U.S. Department of the Interior
U.S. Geological Survey

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

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

*Open-File Report 01-51*

2001

USGS
*science for a changing world*

# Characteristics of Holocene fault scarp morphology, southern part of the Black Mountains fault zone, Death Valley

*Kurt L. Frankel, A.S. Jayko, and Allen F. Glazner*

## ABSTRACT

The 76-km-long Black Mountains fault zone (BMFZ) bounds the western margin of the Black Mountains in the central part of Death Valley. The BMFZ is but one of four active fault zones in the 310-km-long Death Valley fault system (see Chapter J in this volume). Previous workers found evidence for three Holocene events with predominantly normal displacement and 0.3 to 9.4 m of vertical separation on various sections of the fault zone (see Chapter L in this volume). We measured 21 scarp profiles at 11 locations along a 46-km portion on the BMFZ to characterize the relative ages of fault scarps and to determine if scarps of different relative ages could be correlated along the fault. Such information may provide constraints for future delineation of rupture segments. Results of the profiling indicate that at least three different scarp morphologies are present; two of these can be spatially correlated along part of the fault zone. These three morphologies are provisionally interpreted as being related to late, middle, and early Holocene faulting events, and referred to in the text as young, medium and old scarps. The young scarps are recognized mainly near, and south of Badwater (from about 0.5 km north of Badwater to about 17 km south of Badwater). The middle (?) Holocene age scarps are more extensive: they are found between Ashford Mills and about 0.5 km north of Badwater. Heights of the medium age scarps increases progressively from about 0.6 m in the south to about 6 m just north of Badwater, near the northern extent of the study area. The heights of the young scarps do not vary noticeably along the short distance they were measured. These results suggest that the only a portion of the length of the Black Mountains fault zone has ruptured during events in the Holocene.

These results are consistent with previous work and indicate that the scarps are young and that there were at least three rupture events during the Holocene. These results also indicate that surface rupture occurred along at least two spatially different rupture sections. The morphology of the youngest scarps compares favorably with that of the 1872 Owens Valley fault scarp, near Lone Pine, California. All scarps in the study area must be younger than marine oxygen-isotope stage II Lake Manly, the relatively shallow perennial lake that occupied central Death Valley during the latest Pleistocene (>10 ka).

## INTRODUCTION

The Black Mountains fault zone (BMFZ) forms an extensional stepover that connects the Northern Death Valley fault zone (see Chapter J in this volume for fault nomenclature) with the Southern Death Valley fault zone (Burchfiel and Stewart, 1966), locally creating a pull-apart basin and one of the longest fault zones (>310 km) in California (Brogan and others, 1991) (fig. M-1). Displacement on the BMFZ over the past 1 m.y. is characterized by oblique-slip, with horizontal motion comprising only a few hundred meters of offset and dip-slip dominating along the front of the Black Mountains (Butler and others, 1988). Fault scarps on alluvial fans at the base of the Black Mountains show evidence of late Holocene activity (Brogan and others, 1991; Klinger and Piety, 1996), but no major surface-rupturing earthquakes have been recorded in historic time (since 1849).

Brogan and others (1991) divided the BMFZ into 11 fault sections based on the trend of faults, recency expressed by geomorphic features, width of rupture zones, consistency of fault patterns, and proximity of active traces to the range front and bedrock features. In this volume (Chapter C), Knott and others suggest that the BMFZ has five sections. Brogan and others (1991) measured scarp-slope angles at 20 localities and they noted evidence for young faulting events, such as steep free faces and lack of varnish development. In addition, they measured the vertical surface offset of scarps as much as 15 m in height and found evidence for widespread ground rupture within the mapped Q1B unit (late Holocene surface), indicating three or more surface faulting events in the Holocene. Faults mapped along the Golden Canyon area of the fault zone (fig. M-2) were inferred to be almost historic, but no specific dates were assigned to these scarps (Brogan and others, 1991). Brogan and others (1991) study did not include measurement of scarp profiles or reporting of characteristics of offset fan surfaces.

Klinger and Piety (1994, 1996) also evaluated Quaternary activity on the BMFZ (along with many parts of the Death Valley fault system) as part of seismotectonic investigations for the Yucca Mountain high-level nuclear

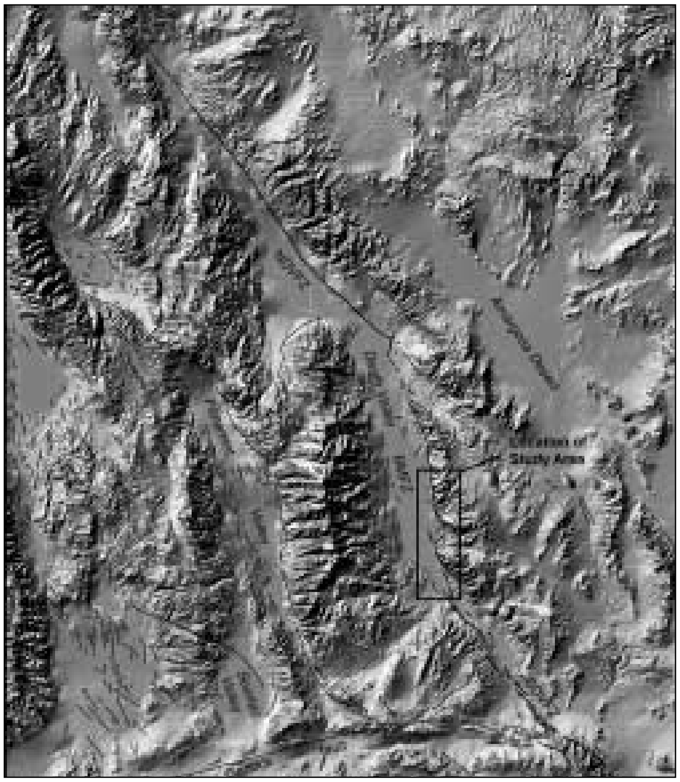


*Figure M-1. Shaded relief map showing location of major faults in the Death Valley area and location of study area shown in figure M-2.*

