Quaternary geology, where available. The Global Land Information System (GLIS) of the USGS National Mapping Division has created DLG (digital line graph) files at 1:24,000 scale for approximately one-third of the Beatty quadrangle. (See <http://edcwww.cr.usgs.gov/Webglis/glisbin/glismain.pl> for a list of DLG files.) Where no DLG files exist, we scanned clear-film positives and used these for the digital base. The traditional analog approach is to compile geology onto a scale-stable base (so-called "green-line mylar"); these data must then either be digitized or scanned. We used a computerized photogrammetric mapping system that consists of Carl Zeiss Inc. CADMAP® software and a digital Kern model PG-2 stereoplotter. A stereo pair of air photos is mounted on the PG-2 and scaled to the map base such that a location pinpointed while examining the air photos in stereo corresponds to the same location on the digital map. We used 1:80,000-scale (USGS-NHAP black-and-white series) diapositive-film air photos. Diapositives have significantly better resolution than paper prints, and with the PG-2 system we use we can zoom in to a scale of about 1:8,000 (10 times magnification). We merged the topographic base with the Quaternary-bedrock contacts from the most recent digital geologic map of the NTS area (Rev. 3 of Wahl and others, 1997) to create a background file. We transferred previously mapped Quaternary geology that was available digitally (fig. 20) into the computerized system as an active (editable) layer. Digital files of mainly W C Swadley's and co-authors' along with S.C. Lundstrom's yet to be published geologic mapping covered about 60 percent of the quadrangle. This system enables us to (1) save time and reduce error by eliminating the steps needed to convert data from analog to digital format, and (2) evaluate preexisting geologic mapping while viewing the area in stereo.

For this 1:100,000-scale compilation, we mapped three alluvial units (Qay, Qam, and QTa), three eolian units (Qe, Qey, and Qem), two playa units (Qp and Qs), lacustrine beach deposits (Qlb), travertine (Qt), and Quaternary-Pliocene undifferentiated surficial deposits (QTu), colluvium (QTc), and marl (QTm). These units correspond to the Quaternary units mapped primarily by W C Swadley in Pahute Mesa, which is the 30 × 60-minute quadrangle north of Beatty. Pahute Mesa is part of Rev. 3 (Wahl and others, 1997) and will be part of Rev. 4 (Slate and others, work in progress). For detailed map-unit descriptions, refer to Rev. 4 (Slate and others, work in progress), which we expect to

<table>
<tr><td rowspan="1">Bullfrog Mountain</td><td>Beatty</td><td colspan="2" rowspan="2">Beatty Mountain   East of Beatty Mountain
Swadley and Parrish, 1988
1:48,000
Carrara Canyon   Crater Flat</td><td>Topopah Spring NW
Lundstrom, unpub. data</td><td>Topopah Spring
Swadley and Hoover, 1989b</td><td colspan="2">Mine Mountain   Yucca Lake
Swadley and Hoover, 1990
1:48,000</td></tr>
<tr><td>Daylight Pass</td><td>Gold Center</td><td>Busted Butte
Lundstrom, unpub. data</td><td>Jackass Flats
Swadley and Hoover, 1989a</td><td>Skull Mountain
Swadley and Huckins, 1990</td><td>Cane Spring</td></tr>
<tr><td>Chloride City</td><td>East of Chloride City</td><td colspan="2" rowspan="2">Ashton   Big Dune
Swadley and Carr, 1987
1:48,000
Lees Camp   Leeland</td><td colspan="2" rowspan="2">Amargosa Valley   Striped Hills
Swadley, 1983
1:48,000
So. of Amargosa Valley   Skeleton Hills</td><td>Specter Range NW
Swadley and Huckins, 1989</td><td>Camp Desert Rock</td></tr>
<tr><td>Beatty Junction</td><td>Nevares Peak</td><td>Specter Range SW</td><td>Point of Rocks</td></tr>
</table>

Figure 20. Grid showing the thirty-two 7.5-minute quadrangles of the Beatty 30 × 60-minute quadrangle, and references (in italics) to Quaternary geologic maps that were available digitally. Boundaries of the sheet are lat 36.5°–37° N. and long 116°–117° W.

release as a digital U.S. Geological Survey Open-File Report by September 30, 1999.

The only other Quaternary mapping published for the Beatty quadrangle was in the Death Valley region. Though not available digitally, we consulted Wright and Troxel (1993), which was largely adapted from Hunt and Mabey (1966). The units Qs (Quaternary saline playa deposits), Qt (Quaternary travertine), and Qlb (Quaternary lacustrine deposits) are confined to Death Valley.

Because of the time constraints of this project, our mapping was principally based on air photo interpretation. We used surface morphology, tone, relative height, and map pattern to differentiate among the alluvial units. For the geomorphic attributes of the alluvial units, which make up about 90 percent of the Quaternary part of the map area, see table below.

Recognize that these attributes are highly generalized. Surface morphology is a product of both depositional and postdepositional processes. Debris flows, stream flows, or some combination of the two are the main processes that deposited these alluvial units. Postdepositional processes include weathering, winnowing by wind, eolian additions (surface accretion), reworking and erosion by water, creep, and bioturbation. Nevertheless, the variation in alluvial surface morphology with age aids in the mapping and correlation of geomorphic surfaces (Bull, 1991, among others). Lithologic variations across the quadrangle influence the tone of the alluvial units. Although young alluvial units are often light toned due to an absence or paucity of rock varnish, they may appear dark in places where the source rocks are dark. Lithology also influences the development of rock varnish; fine-grained or aphanitic rocks, such as quartzite or basalt, tend to become varnished more quickly than rocks such as limestone or granite. More often than not, granite will disaggregate to grus before becoming varnished. Relative height (topographic position) is useful for mapping in individual drainage basins near the range fronts, but out in the basins, especially in tectonically inactive areas, most surfaces grade to the same base level, and relative height differs little among the alluvial units. Faulting—both the magnitude and location—also affects the map pattern of alluvial units.

As faulting uplifts ranges relative to the basins, streams adjust to the new base level, abandoning and incising older alluvial units, thus preserving them. In tectonically inactive areas, streams continue to grade to the same level, thus burying older alluvial units. Therefore, map pattern is an important tool to evaluate basin evolution.

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Quaternary alluvial unit	Surface morphology	Tone (on air photos)	Relative Height	Map pattern
Qay – Young alluvial deposits (Holocene)	Bar-and-swale near range fronts; braided sand plains in basins	Light, in general, due to no or little varnish; can appear variegated	Lowest where surfaces are incised	Emanate from fan apices; form active channels
Qam – Middle alluvial deposits (Pleistocene)	Planar, smooth appearance; locally dissected	Dark, in general, due to accumulation of varnish	Intermediate; higher than Qay, but lower than QTa	Progressively older units flank younger units
QTa – Old alluvial deposits (Pliocene-Pleistocene)	Typically ballena (whaleback form), less often planar	Light, in general, due to erosional exposure of carbonate horizon	Highest where surfaces are incised	Older units typically preserved close to the range fronts

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Strategy for Mapping Quaternary Surficial Deposits in Support of the Death Valley Regional Flow Model in California and Nevada

Christopher M. Menges,[1] Emily M. Taylor,[2] Janet L. Slate,[3] and John C. Dohrenwend[4]

[1]U.S. Geological Survey, M.S. 423, 1261 Town Center Dr., Las Vegas, NV 89134 <cmmenges@usgs.gov>

[2]U.S. Geological Survey, Box 25046, Denver Federal Center, M.S. 425, Denver, CO 80225

[3]U.S. Geological Survey, Box 25046, Denver Federal Center, M.S. 913, Denver, CO 80225

[4]Department of Geosciences, University of Arizona, Tucson, AZ 85721

Regional and local mapping of upper Tertiary to Quaternary surficial deposits is being conducted as hydrogeologic input to the Death Valley regional flow system (DVRFS) model. This regional ground-water model is under development by staff from the Water Resources and Geologic Divisions of the U.S. Geological Survey (USGS), under sponsorship primarily from several projects in the U.S. Department of Energy (DOE), including the Underground Testing Areas (UGTA) and Hydrology Resources Management Programs in the DOE Nevada Test Site (NTS) and the Yucca Mountain Project (YMP), (D'Agnese and others, this volume; Faunt and others, this volume). The 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) and the UGTA geologic model (IT Corp., 1996).

A significant component of this work focuses on development of a comprehensive geologic framework for the DVRFS, including preparation of a consistent regional geologic map at 1:250,000 scale covering a 3.25 × 3 degree area (lat 35° to 38.25° N., long 115° to 118° W.) centered on the Death Valley hydrogeologic basin that contains the DVRFS flow model (Faunt and others, 1997; Faunt and others, this volume). Most of this activity involves compilation and synthesis of existing geologic maps from published and unpublished sources. Most of these maps, however, contain limited definition of late Tertiary and Quaternary surficial deposits in the basins, and there is little consistency among maps that do portray these units in adequate detail. Thus a substantial amount of new photointerpretive mapping, supported by limited field reconnaissance, is required to provide an accurate and consistent set of generalized hydrogeologic surficial-deposit units for the regional geologic map. More detailed compilation and mapping of basin stratigraphy, including a more detailed set of Quaternary surficial deposits, are underway at 1:100,000 scale in the Amargosa Valley region; detailed studies at a similar scale are planned for other important discharge areas in the western part of the DVRFS. All of this work must be completed within the next year for the new data to be incorporated in revision and calibration of the flow model.

The physiography and geology of the 100,000-km^2 area included in the Death Valley hydrogeologic basin are extremely complex. For example, the physiography of the DVRFS includes (1) typical Basin and Range topography in the north and east; (2) diverse sets of ranges, plateaus, basins, and alluvial flats (for example, NTS volcanic highlands and Amargosa Valley) in the center; and (3) the extremely rugged ranges and basins of Death Valley along the western border. Basin altitude likewise ranges from more than 1,750 m in the semiarid basin margins north of the NTS to -86 m in the hyperarid basin center of Death Valley. The bedrock exposed in the ranges includes Precambrian and Tertiary crystalline rocks, Proterozoic and Paleozoic clastic and carbonate rocks, and Tertiary volcanic and sedimentary rocks. The region crosses several tectonic subdivisions of the Great Basin with varying amounts and rates of normal and strike-slip faulting. This diversity in relief, local climate, geomorphology, source-area rocks, and structural setting has produced a complex suite of surficial deposits in the DVRFS that is difficult to map consistently in the restricted time available to the project.

This task cannot be accomplished, given the coverage area, time constraints, and generalization requirements of the project, using standard techniques of Quaternary mapping, which typically consist of photointerpretation from conventional vertical aerial photography, supported by substantial field work and followed by transfer and compilation onto base maps with an analog or digital plotter. A more effective approach consists of directly mapping Quaternary units on suitably processed and projected Landsat Thematic Mapping (TM) satellite imagery. In particular, we are applying high-contrast hue-saturation-intensity processing techniques to data contained in spectral bands 7, 4, and 2, or 7, 4, and 1 from the six Landsat-TM scenes covering the entire regional map. This processing is specifically designed to enhance the differentiation of surface characteristics such as pavement-varnish development, soils, dissection, and texture that are particularly important for regional mapping of hydrogeologic surficial units. Some areas will be enhanced separately where necessitated by local geomorphic or stratigraphic conditions. The processed data will then be rectified and projected onto 1:100,000-scale images georeferenced to 1:100,000-scale topographic sheets in the map area. This process will provide a regionally consistent set of images at a suitable scale for both the small-scale regional (1:250,000) and larger scale detailed (1:100,000 and greater) mapping of Quaternary deposits in the DVRFS area. In order to ensure efficient and timely preparation of maps, units will be identified and mapped directly on scale-stable acetate overlaid on the 1:100,000-scale satellite-image maps, supported where necessary by stereoscopic inspection of conventional high-altitude aerial photography. Interpreted units for each map image will be digitized and compiled at reduced scale for incorporation as a digital layer of the regional geologic map. These processed images can be interpreted and digitized without reduction for development of the local-scale maps, using an appropriate set of units and level of detail.

We have defined two complementary sets of hydrogeologic surficial map units with varying levels of detail to accommodate both the regional and more detailed scales of mapping. Both sets of units have been modified from standard types of surficial-deposit units in order to emphasize factors of potential importance to infiltration or discharge model input. This includes definition of specific units, such as modern channels, active or inactive discharge deposits, and playas, that directly impact these factors. Hydrologically significant variations in grain size are differentiated by adding units or subunits such as coarse-grained proximal to mid-level alluvial fans and fine-grained distal alluvial fans and alluvial plains. Alluvial units are further subdivided by general age categories that reflect other potentially important hydrologic characteristics, such as degree of soil and pavement development, cementation, and amount of internal dissection. Units are assigned only broadly defined Holocene and Pleistocene ages in the regional mapping; the larger scale of the detailed local mapping permits additional subdivision of the Pleistocene and Holocene units.

These hydrogeologic surficial units have been provisionally correlated with upper Tertiary to Quaternary units mapped in and adjacent to the DVRFS area. These include a number of unpublished geologic maps of 1:100,000-scale sheets that will be modified and incorporated into the DVRFS regional map (for example, the Beatty sheet by J.L. Slate and M.E. Berry (this volume); the Pahranagat Range sheet by A.S. Jayko; the Indian Springs sheet by P.L. Guth and J.C. Yount; and the Las Vegas sheet by W.R. Page, S.C. Lundstrom, and others). The hydrogeologic units have also been evaluated and correlated with other published and unpublished Quaternary chronosequences in the DVRFS and adjoining areas in order to test consistency of regional mapping and to provide age control. (See, for example, Peterson and others, 1995; Dorn and others, 1987; Moring, 1986; Reheis and others, 1989; Bull, 1991.)

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Geology of the Saddle Peak Hills 7.5′ Quadrangle, Southernmost Death Valley, California

Bennie W. Troxel, 2961 Redwood Road, Napa, CA 94558

Rocks in the Saddle Peak Hills, northern Salt Spring Hills, and Sperry Hills include an east-dipping succession of late Precambrian rocks that approach 20,000 ft in thickness, Tertiary igneous and sedimentary rocks, and Quaternary gravel of at least three generations. Most of the structural features are detachment faults and related listric faults that merge downward into them. Jumbled rocks that resemble the Amargosa chaos in the Black Mountains, as defined by Levi Noble, overlie a nearly horizontal fault zone in the crest of the Saddle Peak Hills.

ROCK UNITS

The middle member of the Crystal Spring Formation is the oldest of the exposed rocks in the Saddle Peak Hills. It is intruded by diabase, in sills, which has been dated at 1.02 Ga elsewhere in the region. The member consists mostly of limestone and dolomite, commonly algal. Strata in the upper Crystal Spring member comprise sandstone, siltstone, and limestone in alternating beds.

Next is the Beck Spring Dolomite, a unit characterized regionally by dull, blue-gray massive cliffs and mountain crests. It is surprisingly well banded and variegated in the Saddle Peak Hills, due to the introduction of clay and sand, probably from the south.

The next younger is the Kingston Peak Formation, consisting of a lower member of fine-grained, thinly layered siltstone, a middle member of diamictite, and an upper member of marine graded beds and nongraded diamictite, which are remnants of distal marine fans that extended southwest from a source region to the north—the Nopah Upland.

The Crystal Spring and Beck Spring Formations appear to have been deposited in a shallow depression that occupied a modest region near the western margin of North America. Following their deposition a structural trough formed along northwest-trending faults into which strata of the Kingston Peak Formation were deposited. Clasts in the upper Kingston Peak Formation derived from the Beck Spring and Crystal Spring Formations, and finally old basement rocks denote the downward erosion of the Nopah Upland that bordered the sedimentary basin on the north. Occasional striated clasts suggest the presence of a coexistent glacial terrain.

The Noonday Dolomite consists of a lower, algal-dominated unit that formed a platform facies along the northern margin of the basin containing Kingston Peak strata. It is overlain by an upper unit composed of mixed sand and carbonate grains (now sandy dolomite). The upper unit covered gigantic algal mounds and intervening subsea topography along the northern platform. Southward (in the central Saddle Peak Hills), a unit that overlies the lower Noonday was originally described as the basin facies of the Noonday Dolomite but is now known as the Ibex Formation. It consists mostly of silt and limestone. The basal beds overlie eroded lower Noonday algal dolomite and the upper beds grade into upper Noonday sandy dolomite.

Above the Noonday Dolomite, in stratigraphic order, are the Johnnie Formation, Stirling Quartzite, Wood Canyon Formation, Zabriskie Quartzite, and Carrara Formation of late Precambrian to Early Cambrian age.

The still younger rocks comprise Cretaceous(?) quartz monzonite, Miocene basalt to rhyolite as intrusive rocks and flows, Miocene sedimentary rocks, and Quaternary surficial deposits. Volcanic and plutonic rocks appear to be mostly about 12 Ma. The dike swarm in the Saddle Peak and Salt Spring Hills, and some of the flows in the Sperry Hills, are mostly andesitic. A small intrusive body in the northern Saddle Peak Hills is probably about the same age as the pluton in the Kingston Range, which has been dated at ~12.4 Ma.

Tertiary sedimentary rocks in the Sperry Hills mark the southwestern limit of a basin that once occupied a major part of the eastern Sperry Hills. Coarse gravel beds probably reflect the south margin of the basin. The gravel contains abundant pods of megabreccia made up mostly of Precambrian strata. North of the gravel beds are outcrops of highly fractured Tertiary quartz monzonite.

STRUCTURAL FEATURES

Most fault activity recorded in the Saddle Peak Hills quadrangle is Tertiary in age, the exception being the Precambrian faulting that defined the northeast margin of the basin occupied by the Kingston Peak Formation and the lowermost Noonday Dolomite.

The earliest Miocene structural event that can be documented is the emplacement of andesitic dikes that crop out in the southern Saddle Peak Hills and Salt Spring Hills. The dikes, rarely more than a few feet thick, occupy fractures that trend northwest. The dikes occupy an estimated 15 percent, or slightly more, of the belt in which they occur.

Possibly simultaneous with the emplacement of the dikes was the development of flows and intrusive masses in a belt along the southwest margin of the Sperry Hills. The extrusive volcanic rocks are nearly coincident in age with the dikes (~12.4 Ma) and are similar in composition (mostly andesitic) to volcanic rocks exposed along the east flank of the Saddle Peak Hills. The combination of observations of these rocks suggests that extension occurred about 12 Ma, and that extension was to the southwest and on a small scale.

Later, at an undetermined time, extension occurred along major detachment faults. Of these, the oldest may be one that trends north-northwest through the Saddle Peak Hills. The fault defines the westernmost limits of the Kingston Peak Formation in the hills. Faults above it converge downward upon it. The main fault separates all younger sedimentary units from the Crystal Spring Formation.

A set of younger detachment faults occurs in the crestal part of the Saddle Peak Hills, where nearly horizontal fault planes separate steeply tilted Noonday and Ibex strata from underlying tilted strata of the Kingston Peak Formation. The Noonday-Ibex strata, in turn, are separated from the overlying, steeply tilted younger Johnnie Formation strata along other horizontal fault planes. Movement has also occurred along the dikes since their emplacement.

Lastly, the hills have been rotated and pulled apart on an even younger detachment system. Note that northwestward extension was preceded by extension to the southwest and was accompanied by volcanism.

IMAGERY, QUATERNARY STRATIGRAPHY AND GEOMORPHOLOGY, AND QUATERNARY GEOCHRONOLOGY

Thirty Years of Remote Sensing in Death Valley—What Have We Learned?

Alan Gillespie, Department of Geological Sciences 351310, University of Washington, Seattle, WA 98195-1310 <alan@rad.geology.washington.edu>

INTRODUCTION

Death Valley has been used as a testing area for geological remote-sensing studies for nearly 30 years. Several reasons for this are: (1) the lack of vegetation and clouds to obscure the landscape; (2) the well-understood geology and lithologic variety; and (3) the proximity to research and aircraft facilities. In addition, once a body of work becomes known, it generates its own momentum, attracting new studies and investigators.

Remote-sensing studies in Death Valley have spanned the electromagnetic spectrum, from the visible to microwave frequencies. However, examination of the literature reveals a curious fact: improving our understanding of Death Valley has been the primary goal of only 10 percent of the studies. Most (60 percent) of the studies were done to develop remote-sensing techniques and instruments, whereas 30 percent have essentially used Death Valley as a convenient "laboratory" for studies whose application might just as well have been elsewhere. A legitimate question then is, "To what extent has our knowledge about Death Valley been increased by remote sensing?" In this report, in addition to attempting to answer the preceding question, I review the kinds of studies that have been conducted in Death Valley, and what types of things may be understood in arid regions using remote sensing.

In a way, the Death Valley studies parallel the development of remote sensing in this country, and I shall return to this theme later. The impetus for terrestrial remote sensing was mostly the space program and its early successes on the moon and Mars—arid "targets" that led to the search for terrestrial analogs to help explain what was found in the images. (See, for example, Schaber, 1978.) Sunset Crater in Arizona, Mauna Loa, and Death Valley: all were tapped at one time or another to serve in this way. In the early 1960's, NASA actually had to be persuaded (notably by Paul Merifield and Paul Lowman) to let astronauts take a hand-held camera into orbit to photograph the Earth. In the early 1970's, a focus of study shifted to the Earth itself, and appropriate instruments such as Landsat were placed in orbit. Death Valley's role as a remote-sensing laboratory was pretty well established only a few years later.

In fact, in its early stages remote sensing didn't seem to offer much for geologists beyond a synoptic view for photointerpretation. Some remarkable work was done with these images (for example, the tectonic interpretation of Asia by Molnar and Tapponier, 1975), but this was in a distant, poorly understood area. Closer to home, remote sensing mainly replicated what was already known through photogrammetry, or served as a base map for conventional studies. Later, as instrumentation improved, studies that were only science fiction in the early 1970's became feasible, and the potential of remote sensing to map and characterize surfaces by compositional and physical characteristics became clear. Therefore, now seems to be a good time to reevaluate the role of remote sensing in Death Valley. What are the important research questions to ask, and what role can remote sensing play? Before answering this, a digression is necessary to define remote sensing, and how current techniques can be used in geologic studies.

REMOTE SENSING

Remote sensing is generally defined as the measurement of radiant fluxes from a surface, with the understanding that the measurement is done at a distance, from aircraft or satellites. Because of the opacity of the Earth's atmosphere at certain wavelengths of light, terrestrial remote sensing is commonly restricted to wavelengths of about 0.4–2.5 µm, 3–5 µm, 8–14 µm, and 1–100 cm. The first "window" brackets visible light (0.4–0.7µm) and reflected infrared sunlight (0.7–2.5 µm). In the second window, emitted thermal radiation is as strong as reflected sunlight, and in the third window, thermal infrared, it is the dominant term. The fourth window is the microwave region in which radar operates.

Generally, the interaction of light with a surface depends on its composition, orientation, and texture or roughness. At short wavelengths, the reactions are energetic, and at longer wavelengths, they are less so. Thus, in visible light we see mainly electronic processes, such as the charge transfer between iron and oxygen that makes rust red and colors much of Death Valley. Chlorophyll absorbs red light strongly, which is why vegetation is green.

From a geological standpoint, water, hydroxyl, sulfate and carbonate absorptions dominate the reflected infrared part of the window (0.7–2.5 µm). Vegetation, however, is intensely reflective around 0.7–1.2 µm, which is why it appears characteristically red in false-color infrared aerial photographs.

In the thermal infrared window, most of the radiant signal emitted from the Earth is dominated by the surface temperature, which is not an intrinsic property of the surface but changes continuously. However, the radiant spectrum is modulated by the thermal emissivity, which is intrinsic to surface materials. The emissivity is the efficiency with which a surface radiates its heat energy, and it is typically the complement of the reflectivity. Metal is highly reflective but not very emissive; rocks are poorly reflective but efficient radiators of energy.

The characteristic spectral absorptions (and emissivity features) of silicate minerals occur at thermal infrared wavelengths. Quartz, which spectrally is nearly featureless in reflected sunlight, is strongly colored between 8 and 9 µm, and also around 12–14 µm. Thermal infrared spectra can be diagnostic for many silicates, and therefore thermal imaging is of great interest to geologists who are interested in mapping surfaces according to lithology.

Radar is sensitive to the dielectric of surface materials, which is dominated by soil moisture. It is also sensitive to surface roughness. More microwave energy is reflected back to the antenna if a surface is moist or rough. If there is standing water, however, then the radar beam is reflected specularly, little energy returns to the antenna, and the surface appears dark instead of light. The dielectric for most rocks varies only over a narrow range.

Radar is transmitted as a polarized signal, and the antenna may measure the like- or cross-polarized return signal. In general, multiple interactions with complex surfaces tend to depolarize the energy, so that the cross-polarized term is large for plants but smaller for sand dunes. The degree of depolarization, along with the backscatter coefficient, can thus tell us something of the structure of a surface.

Radar is highly sensitive to slope, as is the brightness of a surface in visible and thermal wavelengths. The strength of reflected sunlight, of course, varies with the elevation angle of the sun above the horizon, and with the local slope. In fact, most of the brightness range in photographs is due largely to topographic shading and shadowing. Thermal emissions are not as sensitive to slope, but because different amounts of sunlight strike different slopes, their temperatures vary also. Therefore, thermal images show topography much as aerial photographs do. Both thermal imaging and radar imaging, however, work at night, and radar "sees" through clouds.

Images that are made at several wavelengths within a spectral window are called "multispectral." Color photographs are one good example, but multispectral radar imagers have also been built. Generally, multispectral images have broad spectral bands that cannot resolve all the detail of the surface's reflectivity or emissivity spectra; therefore, they are mainly useful in photointerpretation. The new generation of imaging systems can acquire data in many more bands, and these instruments are called "hyperspectral." The NASA airborne scanner called AVIRIS, with 224 bands of visible and reflected infrared light (between 0.4 and 2.5 µm), is perhaps the best known example, but hyperspectral thermal scanners have also been built. Spectral data from these hyperspectral instruments can rival laboratory spectra, and their use is sometimes referred to as "imaging spectroscopy."

Radars and laser altimeters have the capability of measuring range (distance) to the surface, not just the surface's reflection properties. Radar systems have been used to generate topographic maps. Radar topographic maps are made by interferometry, exploiting phase relationships between two nearby antennas. By repeating the interferometric measurements a short time apart, it is possible to measure topographic changes with accuracies of a few centimeters. Obvious applications include earthquake deformation, landslide movement, and debris flow deposition. Not surprisingly, such differential interferometry has attracted attention because of its potential for mapping strain fields.

All image data are fundamentally spatial, and it may help to regard the image as an "image cube" or hypercube in which two dimensions are spatial. A pixel in this spatial plane consists of a spectrum. Of course, the spectrum may change temporally, there may be multiple polarizations also, and so forth, but with these accounted for the hypercube remains a good way to envision image data.

A new data management technology has sprung up around images and geographic, geologic, or geophysical data, and in recent years this technology has become an integral part of many remote-sensing studies. Geographic Information Systems (GIS) basically facilitate the correlation of spatially related data sets from a wide variety of sources. At the most basic level, the GIS relates digital topographic maps, image data, and geologic, geophysical, or other overlays, but in more advanced use it is possible to drive process models with image and topographic input.

It is a rare Earth scientist who is directly interested in the technical aspects of remotely measured radiant fluxes. Most geologists have been content to use mainly the spatial information in images for photointerpretation. To work with compositional identification, or to extract more subtle information from the data, it is necessary to develop and invert models. Generally, there are several levels of modeling. First, modeling the transfer of radiative energy from the Earth to the imaging system is done to make the necessary and routine corrections that adjust for atmospheric and lighting effects. Then, the parameter of interest needs to be related to the radiative fluxes. For example, to predict flood runoff or shallow landslides, an estimation of vegetation cover from these data may be required. Spectral "unmixing" or inverse mixing models exist that isolate the spectral components of the signal attributable to vegetation and then estimate the fraction of the pixel that they occupy. (See, for example, Smith and others, 1990.) These derived parameters themselves may need to be refined by further modeling: for example, the type and age of vegetation, together with the percent cover, can be used to estimate soil cohesiveness, controlled by root strength (Schaub and Montgomery, 1998). The soil type and cohesiveness, together with slope and precipitation, are input into a GIS model for hillslope failure. Other research goals may require different models, but all share one thing in common: they are likely to be underdetermined, and hence, recovered information is likely to have a degree of ambiguity or uncertainty. Key efforts in remote sensing must therefore be to optimize the tradeoff between model precision and robustness (Weeks and others, 1997).

REMOTE-SENSING STUDIES

As mentioned previously, more than half the remote-sensing studies of Death Valley have been purely methodological, and of the 10 percent that had Death Valley geology as their primary goal, many have been photointerpretive. For example, Reheis and Noller (1991) used aerial photographs to aid in the mapping of lineaments and faults in several quadrangles along the California-Nevada border. Similarly, Clayton (1989) used satellite images in a study of the interaction between the Garlock and southern Death Valley fault zones. Berlin (1980) performed a similar photointerpretive study of faults in Cottonball Basin, using radar images instead of aerial photographs or satellite optical images. Farr (1996) combined images and digital topographic maps to analyze landforms along active range fronts in Death Valley in a technological variant of stereoscopic photointerpretation. Indeed, most geologists mapping in Death Valley in the past five decades have probably used aerial photographs to augment a topographic map or as a base map; thus, a main use of remote sensing, even as the level of technical sophistication reaches new heights, will continue to be photointerpretation.

Imaging-radar research constitutes a large fraction of the remote-sensing methodological literature, perhaps because of the early successes of Schaber and his colleagues (for example, Schaber and others, 1976). One early observation from these studies was that the flat, featureless salt flats on the floor of Death Valley appeared rough in radar images. Attributed to penetration of radar through the smooth, surficial salts to a rough, high-dielectric water table a few centimeters below, this observation anticipated by several years the more widely publicized ability of the Shuttle imaging radars to penetrate dry Saharan sands to “see” buried bedrock channels a meter or more beneath the surface.

Most later radar studies can be divided into three groups: (1) geologic mapping using multispectral and multiple-polarization radar images (Daily and others, 1978; Evans and others, 1986); (2) empirical studies of surface roughness to describe fan evolution and age (such as Farr and Gillespie, 1984); and (3) model inversions to estimate roughness and dielectric values (Rasmussen, 1997). Radar-roughness estimates vary with frequency, because the gravels, cobbles, and boulders that compose fan surfaces are about the same size as the radar wavelengths (1–100 cm). For X-band radar (3 cm), only sand dunes and playas appear smooth; in P-wave (65 cm) radar images only boulders do not appear smooth. In L-band (23 cm) images, the Pleistocene Qg_2 desert pavements of Hunt and Mabey (1966) are readily distinguished from the younger, bouldery Holocene Qg_3 fans and terraces, which are brighter. Radar and optical images of fans can have strong similarities, although radar is insensitive to color and albedo, and optical data are insensitive to soil moisture. Roughness is the common denominator: cobbles on rough surfaces cast shadows that darken the optical image. However, the smooth Qg_2 surfaces are dark in reflected sunlight, not bright as might be suspected from the absence of dark shadows. This is due to the development of dark rock varnish, ubiquitous on older (pre-Holocene) surfaces in Death Valley.

The multispectral/polarization studies of airborne imaging radars successfully built a geological justification for the Shuttle Imaging Radar program, culminating in the launch of SIR-C in the early 1990’s. Death Valley was imaged repeatedly, and for a time, radar corner reflectors and other calibration gear dotted the valley floor.

Radar surface roughnesses are usually calibrated to some kind of root-mean-square estimate of centimeter-scale topography measured over an area of a few square meters. Ronald Greeley’s group at Arizona State University took this measure another step and calculated an aerodynamic roughness, or resistance to wind (Blumberg and Greeley, 1994). The motivation was to study aeolian processes (Greeley and others, 1997), with an obvious application to Mars.

Death Valley also witnessed many of the developmental studies of thermal infrared imaging. Sabins (1984) combined the interpretation of visible, reflected and thermal infrared, and radar images of Death Valley in an effort to determine how much additional information could be gleaned over photointerpretation in any one spectral region. The greatest power in thermal imaging, however, probably lies in the multispectral emissivity images, or in images of thermal inertia (Kahle and others, 1976).

Surface temperature and emissivities are recovered from the thermal radiance measurements by inversion of Planck’s law. Gillespie and others (1984) used emissivities to reconstruct the bedrock lithology and ages of fans near Trail Canyon, as mapped in the field by Hunt and Mabey (1966). The newly constructed fan maps depict compositional information not portrayed in the earlier map. Eastes (1989) determined that evaporites on the floor of Death Valley could be identified using thermal emissivity data also. Crowley and Hook (1996) constructed and validated detailed maps of playa mineralogy.

Thermal inertia is the resistance of matter to temperature change as heat is applied. Thermal inertia governs the daily swings in surface temperature, and it follows that it can be inverted from day/night temperature images. Schieldge and others (1981) calculated thermal inertia data for Death Valley from images taken by the Heat Capacity Mapping Mission flown by NASA in the late 1970's. Thermal inertia differs greatly among porous materials, such as windblown sand, and rock. Therefore, thermal inertia can be used to recognize bedrock beneath as much as 10 cm of eolian cover. Because of evaporative cooling, apparent thermal inertias are also sensitive to soil moisture.

Visible and reflected-infrared images of Death Valley show a wealth of spectral detail that can be used to aid lithologic mapping. (See, for example, Albee and others, 1984; Labotka and Albee, 1990.) However, in broad-band multispectral data, much of this information is controlled by iron minerals, and hence by weathering. Collins and others (1982) showed the potential of imaging spectroscopy for diagnostic mineralogical mapping, and Crowley (1993) mapped evaporites with the airborne imaging spectrometer, AVIRIS.

Much of Death Valley is covered by alluvial fans. In nearby Owens Valley, Fox and others (1990) demonstrated the ability of AVIRIS to measure soil development, and Burke and others (1986) showed the role of bioturbation in exposing soil B horizons on the surface, which was the basis for spectral discrimination. On most Death Valley fans, however, thick silty Av horizons and cobble pavements obscure soil development. Clast varnish and weathering, not soil development, appear to dominate the remotely sensed signal. Nevertheless, mapping of deposit age is possible, provided the local geologic setting is understood, which highlights the continuing role of geologic experience and photointerpretation in analyzing even the most sophisticated hyperspectral images.

Imaging spectroscopy generates enormous quantities of data, and a major hurdle is simply managing all of them. To solve this problem, Kruse and others (1993) used an expert system for mineralogical mapping of AVIRIS images of Death Valley. D'Agnese (1994) combined remotely sensed estimations of vegetation and an aquifer recharge/discharge model in a GIS to analyze the complex Death Valley groundwater flow system. This kind of study, combining analysis of image data and hydrologic or other models, represents one promising frontier of remote-sensing research today.

WHAT HAVE WE LEARNED?

To what extent, then, has nearly three decades of remote-sensing activity added to our geologic knowledge of Death Valley? The answer appears to be—not much. After all, one of the reasons Death Valley attracted this attention was precisely because its geology was already well known. What is it that needs to be added to the story? Most of the topics I can think of are not ones well suited for remote sensing: regional strain distribution, fan evolution, surface-exposure dating, and paleolimnology.

Nevertheless, remote sensing still has the potential to add to our geologic knowledge of Death Valley. For example, differential radar interferometry could be used to map the spatial distribution of displacement associated with an earthquake (for example, Crippen, 1993). Further work requiring remote sensing of surface conditions may be warranted in ground-water studies, and also in studies of geomorphological processes in Death Valley. Existing maps can be refined: imaging spectroscopy makes facies mapping within recognized formations feasible, and even structural maps of the complexly faulted range fronts may benefit from the improved detail afforded by these data.

I mentioned that the remote-sensing history in Death Valley paralleled the remote-sensing story in general. That remote sensing was a victim of over-sell early in its development is commonly recognized. In an effort to promote expensive satellites, premature claims were made about the vast potential soon to be realized, generally in a simplistic view of short-term profits or vague benefits to society. Both have happened, but not at the pace, nor to the degree, envisioned in the early 1970's. Today, detailed examination of distant or hazardous environments such as the sea floor, other planets, and asteroids is a reality. Near-continuous observation of the Earth has improved weather forecasting. Extension of observation from visible light to a wider range of wavelengths has made possible radar mapping of flooded disaster areas through cloud cover, polar ice floes in darkness, and the ozone hole. Imaging spectroscopy has made it possible to identify surface materials directly in previously unknown regions, and to refine mapping in known areas. Laser altimetry has made it possible to measure vegetation canopy height from orbit. Even the standard USGS 7.5' topographic maps do not reliably distinguish between the canopy top and ground; someday this may be routine. Satellite gravimetrics and radar altimetry have made possible rapid regional measures of the Earth's shape, and changes in it, at a range of scales. Death Valley has not been at the forefront of all these developments, but to a remarkable extent Death Valley has played a role in the developments that are most significant to geologists.

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Quaternary Stratigraphy and Geomorphology of Death Valley

J. R. Knott, UNOCAL Corp., Environmental Technology Group, 376 S. Valencia Ave., Brea, CA 92823
(714) 577-2841 <jrknott@unocal.com>

INTRODUCTION

Quaternary stratigraphy and geomorphology are two of the more scrutinized, and yet probably the least understood aspects of Death Valley geology. Sparsity of datable material and discontinuity of outcrops are only two of the many hurdles that Quaternary geologists have had to overcome. In recent years, however, several independent studies have added greatly to the knowledge of the late Cenozoic rocks of Death Valley. Detailed stratigraphic descriptions combined with tephrochronology, paleomagnetism, and radiometric age determinations have resulted in a better definition of the upper Pliocene to lower Pleistocene Funeral Formation, Pliocene Nova Formation, and the addition of a new formation, the upper Pliocene to lower Pleistocene Confidence Hills Formation. Tephrochronologic correlation of lower to middle Pleistocene tephra beds at Mormon Point, Natural Bridge, and the Kit Fox Hills has provided previously unobtainable age control in these areas and enabled the introduction of the Mormon Point formation. The greater age control allows for insights into the paleogeography and geomorphic development of Death Valley. The purpose of this paper is to provide a review of the changes to the Quaternary stratigraphic framework, and then briefly illustrate how this knowledge has been applied to the spatial and temporal geomorphic development of the Death Valley fault zone and the Black Mountains.

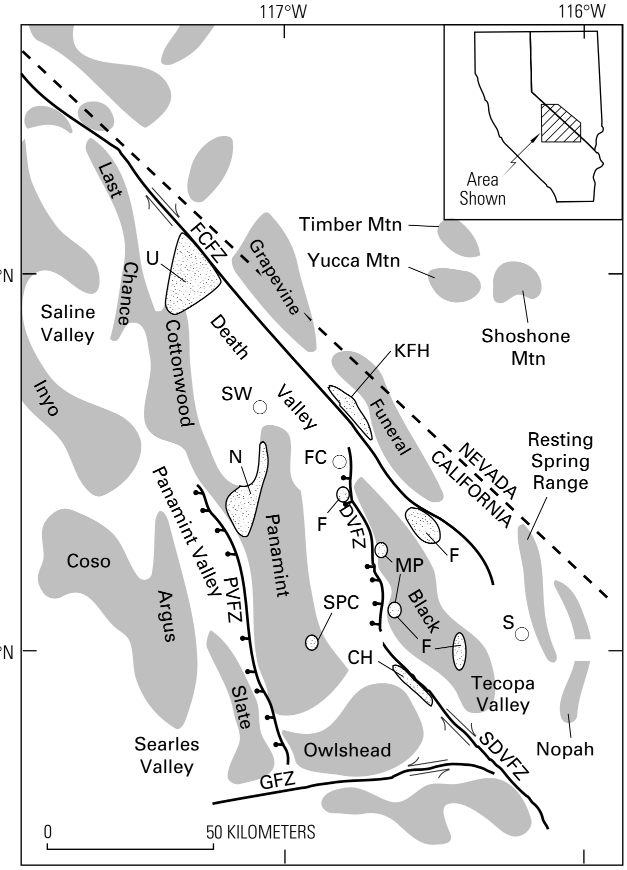

Figure 21. Death Valley and surrounding region showing major geographic features and fault systems. Light shade, mountain ranges; white areas, basins. Arrows, dominant motion of strike-slip faults; bar and ball on relatively downthrown side of normal faults. Areas with stipple pattern, locations of sedimentary basins: F, Funeral; N, Nova; U, Ubehebe; MP, Mormon Point; CH, Confidence Hills; SPC, Six Springs Canyon. Fault zones: DVFZ, Death Valley fault zone; FCFZ, Furnace Creek fault zone; SDVFZ, Southern Death Valley fault zone; PVFZ, Panamint Valley fault zone; GFZ, Garlock fault zone. Towns shown by circles: S, Shoshone; FC, Furnace Creek; SW, Stovepipe Wells.

STRATIGRAPHY

FUNERAL FORMATION

Thayer named the coarse conglomerates with interbedded basalts and basaltic agglomerates of the eastern Furnace Creek basin, the Funeral Formation in 1897 (cited in Noble, 1941). In the Furnace Creek basin, the Funeral Formation overlies the upper Miocene Furnace Creek Formation and is distinguished from younger deposits by its greater cementation and tilting. Consequently, similar deposits throughout the Black Mountains and southern Panamint Mountains (fig. 21) were mapped as Funeral Formation (Noble and Wright, 1954; Hunt and Mabey, 1966; McAllister, 1973). The facies of the Funeral Formation were interpreted to represent an alluvial fan depositional environment with a Pliocene to Pleistocene age (Noble, 1941); however, Noble also postulated that variability and discontinuous exposure prevent actual correlation of the isolated outcrops of the Funeral Formation. Hunt and Mabey (1966) also recognized these correlation problems and further went on to state that there is no evidence that all outcrops of the Funeral Formation are the same age.

Early age determinations of the Funeral Formation focused first on the interbedded basalts, then later on tuff beds. McAllister (1973) dated a basalt flow near the type locality at 4.0 Ma using conventional whole rock K/Ar. Wright and others (1991) stated that the basaltic rock that composes Shoreline Butte in the northern Confidence Hills is 1.7 Ma (conventional K/Ar). Topping (1993) obtained a 5.2-Ma age on a tuff below the basalt dated by McAllister using zircon fission-track dating. Holm and others (1994) dated a tuff in the Funeral Formation of Copper Canyon, central Black Mountains, at 3.1 ± 0.2 Ma ($^{40}Ar/^{39}Ar$ on biotites).

Recent tephrochronologic studies and mapping in the Black Mountains area have identified a number of other tuff beds within the Funeral Formation (fig. 22). Knott (1998) collected geochemical data on seven tuffs at Artists Drive, correlating or naming the following: (1) lower Nomlaki tuff (est. >3.58 Ma), (2) the tuff of Curry Canyon (>3.35 Ma), (3) the lower Mesquite Spring tuff (3.35 Ma), (4) the Nomlaki Tuff (3.28 Ma), (5) the upper Mesquite Spring tuff (3.1–3.28 Ma?), (6) the tuff of Clayton Valley (~2.5 Ma), and (7) a lower Glass Mountain tuff (1.98–2.09 Ma). Correlation of these tuffs and their estimated ages are based on the chemical composition of the volcanic glass, paleomagnetism, and relative stratigraphic position (Knott, 1998). The lower and upper Mesquite Spring tuffs are both normally polarized and chemically indistinguishable; they are similar to tephra from the Long Valley volcanic field. The 3.1-Ma tuff of Holm and others (1994) is a Mesquite Spring tuff that is correlative with either of the Mesquite Spring tuff beds at Artists Drive (similarity coefficient = 0.97). Similarity coefficients listed in this paper are calculated using the methods outlined by Sarna-Wojcicki and Davis (1991) using elements La, Ce, Nd, Sm, Tb, Dy, Lu, Sc, Mn, Fe, Rb, Cs, Hf, Th, and U, which were measured by solution ICP-MS analysis of volcanic glass.

Morphologically, the Funeral Formation is faulted and tilted such that it no longer retains alluvial fan morphology. At Artists Drive, below an elevation of +90 m, the Funeral Formation is cut by shorelines or overlain by deposits from late Pleistocene lake deposits dated at 160–185 ka by Ku and others (1998).

