Chapter H

Late Quaternary Tectonic Activity on the Death Valley and Furnace Creek Faults, Death Valley, California

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Abstract

Published reports contain estimates that the late Quaternary slip rate for the Death Valley fault is between 0.2 and 2.5 millimeters per year and the late Pleistocene slip rate for the Furnace Creek fault is between 2 and 3 millimeters per year. Detailed mapping of geomorphic features associated with both faults indicate that numerous ground-rupturing earthquakes have occurred during the late Holocene and that the activity rates of both faults may be significantly higher than previously reported. Together, the Death Valley and Furnace Creek faults are the longest and most active faults within 100 kilometers of Yucca Mountain. Therefore, assessment of these two faults is important in the evaluation of Quaternary faulting around a site that is under consideration as a potential high-level radioactive-waste repository.

Along the Death Valley fault near Mormon Point, the surface of a middle Holocene alluvial fan is displaced vertically 10.5 meters. Preserved free faces and uplifted stream terraces record at least the last three and, most likely, the last four ground-rupturing events. Average vertical displacement per event at this location is interpreted to be about 2.6 meters. An approximate age of 4,000 to 8,000 years is estimated for the displaced alluvial fan based on its surface characteristics and degree of soil development. These data yield a Holocene vertical slip rate for the Death Valley fault of 1–3 millimeters per year and indicate that the return period for ground-rupturing earthquakes is between 1,000 and 2,000 years.

Along the Furnace Creek fault near Red Wall Canyon, repeated movement has right laterally offset late Holocene channels and preserved evidence for at least the last three ground-rupturing events. Lateral displacements for events at this location range from 2.5 to 4.5 meters. Larger late Pleistocene channels incised into the alluvial fan have also been offset and record the late Pleistocene slip history. Using low-altitude aerial photography and detailed surficial mapping, a palinspastic reconstruction of the alluvial fan surface indicates that the large incised channels have been right laterally offset 250–330 meters across the fault. An age of 35,000–60,000 years is estimated for the offset alluvial fan based on its stratigraphic relation to late Pleistocene lacustrine deposits, the degree of soil development, and its overall surface characteristics. These data yield a late Pleistocene lateral slip rate for the Furnace Creek fault of 4–9 millimeters per year. This is consistent with a late Holocene slip rate of 3–6 millimeters per year recorded in repeatedly offset late Holocene stream channels at the same location. Evidence for at least the last three earthquakes indicates that the return period for ground-rupturing earthquakes on the Furnace Creek fault in northern Death Valley is between 700 and 1,300 years.

Introduction

The Death Valley–Furnace Creek fault system (DVFCFS) consists of several discrete late Quaternary faults that extend for more than 200 km through Death Valley along the California-Nevada border (fig. 1). The Death Valley and Furnace Creek faults are the two dominant structures in the DVFCFS, and together these faults are the longest and most active faults within 100 km of the potential high-level radioactive-waste repository at Yucca Mountain (Piety, 1996). Therefore, an assessment of these faults is important in the evaluation of the Quaternary fault activity. Previous work along the DVFCFS has identified and located most of the major tectonic features associated with the latest Quaternary faulting (Hunt and Mabey, 1966; Moring, 1986; Bryant, 1988; Wills, 1989; Brogan and others, 1991; Reheis, 1991a, 1991b, 1992; Reheis and Noller, 1991; Reheis and others, 1993; Wright and Troxel, 1993). However, the age of the most recent event, recurrence intervals for large ground-rupturing events, amount of displacement per event, lengths of individual ground-rupturing events, and possible fault segmentation remain to be identified and documented for much of the system.

The Death Valley fault, as referred to in this report, is the northwest-striking, high-angle, down-to-the-west normal fault located along the western flank of the Black Mountains (fig. 1). The Furnace Creek fault is the northwest-striking, right-lateral strike-slip fault located on the axis of northern Death Valley along the western flank of the Funeral Mountains (fig. 1). The apparent junction between these two faults is near Furnace Creek Ranch, about 50 km from the potential repository site at Yucca Mountain (fig. 1). The DVFCFS has a long history of activity prior to the Quaternary, but only the late Quaternary faults, which may not correspond directly to older parts of the DVFCFS, are addressed in this study.