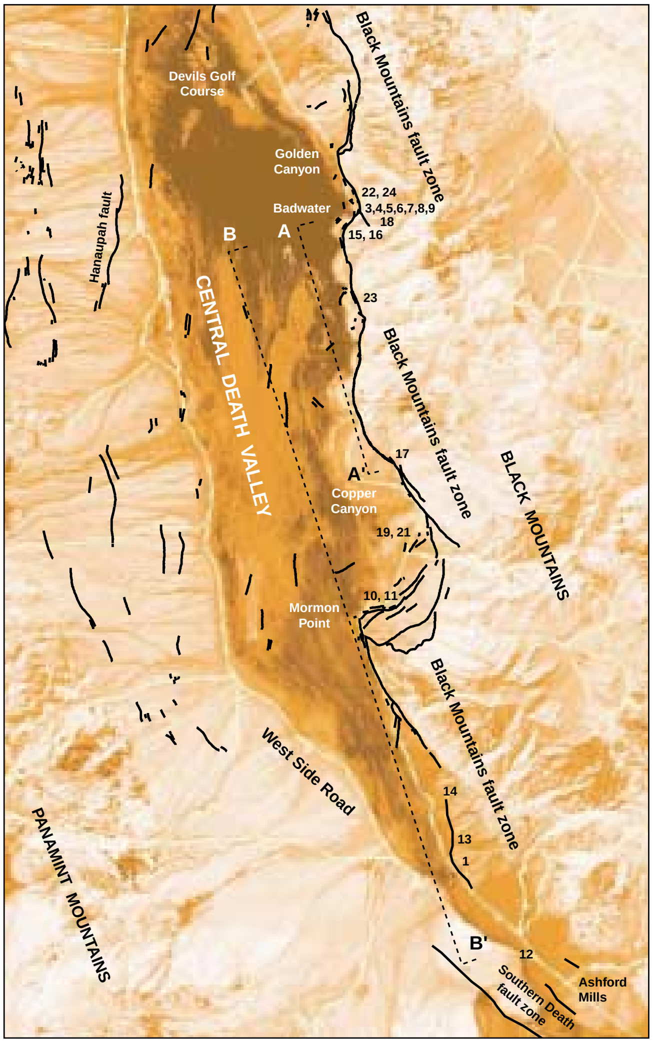


*Figure M-2. Map showing location of study area and numbered scarp profile localities. Faults from Reheis and Noller, 1996. Profile localities in table M-1 and air photo locations are in the Appendix, which follows the references. Lines A-A' and B-B' show extent of young and medium age scarps, respectively.*

waste repository site in Nevada, which is less than 50 km from the fault zone. Klinger and Piety (1994, 1996) found evidence for multiple surface-rupturing events during the late Holocene from a scarp having 10.5 m of displacement on a middle to late Holocene fan near Mormon Point (see Chapter K in this volume). Preserved free faces from the past two ground ruptures and inset tectonic terraces provide evidence for the past three or four events in this area. The average vertical displacement per event at the Mormon Point location was estimated to be 2.6-3.5 m (Klinger and Piety, 1994 and 1996). The age of the displaced fan surface at Mormon Point was estimated to be 2 to 4 ka, yielding an average vertical slip rate along the BMFZ of 3-5 mm/yr (Klinger and Piety, 1994). The most recent event had an average vertical displacement of 2.5 m. Average recurrence intervals for large surface-rupturing earthquakes ranged from 700-1,300 years for three events and 500-1,000 years for four events (Klinger and Piety, 1996).

This study attempts to determine the age and number of faulting events along the central and southern parts of the Black Mountains fault zone through the analysis of tectonic geomorphic features at the base of the Black Mountains. For reference, in the appendix that follows the references, we have included parts of aerial photographs that show the locations of the profiled scarps in a series of illustrations.

## METHODOLOGY

### Relative dating of fault scarps

Fault-scarp morphology is a useful tool in estimating the relative timing of the faulting event that created these young geomorphic features. This approach is especially useful in areas where there are restrictions regarding disturbing the surface or where there is little or no datable material available to determine absolute ages. Scarps younger than a few thousand years may exhibit a steep free face, a debris slope at an angle of at least 33-35° and an abrupt break in slope at the top of the scarp (Wallace, 1977). As scarps increase in age, the slope of the scarp may decrease exponentially through time (Bucknam and Anderson, 1979; Hanks and others, 1984; Andrews and Buchnam, 1987; and Machette, 1989). Early work in the Great

Basin indicated that scarps on the order of 12 ka have maximum slopes of 20-25° (depending on their height). Scarps much older than 12 ka may have slope angles as low as 8-9°, and the break in slope at the top of the scarp becomes progressively more rounded with age (Wallace, 1977).

Many workers have also used a diffusion model in the analysis of scarps (Nash, 1980 and 1984; Colman and Watson, 1983; Pierce and Colman, 1986; Hanks and Andrews, 1989; Jyotsna and Haff, 1997; Hanks, 2000). The diffusion equation estimates ages as well as denudation rates at specific sites. The model requires having morphometric data for a scarp of known age located near the scarps that are being analyzed; unfortunately, no absolute ages have been determined for any of the scarps on the BMFZ, thus limiting application of the technique. However, we used the slope-degradation model of Bucknam and Anderson (1979) ($\theta = -8.5 \log T + 52.5$; where $\theta$ is the scarp angle in degrees and $T$ the time in years) as a first-order approximation of relative scarp age (fig. M-3). This model shows the predicted relationship of scarp angle versus age.