Thus, the Funeral Formation remains the coarse conglomerate with interbedded basalt, basaltic agglomerates, and tuffs deposited in an alluvial fan depositional environment. Radiometric ages and tephrochronologic correlations

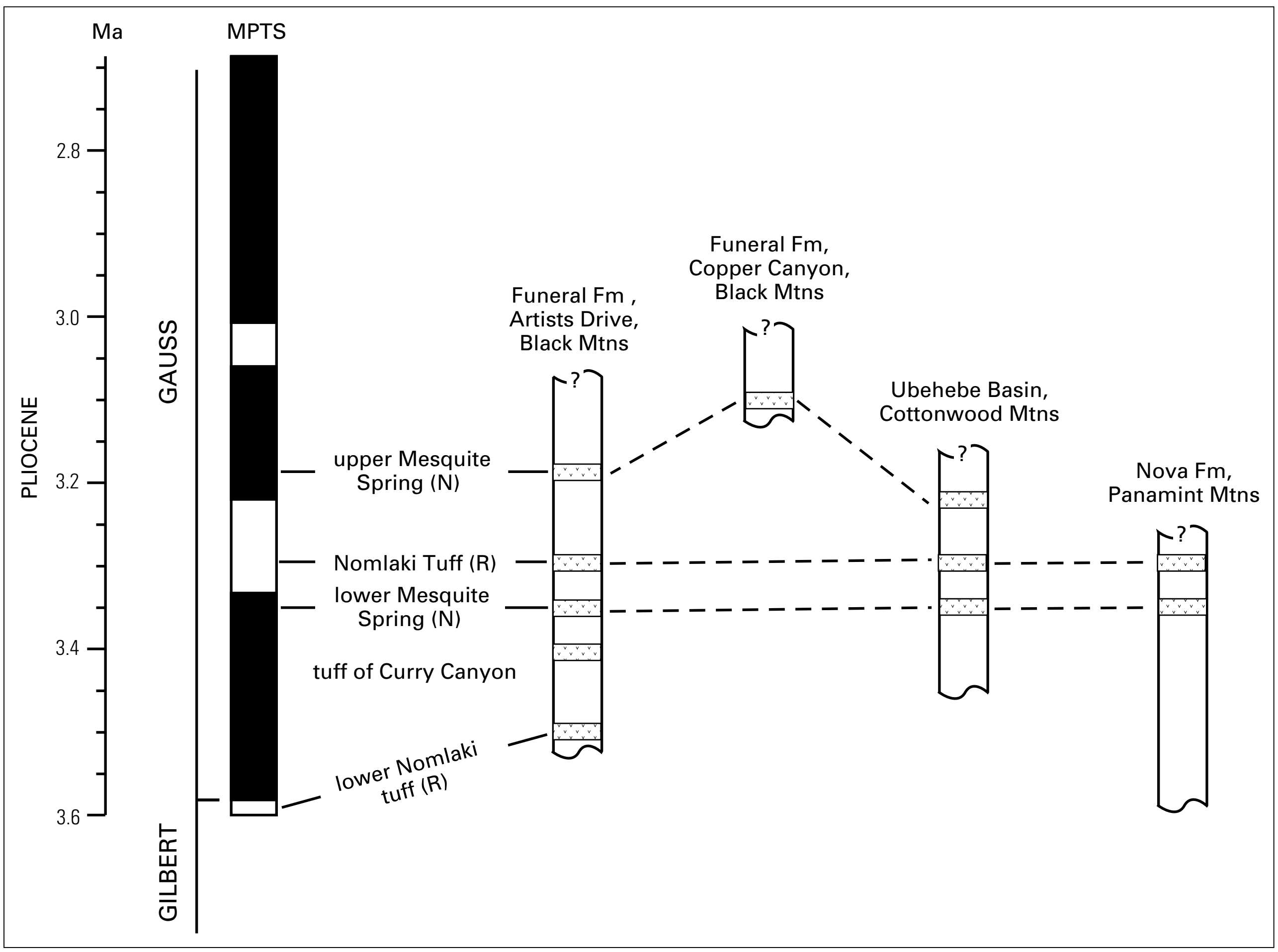

Figure 22. Correlation diagram for Pliocene tuffs of Death Valley. Correlation to the magnetic polarity time scale (MPTS) is signified by N or R, which indicates normal and reverse polarity, respectively. Solid lines, reliable correlation; dashed lines, tentative correlation. Age of the Nomlaki Tuff from A. Deino (personal commun., 1997).

bracket the majority of the Funeral Formation to the Pliocene (5.2 and 1.98 Ma). A 1.7-Ma age on the Shoreline Butte basalt in the northern Confidence Hills, included in the Funeral Formation by Wright and Troxel (1984) and omitted as part of the Confidence Hills Formation (Beratan and Murray, 1992), is the lone Pleistocene age determination.

NOVA FORMATION

The Nova Formation was named for coarse conglomerates and interbedded basalts located along the northwestern flank of the Panamint Mountains (fig. 21). Hunt and Mabey (1966) suggested that the Nova Formation is also Pliocene to lower Pleistocene, and thus so similar to the Funeral Formation that the name Nova Formation should be dropped. Hodges and others (1989), however, argued that Nova Formation be continued, because this name distinguished an important Miocene to Pliocene depocenter; they compiled a stratigraphic section that shows deposition occurred between 5.4 ± 0.4 and 3.7 ± 0.2 Ma (whole rock K/Ar). Snow (1990) dated a 10-m-thick tuff in the upper Nova Formation at 3.35 ± 0.13 Ma (^{40}Ar/^{39}Ar sanidine) and correlated this with the Mesquite Spring tuff in the Ubehebe basin. Using the composition of volcanic glass, Knott and others (1997a) correlated this tuff to the normally magnetized lower Mesquite Spring tuff that underlies the 3.28-Ma Nomlaki Tuff at Artists Drive. Thus, the upper age range of the upper Nova Formation is extended to 3.35 Ma, but does not extend to ~2 Ma as the Funeral Formation does (fig. 22). This adds some support to Hodges and others' (1989) assertion for the continued separation of the Nova and Funeral Formations.

UBEHEBE BASIN

The Ubehebe basin of Snow (1990) is located in the northern Cottonwood Mountains of Death Valley (fig. 21). The Ubehebe basin consists of five sedimentary sequences composed of a variety of rock types from conglomerates to basalts to tuffs (Snow, 1990). Based on radiometric dates, Snow (1990) showed that the age of the Ubehebe basin is Miocene to Pliocene (23.87 ± 0.23 to 3.28 ± 0.07 Ma). Knott (1998) sampled the type locality of the Mesquite Spring tuff (3.28 Ma) and determined that the major-element composition of volcanic glass is very similar to that of the Bishop ash bed (SC = 0.97). The major-element composition of volcanic glass from another tephra bed in the Ubehebe basin is similar to that of either the Nomlaki Tuff (3.28 Ma) or the lower Nomlaki tuff (est. >3.58 Ma) (Knott, 1998). Klinger and Piety (1996), working in the eastern Ubehebe basin, correlated the Bishop ash bed (0.76 Ma) using major-element composition of volcanic glass. Thus, the Ubehebe basin is composed of conglomerates to basalts with an age range of Miocene to middle Pleistocene.

CONFIDENCE HILLS FORMATION

The sequence of tilted conglomerate, mudstone, breccia, and evaporite that composes the Confidence Hills in southern Death Valley has been named the Confidence Hills Formation (Beratan and Murray, 1992). Mapped as Funeral Formation by Wright and Troxel (1984), a late Pliocene age was established by the correlation of the 2.09-Ma Huckleberry Ridge ash bed (Troxel and others, 1986). Later, Beratan and Murray (1992) described the stratigraphy and depositional environments of the exposed section and named these rocks the Confidence Hills Formation. The depositional environment of the Confidence Hills Formation ranges from alluvial fan to playa lake. Pluhar and others (1992) used paleomagnetism to determine that the Confidence Hills Formation ranged in age from >2.15 to <1.79 Ma (fig. 23). Sarna-Wojcicki and others (unpublished data) correlated a number of tuffs and tephra beds within the Confidence Hills Formation with ages ranging from 2.2 Ma to the 1.78–2.09 Ma tuffs of lower Glass Mountain. Thus, the Confidence Hills Formation consists of conglomerate to evaporite that record alluvial fan to playa lake depositional environments in the upper Pliocene to lower Pleistocene (2.2 and 1.78 Ma). The Confidence Hills Formation has not been extended beyond the type locality, and it may be difficult to distinguish from the Funeral Formation, which records similar depositional environments in the same age range.

MORMON POINT FORMATION

The Mormon Point formation is an informally named, early to middle Pleistocene unit of conglomerate, breccia, mudstone, evaporite, and tephra beds exposed at Mormon Point in southern Death Valley (Knott and others, in press). These deposits are interpreted as alluvial fan, playa margin, and perennial to ephemeral lake depositional environments. Tephra layers within the Mormon Point formation (fig. 23), which are correlated by volcanic glass composition, relative stratigraphic position, and paleomagnetism, include several ash beds: upper Glass Mountain (0.8–1.2 Ma), Bishop (0.76 Ma), Lava Creek B (0.665 Ma), and Dibekulewe (~0.51 Ma).

Three perennial to ephemeral lake sequences are found within the Mormon Point formation. The older sequence includes upper Glass Mountain tephra beds, but not the Bishop ash bed. The middle sequence is above the Bishop ash bed and ends with the Lava Creek B ash bed. The youngest and poorly exposed lake deposits are found just below the Dibekulewe ash bed. Thus, lake deposition occurred between ~1 and >0.76 Ma, from <0.76 to ~0.665 Ma, and just prior to 0.51 Ma. The Mormon Point formation is highly faulted; thus, the middle and youngest lake sequences may be the same. Rapid facies changes from green mudstones to evaporites indicate that the lakes recorded by the Mormon Point formation quickly became saline, suggesting that, despite their apparent longevity, the lakes may have been relatively shallow. The timing of these

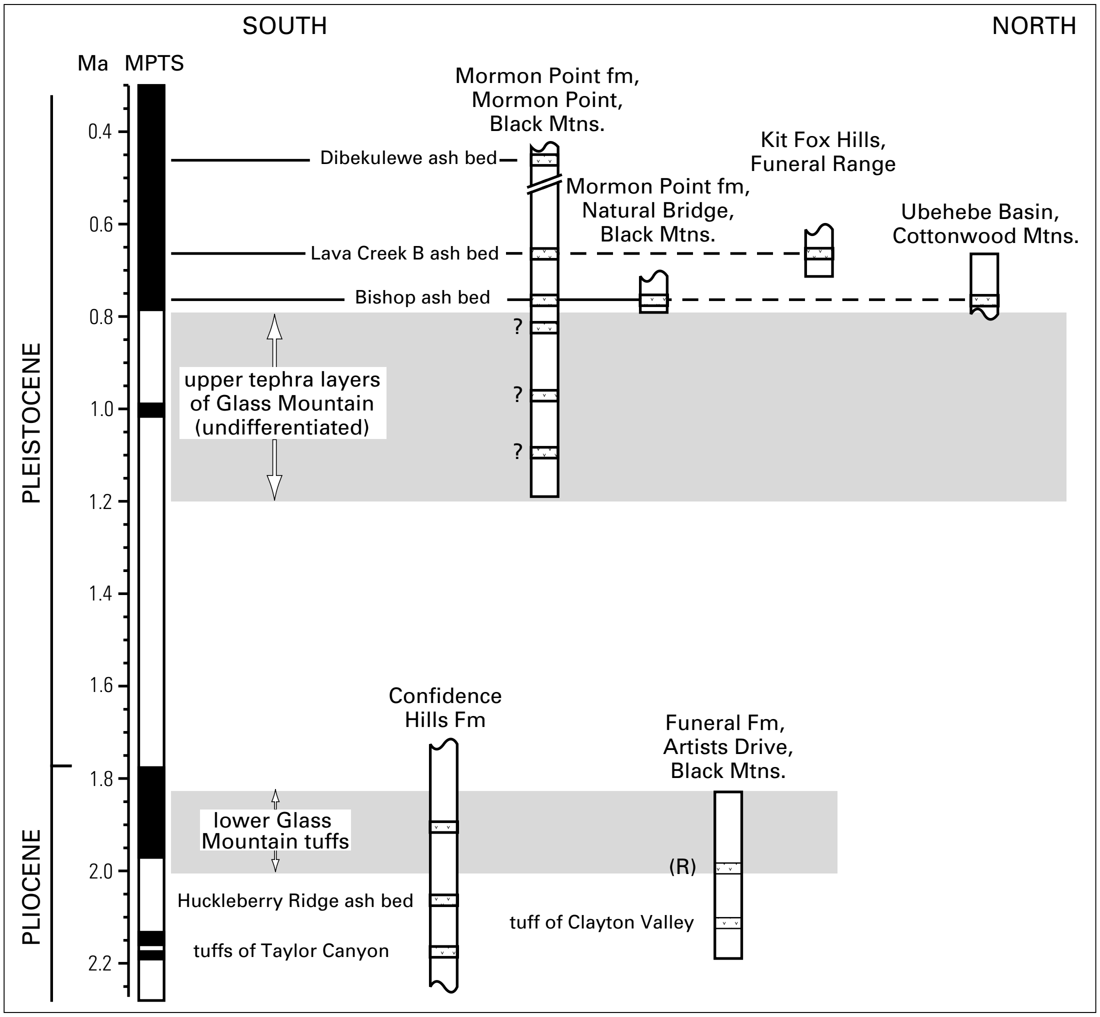

Figure 23. Correlation diagram for upper Pliocene to middle Pleistocene tuffs and tephra beds of Death Valley. Shaded areas, range of ages for upper and lower Glass Mountain families of tephra beds and tuffs. Solid lines, reliable correlation; dashed lines, tentative correlation. Question marks by upper Glass Mountain tephra layers found at Mormon Point indicate that exact age of these tephra beds is not established. Lower Glass Mountain tuff at Artists Drive has reverse paleomagnetic declination, limiting its age to between 1.98 and the age of the Huckleberry Ridge ash bed (2.09 Ma).

lakes is coincident with wetter climatic conditions in Searles Lake to the west (Smith, 1984).

The coarse conglomerate at Natural Bridge, just north of Badwater, contains the Bishop ash bed and thus is included as part of the Mormon Point formation. Klinger (unpublished data) correlated the Lava Creek B ash bed in the southwestern Kit Fox Hills. This area is tentatively considered part of the Mormon Point formation; however, further investigation should be completed to confirm the correlation of Lava Creek B. Like the Funeral Formation, the Mormon Point formation does not have alluvial fan morphology. In the absence of tuffs, the Mormon Point formation is distinguishable from the Funeral Formation because it is generally less indurated and less tilted.

Geologic and geomorphic mapping at Mormon Point and the discrimination of the Mormon Point formation settles an unresolved stratigraphic conflict described by Hunt and Mabey (1966). In most locations in Death Valley, they determined the relative geomorphic relationships to show that the prominent late Pleistocene (160–185 ka) lake strandline was older than their Qg_2, except, and most prominently, at Mormon Point. Knott and others (1997b) showed that the Mormon Point formation and not the Qg_2 are cut by the late Pleistocene strandlines. An alluvial fan, morphologically equivalent to the Qg_2 unit, is inset below the late Pleistocene lake deposits (Knott, 1998).

ALLUVIAL FANS

Some of the more dramatic features of Death Valley are the alluvial fans that are found between the mountain front and the salt pan. Many studies have been made of the alluvial fan deposits; however, the observations of Denny, Hunt, and Hooke have guided the study of alluvial fans in Death Valley, and many other places, for more than 40 years.

Denny (1965) described the morphology of the alluvial fans in central Death Valley. In his study, Denny noted the contrast between the elongate, areally extensive fans and adjoining drainage basins of the Panamint Mountains with the relatively smaller fans and basins of the Black Mountains. Denny suggested that mathematical relationships existed among drainage-basin size, size of active fan, channel width, and clast size. Denny hypothesized that the differences among these and other variables were related to bedrock composing the drainage basin, elevation of the mountain range, which affected precipitation, and locus of tectonic activity.

Hunt and Mabey (1966) followed with detailed maps of Death Valley alluvial fans, including those described by Denny. Building on the observations of Denny, that degree of desert pavement formation and varnish covering of clasts were age dependent, Hunt and Mabey divided the alluvial fans into four units. The oldest alluvial fan unit (g_1) has gone through several revisions. Originally, Hunt and Mabey (1966) designated the Funeral Formation as the first gravel with a map symbol of QTg_1. Wright and Troxel (1984) dropped this awkward dual usage, preferring to use Qg exclusively for units that maintain alluvial fan morphology. As a result, they designated uplifted conglomerates with alluvial fan morphology and an ancient shoreline cut into the surface in southern Death Valley as Qg_1. Subsequently, Knott (1998) found tephra beds within the Qg_1 unit of Wright and Troxel with volcanic glass composition similar to the lower Glass Mountain family of tephra beds (1.7–2.09 Ma), making this unit equivalent to the upper Funeral and Confidence Hills Formations. Thus, I recommend that Qg_1 as used by Wright and Troxel (1984) be discontinued. Dorn (1988) has also used Qg_1 for the older surface facies of Hooke (1972), about 60 m above the channel at Hanaupah fan.

The next oldest unit (Qg_2) of Hunt and Mabey (1966) has a well-developed desert pavement surface, and most clasts are coated with desert varnish. Gravels with Qg_2 surface morphology cover large areas of the alluvial fans in Death Valley. As described above, the relative stratigraphic relations between Qg_2 and the 160–185 ka lake deposits at Mormon Point suggest that Qg_2 is younger than 160–185 ka (Knott and others, 1997b).

The next geomorphic unit (Qg_3) is generally a few meters or less above the active channel and has a remnant bar-and-swale topography; clasts are only partially coated with desert varnish. Based on archeological data, Hunt and Mabey (1966) estimated the age of Qg_3 between 10,000 and 2,000 yr. The youngest alluvial fan unit (Qg_4) occupies the active channels of washes and has prominent bar-and-swale topography and very few varnish-coated clasts.

GEOMORPHOLOGY

WESTERN BLACK MOUNTAINS PIEDMONT

The paradigms that dominate Death Valley geomorphology were established through the work and observations of Hunt, Denny, and Hooke. Denny (1965) observed and measured elements of alluvial fans and drainage basins on both sides of Death Valley between Artists Drive on the north and Mormon Point on the south. One of many important observations in Denny's study was that there appeared to be a numerical relationship between the area of the drainage basin and the area of the alluvial fan. He concurred with Hunt that eastward tectonic tilting of Death Valley by normal slip on the Death Valley fault zone restricts the areal extent of alluvial fans on the east side to about 1/10 the area of their respective basins. In contrast, fans on the west side of Death Valley, which emanate from the Panamint Mountains, are unconfined by tectonic activity, and thus the area covered by the alluvial fans is 1/3 to 1/2 the area of their drainage basins. Hunt and Mabey (1966) also suggested that greater incision of older fan deposits toward the north, along the Panamint Mountain piedmont, indicated a general northward tilting of the range. Hooke (1972) noted that this eastward tilting of Death Valley caused the locus of deposition on east side fans to be nearer the mountain front than on west side fans. In addition, he measured longitudinal profiles along Panamint Mountain alluvial fan surfaces which suggested that the eastward tilting caused burial of older alluvial fan surfaces by younger fan deposits.

Knott (1998) examined drainage basin and alluvial fan morphology along the entire length of the Black Mountains. He found that, although basins and fans along the mountain front from Badwater to Copper Canyon fit the model of an east-tilting basin bound by a single-strand normal fault, other reaches of the mountain front do not fit this model. In the Artists Drive fault block of Hunt and Mabey (1966), just north of Badwater, the Death Valley fault zone is currently expressed as a broad graben with an east-dipping antithetic fault. Alluvial fans at Artists Drive are large, relative to fans to the south, and incision across the uplifting Artists Drive block has resulted in the location of fan apexes and basin mouths away from the mountain front and out on the piedmont, rather than at the mountain front. The incorporation of piedmont areas into the drainage basin makes the balance between alluvial fan and basin area more similar to the Panamint Mountain system of Denny (1965) than to the Black Mountains.

The mountain front along Artists Drive was not always a graben with an antithetic fault, however. The ~3.5–2-Ma alluvial fan deposits of the Funeral Formation, presently uplifting in the Artists Drive block, were most likely deposited along a single-strand normal fault that records the northward propagation of the Death Valley fault zone (Knott and others, in press). This is consistent with the ~4-Ma age of cessation of deposition of the Furnace Creek Formation (Hunt and Mabey, 1966). The youthfulness of the Black Mountains north of Badwater is expressed by smaller drainage basins and a lower mountain crest elevation compared to the remainder of the range (Knott, 1998). This northward growth of the Death Valley fault zone and other normal faults in Death Valley (Knott and others, this volume) may also explain Hunt's hypothesis that the Death Valley region has a slight northward tilt.

At Mormon Point, just south of the area studied by Denny and Hooke, the north-south-trending segments of the Death Valley fault zone are linked by an east-west-trending, north-dipping normal fault. This sequence of faults defines a 5-km right-step in the Death Valley fault zone at the Mormon Point Turtleback. Geologic mapping and tephrochronologic studies that have defined the Mormon Point formation (described previously) show that the east-west-trending segment of the Death Valley fault zone stepped about 1 km northward since the early Pleistocene (Knott and others, in press). The northward stepping of the east-west-trending fault is likely driven by along-strike (northward) propagation of the westerly north-south-trending segment. Geologic relations suggest that the western segment of the Death Valley fault zone is propagating northward at a rate of 1 km/m.y.

This northward propagation is expressed morphologically by a relatively small alluvial fan at the mouth of the Willow Creek basin. Denny (1965) explained the discrepancy between basin and fan area as a result of less resistant bedrock in the basin. Although more erosive bedrock may very likely remain a factor, the evidence of incorporation of Pleistocene fan deposits by northward stepping of the Death Valley fault zone must be considered a significant—and most likely the main—cause for a smaller alluvial fan at Willow Creek. Leeder and Jackson (1993) described mountain front morphology similar to Mormon Point, in central Nevada, suggesting there that, even with consistent underlying bedrock, a long-lived step and along-strike propagation were main elements in the geomorphic expression of the mountain front.

SUMMARY

A number of recent studies have added significantly to the Quaternary stratigraphy of Death Valley. Dating and correlation of tuffs within the Funeral Formation provide reliable bracketing ages between 5.2 and 1.98 Ma. Similarly, the age range of the Nova Formation is between 5.4 and 3.35 Ma, suggesting that deposition in the Nova basin ceased earlier. Speculation had been that both the Funeral and Nova Formations extended into the Pleistocene (<1.79 Ma); the available data, however, do not support this idea. The Ubehebe basin in the northern Cottonwood Mountains records deposition between ~3.28 and 0.76 Ma; more extensive work is ongoing in this area (R.E. Klinger, personal commun., 1999).

Two new Quaternary formations have been established in Death Valley: the Confidence Hills Formation and the Mormon Point formation. The Confidence Hills Formation of Beratan and Murray (1992) is found only in the Confidence Hills and records deposition from 2.2 to 1.7 Ma. The Mormon Point formation is found in central Death Valley at Mormon Point, Natural Bridge, and the Kit Fox Hills, and is lower to middle Pleistocene in age. Tephrochronology has been shown to be a useful tool in deciphering the Pliocene-Pleistocene stratigraphy.

Application of the recently revised and more reliable stratigraphy to resolve geomorphic issues in Death Valley has been limited. Studies along the western Black Mountains indicate that spatial and temporal variations in the behavior and location of the Death Valley fault zone affect the alluvial fan and drainage basin morphology.

ACKNOWLEDGMENTS

This work was supported by grants from the National Science Foundation (EAR-94-06029 to S.G. Wells), the Geological Society of America, and Sigma Xi. The National Park Service permitted the work. I would like to thank R. Klinger, A. Sarna-Wojcicki, J. Tinsley, III, B. Troxel, S.G. Wells, and L. Wright for countless discussions and assistance.

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Quaternary Dating Methods—Applications to Death Valley Studies

Marith Reheis, U.S. Geological Survey, Box 25046, Denver Federal Center, M.S. 980, Denver, CO 80225-0046

Methods of dating Quaternary deposits and geomorphic surfaces are an integral part of studies in the Death Valley area. Investigations into climate change, neotectonics, geomorphic and hydrologic history, and process studies can produce only general or speculative results without accurate chronologies.

The development and use of methods for dating Quaternary deposits and geomorphic surfaces have undergone explosive growth in the last two decades. Papers describing new techniques, summaries of dating applications, and especially review volumes are scarcely printed before they are superseded. Many methods, however, can be used only in restricted situations with specific types of materials. This short report will review Quaternary dating methods that are applicable to studies in the Death Valley area of California and Nevada, where the arid climate and geologic setting limit the utility of some methods and encourage that of others. Brief descriptions of each method will be followed by examples of applications, focusing on studies in the Death Valley area or similar settings. The description of methods relies heavily on the most recent comprehensive review of Quaternary dating methods entitled, "Dating and Earthquakes: Review of Quaternary Geochronology and its Application to Paleoseismology" (Sowers and others, 1998), soon to be republished by the American Geophysical Union.

TYPES OF DATING METHODS AND APPLICATIONS

Colman and Pierce (1998) categorized dating methods in two ways: (1) by type of result (numerical, calibrated, relative, or correlated), and (2) by the methods themselves, meaning shared similarities in assumptions, techniques, and applications. The following discussion is structured around the latter categories, because the type of result produced by a given method may vary depending on how well we understand the physical or chemical basis of the method and, for relative or correlated ages, on the precision of calibration by independent chronologic control. The six groups of methods are sidereal (calendar or annual), isotopic, radiation-effects, chemical-biological, geomorphic, and correlation (fig. 24). Because sidereal techniques depend on counting annual increments such as tree rings and varves, examples of which are scarce to nonexistent in Quaternary deposits of the Death Valley area, they are not discussed further in this summary.

ISOTOPIC METHODS

Isotopic methods measure changes in isotopic composition caused by radioactive decay. Developments in the last two decades require this category to be divided into two groups (Sowers and Noller, 1998): (1) Standard isotopic methods assume a closed system and are based on constant-rate decay of radioactive nuclides incorporated at the time a sample forms. Methods of this type that may be useful in Death Valley studies include ^{14}C, K-Ar, $^{40}Ar/^{39}Ar$, and U-series. (2) Cosmogenic nuclide methods assume continual formation and decay of radioactive nuclides within a closed system by near-ground-surface cosmic-ray bombardment. Cosmogenic methods must account for environmental variables such as depth below surface, altitude, and latitude that affect the cosmic-ray flux. Cosmogenic methods currently applied in Quaternary studies include ^{10}Be, ^{14}C, ^{3}He, ^{26}Al, and ^{36}Cl; of these the latter three are the most commonly used.

Radiocarbon (^{14}C) dating (recently summarized by Trumbore, 1998) is based on the decay of ^{14}C to ^{14}N. ^{14}C is produced in the atmosphere by cosmic-ray bombardment and incorporated into organic and inorganic materials in equilibrium with the atmosphere. Production rates of ^{14}C in the atmosphere have fluctuated through geologic time; ^{14}C ages younger than about 20,000 yr B.P. can be calibrated to calendar years using curves based on dendrochronology and U-series dates on corals. Radiocarbon dating is most commonly used to date organic matter, but it has also been applied to inorganic $CaCO_3$, including pedogenic carbonate. The practical age range is >400 and <50,000 years, but samples are increasingly susceptible to contamination in the older part of this range. ^{14}C dating using an accelerator mass spectrometer has greatly extended the usefulness of the technique by providing precise ages on milligram-sized samples (as opposed to ~1-g-sized samples for conventional ^{14}C dating). Though hot arid climates are inimical to preservation of organic material, the abundant springs in and around Death Valley are environments where organic-rich sediment may be preserved, as shown in studies by Quade and others (1995, 1998) and Mehringer and Warren (1976). Packrat middens also preserve organic material in desert environments (Spaulding, 1985). In addition, Reheis and others (1996, and references therein) showed that wood and charcoal are commonly preserved in middle to late Holocene debris-flow sediments shed from forested ranges northwest of Death Valley. In principle, ^{14}C dating of pedogenic carbonate is possible (Quade and others, 1989), but such ages apparently can be reset by wetting events (Pendall and others, 1994) and should

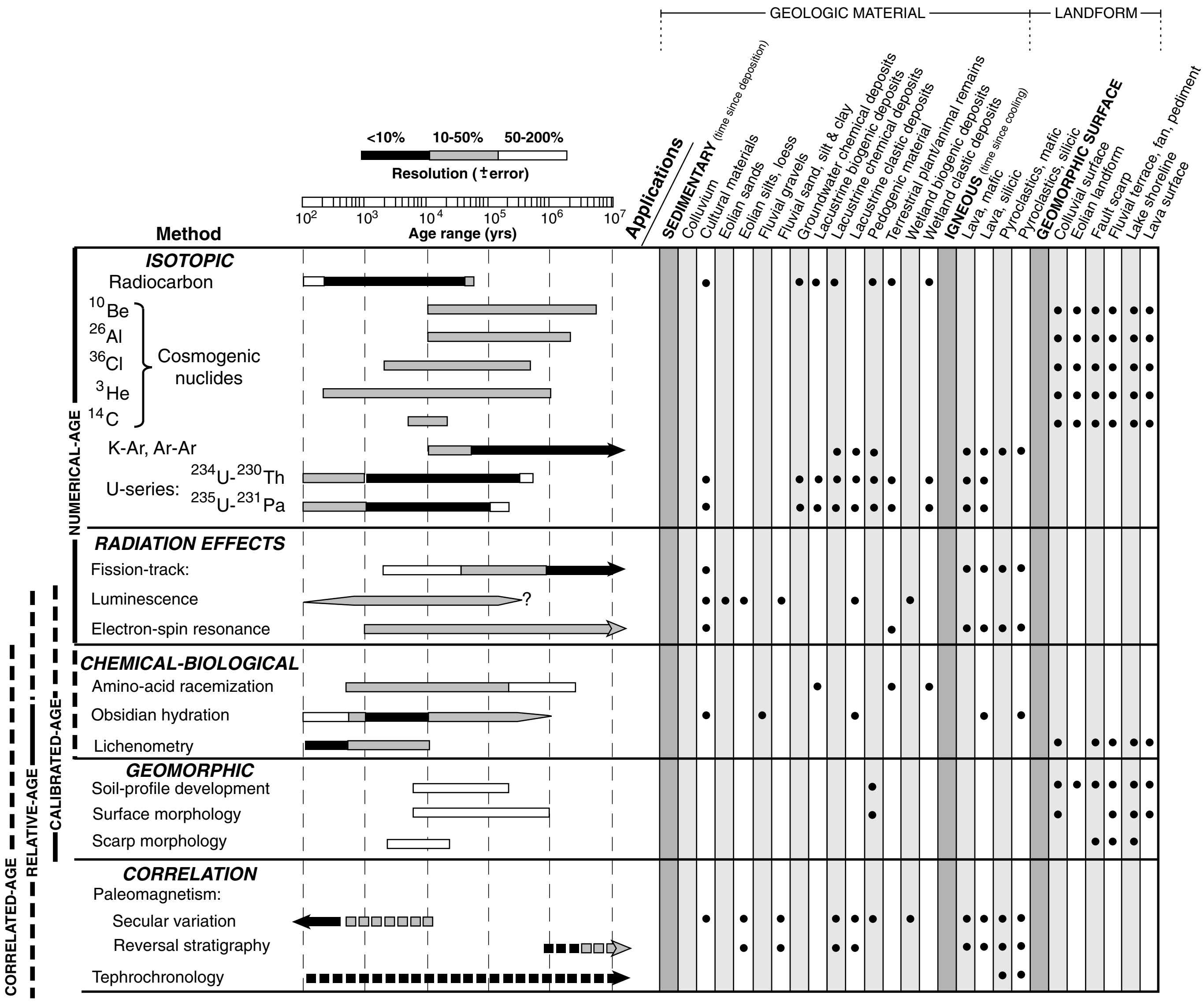

Figure 24. Methods for dating Quaternary surficial deposits in the Death Valley area (modified from Sowers and others, 1998). Broken bar indicates that method may not be continuously applicable through time range shown due to lack of reference stratigraphies or non-unique solutions.

be considered minimum ages for both the surface and the underlying deposit.

K-Ar and $^{40}Ar/^{39}Ar$ dating (recently summarized by Renne, 1998) are based on radioactive decay of ^{40}K to ^{40}Ar. These methods assume a closed system and are usually applied to volcanic or plutonic rocks, but they can also be used on K-bearing authigenic minerals (such as in closed-basin lake sediments). The age range of the methods is reported to be <10,000 yr to >3 b.y., but in practice, samples less than about 100 ka are difficult to date. K-Ar requires determination of isotopes of both K and Ar, whereas $^{40}Ar/^{39}Ar$ dating uses mass spectrometry only on isotopes of Ar to determine the content of artificially produced ^{39}Ar as an indirect proxy for ^{40}K. This indirect measurement is more precise and sensitive than other techniques, such as wet-chemical methods, for measuring ^{40}K. K-Ar and $^{40}Ar/^{39}Ar$ dating techniques have been widely applied in bedrock mapping (for example, Topping, 1993; Cemen and others, 1985; Hodges and others, 1989) but have been little used in Quaternary studies around Death Valley (Turrin and others, 1991).

Uranium-series dating is based on three naturally occurring radioactive decay series of ^{238}U, ^{235}U, and ^{232}Th and involves measurement of these isotopes and certain intermediate long-lived daughter nuclides (summarized by Ku, 1998). The most commonly used U-series method in Quaternary dating, $^{230}Th/^{234}U$, is a daughter-deficiency method based on accumulation of decay products of U. Until recently, the practical age limits using decay-counting techniques were 1,000 to 350,000 yr; application of thermal-ionization mass spectrometry methods has potentially extended these limits to 10 yr to more than 500,000 yr (fig. 24). U-series dating can be used on authigenic minerals crystallized within a sedimentary deposit or on detrital materials such as coral. U is ubiquitous in natural solutions and so is commonly included in inorganic or organic precipitates such as carbonates, sulfates, phosphates, opaline silica, and evaporites, whereas Th is nearly insoluble. A common problem in ^{230}Th/^{234}U dating is the amount of initial ^{230}Th and ^{232}Th incorporated into the sample; Th is commonly present in detrital minerals that are physically mixed with the authigenic phases and are difficult to separate in the laboratory. Suitable materials for U-series dating in the Death Valley area include lacustrine halite from core samples (Lowenstein and others, 1999), lacustrine tufa (Hooke and Dorn, 1992; Lowenstein and others, 1999), calcite vein fillings and spring deposits (Winograd and Szabo, 1988; Winograd and others, 1992; S. Mahan, shown in Taylor, 1998, p. 162–166), and secondary carbonate and silica in soils (Peterson and others, 1995; Lundstrom and others, 1998; Menges and Taylor, 1998; Menges and others, 1998) and faults (Ramelli, 1998). Ages obtained on pedogenic carbonates are often difficult to interpret due to the impurity of the sample material, the progressive but irregular accretion of carbonate with time, and the difficulty in accounting for inherited Th.

Probably the most famous application of U-series dating in the Death Valley area is in dating the climate record preserved by spring-deposited calcite in Devils Hole. The chronology of U-series ages at this site has been extended back to about 560,000 yr (Ludwig and others, 1992; Winograd and others, 1992, 1997) using mass spectrometry. Although these ages (and their climatic implications) have been controversial, they have been repeatedly validated (for example, Edwards and Gallup, 1993; Edwards and others, 1997) and stand as the premier example of results possible with U-series dating in ideal materials (no initial contamination, closed-system behavior).

The most dramatic advance in Quaternary dating techniques in the past decade is the development of surface dating by cosmogenic nuclide accumulation using the isotopes ^{10}Be, ^{14}C, ^{3}He, ^{26}Al, and ^{36}Cl (reviewed by Zreda and Phillips, 1998). Until development of cosmogenic dating, numerical ages for geomorphic surfaces and landforms (as opposed to deposits) could be obtained only in limited circumstances, for example by lichenometry where lichen-growth curves had been developed for Holocene-aged surfaces. The cosmogenic nuclide methods are based on formation of nuclides when cosmic rays interact with nuclides in minerals exposed at the Earth's surface. The selection of a specific isotopic technique for a study depends on the types of rocks and minerals available for sampling and on the age range of interest. For example, ^{3}He has the longest half-life of the nuclides presently used for cosmogenic dating but is only well retained (closed-system behavior) in olivine crystals, so it is best applied to mafic igneous rocks. Quartz is considered the best mineral for application of ^{10}Be and ^{26}Al. ^{36}Cl is produced by cosmic-ray interactions with several elements and thus has the broadest application. The cosmic-ray flux incident on the Earth's surface depends on altitude, latitude, and aspect, and also varies with changes in factors such as galactic flux, the Earth's magnetic field, and solar activity. In practice, most of these variations are ignored, but corrections may be required for changes in the geomagnetic field intensity over the last 20,000 years (Zreda and Phillips, 1998). The most important constraint on the application of cosmogenic-isotope surface dating, however, is the assumption that the material analyzed has been continuously exposed and in the same orientation; both erosion and shielding by deposition can result in significant underestimates of the true surface age.

Applications of cosmogenic-nuclide dating in the Death Valley region have been few. ^{36}Cl dating and some ^{10}Be dating have been used to estimate the ages of the following: beach pebbles of pluvial Lake Manley (data of F. Phillips cited in Orme and Orme, 1991), boulders and tufa from pluvial lake shorelines in Death and Panamint Valleys (Phillips and Zreda, this volume), basalt flows and bombs of the nearby Lathrop Wells cone (Zreda and others, 1993), basalt flows and pavements at Lunar Craters (Shepard and others, 1995), and individual boulders on alluvial fan surfaces in Fish Lake Valley (data of M. Zreda cited in Reheis and others, 1996). The recent application of ^{36}Cl dating to alluvial surfaces by amalgamating many small clasts and integrating the cosmic-ray exposure over a depth interval below the surface (Ayarbe and others, 1998) promises to be extremely useful in dating desert landforms. This technique also can account for cosmogenic-isotope inheritance by reworking from older deposits, because surface samples are compared to those at depth where cosmic-ray bombardment since deposition has been minimal.

RADIATION-EFFECTS METHODS

Radiation-effects methods (fig. 24) (radiogenic methods of Colman and Pierce, 1998) provide numerical ages and consist of measurements of the cumulative effects of radioactive decay on minerals such as physical traces visible in crystal structures and accumulation of emitted electrons in crystal-lattice defects and other traps. Fission-track dating relies on counting the tracks formed by particles emitted during radioactive decay in a crystal, usually zircon or apatite, or in volcanic glass, and can be used to date igneous rocks or tephra. Except as an alternative to ^{40}Ar/^{39}Ar dating to determine the age of an unknown tephra or volcanic rock, it is little used in Quaternary studies.

Luminescence dating (recently summarized by Forman and others, 1998) is based on the progressive accumulation of electrons within defects in crystal lattices; the electrons are displaced when atoms are struck by particles emitted by radioactive decay of naturally occurring nuclides (^{238}U, ^{232}Th, ^{40}K). The accumulated electrons can be released from these crystal traps either by heating (thermoluminescence) or by light (optically stimulated luminescence), and so the luminescence signal begins to accumulate when sediments are buried and exposure to heat and light ends. The applicable age range is commonly about 100–100,000 yr, but in certain ideal situations (for example, minerals containing relatively small amounts of nuclides) it may be extended to 500,000 yr or more (fig. 24). The commonly used materials are silt- and fine-sand-sized quartz and feldspar that have been exposed to sunlight for at least 8 hours before burial. Luminescence dating has been hampered by the sample-size requirement (thousands of grains), thus potentially overestimating ages by the inclusion of a population of grains that were insufficiently bleached (not exposed to enough light) before burial. Recent advances that allow the analysis of single grains (McFee, 1998 among others) permit detection of populations of grains with non-zeroed electron traps.

Luminescence dating is particularly appropriate for desert environments where eolian sediment accumulates as dunes, as desert loess (dust) admixed with soils, and as the detrital component of spring mounds and marsh deposits; even fault-scarp colluvium may contain layers of eolian sediment that accumulated against the scarp. Episodes of Holocene to late Pleistocene dune activity at Yucca Mountain (Menges and others, 1998) and elsewhere in the Mojave Desert (Wintle and others, 1994; Rendell and Sheffer, 1996; Clarke and Rendell, 1998) have been dated using luminescence methods. Luminescence dating has been applied to spring deposits near Yucca Mountain (ages of S. Mahan, shown in Taylor, 1998, p. 162–166); this application may be appropriate because much of the fine-grained material in such deposits is likely to be wind-blown dust, as Reheis and others (1996) reported for Fish Lake marsh. Eolian sediment incorporated into gravelly soils before burial has been dated in several studies near Yucca Mountain (for example, Lundstrom and others, 1998 and this volume; Menges and Taylor, 1998). Such ages are minimum estimates for the buried soils because the period of exposure before burial is unknown, but the technique optimally can provide maximum-limiting ages for overlying deposits.

Electron-spin resonance (ESR) dating, like luminescence dating, is a radiogenic method based on progressive accumulation of radiation damage in a crystal or other geologic material caused by radioactive decay of the naturally occurring nuclides (mainly ^{238}U, ^{232}Th, ^{40}K). New techniques suggest that the maximum age determinable by ESR is several million years and possibly much more (Ye and others, 1998, among others). It has been applied to a wide range of materials, including quartz grains from sediments, certain minerals from volcanic rocks, fossil teeth and bones, ground-water and pedogenic calcite, and quartz in fault gouge (recently summarized by Schwarcz and Lee, 1998). Thus, its application overlaps those of the more commonly employed luminescence and U-series methods, but it may be possible to date much older materials with ESR.

CHEMICAL AND BIOLOGIC METHODS

Chemical and biologic methods are based on chemical and biologic changes with time and must be calibrated by independent dating to yield numerical ages (fig. 24). Methods of this type that could be relevant to studies in Death Valley (fig. 24) include amino-acid racemization, obsidian hydration (only in archeological contexts; not discussed further), lichenometry, and rock-varnish techniques. Lichenometry has been used successfully used in many cold climates and is especially useful in studies of glacial deposits and rockfalls. However, no lichen-growth curves have been established in the arid parts of the southwestern U.S.

Amino-acid racemization (AAR) is a dating method based on the progressive diagenetic alteration of protein material during fossilization (recently reviewed by Wehmiller and Miller, 1998). The rate of racemization is highly dependent on temperature and sample type (both material and species), and the possible maximum age range of the method may span a few thousand to several million years (in polar regions). Thus, the method is best used as a correlation technique (fig. 24) because the “shapes” of the diagenetic curves (racemization) are poorly defined. Recent developments permit the rapid, precise measurement of several types of amino acids from a single milligram-sized sample (Kaufman and Manley, 1998), greatly extending the utility of the method where fossil material is scarce. Quade and others (1995) used amino-acid dating on mollusc shells to correlate spring-discharge deposits of middle(?) and late Quaternary age in the region around Death Valley.

Rock varnish is ubiquitous in arid and semiarid environments as a manganese-iron coating that forms over time on rock surfaces. At least 11 different methods ranging from the observational (such as percent cover, thickness) to the quantitative (such as change in elemental composition) have been proposed and applied in attempts to use the development of rock varnish in dating surfaces, but as so succinctly stated in the recent review by Sowers (1998 sec. 2, p. 387), “Rock varnish properties are not known to change systematically or predictably with time, except on a very gross scale.” Attempts to date organic or other materials trapped in varnish, including studies in Death Valley (for example, Hooke and Dorn, 1992), have yielded highly controversial results (see Beck and others, 1998, followed by response from Dorn).

GEOMORPHIC METHODS

Soil-profile development is a well-known relative dating method that can be used as a correlation tool or to provide rough numerical age estimates when properly calibrated for factors such as climate and parent material. In general, surface-age estimates derived from soil properties are most accurate in the range of 1,000 to 100,000 yr; older soils are progressively more affected by climate change, erosion, decreasing rates of chemical weathering, and physical changes within the soil that affect depth of leaching (for example, Birkeland, 1984; Harden, 1990). Most aridic soils in the southwestern U.S. accumulate eolian dust with time; as a result, younger soils are sensitive to changes in the rate of dust deposition (Chadwick and Davis, 1990). Numerous studies of soil chronosequences exist for the region around Death Valley and can potentially be used to calibrate soil-profile development rates for surfaces within Death Valley (summarized in Harden and others, 1991; Reheis and others, 1995a).