Abundant evidence for multiple late Holocene surface ruptures is well preserved at numerous locations along both faults. Traditionally, many of the data collected in studies of fault activity are derived from trench excavations. However, the part of the DVFCFS closest to Yucca Mountain lies in designated wilderness within Death Valley National Park, and the National Park Service has not permitted trenching. The means used during the present study to improve understanding of the DVFCFS included detailed mapping of the faults, associated surficial deposits, and geomorphic features at specific sites where Quaternary tectonic activity is clearly indicated. This report summarizes some of the well-preserved evidence of past faulting and reports estimates of late Quaternary slip rates, slip per event, and return periods for ground-rupturing earthquakes derived from two sites: one along the Death Valley fault near Mormon Point and one along the Furnace Creek fault north of Red Wall Canyon (fig. 1).

Acknowledgments

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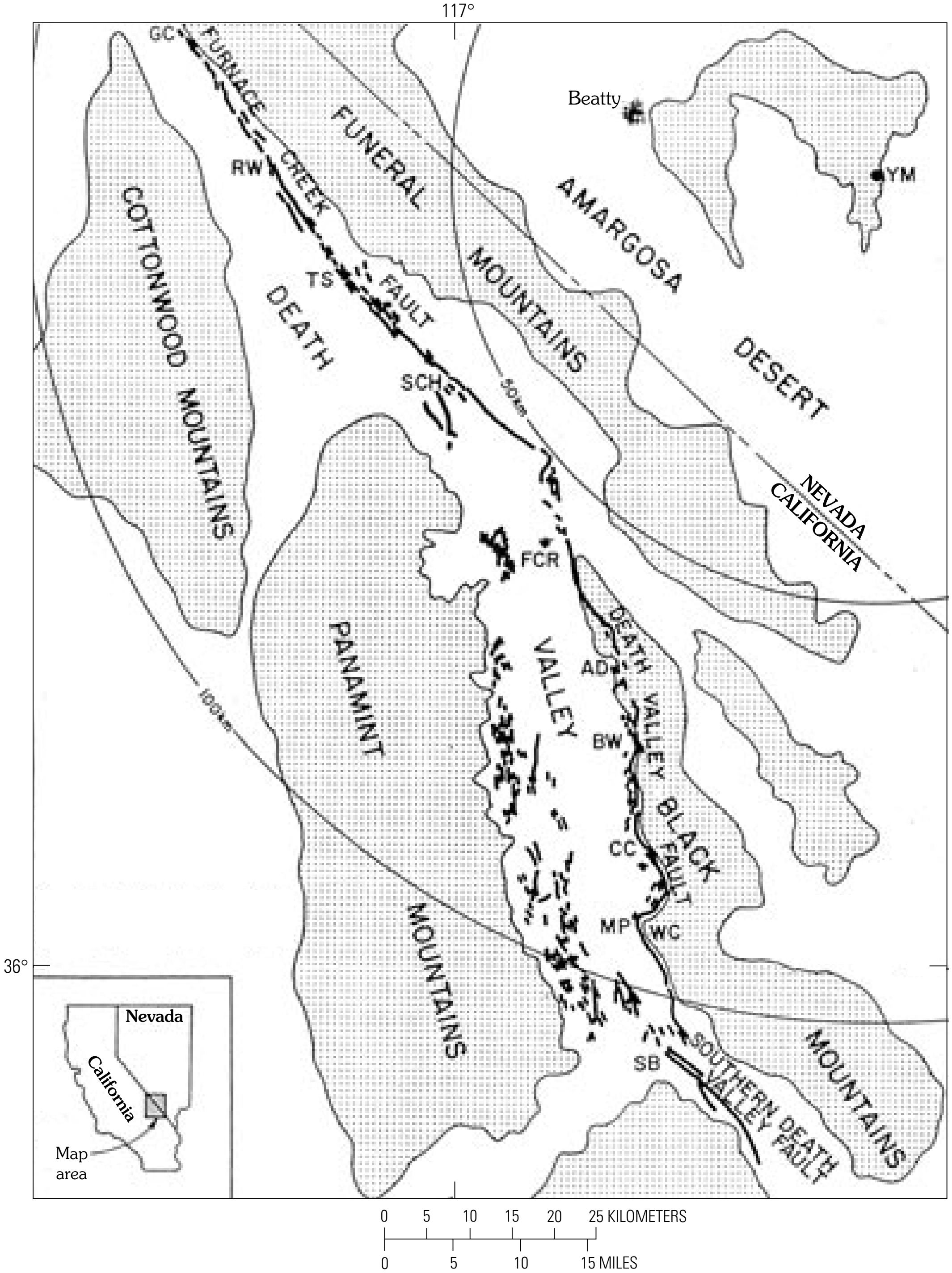