## Relative dating of offset deposits

Rock weathering and soil formation are widely accepted as useful tools in assessing relative ages of surface deposits (Bachman and Machette, 1977; Machette, 1985; McFadden and others, 1989; Bull, 1991). McFadden and others (1989) established that soil profiles, silt accumulation, carbonate cementation and varnish development are useful measures for distinguishing ages of Holocene and Pleistocene deposits in the southwestern U.S. They showed that rock varnish/soil horizon development may be directly proportional to age. The degree of rock varnish development can be characterized by color; for example, an alluvial fan having rock varnish with a 7.5YR3/4 color (moderate to dusky yellowish brown) was assigned an age of 4-8 ka, or middle Holocene (Bull, 1991). Others have also used development of bar-and-swale structures (small surficial channels created by drainage on alluvial fans) as an estimation of relative age (McFadden and others, 1989) (also see morphometric and soil criteria of Klinger in Chapter A, this volume).

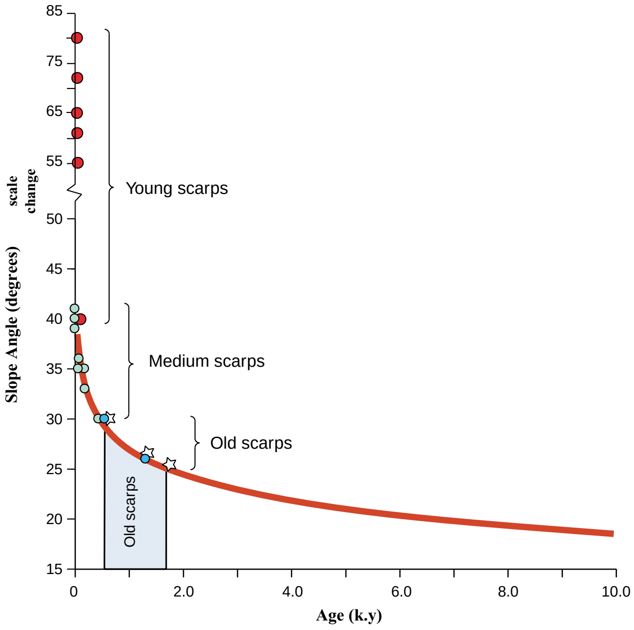


*Figure M-3. Plot showing decrease in scarp height with age from Bucknam and Anderson (1979).*

## Constraints from paleoshorelines

Paleoshorelines, tufa deposits, and lacustrine sediments record evidence for a perennial lake (ancient Lake Manly) that occupied the area between the Black Mountains and the Panamint Range once to several (?) times in the Quaternary (Blackwelder, 1954). A paleoclimate record from a salt core in Death Valley shows variations in lake level relating to climatic changes over the past 200 ka (Lowenstein and others, 1999). The most significant (deepest) of these lakes occupied the basin from 186 ka to 120 ka and from 35 ka to 10 ka (Lowenstein and others, 1999), although the younger lake seems to have been of much less extent (see Chapter C, Stop C1 in this volume). Lakes such as Lahontan, Bonneville, Russell, and Searles also experienced significant variations in their levels during these times. The levels of these lakes dropped significantly between 14,000 and 13,500 years ago in response to deteriorating pluvial conditions (Benson and others, 1990). Lake levels seem to have stabilized or even increased slightly from 11.5 ka until approximately 10 ka, at which time a sudden decline in water levels took place as climate changed and lakes dried up throughout the Great Basin (Benson and others, 1990; Lowenstein and others, 1999). From 10 ka to the present, very shallow lakes have intermittently occupied parts of Death Valley during wet years, but none of these have been of significant size. For example, Hunt and Mabey (1966) report evidence for a shallow lake that extended though central Death Valley about 2,000 years ago. Locally, features like erosion of varnish are evidence for the most recent lake stands. Some of the offset fans profiled in this study are located at the lowest part of the basin (near Badwater), which would have been the final area to be exposed as the last pluvial lake receded. The absence of shoreline features on faulted alluvial fans in these regions supports the Holocene age inferred for the scarps.

## Field Methods

The scarp profiling and field observations were made during 16 days in October-November 1999, and March 2000. Scarp profiles were measured using measuring tapes and vertical rods with standard trigonometric corrections (fig. M-4). National Park Service restrictions regarding digging soil pits prevented subsurface observations of the soil characteristics. However, observations about the character of surface features were noted. The surface color characteristics were described using the GSA Rock Color Chart (1991). Given there is little if any soil development on the small conical Holocene fan surfaces, clasts on the fan surface and on scarps were overturned (and later replaced) to estimate the amount of silt accumulation and development of vesicular texture in the silty A horizon. The surface of the fans along the Black Mountain range front is underlain by a clast-supported matrix (soil parent material).

## RESULTS

Scarp profiles were measured at 11 locations (fig. M-2) along 46 km of the central and southern parts of the BMFZ. All the fault scarps studied are on unconsolidated alluvial fan deposits at the western base of the Black Mountains. Information noted on relative ages of the deposits and scarps includes 1) the amount of varnish development on the footwall and hanging wall blocks of the fault, as well as on each scarp, 2) an estimate of silt accumulation beneath large clasts on the fan, and 3) an estimate of the height (relief) of bar and swale structures on each fan (table M-1). Presence or absence of fractured clasts and development of desert pavement were also noted on the fan surfaces. The scarps that were profiled were identified on air photos prior to field studies, concentrating on the youngest accessible scarps. In addition, the 1872 Owens Valley fault scarp near Lone Pine, California (see appendix M-1 for location) was profiled using the same technique for comparison with a historic event in a nearby region. We use this profile to provide additional relative age control for the scarps in Death Valley, acknowledging that the difference in precipitation between the two localities may have a consequence on the morphology and rates of color development.

*Figure M-4. Scarp profile setup. Steel measuring tape strung across two vertical rods.*

The scarp faces have little to no varnish development relative to the alluvial fans they are formed on (fig. M-5); however, comparison of the color on scarp faces of different ages is revealing. The youngest scarp faces all have grayish orange pink, grayish orange, or pale brown colors (5YR7/2, 5YR5/2, or 10YR7/4). The medium and old age scarps range in color from grayish orange pink (5YR7/2) to dusky brown (5YR2/2) and generally exhibit slightly more varnish development than the young scarps. It appears that the majority of scarp faces range from grayish orange pink (5YR7/2) to pale brown (5YR5/2), indicating little to no varnish development. Conversely, the colors of the fan surfaces range from very pale orange (10YR8/2) indicating very little varnish development (young fans) to dusky brown (5YR2/2) indicating heavy varnish development, depending on the age and depositional activity on the fans. Hangingwall and footwall surfaces at the same location generally had the same degree of varnish development (table M-1), suggesting that the faulted surfaces are of similar age.