The morphology of alluvial fan surfaces changes progressively with time due to overland flow, bioturbation, formation of desert pavement, soil genesis, and erosion. These processes result in reduction of original debris-flow morphology, smoothing and pavement development, surface lightening due to upward movement of soil-calcrete fragments, and dissection by development of secondary drainages (comprehensively discussed by Bull, 1991). Such changes are so universally recognized in the southwestern U.S. that they have been used for decades as mapping tools to discriminate Holocene, late Pleistocene, and older fan surfaces (for example, Hunt and Mabey, 1966; Reheis and others, 1995b). Some studies have attempted to use relative-age techniques such as rock-weathering parameters to distinguish fan surfaces of known ages, but they were only able to separate surfaces of Holocene age from those of late Pleistocene age with statistical certainty (McFadden and others, 1989). Nevertheless, these progressive changes in surface morphology can be used to make broad age assessments and correlations.

Scarp morphology is a dating method that can be applied to estimate the age of formation of scarp landforms, usually those produced by faulting, but also erosional scarps. Quantitative applications employ diffusion equations to model the degradation of a scarp and the associated deposition of material at its base (recently reviewed by Hanks, 1998). However, such modeling is normally applicable only to scarps formed by a single event in unconsolidated, relatively uniform (that is, not strongly bedded) material. Furthermore, Nash (1998) has suggested that use of the equations should be restricted to scarps less than 5 m high. More qualitatively, measurements of scarp-slope angle and scarp height for a scarp of unknown age may be compared to similar measurements for scarps of known age (Bucknam and Anderson, 1979) to estimate the time of scarp formation. Several studies of Quaternary faulting in the Death Valley area have employed this qualitative method (Anderson and others, 1995a, 1995b; Anderson and Klinger, 1996).

CORRELATION METHODS

Correlation methods provide ages by establishing correlations to independently dated materials using properties that do not change over time. The most useful correlation methods in the southwestern U.S. are paleomagnetism and tephrochronology. However, precise dating is rarely possible with paleomagnetic methods unless long sedimentary sequences are preserved that record a reversal stratigraphy, or for the Holocene, a regional pattern of secular variation (reviewed by Verosub, 1998). In the Death Valley area, paleomagnetic reversal stratigraphy has been used to provide age control in sedimentary sequences exposed in the Tecopa basin (Hillhouse, 1987) and in southern Fish Lake Valley (Reheis and others, 1991). Paleomagnetic polarity can help to refine tephrochronologic correlations in cases where tephra of similar composition were erupted during episodes of different polarity.

Tephrochronology employs physical, chemical, and mineralogical characteristics of pyroclastic materials to provide correlations to volcanic eruptions of known age (recently reviewed by Sarna-Wojcicki and Davis, 1991). Because eruptions are geologically brief events, tephra that falls downwind of the source and is deposited within sedimentary units can be used as a time marker for correlation among widely separated areas. Tephra layers can be dated directly using numerical methods such as $^{40}Ar/^{39}Ar$ and fission-track methods. More commonly, and especially for distal fine-grained tephra layers, the chemistry and morphology of glass shards are used to correlate samples to proximal ash-flows that in turn are dated numerically. Multiple tephra layers commonly occur within sedimentary sequences; thus, a successful correlation of one or more layers to tephra of known age provides age constraints for interbedded layers that do not correlate with a dated eruption. The Death Valley region, happily, lies within the fallout area of Pliocene and Quaternary tephra derived from several different volcanic source areas, including the southwest Nevada volcanic field, the Long Valley area of California, the Sonoma and southern Cascade volcanic fields of northern California and Oregon, and the Snake River Plain–Yellowstone area (Reheis and others, 1991; Sarna-Wojcicki and Davis, 1991); thus, the opportunities for tephrochronology are excellent. Death Valley contains numerous outcrops with tephra layers and some have been correlated with eruptions of known age (for example, Knott and others, 1996 and this volume; Sarna-Wojcicki and others, in review). Tephrochronology has also played an important role in nearby studies of neotectonics and lacustrine history (Hillhouse, 1987; Reheis and others, 1991, 1993; Brown and Rosen, 1995; Reheis and Sawyer, 1997).

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Imaging Radar Applications in the Death Valley Region

Tom G. Farr, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA <tom.farr@jpl.nasa.gov>

Death Valley has had a long history as a testbed for remote-sensing techniques (Gillespie, this volume). Along with visible-near infrared and thermal IR sensors, imaging radars have flown and orbited over the valley since the 1970's, yielding new insights into the geologic applications of that technology. More recently, radar interferometry has been used to derive digital topographic maps of the area, supplementing the USGS 7.5' digital quadrangles currently available for nearly the entire area.

As for their shorter-wavelength brethren, imaging radars were tested early in their civilian history in Death Valley because it has a variety of surface types in a small area without the confounding effects of vegetation. In one of the classic references of these early radar studies, Schaber and others (1976) explained in a semiquantitative way the response of an imaging radar to surface roughness near the radar wavelength, which typically ranges from about 1 cm to 1 m. This laid the groundwork for applications of airborne and spaceborne radars to geologic problems in arid regions. Radar's main advantages over other sensors stem from its active nature—supplying its own illumination makes it independent of solar illumination, and it can also control the imaging geometry more accurately. Finally, its long wavelength allows it to peer through clouds, eliminating some of the problems of optical sensors, especially in perennially cloudy and polar areas.

Imaging radars are almost always monostatic, meaning that they use the same antenna for illumination and reception. Thus, image tone, which is proportional to the amount of energy arriving back at the antenna after scattering off the ground, is related to how diffuse the scattering is. A smooth surface (at the scale of the wavelength), such as a still body of water or a paved parking lot, will reflect the energy like a mirror, sending it away from the receiving antenna, yielding a dark image tone. As a surface becomes rougher, say from sand to gravel to cobbles to boulders, more and more energy is scattered in random directions, rather than in the specular direction; so, more energy makes it back to the receiver and the area appears in lighter tones. Thus imaging radars produce images of the physical nature of the surface, complementary to the compositional information produced by optical sensors. A secondary characteristic of the surface, its dielectric constant, which is proportional to moisture content, plays a much smaller part, but can sometimes be seen to affect image tone around springs and after rainfall.

The earliest imaging radars to be flown over Death Valley included military tests of short-wavelength (3-cm) X-band sensors (Schaber and others, 1976). Later, the Jet Propulsion Laboratory (JPL) began its development of imaging radars with an airborne sensor, followed by the Seasat orbital radar in 1978. These systems were L-band (25 cm). Seasat was designed for oceanographic work, but that its data were highly useful for geologic studies was quickly realized. Its early failure probably helped bring more attention to its land applications, as well. Following Seasat, JPL embarked upon a series of Space Shuttle Imaging Radars: SIR-A (1981), SIR-B (1984), and SIR-C (1994). The most recent in the series was the most capable radar sensor flown in space and acquired large numbers of data swaths in a variety of test areas around the world. Death Valley was one of those test areas, and was covered very well.

At the same time, the aircraft radar program continued improving and collecting data over Death Valley, including tests of a relatively new technique called imaging radar interferometry. This adds a second antenna analogous to stereo imaging, allowing digital topographic maps to be generated. In September 1999, SIR-C will ride again as the Shuttle Radar Topography Mission, with the addition of a second antenna at the end of a 60-m mast; the goal is to collect data for a global 30-m-resolution digital topographic map.

Other countries have not been idle during this time. The European Space Agency has operated a pair of radar satellites, ERS-1 and 2, for a number of years; Japan has flown JERS-1; and Canada has Radarsat-1.

Geologists have used radar images for a long time as surrogates for air photos in areas of perennial cloud cover. Structures, even though covered with a vegetation canopy, show up surprisingly well, not because the radar is penetrating through the canopy, but because the small illumination-angle variations caused by the canopy following the underlying topography are highlighted more in radar images than in optical images. In arid regions, it has been recognized that the weathering habit of a rock outcrop will determine its appearance in a radar image. Resistant, jointed rocks tend to appear bright, whereas fissile easily comminuted rock types appear dark. These characteristics may be helpful in sorting out ambiguities in optical remote sensing data.

Another useful application for imaging radar is mapping of surficial deposits and processes. Many surficial geomorphic processes act to change the roughness of a surface. In Death Valley, the most common processes are salt weathering (in the lower elevations), aeolian deposition, and desert pavement formation. Daily and others (1979) found that combining Landsat optical images with airborne radar images was useful for mapping several alluvial fan units, based on desert varnish formation in the optical wavelengths and desert pavement formation in the radar images. Taking this further afield, Farr and Chadwick (1996) applied a similar approach to map fan units in a high valley in western People's Republic of China. These results make a case for the possibility that different surficial processes leave diagnostic signatures in multi-sensor remote sensing data, a possibility that will require much more extensive tests for uniqueness in different environments. A more quantitative attempt at connecting radar images with surficial processes was undertaken by Farr (1992). Building on the work of Dohrenwend and others (1984) and Wells and others (1985), roughness changes with age at Cima Volcanic Field were quantified using close-range stereo photography from a helicopter. The results were then compared with radar images inverted to become maps of surface roughness (Evans and others, 1992).

ACKNOWLEDGMENTS

Work performed under contract to NASA. JPL Radar Program web site: <http://southport.jpl.nasa.gov/>.

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Regional 1:100,000 Mapping of Quaternary Units from SPOT Images and 30-m DEMs

A.S. Jayko[1] and D.W. Prichett[2]
[1]U.S. Geological Survey, 345 Middlefield Road, M.S. 975, Menlo Park, CA 94025 <ajayko@usgs.gov>
[2]University of California White Mountain Research Station, 3000 East Line St., Bishop, CA 93514

SPOT satellite images provide spectral data at 10-m resolution that is registered to geographic coordinates and appears to have high enough resolution to map Quaternary units as required for 1:100,000- and 1:250,000-scale regional compilations (approximately equivalent detail as can be obtained from 1:80,000-scale air photos). The units that can be subdivided using digital raster analysis include Holocene drainages and channels, Quaternary alluvial fans, Pliocene-Pleistocene alluvial fans, playa deposits, dune deposits, and spring/marsh deposits. The raster (or grid) boundaries and regions defined by the spectral data are vectorized for compilation in geologic databases. As SPOT images are not spectrally corrected between scenes, some digital processing is required to edge-match scenes. Each scene covers approximately one-half a 1:100,000 map (1/2 × 1/2 degree). Preliminary mapping based on spectral characteristics can be refined and augmented by combining the spectral data with 30-m digital elevation models (DEMs), which provide more quantitative means to characterize the morphological properties of the units. Digital morphological properties of other surface features, particularly those with tectonic significance, such as faults and deformed surfaces, can also be enhanced and mapped using the raster analysis. A test area in the central Death Valley region has been selected to compare digitally mapped Quaternary units and fault traces with those mapped by conventional air-photo and field methods at 1:96,000 (Hunt and Mabey, 1966). In addition to mapping unit boundaries, determinations of the surface area and volume(?) of some geologic units and watersheds are made to estimate erosion/deposition rates for parts of the basin.

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Differential GPS/GIS Analysis of the Sliding Rock Phenomenon of Racetrack Playa, Death Valley National Park

Paula Messina[1] and Phil Stoffer[2]

[1]Department of Geology, San José State University, One Washington Square, San José, CA 95192-0102 <pmessina@geosun1.sjsu.edu>

[2]U.S. Geological Survey, 345 Middlefield Road, M.S. 955, Menlo Park, CA 94025 <pstoffer@usgs.gov>

The Racetrack Playa, at an elevation of 1,131 m, is a dry lakebed nestled in the Panamint Range in Death Valley National Park, California. Though almost perfectly flat, it shows evidence of dynamic traction (sliding) of boulder-sized and smaller rock fragments that tumble onto it from two abutting cliffs and surrounding alluvial fans. Scars of sliding rock activity in the form of recessed furrows have been noted since the beginning of the 20th century (Clements, 1952; Kirk, 1952; Shelton, 1953; Stanley, 1955; Schumm, 1956; Sharp, 1960; Sharp and Carey, 1976; Reid and others, 1995; Messina, 1998), yet to date no one has witnessed the actual surface process that causes the rocks to slide.

Previous mapping (Stanley, 1955; Reid and others, 1995), showed a high degree of parallelism among selected sliding rock trails. These surveys hypothesized that rocks inscribe grooves on the playa surface while embedded in a cohesive ice sheet, particularly during winter storms. Through experimentation, Sharp and Carey (1976) and Bacon and others (1996) concluded that ice rafts may not necessarily contribute to the phenomenon.

The location of every rock and its associated trail was recorded using Differential Global Positioning System (DGPS) and Geographic Information System (GIS) methods in July 1996 (Messina and others, 1997). The resulting map shows a total of 162 rocks and trails to a horizontal accuracy of about 30 cm. Surprisingly, a follow-up mapping project conducted in May 1998, showed that the abnormally stormy El Niño winter conditions of 1997–98, while favorable to the development of ice sheets, contributed little to the displacement of rocks from their original mapped locations.

Examination of trail patterns shows an inferred general trend in rock movement toward the north-northeast. This is consistent with the direction of prevailing winds. However, there is a high degree of variation in trail character. Surprisingly, trail lengths and headings are not well correlated with rock shape, volume, or area of surface contact.

Analysis of the digital data set shows that large rocks tend to produce shorter, straighter trails. However, a rock's total distance traveled and the degree to which it follows a straight-line path are more significantly influenced by its location on the playa at the onset of motion than on any physical attribute of the rock itself.

The Racetrack's southeast sector, about 5 cm lower in elevation than the main playa, is more frequently saturated by collecting rain water. In addition, three natural springs there may contribute to lower friction coefficients over the long term in this region. The longest and straightest trails are preferentially concentrated in the southeast, as rocks are propelled by the amplified force of horizontal winds when air is channeled through one of two topographic corridors to the south. On the central part of the playa, which is a focal point for two such natural wind tunnels, trails are most convoluted suggesting entrainment of rocks in wind vortices.

GIS integration of the DGPS data with the USGS 30-m 7.5-minute Ubehebe Peak quadrangle DEM provided the framework for extensive geomorphometry and statistical tests. Terrain analysis of the surrounding basin quantifies the influence of topography on inferred airflow, which ultimately governs the nature and magnitude of sliding rock episodes.

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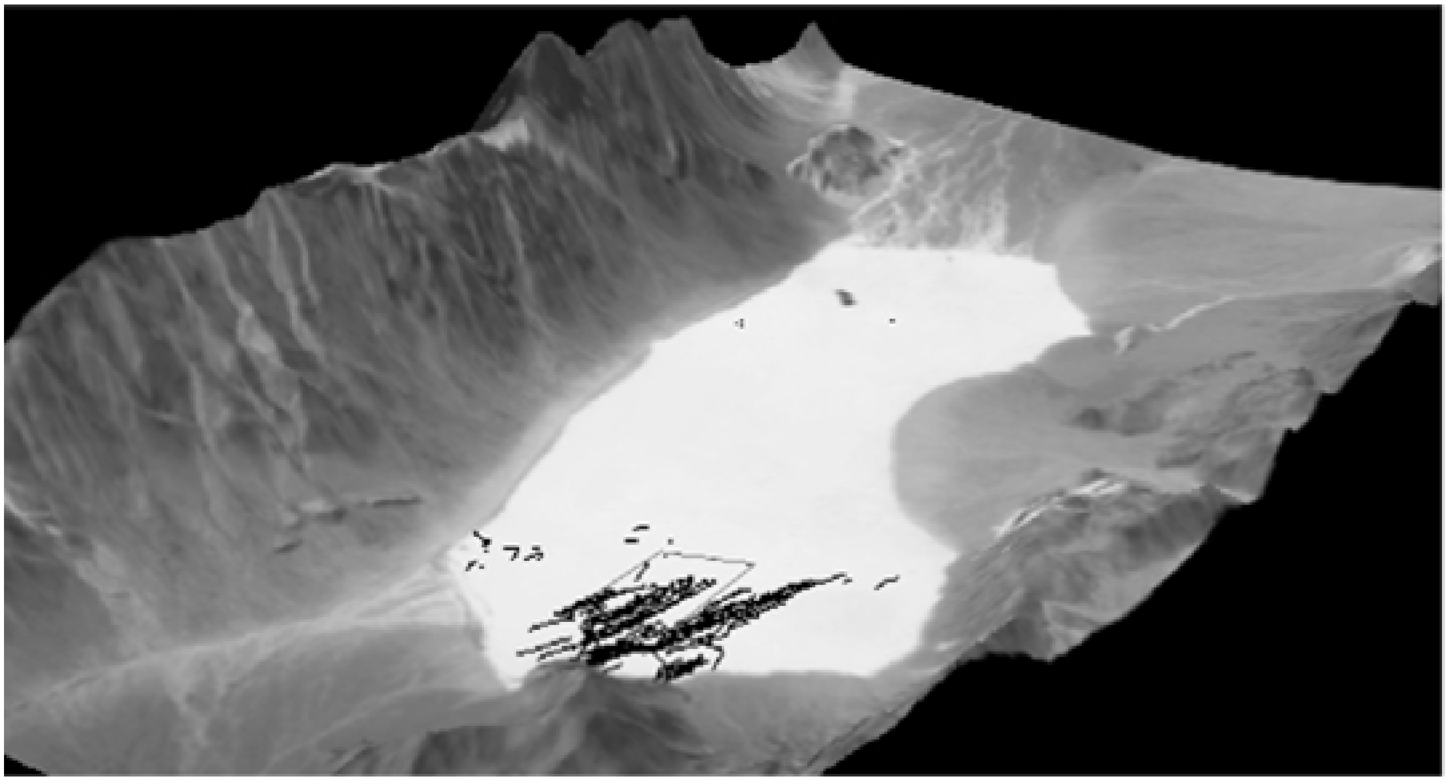

Figure 25 (left). Oblique USGS aerial image of the Racetrack, draped on the USGS Ubehebe Peak 7.5′ DEM (2× vertical exaggeration). DGPS sliding rock trails are denoted by black lines. (Figure 26 extent is shown by the rectangle near the playa's center.)

Figure 26 (upper right). Large-scale detail of trails in the Racetrack's central region.

Figure 27 (lower right). Photograph of two diverging sliding cobbles.

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Quaternary Geologic Mapping and Geochronology of the Las Vegas 1:100,000 Sheet and Yucca Mountain Area—Geomorphic and Hydrologic Response to Climate Change near Death Valley

S.C. Lundstrom <sclundst@usgs.gov>, J.B. Paces, S.A. Mahan, W.R. Page, and J.B. Workman,
U.S. Geological Survey, Box 25046, Denver Federal Center, M.S. 913, Denver, CO 80225

Geologic mapping, stratigraphic studies, and geochronology of Quaternary deposits in areas to the east of Death Valley provide records of the responses of regional hydrologic systems, landscapes, and soils to Quaternary climate change.

Extensive areas of fine-grained deposits dominate the land surface in the lower portions of Las Vegas, Pahrump, and Amargosa Valleys. Most of these deposits were formed during episodes when past ground-water discharge was much larger than historically observed (Haynes, 1967; Quade and others, 1995; Paces and others, 1997; Bell and others, 1998; Lundstrom and others, 1998). The presence of these deposits on the up-gradient side of faults suggests that these faults were hydrologic barriers to ground-water flow. Exposed stratigraphy, and U-series, luminescence, and radiocarbon geochronology indicate multiple episodes of ground-water discharge in the northern Las Vegas Valley, Pahrump Valley, and Amargosa Desert. The most areally extensive period of discharge during the past 50,000 years occurred between about 40 ka and 25 ka, preceding and overlapping the last global glacial maximum. Comparison to proxy climate records (for example, Spaulding, 1990) indicates that this was a period of relatively high effective moisture and ground-water recharge. A less extensive period of discharge occurred during 13–8 ka.

Extensive alluvial fans coalesce between the fine-grained areas of past discharge and the upland sources of the fans. Like past discharge events, fan sedimentation was also episodic and hydroclimatically driven. Extensive Holocene alluvial-fan sedimentation overlapped the younger period of prehistoric ground-water discharge (13–8 ka). Somewhat wetter than historic climates with surface flooding events of larger than historic magnitude produced these fans. In contrast, the most extensive period of past discharge (40–25 ka) did not coincide with fan building, but overlapped and preceded major fanhead incision in watersheds that include the highest portions of the Spring Mountains and Timber Mountain area. The fanhead incision required concentrated runoff and low sediment yield, and was probably dominated by snowmelt, as perhaps were ground-water recharge and associated discharge. The latter part of the last major episode of carbonate cementation in soils in the area occurred during this period of greater late Pleistocene effective moisture, which determined part of the major mappable difference between cemented Pleistocene alluvial soils, and noncemented Holocene soils. Prior to fanhead incision, the penultimate period of extensive fan deposition and aggradation similar to that in the Holocene occurred during 120–50 ka, probably in response to high-intensity rainfall, runoff, and erosion of uplands.

The mode and timing of eolian additions to alluvial soils and to ground-water discharge areas also varied spatially and temporally in response to climate, sediment supply, and sediment-trapping processes. Two texturally distinct modes of eolian addition are indicated—one dominated by fine sand and the other by silt. Each of these modes is associated with different past episodes of influx and climatically driven processes. The particle-size distribution of soils on Holocene alluvial-fan gravel includes a ubiquitous predominance of fine sand that increases upward in soil profiles. The less than 2-mm fraction is dominated by fine sand, and represents eolian additions from slackwater facies of freshly deposited fan alluvium, as occurred following the March 11, 1995, flood event of Fortymile Wash. Thermoluminescence (TL) dates on fine-sand-rich buried soils interbedded with alluvium also indicate similar episodes of eolian sand influx associated with aggradation during 120–50 ka. In contrast, TL dates on eolian components of silt-rich soil horizons developed on Pleistocene alluvium are typically in the range of 40–20 ka, overlapping the last glacial maximum. These dates are consistent with the higher global silt production and influx during that time as determined from ice cores and lake records. Several TL dates on silt-rich components of buried soils also indicate earlier episodes of high silt production and atmospheric influx, perhaps related to glacial episodes within marine stages 6 and 5. The presence of silt-enriched horizons near the surface—the ubiquitous Av horizon—is typically associated with well-packed desert pavement, which greatly facilitates the recognition and mapping of Pleistocene fan deposits.

Wetland environments associated with past ground-water discharge were much more efficient dust traps than alluvial soils. Luminescence dates on eolian silt components of these deposits are consistent with episodic but generally greater rates of eolian influx to these environments than to alluvial soils during the varying climates of the late Pleistocene. Where the deposits were eroded into badlands during drier intervals of the Holocene, these areas became local fine-sediment sources. Holocene alluvial fans near these badlands have silt-enriched soil profiles associated with well-packed desert pavements because of the locally high silt influx. These surfaces and their noncemented soils are gradational to more typical fine-sand-enriched and silt-poor soils on Holocene fans that are more distant from local badland-dust sources.

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A Soil Survey of Death Valley National Park—New Techniques in Standard Soil Survey

Douglas J. Merkler,[1] Leon Lato, [1] and Peter Scull[2]
[1]USDA, Natural Resources Conservation Service, 2357A Renaissance Drive, Las Vegas, NV 89119
<doug.merkler@nv.usda.gov>; <leon.lato@nv.usda.gov>
[2]Departments of Geography, San Diego State University, and University of California, Santa Barbara, CA
<scull@geog.ucsb.edu>

In addition to its traditional role as an essential medium for agriculture, soil is a fundamental component of natural ecosystems. We must understand the spatial distribution of soil in order to provide a basis for land-use decisions. A soil survey is the primary means by which the spatial properties of soil are collected, presented, and stored in the U.S. and throughout the world. The USDA, in cooperation with various other Federal and State agencies, began soil survey work in 1896. The combined State and Federal government effort became known as the National Cooperative Soil Survey (NCSS) (Indorante and others, 1996). The NCSS mission is to furnish private landowners, land managers, and consultants with soil maps as an aid in land-use decision making. Through the years many changes have been made; present methods are outlined in the *Soil Survey Manual* (U.S. Soil Conservation Service, 1993) and in the *Keys to Soil Taxonomy, Eighth edition* (U.S. Natural Resources Conservation Service, 1998). These publications describe a variety of survey tasks including investigations of soil genesis, morphology, classification, and behavior. The ultimate goal of a soil survey is to elucidate soil-landscape relationships in order to map the soil resource for a given survey area.

Survey methodology is fundamentally limited by the fact that we can directly sample only a tiny fraction of the soil, and doing so (by auger or shovel) results in the destruction of the original characteristics of the site (Avery, 1987). To remedy this situation, we rely on the use of more easily observed environmental features that we believe to be related to soil distribution via soil genesis, such as why the soil is there in the first place. We combine a host of such environmental features (including geology, geomorphology, vegetation, and climate) into a conceptual model describing soil-landscape variation. We then use this model to predict soil characteristics at unvisited or unsampled sites. So, even though we have seen the soil itself in a minuscule proportion of its total volume, by relating soil properties to visible landscape features, we can reliably infer soil properties over the entire landscape (Dent and Young, 1981). Starting in 1999, we will use this procedure to map the soil resources of Death Valley National Park (DVNP). The products of the survey will be a level 4 soil association map, a digitized GIS spatial database that is Soil Survey Geographic (SSURGO) certified, and a detailed description of the physical and chemical properties of the soil associations.

Many fundamental questions have been raised about standard soil survey methods in the scientific literature: What are legitimate uses of survey data? How reliable are they? How specific are its statements? Many of these questions stem from two criticisms levied against soil survey. First, the conceptual model developed by the soil surveyor is initially based on incomplete information relative to the final soil-survey product (Cook and others, 1996). This aspect of soil survey is especially frustrating because it fails to document most of the knowledge that the soil surveyor accumulates during the expensive field-mapping process. Clearly one direction of innovation in soil survey is to add objectivity to model development which will allow more explicit scientific communication (Gessler and others, 1995). The second major criticism of soil survey is that the choropleth map divides survey regions into homogeneous units with unknown variability and sharply defined boundaries (Burrough and McDonnell, 1998). The choropleth model was adopted at a time when soil information had to be abstracted to the level of the modal profile (classified in *Soil Taxonomy*), because it was impossible to catalog and present the full amount of soil variability (Cambell and Edmonds, 1984). In concert with the environmental variables, soil properties vary continuously across landscapes, exhibiting different and complex scales of variation (Simonson, 1959). Therefore, soil distribution is not well represented by choropleth maps (Gessler and others, 1995).

Technological advances during the past few decades have created a tremendous potential for improvement in the way that soil maps are produced and displayed (McBratney, 1992). Remote sensing and terrain analysis provide spatially explicit, digital data representations of the Earth's surface that can be combined with digitized paper maps in geographic information systems (GIS) to allow efficient characterization and analysis of vast amounts of data. The future of soil survey lies in using GIS to model spatial soil variation from more easily mapped environmental variables (Hewitt, 1993; Indorante and others, 1996).

To begin to explore some of these options, the University of California at Santa Barbara (UCSB), San Diego State University (SDSU), and the USDA–Natural Resources Conservation Service (NRCS) have formed a consortium to investigate technologically advanced soil-modeling techniques to support future soil-survey efforts in the Mojave Desert Eco-region, which contains Death Valley National Park (DVNP). The northern part of DVNP will serve as a test for our methods. Predictive soil-modeling techniques hold promise to lower cost and increase specificity, but NRCS lacks the expertise and resources to test new approaches, and universities lack the field expertise and extensive data-gathering capability of the USDA. Through this partnership we will test new approaches and lay the groundwork for long-term incorporation of the new techniques in standard soil-survey procedures.

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Surficial Geology and Geomorphic Process Studies in Support of Multidisciplinary Ecosystem Investigations—Examples from Parts of Greenwater and Valjean Valleys, Mojave Desert Ecosystem

David M. Miller[1] and James C. Yount[2]

[1] U.S. Geological Survey, 345 Middlefield Road, M.S. 975, Menlo Park, CA 94025 <dmiller@usgs.gov>

[2] U.S. Geological Survey, Box 25046, Denver Federal Center, M.S. 980, Denver, CO 80225 <jyount@usgs.gov>

Ecosystems, which identify a natural community of interacting organisms and their physical environment, can also serve as organizational and conceptual units that define land-use regions for land-management agencies and study boundaries for large interdisciplinary scientific investigations. The geologic and hydrologic frameworks constitute a fundamental part of the physical environment at the core of the definition of an ecosystem. Of particular importance are surficial geologic studies that involve characterizations of near-surface geologic materials, including soils, determinations of age and nature of geomorphic surfaces, and interpretations of geologic and hydrologic processes that emplace the materials.

The Mojave Desert Ecosystem Science Project <http://geology.wr.usgs.gov/MojaveEco/> is an interdisciplinary investigation that emphasizes the understanding of vulnerability and recoverability of an ecosystem's components in an arid environment. The overall methodology is to characterize the ecosystem's attributes and study key functional links and processes in order to quantitatively model its vulnerability. Surficial geology plays an important role in this approach because data from near-surface deposits provide fundamental information to characterize and model such effects as soil compaction, wind erosion, and water erosion. In addition, surficial deposits contain a physical record of historic and prehistoric processes and can therefore be used to establish baselines for comparisons of human-induced impacts on these natural systems. For these reasons, we have undertaken detailed and regional characterizations of surficial deposits in the Mojave Desert Ecosystem.

Detailed surficial geologic studies are underway in a part of the Greenwater Valley in the eastern portion of Death Valley National Park and in the Valjean area in northern Silurian Valley, approximately 30 km north of Baker, Calif. Each of these areas contains old townsites that are being studied by other project members to establish patterns of soil and vegetative recovery from the disturbances that date to near the beginning of the 20th century.

Greenwater Valley is an intermontane valley formed along the east flank of the Black Mountains; it begins approximately 5 km south of Ryan, Calif., and extends southeast for 60 km to the town of Tecopa. The northern 15 km of the valley contains at least three townsites and is the focus of these studies. The northern portion of the valley is asymmetric in cross section with gentle western slopes, mantled by thin alluvial fans. These fans feed an axial drainage, Furnace Creek Wash, which intermittently flows northwest along the foot of the steeply sloped western flank of the Greenwater Range. Northern Greenwater Valley is perched 1,300 m above the floor of Death Valley and lies immediately above a pronounced nick point in Furnace Creek Wash, below which active erosion and sidestream entrenchment dominate the landscape. Virtually all sediment mantling the valley margins is sandy gravel derived from nearby welded and nonwelded silicic ash-flow tuffs of Tertiary age. The fan surfaces of the broad west-side piedmont are dominantly Holocene (<10,000 yr) in age, based on weak to no soil development, lack of any eolian silt cap or associated desert pavement, and preservation of distinct, yet low-relief microtopography. A few remnants of late to middle Pleistocene surfaces are recognized, based mainly on soil development. These remnants are being buried by Holocene debris near the toe of the slope, and stripped middle Pleistocene surfaces that are overlain by thin Holocene deposits are only visible in the walls of shallow washes in the upper portions of the slope. The short, steep fans of the eastern valley slope and the axial stream system of Furnace Creek Wash share soil properties with their correlatives on the west side of the valley, but the latter deposits are dominated by cobble to boulder gravel and their microtopography is more pronounced. The causes of the asymmetric valley and its opposing stratigraphic relations between valley sides are not completely clear. They probably result from a combination of the following: (1) active back-tilting of the entire valley and the associated Greenwater Range that forms in the footwall block of the Death Valley fault, (2) possible minor down-to-the-west Pliocene and early Quaternary displacement along a fault at the western foot of the Greenwater Range, (3) gentle east dip of the underlying tuff on the west side of the valley, and (4) inheritance of relict (Pliocene to early Quaternary) topography.

To the southeast, the Valjean area comprises the gently west sloping Valjean piedmont, located largely north of the Silurian Hills and east of Silurian Lake. Steep fans from the high Avawatz Mountains meet the Valjean piedmont at Salt Creek Wash. The north edge of the Valjean piedmont is bordered by Kingston Wash, where it exits an hourglass-shaped canyon below the immense (>1,500 km^2) Shadow Valley drainage basin. Kingston Wash carries a distinctive assemblage of granitoid-rich clasts and forms simple fans unlike those of the Valjean piedmont, which is composed of complexly interbraiding systems carrying a mixed assemblage of quartzite/silicic metasediment/granitoid clasts. An unusually complete set of geomorphic surfaces is preserved on the Valjean piedmont, including three or more probable early to middle Pleistocene-age surfaces underlain by Stage IV calcic soils (Gile and others, 1966; Machette, 1985) that are partially to completely stripped of eolian silt caps and dissected to depths of at least 10 m. Middle to late Pleistocene surfaces are distinguished by soils with well-developed to weakly developed Bt and Btk horizons, pronounced eolian silt caps and desert pavements, and flat surfaces lacking bar-and-swale topography. Holocene surfaces have weak or no soil development, no eolian silt caps, and moderate to pronounced bar-and-swale topography. One enormous debris-flow deposit that mantles much of lower Kingston Wash with boulders as much as 2 m in diameter, appears to be early Holocene in age. Finally, the alluvial deposits complexly interfinger with eolian materials along southeast-trending belts downwind of two local sources—Silurian Lake and the lower Amargosa River. The eolian contributions modify microtopography and soil development characteristics, leading to differences in infiltration and vegetation in these belts.

Although several plant, animal, and soil vulnerability and recovery studies are still underway at various Mojave sites, a few initial generalizations can be made regarding surficial geologic controls on ecosystem components, at both Greenwater Valley and the Valjean area. Distinct associations of plant communities with various-age geomorphic surfaces (as noted by several botanists) may be responses to different soil-geomorphic controls depending on the age of the surface. In and near active washes, surface stability is low as a result of active aggradation in channels and flooding of late Holocene surfaces by large depositional events. In such environments, longer lived plants, such as creosote bush, seem to be excluded by rapid colonizers, such as grasses. On Pleistocene surfaces, stability is high, but variations in subsurface soil composition and development, and presence of significant areas of desert pavement, appear to partly control the density and height, if not species composition of the plant community. Clearly, soil compactibility and recoverability also vary with surficial geologic conditions, with the eolian silt caps of middle to late Pleistocene surfaces being particularly compactable. For many recovery-site studies, conventional, stratigraphy-based surficial mapping at 1:12,000 to 1:24,000 scale is inadequate for characterizing all the geologic parameters controlling plant distributions and soil compactibility. Detailed surface and subsurface particle-size distributions and inventories of lithologic composition of gravel clasts and matrix are also required.

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Late Cenozoic Tephrochronology of Death Valley, California—New Insights into Stratigraphy, Paleogeography, and Tectonics

J. R. Knott,[1] Andrei M. Sarna-Wojcicki,[2] Ralph E. Klinger,[3] John C. Tinsley, III,[2] and Bennie W. Troxel[4]

[1]UNOCAL Corporation, Environmental Technology, 376 South Valencia Avenue, Brea, CA 92823 <jrknott@unocal.com>

[2]U.S. Geological Survey, 345 Middlefield Road, M.S. 975, Menlo Park, CA 94025 <asarna@usgs.gov>; <jtinsley@usgs.gov>

[3]U.S. Bureau of Reclamation, P.O. Box 25007, D–8330, Denver, CO 80225 <rklinger@do.usbr.gov>

[4]2961 Redwood Rd., Napa, CA

At present, Death Valley is a large, structurally simple depression reflecting both crustal spreading and right-lateral crustal-block translation. The valley is a large pull-apart basin formed by a major right-step between the right-lateral Southern Death Valley fault zone on the southwest, and the Furnace Creek fault zone to the northeast. These two fault zones are joined by the north-trending, normal-oblique Death Valley fault zone. In addition, the Death Valley basin is bounded by several other arcuate normal faults that are a consequence of block rotation and collapse into the pull-apart basin formed by this large right-step.

The development of this basin through time, however, has been complex as indicated by evidence for the prior existence of separate basins, the changing loci of sedimentation, and the progressive amalgamation of smaller basins into the present larger depression. Evidence for the timing and geometry of this transformation is obtained from integrating four major lines of study: detailed stratigraphy, sediment provenance studies, structural analysis, and tephrochronology.

Geologists mapping in Death Valley during the past several decades have recognized and identified a large number of widespread tephra layers that correlate to dated eruptive sources (see table). These tephra layers provide previously unobtainable precise age control for correlating strata in the several spatially isolated paleobasins. Together with stratigraphic evidence, provenance studies, and structural analysis, the tephrochronologic data support the following inferences:

- Significant and synchronous alluvial fan deposition occurred during the late Pliocene. In particular, deposition was focused at the north ends of the Black (Artists Drive), Panamint (Nova Basin), and Cottonwood (Ubehebe Basin) Mountains, and in Copper Canyon. The timing of alluvial fan deposition is consistent with an increase in tectonic activity about 4 Ma noted in other areas of the Basin and Range province, and a wetter climatic regime as noted in the Searles Lake core.
- The initiation of the alluvial fan complex at Artists Drive 3.5 Ma is roughly coincident with the end of deposition in the Miocene to Pliocene Furnace Creek basin. We interpret these two events as indicating ~20 km of northward growth of the Death Valley fault zone in this area. Uplift of Pliocene deposits in the Ubehebe Basin may record similar northward growth of the Tin Mountain fault zone.
- Cessation of deposition and initiation of uplift and deformation in both the Artists Drive block and the Confidence Hills areas are roughly coincident (~2 Ma).
- The low-angle, right-normal Mormon Point and Badwater turtleback faults offset the middle Pleistocene Bishop ash layer, but not late middle Pleistocene (160–185 ka) lake gravels. These data effectively bracket the latest slip event on these turtleback faults within the Quaternary.
- The Death Valley fault zone has stepped basinward, thereby incorporating middle Pleistocene basinal deposits at Mormon Point and Natural Bridge, and Pliocene and older basinal deposits at Copper Canyon. We interpret uplift of alluvial fan deposits of the Nova basin in the northern Panamint Mountains as basinward stepping of the Towne Pass fault zone since the Pliocene.
- Pluvial lake deposits >0.8 Ma and between 0.76 and 0.66 Ma are found at Mormon Point and Ubehebe in the extreme southern and northern parts of Death Valley, respectively, but not in the more central Kit Fox Hills or Natural Bridge areas. These limited data suggest that these lakes were relatively small and isolated.
- Provenance data indicate that pre-latest Pliocene alluvial fan deposits preserved in the northern Noble Hills were derived from the part of the Owlshead Mountains that now sheds gravel into the Confidence Hills. Thus, the Noble Hills gravels have been transported about 25 km along ancient branches of the Southern Death Valley fault zone.
- Provenance studies of alluvial fan deposits along the eastern margin of the Ubehebe Basin and the interbedded tephra beds provide constraints on the total slip across the Furnace Creek fault zone since 0.76 Ma.

Late Cenozoic tephra beds in Death Valley, California

Tephra unit name	Age, in Ma	Eruptive source	Locality
Ubehebe Crater ash bed	Holocene (~300 yr?)	Ubehebe Crater, Death Valley, Calif.	Ubehebe Basin
Mono Craters ash bed	<1,200 yr	Mono Craters, Calif.	Mesquite Flat, Ubehebe Basin
Dibekulewe ash bed	>0.435 – <0.614	Unknown	Mormon Point
Lava Creek B ash bed	0.665 ± 0.010	Yellowstone, Wyo.	Mormon Point, Mud Hills
Bishop ash bed	0.759 ± 0.002	Long Valley, Calif.	Mormon Point, Natural Bridge, Ubehebe Basin
Glass Mountain ash beds	~0.8 – ~1.95	Long Valley, Calif.	Mormon Point, Artists Drive, Ashford Canyon, Confidence Hills
Ash bed of Confidence Hills	>~1.95; <2.09	Cascade Range	Confidence Hills
Huckleberry Ridge ash bed	2.09 ± 0.008	Yellowstone, Wyo.-Idaho	Confidence Hills
Ash bed of Clayton Valley	>2; <3.35	Unknown; Long Valley, Calif.?	Artists Drive
Mesquite Spring ash beds	~3.28 – 3.40	Unknown; Long Valley, Calif.?	Copper Canyon, Artists Drive, Six Springs Canyon, Nova Basin, Cottonwood Mountains, Ubehebe Basin
Nomlaki Tuff	3.28	S. Cascade Range, Calif.	Artists Drive, Nova Basin, Ubehebe Basin
Tuff of Curry Canyon	>3.35	Unknown; Long Valley, Calif.?	Artists Drive
Lower Nomlaki tuff	>3.58?	S. Cascade Range, Calif.?	Artists Drive

Chlorine-36 Ages of Pluvial Shoreline Features in the Death Valley/Panamint Valley Area

Fred M. Phillips[1] and Marek G. Zreda[2],
[1]Department of Earth & Environmental Sciences, New Mexico Institute of Technology, Socorro NM 87801
<phillips@nmt.edu>
[2]Department of Hydrology & Water Resources, University of Arizona, Tucson AZ 85721

We report ^{36}Cl ages from boulders in shoreline cuts, gravel bars, and tufa from pluvial lake shorelines in Death and Panamint Valleys. Most of the samples were collected as part of a reconnaissance study about 10 years ago.

One boulder from the Blackwelder shoreline at Mormon Point in Death Valley, and two boulders from the "15-foot" shoreline below it, produced ages in the range 95 to 135 ka and are probably consistent with an oxygen-isotope stage 6 age for the shorelines. Such boulders from wave-cut notches in alluvial fan materials could either contain cosmogenic nuclides inherited from exposure during erosion and transport and thus be anomalously old, or could be eroded out subsequent to regression of the lake and thus be anomalously young.

A rudimentary depth profile was sampled through the Beatty beach bar, a major barrier bar feature at 73 m elevation. Poor analytical precision for the deeper sample inhibits interpretation of the results, but maximum and minimum ages of the bar appear to be about 85 and 20 ka, indicating at least one deep lake stand after isotope stage 6.

Two tufa and two boulder samples were measured from the "Gale" shoreline at Pleasant Canyon in Panamint Valley. The tufa samples gave ages ranging from 100 to 150 ka, depending on assumed erosion rates. The boulder samples were somewhat older, probably indicating some inheritance. These ages are consistent with an isotope stage 6 age for the Gale lakestand, but would also be consistent with an isotope stage 5c-5e assignment.

Two tufa samples were collected from the "1900-ft" (580-m) shoreline at Ash Hill in the northern portion of Panamint Valley. One was collected and analyzed in 1988 and the second in 1996, using improved analytical methods. The 1988 sample gave ages ranging from 70 to 80 ka and the 1996 sample from 84 to 100 ka, depending on assumed erosion rate. The reasonably good agreement of the two analyses tends to support the 1980's data from other sites. The ages strongly indicate that the 1,900-ft shoreline is younger than isotope stage 6. The Beatty beach bar may date from the same lake highstand, most likely in the age range of 70 to 80 ka.

All these data support an isotope stage 6 age for the highest reasonably well preserved shorelines in the two valleys (the Blackwelder and Gale shorelines). This agrees well with independent U/Th and sediment-core data (Ku and others, 1998; Lowenstein and others, 1999). However, they also indicate at least one slightly lower pluvial episode close to the isotope stage 4/3 boundary. Such a pluvial episode is not well evidenced in the core data but is supported by one U/Th date of 81.7 ± 1.0 ka (Ku and others, 1998) at 72 m elevation from Badwater, Death Valley. The data also indicate that boulders and cobbles in shoreline cuts are frequently subject to ^{36}Cl inheritance (and possibly erosion) and that the best strategies for cosmogenic dating are either from tufa or from depth profiles.

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Geochemistry of Archeological Obsidian Sources in the Saline Range, Death Valley National Park, California

Lynn Johnson,[1] David L. Wagner,[2] and Craig E. Skinner[3]

[1]Archaeological Research Center, California State University–Sacramento, Sacramento, CA 95819 <ljohnson@cwo.com>

[2]California Division of Mines and Geology, Sacramento, CA 95814 <dwagner@consrv.ca.gov>

[3]Northwest Research Obsidian Studies Laboratory, 1414 NW Polk, Corvallis, OR 97330 <cskinner@obsidianlab.com>

The Saline Range, a remote volcanic tableland located within Death Valley National Park, has recently been reported as a source for archeological obsidian (Johnson and Wagner, 1998). Obsidian-bearing rhyolitic flows and tuffs in the Saline Range were emplaced over preexisting topography and later disrupted by Basin and Range faulting, creating complex outcrop patterns. Furthermore, obsidian nodules have been transported and redeposited more than 20 km from outcrops of the source rocks. In some instances, these deposits contain nodules derived from different stratigraphic units. The geologic complexity of the Saline Range volcanic field presents substantial interpretive problems as discussed by Hughes and Smith (1993), Hughes (1998a), and Shackley (1994, 1998a, 1998b).

Our research in the Saline Range began in 1989. Initial efforts focused on locating and mapping both primary outcrops and secondary deposits in the eastern and western portions of the range, as well as documenting evidence of prehistoric exploitation. In addition, a systematic sampling program was conducted in order to establish a geochemical database for fingerprinting archeological obsidian.