Figure 1. Location of southern Death Valley, and Death Valley and Furnace Creek faults, based on Brogan and others (1991) and Reheis (1991a). Dot pattern, major mountain ranges adjacent to Death Valley. GC, Grapevine Canyon; RW, Red Wall Canyon; TS, Triangle Spring; SCH, Salt Creek Hills; FCR, Furnace Creek Ranch; AD, Artists Drive; BW, Badwater Basin; CC, Copper Canyon; WC, Willow Creek; MP, Mormon Point; SB, Shoreline Butte. 50 km and 100 km arcs indicate distances from Yucca Mountain (YM). Faults shown by heavy black lines.

Neotectonic Setting

The effects of recent tectonism on the landscape in Death Valley have been recognized since the 1920's. Following reconnaissance in the region, Noble (1926, p. 425) noted that the scarps along the Death Valley fault were "*** fresher than any other scarps of similar magnitude in the West." Similarly, Curry (1938) reported abundant geomorphic evidence in northern Death Valley that suggested extensive lateral displacement along the Furnace Creek fault. However, the importance of these two faults in the evolution of Death Valley was not described until Burchfiel and Stewart (1966) presented their pull-apart basin hypothesis. Their model describing the basin development—wherein right-lateral slip on the parallel northwest-striking Furnace Creek and southern Death Valley faults was translated to oblique-normal slip on the Death Valley fault (fig. 1)—is now widely accepted. The youthfulness of Death Valley is also widely recognized; however, details regarding the late Quaternary activity on these faults and how they behave seismogenically remain largely unknown.

Hunt and Mabey (1966, p. A100) estimated that the most recent activity along the Death Valley fault was younger than about 2 ka, based on observations of the fault scarps in central Death Valley and their relation to late Holocene lake shorelines and dated archeological sites. Clements (1954, p. 58–60), on the basis of newspaper accounts and other late 19th–early 20th century written records, had earlier speculated that the young scarps along the Death Valley fault were the result of the November 4, 1908, magnitude 6.5 earthquake. This event is reported in detail by Stover and Coffman (1993, p. 75). Records for this particular earthquake are inadequate and the epicenter is imprecisely located—so the correlation remains in doubt.

In northern Death Valley, Curry (1938, p. 1875) implied that activity on the Furnace Creek fault was relatively recent based on the presence of "*** a churned-up furrow in recent alluvium." However, specific details of this recent activity along the fault were not documented until Reynolds (1969, p. 238) noted that the margin of a Pleistocene alluvial fan north of Red Wall Canyon was right laterally offset about 46 m. Reynolds (1969) postulated late Holocene activity along the Furnace Creek fault but interpreted the displacement of the alluvial fan margin as being middle to late Pleistocene. Bryant (1988, p. 8–9) later reevaluated the offset fan margin and developed the only published late Quaternary slip rate, 2.3 mm/yr, for the Furnace Creek fault in Death Valley. 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 margin followed this incision. He also emphasized that an unknown amount of erosion had most likely removed part of the fan margin, and therefore the estimated slip rate of 2.3 mm/yr was a crude minimum estimate.

In a detailed study of the late Quaternary activity on the Death Valley and Furnace Creek faults, Brogan and others (1991) documented the location of the major traces and prominent tectonic features along the length of the DVFCFS. However, they did not evaluate ages of either the deposits or geomorphic surfaces adjacent to or displaced by the faults. Their assumptions regarding the ages of the deposits along the DVFCFS are based primarily on the stratigraphic work of Hunt and Mabey (1966) with some chronologic control inferred from Hooke (1972) and Sawyer and Slemmons (1988). Although Brogan and others (1991) did not report any new slip rates for either fault, they acknowledged the minimum rate of 2.3 mm/yr reported by Bryant (1988) for the Furnace Creek fault. Additionally, by using the range of vertical separations for Holocene surfaces along the Death Valley fault reported by Brogan and others (1991, p. 21) in combination with their age estimates, a vertical slip rate of 0.2–2.5 mm/yr can be estimated for the Death Valley fault.