Silt accumulation commonly is weak beneath clasts in the A horizon (uppermost soil horizon). A small percentage of soils have a slight vesicular A horizon beneath larger cobbles and generally correspond to greater varnish development on fan surfaces. No evidence was found for the development of carbonate cement or soils on scarp surfaces, free faces, or in drainages cutting the scarps.

*Figure M-5. Scarp 17 showing a significant difference between varnish development on fan versus scarp face.*

*Figure M-6. Graben defined by line of vegetation (shown by arrow) below scarp 10.*

Table M-1. Information on scarp morphology and data for accessing relative ages of faulted deposits

| Scarp | | Height | Max. slope | Dry color of surface | | Dry color of | Comments |
|---|---|---|---|---|---|---|---|
| | age | | angle | | block | hanging-wall block | |
| 3 | Young | 1.6 | 61 | 5YR7/2—5YR5/2 | 10R 6/2-5R 4/2 | 10R 6/2-5R 4/2 | Area of multiple scarps (scarps 3-9) |
| 9 | Young | 2.6 | 72 | 5YR7/2—5YR5/7 | 10R6/2—5R4/7 | 10R6/2—5R4/7 | Area of multiple scarps (scarps 3-9) |
| 15 | Young | 4.2 | 65 | 10YR7/4 | 10YR8/2—5YR5/2 | 10R8/2—10R5/4 | Free face present |
| 17 | Young | 1.6 | 38 | 10YR6/2—5YR2/2 | 10YR6/2—5YR5/2 | 5YR5/2—5YR2/2 | Evidence for strike slip movement |
| 23 | Young | 2.2 | 80 | 5YR7/2 | 5YR7/2—5YR4/4 | 5YR7/2—5R4/6 | Free face present, very young |
| 24 | Young | ? | ? | 10YR6/2 | 10YR8/2—5YR3/2 | 10YR8/2—5YR3/2 | Large graben system visible from Dante's View |
| 25 | Young | 2.9 | 70 | N/A | N/A | N/A | 1872 fault scarp in Owens Valley |
| 1 | Medium | 1.5 | 40 | N/A | N/A | N/A | |
| 5 | Medium | 2.3 | 35 | 5YR7/2—5YR5/3 | 10R6/2—5R4/3 | 10R6/2—5R4/3 | Area of multiple scarps (scarps 3-9) |
| 6 | Medium | 1.15 | 35 | 5YR7/2—5YR5/4 | 10R 6/2—5R4/4 | 10R6/2—5R4/4 | Area of multiple scarps (scarps 3-9) |
| 7 | Medium | 0.75 | 35 | 5YR7/2—5YR5/5 | 10R 6/2—5R4/5 | 10R6/2—5R4/5 | Area of multiple scarps (scarps 3-9) |
| 10 | Medium | 4.1 | 30 | 10YR6/2 | 5YR7/2—5YR3/4 | 5YR5/2—5YR3/2 | |
| 12 | Medium | 0.65 | 25 | 10YR6/2 | 10YR6/2 | 5YR7/2 | Southernmost scarp |
| 13 | Medium | 2.5-3.5 | 30-35 | 5YR7/2 | 5YR7/2—10YR6/2 | 5YR7/2 | |
| 14 | Medium | 1.1 | 40 | 5YR5/2 | 5YR5/2 | 5YR7/2—10YR6/2 | |
| 19 | Medium | 1.2 | 40 | 5YR7/2—5YR4/4 | 5YR5/2 | 10YR6/2—5YR7/2 | |
| 21 | Medium | 1.6 | 40 | 10YR6/2 | 5YR7/2—5R3/4 | 10YR6/2—5YR5/2 | Graben, lower fan has salt fracturing |
| 22 | Medium | 6.0 | 55 | 5YR7/2—10YR4/2 | 5YR7/2—10R3/4 | 10YR6/2—10R3/4 | Steep fan/debris flow |
| 8 | Old | 3.0 | 25 | 5YR7/2—5YR5/6 | 10R6/2—5R4/6 | 10R6/2—5R4/6 | Possible stream modification |
| 11 | Old | 3.4 | 30 | 5YR7/2—10YR6/2 | 5YR5/2—5YR3/2 | 5YR7/2—5YR3/2 | Graben has ~95% fine clasts |
| 18 | Old | 1.1 | 25 | 5YR7/2 | 5YR5/2—5YR4/4 | 5YR7/2 | Scarp in active channel |

Bar-and-swale structures were developed on the majority of fan, indicating youthfulness of their surface. These features were generally small, ranging from about 1.0 to 2.0 m in amplitude (height). Some of the subtle bar-and-swale structures represent mature channels that cut through the scarps, but none of these channels appeared old enough to have developed tectonic terraces.

Approximately 10 percent of the main fault scarps were accompanied by antithetic (mountain-side down) scarps, which create small grabens (fig. M-6). The antithetic scarps were all considerably smaller than the main (valley-side down) scarps. The small graben systems commonly control drainage across the fans, as do many of the scarps in general (see also Stop B3, this volume). Drainages along graben systems often accentuate the steepness of scarp slopes, and locally this created a problem in deciding where to measure the scarp profile. Sediments captured in the grabens are commonly fine-grained silt to pebble-sized.