A small population of obsidian nodules sampled from both primary and secondary contexts was analyzed at the University of Missouri Research Reactor Facility (MURR) by Jelmer Eerkens and Michael Glascock. Data from neutron-activation analysis suggested the presence of three geochemically distinct obsidians in the Saline Range. A much larger population was recently analyzed at Northwest Research Obsidian Studies Lab in Corvallis, Oregon. X-ray fluorescence (XRF) data confirm that the Saline Range obsidians can indeed be separated geochemically into three source groups, provisionally named Saline Valley 1, Saline Valley 2, and Saline Valley 3 (fig. 28).

Although Saline Valley has previously been reported as a source for archeological obsidian (Norwood and others, 1980; Delacorte and others, 1995; Burton, 1996a, 1996b; Burton and Farrell, 1996; Reynolds, 1996), the geologic provenance of the obsidian nodules used to characterize the "Saline Valley" glass type and the sample provenance were uncertain. Nodules were likely collected in Saline Valley from alluvial fans emanating from the east side of the Saline Range. The samples analyzed at Northwest Research Obsidian Studies Lab were collected from source-area outcrops in the Saline Range. The trace-element chemistry of the Saline Range samples was compared with data from XRF analysis of artifacts recovered from archeological sites in Owens Valley (Hughes, 1996b, 1998b; Hughes, 1997; Delacorte, 1999; Gilreath and Nelson, 1999) and on Hunter Mountain (Hughes, 1996a). A strong correlation between Saline Valley 3 and the "Saline Valley" glass type and Saline Valley 1 and an unknown glass type dubbed "Queen Imposter" was noted (fig. 29). Although it has yet to be determined, Saline Valley 2 probably correlates with one of the other "unknown" glass types found at archeological sites in the region.

This study underscores the need to conduct a systematic sampling strategy in order to document possible intrasource geochemical variability within a particular "source" area. Continued research on the geochemical variability of obsidians in the Saline Range, as well as on spatial and temporal patterns of exploitation, will aid our understanding of obsidian procurement and use in the southwestern Great Basin.

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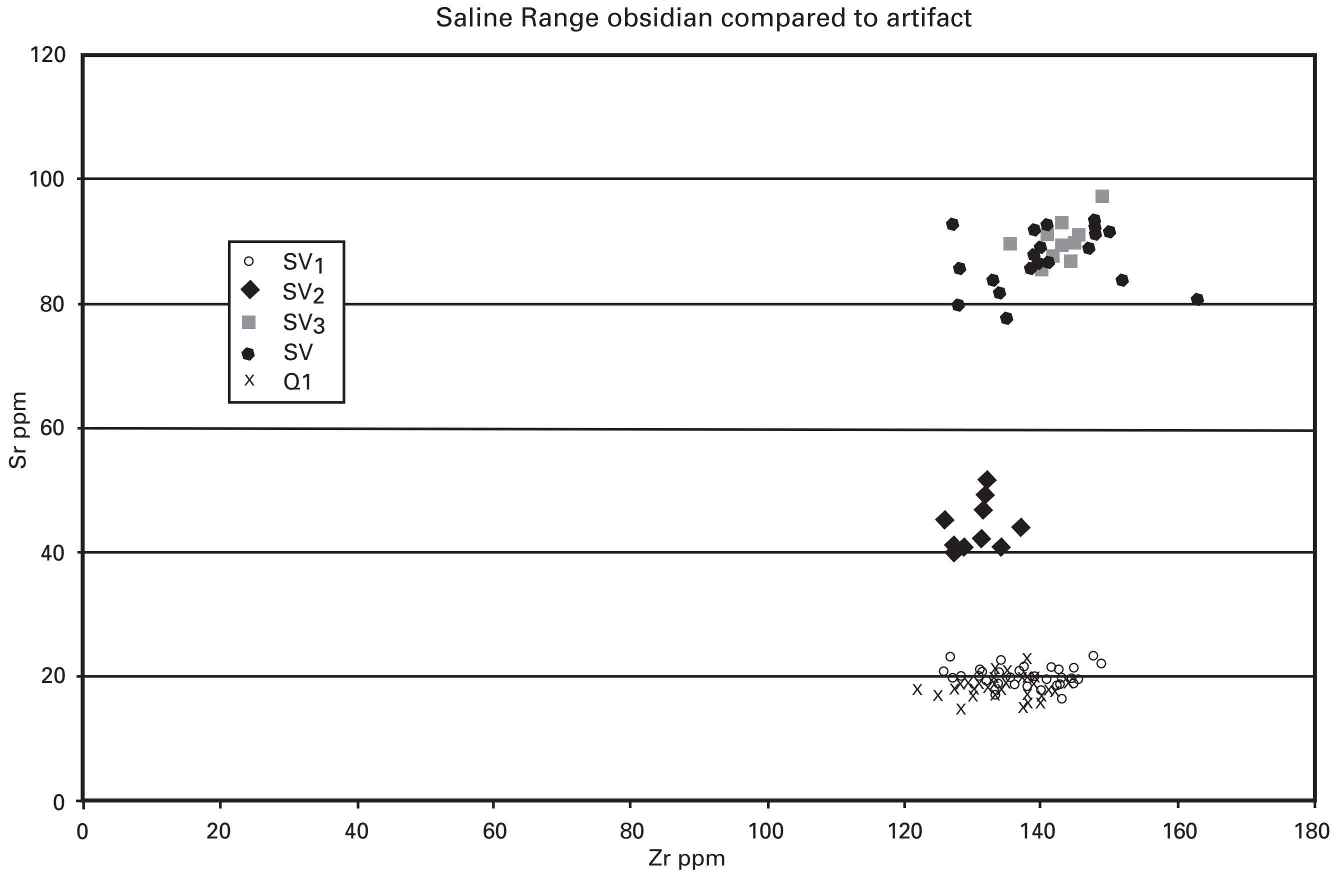

Figure 28. Scatterplot based on XRF data showing Saline Valley glass types.

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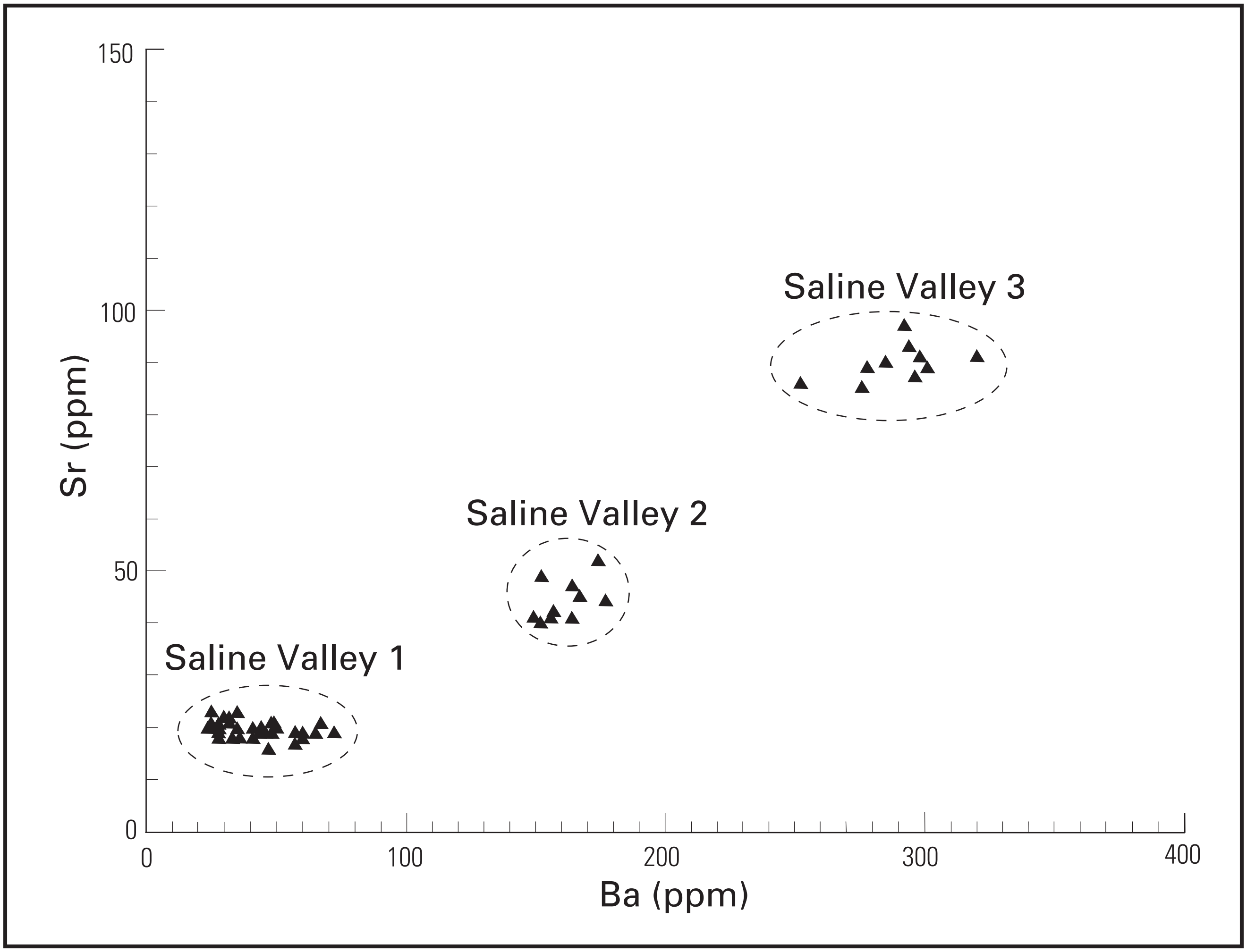

Figure 29. Scatterplot showing correlation of artifacts manufactured from the “Saline Valley” (SV) and “Queen Imposter” (QI) glass types and geologic samples of the Saline Valley 1, 2, and 3 (SV1, SV2, and SV3, respectively) glass types.

PALEOCLIMATE AND ACTIVE TECTONICS

Middle to Late Quaternary Environmental Changes in Death Valley and Vicinity

W. Geoffrey Spaulding, Dames & Moore, 7115 Amigo Street, Suite 110, Las Vegas, NV 89119

Death Valley lies astride the boundary of the central and northern Mojave Desert and, with the trough of the Lower Colorado River, vies for the designation of the most arid region on the North American continent. For this reason alone, climatic changes that led to conditions much moister than the present have been of substantial interest not only to geologists, but also to ecologists seeking to understand the developmental history of the area's biota.

As the ultimate hydrologic sink for the region, this basin—and its lacustrine history—have traditionally been seen as a key to understanding impacts of past climates. Although this work is important, the history of Pluvial Lake Manly has been strongly influenced by runoff from three major river systems, which integrate the climate signal from a vast area, and filter it as well. These rivers are (1) the Amargosa River in the east, the drainage of which extends east and north to the vicinity of the Mojave/Great Basin boundary near Beatty, Nev.; (2) the Mojave River, extending southwest to the San Bernardino Mountains; and (3) the Owens River, which lies north and west and drains an extensive portion of the east flank of the Sierra Nevada. Of these important river systems, two have large basins that intervened to collect waters that otherwise would have flowed directly into Death Valley. China Lake, Searles Lake, and the Panamint Valley lie along the Owens River, and all three would have had to fill prior to the Owens River contributing any water to Death Valley (Smith and Street-Perrott, 1983). Similarly, the vast Manix Basin, the Silver/Soda Lake basins, and the Silurian Basin would have had to fill successively in order for Death Valley to have received runoff from the Mojave River drainage. To this, it is important to add the *caveat* that the Manix Basin was breached ~14,500 yr B.P. (Meek, 1989), and therefore was not an impediment to through-flowing waters during the terminal Wisconsin and early Holocene. Therefore, if one were to seek continuous, sensitive records of pluvial climatic change for this area, the sedimentologic record from Death Valley itself would not necessarily be the best place to look. Accordingly, this paper focuses on data from two other sources that provide detailed records of climatic changes and vegetational responses in the Death Valley region. These are (1) calcite ground-water deposits that provide long-range records of climatic change, and (2) packrat middens that provide records of vegetation during the last half of the last glacial age, and of the current interglacial.

Two principal factors contribute to the aridity of Death Valley in particular, and to the Mojave Desert in general. First, the area lies near the southwestern margin of the continent and, for obscure reasons having to do with global circulation patterns, such areas are usually arid to semiarid (other examples being Chile and western Peru, the southwest edge of Europe, the Namib). Although this circumstance has not changed appreciably during the Cenozoic, the second factor is a relatively new development on the geologic time scale, the final uplift of the Sierra Nevada and the Transverse Ranges. Winograd and others (1985) studied changes in the deuterium content of fluid inclusions in calcite veins dated by uranium-series techniques. These are currently spectacularly exposed by uplift in the Furnace Creek Wash area. Because deuterium is depleted in meteoric water proportionate to the amount of its orographic uplift, progressive deuterium depletion with decreasing age in ground-water-deposited calcite was related to uplift of the Sierra Nevada and Transverse Ranges (the San Gabriel and San Bernardino Mountains; Winograd and others, 1985). A reduction in fluid inclusion δD of 30 to 40‰ between ~1 Ma and the present was attributed to a 600-m uplift of the Sierra Nevada, and a potential uplift of the Transverse Ranges exceeding 1,000 m. Interestingly, veins dated between ~2.6 and 1 Ma show no distinct trends in δD, suggesting that a pronounced episode of mountain uplift may have taken place during the last million years or so, forcing the final transition to the Mojave Desert's late Quaternary climatic regime.

The stable isotopic composition of calcite veins, and the long-term environmental signal that they provide, are now well known from another context near Death Valley. A series of diving expeditions into the regional carbonate aquifer accessed at Devils Hole by the Water Resources Division of the U.S. Geological Survey, with the cooperation of Death Valley National Park, have produced a wealth of information. This research, led by Issac J. Winograd, has greatly increased our knowledge of the effects of glacial climatic changes not only on the Death Valley region, but also on the continents themselves. Cores of vein calcite deposited on the walls of Devils Hole, typified by Core DH-11, are less than 36 cm (14 in.) long, but uranium-series dating demonstrates that they span as much as a half-million years of continuous deposition. In a pioneering paper dealing with a 250,000-yr record, and a subsequent follow-up paper extending the record to more than a half-million years, Winograd and others (1988, 1992) demonstrated that global, glacial-interglacial cycles had profound effect on local climates and hydrology. This was not all, however; their data also challenged the recently established model that glacial-to-interglacial climatic cycles could be explained exclusively by the geometry of the Earth's orbit around the Sun. Using the well-established relationship between the relative abundance of the stable isotope ^{18}O ($\delta^{18}O$) and temperature, Winograd and others (1992) were able to produce a proxy temperature record for the region that spanned the period from about 560 to 60 ka. Differences between the timing of major temperature excursions recorded in Devils Hole and those reflected in the deep-sea records dated by orbital mechanics were the basis of substantial criticism. (See, for example, Imbrie and others, 1993.) However, other evidence from half a world away in New Guinea has demonstrated the Devils Hole record to be accurate (East and others, 1999), and the assumption that orbital mechanics is the sole determinant of global climate change is in need of rethinking. The Devils Hole record demonstrates the existence of at least three periods during the last 500,000 yr when temperatures approximated those of the present, and each lasted for ~20,000 yr (Winograd and others, 1992).

The above observation may strike the astute reader. Three periods over the last 500,000 yr, each no more than about 20,000 yr long, that approximated the temperature regimes of the present? Were the remaining 420,000 yr much different than the present? The answer is "yes." The current environmental conditions of Death Valley, and the Mojave Desert in general, are anomalous when viewed on these time scales. The floristically defined Mojave Desert has existed in its current form for less than 10,000 yr. The evidence for this comes from the second source of data discussed here: ancient packrat (*Neotoma* spp.) middens. (See Betancourt and others, 1990, for a series of papers that discuss packrat middens and the nature of the data that they yield.)

The evidence for vegetation development from packrat middens spans the last ~45,000 yr, and comes not only from Death Valley itself, but also from the Amargosa River basin to the east. These show vegetation conditions that were appreciably different from today's in terms of both composition and elevational zonation. At low elevations within Death Valley itself (~425 to 775 m), Woodcock (1986) recovered full-glacial middens (~19,000 to 17,000 yr B.P.) that record a succulent-rich semidesert where today there is but sparse creosote bush (*Larrea tridentata*) scrub. Along with species that could be expected to be present at low elevations in response to cooler and effectively wetter conditions, such as Joshua tree (*Yucca brevifolia*), there is a definite surprise—the common remains of Whipple yucca (*Y. whipplei*). Today, Whipple yucca is common on the west and east flanks of the Peninsular and Transverse Ranges and, with the exception of a single relictual population in the Lower Grand Canyon, is absent from the Mojave Desert. Juniper (*Juniperus* sp.; perhaps *J. californica* at elevations below 1,000 m and south of lat 36° N., and *J. osteosperma* at higher elevations and to the north) also occurred widely throughout the area (Woodcock, 1986; Spaulding, 1990a).

Just as Death Valley straddles the transition from the winter-warm central Mojave Desert to the colder environments of the northern Mojave Desert, evidence from packrat middens suggests that it spanned an analogous transition during the last glacial age. Packrat middens from the Amargosa Desert as old as those from Death Valley reflect a distinctly colder environment at elevations as low as 930 m on south-facing slopes. As on xeric slopes in Death Valley, juniper was absent, but so were Joshua tree and Whipple yucca. Instead, the dominant shrubs are those of the current dry steppe of south-central Nevada: horsebrush (*Tetradymia* sp.), shadscale (*Atriplex confertifolia*), rubber rabbitbrush (*Chrysothamnus nauseosus*) and Mormon tea (*Ephedra* sp.; Spaulding, 1990b). Thus, spanning less than a degree of latitude and approximately 400 m of elevation, glacial-age vegetation changed from succulent-rich semidesert to xeric steppe.

The climatic changes that accompanied the end of the last glacial age did not describe a simple monotonic trend from "colder and wetter" to "hot and dry," as may be inferred from some references. There were unusual climatic circumstances during deglaciation that are reflected in the packrat midden record. Steppe shrubs disappeared and grasses and succulents (yucca and cacti [particularly *Opuntia* spp.]) became important—so important that the relative abundance of *Opuntia* spines is used by some midden analysts as a field indicator for middens dating from ~12,000 to 9,000 yr B.P. These changes led Spaulding and Graumlich (1985) to postulate that this period was typified by a substantial increase in warm-season precipitation. In this light, note that the stable-carbon isotope record from Devils Hole, while not recording the last glacial/interglacial transition, suggests that prior transitions were typified by maximum regional vegetation cover, relative to both the preceding glacial age and the succeeding interglacial (Coplen and others, 1994).

It must be stressed that nowhere in this region are there glacial-age macrofossil records of the thermophilous shrubs that currently typify the Death Valley ecosystem. Creosote bush was restricted to areas around the Gulf of California and perhaps farther south. Other species typical of the region today, such as burrobush (*Ambrosia dumosa*), desert spruce (*Peucephyllum schottii*), catclaw acacia (*Acacia gregii*) and mesquite (*Prosopis* sp.), were also restricted to southerly latitudes (Van Devender, 1990, among others) by winter temperatures as much as 6°C below those of the present (Spaulding, 1985). Deglacial climatic change led to the northward migration of these species beginning in the waning millennia of the last glacial age (~12,000 to 10,000 yr B.P.), and the staggered arrival times of various thermophilous desert shrubs are of considerable interest. Species such as desert spruce and burrobush arrived first; the earliest record of burrobush is from Death Valley and dates to ~10,200 yr B.P. (Woodcock, 1986), while both burrobush and desert spruce immigrated to the Amargosa Desert by about 8,800 yr B.P. (Spaulding, 1990b). Interestingly, creosote bush was one of the slowest immigrants into the area. Its arrival time is not documented by middens from Death Valley, which are as young as ~9,100 yr B.P. The more detailed Amargosa Desert midden record is also mute; creosote bush arrived after the youngest sample was deposited at ~8,200 yr B.P. To the north, in Eureka Valley, creosote bush did not arrive near its current northern limit until after ~5,400 yr B.P. (Spaulding, 1990a).

The northward migration of creosote bush may have been retarded by hyperarid conditions in many desert valleys during the middle Holocene. We may never know for sure because, in apparent response to enhanced aridity, middens dating to the middle Holocene thermal maximum (~7,500 to 5,000 yr B.P.) are scarce. As discussed by Spaulding (1990a, 1991), enhanced aridity and reduced ecosystem productivity likely led to reduced packrat population densities, and therefore the deposition of few middens during this period. In contrast, the last 5,000 yr, and particularly the period between ~4,000 and 2,500 yr B.P., were characterized by a return to increased effective moisture. It is during this period that the final modernization of ecosystems in the Death Valley region occurred.

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Latest Quaternary (<30 ka) Lake High-Stand Fluctuations and Evolving Paleohydrology of Death Valley

Diana Anderson, Center for Environmental Sciences and Education and the Quaternary Studies Program,
P.O. Box 5694, Northern Arizona University, Flagstaff, AZ 86011 (520) 523-1276 <Diana.Anderson@nau.edu>

INTRODUCTION

During the latest Quaternary, pluvial "Lake Manly" and other lake stands of Death Valley were the end-points for surface waters from at least two rivers emanating from diverse hydrogeologic settings: the Mojave River, flowing through the Mojave Desert with headwaters in the San Bernardino Mountains; and the Amargosa River, draining highlands with elevations up to 2,400 m in the Great Basin Desert. Both river systems flow through areas of regionally low relief, including some of the driest regions of the western U.S. (fig. 30). Latest Pleistocene lake stands in Death Valley potentially received discharge from both these drainages. In addition, lake stands in Death Valley received ground water discharging from a regional carbonate aquifer whose recharge area includes the Spring Mountains (with elevations up to 3,635 m) near Las Vegas, Nev.

Elsewhere in the Mojave Desert and Great Basin, study of such interior continental basin lacustrine sediments and surficial features has led to the reconstruction of paleoenvironmental changes during the late Pleistocene (Mifflin and Wheat, 1979; Smith, 1984, 1991; Smith and Street-Perrott, 1983; Smith, 1978; Benson, 1981; Benson and Paillet, 1989; Benson and others, 1990, 1995; Oviatt, 1990; Oviatt and others, 1990; Winograd and Doty, 1980; Wells and others, 1997). These reconstructions may be used in conjunction with other paleohydrologic indicators, such as oxygen isotopes from vein calcite (Winograd and others, 1985, 1992), to elucidate the hydrologic response to climate change during the latest Quaternary.

As reported in Hunt and Mabey (1966), early studies by Russell (1885, 1889), Gilbert (1890), Bailey (1902), Gale (1914), and Noble (1926) recognized the past existence of a paleo-lake in Death Valley based on surficial features extant in the basin. Means (1932) and Blackwelder (1933, 1954) named the "lake or lakes" that formed the shoreline features "Lake Manly." Blanc and Cleveland (1961) described the cascading sequence of Owens River basins that potentially contributed flow to lakes in Death Valley. Hunt and others (1966), Hunt and Mabey (1966), and Hunt (1975) described lakes and features of the underlying stratigraphy and saltpan, finding evidence for a late Pleistocene lake as well as a Holocene lake. Hooke (1972) recovered several cores from Badwater Basin and described lake sediments ranging from 26 to 10.5 ka based on radiocarbon dating, concluding that the terminal high stand (Blackwelder stand) occurred from 11 to 10 ka. Hooke and Lively (1979) have since revised the Blackwelder stand to apply to an earlier lake phase.

A single, 185-m core recovered from Badwater Basin in Death Valley was the focus of recent study (Lowenstein and others, 1994, 1999; Li and others, 1994, 1996). Based on this well-studied core (DV93-1), Li and others (1996) and Lowenstein and others (1999) have suggested the presence of a perennial saline lake from approximately 35 to 10 ka. These workers have suggested, based on shoreline features and on ostracodes in mud layers interbedded with halite, that salinities and lake depths fluctuated during this interval but the overall climate was relatively wet. Core DV93-1 was dated using U-series ages on halite that were extrapolated by facies-specific sedimentation rates (Ku and others, 1994). Lowenstein and others (1994), Spencer and others (1996), Yang and others (1996), and Roberts and others (1994, 1996) have described an older perennial lake phase, which existed from approximately 186 to 128 ka. The presence of two lakes was further substantiated by Forester and others (1996), who found ostracodes in siliciclastic muds of Core DV93-1 that suggest the existence of wetter climates manifested in deeper lakes from 35 to 10 ka and 186 to 128 ka.

Preliminary field geomorphic assessment of the Wingate Pass area (Wells and Anderson, unpublished), through which the Owens River drainage must flow if it is to reach Death Valley, did not reveal young (<30 ka) fluvial features. The model of surface flow into Death Valley during the past 30 ka, therefore, includes only the Amargosa and Mojave Rivers (fig. 30), in addition to local runoff. Based on stable isotopes and sediment chemistry from the Badwater core, Spencer and others (1996) substantiated this assessment by suggesting that inflow from the west (Owens River via Wingate Pass) was not significant and occurred only briefly prior to desiccation of the 186–128-ka lake. Forester and others (1996) also suggested, based on solute composition and total dissolved solids from ostracode samples, that the 35–10-ka lake probably had an Amargosa River source, whereas the penultimate (186–128 ka) lake may have included Amargosa, Mojave, and (or) Owens River inputs.

CORES DVDP96-10, -9, -6, AND –2

Ten shallow (<30 m) sediment cores were taken from southern Death Valley (Anderson and Wells, 1996, 1997a; 1997b; Anderson, 1998) (table 1). Site selection was based on two criteria: (1) distribution of sites should encompass a range from the basin depocenter to the area of the delta of the Amargosa River as it enters the basin; and (2) locations were allowable by National Park Service Wilderness Area policies and procedures. Cores were acquired using a

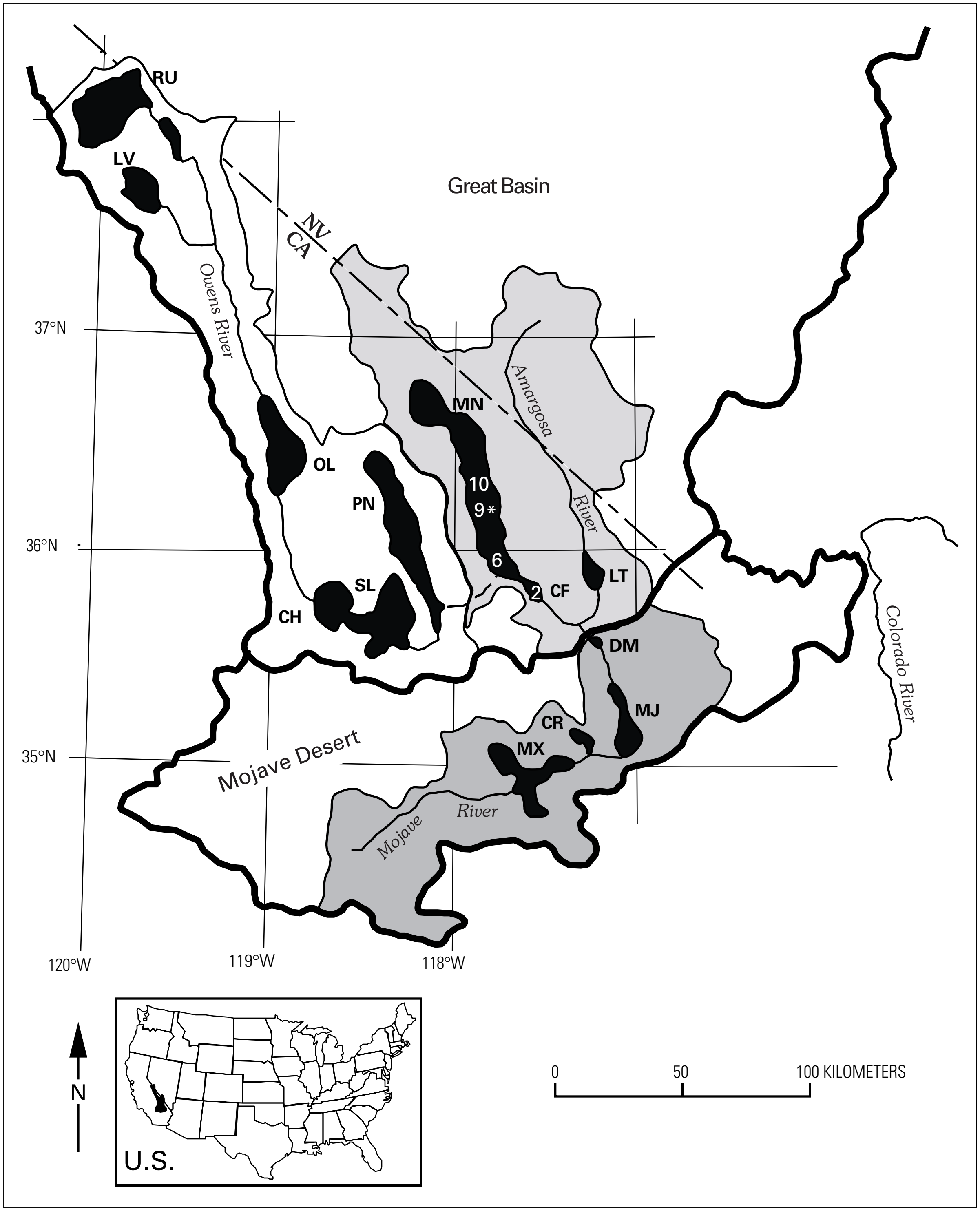

Figure 30. Pluvial lakes in basins of Owens, Mojave, and Amargosa Rivers. RU, Lake Russell; LV, Long Valley; OL, Owens Lake; CH, China Lake; SL, Searles Lake; PN, Panamint Lake; MN, "Lake Manly" (in Death Valley); LT, Lake Tecopa; DM, Lake Dumont; MJ, Lake Mojave; CR, Cronese Lakes; MX, Lake Manix. CF denotes Confidence Flats sub-basin. Figure modified from Morrison (1991). Numbers, approximate locations of core sites DVDP96-10, -9, -6, and -2; asterisk, approximate location of Badwater Basin.

truck-mounted hollow-stem auger; segments were drilled in 5-ft sections, each containing two $2^1/_2$-ft lengths of 4"-diameter acrylic liners. The deepest core was 26.03 m; total core length for all 10 sites was 185.2 m.

Core recovery was good, and the stratigraphy well preserved. Fluvial, alluvial fan, mudflat, saline pan, lacustrine, and soil facies have been identified based on apparent texture, bedding, and Munsell color. Lacustrine sediments were identified according to the following criteria (modified from Smith, 1991, p. 344): (1) sediment hues were green, yellow, or olive brown (Munsell colors 5*GY*, 10*Y*, 5*Y*, or 2.5*Y*); (2) clasts were well sorted and their sizes range from clay to medium sand; (3) bedding was distinct, thin, laminar, or massive; (4) saline layers were absent; and (5) strata were >25 cm thick.

This report focuses on four ^{14}C-dated cores (cores DVDP96-2, -6, -9, and -10) (fig. 30, table 2). A preliminary attempt was made to discriminate the types of organic material used for radiocarbon dating by running two sets of sample splits on the two cores farthest apart—the northernmost core and the southernmost core, DVDP96-10 and DVDP96-2, respectively (fig. 30). For all cores dated, acid pretreatments were done; but for the sample splits, an additional sample was run using an alkali/acid/alkali pretreatment. This was done in an effort to differentiate between humic and fulvic acids and humin compounds as sources for the age determination (Abbott and Stafford, 1996) and for a preliminary assessment of potential contamination by modern material or ancient ground water. The splits from core DVDP96-2 suggest the possibility of slight contamination from older ground water since the acid-pretreatment split of the sample indicates an older relative age compared to the acid/alkali/acid pretreatment split of the sample (R. Hatfield, BETA, personal commun., 1996). The sample splits from core DVDP96-10 show the opposite trend and suggest the possibility of slight contamination from younger material.

The site drilled for core DVDP96-10 is located immediately off Devil's Speedway east of the modern drainage of Salt Creek (fig. 30). The core is 18.74 m long and penetrates sediments from a variety of subenvironments. Two radiocarbon dates were obtained from the core at –86.98 m and –98.20 m below sea level. The upper sample was submitted as a sample split; the sample with an acid pretreatment yielded an age of 12,160 ± 80 yr B.P. (uncalibrated), and the sample with an acid/alkali/acid pretreatment yielded a resultant age of 12,420 ± 60 yr B.P. (uncalibrated). The lower sample had a resultant infinite age of 45,800 ± 1,300 yr B.P. (uncalibrated), which was close to the limit of the ^{14}C-dating technique.

Table 1. GPS-determined locations, elevations, and recovery of cores DVDP96-1 through DVDP96-11.
[Recoveries below 80 percent due to interval sampling (0.6 m preserved per 1.5 m drilled in unconsolidated gravels)]

Core DVDP96-	Access Road	UTM Northing	UTM Easting	Surf. elev. (m)	Core depth (m)	Re-cov-ery (%)	Geomorphic Setting
1	Harry Wade	3958190	542797	10.	8.98	50	fan/terrace
2	Harry Wade	3958138	542739	9.	20.61	60	channel floor
3	Harry Wade	3963256	541911	-1.6	22.04	85	fan
4	Harry Wade	3965354	540749	-2.5	16.54	62	fan
5	West Side	3977435	524152	-61.	19.	84	fan
6	West Side	3978643	522977	-66.5	26.03	92	fan
7	West Side	3986492	516310	-74.	22.04	88	fan
9	West Side	4010770	510703	-76.2	15.05	89	fan
10	Devil's Speedway	4022029	512316	-84.	18.74	92	saltpan
11	Devil's Speedway	4019354	510057	-75.6	16.11	62	fan

Table 2. AMS radiocarbon dates from cores DVDP96-2, 6, 9, and 10 from bulk organic fraction; samples underwent acid wash pretreatments.

[Cores DVDP96-2 and DVDP96-10 include splits using acid/alkali/acid pretreatments (second date listed). Uncalibrated dates <18,000 yr were calibrated using Radiocarbon Calibration Program rev. 3.0.3 (Stuiver and Reimer, 1993)]

Core DVDP96-	Sample Elevation (m)	Uncalib. Ages (yr B.P.)	Laboratory Number	Calibrated Intercept and Range (yr B.P.)
2	-6.78	20,020 ± 80	Beta-97591	
		19,530 ± 80	Beta-97592	
2	-7.90	19,710 ± 70	Beta-93412	
6	-84.05	17,550 ± 80	Beta-97797	20,890 (20,672-21,104)
6	-91.85	26,200 ± 150	Beta-94206	
9	-84.20	9,780 ± 60	Beta-97593	10,980 (10,957-10,998)
9	-86.87	14,450 ± 60	Beta-94205	17,313 (17,207-17,422)
			Beta-97594	14,190 (14,036-14,359)
10	-86.98	12,160 ± 80	Beta-97595	14,291 (14,146-14,453)
		12,420 ± 60		
10	-98.20	45,800 ± 1,300	Beta-93413	

Two lacustrine units were identified, at –100.45 m to –99.63 m below sea level, and –87.20 m to –86.59 m below sea level (fig. 31).

Core DVDP96-9 was extracted at Tule Springs off the West Side Road in Death Valley (fig. 30). The core is 15.05 m long and contains one lacustrine interval at –86.02 m to –83.71 m (fig. 31). Two AMS-radiocarbon ages were acquired from the core: 14,450 ± 60 yr B.P. (uncalibrated) at –86.87 m below sea level, and 9,780 ± 60 yr B.P. (uncalibrated) at –84.20 m below sea level.

Core DVDP96-6 came from 5 km north of Shoreline Butte in southern Death Valley, downstream of Wingate Wash (fig. 30). The core is 26.03 m long and contains several distinct strata that have been identified as lacustrine. Two AMS-radiocarbon ages were acquired from the core: 26,200 ± 150 yr B.P. (uncalibrated) at –91.58 m below sea level, and 17,550 ± 80 yr B.P. (uncalibrated) at –84.05 m below sea level. Four lacustrine intervals were identified at –92.53 m to –92.15 m below sea level, from –85.47 m to –85.22 m below sea level, from –84.32 m to –84.00 m below sea level, and from –78.93 m to –78.47 m below sea level (fig. 31).

Core DVDP96-2 was extracted from the river bed of the Amargosa River where it intersects the Harry Wade Road in southern Death Valley, approximately 9 km southeast of the Confidence Hills (fig. 30). The core is 20.67 m long, extending from the surface at 9 m to –11.6 m below sea level. The sediments are predominantly fluvial sand and gravel with the exception of the interval between –5.8 m and –9.6 m below sea level, which contains light-olive-gray to olive-gray sandy clay to clay (fig. 31). This predominantly clayey unit contains occasional <1-cm-thick

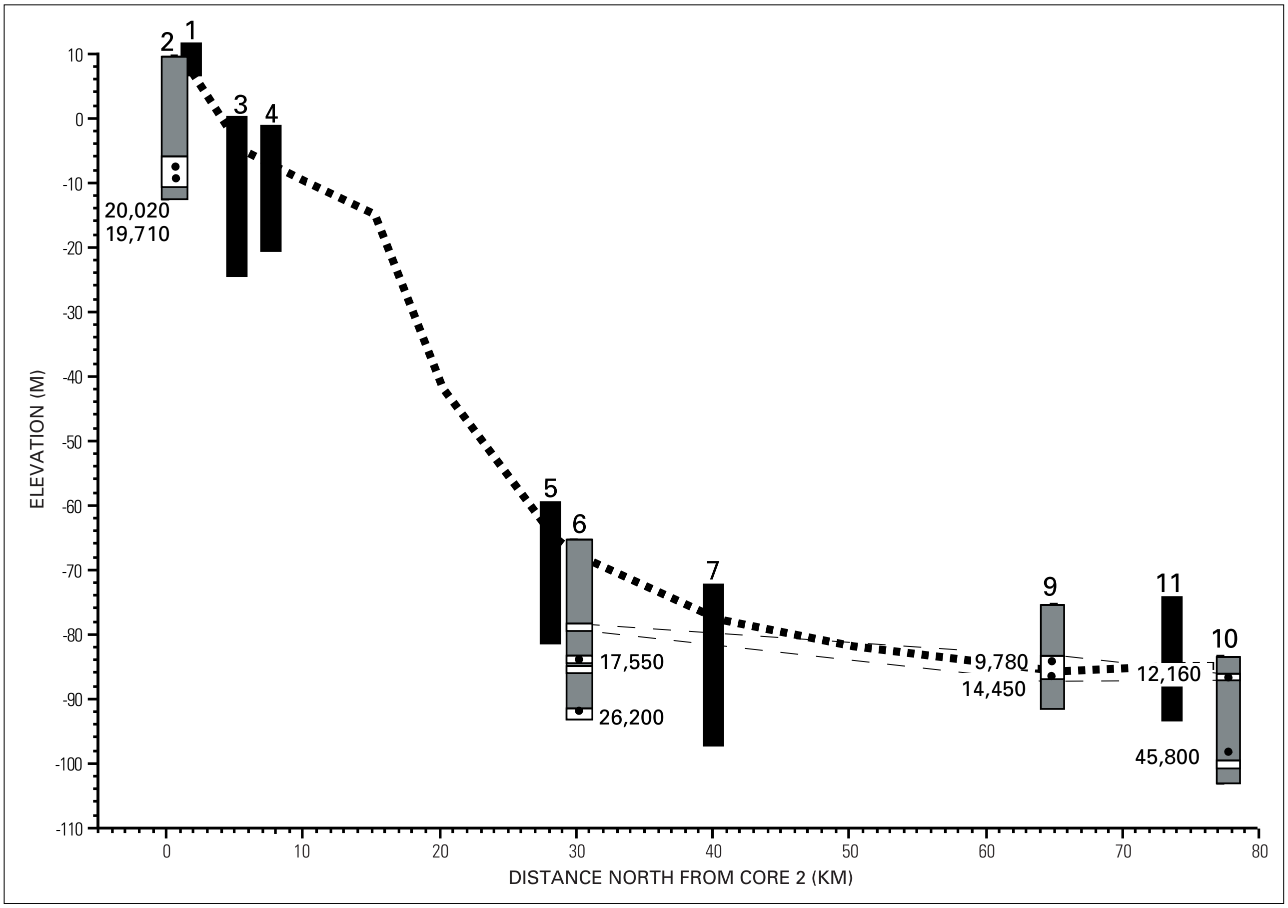

Figure 31. Longitudinal profile of coring sites (see fig. 30 for map locations) showing sediments defined as lacustrine in white with radiocarbon ages noted by large black dots. Thick dotted line, basin floor; note the higher elevation Confidence Flats basin separate from Death Valley basin proper. Dramatic change in gradient between cores DVDP96-4 and -5 occurs near constriction provided by the Confidence Hills and the Rhodes and Jubilee alluvial fans.

brown sandy strata. The clayey strata are thought to represent nonfluvial, subaqueous conditions with sandy strata representing flooding events within the overall lacustrine environment. They date to approximately 19,710 ± 70 yr B.P. (uncalibrated) to 20,020 ± 80 yr B.P. (uncalibrated) (table 2). Core DVDP96-2 (along with cores DVDP96-1, 3, and 4) is considered to be located in a separate sub-basin, “Confidence Flats,” which includes lacustrine sediments ponded behind a constriction created by the Confidence Hills and the Jubilee and Rhodes alluvial fans.

CORE SUMMARY

Sediment character and radiocarbon ages of the four dated cores suggest the presence of more than one lake event between 35 and 10 ka (fig. 32). Sites of cores DVDP96-1 through DVDP96-4 are in the Confidence Flats sub-basin, whereas sites of cores DVDP96-6 through DVDP96-11 are in Death Valley proper (figs. 30 and 31). Sediment analyses of dated DVDP96 cores suggest lake high-stand fluctuations when lake depths and concurrent sedimentation reached higher elevations during the perennial lake phase between 35 and 10 ka. Cores DVDP96-6, 9, and 10 show correlative lacustrine deposits at ~12 ka (uncalibrated radiocarbon years). Older lacustrine strata are found in core DVDP96-10 at ~48 ka, in core DVDP96-2 at 20 ka, and in core DVDP96-6 at ~18 ka and at >26 ka (uncalibrated radiocarbon years). The lack of lacustrine strata dating to ~18 ka in core DVDP96-10 may be attributable to any of the following reasons: (1) lack of good chronologic control in the base of core DVDP96-10; (2) failure to recognize lacustrine strata in core DVDP96-10 based on the established criteria; and (3) reworking of the lower strata by the nearby Salt Creek.