Quaternary Stratigraphy

The most extensive Quaternary stratigraphic work so far undertaken in Death Valley is the reconnaissance-level work of Hunt and Mabey (1966; mapping scale 1:96,000). Their mapping remains the most comprehensive in regard to the late Quaternary stratigraphy, but as it is confined to the south half of Death Valley, it lacks the detail needed to evaluate late Quaternary faulting activity. More detailed mapping of the surficial deposits along the Furnace Creek fault was completed by Moring (1986; mapping scale 1:62,500) in northern Death Valley and by Wright and Troxel (1993; mapping scale 1:48,000) in central Death Valley. The differentiation of alluvial units by Moring (1986) was made primarily on the basis of morphological characteristics. This methodology has been shown to be quite accurate for delineating stratigraphic units (McFadden and others, 1989). On the basis of his mapping, Moring (1986) concluded that the youngest deposit clearly faulted by the Furnace Creek fault was late Pleistocene. The work of Wright and Troxel (1993), which extends into Death Valley and includes the surficial deposits along the south end of the Furnace Creek fault, primarily emphasizes the bedrock geology of the southern Funeral Mountains. Mapping of the surficial deposits in Death Valley at a level adequate to evaluate late Quaternary faulting still remains areally limited and incomplete for the most part.

The climate in Death Valley is hyperarid with a mean annual temperature of 26°C and mean annual precipitation of 40 mm. Because of the hyperarid environment and the accompanying lack of vegetation in Death Valley, the ages of deposits have been difficult to obtain utilizing conventional radiometric techniques. Hence, the ages of alluvial surfaces presented by previous workers in Death Valley have been based on archeological correlations and relative age criteria. Other studies in the Death Valley area that have examined Quaternary processes such as alluvial fan deposition, pluvial lake history, and the effects of climatic change provide some numerical ages for Quaternary deposits and geomorphic surfaces (Hooke, 1972; Hooke and Lively, 1979; Dorn, 1988; Dorn and others, 1990; Hooke and Dorn, 1992). Some of the ages developed in these studies were based on experimental dating techniques with questionable results. Many of the remaining ages are not referenced to specific locations or deposits that are needed to make stratigraphic correlations elsewhere.

The ages of alluvial fans in Death Valley can also be estimated based on their stratigraphic relation to late Pleistocene deposits at Lake Manly. Details about the history of Lake Manly have been fragmentary (Blackwelder, 1933, 1954; Hooke, 1972; Dorn and others, 1990) until recently. Li and others (1997) have detailed the late Pleistocene lake history in Death Valley on the basis of evaporite mineralogy and geochronology of a core recovered from Badwater Basin (fig. 1). Late Pleistocene alluvial fan deposits adjacent to the DVFCFS can be correlated directly to strand lines and constructional landforms that record former highstands of Lake Manly. Since the recession of Lake Manly, larger drainages have incised the late Pleistocene alluvial fans and redeposited the sediment into younger alluvial fans downslope. This observation relates well to studies by Bull (1991), who established a stratigraphic framework for surficial deposits in the arid southwestern United States after recognizing that the alluvial sequences throughout the region are related to major climatic changes.

Slip-Rate Estimates

Methodology

Geomorphic surfaces and faulted alluvial fans were mapped on low-altitude, low sun-angle photographs, and stratigraphic units were initially delineated on the basis of their tonal differences and surface textures. These characteristics relate directly to the degree of varnish development and desert pavement formation and reflect the amount of time since the surface stabilized. Descriptions of these surfaces were later made in the field along with descriptions of the bar-and-swale morphology and surface dissection, extent of pavement packing, varnish color, and degree of soil development (table 1). Unit designations were adapted from Bull (1991) and were made by comparing relative age characteristics and soil properties described in Death Valley to those in the Mojave Desert and Lower Colorado River regions (Wells and others, 1987; McFadden and others, 1989). Age estimates were made by comparing the degree of soil development in Death Valley with dated soil sequences in the region (Reheis and others, 1989; McFadden and others, 1992), and correlations to the Lake Manly lacustrine record (Li and others, 1997).