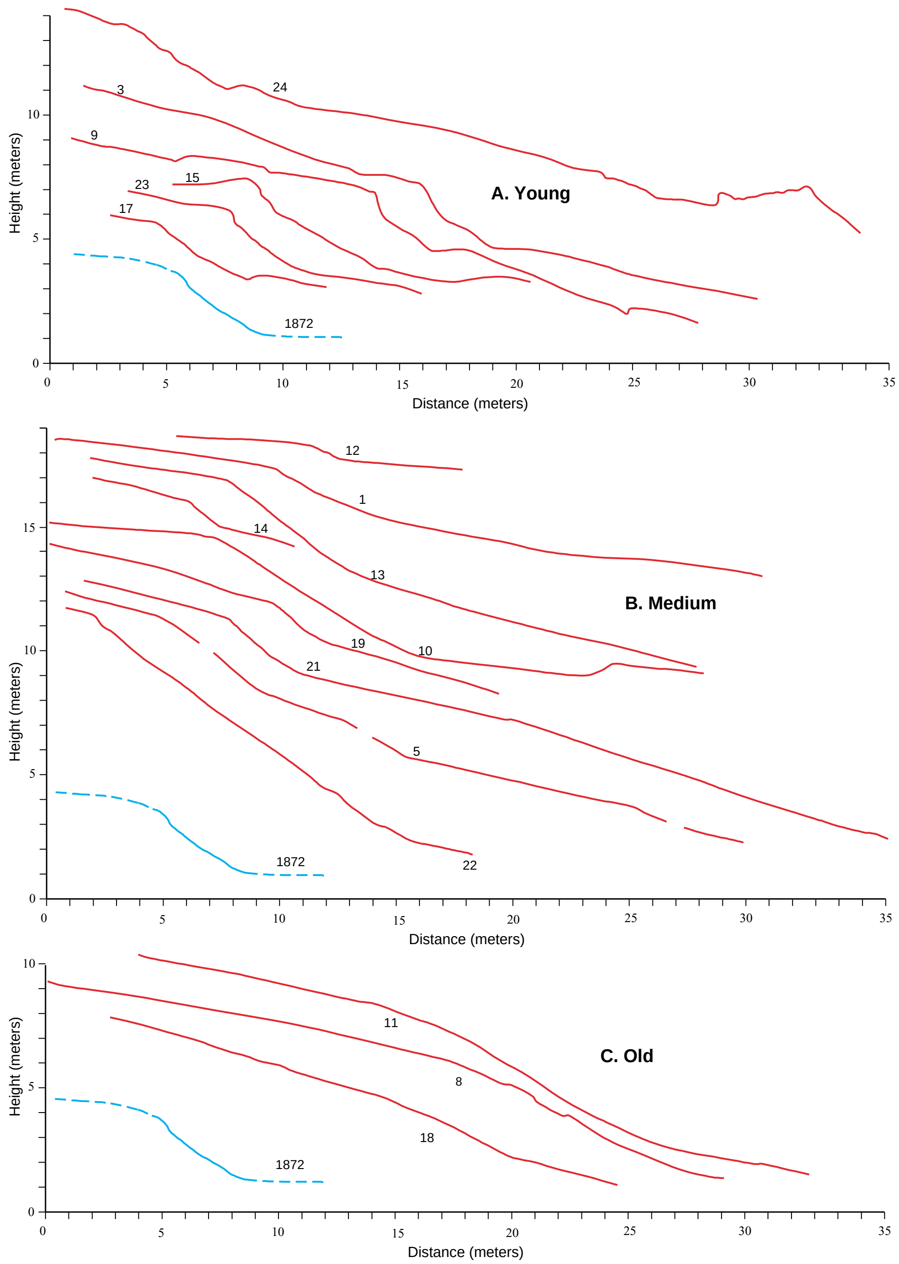


*Figure M-7. Profiles for scarp along Black Mountains fault zone. A) young-scarp morphologies; B) medium-scarp morphologies; and C) old-scarp morphologies. Numbers indicate locations on figure M-1 and table M-1. Lower scarp labeled "1872" is from Owens Valley fault zone in Lone Pine, California. No vertical exaggeration was used on profiles.*

## SCARP MORPHOLOGY

Strong evidence had been demonstrated for multiple Holocene events along the BMFZ (Butler and others, 1988; Brogan and others, 1991; Klinger and Piety, 1994 and 1996). Based on our profiles, the Holocene fault scarps along the central and southern parts of the BMFZ can be divided into three main morphological groups, which we refer to as young, medium and old scarps (figs. M-7A, B, and C, respectively). The scarp degradation equation of Bucknam and Anderson (1979) was used to estimate relative scarp ages (fig. M-3). Because of climatic variations Bucknam and Anderson (1979) cautioned against use of the relation in regions other than their field area (Utah). A scarp in Death Valley with the same maximum slope angle as a scarp in the Utah study site will likely be older than indicated by Bucknam and Anderson's curve, due to the lower mean annual precipitation in Death Valley.

### Young scarps (late Holocene)

The five profiles we measured from the youngest scarps (no. 3, 9, 15, 17, and 23) are located between about 0.5 km north of Badwater to about 17 km south of Badwater (see fig. M-2). These scarps have an average maximum scarp-slope angle of about 65°, with the steepest being about 80°. The young scarps have noticeably irregular, bumpy profiles and angular crests with convex upward profiles (fig. M-7A). Regardless of the large difference in climate between Death Valley and the northern Great Basin, the scarps appear to be extremely young ("zero" age; Wallace, 1977). Wallace (1977) determined that scarps with a steep free face and debris slope greater than 35° (at or above the angle of repose), are less than a few thousand years old. Further constraints on the age of the scarps are gained when data for the young scarps are plotted relative to Bucknam and Anderson's curve; scarps with slopes greater than 35° appear to be only a few hundred years old (see also young scarp data at Stop B3). We estimate that the young scarps are a few hundred to 1,000(?) years old. The lack of young scarps more than 17 km south of the Badwater area suggests that the youngest event may have terminated a short distance south of Badwater. These scarps seem to be morphologically similar to scarps recognized by Klinger and Piety (1996) to the north, at Golden Canyon.