In this study, terminology is used to denote the late Pleistocene high-stand chronology, based on locality and sequence—lake DVLP-1 (Death Valley Late Pleistocene lake high-stand 1), DVLP-2, and DVLP-3 for high-stands at >26,000, ~18,000, and ~12,000 years ago, respectively (fig. 32). This labeling system serves to subdivide the late Pleistocene “perennial saline lake” reported by Li and others (1996) and Lowenstein and others (1999). I recommend the

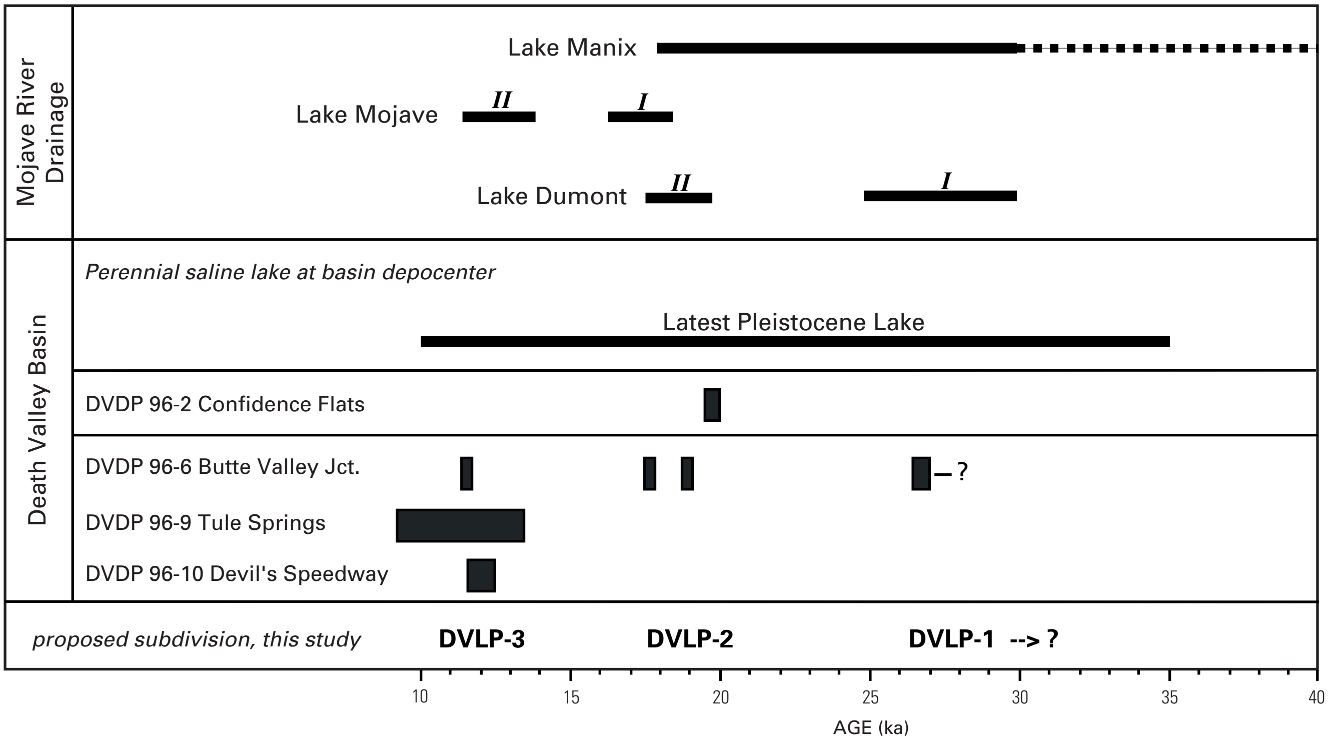

Figure 32. Composite of 10–30-ka lacustrine chronologies for the Mojave River drainage basin lakes Manix (Meek, personal commun. 1996; Dohrenwend and others, 1991), Mojave (Wells and others, 1989; Enzel, 1992; Enzel and others, 1989, 1992), and Dumont (K. Anderson and Wells, 1996, 1997) and the chronologies for Death Valley basin (Hunt and others, 1966; Hunt and Mabey, 1966; Hooke, 1972; Hunt, 1975; Lowenstein and others, 1994; 1999; Li and others, 1996; Anderson, 1998) with proposed subdivisions.

term "Lake Manly," originally used in regard to the shoreline features such as those on Shoreline Butte, and in reference to a lake that received input from the Amargosa, Mojave, and Owens River drainages (Blanc and Cleveland, 1961), be restricted to the middle Pleistocene (186–128 ka) lake as dated by Li and others (1996) and Lowenstein and others (1999).

CORRELATIONS WITH REGIONAL PALEOHYDROLOGIC EVENTS

Lake-filling events in the Lake Mojave basin (the modern Silver Lake Playa) along the Mojave River represent possible overflow events when the Mojave River drainage basin could have contributed significant volumes of water to Death Valley lakes. Studies of Pleistocene Lake Mojave (fig. 30) (Wells and others, 1989; Enzel and others, 1989, 1992; Enzel, 1992) revealed a record of hydrologic responses to climatic events in the Transverse Ranges during the past 20 k.y. The headwaters of the Mojave River, where most of the runoff is generated, is ~200 km from Pleistocene Lake Mojave. Evidence was found for two lake stands during the latest Pleistocene: Lake Mojave I at ~18.4–16.6 ka and Lake Mojave II at ~13.7–11.4 ka (fig. 32). A bedrock spillway at the north end of the lake basin is related to the Lake Mojave II phase, with an elevation of 287.2 m. A second shoreline feature at 285.4 m corresponds to the Lake Mojave I (and Intermittent Lake II) levels (Wells and others, 1989). Water crossing the spillway debouches northward, ultimately into southern Death Valley (fig. 30).

Between the Lake Mojave basin and Death Valley lies Lake Dumont (fig. 30), which contains sediments from at least two lake events during the past 30 ka (Anderson and Wells, 1996, 1997). The two phases of Lake Dumont include Lake Dumont I at ~30–25.3 ka and Lake Dumont II at ~19.4–18 ka (fig. 32). The sill at the north end of the Dumont basin was breached after Lake Dumont II (Anderson and Wells, 1996, 1997).

Death Valley lake high-stand DVLP-1 at >26 ka is contemporaneous with Lake Dumont I in Dumont basin (fig. 32). The lack of evidence of an overflow from the Mojave River system into either Dumont or Death Valley basins suggests that these two basins (Dumont and Death Valley) contained lakes that were maintained by local, interior continental, dominantly low elevation drainages (figs. 30 and 32). The hypsometric curve for the present upper and lower Amargosa River drainage basins, which includes the modern Dumont basin, shows that ~50 percent of the area (~11,313 km^2) is below 1,000 m with

<3 percent of the drainage basin above 2,000 m, where precipitation is greatest.

Death Valley lake high-stand DVLP-2 at ~18 ka correlates regionally with Lake Mojave I and Lake Dumont II, suggesting that at this time exotic waters flowed into Death Valley from precipitation in the headwaters of the Mojave River in the Transverse Ranges (figs. 30 and 32). The Lake Mojave drainage area was approximately 9,500 km^2 (Wells and others, 1989). Death Valley lake high-stand DVLP-3 at ~12 ka correlates regionally with Lake Mojave II (figs. 30 and 32). At this time, Dumont basin had been breached and was a through-flowing basin. Again, based on the presence of an overflowing Lake Mojave II, exotic runoff reached Death Valley.

CONCLUSIONS

Li and others (1996) and Lowenstein and others (1999) have reported the presence of a perennial saline lake at the basin depocenter at Badwater Basin from 35 to 10 ka. The DVDP96 cores, from higher elevations in the basin, show evidence of lake fluctuations within this time interval. Core DVDP96-6 (Butte Valley Junction core), at 26.03 m deep, preserves lacustrine strata from at least three lake events or lake high-stands. These high-stands are variously represented in dated cores DVDP96-2, -9, and -10 and include DVLP-1 at >26 ka, DVLP-2 at ~18 ka, and DVLP-3 at ~12 ka (all uncalibrated ages).

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Tectonic Geomorphology along the Death Valley Fault System—Evidence for Recurrent Late Quaternary Activity in Death Valley National Park

Ralph E. Klinger, Bureau of Reclamation, Geophysics, Paleohydrology, and Seismotectonics Group, M.S. D8330, P.O. Box 25007, Denver, CO 80225 <rklinger@do.usbr.gov>

ABSTRACT

The Death Valley fault system is one of the longest and most active fault systems in the western United States. Discrete faults in the system are in large part responsible for the evolution of the present landscape in Death Valley National Park. Geomorphic evidence of late Quaternary tectonic activity is present along much of the fault system, but its paleoseismic history remains to be fully developed. The geomorphology, however, provides a means in which to evaluate past faulting behavior that can be used to estimate the effects of future large earthquakes. Results of recent geologic studies at various sites along the fault system have increased our understanding of this behavior, but many important questions still remain.

INTRODUCTION

The Death Valley fault system (DVFS) is one of the longest and most continuous fault systems in the western U.S., extending for more than 350 km subparallel to the California-Nevada State line. The DVFS comprises several discrete faults; those that lie within Death Valley National Park include, from north to south, the Furnace Creek fault, the Death Valley fault, and the Southern Death Valley fault (fig. 33). These faults are discriminated from each other primarily on the basis of their strike direction and style of faulting. This pattern of faulting led to the widely accepted interpretation that the central portion of the Death Valley trough is a large pull-apart basin formed by lateral movement on the DVFS (Burchfiel and Stewart, 1966).

The DVFS has had a long history of activity prior to the Quaternary, and the late Quaternary activity may not correspond directly to older parts of the system. Most of what is known about the Quaternary history of the DVFS in Death Valley National Park comes primarily from observations and inferences made by geologists who have mapped the stratigraphy and structure of bedrock in the mountain ranges surrounding Death Valley (for example, Noble and Wright, 1954; Drewes, 1963; Hunt and Mabey, 1966; McKee, 1968; Reynolds, 1969; McAllister, 1970; Streitz and Stinson, 1974, Wright and Troxel, 1993). Examination of the late Quaternary tectonic activity, however, is limited to fewer studies (Moring, 1986; Bryant, 1988; Butler and others, 1988; Wills, 1989; Brogan and others, 1991; Klinger and Piety, 1996). Uncertainties exist regarding the recency of the last event on each of the faults, surface displacement associated with these events, possible segmentation of faults in the system, recurrence intervals between large ground-rupturing earthquakes, and slip rates; certainly each of these parameters could be refined (table 1).

SOUTHERN DEATH VALLEY FAULT

The Southern Death Valley fault, also referred to as the Confidence Hills fault, is a northwest-striking, right-lateral strike-slip fault zone that runs along the axis of southern Death Valley (fig. 33). The fault zone is several kilometers wide, extends southeastward for more than 50 km along the eastern flank of the Owlshead and Avawatz Mountains, and comprises multiple strands of apparently differing histories. In the Confidence Hills, which are bounded by two strands of the Southern Death Valley fault, early Pleistocene strata have been intensely folded and faulted (Wright and Troxel, 1984). In addition, the effects of ongoing late Quaternary tectonism on the Southern Death Valley fault are also recorded by the deformed stream terraces along the Amargosa River (Butler, 1984). Longitudinal profiles indicate that the terrace surfaces merge in a downstream direction, which Butler interpreted as the direct result of recent uplift. Although deformed Pleistocene sediment along the fault in several locations indicates that Quaternary deformation has been ongoing, specific details regarding the late Quaternary tectonic activity of the Southern Death Valley fault remain very limited. Wills (1988) noted evidence for both lateral and vertical displacement along the fault. At one location, a small drainage has 1.2 m of right-lateral offset. At a different location, the recency of movement is estimated from a 1.8-m-high scarp with a 28° maximum slope angle on alluvium. The best constraint on a late Quaternary slip rate is from the northernmost trace of the Southern Death Valley fault at Cinder Hill (fig. 34). Cinder Hill is a basaltic cinder cone that is reported to have erupted about 0.69 Ma and appears to have been offset about 215 m in a right-lateral sense (Troxel and others, 1986). These data yield a slip rate of about 0.3 mm/yr for this site (table 1). Details remain unknown regarding the age of the most recent event, length of rupture, and return period for large ground-rupturing earthquakes for the Southern Death Valley fault.

DEATH VALLEY FAULT

The Death Valley fault is a north-striking, high-angle, down-to-the-west normal dip-slip fault that runs along the

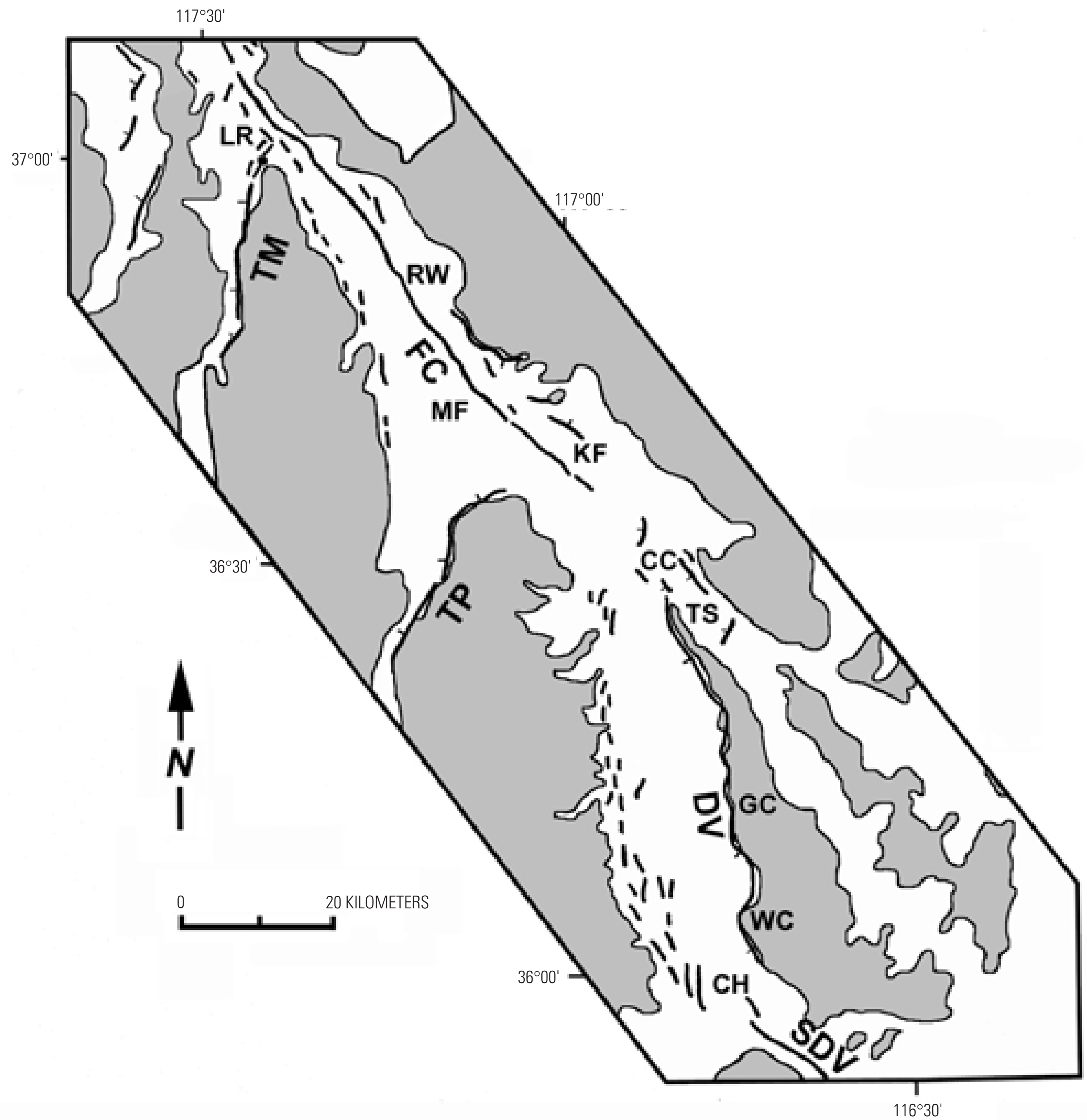

Figure 33. Generalized Quaternary fault map of Death Valley (SDV, Southern Death Valley fault; DV, Death Valley fault; FC, Furnace Creek fault; TP, Towne Pass fault; TM, Tin Mountain fault; CH, Cinder Hill; WC, Willow Creek; GC, Goblet Canyon; TS, Texas Spring syncline; CC, Cow Creek; KF, Kit Fox Hills; MF, Mesquite Flat; RW, Red Wall Canyon; LR, Lake Rogers basin).

western flank of the Black Mountains (fig. 33). The effects of recent tectonism on the landscape in Death Valley have been recognized since the 1920's, when Noble (1926) noted the scarps along the Death Valley fault were "***fresher than any other scarps of similar magnitude in the West." Hunt and Mabey (1966) estimated that the most recent activity along the Death Valley fault was less than about 2,000 yr old. This interpretation was based on observations

Table 1. Characteristics of major faults in the Death Valley Fault System

Fault	Recency	Displacement per event (m)	Rupture length (km)	Recurrence interval (yr)	Slip rate (mm/yr)
Southern Death Valley	Late Holocene?	1.8 (V)[2] 1.2 (L)[3]	>50	?	<<1(?)
Death Valley	<1800? C.E.[1]	2.5 ± 0.5 (V)	45–60	<1,000–>2,000	1.5 ± 1
Furnace Creek	1640–1790 C.E.	3 ± 1 (L)	105 ± 5	700–1,300	5 ± 2

[1]C.E. – Common Era
[2](V) – Vertical displacement
[3](L) – Lateral displacement

Figure 34. Cinder Hill, a basaltic cinder cone astride north end of Southern Death Valley fault, is right laterally offset approximately 215 m.

of relationships of the fault scarps in central Death Valley to late Holocene shorelines and dated archeological sites. Clements (1954), on the basis of early newspaper accounts and other turn-of-the-century written records, had earlier speculated that the young scarps along the fault were the result of the November 4, 1908, magnitude 6.5 earthquake. Stover and Coffman (1993) described this event in detail, but unfortunately the records are inadequate, and the epicenter is imprecisely located; so, the correlation remains speculative. Brogan and others (1991) similarly noted that the evidence for recent faulting was widespread but were unable to resolve the timing of the most recent event. However, based on the pervasive scarps along the length of the fault that offset every unit except the youngest alluvium, they suggested that the most recent event probably occurred in the past 200 years.

Detailed studies at two sites, Goblet Canyon and Willow Creek, were recently undertaken to better characterize the late Quaternary behavior of the Death Valley fault (Knott, 1998; Klinger and Piety, this volume). Hooke (1972) referred to a prominent wineglass canyon about 5.1 km south of Badwater as Goblet Canyon (fig. 33). On the interfluve between Goblet Canyon and the next canyon to the north (Tufa Canyon of Hooke, 1972) is a group of large rock avalanches. Hunt and Mabey (1966) and Hunt (1975) noted that this debris had been displaced about 23 m by the fault. They made no further inferences, however, regarding its relationship to the fault other than that the displacement seemed to be late Pleistocene, based on its relationship to deposits of Lake Manly. Knott (1998) studied the faulted rock avalanche in much greater detail to evaluate the late Quaternary activity rate. He concluded that the rock avalanche had actually been displaced about 28 m, based on a topographic profile surveyed across the faulted avalanche deposits and detailed mapping of the deposits. He also derived a slip rate of 0.9 mm/yr from three cosmogenic exposure ages from head-scarp samples and inferences regarding the stratigraphic relationships between various-age avalanche deposits and the fault.

Willow Creek, which is about 3 km east of Mormon Point, is one of several large streams draining the west flank of the Black Mountains. This area is the focus of the first field trip stop (see this volume). Approximately 300 m north of the mouth of Willow Creek, a 10.5-m-high scarp cuts a Holocene alluvial fan surface estimated to be 4–8 ka (fig. 35). The age of the alluvial fan is based on the degree of soil development, specifically on the soluble salt accumulation relative to dated profiles elsewhere in Death Valley. Evidence for at least the last three and probably the last four events is preserved at this site. These data were used to develop an average displacement per event of 2.5 m, a recurrence interval for large ground-rupturing earthquakes of about 1,000–2,000 yr, and a Holocene slip rate of 1–3 mm/yr (Klinger and Piety, this volume).

TRANSITION ZONE

The apparent junction between the Death Valley and Furnace Creek faults is in the area between the Texas Spring syncline and the south end of the Kit Fox Hills (fig. 33). Klinger and Piety (1996) referred to this area as the transition zone, owing to the lack of a clear through-going fault trace, the diffuse nature of faulting, and the varying orientation and style of deformation within this zone. Clear geomorphic evidence does exist within this zone for late Pleistocene, and perhaps Holocene, deformation associated with ongoing tectonic activity on the Death Valley and Furnace Creek faults. The Texas Spring syncline forms the trough through which Furnace Creek Wash flows to Death Valley. Deformation associated with flexural-slip folding and faulting in the syncline is described in Klinger and Piety (this volume). In addition, work undertaken as part of a seismic-hazard study near the National Park Service (NPS) administrative area at Cow Creek has been recently completed (Machette and others, in press).

Near Salt Springs (about 4 km north of Cow Creek), a 3.0-m-high scarp has formed across a 2,000-yr shoreline identified by Hunt and Mabey (1966). Brogan and others (1991) examined this site in detail because of its association to a relatively well dated feature. The age of the shoreline is based on a correlation by Hunt and Mabey (1966) to lacustrine deposits at a similar elevation that are overlain by dated archeological artifacts. The scarp strikes northeast, but, in part, parallels a drainage channel on an alluvial fan. Displacement appears to be predominantly down to the northwest, and the 3-m-high part of the scarp has a maximum slope angle of 31°. Brogan and others (1991) estimated a late Holocene slip-rate of 1.5 mm/yr, based on the inferred age of the shoreline.

FURNACE CREEK FAULT

The Furnace Creek fault, also commonly referred to as the Northern Death Valley fault, is a northwest-striking, right-lateral strike-slip fault that runs near the axis of northern Death Valley and along the western flank of the Grapevine and Funeral Mountains (fig. 33). The Furnace Creek fault has been recognized as a major Quaternary structural feature since Curry (1938) noted that the geomorphology was indicative of extensive lateral displacement. He suggested that activity was relatively recent based on the presence of "***a churned-up furrow in recent alluvium." Geomorphic features indicative of recent tectonic activity are both abundant and well preserved along the fault. The surface trace is linear and nearly continuous with no evidence of large, lateral steps or bends for more than 100 km north from Beatty Junction.

The surface trace along the south end of the Furnace Creek fault is distinct, accentuated by the uplifted sediment of the Funeral Formation (Wright and Troxel, 1993) that

Figure 35. The 10.5-m-high Willow Creek scarp along the Death Valley fault northeast of Mormon Point (photograph by Lucille Piety).

forms the Kit Fox Hills east of the fault. Strata west of the fault have been folded into the northwest-trending Salt Creek Hills anticline (Hunt and Mabey, 1966). Hunt and Mabey (1966) noted that late Pleistocene stream terraces of Salt Creek had been uplifted 10–25 ft (3.0–7.6 m) on the flank of the anticline. Similarly, late Pleistocene geomorphic surfaces and stream terraces formed in the Kit Fox Hills have been uplifted and warped. Along the fault, however, offset stream channels and related features indicate that deformation from the past several ground-rupturing earthquakes has been nearly pure right lateral (Klinger and Piety, 1996).

At the north end of the Kit Fox Hills, a late Pleistocene Lake Manly shoreline is preserved and extends continuously for more than 7 km along the eastern margin of Mesquite Flat. The elevation of this shoreline increases to the south—from ~37 m near Titus Canyon to ~46 m at the mouth of Mud Canyon. Lacustrine beach ridges are also present at an elevation of about 48 m at the south end of the Kit Fox Hills, just north of Beatty Junction. In addition, Hunt (1975) found lacustrine deposits north of Cow Creek at elevations as high as 60 m. However, due to their position relative to various faults, he suggested that they may have been deposited at lower elevations and uplifted to their present elevations. Whether these deposits are correlative is unclear because the ages of the deposits near Cow Creek and Beatty Junction have not been determined. However, similarities in the degree of soil development and weathering of gravel in the desert pavement overlying the deposits at each of the sites suggest that they may be of similar age. Regardless, given the increasing height of the shoreline in a southerly direction along the eastern margin of Mesquite Flat, it is evident that the southeastern margin of the Mesquite Flat basin has been uplifted relative to the northern part of the basin by about 9 m.

North of the Kit Fox Hills, the trace of the Furnace Creek fault crosses Mesquite Flat (fig. 33). Mesquite Flat is a large structural depression formed north of the intersection of the Furnace Creek fault and the Towne Pass fault, which is a northeast-striking, down-to-the-northwest fault. Displacement on the Towne Pass fault appears to be primarily dip slip, but it may include a significant component of left-lateral slip, due to its oblique orientation relative to the regional stress field. The below-sea-level Mesquite Flat formed the northernmost basin of late Pleistocene Lake Manly. Lacustrine silt, beachshore sand, evaporites, and tufa deposits underlie the floor and the margins of the basin.

Death Valley Wash and some of the larger canyons around the basin shed gravelly alluvium across the basin margin and onto the basin floor. The southern portion of the basin is overlain by a thick blanket of eolian sand (Stovepipe Wells dune field). The northern part of the basin is covered by a thin veneer of eolian sediment, primarily in small coppice dunes formed around mesquite (*Prosopis*) trees. The fault trace is expressed as a linear furrow with low east- and west-facing scarps. The only deposits in the flat that are unfaulted are certainly less than several hundred years old: this estimate of recency is based on the trace of the fault that cuts to within a few centimeters of the ground surface. A 2–3-cm-thick rhyolitic ash bed is interbedded in a dune that is truncated by the fault at a site about midway across the flat. The chemical composition of the volcanic glass from this ash bed is very similar (similarity coefficient of 0.963) to the Mono Craters family of tephra beds. The ash bed in Mesquite Flat is tentatively correlated to the Panum Crater tephra bed (640 ± 40 ^{14}C yr B.P.) of Wood and Brooks (1979), based on its stratigraphic position relative to dated alluvium and the reported areal distribution of the ashes. The tephra bed provides a maximum age for the last ground-rupturing event at this site.

Following the initial observations of Curry (1938), specific details regarding activity on the Furnace Creek fault were not reported again until Reynolds (1969) noted that the margin of a Pleistocene alluvial fan north of Red Wall Canyon was offset about 46 m in a right-lateral sense (fig. 36). Reynolds indicated that activity along the fault was certainly late Holocene, but he interpreted the large displacement of the alluvial fan margin as being middle to late Pleistocene. Bryant (1988) reevaluated the offset fan margin and developed the first published late Quaternary slip rate for the Furnace Creek fault. He acknowledged the 46 m offset, but assumed that the stream incision that produced the alluvial fan margin occurred about 20 ka and that the right-lateral movement that displaced the fan followed this incision. He also emphasized that an unknown amount of erosion had most likely removed part of the fan margin and, therefore, his estimated slip rate of 2.3 mm/yr was a crude minimum estimate. A more recent palinspastic reconstruction of stream channels incised into the alluvial fan indicates that the alluvial fan has been offset between 250 and 330 m in a right-lateral sense (Klinger and Piety, this volume). An age of 35–60 ka was assigned to the alluvial fan on the basis of the degree of soil development, thus yielding a late Pleistocene-Holocene slip rate of 4–9 mm/yr.

In addition to this slip rate for the Furnace Creek fault, a repeatedly offset stream channel provides evidence for the last three events (Klinger and Piety, this volume). A small stream channel has been offset a total of 12.2 m across the fault at a site ~250 m northwest of the alluvial fan margin described by Reynolds (1969). The channel margin on the uphill side of the fault has been progressively offset, and following each faulting event a new channel margin formed, leaving the old margin and bar deposits preserved adjacent to the active channel. Displacement per event ranges from 2.5 to 4.5 m. The timing between this sequence of faulting events is reflected in the successively greater degree of varnish developed on each successively older bar deposit. An age of 2–4 ka is assigned to the oldest channel-margin bar deposit based on the degree of varnish and soil development. This yields a slip rate of about 3–6 mm/yr for the late Holocene, and a recurrence interval for ground-rupturing earthquakes of 700 to 1,300 years at this location.

North of Ubehebe Crater is a structural depression herein referred to as the Lake Rogers basin (fig. 33). The Lake Rogers basin is structurally similar to Mesquite Flat in that it is formed at the intersection of the Furnace Creek fault and the Tin Mountain fault (fig. 33), a northeast-striking, down-to-the-northwest fault. The Tin Mountain fault also appears to be primarily dip slip, but northwest- and southeast-facing scarps suggest a component of left-lateral slip. Along the eastern margin of the basin, the trace of the Furnace Creek fault cuts a series of alluvial fans shed off the western flank of the Grapevine Mountains. The surface trace of the fault is very linear and nearly continuous, is marked by prominent east- and west-facing scarps, and cuts all surficial deposits except active channel alluvium. A thick sequence of interbedded alluvial fan gravel, lacustrine sediment, and tuffs lies along the eastern margin of the basin (Moring, 1986). These deposits have been uplifted and folded into a broad, northwest-plunging anticline. Death Valley Wash and its tributaries have cut across the axis of the anticline and incised the limbs of the anticline, thereby exposing a section of interbedded alluvial fan gravel and lacustrine silt and clay. Near the top of the section, a 25- to 30-cm-thick bed of tephra that correlates with the Bishop Tuff overlies a bouldery basaltic gravel that has been offset 4 km north (right-lateral) from its source. These data yield a late Quaternary slip rate of 5 mm/yr.

At two different locations, the fault has formed shutter ridges that were used by the National Park Service as borrow pits for road construction materials. In each of these pits, extensive deposits of flat-lying air-fall basaltic tephra from Ubehebe Crater have been buried by about 25 cm of sediment ponded behind shutter ridges. Radiocarbon analysis of burned *Atriplex* (charcoal) recovered from a well-sorted sand bed 3 cm below the air-fall tephra in one pit yielded an age of 210 ± 50 ^{14}C yr B.P. (uncalibrated). In the second pit, a thin rhyolitic tephra bed is interbedded with gravelly sand about 25 cm below the Ubehebe Craters tephra bed. The volcanic glass from this tephra bed is also chemically similar to the Mono Craters family and is tentatively correlated to the Panum Craters tephra bed (640 ± 40 ^{14}C yr B.P.) of Wood and Brooks (1979), based on its stratigraphic position reative to the overlying dated alluvium. At one location near the old monument boundary, the Ubehebe Crater tephra still blankets the ground surface. Commonly, the tephra has been washed into the active channels, where it has been

Figure 36. Vertical aerial photograph of an alluvial fan north of Red Wall Canyon. The late Pleistocene fan has been right laterally offset between 250 and 310 m.

concentrated in beds of basaltic sand. The trace of the Furnace Creek fault cuts across the terraces adjacent to drainages on the alluvial fans. The trace of the fault can be seen cutting upward through the terrace deposits exposed in the stream bank, and the Ubehebe Crater tephra fills fissures along the fault. In addition, small drainages and rills along the fault have been right laterally offset by the Furnace Creek fault. In many places, low terraces either blanketed with or formed of basaltic tephra have been laterally offset.

CONCLUSIONS

Clear evidence for the past three late Holocene surface-rupturing earthquakes is well preserved along the Death Valley and Furnace Creek faults. Little is known, however, about the timing of the last event on the Southern Death Valley fault; there may have been at least two Holocene events (Wills, 1988). Along the Black Mountains, the surface trace of the Death Valley fault is nearly continuous for at least 45 km south of Furnace Creek Wash, but it may extend as far as 60 km. Average vertical displacement per event is estimated to be in the range of 2.5 ± 0.5 m based on measured vertical separations along the length of the fault and preserved scarp free faces at Willow Creek (table 1). The preserved scarp free faces near Willow Creek also support a youthful age for the most recent event, but scarp degradation may be inhibited by the hyperarid environment and cementation of the scarp by soluble salts. A more precise constraint on the timing of the last surface-rupturing earthquake remains to be determined. Based on three independent studies (Brogan and others, 1991; Knott, 1998; and Klinger and Piety, this volume), the best estimate of the latest Quaternary slip rate on the Death Valley fault is 1.5 ± 0.5 mm/yr. The recurrence interval between ground-rupturing earthquakes on the Death Valley fault ranges from <1,000 to >2,000 yr, also reflecting the uncertainty associated with dates.

The surface trace of the Furnace Creek fault is nearly continuous, extending north from Beatty Junction for 105 km. Activity on the Furnace Creek fault in this part of Death Valley seems to be related structurally to the Towne Pass fault on the south and the Tin Mountain fault on the north. Average lateral offset per event is estimated to be about 3 ± 1 m on the basis of measured right-lateral offset. This value is poorly constrained due to the poor preservation of offset piercing points, a common problem along strike-slip faults. The timing of the last ground-rupturing event along the Furnace Creek fault occurred sometime after 1640 and before 1790 C.E., as constrained by the tephra of Ubehebe Crater. At several locations, beds containing the Ubehebe Crater tephra have been offset by and incorporated into the fault. Based on data from three different sites, the slip rate along the Furnace Creek fault during the past several thousand years (latest Holocene) is 3–6 mm/yr, since the late Pleistocene is 4–9 mm/yr, and for the latter half of the Quaternary is 5 mm/yr. The recurrence interval between large ground-rupturing earthquakes derived from these data is about 700 to 1,300 years.

ACKNOWLEDGMENTS

Much of my work in Death Valley was supported by the Nevada Operations Office of the U.S. Department of Energy in cooperation with the U.S. Geological Survey under Interagency Agreement DE-AI08-92NV10874. Additional support was provided by the U.S. Bureau of Reclamation. I thank Larry Anderson, Peter Birkeland, Jeff Knott, Ed Larson, Silvio Pezzopane, Lucy Piety, Andrei Sarna-Wojcicki, and John Whitney for everything from time in the field and sample analyses, to discussions and reviews. Some of this work summarizes part of my current Ph. D. dissertation at the University of Colorado–Boulder.

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Lake Manly(?) Shorelines in the Eastern Mojave Desert, California

Roger LeB. Hooke <rhooke@maroon.tc.umn.edu>,
Department of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55455

Near Mesquite Spring, on the south edge of the Soda Lake basin in the Mojave Desert, shorelines of an ancient lake are at an elevation of 340 m above sea level (fig. 37*A*). At present, Soda Lake would overflow at 280 m; a lake surface at 340 m would extend about 240 km northward, to the north end of Death Valley.

Shorelines and lacustrine deposits near Salt Spring and the Saddle Peak Hills, 75 km north of Mesquite Spring, are at about 180 m (fig. 37*A*); a lake surface at this elevation today would also extend to the north end of Death Valley.

The most prominent shoreline of the deep pluvial lake that occupied Death Valley during the Pleistocene, Lake Manly, is that of the Blackwelder stand, which ended about 120,000 years ago. This shoreline is best developed on Shoreline Butte (fig. 37*A*) and at Mormon Point, where it is about 90 m above sea level.

The Mesquite Spring and Salt Spring Hills shorelines were probably formed during the Blackwelder stand and subsequently tectonically displaced with respect to one another, due to transpression in the northeastern Mojave Desert and NW-SE extension across Death Valley. This tectonic model would result in subsidence of Death Valley and the Salt Spring Hills relative to Mesquite Spring. A tectonic reconstruction (fig. 37*B*) suggests that the topography at the time of the Blackwelder stand would have had sills near the level of the highest lake, and also about 20 m lower, which corresponds to the next most prominent shoreline in Death Valley. Expansion of the lake over these sills would have increased evaporation, thus possibly controlling the maximum lake level. The rate of vertical displacement of the Mesquite Hills relative to Shoreline Butte required by this hypothesis is about 2 mm/yr (fig. 37*C*), which is not unreasonable considering known slip rates on nearby faults.

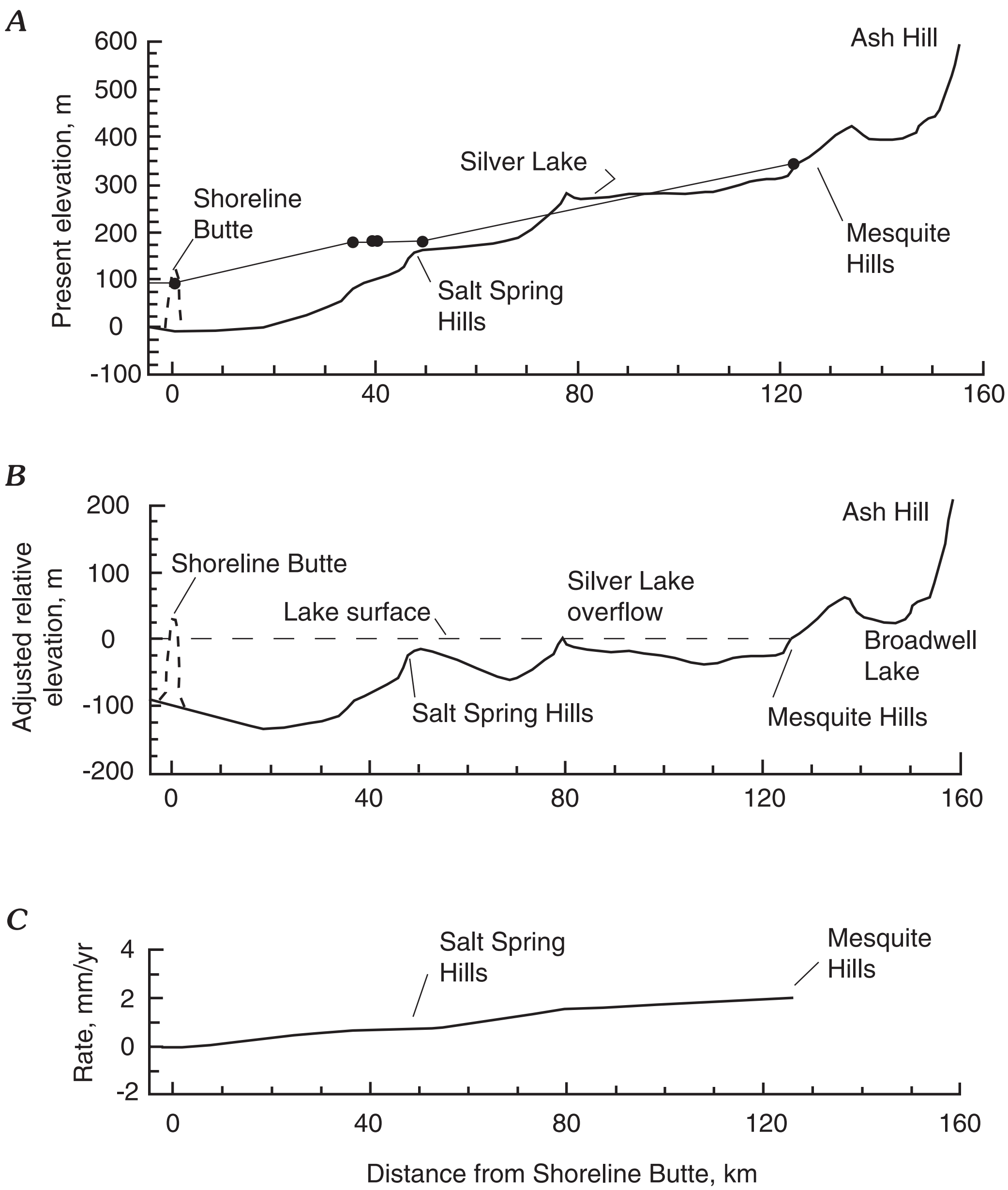

Figure 37. *A*, Topographic profile from Shoreline Butte to Ash Hill. Upper line connects sites of known and suspected shorelines of Blackwelder stand of Lake Manly (denoted by •). *B*, Topographic profile in *A* adjusted for inferred tectonic deformation since the end of Blackwelder stand. Adjustment is linear with distance, and reduces the lacustrine features between Saddle Peak and Salt Spring Hills, those at Mesquite Spring, and Silver Lake overflow to a common elevation, arbitrarily chosen to be 90 m. *C*, Relative rate of vertical displacement required to yield present topography from that shown in *B*.

200-k.y. Paleoclimate Record from Core DV 93-1, Badwater Basin, Death Valley, California

Tim Lowenstein <lowenst@binghamton.edu>, Department of Geological Sciences,
State University of New York–Binghamton, Binghamton, NY 13902

Core DV93-1, drilled in 1993, 3.2 km northwest of Badwater Springs, comprises interbedded muds and salts. The core contains a 186-m-long, 200-k.y. history of paleoclimate, interpreted on the basis of sedimentology, ostracodes, halite fluid-inclusion homogenization temperatures, saline mineralogy, and correlation with shoreline tufa. The 200-k.y. paleoclimate record is marked by two dry and (or) warm and wet/cold cycles that occurred on a 100-k.y. time scale. Of note are two major lake phases, 10–35 ka and 120–186 ka (oxygen isotope stages 2 and 5e-6, respectively), which record colder and wetter climates than modern Death Valley. Of the two lake periods, the penultimate glacial lakes were deeper and longer lived than those of the last glacial.

Ku and others (1998) dated Core DV93-1 using the U-series method (total dissolution isochron technique), which determines the time uranium was incorporated into a sample. Samples from 12 stratigraphic intervals were measured by counting, using alpha-particle spectrometry. All dates not obtained directly from the U-series method were interpolated, assuming constant accumulation rates for each sediment interval. Sedimentation rates for the entire core are 1 m/k.y. Salts were deposited rapidly, 1.7–3.8 m/k.y., whereas muds accumulated more slowly, 0.4–1.0 m/k.y. Carbonate tufas from the east side of Death Valley were dissolved, and ^{238}U, ^{234}U, ^{232}Th, and ^{230}Th were counted by alpha-particle spectrometry.

Paleoenvironments in Death Valley were interpreted by comparing sedimentary features described from modern closed basins with those in core DV93-1 (Roberts and others, 1994; Li and others, 1996). Core DV93-1 contains a record of ancient environments ranging from hot dry mudflats, similar to modern Death Valley, to temperate-climate deep perennial lakes. Disrupted brown muds overlain by a 0.25-m surface halite crust (in the interval 0–7.7 m) indicate that Death Valley has been a mudflat and saline pan for the past 10 ka. A perennial lake existed in Death Valley for a ~25 k.y. period, from 35 to 10 ka (core depths of 7.7–18 m). Interbedded mud and halite accumulated during the early lake stage, followed by interlayered thenardite (Na_2SO_4) and mud, and finally, a cap of chevron halite. These deposits record a relatively wet climate, with fluctuating lake levels and salinities. Mud layers are structureless with rare ostracodes; halite textures include cumulate settle-out layers and bottom-grown crusts. The thenardite is ~16–22 ka, coincident with the last glacial maximum, which suggests that Na_2SO_4 crystallized as mirabilite during winters, at temperatures probably below ~10°C. Saline pan evaporites (18–60 m) indicate that Death Valley was normally desiccated between ~35 and 60 ka, but received enough inflow water to maintain shallow saline lakes at times and supply the solutes required to accumulate salts rapidly. Saline pan halites contain a distinctive vertical pipework fabric, which signifies many episodes of subaerial exposure, dissolution of halite by dilute floodwaters, and cementation. Clayey silts, some massive and some mudcracked with sand-patch textures, indicate dry mudflats were the dominant environment from 60.5 to 109 m (60–120 ka) (Roberts and others, 1994; Li and others, 1996). Sand patches are wind-blown or water-deposited sediments that fill surface depressions in salt crusts. Later flooding dissolved the salt crusts, which caused collapse of the overlying sediments, and produced fractures, faulting, and rotation of sand patches. Dark lacustrine muds (127–161 m) overlain by saline lake halites interlayered with muds (109–127 m) form a thick sequence of perennial lake sediments deposited for 65 k.y., between 120 and 186 ka (Roberts and others, 1994, 1997). Halite layers at 152 m (166 ka) and 137.5–139.5 m (146 ka) indicate high salinities and shallower waters for those intervals. Perennial lake halites are commonly sorted cumulates formed at the brine surface as rafts, skeletal crystals, and cubes (Roberts and others, 1994, 1997). The upper 18 m of the lake succession (109–127 m) consists of subaqueous halite and mud that record two shallowing events between 120 and 128 ka, and desiccation at 120 ka. The bottom 25 m of the core, 186–192 ka (161–186 m) is layered halite and mud, formed in saline pans and shallow saline lakes. Halite layers contain some chevrons and cumulate layers (Roberts and Spencer, 1995). Vertical pipework fabrics indicate exposure of salt layers to dilute floodwaters above the water table. The lowest meter of the core is mudcracked silty mud, interpreted as a mudflat deposit.

Ostracodes from core DV93-1 provide information on the lower limits of water salinities of the two long-lived perennial lakes in Death Valley during the last glacial, 10–35 ka, and the penultimate glacial, 120–186 ka. Perennial lake muds contain ostracode species *Limnocythere staplini, Limnocythere sappaensis, Limnocythere ceriotuberosa,* and *Candona caudata*. Although not abundant, these ostracode species indicate that the salinity of the Death Valley lakes in which they lived was typically below 10,000 ppm, and at times, less than 3,000 ppm for the salinity-sensitive species *C. caudata*.