All slip measurements and scarp profiles were measured in the field with a tape and level or electronic theodolite. All scarp heights and scarp-slope angles were derived from computer-generated plots of field data. We note that, owing to (1) any subsequent erosion or deposition along the channel margins or on geomorphic surfaces, and (2) the angle of intersection between offset drainages or displaced ground surfaces and the strike and dip of the fault, slip measurements may include a certain amount of error. However, the uncertainties inherent in the measurement of these morphologic features in coarse-grained alluvial deposits have less of an impact on the slip-rate estimates than those arising from the constraints provided by available age determinations.

Willow Creek

Young scarps are nearly continuous on Holocene alluvial fans along the Death Valley fault from Furnace Creek Ranch south to Shoreline Butte with the exception of a gap near Artists Drive (fig. 1). At Mormon Point (fig. 1), an embayment in the range is formed where the fault rounds the turtleback and changes strike from north-northwest to east-northeast. Between Willow Creek and the western flank of the Copper Canyon turtleback (fig. 1), the strike of the fault gradually returns to the north-northwest direction. Pronounced triangular facets and fault-line scarps are preserved in 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 (fig. 2), but correlative geomorphic surfaces across the fault generally are poorly preserved. Commonly, surfaces on the hanging wall side of the fault have been modified by erosion or deposition (fig. 2). This complicates efforts to determine the sense of displacement, slip-per-event, or the age of faulting, hence also the activity rates. However, approximately 300 m north of the mouth of Willow Creek, a middle Holocene surface (Q3b; table 1) is preserved on both sides of the scarp (fig. 3).

A profile near Willow Creek was measured perpendicular to the scarp (fig. 3), at a location where the scarp obliquely crosses the alluvial slope. Rills developed on the fan surface prior to faulting give the impression of lateral offset on the fault, but no clear evidence for lateral displacement was observed at the 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 (Brogan and others, 1991) also implied that the overhanging scarps provided evidence of local reverse faulting. However, close examination of these scarps indicates that the original scarp morphology is being preserved by the cementation of the alluvium by soluble salts (primarily halite and gypsum) blown off the adjacent playa and translocated into the developing soil profile. Cementation of the alluvium by salts within 0.3–0.5 m of the ground surface (fig. 4) was commonly observed, as would be expected given the proximity of the scarps to the salt pan and the extremely low mean annual precipitation in this part of Death Valley. We therefore suggest that the overhanging scarps along the Death Valley fault result from the relation between the more resistant, salt-impregnated alluvium and the underlying erodible, uncemented alluvium at the base of the scarp.

Some portions of most scarps along the length of the Death Valley fault were found to be vertical or near vertical. In these places, analysis of the scarp height and slope-angle measurements was complicated owing to the probable young age of the scarp and the complex factors controlling its degradation. Although the vertical or overhanging morphology of these scarps could be viewed as an indicator of scarp youthfulness, the morphology equally reflects the conditions of the environment in which the scarps are preserved and the scarp degradation process. Rather than following a slope-decline model of fault-scarp degradation as described by Wallace (1977), the scarps in Death Valley tend to follow a parallel retreat model as outlined by Young (1972).

A scarp profile was measured at the Willow Creek locality (fig. 5) in order to resolve surface displacement across the Death Valley fault during the Holocene and to estimate the slip rate and return periods on the Death Valley fault. The maximum scarp-slope angle of 90° and total scarp height of 10.5 m were measured from a computer-generated plot of the profile. Slope angles across the scarp range from the angle of repose at the toe to vertical at the crest. The scarp height is believed to be within about 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

Table 1. Generalized descriptions of late Quaternary stratigraphic units in Death Valley

Unit	Age (ka)	Desert pavement[1]	Bar/swale morphology[2]	Varnish color[3]	Soil horizon sequence[4]	Profile thickness[5] (cm)	Maximum profile color[6]	Soil development index[7]
Q4b	<0.2	None	Prominent	None	None	None	10*YR*6/3	0.0
Q4a	0.2-2	None	Prominent	None	Av/2C	4	10*YR*7/2	0.5
Q3c	2-4	PP	Distinct	5*YR*6/6	Avk/2Bkz/2C	20	10*YR*7/3	5.2
Q3b	4-8	MP	Subdued	5*YR*5/8	Avk/2Bkz/2C	50	10*YR*7/3	12.8
Q3a	8-12	MP-WP	Subdued	5*YR*5/8 to 2.5*YR*4/8	Avkz/Bkz/2C	72	10*YR*7/3	30.4
Q2c	12-60	WP	None	2.5*YR*4/8	Avkz/Btkz/2Bkz	100	7.5*YR*5/6	45.0

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

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

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

[4]Soil properties were described in the field as outlined by Birkeland (1984) and the Soil Survey Division Staff (1993).