### Medium scarps (middle or late? Holocene)

Most of the scarps profiled in this study are interpreted as being of medium age and have average slope angles of 35-40°. These scarps commonly have a sharp, somewhat angular crest and asymptotic lower slopes (fig. M-7B). The crest is commonly sharper than the toe. Medium-age scarps exhibit notably smoother profiles than the group of young scarps; in addition, the middle parts of the scarp slope are relatively linear. We estimate the age of these scarps to be ~2-6 ka from scarp slope angles (fig. M-3). If all of these scarps represent a single, same-age faulting event, then the rupture would have extended from the West Side Road junction near Ashford Mills (fig. M-2) north to at least Badwater, a distance of about 46 km. This rupture has an apparent vertical displacement that increased from about 0.6 m in the south to about 6 m in the north (fig. M-8).

### Old scarps (early or middle? Holocene)

The scarps in the old category have smooth profiles and somewhat concave middle sections between the toe and crest that distinguish them from the young- and medium-age scarps (Fig. M-7C). The old scarps have an average scarp-slope angle of about 28° with a common range of 25-30°. Although these scarps are still clearly noticeable in the landscape, they lack free faces and steep debris slopes, and have well-rounded crests and toes. They are inferred to be younger than about 10 ka because any significant rise of Lake Manly would have obliterated scarps formed before this time and left evidence of shorelines on faulted alluvial fans of pre-Holocene age. Morphometric comparisons with Bucknam and Anderson's (1979) curves as well as Wallace's (1977) age determinations suggests the scarps could be considerably less than 10,000 years old (i.e., middle or early? Holocene).

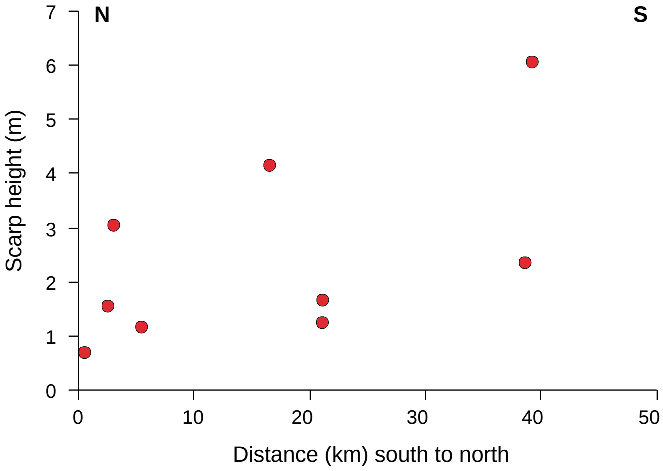


*Figure M-8. Plot showing increase in height for medium age scarps from south to north along the Black Mountains fault zone. Points represent individual scarp heights.*

### 1872 Owens Valley fault scarp, Lone Pine, California

Owens Valley experienced a significant earthquake (M 7.7-8.0) on the Owens Valley fault in 1872. This is the most recent of three Holocene events that formed the composite scarp near Lone Pine, California (Lubetkin and Clark, 1988; Beanland and Clark, 1991). Because its age is known, the Owens Valley scarp was used for calibration in morphologic comparisons with scarps from the Death Valley study area. One uncertainty regarding the diffusion process is that the Lone Pine area receives approximately 2.5 times as much annual precipitation (about 13 cm/yr) as Death Valley (about 5 cm/yr; Hollet and others, 1991). Similarities in profiles from the Black Mountains fault scarps (no. 3, 9, 15, 17, and 23) relative to the 1872 Owens Valley fault scarp are consistent with the other scarp-evolution models and indicate that the most recent faulting at these locations (fig. M-2) along the BMFZ is very recent. Figures 6A and 6B show several scarp profiles that have even more youthful characteristics than the Lone Pine scarp, a relation which is likely a function of the differences in aridity between the two areas (see discussion of scarp-degradation rates at Stop B3 in this volume).

## CONCLUSIONS

Our analyses of scarp profiles and field relations suggest that the BMFZ ruptured in discrete parts (segments?) and that no single Holocene event ruptured the entire 76-km length of the fault zone. However, we recognize the limited scope of this effort and the necessity for more thorough investigations. The scarp morphologies that define the three events seem distinctive and do not grade from one type to the other, suggesting that some time elapsed between events. Preliminary results further suggest the central part of the BMFZ ruptured more recently than the southern part. The young event produced a scarp at least 3-4 m high near Badwater. The middle Holocene event produced a scarp at least 6 m high that may be at least 45 km long. This rupture may have been significantly longer in as much as it is not likely that the rupture terminated at the northern end of our study area where its had its maximum vertical separation. The minimum moment magnitude (M) of the middle Holocene event is approximately 7.0-7.2, an estimate that is based on at least a 45-km rupture length and 6 m of displacement (Wells and Coppersmith, 1994). This estimate is consistent with previous estimates by Brogan and others (1991) and predictions for earthquake magnitudes over the next 10,000 years by Bennett and others (1997).

All of the young scarps are characterized by steep free faces and steep debris slopes. The youngest scarps (no. 3, 9, 15, 17, and 23) are along the central part of the Black Mountains fault zone, within 17 km of Badwater (locations shown in fig. M-2) and are estimated to be about 200-1,000(?) years old. This young time estimate is consistent with morphometric comparisons to the 1872 Owens Valley fault scarp near Lone Pine and scarp-age relations suggested by Bucknam and Anderson (1979) and Wallace (1977). The medium age scarps are estimated to be 500-2,000 years old based on comparison with Bucknam and Anderson's data (1979). Underestimating their age by half still only pushes their time of formation to about 1,000-4,000 years. The old (Holocene) scarps would also be estimated at 500-2,000 years old using Bucknam and Anderson (1979) curves, because the measured scarp slopes are still above 25° on all of the profiles. Thus, the timing of formation of the older scarps remains undetermined, but it appears to be quite recent and clearly postdates the last advance of Lake Manly.