The paleotemperature component of the climate record was obtained from homogenization temperatures of fluid inclusions in halites, which record brine temperatures during salt precipitation (Roberts and Spencer, 1995; Roberts and others, 1997; Lowenstein and others, 1998). Shallow saline-lake temperatures, in turn, correlate closely with air temperatures in modern settings. Crystals of lacustrine halite (cumulates, chevrons, bottom-grown crusts) with initially one-phase liquid inclusions were chilled in a freezer in order to nucleate vapor bubbles. These crystals, now with abundant two-phase liquid-vapor inclusions, were heated to the temperature at which the vapor phase disappeared and the fluid inclusions "homogenized" back to one-liquid phase. Homogenization temperatures record the original brine temperatures at which crystals grew in the saline lakes. We use maximum homogenization temperatures of fluid inclusions in halite, (T_{hMAX}), as a record of maximum brine temperature and maximum air temperature during halite crystallization. Halites in 66 stratigraphic intervals of core DV93-1, from depths of 0 to 183.5 m (0–192 ka) commonly have fluid-inclusion homogenization temperatures below the modern T_{hMAX} of 34°C (maximum brine and air temperature during halite precipitation, late April and early May 1993). Halites from the last glacial period, 10-35 ka, have low T_{hMAX} (19°–30°C), which suggests brine temperatures 4°–15°C below modern, late April-May values. Lacustrine halites from 35–60 ka have T_{hMAX} between 23° and 28°C, 6°–11°C below the modern T_{hMAX} values. Relatively higher T_{hMAX} values—34°C and 35°C in ~100-ka halite and 32°C in 120-ka halite—may record climate regimes more similar to the modern. These temperatures, however, are still below modern mid-summer temperatures in Death Valley. (Average air temperatures in Death Valley are 39°C in July and 37°C in August; average maximum air temperatures are 46°C in July and 45°C in August.) Generally colder conditions are recorded in most fluid inclusions for the 120-186 ka perennial lake sequence, where T_{hMAX} values range from 25° to 32°C, but only 3 of 22 stratigraphic intervals have T_{hMAX}>30°C (Roberts and others, 1997). A combination of fluid-inclusion homogenization temperatures and crystal pseudomorphs of hydrohalite ($NaCl \cdot 2H_2O$) suggest that lake temperatures may have dropped below 0°C at times and that temperatures during this period probably averaged 10°–15°C below modern (Roberts and others, 1997). In the bottom 25 m of the core (164–184 m, 186–192 ka), homogenization temperatures are relatively high. Of 19 stratigraphic intervals analyzed, 14 have T_{hMAX} values greater than or equal to 30°C, which is similar to those obtained from halite precipitated in Death Valley in late April and early May.

Sulfate and carbonate minerals in core DV93-1 provide information on Pleistocene water sources and climate (Li and others, 1997). Abundant glauberite and gypsum and relatively small amounts of calcite (13–35 percent of the >1-μm insoluble fraction) are associated with dry periods (mudflat deposits 0–10 ka and 60–120 ka, and saline pan sediments 186–192 ka). In contrast, scarce $CaSO_4$-bearing minerals but relatively abundant calcite (20–50 percent) are associated with halite and mud layers from wetter periods (10–60 ka; 120–186 ka). Different mixing ratios of inflow waters between wet and dry periods may be responsible for the relationship between saline minerals and climate. The current dry period of modern Death Valley is characterized by $Na\text{-}Cl\text{-}SO_4$ brines, produced by mixing two basic inflow waters: (1) $Na\text{-}HCO_3$-rich and $Na\text{-}Cl\text{-}SO_4\text{-}HCO_3$-rich meteoric water from the Amargosa River, springs, and ground water from northern and central Death Valley; and (2) Na-Ca-Cl-rich springs and ground water from southern Death Valley, possibly related to volcanism, hydrothermal activity, and a 15-km-deep magma body. During dry periods, relatively abundant Ca-rich spring inflow removes HCO_3 as calcite during early brine evolution. Further evaporative concentration produces gypsum and glauberite from the remaining Ca. During wetter periods, increased discharge of meteoric HCO_3-rich Amargosa River water and basin-margin springs removes most Ca from the brine via precipitation of calcite; then $CaSO_4$-minerals are not abundantly formed during evaporation because of the low Ca concentrations. Such Ca-poor, $Na\text{-}Cl\text{-}SO_4$-rich brines precipitate thenardite (Na_2SO_4) during later stages of brine evolution.

Shoreline carbonate tufas constrain the depths of Pleistocene lakes in Death Valley. Tufas, most prominent ~90 m above sea level, form horizontal terraces encrusting bedrock and gravel on the east side of Death Valley, including Badwater, Goblet, Westilt, and Mormon Point (Hooke, 1972; Ku and others, 1998). Relatively fresh tufas are porous and fine grained with massive or radiating fabrics. Electron-microprobe elemental mapping for Mg and Sr shows zonation of these elements coincident with textural and mineralogical (calcite and minor aragonite) zones in the tufas, which confirms their unrecrystallized origin. Eleven samples of tufa from the 90-m shoreline were dated. Of the 11 samples, 7 are 150–185 ka, which match results (120–200 ka) obtained by Hooke and Lively (1979) and Hooke and Dorn (1992). These tufas indicate lake depths of as much as 335 m, ignoring faulting, and adding 130–160 m of basinal sediments to reach equivalent-age lacustrine sediments in core DV93-1. Four shoreline tufas, 73–90 m above sea level (194–216 ka) are older than sediments from core DV93-1. These oldest tufas suggest a third paleolake in Death Valley ~200 ka, consistent with earlier dating.

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Using Event-Based Simulation of Water Budgets to Study the Hydroclimatology of Lakes in Death Valley, California

Larry Mayer, Department of Geology, Miami University, Oxford, OH 45056 <mayerL@muohio.edu>

Death Valley was the site of large perennial lakes during the Quaternary (Hunt, 1966, 1975; Li and others, 1996; Li and others, 1997), but historically, only ephemeral lakes have occupied the basin. Historical lakes developed largely in response to storm runoff; none of these recent lakes, however, formed under the hydroclimatic conditions required for a perennial state. Thus, conditions required to maintain a lake in Death Valley are of considerable interest. In a recent study that focused on the hydrology of the 1969 winter lake in Death Valley, Grasso (1995) began to explore the climatic conditions responsible for perennial lakes. The water budget required to sustain perennial lakes (Hunt, 1966) would suggest a doubling of water input and a 50 percent decrease in lake evaporation over a 12-year period of time (Grasso, 1995). How the source of precipitation, its delivery, cadence with respect to seasons, and how the interplay with potentially related changes in temperature regime directly modulates the hydroclimatology of the region remains obscure (Brakenridge, 1978).

In order to evaluate the importance of particular climatic conditions and weather patterns on the hydroclimatology of Death Valley, a finite-difference model was constructed that uses recorded climate data as the basis for creating climatic scenarios. The simulation model consists of three modules: precipitation, flood routing, and evaporation (fig. 38). The simulation method uses a model increment (dt) that corresponds to 1 day. All water-budget calculations are done on a daily basis thus eliminating the large integration errors associated with annually based calculations. The precipitation module simulates daily precipitation according to seasonal and clustering conditions, and can be varied statistically within a year or modulated by cyclic functions to simulate periodic climatic functions. Storm precipitation can be applied in highly intense mode (that is, 20 cm) over a 24-hour period, or it may be distributed more evenly over a month. A randomizer function allows the model to vary the amount and delivery of precipitation around a mean value, according to a nested Poisson distribution or other parametric distributions.

The flood routing module, which is designed to permit addition of estimated hydrograph functions from the contributing watersheds, partitions the total precipitation into runoff and losses, according to the runoff estimates made by Grasso (1995) for the 1969 flood. The runoff percentage estimates

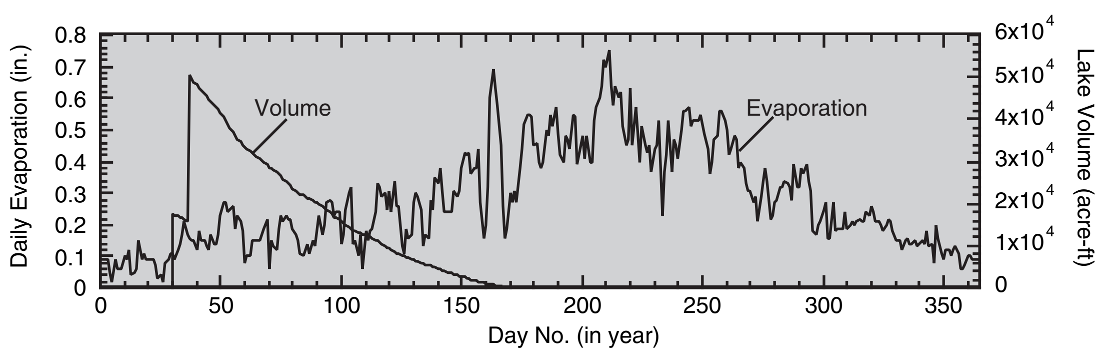

Figure 38. Sample-model run for Death Valley, showing temperature-derived evaporation potential and lake volume for a 1-year simulation using historical temperature extremes. In the model run, several February storms result in a 50,000 acre-ft lake which then begins to evaporate. Before the end of May, the lake has completely evaporated.

are not affected by storm size but can be modified to include the effects of antecedent conditions, for example, increased runoff caused by a second storm following closely after the first. Water is routed into the lake, where it is subject to evaporation and loss.

Evaporation potential is modeled by estimating daily water-vapor pressure differences using the maximum and minimum daily temperatures. This method produces annual estimates on the order of 200 cm, consistent with average temperature conditions. The calculation method permits one to examine the affects of temperature modulation on the rate of evaporation. This is an important factor in the lake budget, because historical pan-evaporation data for Death Valley suggest that evaporation, even in July, can decrease by 300 percent from its maximum amount. In addition, the rates of pan evaporation have been decreasing for the past half-century over the western United States, a direct result of a decrease in diurnal temperature differences (Karl and others, 1993). The actual lake evaporation must be applied to the surface area of the lake, which in turn is a function of the topographic basin it occupies. A crude hypsometric function, which describes lake area as a function of lake volume, was derived from digital topography using ArcView grid functions.

The climatic conditions that are required to sustain a perennial lake may also be represented by combinations of conditions in the historical climate record. Large variation in evaporation and increased precipitation from winter storms and East Pacific tropical storms are all represented in the historical record. Simulation provides a way to make the linkage between regional hydroclimatic conditions and actual local weather events and conditions, and to subsequently evaluate the importance of these factors on the water budget of Death Valley lakes.

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Eolian Processes and Deposits in the Southwestern U.S.—Integrated Studies to Evaluate Impacts from Climatic Variability and Land Use

U.S. Geological Survey[1] and Desert Research Institute[2]

[1] Rich Reynolds <rreynolds@usgs.gov>, Marith Reheis, Gary Clow, Rich Tigges, Todd Hinkley, Dan Muhs, Nilah Mazza, Randy Schumann, Paul Lamothe, Greg Meeker (Box 25046, Denver Federal Center, M.S. 980, Denver, CO 80225); Pat Chavez <pchavez@usgs.gov>, Dave MacKinnon <dmackinn@flagmail.wr.usgs.gov>, Miguel Velasco, Stuart Sides, Deborah Soltesz (2255 N. Gemini Dr., Flagstaff, AZ 86001); Jayne Belnap <jayne_belnap@usgs.gov> and Sue Phillips (2282 S. Resource Blvd., Moab, UT 84534)

[2] Nick Lancaster <nick@dri.edu>; (DRI, 2215 Raggio Parkway, Reno, NV 89512)

Major objectives of global change studies in the USGS are to understand how climatic change and variability affect surficial geologic processes, as well as to assess future regional impacts through climate modeling. Integrated studies are being applied to understand responses of eolian processes to climatic and land-use change in the southwestern U.S., with emphasis on the Mojave Desert. Goals include (1) assess wind-erosion vulnerability and surface stability to assist land-management decisions; (2) evaluate the influence of dust emission and deposition on desert ecosystems; (3) investigate natural and human impacts on eolian processes of arid lands; and (4) model future regional climate of the Southwest and eolian process response using likely climate scenarios. Our activities and findings commonly apply to one or more of the goals.

Wind erosion at specific sites is investigated both with wind-tunnel experiments and with meteorological stations capable of measuring sand transport. The wind-tunnel experiments are employed to determine the effects of disturbance and recovery histories on wind-erosion vulnerability, and to evaluate the roles of different desert surfaces (natural pavement, biologic soil crust, among others) in providing soil-surface stability. At the abandoned Greenwater townsite (Death Valley National Park), threshold friction velocities (TFV; a function of wind speed that moves particles along the surface) indicate that modern footprint and tire-track disturbances decrease soil stability. Studies elsewhere in the Mojave Desert (near Valjean, Calif. (see Miller and Yount, this volume), and at Joshua Tree, Calif.) also quantitatively document that increasing disturbance results in (1) lower TFV and (2) greater wind erosion (higher sediment production), for wind velocities that exceed the TFV.

Wind erosion is monitored at ecologically sensitive sites, using meteorological stations that measure precipitation, wind speed and direction, soil moisture, temperature, incoming solar and outgoing infrared radiation, and sand flux at various elevations in the saltation layer. Currently, six stations operate in the Southwest, with plans to install more in the Mojave Desert.

Several approaches are taken to monitor and characterize modern eolian dust—its sources, flux, and composition—to document potential aridification and wind erosion, as well as to understand soil destruction and formation. New remote-sensing methods have been developed to determine the location, frequency, magnitude, and duration of dust-emission events. Remote-sensing images of vegetation change, combined with those that illustrate high soil reflectivity, complement dust-detection methods to identify areas especially susceptible to wind erosion.

Dust trapped in collectors and snow is being characterized for its physical and chemical properties. Annual collection and analysis from passive-type pan samplers at numerous sites in southern Nevada and California since 1984, combined with soil and weather data, shed light on (1) the genesis of soils in or downwind from arid environments; (2) the relation between dust storms and climate, such as the finding that high dust flux follows periods of high precipitation, because floods deposit fine-grained sediment susceptible to deflation; (3) natural dust sources, such as along a Death Valley transect showing that the modern playa contributes salt- and carbonate-rich dust, but the wide plain of the Amargosa is a more important source of silt and clay; (4) Owens (dry) Lake as a source for a significant part of deposited dust as much as 400 km downwind; and (5) human disturbances in the desert, revealed by signatures of agricultural and construction dust.

Dust trapped both in snow at high elevations and on passive, air-foil collectors is analyzed in minute quantities by microbeam methods and ICP-MS. The dust from snowpack provides a record of regional background composition and flux, and it is strongly enriched in some trace elements (such as Cu, Zn, As, Ag, Cd, and Pb) relative to an average crustal rock composition.

A new combination of magnetic and chemical methods has been developed for the rapid recognition of eolian dust in soils and surficial deposits of ecosystems, with applications to understanding plant distribution and substrates for biologic soil crust. This approach reveals a large component of eolian silt in the surficial deposits, which harbor much of the biologic fertility of the Colorado Plateau. Moreover, the biologic soil crust there is a natural dust trap that records over the past several decades a shift in dust source, from relatively mafic to more silicic, on the basis of relative abundances of magnetite to titanomagnetite, and of Zr to Ti. Human activities in deserts off the Colorado Plateau, such as the Mojave Desert, may be partly responsible for this shift in dust source.

Sand-dune fields in the Mojave Desert, as well as those on the Colorado Plateau and Southern High Plains, are being investigated for their evolution, sand-transport pathways, and vulnerability to future climate change. A recently developed concept is that eolian sand is moved between basins in the Mojave Desert along distinct sand-transport pathways. Part of this model is that sand dunes near Parker, Ariz., east of the Colorado River, may be the endpoint for one of these sand-transport pathways. If this hypothesis is true, it implies a period or periods in the past when the Colorado River was completely dry to allow sand transport by wind across the river valley. Chemical and mineralogic tests of this hypothesis indicate that the Parker dunes have compositions that are very close to Colorado River sediments and much different from dunes in the Mojave Desert of California. Therefore, the Parker dune field has a different origin from those in the Mojave, and it is derived from Colorado River sediments, similar to the Algodones dunes. The sand-transport pathway-model may be partly correct for the Mojave Desert, but it does not apply across the Colorado River.

The modeling component includes the development of a wind-erosion model based on wind strength, atmospheric shear stress on the surface, and atmospheric stability. This model will be linked with a regional climate model and an interactive vegetation package to forecast (1) critical wind speeds required to move surface materials and (2) wind-speed variability under various climatic and land-use scenarios. We will attempt to answer the following questions: How does wind strength vary with natural climate cycles on decadal and century time scales? If climate changes as a result of human activities, to what extent will winds become stronger or weaker? How have soil moisture and vegetation changes affected wind erosion in the past? What can we expect in the future? As an example, $2 \times CO_2$ projections for the Southwest suggest a decrease in the diurnal temperature range, which will affect atmospheric stability, and a decrease in soil moisture, especially during the winter. The latter effect may lead to enhanced wind erosion in the future.

Scenario Earthquakes along the Death Valley Fault System

Craig M. dePolo and Ron H. Hess

Nevada Bureau of Mines and Geology, University of Nevada–Reno, Reno, NV 89557
<cdepolo@unr.edu>, <rhess@unr.edu>

"Scenario earthquakes" along the Death Valley fault system indicate that this system poses a significant hazard to Death Valley National Park, as well as to adjacent areas in southern Nevada and southern California. Scenario earthquakes are deterministic representations of ground shaking from individual events along a fault or in an area. They are especially useful in planning the emergency response to an earthquake because one can visualize the extent of strong shaking and the kinds of problems that shaking and fault offsets might create. (See, for example, dePolo and others, 1996.)

The Death Valley fault system is the largest and fastest moving system in the Basin and Range province, capable of generating major earthquakes every several hundred to several thousand years (Sawyer and others, 1998). This system poses a regional hazard to southern Nevada and southern California, as well as the obvious local hazard in the park. Of particular concern for Nevada is the response of the Las Vegas basin, about 125–160 km away and home to more than 1.2 million people. This analysis is only the beginning of the effort to create scenario earthquakes aimed at better understanding earthquake threats in this region. Only simple models are used, and details such as basin response are not included at this time. The computer program used to generate the ground motion (and then convert to earthquake intensity) is HAZUS, which is provided by the Federal Emergency Management Agency. This is a loss-estimation program that is relatively simple to use for constructing earthquake scenarios and has the ability to model potential consequences and losses from earthquakes. This is particularly valuable for emergency-management planning.

For Death Valley, two scenario earthquakes are modeled: one along the Central Death Valley fault zone, and one along the Furnace Creek fault zone. The event modeled along the Central Death Valley fault zone is a normal-slip earthquake with a moment magnitude (Mw) of 7.2. It is based on a 60-km-long surface rupture and a maximum surface displacement of 3.5 m (Klinger and Piety, 1996) and using Wells and Coppersmith's (1994) empirical relationships (Smith and others, 1998). The event along the Furnace Creek fault zone is a strike-slip earthquake of Mw 7.4 based on a 105-km-long surface rupture and a 6-m maximum surface displacement (Smith and others, 1998). These are the largest events expected from these faults without allowing multiple faults or fault segments to fail during the same event. Note that these events are a subset of the distribution of events that can occur along or proximal to these faults. Thus, they are likely larger than the next major earthquake that will occur, assuming smaller earthquakes occur more frequently. Nevertheless, with these two events we can learn a lot about the potential seismic vulnerabilities of this region, and help limit some of the surprises that are not evident in short-term probabilistic studies. We plan to continue building these models, including conditions such as low-velocity sediment and basin effects that can produce higher ground motions.

The results of these models indicate that severe shaking can be expected in Death Valley National Park from earthquakes along the Death Valley fault system. This is not at all surprising, but it emphasizes the importance of mitigating seismic risk within the park. For example, the mitigation of nonstructural hazards in high-occupancy places, such as the Park Visitor Center, should be considered.

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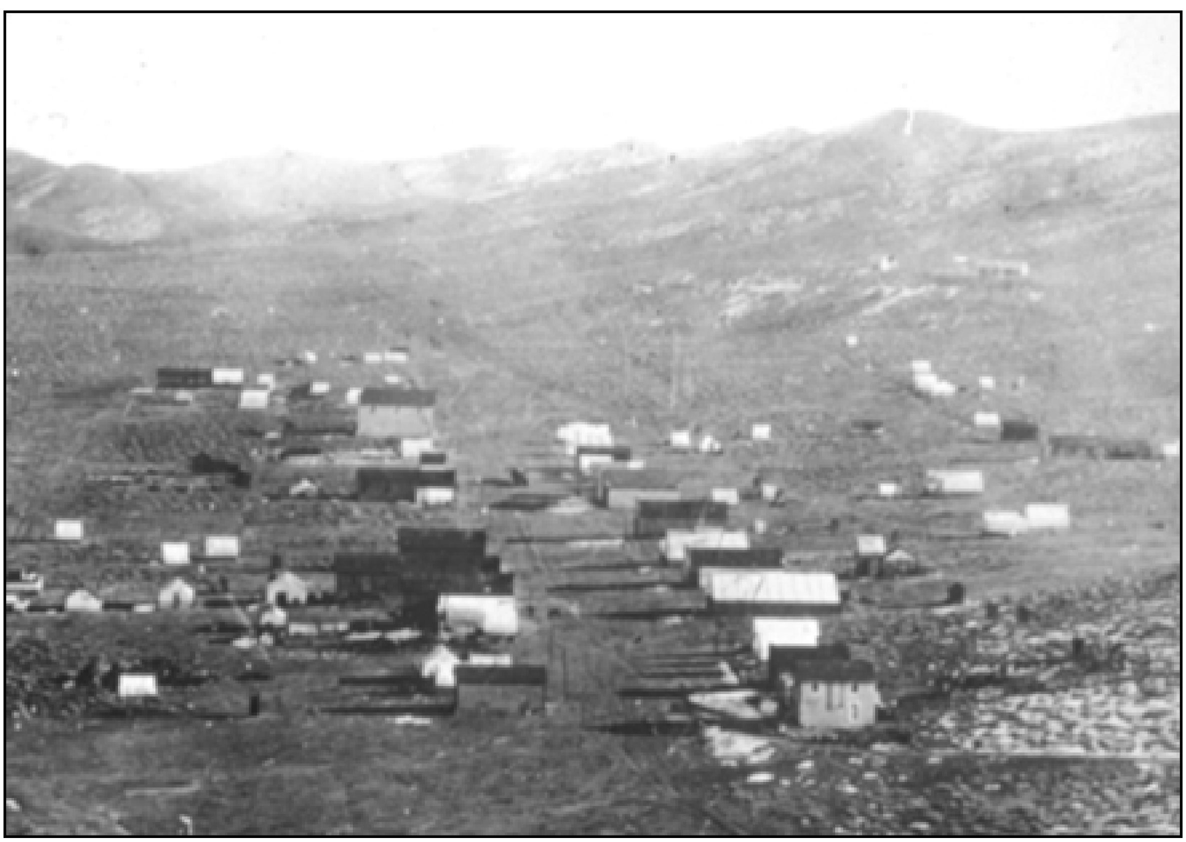
GPS-Determined Constraints on Interseismic Deformation along Active Fault Zones within the Death Valley Region, Southeastern California

Todd B. Williams <twilliams@chandler.mit.edu >,[1] Daniel J. Johnson,[1] M. Meghan Miller,[1] and Timothy H. Dixon[2]
[1]Department of Geology, Central Washington University, Ellensburg, WA 98926
[2]Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL 33149

Active deformation in the Death Valley region accommodates a part of the Pacific–North America relative plate motion along a zone of right-lateral shear on predominantly NW-striking faults. Right-lateral shear through the Death Valley region is associated with extensional pull-apart basins as well as large-scale normal faults. Displaced Holocene strata throughout the Death Valley and Panamint Valley regions, as well as GPS-determined point-position velocities, confirm that the uppermost crust in this region is currently being deformed. Annual GPS observations between 1993 and 1998 indicate 4.9 $\pm$ 0.6 mm/yr of relative motion at N. 42° W. distributed between the eastern flank of the Funeral Mountains and the Darwin Plateau. As much as 2.9 $\pm$ 0.6 mm/yr at N. 36° W. and 2.0 $\pm$ 0.8 mm/yr at N. 51° W. of motion occur in Death Valley and Panamint Valley, respectively. Slip rates on individual fault zones, including the Panamint Valley and Death Valley faults, are determined from elastic deformation modeling of this interseismic strain rate. This data set is incorporated into an elastic dislocation model, which attempts to fit observed geodetic data for various geologic scenarios throughout the Death Valley region.



Seismic Potential of the Fish Lake Valley Fault Zone, Nevada and California

T.L. Sawyer[1] and M.C. Reheis[2]

[1]Piedmont Geosciences, Inc., 10235 Blackhawk Dr., Reno, NV 89506 <tom-piedmont@eze-inter.net>

[2]U.S. Geological Survey, Box 25046, Denver Federal Center, M.S. 980, Denver, CO 80225 <mreheis@usgs.gov>

Dextral shear on the Death Valley fault system accounts for nearly half of the 10–12 mm/yr of relative motion between the Pacific-North American plate accommodated in the Basin and Range province between about lat 36°30' and 38° N. (Reheis and Sawyer, 1997; Klinger and Piety, 1996). Geometry and style of faulting provide a basis for subdividing this approximately 350-km-long fault system into four distinct fault zones. The northernmost, the Fish Lake Valley fault zone (FLVFZ), extends northwest from a large left (restraining) step in the Sylvania Mountains. This fault zone generally bounds the east front of the northern Inyo Mountains, forms the prominent eastern escarpment of the White Mountains, and exhibits subparallel faults on the flanking piedmont slopes in western and southern Fish Lake Valley.

We characterize the 70-km-long FLVFZ as three surface-rupture segments (fig. 39) based on (1) the right-stepping geometry of portions of the fault zone; (2) significant variations in the sense of secondary dip-slip components along strike; (3) age constraints derived from detailed mapping of a widespread sequence of piedmont-slope deposits dated by numerous ^{14}C ages and tephrochronologic correlations; (4) analysis of scarp morphology and progressively higher scarps on successively older geomorphic surfaces; and (5) the timing of faulting constrained by fault terminations at different stratigraphic levels and scarp-derived colluvial and fissure-fill deposits exposed in exploratory trenches at six of seven sites. From north to south the three surface-rupture segments are the Leidy Creek, Wildhorse Creek, and Oasis segments; a fourth, the Cucomongo Canyon segment, separates the FLVFZ from the remainder of the Death Valley fault system to the south. (See Klinger, this volume, for a discussion of that part of the fault system.)

These data show that the segments of the FLVFZ have repeatedly produced large to moderate earthquakes in the past 5,000 years; a few events appear to have ruptured more than one segment. In addition, the data suggest that adjacent rupture segments have opposing senses of secondary dip-slip displacement, and that boundaries between segments are delineated by releasing or restraining bends. However, the most recent event (MRE) on the northern segment (Leidy Creek) ruptured through a 2-km-wide restraining step and a 30° releasing bend (fig. 39).

The en echelon northwest-striking Leidy Creek and Oasis segments form an approximately 4-km-wide left-restraining step across the relatively short west-northwest-striking Wildhorse Creek segment (fig. 39), similar to the left step across the N. 60° W.- to east-west-striking Cucomongo Canyon segment to the south. The Leidy Creek and Oasis segments are characterized by right-oblique-normal slip; both have ruptured in the past 1,000 yr (700 to $\leq$1,500 yr). The average recurrence intervals on these segments is approximately 500 to 1,000 yr. In contrast, the Wildhorse Creek segment (and the Cucomongo Canyon segment) exhibits an apparent reverse-slip component and has not ruptured in the past $\geq$1,700 yr, suggesting recurrence intervals of longer duration.

These data indicate that (1) the MRE on each of the three segments is distinct in time and space; (2) roughly $\geq$7 m of right-lateral strain has accumulated on the Wildhorse Creek segment (and on the Cucomongo Canyon segment), provided strain accumulates at the preferred rate of 4 mm/yr on the FLVFZ (Reheis and Sawyer, 1997); (3) characteristic earthquakes on the Leidy Creek and Oasis segments represent M_w 6.7 to 6.8 events and on the Wildhorse Creek segment represent M_w 6.2 events, based on empirical relationships between rupture length and magnitude; (4) less frequent events appear to have involved the Wildhorse Creek segment and one or both of the adjacent segments in a multiple-segment earthquake of M_w 7 or greater, which is consistent with the prominent geomorphic expression of this segment; (5) recurrence intervals range from 500 to $\geq$1,700 yr for all segments and are longest where the dip-slip component is reverse, rather than normal; and (6) intervals since the MRE on the Leidy Creek and Oasis segments equal or exceed their recurrence intervals.

Based on evidence of the behavior of the Death Valley fault system, (1) prominent releasing and restraining bends in strike-slip faults should be considered as potential rupture-segment boundaries, and (2) large ($\geq$4 km wide) restraining and (in the case of the central Death Valley fault system) releasing steps may contain oblique- to dip-slip rupture segments that periodically are involved in cascading multi-segment ruptures. The time elapsed since the MRE suggests that the FLVFZ is a prime candidate for producing an earthquake within the White Mountain seismic gap.

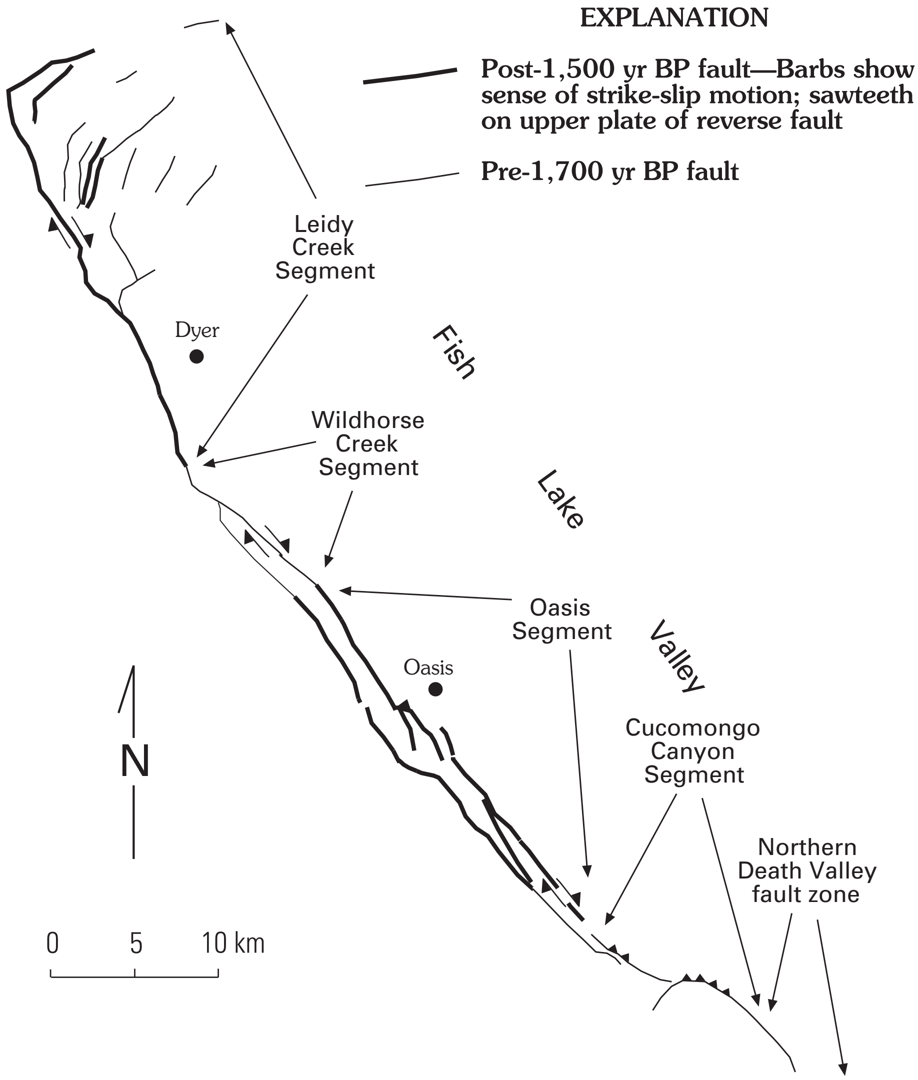


Figure 39. Earthquake-rupture segmentation model of the Fish Lake Valley fault zone (FLVFZ), Nevada and California (modified from Reheis and Sawyer, 1997).

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Quaternary Strike-Slip Components of the Death Valley Fault between the Furnace Creek and Southern Death Valley Fault Zones

D. Burton Slemmons[1] and George E. Brogan[2]
[1]905 Autumn Haze Lane, Las Vegas, NV 89117 <bslemmons@aol.com>
[2]2081 Business Center Dr., Suite 140, Irvine, CA 92614 <gebrogan@aol.com>

This evaluation of Quaternary strike-slip components of faulting in Death Valley is based on the widely accepted "pull-apart" neotectonic basin model (Burchfiel and Stewart, 1966), which includes the Death Valley fault (DVF). It also is grounded on the interpretation of special low-sun-angle aerial photographs (1:12,000 scale) that were used to map the youthful features of surface faulting. Subsequent regional neotectonic field work was conducted along the main rupture zone, which extends 282 km (175 mi) from the south end of Death Valley, to the north end of Fish Lake Valley.

Death Valley is a rhomb-shaped depression that extends N. 48° W., parallel to the right-slip ~N. 50° W. Furnace Creek fault zone (FCF) on the north and the Southern Death Valley fault zone (SDVF) on the south. The eastern boundary of the rhomb is the DVF (N. 12° W.), which was mapped by Brogan and others (1991) and described by Klinger and Piety (1996). This mapping and analyses of late Holocene scarps showed vertical separations, with few measurements of the right-slip component. This suggests that there may be a major discrepancy between their field data and the Burchfiel and Stewart (1966) model.

A vector diagram for DVF based on the Burchfiel and Stewart (1966) extension model, N. 48° W. extension (average of ~N. 50° W. for FCF, and ~N. 45° W. for SDVF), ~N. 12° W. strike, and 40°–60° W. dip shows sub-equal components for the vertical and right-lateral vectors. Although many Basin and Range faults have dips of ~60°, lower dip angles are suggested by some listric-shaped fault models, dips of 30°–50° on the 1954 Dixie Valley fault (Caskey and others, 1996), and the 50° dip for the 1983 Borah Peak fault (Crone and others, 1987). Assuming DVF with a dip of 60° W., this resolves into the following components:

Vertical:	1.00
Net dip-slip:	1.15 down-dip in S. 78° W. direction
Horizontal extension:	0.58 in a S. 78° W. direction
Horizontal right-slip:	0.79 in N. 12° W. direction
Net resultant:	1.40 in N. 48° W. direction

(Note: For a fault dipping 50° W., the horizontal right-slip component is 1.15, and for 40° W. it is 1.64.)

A major factor that makes it difficult to measure the lateral component for normal-oblique faults is that the strike-slip components generally lack distinct linear geomorphic features that cross the fault. In addition, their low relief causes them to become degraded sooner. For example, for historic oblique-normal faults in the Great Basin there are fewer locations where the strike-slip components can be easily measured than the vertical components. Even for the well-studied 1872 Owens Valley (Beanland and Clark, 1994) and 1954 Fairview Peak faults, the percentage of strike-slip measurements versus vertical separations ranged from 19 to 48 percent on five faults. Older, more degraded Holocene and late Quaternary scarps have even fewer measurements of lateral offset. These percentages could be even less, since many more locations could be added for vertical separation measurements, but few new measurements of strike-slip components can be added.

Evidence for a right-slip component includes observations by many investigators at locations distributed along the entire length of Death Valley (Curry, 1938; Hooke, 1972; Wills, 1989; Keener and others, 1993). Hill and Troxel (1966) discussed six types of evidence for a strike-slip component. The DVF is 71 km long, and between an abrupt truncation by the FCF, about 1 km northeast of Salt Springs and its south end at Shoreline Butte, it strikes N. 12° W. The position of the northern end is similar to that shown by Wills (1989), but is 10 km north of the location of Klinger and Piety (1996). We use the more northerly end point because it forms a semi-continuous rupture with the DVF, is truncated by the FCF, and appears to separate two areas of different behavior.

There are many reports of lateral offset, tectonic geomorphology, or fault-slip directions with a strike-slip component in each 10 km section of the DVF. These sections are herein arbitrarily labeled A to G, from Salt Springs to Shoreline Butte. Some observations are:

A. 0–10 km: Observation by Willis at Mustard Canyon and near the Visitors Center;

B. 11–20 km: Observation by Willis at Breakfast and Desolation Canyons, Slemmons for this study, and by Miller (oral commun.) for late Cenozoic fault striations along the Artists Drive section;

C. 21–30 km: Striation observations by Wills, Miller, and Slemmons;

D. 31–40 km: Observations by Hooke at the Badwater and Warren fans;

E. 41–50 km: Observations by Brogan and Hooke at Tufa, Goblet, Westilt, and Coffin Canyon fans;

F. 51–60 km: Five measurements of oblique-slip and strike-slip striations by Keener, Serpa, and Pavlis;

G. 61-70 km: Fault pattern observations of Brogan and Wills.

Assuming that oblique-normal extension is required, the possible mechanisms could include either one or both of the following: (1) there is inadequate recognition of lateral-slip components along many normal-slip portions of the DVF, or (2) partitioning (at or above seismogenic depths) of a west-dipping, mainly normal DVF, and steeply dipping to vertical, mid-valley, surface faults that may be concealed by young Quaternary deposits.

DISCUSSION

1. This is a typical relationship for normal-oblique faults in the extensional Basin and Range province setting. Widespread evidence, listed above, suggests to the authors that this discrepancy could be reduced by future, more-detailed paleoseismological investigations.

2. This reason is more difficult to assess, since most of the area is covered by young, Holocene lacustrine, alluvial, and (or) saline deposits. There is a possible 80–200 m right-lateral offset on a N. 20–30° W. fault that bisects the volcanic cinder cone at Cinder Hill (elevation of ~150 ft). The age of the cinder cone is late- to mid-Pleistocene. This suggests that the fault has a moderate to high slip rate, a relationship that appears to be anomalous, since Holocene scarps are absent or weakly developed at the cone, and the entire surface appears to postdate Lake Manly at this site. Other widely disbursed evidence of possible strike-slip faulting includes the up-domed(?) Holocene deposits 3 km south-southeast of Mushroom Rock and just north of the road to Devils Speedway, and north-south faults in the McClean Spring area. Accordingly, current evidence from the mid-valley area suggests important strike-slip faulting there, but it does not permit specific conclusions regarding the partitioning mechanism, or prevalence of strike-slip faults in Death Valley.

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Using Geomorphic Features to Constrain Tectonic Activity near Pahrump Valley, Nevada and California

K.M. Schmidt and J.G. Davidson
U.S. Geological Survey, M.S. 989, 345 Middlefield Rd., Menlo Park, CA 94025
<kschmidt@mojave.wr.usgs.gov> and <davidson@mojave.wr.usgs.gov>

Regionally distributed, middle to late Cenozoic extensional tectonism (Wernicke and others, 1988) produced the principal topography of the Basin and Range province. The timing and relative uplift rates of individual mountain ranges within the province, however, may be highly variable. Here we investigate the relative magnitude of tectonic activity surrounding Pahrump Valley, Nevada and California, based on a variety of geomorphic indices: (1) the mountain-front sinuosity, (2) the ratio of valley floor width to the height, (3) the plan-form drainage basin shape, and (4) the surface traces of mapped faults and lineaments in relation to the Paleozoic basement surface characterized by inversions of gravity data.

In the fault-block landscape of the Basin and Range province, drainage patterns are typically perpendicular to the mountain ranges and their bounding faults. Eroded sediments produce aprons of coalescing fans along the mountain fronts. This interface between the erosional and depositional environments characterizes the mountain-front sinuosity where S is defined as the ratio of the length along the edge of the mountain front (contact of bedrock and alluvium) (Lmf), to the overall straight line length of the mountain front (Ls) such that:

$$S = \frac{Lmf}{Ls} \qquad (1)$$

Sinuosity reflects the interplay between the tendency of uplift across range-bounding faults to maintain a fairly straight front and of channel erosion to produce embayments and a sinuous front (Bull, 1977; Bull and McFadden, 1977; Keller, 1986; Mayer, 1986, among others). Thus, high S values represent areas where the erosion rate exceeds the tectonic uplift rate and low S values are characteristic of regions where the uplift rate, along the mountain front exceeds the erosional rate. Using equation 1, we calculated mountain-front sinuosity along portions of the Nopah and Resting Spring Ranges from 1:62,500-scale USGS topographic maps. High mountain-front sinuosities for the southern part of the Nopah Range indicate low rates of uplift along the mountain-front faults compared to rates of channel erosion.

Changes in base level of a channel network arise through variations in either climate or tectonics. Uplift across a fault can alter the erosive power of a channel from predominantly lateral to vertical incision producing narrow, deeply entrenched channels and leaving abandoned floodplains and (or) bedrock strath terraces. The valley floor width to valley height ratio, V, is used to portray the relative degree of channel incision such that:

$$V = \frac{2\,Vfw}{(Eld - Esc) + (Erd - Esc)} \qquad (2)$$

where Vfw is the width of the valley floor, Eld is the altitude of left divide, Erd is the altitude of right divide, and Esc is the altitude of stream channel (for example, Bull and McFadden, 1977; Mayer, 1986). This index (V) reflects differences between broad-floored canyons with relatively high values that represent significant lateral erosion and V-shaped canyons with relatively low values that represent active downcutting. Cross sections of 21 single-thread, alluvial channels were measured at the mouths of bedrock valleys, normal to the active channel, using tape, compass, stadia rod, and level. Contributing drainage areas (DA) of the basins upslope of the cross sections were digitized from 1:24,000-scale USGS topographic quadrangles, whereas local channel slopes were measured in the field with an inclinometer. The product of drainage area and local slope (DA*Slope) (fig. 40) is used as a proxy for stream power or sediment transport capacity for the 21 alluvial channels surveyed in the field. Sites with high values of DA*Slope are more erosive because any excess flow capacity not used by sediment transport may be expended by eroding the channel banks and (or) bed.

Pahrump Valley, a rapidly growing urban area, is between the Spring Mountains and the Nopah Range about 80 km west of Las Vegas. Numerous faults are situated along the mountain fronts of the Nopah Range and Resting Spring Range, as well as within Pahrump Valley. The west side of the Nopah Range is bounded by short, discontinuous faults, whereas faults on the east side of the range are more continuous with multiple parallel branches. The sub-basin architecture of the underlying Paleozoic basement rock imaged through gravity model inversions is strongly correlated with surface fault traces. Field mapping and aerial photograph analyses of faults on the east side of the Nopah Range revealed beheaded alluvial channels and channels with a pronounced right-lateral sense of displacement, consistent with the regional tectonic sense of motion. A previously unmapped northwest-trending fault located directly adjacent to the mountain front would align these offset channels as well as numerous truncated bedrock ridges.

The southern portion of the Nopah Range is characterized by less incised alluvial channels with generally higher values of V and greater mountain-front sinuosities, which are

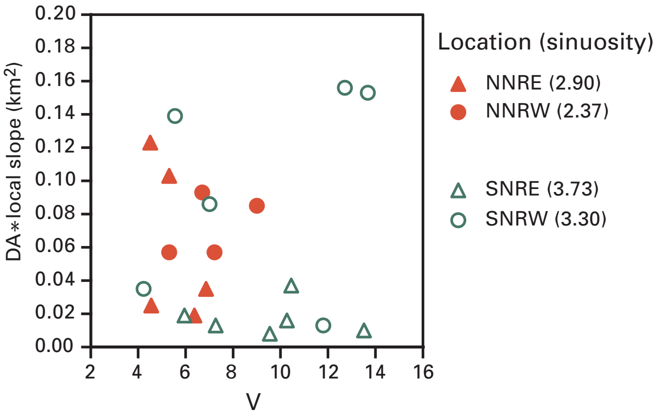

Figure 40. Product of contributing drainage area and local slope (DA*Slope) versus valley width to valley height ratio, *V*, for the 21 single-thread, alluvial channels of Nopah Range. Sites in northern and southern portions of Nopah Range represented by solid and open symbols, respectively. Triangle, site on eastern portion of range; circle, western study site. Mountain-front sinuosity for the portion of the range shown in parentheses. Abbreviations correspond to segments of measured mountain-front sinuosity; NNRE, north Nopah Range east; NNRW, north Nopah Range west; SNRE, south Nopah Range east; SNRW, south Nopah Range west. Channels issuing from western front of Nopah Range (circles) are characterized by larger products of DA*Slope (≥ 0.04) than the eastern range front (triangles), indicating a pronounced asymmetry to the range such that channels in drainage basins on west of range have higher sediment transport capacities.

indicative of constant base levels and (or) low uplift rates. In contrast, the northern Nopah Range has alluvial channels that are more incised with lower values of *V* (for the same range of DA*Slope) and lower mountain-front sinuosities, which are indicative of changing base levels and (or) high rock uplift rates. Hence, given that the area is exposed to the same climatic signal, the southern segment of the range is likely to be tectonically less active. The southeast part of the Nopah Range represents channels with high slopes and small drainage areas characteristic of channels near the drainage basin headwaters where alluvial fan heads are situated close to the steep hillslopes constituting the drainage divides. The measured coarse grain sizes of active sediment transport through the channels in the southeast support the interpretation that the fan heads are near the sediment source. In addition, sites measured in the southeast portion of the range are distinguished by broad-floored alluvial channels. Furthermore, the association of large values of *V* with high mountain-front sinuosities suggests that the range-bounding faults are tectonically quiescent to the southeast and that the drainage basins may be filling with sediment, thus shifting the locus of alluvial fan deposition toward the headwaters of the basin. Curiously, this southeast part of the Nopah Range also corresponds with one of the larger sub-basins imaged through gravity model inversions.