[5]Maximum profile thickness observed.

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

[7]Soil development index was calculated following the methodology of Harden and Taylor (1983) on the basis of the five soil characteristics: total texture, rubification, profile lightening, dry consistence, and soluble salt accumulation.

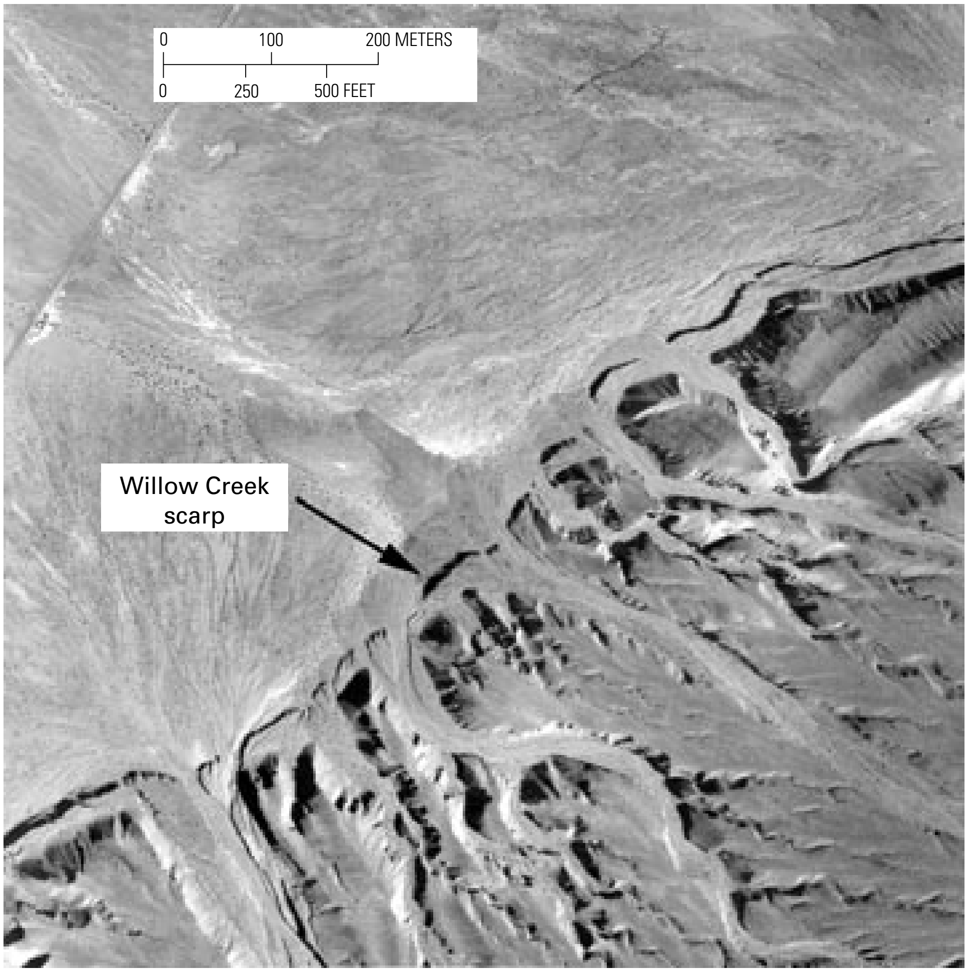

Figure 2. Vertical aerial photograph of faulted alluvial fans along Death Valley fault near Willow Creek. Alluvial fan in lower left corner is formed at mouth of Willow Creek.

preserved free faces produced by separate ground-rupturing earthquakes. 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 that can be traced to the base of each free face (fig. 6).