## ACKNOWLEDGEMENTS

This project was part of an undergraduate senior thesis completed by Frankel in August 2000. The project was funded by the University of North Carolina Burch Field Seminar, University of North Carolina-Chapel Hill (UNC-CH) Department of Geological Sciences, and by Charles and Joanne Frankel. Field equipment for scarp profiling and transportation was provided by the U.S. Geological Survey (USGS) and by the University of California White Mountain Research Station (WMRS). Special thanks to Ralph Klinger (U.S. Bureau of Reclamation) and Michael Machette (USGS) who shared time and thoughts in the field. We also thank Michael Rymer USGS) and Michael Machette for thoughtful and constructive reviews, Blair Davenport (NPS) for access to park archive information, and Mel Essington (NPS) who assisted with field logistics. Thanks also go to John Rogers (UNC-CH) and Audrey Huerta for academic guidance, and to Stephanie Briggs (UNC-CH), John Templeton (UNC-CH), and Cecil and Clementine Patrick (WMRS) for assistance with field studies.

## REFERENCES

Andrews, D.J., and Bucknam, R.C., 1987, Fitting degradation of shoreline scarps by a nonlinear diffusion model: Journal of Geophysical Research, v. 92, p. 12,857-12,876.

Bachman, G.O., and Machette, M.N, 1977, Calcic soils and calcretes in the southwestern United States: U.S. Geological Survey Open-File Report 77-0794, 163 p.

Beanland, S., and Clark, M.M., 1991, The Owens Valley fault zone, eastern California, and surface faulting associated with the 1872 earthquake: U.S. Geological Survey Bulletin 1982, 29 p.

Bennett, R.A., Wernicke, B.P., Davis, J.L., Elosegui, P., Snow, J.K., Abolins, M.J., House, M.A., Stirewalt, G.L., and Ferrill, D.A., 1997, Global positioning system constraints on fault slip rates in the Death Valley region, California and Nevada: Geophysical Research Letters, v. 24, p. 3,073-3,076.

Benson, L.V., Currey, D.R., Dorn, R.I., Lajoie, K.R., Oviatt, C.G., Robinson, S.W., Smith, G.I., and Stine, S., 1990, Chronology of expansion and contraction of four Great Basin lake systems during the past 35,000 years: Palaeoceanography, Paleaeoclimatology, Palaeoecology, v. 78, p. 241-86.

Blackwelder, E., 1954, Pleistocene lakes and drainage in the Mojave region, southern California, Chapter 5, *in* Jahns, R.H., ed., Geology of southern California: California Division of Mines Bulletin 170, p. 35-40.

Brogan, G.E., Kellogg, K.S., Slemmons, D.B., and Terhune, C.L., 1991, Late Quaternary faulting along the Death Valley-Furnace Creek fault system, California and Nevada: U.S. Geological Survey Bulletin 1991, p. 1-23.

Bucknam, R.C., and Anderson, R.E., 1979, Estimation of fault scarp ages from a scarp height slope angle relationship: Geology, v. 7, p. 11-14.

Bull, W.B., 1991, Geomorphic responses to climatic change: Oxford University Press, 326 p.

Burchfiel, B.C., and Stewart, J.H., 1966, Pull apart origin of the central section of Death Valley, California: Geological Society of America Bulletin, v. 77, p. 439-442.

Butler, P.R., Troxel, B.W., and Versoub, K.L., 1988, Late Cenozoic history and styles of deformation along the southern Death Valley fault zone, California: Geological Society of America Bulletin, v.100, p. 402-410.

Colman, S.M., and Watson, K., 1983, Ages estimated from a diffusion equation model for scarp degradation: Science, v. 221, p. 263-265.

Geological Society of America Rock Color Chart Committee, 1991, The Geological Society of America rock color chart with genuine Munsell color chips: Munsell Color Company.

Hanks, T.C., Bucknam, R.C., Lajoie, K.R., and Wallace, R.E., 1984, Modification of wave-cut and faulting controlled landforms: Journal of Geophysical Research, v. 89, p. 5,771-5,790.

Hanks, T.C., and Andrews, D.J, 1989, Effect of far field slope on morphologic dating of scarplike landforms: Journal of Geophysical Research, v. 94, p. 565-573.

Hanks, T.C., 2000, The age of scarp-like landforms from diffusion-equation analysis, *in* Sowers, J.M., Noller, J.S., and Lettis, W.R., eds., Quaternary Geochronology—Methods and Applications: Washington, D.C., American Geophysical Union Reference Shelf 4, p. 313-338.

Hollet, K.J., Danskin, W.R., McCaffrey, W.F., and Walti, C.L., 1991, Geology and water resources of Owens Valley, California: U.S. Geological Survey Water Supply 2370, p. B1-B27.

Jyotsna, R., and Haff, P.K., 1997, Microtopography as an indicator of modern hillslope diffusivity in arid terrain: Geology, v. 25, p. 695-698.

Klinger, R.E.. and Piety, L.A., 1994, Seismotectonic evaluation of the Death Valley—Furnace Creek fault zone, Death Valley, California (Activity 8.3.1.17.4.3.2): Yucca Mountain Project Seismotectonic Report 94-10, p. 1-15.

Klinger, R.E., and Piety, L.A., 1996, Evaluation and characterization of the Quaternary faulting on the Death Valley and Furnace Creek faults, Death Valley, California (Activity 8.3.1.17.4.3.2): Yucca Mountain Project Seismotectonic Report 96-10, p. 1-98.

Lowenstein, T.K., Li, J., Brown, C., Roberts, S.M., Ku, T.L., Luo, S., and Yang, W., 1999, 200 k.y. paleoclimate record from Death Valley salt core: Geology, v. 27, p. 3-6.

Lubetkin, L.K.C., and Clark, M.M., 1988, Late Quaternary activity along the Lone Pine fault, eastern California: Geological Society of America Bulletin, v. 100, p. 755-766.

Machette, M.N., 1985, Calcic soils of the southwestern United States, *in* Weide, D.L., ed., Soils and Quaternary geology of the southwestern United States: Geological Society of America Special Paper 203, p. 1-21.