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USGS Geologic and Seismic-Hazard Investigations of the Cow Creek Area, Death Valley National Park

Michael N. Machette,[1] Anthony J. Crone,[1] Kathleen M. Haller,[1] Lee-Ann Bradley,[1] Carlos Ninci Martinez,[2] and Giuliana D'Addezio[3]

[1] U.S. Geological Survey, Box 25046, Denver Federal Center, M.S. 966, Denver, CO 80225-0046 <machette@usgs.gov>

[2] Comisión Nacional de Energía, Agencia Minipost 1842, Partido Esteban Echeverría, Buenos Aires 1414, Argentina

[3] L'Instituto Nazionale di Geofisica, Via di Vigna Murata 605, Roma, Italy

In the summer of 1998, the U.S. Geological Survey (USGS) and National Park Service (NPS) entered into a cooperative agreement to address short-term seismic hazards at the Cow Creek Administrative area (facility), about 8 km north of Furnace Creek. Their plans called for construction of a new museum curator's building, a new building for the Death Valley Natural History Association, and relocation of the existing maintenance yard. In addition, a number of existing buildings at the site are constructed of adobe, and these present special challenges in terms of seismic hazard.

The construction was contingent upon gaining site clearance for surface faulting. Although the area is outside of mapped Alquist-Priolo special study zones, NPS is obliged to address seismic hazards for all federally operated, federally funded, or federally insured structures under the Federal Emergency Management Agency's National Earthquake Hazard Reduction Program (NEHRP) standards, "Recommended provisions for seismic construction for new buildings."

Under terms of the NPS/USGS agreement, the USGS agreed to:

1. Create a GIS base map using existing NPS 1:1,200-scale topographic maps.
2. Acquire detailed aerial photography for geologic mapping.
3. Conduct a reconnaissance study to locate trenches at potential construction sites.
4. Excavate and map trenches to document evidence for faulting or ground failure.
5. Analyze and interpret these data and write an administrative report on seismic hazards at the site. The administrative report was submitted as USGS Open-File Report 99-155 (in press) and is the basis for the interpretations presented here and the graphics used in the accompanying poster.

CONCERNS ABOUT SURFACE RUPTURES

There are several geologic maps showing a fault zone that strikes SSE through the eastern margin of the facility. About 100 ft (30 m) west of this mapped fault zone are a series of low hills and anomalous topography that are suggestive of antithetic faulting along a west-bounding fault of a graben. This possible graben would extend north-northwest to the Old Ghost Road, and south-southeast of the facility to the next major alluvial fan (Cow Creek). If this fault zone exists, then all the new buildings would be along or close to the fault zone. In addition, northwest of the facility we found a young zone of deformation composed of a main and an antithetic scarp, a shallow graben between them, and numerous sediment-filled fissures. These scarps indicated that young surface rupturing had occurred near the facility.

FAULTS AND EARTHQUAKES

The Cow Creek facility is located in a transition zone between the south end of the Furnace Creek fault and the north end of the Death Valley fault. This transition zone is a structurally complex area that accommodates a transfer of right-lateral slip on the Furnace Creek fault to the Death Valley fault, which is considered to be a predominantly normal fault. This area has been mapped at intermediate detail, but little is known about the subsurface linkages and recent faulting history of these two fundamental seismic sources. The USGS probabilistic seismic-hazards map of the region shows that much of Death Valley has a 10 percent probability of experiencing >0.4 g to 0.6 g (gravity) acceleration in the next 50 yr. Adobe buildings such as those currently occupied at the Cow Creek facility are particularly vulnerable to these levels of shaking. On the other hand, little significant seismic activity has occurred in the valley since 1900, with most activity being at M 3–4 or less. This low level of historical seismic activity may be a result of a short observation window for seismicity and the aseismic nature of some major faults.

SURFICIAL GEOLOGY AT THE SITE

Most previous surficial geologic mapping of the area used a four-fold division of Quaternary units. This scheme originated with the early mapping of Hunt and Mabey (1966) and was accepted and utilized by Wright and Troxel (1993). For detailed studies, further subdivison is based on geomorphic and soil characteristics as outlined by Klinger and Piety (1996). In this study, we are using the stratigraphic column of Klinger and Piety (1996) with minor modifications. For example, our youngest unit (Q4) represents their alluvial units Q4a (historic) and Q4b (0.1–2.0 ka). Unit Q4 forms the youngest part of the landscape, which often has been the sites of debris-flow and flooding events during intense rainstorms. The surface of unit Q4 has original or slightly modified morphology (bar-and-swale topography), and no to light desert varnish on poorly developed desert pavement; it lacks zonal soils (Klinger and Piety, 1996, table 2).

Alluvial unit Q3 and the two subunits we use (Q3c and Q3ab of increasing age) form about half of the alluvial fan landscape on the piedmont-slope west of Park Village ridge. The surfaces underlain by subunits of Q3 are characterized by subdued bar and swale topography (typically equal portions), medium to dark desert varnish on well-developed desert pavements, medium to thick vesicular A horizons, and weakly developed zonal soils on subunit Q3ab.

Of the four basic units, the most easily differentiated are Q3 and Q2 owing to the dramatic change in surface tone (from medium to dark varnish) and geomorphic expression (from rough to smooth surfaces). For unit Q2, which is entirely pre-Holocene, we have differentiated three subunits—Q2c, Q2b, and Q2x—on the basis of topographic position, geomorphic preservation, and soil development. Q2b and Q2x are the most extensive of the three subunits in the Cow Creek area, whereas we only mapped unit Q2c in one small area. The correlation of these three units, which span a potential time interval of 700,000 yr, is problematic inasmuch as the most definitive characteristic for subdividing these deposits is their soil development. Few exposures of the soils exist in the Cow Creek area; thus we feel least comfortable with our age assignments for unit Q2.

Aerial photographs of the Park Village ridge indicate several levels of erosion surfaces that appear to be capped by thin (<1 m) to moderate (1–5 m) gravel (unit Q2x) reworked from the upper part of the Funeral Formation. These surfaces project westward into the air and do not appear to have ever been of wide extent. They are probably equivalent to unit Q2a of Klinger and Piety (1996). We have not seen good exposures of unit Q2x, so the correlation with Q2a is somewhat questionable.

PALEOSEISMIC STUDIES AT THE FACILITY

Three sites at the Cow Creek facility were investigated by exploratory trenching. Two backhoe trenches cut through alluvial deposits and into the underlying lacustrine or bedrock materials. The purpose of these trenches was to provide exposures to determine if the underlying Quaternary materials were deformed by faulting. No evidence of faulting was found in either backhoe trench, and, as such, these sites were cleared for future construction. About 1/2 km northwest of the facility, we hand-dug a small (1.5 m deep, 3 m long) trench to expose mapped faults that have formed seemingly young scarps.

These small but fresh fault scarps are preserved on the Old Ghost alluvial fan complex, particularly on those surfaces underlain by unit Q3c (mid to late Holocene) or older materials. We found no evidence for displacement of unit Q4 (latest Holocene), thus precluding extremely young offset (historic to several hundred years). However, the steep slopes associated with the scarps on unit Q3c, which are typically <1 m high, suggest that they were formed in the late Holocene. To the north, we found fault scarps formed on unit Q2b that are 7 m high, and these might relate to as much as 14 m of stratigraphic throw.

The fault zone comprises a main and an antithetic scarp, a shallow 20-m-wide graben between them, and numerous sediment-filled fissures. A hand-dug trench across the main scarp revealed only a single deposit of colluvium—evidence that a single faulting event formed all the scarps on unit Q3c. No deposits related to a second (older) faulting event were found, and the stratigraphic throw on the top of unit Q3c is roughly equivalent to the scarp height. Both these observations demand a single faulting event that postdates stabilization of Q3c and formation of its Av horizon, which is now buried. Klinger and Piety (1996) suggested that unit Q3c was deposited between 0.2 ka and 2 ka; we favor the older portion of this range (>1 ka) owing to the burial of the Av horizon, which must have required at least several hundred years to develop on the Q3c surface.

TIME AND RECURRENCE OF FAULTING EVENTS NEAR THE FACILITY

Although no evidence of faulting was found at the facility, the scarps on the Old Ghost alluvial fan complex indicate the potential for continued surface faulting within 1/2 km of the facility. The apparent youth of the Cow Creek scarps is obvious from the morphometric data on scarp height and maximum scarp-slope angle. The Cow Creek scarps are clearly younger than those of the 2-ka Fish Springs fault of western Nevada, but the question is, how much younger? The larger of the Cow Creek scarps (which are only about 1 m high) have maximum slope angles that are at or exceed the angle of repose (commonly taken as 33° for unconsolidated sandy gravel).

In order to estimate the time of formation for the Cow Creek scarps, we used Bucknam and Anderson's (1979) empirical approach to scarp morphology, but modified it for local scarp degradation rates of 0.4–0.64 m^2/ka (see Hanks, 1998). The 0.64 m^2/ka rate yielded a minimum scarp age of 500–600 yr, whereas the 0.4 m^2/ka rate yielded a maximum scarp age of 740–840 yr. Using an average offset of 2/3 m per event, and a time interval of 70–200 k.y. for the 7–14 m of offset to the north, we estimate a preferred slip rate of 0.1 mm/yr and an average recurrence interval of 6,700 yr. These parameters are but a fraction of those estimated for the Death Valley and Furnace Creek fault zones (Klinger, this volume) and indicate that faulting within the transition zone is clearly subordinate to the major tectonic elements of the valley.

RECOMMENDATIONS

As a result of our geologic and seismic-hazard investigations in the Cow Creek area, we made the following comments and recommendations about new building sites and the older building inventory.

1. We found no evidence of surface ruptures through the Cow Creek facility (historical district). However, young fault movement may be difficult to identify in areas that lack a cover of surficial geologic materials (they typically preserve fault scarps). Basin-fill deposits are mainly exposed in the upper part of the facility and most of the surface there has been modified by construction since 1934, so we cannot preclude future surface rupturing at the site. Surficial faulting on the nearby Old Ghost site probably occurred between 500 and 840 yr ago, during the late Holocene.

2. Since young faulting commonly reactivates existing structures, we believe that future faulting in the Cow Creek area will continue to take a path around the western margin of the facility, as the most recent ruptures did. Thus, we do not expect that surface rupturing would occur at or near the Salt Pan Vista site or along the eastern margin of the facility.

3. Of the two building sites investigated, Salt Pan Vista is the superior building site. This area is underlain by poorly to moderately indurated sandy gravels that are about 3 m thick. Such material would form a natural, highly compacted pad for buildings or the maintenance facility. The Ridgecrest site, as well as sites both west and south of the facility swimming pool, may have thin alluvial cover materials, but they basically are underlain by soft sediments of the Funeral Formation. These materials have relatively low density (especially when weathered within about 1 m of the ground surface), often retain high moisture content, and may have moderate to high shrink-swell potential. These factors may present special engineering challenges if such sites are chosen for construction.

4. Any new buildings in this area should be designed for ground-motion values as defined in the most recent seismic-hazard guidelines and maps. In the past, relative levels of seismic hazards were defined by zones (increasing from I to IV), which are no longer applicable to federally operated, federally funded, or federally insured structures. Since about 1980, the Federal building code maps have been based on two ground-motion contour maps: one relating to long-period (1 s) ground motions, one to short-period (0.2 s). Fault ruptures, which were the main focus of our investigations, are an important issue in evaluating seismic hazards in earthquake-prone areas. Although we did not find fault ruptures to be a likely hazard at the site, seismic shaking is a major concern. Owing to the high activity rates for the Furnace Creek and Death Valley fault zone, the possible levels of ground shaking at the Cow Creek facility and the intervening transition zone would exceed 0.4 g and may approach 0.6 g (60 percent of gravity) as shown on the latest NEHRP probabilistic ground-motion maps (Frankel and others, 1997).

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Late Quaternary Flexural-Slip Folding and Faulting in the Texas Spring Syncline, Death Valley National Park

Ralph E. Klinger and Lucille A. Piety, Bureau of Reclamation, Geophysics, Paleohydrology, and Seismotectonics Group, P.O. Box 25007, D8330, Denver, CO <rklinger@do.usbr.gov>

The Texas Spring syncline is a northwest-trending, southeast-plunging asymmetric fold located between the north-striking, down-to-the-west normal-slip Death Valley fault (to the south) and the northwest-striking, right-lateral strike-slip Furnace Creek fault (to the north). The syncline is part of a structural trough referred to as the Furnace Creek basin by Cemen and others (1985). Stratigraphic relationships between the late Cenozoic strata in the Furnace Creek basin indicate that deformation across the syncline has occurred periodically since about 25 Ma (Hunt and Mabey, 1966; McAllister, 1970; Cemen and others, 1985) and as recently as the late Pleistocene, and possibly Holocene (Klinger and Piety, 1996).

Deformation both parallel and normal to the axis of the Texas Spring syncline is indicated by young fault scarps and stratigraphic relationships between late Pleistocene and Holocene alluvial deposits within the syncline. The deformation associated with flexural-slip folding on the southwest limb of the Texas Spring syncline is described by Klinger and Piety (see field trip stop 4, this volume). Late Quaternary normal faulting within the Texas Spring syncline is expressed by scarps on alluvial fan surfaces along the Cross Valley fault (fig. 41). The Cross Valley fault is a northeast-striking, down-to-the-northwest, normal-slip fault referred to as the Mont Blanco fault by Hunt and Mabey (1966) and the valley-crossing fault by McAllister (1970). Hunt and Mabey (1966) proposed that the fault extends southwestward into Death Valley to near the mouth of Hanaupah Canyon on the basis of (1) its alignment with four small faults represented by linear breaks in the salt pan of Death Valley; (2) a pair of linear hills composed of Funeral Formation near Artists Drive; and (3) a gravity anomaly along the axis of Death Valley that corresponds to vertical subsurface separation of the Funeral Formation. In contrast, McAllister (1970) suggested that the Cross Valley fault joins the Furnace Creek fault (to the northeast) with the northwest-striking Grand View fault (to the southwest).

Figure 41. Photograph of the Cross Valley fault scarp north of the Hole-in-the-Wall road. At this location, maximum scarp height is about 5.4 m.

Southeast (upvalley) of the Cross Valley fault, the geomorphic expression of the Texas Spring syncline is lost. The 4.5-km-long surface trace of the Cross Valley fault is delineated by a scarp that is as much as 12 m high on late Quaternary alluvial fans (fig. 42). Vertical separation of the Funeral Formation across the fault, however, has been reported to be as much as 300 m (McAllister, 1970). Measured scarp-slope angles range from 9° on a 1.8-m-high scarp to 26° on a 7.2-m-high scarp. In the larger drainages, at least two perched faulted terraces show clear evidence for at least three events. In addition, weakly developed benches and bevels are commonly present on the higher scarp slopes. At several locations, the fault trace is marked by a pair of low, parallel scarps or a narrow graben. These features are generally where the fault changes strike adjacent to and around flatirons of Furnace Creek and Funeral Formation (fig. 41). Evidence for the youngest movement on the Cross Valley fault is preserved in a small arroyo that is incised into an older alluvial fan, about 300 m northeast of the Hole-in-the-Wall road. At this location, a 0.5-m-high scarp is formed on a late Holocene debris flow. Due to the bouldery nature of the deposit, it is not clear that this scarp has a tectonic origin. It is on strike, however, with a 1.8-m-high scarp on older alluvial fans both to the northeast and southwest.

Although late Quaternary deformation has occurred across the Texas Spring syncline and Cross Valley fault, the southeastern part of the Furnace Creek fault has not experienced significant displacement since at least the early Pleistocene. The surface expression of the fault is limited to several short traces along its length (McAllister, 1970). In this area, the fault is primarily within sediment of the Furnace Creek and Funeral Formations or at the contact between one of these formations and older rocks of the southern Funeral Mountains (McAllister, 1970). Southeast of Navel Spring, however, late Pleistocene displacement along the projection of the Furnace Creek fault can be ruled out. In this area, a highly dissected surface (ballena form) with a strongly developed carbonate soil and a desert pavement that includes calcium carbonate rubble is preserved. McAllister (1970) noted that this surface “***extends across the entire Furnace Creek fault zone, but is not displaced by any of the faults.” This conclusion is supported by our field observations along the range front. First, an early to middle Quaternary age is estimated for the surface near Navel Spring based on pavement characteristics and a degree of soil development similar to surfaces that overlie the Bishop Tuff (>760 ka). Second, near the mouth of Echo Canyon, the fault is overlain by late Pleistocene alluvial fan sediment that extends across the axis of the syncline (see field trip stop 4, this volume). Similarly, the southeast (upvalley) extension of the Grand View fault is pre-Quaternary because 4–5-Ma basalt members in the lower part of the Funeral Formation cross the fault and are not displaced (McAllister, 1970; Cemen and others, 1985).

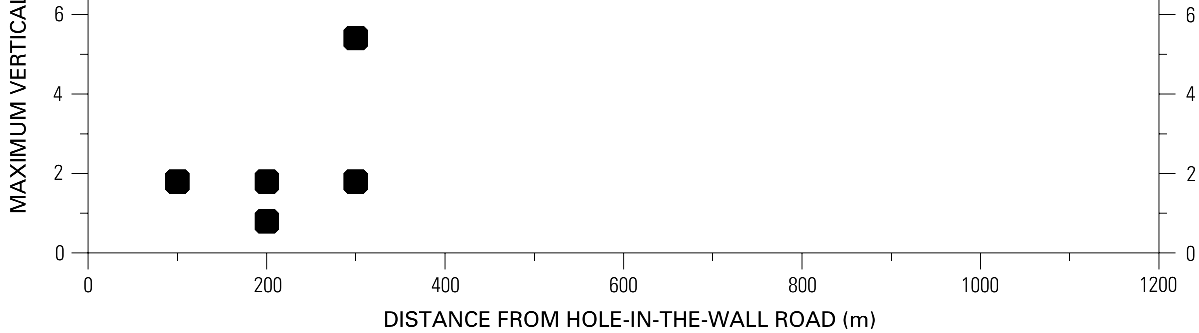

Figure 42. Maximum vertical separation of alluvial surfaces along the Cross Valley fault as measured on the southwest limb of the Texas Spring syncline.

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Geology of the Stump Spring Quadrangle—Evidence of Late Quaternary Transpression on the Southern Segment of the Pahrump Valley Fault Zone, Nevada and California

Matthew R. McMackin, Department of Geology, San Jose State University, One Washington Square, San Jose, CA 95192-0102, Telephone (408)924-5035 <mcmackin@pacbell.net> or <mcmackin@geosun1.sjsu.edu>

Previous studies have noted the lack of clear evidence of late Quaternary slip on the Pahrump Valley fault zone (Hoffard, 1991; Anderson and others, 1996). Detailed mapping in the Stump Spring area at the south end of Pahrump Valley confirms the observations of previous workers, who have focused their attention largely on the northern and central segments of the Pahrump Valley fault zone. In the southern part of Pahrump Valley, at least two clearly defined fault scarps mark the southern extension of the Pahrump Valley fault zone into the area just north of Black Butte (also known as Valley Ridge). Although these fault scarps are as high as 6 m, they are significantly rounded by weathering. The scarps are sealed by a 1- to 2-m-thick pedogenic carbonate layer that drapes over the eroded scarps but reveals no evidence of cross cutting faults. Anderson and others (1996) suggested that the carbonate, with Stage III-IV carbonate morphology (Gile and others, 1966; Machette, 1985), is older than 100 ka. Evidence presented here, however, suggests that the pedogenic carbonate is gently folded about northwest-trending axes to form two anticlines that are subparallel to the fault zone, indicating younger deformation without apparent surface ruptures. The most prominent folds are two anticlines subparallel to northwest-trending fault scarps in the north half of the quadrangle.

Evidence of folding of the carbonate layer includes fold limbs dipping as much as 10°, although separating initial inclination of the carbonate layer along the fault scarp from actual tilting due to deformation is difficult. Less equivocal dips are approximately 5°. Well-formed fractures in the carbonate layer also suggest that the folding is of tectonic origin. Well-formed planar fractures are observed in the carbonate layer subjacent to the fault scarps and throughout the apparent folds. Cumulative analysis of planar fractures greater than 1 m in length reveals dominant orientations N. 50° E. and N. 40° W., corresponding to cross-strike and strike-parallel fractures in a northwest-trending fold. Fractures in the carbonate horizon control the surface drainage pattern as well as shallow subsurface piping. The folding appears to have disturbed the patterns of surface drainage resulting in the abandonment of older channels, while other streams are entrenched across the axis of the anticline. Gravel deposits from an abandoned channel contain carbonized wood dated at 31,790 +1520/-1290 by Quade and others (1995), who noted that this is probably a minimum age due to the possibility of contamination. The folding of the pedogenic carbonate and the resulting effects are difficult to interpret, but they imply that late Quaternary deformation has progressed as transpressional deformation, albeit at a reduced rate compared to the deformation indicated by earlier fault scarps.

The folding of the late Pleistocene(?) carbonate layer is compatible with the deformation observed in middle to late Tertiary rocks that are more strongly deformed by faults and folding along the trace of the fault. Middle to late Tertiary sedimentary rocks are exposed in the core of one of the anticlines in the northern part of the map area. The older units are more strongly deformed. Bedding inclined as much as 50° and clay-gouge faults, with oblique slip striae, can be observed in clean exposures in recent gullies. Sanidine from an interbedded crystal tuff yielded a $^{40}Ar/^{39}Ar$ age of 10.76 ± 0.09 Ma (courtesy of C. Henry). In the southern part of the map area in the low hills surrounding Black Butte, Tertiary rocks are folded and uplifted along buried faults with no evidence of Quaternary displacement. The faults in the southern part of the area are poorly exposed or concealed, but inferring a simple alignment with the Pahrump Valley fault zone extending through the hills around Black Butte is difficult.

It has been suggested that the Pahrump Valley fault is contiguous with the Stateline fault, which can be traced through Mesquite Valley to the south. A possible explanation of the apparent shift in late Quaternary deformation may be that late Tertiary to early Quaternary deformation of the fault in the area around Black Butte may have resulted in a misalignment of the Pahrump Valley fault zone with faults farther south in the Mesquite Valley. Misalignment of the Pahrump Valley and Stateline faults in the area around Black Butte may impede lateral slip resulting in a change in the expression of ongoing regional deformation.

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Work in Progress—A Connection Through the Brittle Crust Between Death Valley and the Salton Basin

Robert O. Castle
U.S. Geological Survey, 345 Middlefield Rd., M.S. 975, Menlo Park, CA 94025
<rcastle@isdmnl.wr.usgs.gov>

The straight-line distance of about 350 km between Badwater and the center of the Salton Sea puts the two lowest points in North America in remarkably close proximity. The indicated straight line, moreover, falls largely or entirely within the Eastern California shear zone of Dokka and Travis (1990a, 1990b). Partitioning of plate motion across the entire width of the Pacific-North American plate boundary allots 20–25 percent (~12 mm/yr) of this motion to the Eastern California shear zone; assuming this rate operated continuously during the past 4 Ma produces cumulative right-lateral slip of approximately 48 km across the ~100-km width of this diffusely defined shear zone.

The straight line between Badwater and the Salton Sea coincides roughly with (1) a break in heat-flow values from high on the east to moderate or low on the west; (2) the west edge of Quaternary eruptive volcanic activity in the eastern Mojave; (3) the eastern margin of both significant historic seismic activity and late Quaternary faulting in southern California; and (4) the break in slope along the eastern flank of the southern California uplift. If this same straight line is broken into four or five equal-length segments (fig. 43), each of which is then rotated counter-clockwise about 25°, the azimuths of the resulting segments closely parallel (1) the trends of the bounding faults of the Salton Trough rhombochasm; (2) the northwest-trending faults through the western Mojave block; (3) the bounding faults (the Southern Death Valley and Furnace Creek) that define the Death Valley rhombochasm, which probably began to open about 4 Ma (Knott, 1998); and (4) perhaps most importantly, the consistently right stepping transforms marching northward through the Gulf of California, finally terminating in the Salton Trough. Without attempting to assign cause, this termination and the corresponding westward bend in the San Andreas fault are compelled by the persistence northward of most of the Pacific-North American plate motion well outboard of the plate boundary southward from and including the Salton Trough.

The thesis presented here argues that the brittle-crust connection between Death Valley and the Salton Basin is along a jagged boundary consisting of a series of right-stepping actual or incipient transforms and intervening incipient rhombochasms—that is, along the boundary obtained by segmenting the straight line between Badwater and the Salton Sea. This jagged boundary, moreover, coincides somewhat more closely with the first four features listed in the preceding paragraph than does the straight-line connection between the Badwater and Salton Sea lows. The connection between these two lows within the ductile layer beneath the brittle crust, however, may be more directly linked through a much broader, more diffusely defined shear zone.

A number of the northwest-trending faults within the western Mojave, all of which are assumed to have been in existence long before taking on their postulated transform roles, represent incipient transform candidates. Especially favored are the Camp Rock–Emerson and Ludlow faults, both of which can be identified with evolving rhombochasms or pull-apart basins. Less certain are the Calico and Pisgah faults—chiefly because associations with incipient rhombochasms are more poorly defined. Deformation preceding and accompanying the 1992 Landers earthquake indicates that the epicentral region is today a fairly well defined northwest-southeast-trending extensional or pull-apart zone that permits transfer of right-lateral motion between the San Andreas and the Camp Rock–Emerson faults. Similarly, the subsiding region centering on and immediately west of Soda Lake is

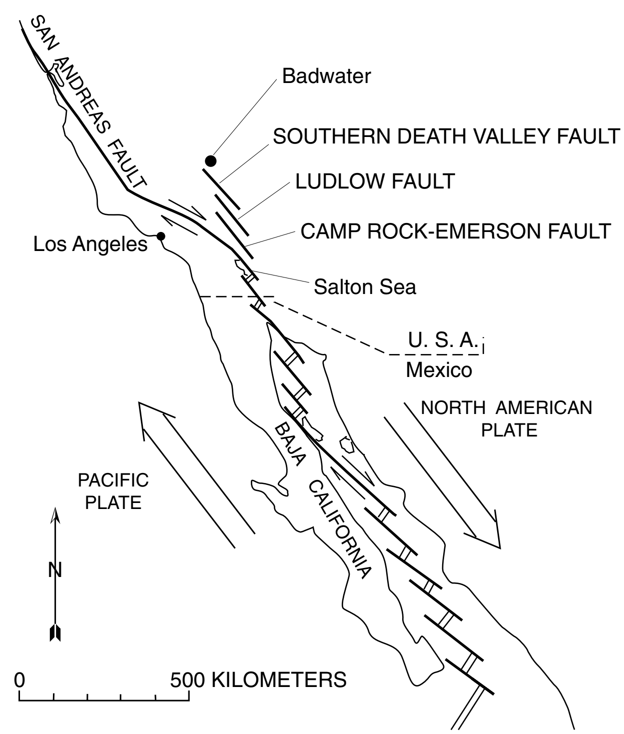

Figure 43. Schematic illustration showing essential elements involved with the postulated connection between Death Valley and the Salton Basin.

provisionally interpreted as an incipient rhombochasm permitting transfer of right-lateral motion between the Ludlow and Southern Death Valley faults. Cumulative right-lateral displacement stepping eastward from the Camp Rock–Emerson fault to the Ludlow fault could account for a major part of the postulated 48-km displacement athwart the Eastern California shear zone during the past 4 Ma.

At least two considerations challenge the acceptability of the argument developed in the preceding paragraphs. (1) If this process has been operating over geologically significant time intervals, relatively deep sediment-filled basins coincident with the postulated rhombochasms might be reasonably expected, yet there seems to be little evidence of their existence. (2) The postulated rhombochasm that falls within the epicentral region of the Landers earthquake is associated with a pronounced heat-flow low—although this thermal low does neck down significantly within this region. Both of these objections are conceivably explained in much the same way. Because the displacements across the western Mojave block based on the geodetic analysis of Sauber and others (1986) suggest no more than about 25 km of cumulative right-lateral movement eastward as far as the Ludlow fault during the past 4 Ma, the modest magnitude of the probable displacements across any postulated transform pair would tend to produce equally modest extension within the intervening area. Such tectonic subsidence as may have accompanied this extension would tend to be diminished, moreover, owing to the inherent buoyancy of the extended block. The likelihood that any tectonic subsidence or associated extensional strain could be easily recognized is further reduced if the incipient transforms migrated westward, albeit irregularly, as the western Mojave block moved southeastward against the San Andreas—as suggested by the current deformation over the heat-flow low centering on the epicentral region of the Landers earthquake.

Acceptance of the postulated model allows two general conclusions: (1) It permits a direct, relatively narrow, somewhat jagged connection through the brittle crust between Death Valley and the plate boundary coursing southward through the Salton Trough and into the Gulf of California—well inside the ~100-km-wide Eastern California shear zone. (2) The active rifting through the Gulf of California, which began with the opening of the gulf about 3.8–4.0 Ma, probably persists northward through the Salton Trough into the continental interior, but at only a fraction of the rate currently recognized in the gulf.

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FIELD TRIP: STATUS OF GEOLOGIC RESEARCH AND MAPPING IN DEATH VALLEY NATIONAL PARK APRIL 10, 1999

INTRODUCTION

Welcome to the field-based portion of the conference. We have asked several conference participants to act as field trip leaders and to facilitate discussion at the five field trip stops identified in this guide. Our selection of stops was determined by both the logistics of moving a large group through Death Valley National Park and the opportunity to present participants with summaries of recent and ongoing research activities encompassing a broad range of topics. We anticipate this trip to be informal and rich with discussion. Given the nature of this trip we did not require extensive field trip materials from the discussion leaders. Those contributions generously offered up by participants are included in this guide, and we trust they will enrich the field trip experience.

This field trip takes us to Death Valley via Nevada Highway 160 (Blue Diamond Hwy) from Las Vegas, Nev., to Pahrump and then via Nevada Highway 372 and California Highway 178 to Stop 1. Please refer to figure 1 in this guide for route information and stop locations.

STOP 1 – Mormon Point (T. Pavlis, J. Knott, and R. Klinger, Discussion Leaders)

T. Pavlis (modified from Wright and others, 1991):

Dominating the landscape north to northeast of the highway is the smooth, convex, northwest-plunging surface of the Copper Canyon Turtleback fault. It separates, in a brittle manner, the gray quartzofeldspathic complex of the lower plate from an upper plate of which the exposed part consists mostly of brightly colored strata of the late Neogene Copper Canyon Formation. The southeastward continuation of the northeast limb of the antiform is expressed in the trace of a narrow, light-colored band which separates the pale-gray complex from the darker gray gabbro of the Willow Spring pluton. It consists of the metamorphosed and ductilely deformed carbonate-bearing strata that have been tentatively correlated with the Noonday Dolomite and (or) Johnnie Formation. The visible part of the mountain front east and southeast of this stop is underlain almost entirely by gabbro and dikes that have intruded it. Most of the dikes are gently dipping, and are roughly correlated with a tabular granitic pluton exposed on the skyline to the south. The pluton and related dikes are similar to those dated elsewhere in the central Death Valley region at 10.5 to 10 Ma. Contrasting in age and orientation are the silicic dikes (7.2 Ma) that cut the Copper Canyon Turtleback, providing an upper limit for the formation of the antiform.

A BRIEF SUMMARY OF QUATERNARY GEOLOGY OF MORMON POINT

J.R. Knott, UNOCAL Corporation, Environmental Technical Services, 376 S. Valencia Avenue, Brea, CA 92823
(714) 577-2841 <jrknott@unocal.com>

MORMON POINT FORMATION

Several ash beds have been correlated at Mormon Point (MP) including one from upper Glass Mountain (0.8–1.2 Ma), Bishop ash bed (0.76 Ma), Lava Creek B ash bed (~0.66 Ma), and the Dibekulewe ash bed (~0.51 Ma), which erupted from the Long Valley volcanic field (upper Glass Mountain and Bishop), Yellowstone caldera, and southern Cascades, respectively (Knott and others, 1996a, in press). Correlation of these ash beds is based on a combination of the major-, minor-, and trace-element composition of the glass shards, paleomagnetism, and relative stratigraphic position. Based on these correlations, the sedimentary rocks at MP were informally named the Mormon Point formation (fig. 2). The Mormon Point formation records alluvial fan, lacustrine, and playa margin sedimentation from about 0.5 to 1.0 Ma. The base of the Mormon Point formation is either unexposed or is a fault contact with the Mormon Point Turtleback fault.

The Mormon Point formation can be divided into several stratigraphic members. The conglomerate member consists of angular, poorly sorted debris flow deposits and moderately sorted braided stream deposits that are interpreted as an alluvial fan depositional environment. The mudstone member is composed of deposits from several depositional environments and is exposed only west of MP. The most prominent beds are green, laminated, ripple-marked mudstone interpreted as a perennial lake depositional environment. In some areas, the mudstone is interbedded with scarce alluvial fan breccia and resistant and sandy marl. The interbedding of breccia and marl is interpreted to indicate that MP was near the lake shore (Knott and others, 1996b). The mudstone member can be further divided into a lower mudstone containing upper Glass Mountain ash beds, a middle mudstone member including the Lava Creek B (LCB) ash bed, and an upper mudstone member that contains the Dibekulewe ash bed (~ 0.51 Ma). The ages of the lake stands recorded by the mudstone members of the Mormon Point formation are roughly the

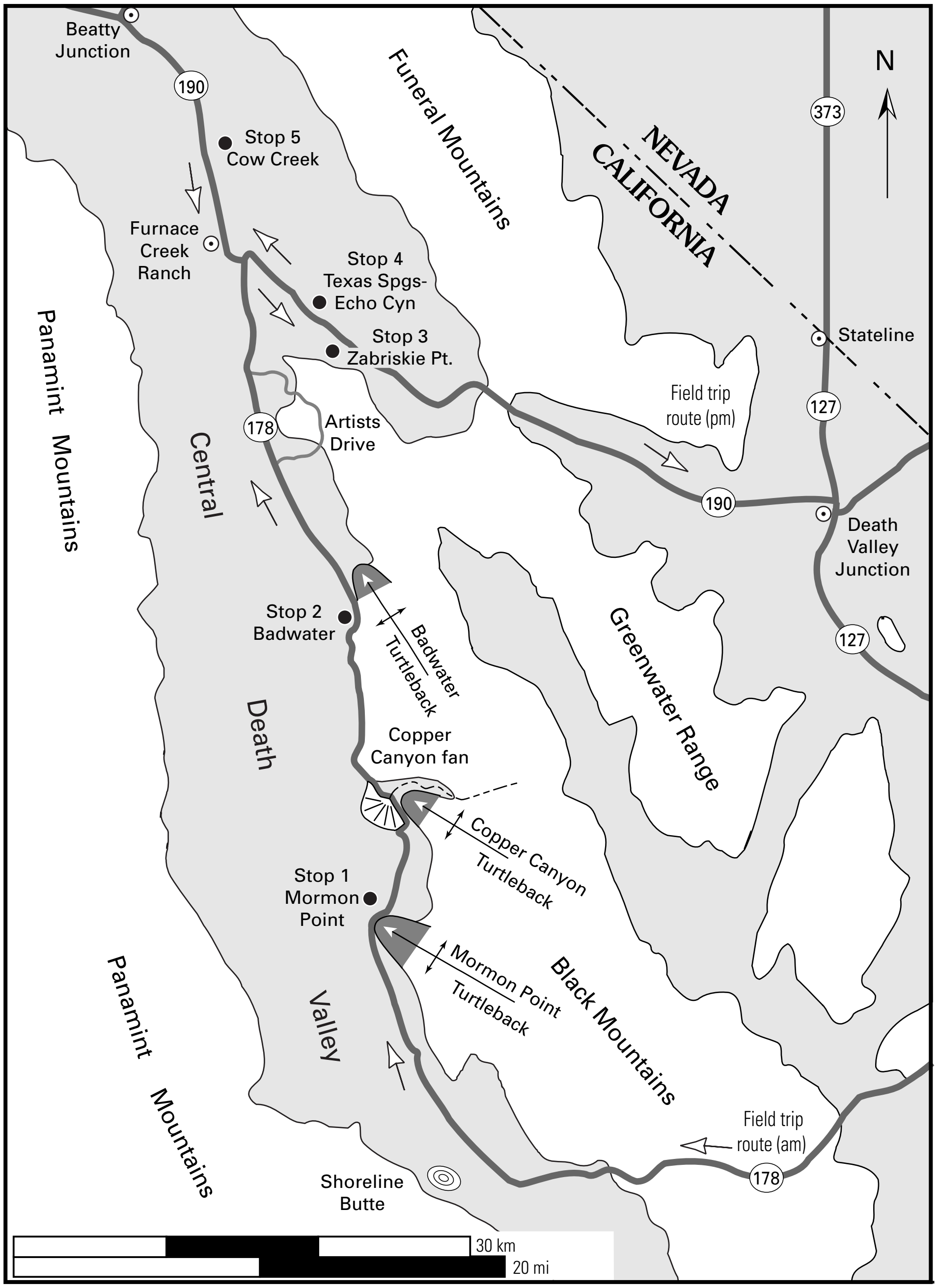

Figure 1. Map showing field trip route (arrows) and stops. Quaternary basins shown by light shade.

same as lake stands in pluvial Searles, Tecopa, Bonneville, and other Pleistocene basins of the Great Basin (Jannik and others, 1991; Smith, 1984; Morrison, 1991).

The Mormon Point formation is also found as conglomerates overlying the north end of the Badwater Turtleback at Natural Bridge. Both of these localities are examples of basinward stepping of the Death Valley fault zone, and incorporation of hanging-wall basin sediments onto the footwall.

STRANDLINES VS. FAULT SCARPS

Noble, Gregory, and Davis first described pluvial lake strandlines in Death Valley (Noble, 1926). Subsequently, the near-horizontal benches* at Mormon Point (MP) that Noble and Davis interpreted as strandlines have been cited (Blackwelder, 1933, 1954; Hunt and Mabey, 1966; Hooke, 1972; Burchfiel and others, 1995; Li and others, 1996),

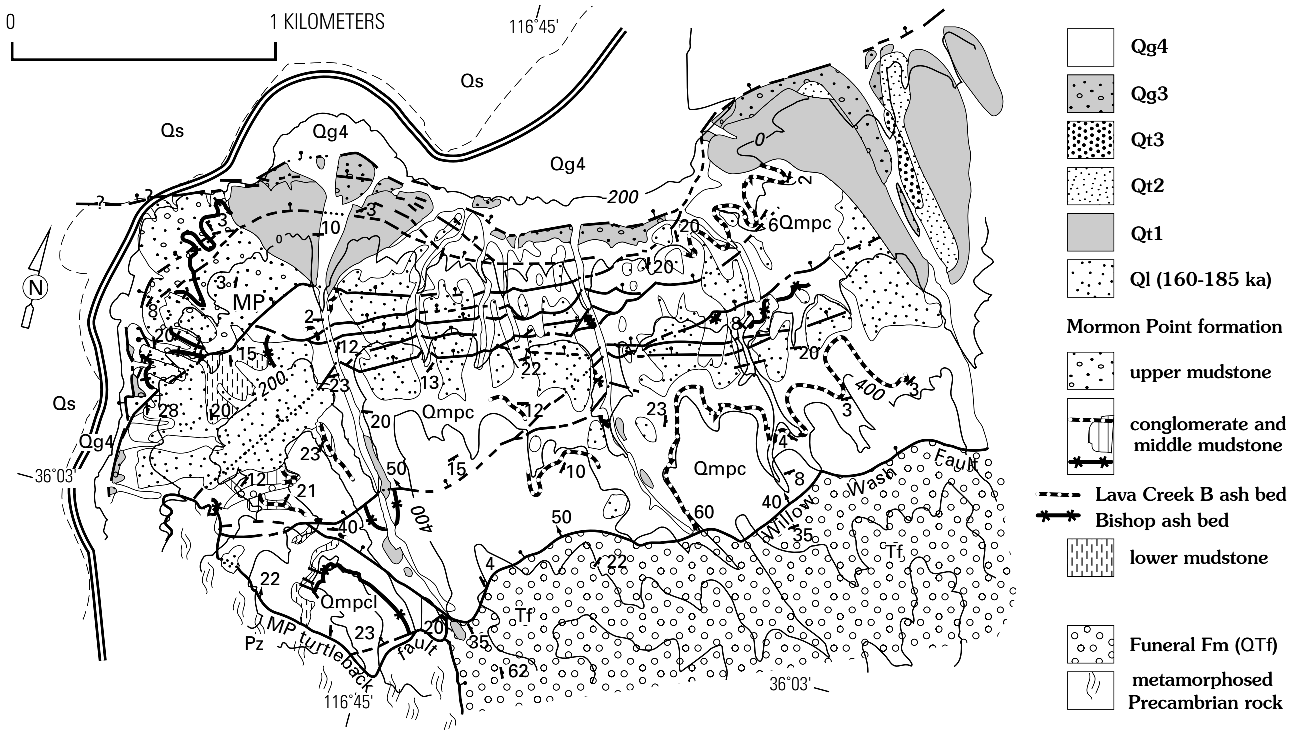

Figure 2. Map showing ash beds at Mormon Point (MP).

measured (Hooke, 1972; Pack and Reid, 1995; Meek, 1997) and dated (Dorn and others, 1989, 1990; Trull and others, 1995) to elucidate the history of pluvial Death Valley lakes.

Several later studies of the paleobathymetry of Death Valley lakes (Hooke, 1972; Dorn and others, 1990; Li and others, 1996) have linked lacustrine muds found in cores through the salt pan to strandline features at MP. The MP area has been of particular interest because it is here that strandlines from both the older (128–186 ka) and younger (10–36 ka) lake events identified in cores are found (Dorn and others, 1990). Tufa near elevation +90 m that is interbedded with gravels near Badwater has been dated between 160 and 185 ka by uranium series (Lowenstein and others, 1994).

In contrast to previous studies, our observations, geologic mapping, and geomorphic analysis indicate that only the highest bench at MP (+90 m) is a lake strandline. Based on nearly continuous exposure to Badwater, this strandline is correlated with the 160–185 ka strandline at Badwater by nearly continuous exposure. The topographically lower benches on the north-descending slope below the strandline are fault and fault-line scarps that offset the abrasion platform from the 160–185 ka lake.

On the topographically lowest bench, no evidence of lacustrine deposits from the ~13-ka lake strandline of Dorn and others (1990) was found. Facies exposed in the canyon walls, the surface morphology, surface gradient, and map pattern all suggest that this bench is the surface of an older alluvial fan. The surface of the older alluvial fan is inset below the surface of the 160–185-ka lake abrasion platform, thus providing a maximum age for this fan. Surface morphology and preliminary observations of soil development suggest that the age of the alluvial fan surface is probably late Pleistocene.

Thus, the MP benches are reinterpreted as a single strandline near 90 m above sea level, and the remaining benches are interpreted as fault scarps. This interpretation implies that (1) the 160–185 ka lake receded rapidly enough so as not to cut strandline benches into the abrasion platform at MP; (2) the 10–30 ka lake did not cover the older alluvial fan whose toe extends to elevation –30 m. In addition, (3) late Quaternary activity on the Death Valley fault zone at MP has been over a 1-km-wide zone; however, the fault zone has stepped basinward about 0.5 km since the late Pleistocene.

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* A bench is defined as a small steplike ledge breaking the continuity of a slope that is formed by either wave action, fluvial, tectonic, gravity, or erosional processes. Bench is preferred over terrace or strandline because it is observational and does not imply a particular process.

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WILLOW CREEK FAULT SCARP

Ralph E. Klinger* and Lucille A. Piety, Bureau of Reclamation, Denver, CO (*stop leader)

Young scarps are nearly continuous on Holocene alluvial fans along the Death Valley fault from Furnace Creek Ranch south to Shoreline Butte. At Mormon Point, an embayment in the Black Mountains is formed where the fault rounds the “Turtleback” and changes strike from NNW to NE. Between Willow Creek and the western flank of the Copper Canyon Turtleback, the strike of the fault gradually returns to NNW. Pronounced triangular facets and fault-line scarps are preserved on older alluvial deposits along this section of the fault. Younger fault scarps parallel these features and form the most recent trace of the Death Valley fault, but correlative geomorphic surfaces across the fault generally are poorly preserved. Commonly, surfaces on the hanging wall of the fault have been modified by erosion, deposition, or both. This complicates efforts to determine the sense of displacement, slip-per-event, the age of faulting, and hence fault activity rates. However, approximately 300 m north of the mouth of Willow Creek, a middle Holocene alluvial fan is preserved on both sides of the scarp (fig. 3).