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 this relation between the scarp and the uplifted terraces, the scarp near Willow Creek records at least three events in middle Holocene deposits. The measured height 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 has occurred between events. This is in close agreement with vertical separations measured elsewhere along the Death Valley fault (fig. 7). If these values of displacement per event are characteristic of ground-rupturing earthquakes at this site, then the scarp at Willow Creek most likely represents four events. Because of its stratigraphic position relative to latest Pleistocene Lake Manly shorelines, its surface characteristics, and the degree of soil development, the faulted geomorphic surface at this site was assigned an age of 4–8 ka (Q3b surface of Bull, 1991; table 1). 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, a scarp height of 10.5 m yields an average Holocene vertical slip rate of 1–3 mm/yr (table 2).

Table 2. Late Quaternary slip rates and return periods.

Fault	Site	Displacement (m)	Age (ka)	Slip rate (mm/yr)	Return period (yr)
Death Valley	Willow Creek	10.5	4-8	1-3	870-2,600
Furnace Creek	Red Wall Canyon	250-330	35-60	4-9	No data
Furnace Creek	Red Wall Canyon	12.2	2-4	3-6	700-1,300

Figure 3. Willow Creek scarp. Fan surface on footwall block is correlative with fan surface on hanging wall block of Death Valley fault (fig. 2).

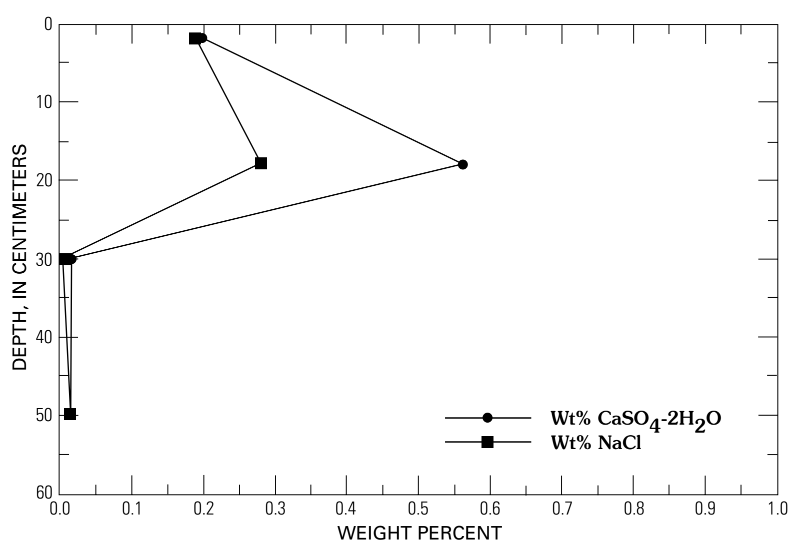

Figure 4. Distribution of soluble salts (halite and gypsum) with depth in a Q3b soil profile. (See table 1.)

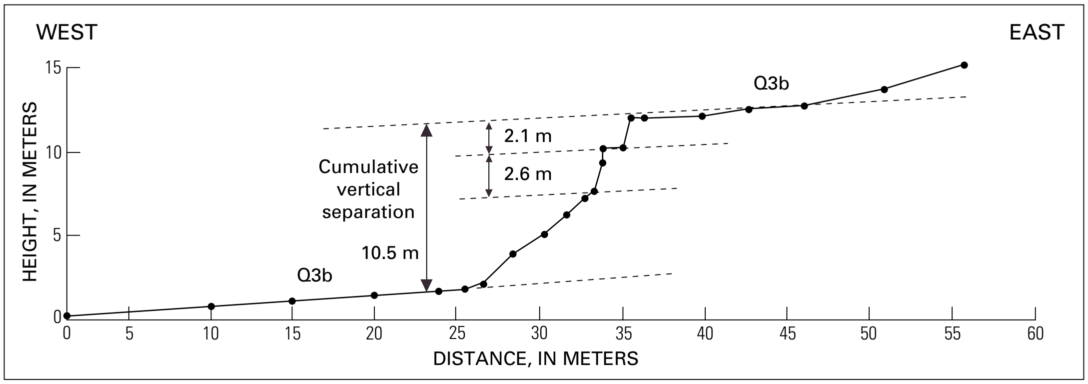

Figure 5. Topographic profile of Willow Creek scarp. The two near-vertical segments near crest of scarp (2.1 and 2.6 m) are interpreted as preserved free faces. Zero points define an arbitrary datum; dots mark sites where distance and height measurements were taken along surface profile.