Machette, M.N., 1989, Slope-morphometric dating, *in* Forman, S.L., ed., Dating methods applicable to Quaternary geologic studies in the Western United States: Utah Geological and Mineral Survey Miscellaneous Publication 89-7, p. 30-42

McFadden, L.D., Ritter, J.B., and Wells, S.G., 1989, Use of multiparameter relative age methods for age estimation and correlation of alluvial fan surfaces on a desert piedmont, eastern Mojave Desert, California: Quaternary Research, v. 32, p. 276-290.

Nash, D.B., 1980, Morphologic dating of degraded normal fault scarps: Journal of Geology, v. 88, p. 353-360.

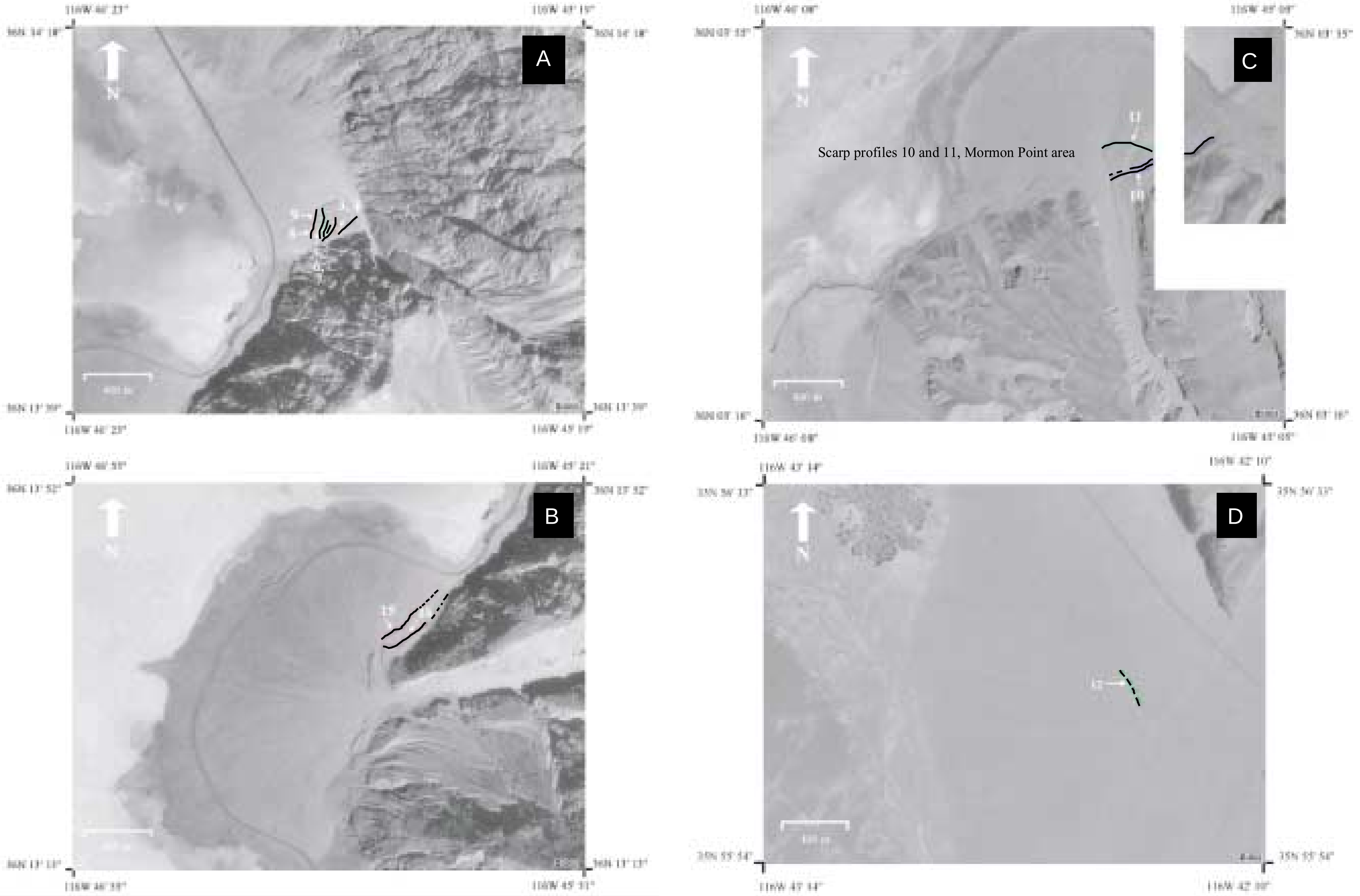
Nash, D.B., 1984, Morphologic dating of fluvial terrace scarps and fault scarps near West Yellowstone, Montana: Geological Society of America Bulletin, v. 95, p. 1,413-1,424.

Pierce, K.L., and Colman, S.M., 1986, Effect of height and orientation (microclimate) on Geomorphic degradation rates and processes, late glacial terrace scarps in central Idaho: Geological Society of America Bulletin, v. 97, p. 869-885.

Reheis, M., and Noller, J., 1996, Aerial photographic interpretation of lineaments and faults in late Cenozoic deposits in the Benton, Goldfield, Last Chance, Beatty and Death Valley 1:100,000 quadrangles: U.S. Geological Survey Open-File Report 90-41, scale 1:100,000.

Wallace, R.E., 1977, Profiles and ages of young fault scarps, north-central Nevada: Geological Society of America Bulletin, v. 88, p. 1267-1281.

Wells, D.L., and Coppersmith, K.J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Bulletin of the Seismological Society of America, v. 84, p. 974-1,002.



APPENDIX. Air photos showing locations of scarp profiles, Death Valley. Localities also shown on figure M-2 and described in table M-1.

APPENDIX—Continued. Air photos showing locations of scarp profiles, Death Valley. Localities also shown on figure M-2 and described in table M-1.

1872 Lone Pine Scarp

APPENDIX—Continued. Air photos showing locations of scarp profiles, Death Valley. Localities also shown on figure M-2 and described in table M-1.