At this location, the scarp crosses the alluvial slope at a high angle, and rills developed on the fan prior to faulting give the illusion of lateral offset across the fault. However, no evidence for lateral displacement was recognized at this site. Brogan and others (1991, p. 17) reported that the fault scarps in the Willow Creek area reach a maximum height of 9.4 m and that scarp angles range from 21° to overhanging. They also implied that the overhanging scarps provide evidence for local reverse faulting. However, close examination of these scarps indicates that the original scarp is being preserved by cementation of the alluvium by soluble salts (primarily halite and gypsum) blown from the adjacent salt pan and translocated into the soil profile. Cementation by salts of the alluvium within 0.3–0.5 m of the ground surface is common, as would be expected given the proximity of the scarps to the salt pan and the very low mean-annual precipitation (~40 mm) in this part of Death Valley. Rather than

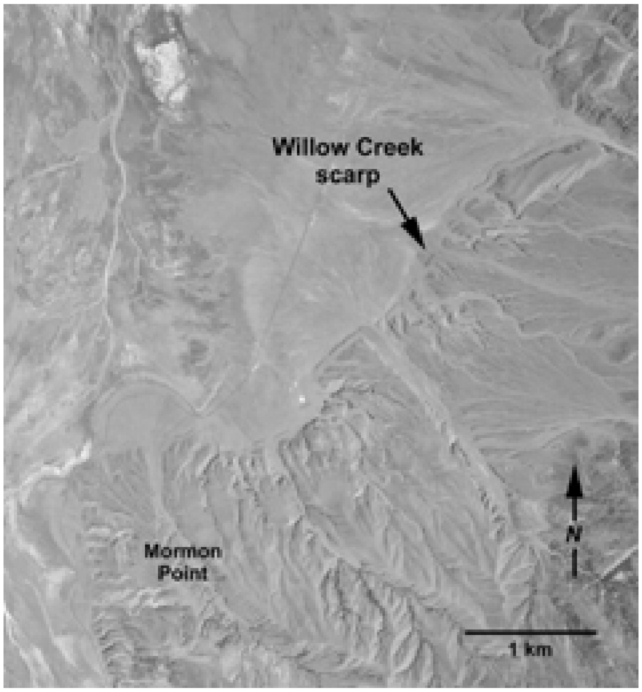

Figure 3. Vertical aerial photograph of the area near Mormon Point.

indicating local reverse faulting as suggested by Brogan and others (1991), the overhanging scarps along the Death Valley fault may reflect the more resistant, salt-impregnated alluvium that overlies erodible, poorly cemented alluvium at the base of the scarp and thus represents an unusual style of scarp degradation.

Owing to the probable young age of the scarps and the complex factors controlling their degradation, analysis of the scarp height and slope-angle measurements is complicated. Most scarps along the length of the Death Valley fault have a vertical or near-vertical section. While the vertical or overhanging morphology of these scarps could be viewed as an indicator of scarp youthfulness, the morphology also reflects the environment in which the scarps are preserved as well as the scarp degradation process. Rather than following a slope-decline model of fault-scarp degradation as described by Wallace (1977), some scarps in Death Valley follow a model of parallel retreat as outlined by Young (1972).

A scarp profile was measured near Willow Creek in order to determine the amount of surface displacement across the fault since the middle Holocene and to estimate the slip rate and return periods on the Death Valley fault (fig. 4). The maximum scarp-slope angle of 90° and total scarp height of 10.5 m were measured. Scarp-slope angles range from the angle of repose at the toe to vertical near the crest. On the basis of the alluvial-fan surface characteristics, the scarp height is within 0.5 m of the total vertical displacement of the surface since its stabilization. The two near-vertical portions of the scarp near the crest (2.1 and 2.6 m high) are interpreted to be separate free faces, each produced by a ground-rupturing earthquake. This hypothesis is supported by the relation between the vertical portions of the scarp and adjacent uplifted stream terraces near the mouth of Willow Creek. Terraces can be traced to the base of each free face and illustrate incision that followed the surface displacement.

Assuming that the uplifted terraces associated with the scarp are the result of deformation produced by past earthquakes, then the height of preserved free faces approximates the amount of surface displacement resulting from each ground-rupturing event. In addition, based on the

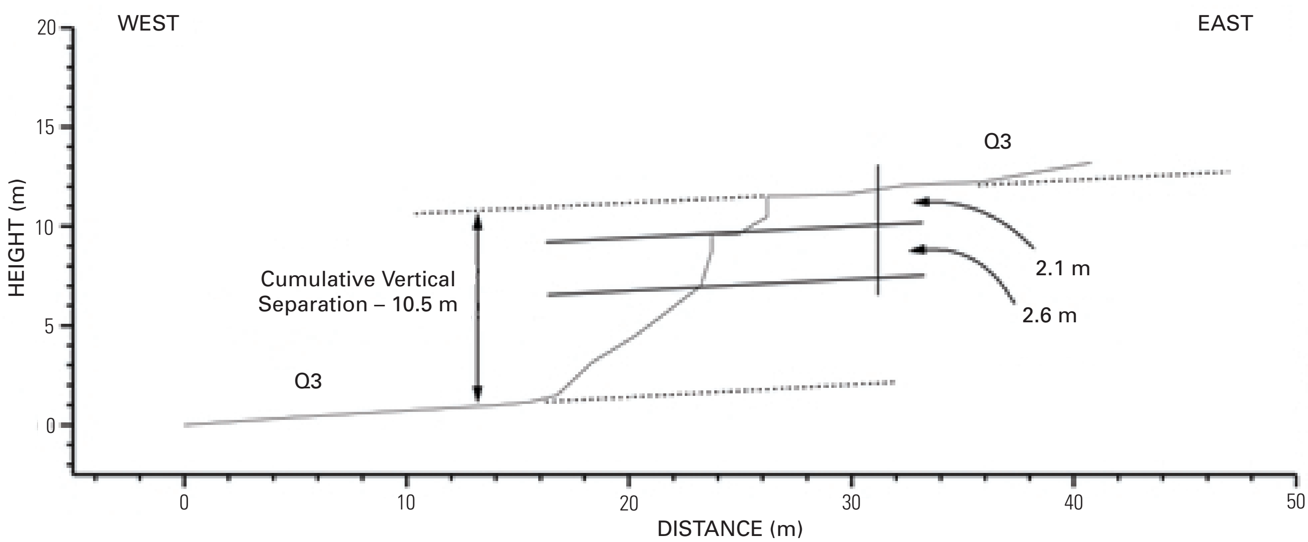

Figure 4. Topographic profile of the Willow Creek scarp.

relation between the scarp and the uplifted terraces, the scarp near Willow Creek records at least three events in middle Holocene deposits. The measured heights of 2.1 and 2.6 m for the two relatively well preserved free faces would then represent the minimum surface displacement per event assuming that minimal scarp degradation occurred between events. This is in agreement with vertical separations measured elsewhere along the Death Valley fault. If these values of displacement per event are characteristic of ground-rupturing earthquakes at this site, then the 10.5-m fault scarp at Willow Creek most likely represents four events. On the basis of its surface characteristics and the degree of soil development, the faulted geomorphic surface at this site is assigned a middle to early Holocene age (approx. 4–8 ka). This indicates that the return period for ground-rupturing earthquakes is between 1 and 2 k.y. Based on the estimated age for this surface and a scarp height of 10.5 m, the average vertical slip rate since the middle Holocene is about 1.3 to 2.6 mm/yr.

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STOP 2 – Badwater (M. Miller, T. Lowenstein, and D. Anderson, Discussion Leaders)

BEDROCK GEOLOGY NEAR BADWATER SPRING

Martin G. Miller
Dept. of Geological Sciences, University of Oregon,
Eugene, OR 97403

The mountain front behind Badwater consists of Precambrian metamorphic basement rock intruded by the late Tertiary Willow Spring pluton. These rocks are intruded by felsic dikes and cut by three generations of faults. Figure 5 illustrates the most important relations.

Basement rock consists largely of mylonitic quartz-feldspar gneiss that yields a strongly discordant U-Pb zircon age of 1.7 Ga (Miller, 1992). A prominent northwest-trending stretching lineation, combined with abundant micro- and mesoscale kinematic indicators, indicates top-to-the-northwest translation during late Tertiary extension. These mylonites mark the southern extent of the mylonitic footwall of the Badwater Turtleback. The Willow Spring pluton, which intruded at 11 Ma (Asmerom and others, 1990), displays a range of compositions from diorite to gabbro (Wright and others, 1991). It generally lies structurally above, and roughly concordant to foliation in the basement rock of all three turtlebacks. The exposures near Badwater mark its northernmost extent.

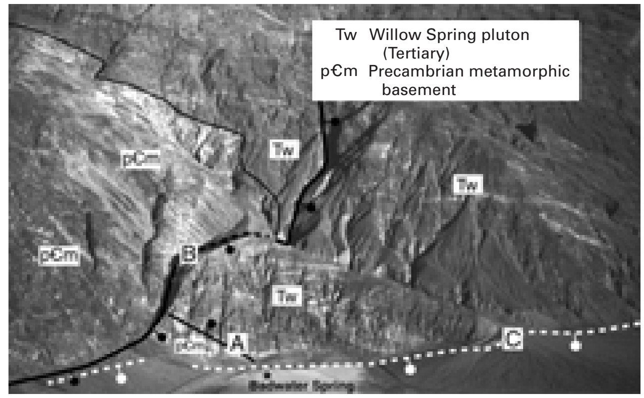

Figure 5. Aerial view of Badwater Spring and bedrock geology of adjacent mountain front looking southeastward. Note that the Willow Spring pluton (Tw) forms a sill-like body structurally above mylonitic basement rock of the Badwater Turtleback.

The main faults near Badwater are labelled A, B, C in figure 5. Each postdates the Willow Spring Pluton, but all show crosscutting relations to indicate they represent at least three stages of faulting. Fault A, the oldest fault, is exposed in the cliffs immediately behind Badwater where it separates basement gneiss from overlying rocks of the Willow Spring pluton. This fault may be equivalent to a similar early-stage fault at the north end of the Badwater Turtleback (Miller, 1991). Fault B, the southern extent of the main Badwater Turtleback fault, cuts fault A (fig. 5). There, fault B leaves the mountain front but rejoins it just south of the area of figure 5. Gravel deposits, stranded above the valley floor immediately north of Badwater Spring, depositionally overlie fault B to indicate it is no longer active. Fault C, the modern range-front fault, is marked by abundant fault scarps in the alluvium and appears to localize Badwater Spring.

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BADWATER CORE STUDIES

T. Lowenstein:

A 186-m-long core (DV93-1) from Badwater Basin was drilled during April and May 1993 by the USGS drilling team under the direction of Art Clark. The particular site was chosen to (1) recover a thick section with abundant evaporites; (2) minimize the chance of a well blowout, by drilling far away from alluvial fan sediments; and (3) comply with acceptable locations designated by the National Park Service. All equipment was flown to and from the drill site by helicopter. The core is composed of interbedded salts and muds, which contain a 200-k.y. record of closed-basin environments and paleoclimates, interpreted on the basis of sedimentology, ostracodes, homogenization temperatures of fluid inclusions in halite, and saline mineralogy. Virtually all salt layers were completely recovered but some mud intervals were lost (~60 percent recovery of muds). Much of the work on the core was done by graduate students from SUNY Binghamton (Jianren Li and Chris Brown) and from the University of Calgary (Sheila Roberts and Wenbo Yang). Richard Forester, USGS Denver, studied the ostracodes. Twelve U-series dates were obtained by Richard Ku and Shangde Luo from the University of Southern California. The 200-k.y. paleoclimate record is dominated by two dry and (or) warm and wet and cold cycles that occurred on a 100-k.y. time scale. These cycles begin with mudflat deposits (192 ka to bottom of core, and 60 ka to 120 ka). Wetter and (or) colder conditions produced greater effective moisture; saline pan and shallow saline lake evaporites overlie mudflat sediments (186 ka to 192 ka and 35 ka to 60 ka). Eventually, enough water entered Death Valley to sustain perennial lakes that had fluctuating water levels and salinities (120 ka to 186 ka and 10 ka to 35 ka). When more arid conditions returned, mudflat deposits accumulated on top of the perennial lake sediments, completing the cycle (120 ka and 10 ka). Of particular significance are the major lacustrine phases, 10 ka to 35 ka and 120 ka to 186 ka (oxygen isotope stages 2 and 5e-6), which represent markedly colder and wetter conditions than those of modern Death Valley. Of the two major lake periods, the penultimate glacial lakes were deeper and far longer lasting than those of the last glacial.

D. Anderson:

Ten shallow sediment cores were taken from Death Valley along a 75-km transect from Devil's Speedway south to near the Confidence Hills (D. Anderson, this volume). The cores were acquired using a truck-mounted hollow-stem auger; the deepest core was 26.03 m, total core length for all 10 sites was 185.2 m. Four of the cores, DVDP96-10, -9, -6, and -2 were dated by AMS radiocarbon on bulk organic carbon from core sediments. Fluvial, alluvial fan, mudflat, saline pan, and lacustrine depositional facies were identified in the cores. Lacustrine events date to ~12 ka, ~18 ka, and >26 ka (uncalibrated ages). These data may be used in tandem with the lacustrine framework provided by Li and others (1996), to provide a chronology of high-stands within the 35–10 ka latest Pleistocene lake event.

STOP 3 – Zabriskie Point (L. Wright and R. Blakely, Discussion Leaders)

Modified from Wright and others, 1991:

From the lookout at Zabriskie Point (fig. 6), the observer stands upon northeast-dipping, lacustrine sandstones, and mudstones of the middle part of the Furnace Creek Formation. These strata are characteristic of most of the thickness of the formation. The lower part of the Furnace Creek, including a basal conglomerate, coincides with the low badland topography to the southwest. The underlying Artist Drive Formation forms the ridge beyond. The break in slope approximates the depositional contact between the two. A thick conglomerate in the upper part of the Furnace Creek Formation underlies the low ridge immediately north and northwest of the viewing area and is well exposed in a nearby bank on the southwest side of the highway. This is one of the conglomerates that contain clasts derived from the Proterozoic and Paleozoic formations no longer exposed in the northern Black Mountains, but present as remnants in the subsurface beneath the Furnace Creek Basin.

This stop affords an opportunity to discuss Furnace Creek Basin stratigraphy in some detail, the relationship of basin formation to regional structural elements, and the proximity to the central Death Valley volcanic highland to the south (presented by L. Wright). Additionally, a summary of ongoing geophysical efforts to constrain present basin geometry, including estimates of depth-to-basement for Death Valley and Amargosa Valley will be discussed (presented by R. Blakely).

Figure 6. View west from Zabriskie Point lookout.

STOP 4 – Texas Springs–Echo Canyon (L. Piety, Discussion Leader)

TEXAS SPRING SYNCLINE AND ECHO CANYON THRUST

Ralph E. Klinger and Lucille A. Piety*, Bureau of Reclamation, Denver, CO (*stop leader)

The Texas Spring syncline is a NW-trending, SE-plunging asymmetric fold that forms the valley through which Furnace Creek Wash flows to Death Valley. Furnace Creek Wash presently flows parallel to and just SW of the axial plane against the steeply NE 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 that was 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 wedge of upper Cenozoic sedimentary rocks sandwiched between the N-striking, down-to-the-west normal Death Valley fault to the S- and NW-striking, right-lateral strike-slip Furnace Creek fault to the north. The uplifted Black Mountains, the footwall block of the Death Valley fault, forms the southwestern margin of the Furnace Creek trough (Cemen and others, 1985).

Stratigraphic relations indicate that deformation across the syncline has occurred periodically since about 25 Ma (Hunt and Mabey, 1966; McAllister, 1970; Cemen and others, 1985). Late Pleistocene and possibly Holocene deformation both parallel to and normal to the axis of the syncline is indicated by young scarps and the geomorphic relations between the alluvial deposits along and near the axis of the syncline.

Along the length of Furnace Creek Wash, gravelly alluvial fan deposits are being moved from the Funeral Mountains into the structural trough to the SW. The young gravelly deposits on the NE limb of the fold are typically inset into Pleistocene Funeral Formation, but near the axis of the syncline, the younger alluvial deposits bury older units. These relations are illustrated in topographic profiles that were measured along an upper Pleistocene surface that is almost continuous across the axis of the syncline (fig. 7*A*) and along adjacent Holocene surfaces. Tectonic deformation of the upper Pleistocene surface, and possibly the lower and middle Holocene surfaces, is indicated by the varying heights of the surface profiles above the active

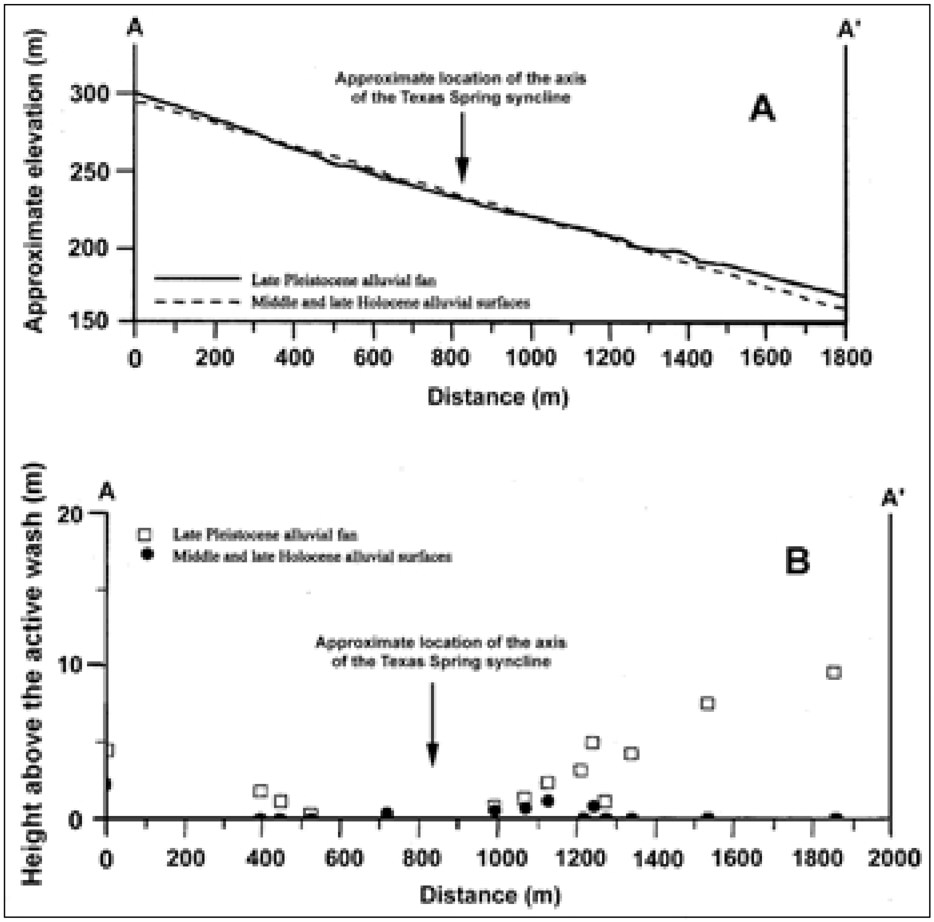

Figure 7. *A*, Topographic profiles of late Pleistocene and Holocene alluvial fan surfaces across axis of Texas Spring syncline near Echo Canyon road. *B*, Heights of surfaces above active wash.

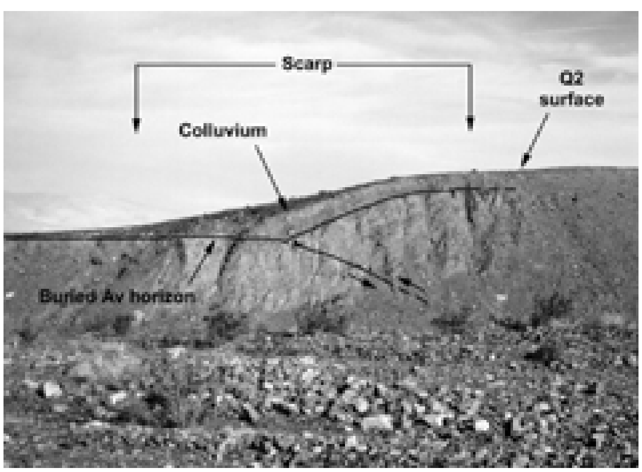

Figure 8. Photograph of fault exposed below scarp near Echo Canyon road.

wash (fig. 7*B*). The upper Pleistocene surface, which is well above younger surfaces near the range front, is buried by younger surfaces near the axis of the syncline, then progressively rises above the younger surfaces on the southwest limb. Deformation of the upper Pleistocene surface mimics the morphology of the broad syncline and the deformed strata of the underlying Furnace Creek and Funeral formations (McAllister, 1970), although the amount of deformation of the upper Pleistocene surface is much less than that of the older sediment. It is difficult to explain these relations by erosion and alluvial deposition without accompanying tectonic deformation of the Texas Spring syncline.

Northwest-trending fault scarps are also preserved on upper Pleistocene surfaces on both limbs of the Texas Springs syncline (fig. 8). Natural exposures in stream channels incised into the scarps on the SW limb of the syncline near the Echo Canyon road reveal a fault that displaces the soil associated with the upper Pleistocene surface. Due to their short length, their orientation parallel to the axis of the syncline, and their presence on both limbs of the fold, displacement along these faults is probably related to deformation of the syncline. This fault is referred to by Klinger and Piety (1996) as the Echo Canyon thrust, but it represents a bedding-plane fault associated with flexure of the SW limb of the Texas Spring syncline.

The morphology of the scarps associated with the fault indicates that deformation has occurred across the syncline since the late Pleistocene, and perhaps as recently as late Holocene. The rock varnish and desert pavement formed on the upper Pleistocene surface are disrupted at the scarp; varnish on the scarp slope is poorly developed. A scarp height of 5.4 m and maximum scarp-slope angles of 22°–25° were measured along the Echo Canyon thrust fault. The sense of slip across the fault is readily apparent in channel exposures and the fault extends nearly to the surface, indicating young movement. The soil developed on the surface is clearly disrupted, and the stone pavement developed on the surface is buried by material that has been thrust up along the fault and over the footwall block. The total displacement across the fault at this site most likely did not occur during a single event, but probably represents brittle deformation on the SW limb of the fold as the result of numerous deformational events. Based on observations of coseismic deformation in a fold accompanying ground rupture from the Superstition Hills earthquake sequence in the Salton Trough in 1987 (Klinger and Rockwell, 1989), movement on the thrust fault and bedding-parallel slip on beds within the deformed strata in the syncline likely occurred during a seismic event on either the Furnace Creek fault, the Death Valley fault, or both. Observed displacement on secondary faults and bedding planes within the fold associated with the Superstition Hills event ranged between 20 and 40 percent of the average slip on the main fault. If this relationship is representative of the strain across the Texas Spring syncline, then the total displacement observed on the Echo Canyon thrust may be the product of 6–8 events on the adjacent Death Valley and (or) Furnace Creek fault zones.

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STOP 5 – Cow Creek (M. Machette, Discussion Leader)

EVIDENCE FOR RECENT FAULTING ADJACENT TO THE COW CREEK ADMINISTRATIVE AREA, DEATH VALLEY

Michael N. Machette, U.S. Geological Survey, P.O. Box 25046, Denver Federal Center, M.S. 966, Denver, CO 80225

This stop is located on the northern margin of the Cow Creek Administrative area, about 8 km north of Furnace Creek. The landscape here is dominated by the Old Ghost alluvial fan complex, which consists of Holocene to middle(?) Pleistocene piedmont surfaces that have been deformed by surface faulting. The scarps we visit here are small but young—*please make every effort to stay off the scarps in order to preserve their fragile morphology.*

In summer 1998, the USGS and NPS entered into a cooperative agreement in order to address the short-term seismic hazards at the Cow Creek Administrative area (the facility). Their immediate plans called for construction of a new Museum Curator's building, a new Death Valley Natural History Association building, and relocation of the existing maintenance yard. At least one of these buildings is under construction now (April 1999). In addition, a number of existing buildings at the site are constructed of adobe, and these present special challenges in terms of seismic risk. (For a more complete discussion of seismic hazards in this area, see Machette and others, this volume and in press.)

PALEOSEISMIC STUDIES

Three sites at the Cow Creek facility were investigated by exploratory trenching. Two backhoe trenches penetrated alluvial deposits and the underlying lacustrine or bedrock materials. The purpose of these trenches was 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, and as such, these sites were cleared for future construction. The hand-dug trench on the Old Ghost alluvial fan complex was only 1.5 m deep and 3 m long, but it exposed faults associated with young scarps northwest of the facility (at the Old Ghost site). The purpose of this stop is to explore evidence for the timing and recurrence of young faulting at this locality.

SURFICIAL GEOLOGY

Most previous surficial geologic mapping of the area used a four-fold division of Quaternary units. This scheme originated with the early mapping of Hunt and Mabey (1966) and was accepted and utilized by Wright and Troxel (1993). For detailed studies, further subdivison is based on geomorphic and soil characteristics as outlined by Klinger

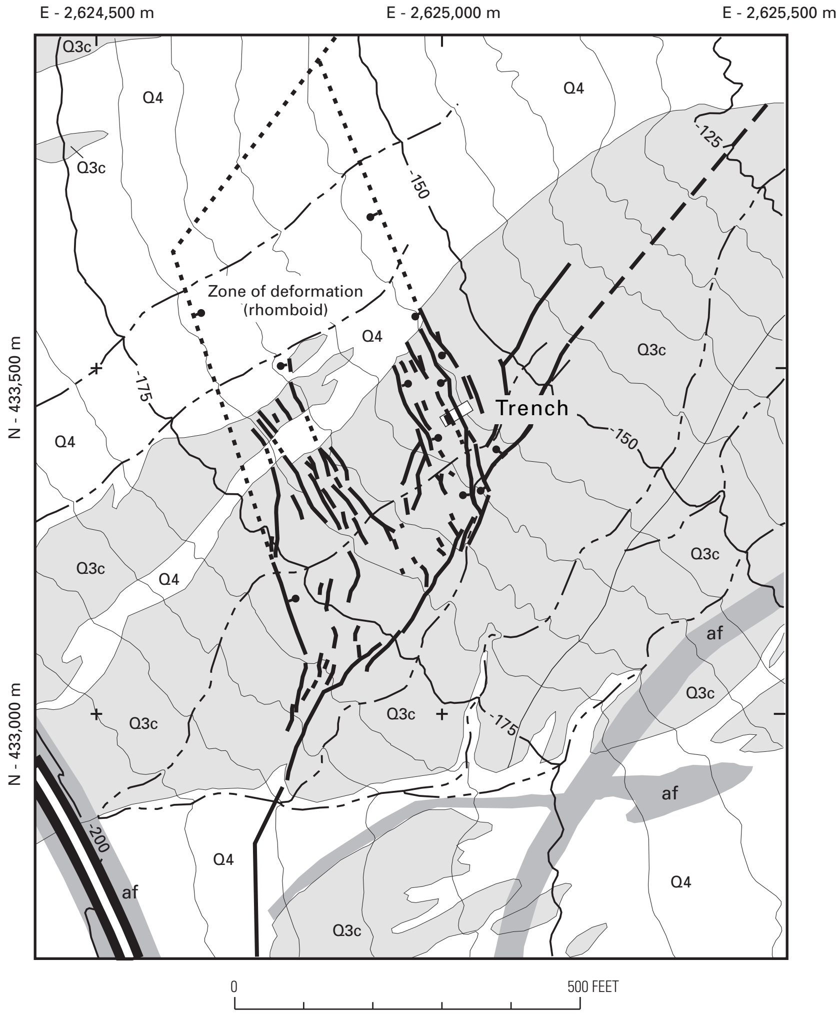

Figure 9. Detailed map of young faulting on the Old Ghost alluvial fan complex, Cow Creek area, Death Valley, Calif. Old Ghost trench site shown by white box. Refer to text for explanation of units. Faults slightly modified from Machette and others (in press, pl. 1); af, artificial fill; highway 190 shown at lower left.

and Piety (1996). In this study, we used a modified version of Klinger and Piety's (1996) stratigraphic column (see Machette and others, in press). The three younger units (Q4, Q3, and Q2) were mapped at the site, but unit Q1 was not recognized in this area.

Unit Q4 underlies about 50 percent of the Cow Creek alluvial-fan complex (fig. 9), and forms the youngest parts of the landscape. These areas are commonly the location of historic debris-flow and flood events. Unit Q4 has original or slightly modified surface morphology (expressed as bar-and-swale topography), exhibits light to no desert varnish on poorly developed desert pavement, and lacks zonal soils (see Klinger and Piety, 1996, table 2).

Alluvial unit Q3 and its two subunits (Q3c and Q3ab of increasing age) form about 30 percent of the piedmont-slope west of Park Village ridge, which is the high ridge east of this stop. The surfaces underlain by subunits of Q3 are characterized by subdued bar-and-swale topography (typically equal parts), medium to dark desert varnish on well-developed desert pavements, medium to thick vesicular A horizons, and weakly developed zonal soils on subunit Q3ab. Unit Q3c is the youngest faulted unit at the site.

Unit Q2, which is entirely pre-Holocene, is divided into three subunits—Q2c, Q2b, and Q2x—on the basis of topographic position, geomorphic preservation, and its characteristically dark varnished desert pavement. Subunits

Q2c and Q2b form about 20 percent of the Cow Creek alluvial fan complex. Aerial photographs of the Park Village ridge indicate several levels of erosion surfaces that appear to be capped by a thin (<1 m) to moderate (1–5 m) thickness of gravel (unit Q2x) reworked from the upper part of the Pliocene-Pleistocene Funeral Formation. These surfaces project westward into the air and do not appear to have ever been of wide extent. 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 numerous faulting events (see following discussion).

EVIDENCE FOR FAULTING AT AND NEAR THE FACILITY

The Cow Creek facility is located in a transition zone between the south end of the Furnace Creek fault and the north end of the Death Valley fault. This transition zone is a structurally complex area that accommodates a transfer of right-lateral slip on the Furnace Creek fault to the Death Valley fault, considered to be a predominantly normal fault. This area has been mapped at intermediate detail, but little is known about the subsurface linkages and recent faulting history of these two fundamental seismic sources.

Although no evidence of young faults was found within the facility, evidence for young faulting (the Cow Creek scarps) are preserved at the Old Ghost site, just 1/2 km to the north. We found no evidence for displacement of unit Q4 (late Holocene), thus precluding extremely young offset (historic to several hundred years). However, the steep slopes associated with the scarps on unit Q3c, which are typically <1 m high, suggest that they were formed in the late Holocene.

At the Old Ghost site, the fault zone comprises a main and an antithetic scarp, a shallow 20-m-wide graben between them, and numerous sediment-filled fissures (fig. 9). A hand-dug trench across the main scarp revealed only a single deposit of colluvium—evidence that a single faulting event formed the existing scarp on unit Q3c. Klinger and Piety (1996) suggested that unit Q3c was deposited between 0.2 ka and 2 ka; we favor the older portion of this range (>1 ka) owing to the burial of the Av horizon, which must have required several hundred years (or more) to develop on the Q3c surface.

The fault pattern here forms a series of right-stepping rhomboids, the east and west sides being defined by prominent normal faults, and the north and south sides being defined by subdued normal or strike-slip faults. The latter faults are typically parallel or subparallel to drainage channels, making their recognition difficult. This pattern, although most apparent at the Old Ghost site, is also seen to the north on older deposits (unit Q2b). 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 Hills and ultimately connect to the Death Valley fault zone near Furnace Creek.

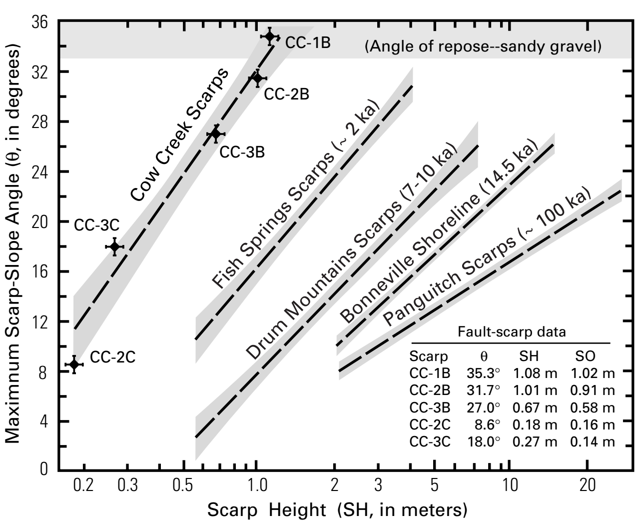

Figure 10. Morphometric data for fault scarps at the Old Ghost site. Abbreviations: θ, maximum scarp-slope angle; SH, scarp height (m); and SO, surface offset (m).

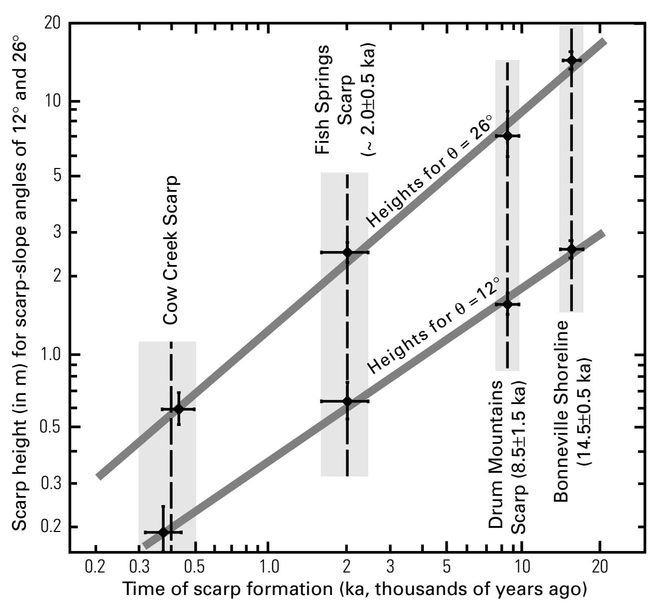

Figure 11. Data for estimating time of scarp formation at Old Ghost site, northwest of Cow Creek facility.

TIMING AND RECURRENCE OF FAULTING

The apparent youth of the Cow Creek scarps is obvious from the empirical data of scarp height and slope angle (fig. 10). The Cow Creek scarps are clearly younger that those of the 2-ka Fish Springs fault of western Nevada (Machette, 1989), but the question is how much younger? The larger of the Cow Creek scarps (which are only about 1 m high) have maximum slope angles that are at or exceed the angle of repose (commonly taken as 33° for unconsolidated sandy gravel).

In order to estimate a time of formation for the Cow Creek scarps (fig. 11), we used Bucknam and Anderson's (1979) approach to scarp morphology, added an estimated 100–200 yr for scarp collapse to the angle of repose, and applied degradation rates of 0.4–0.64 m^2/ka (see Machette and others, in press). The 0.64 m^2/ka rate (of the northern Basin and Range) yielded a minimum scarp age of 500–600 yr, whereas the 0.4 m^2/ka rate yielded a maximum scarp age of 740–840 yr. Using an average offset of 2/3 m per event, and an age of 70–200 k.y. for the 7 m to 14 m (buried) scarps to the north, we estimated a preferred slip rate of 0.1 mm/yr and an average recurrence interval of 6,700 yr. These parameters are but a fraction of those estimated for the Death Valley and Furnace Creek fault zones (see articles by Klinger, and dePolo and Hess, this volume) and indicate that faulting within the transition zone is clearly subordinate to the major tectonic elements of the valley.

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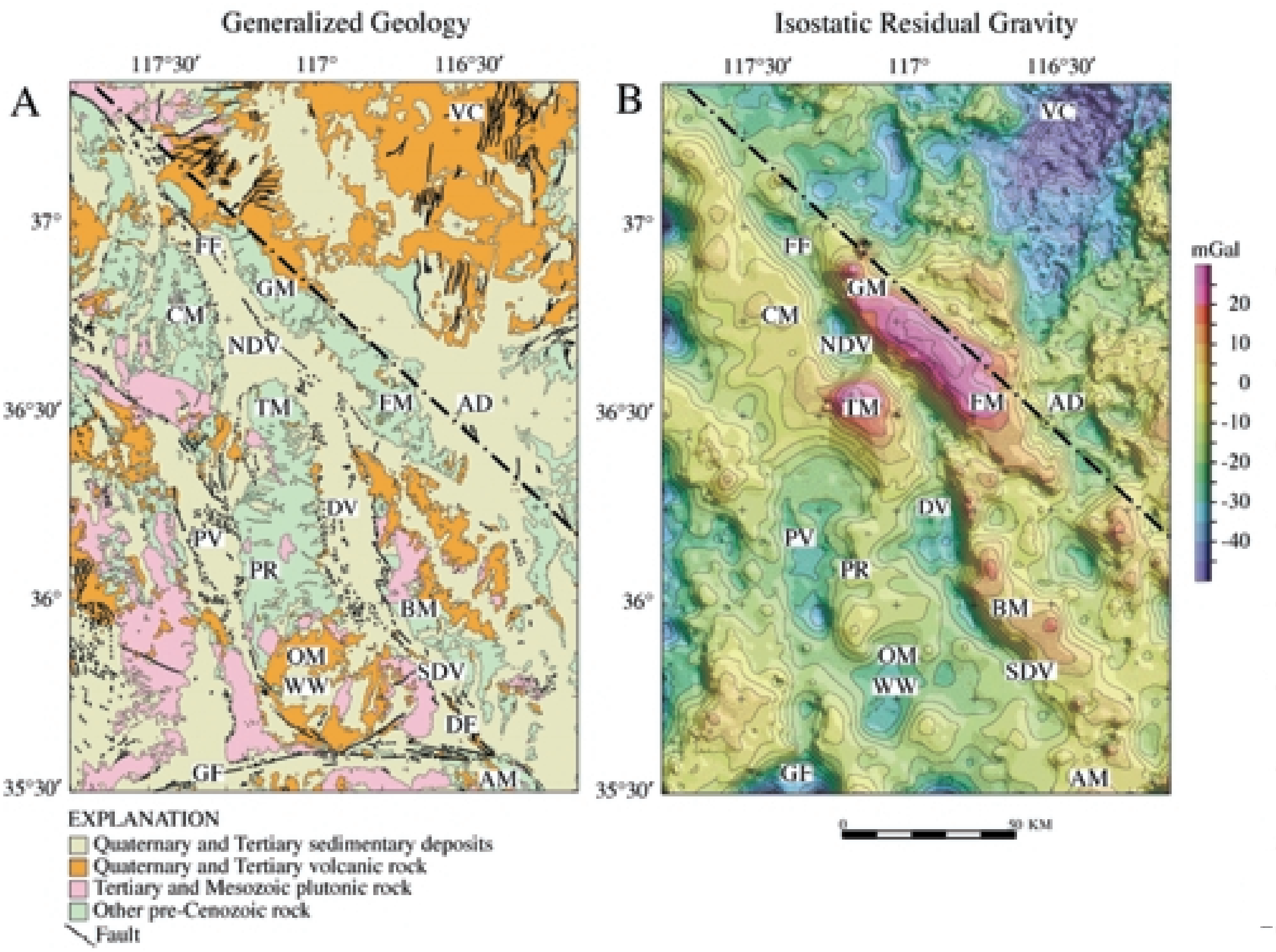
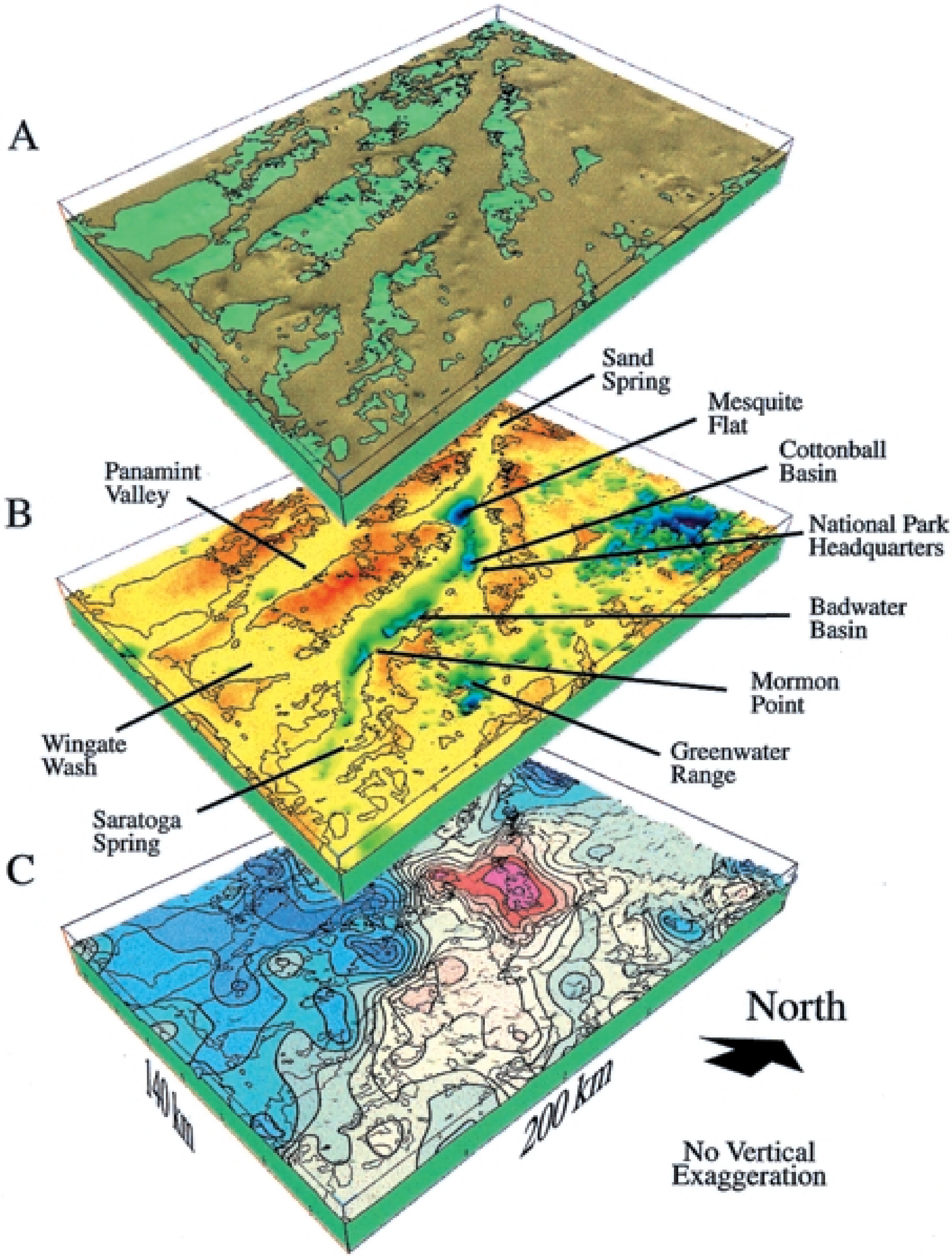
Manuscript approved for publication March 31, 1999
Published in the Central Region, Denver, Colorado
Graphics by the authors; completed for publication by
Gayle M. Dumonceaux
Photocomposition by Gayle M. Dumonceaux
Technical editor L.M.H. Carter



Generalized Geology
Isostatic Residual Gravity
A
B
117°30′
117°
116°30′
37°
36°30′
36°
35°30′
VC
FF
GM
CM
NDV
TM
FM
AD
DV
PV
PR
BM
OM
WW
SDV
DE
GF
AM
mGal
20
10
0
-10
-20
-30
-40
0
50 KM
EXPLANATION
Quaternary and Tertiary sedimentary deposits
Quaternary and Tertiary volcanic rock
Tertiary and Mesozoic plutonic rock
Other pre-Cenozoic rock
Fault


A
B
C
Sand Spring
Mesquite Flat
Cottonball Basin
Panamint Valley
National Park Headquarters
Badwater Basin
Mormon Point
Wingate Wash
Greenwater Range
Saratoga Spring
North
140 km
200 km
No Vertical Exaggeration