Figure 6. Uplifted fluvial terraces inset into a middle Holocene alluvial-fan surface (A) near mouth of Willow Creek. The terrace tread (B) can be traced laterally to base of uppermost vertical segment of scarp (fig. 5). A second terrace (C) can be traced to base of lower vertical segment of scarp and top of debris slope.

Red Wall Canyon

Geomorphic features indicating recent tectonic activity are both abundant and well preserved along the Furnace Creek fault (fig. 8). From its junction on the south with the Death Valley fault, the Furnace Creek fault generally strikes northwest parallel to the Funeral Mountains (fig. 1). Its trace is linear with no evidence of large, lateral steps or bends. The geomorphology along the fault indicates that displacement is almost entirely lateral except in the vicinity of the Salt Creek Hills and near-Grapevine Canyon (fig. 1). In the Salt Creek Hills, the Funeral Formation of early Pleistocene age (Wright and Troxel, 1993)

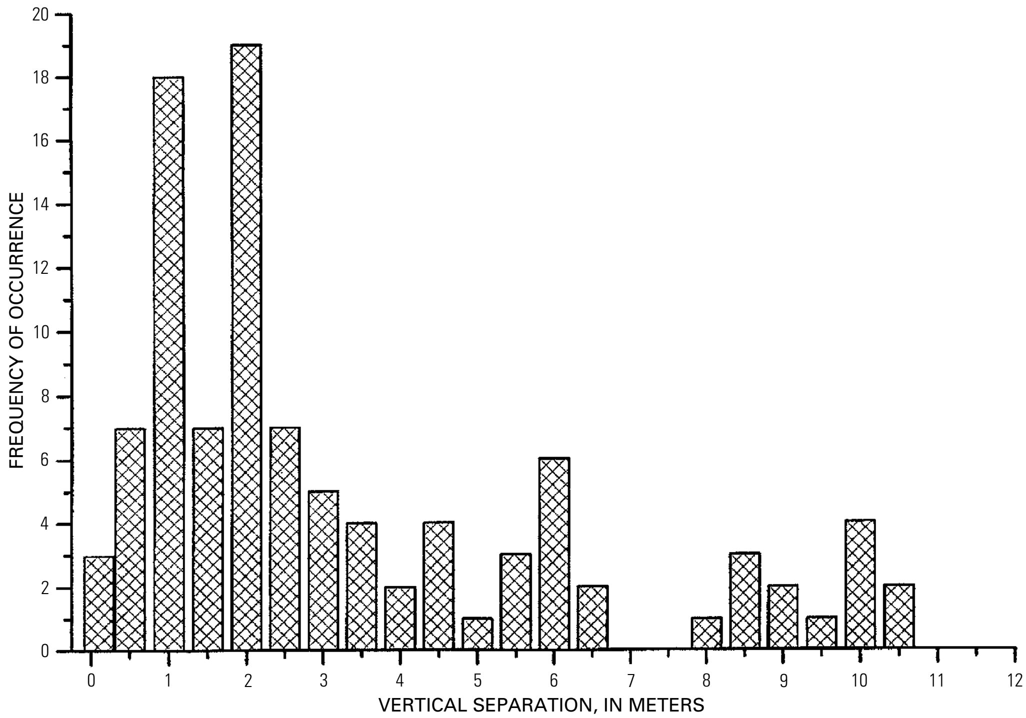

Figure 7. Frequency plot of vertical separations measured along the Death Valley fault (*n*=101).

has been uplifted along the east side of the fault and folded into the northwest-trending Salt Creek anticline west of the fault (Hunt and Mabey, 1966). Similarly, north of Grapevine Canyon, alluvial fan deposits of Pliocene age have been uplifted along the fault. Late Pleistocene terraces and alluvial fan surfaces that overlie the Pliocene and early Pleistocene deposits at these locations reflect this deformation and indicate that some transpression is occurring across the south and north ends of the Furnace Creek fault in Death Valley. North of the Salt Creek Hills, the fault crosses the valley floor and is expressed as a linear furrow with low east- and west-facing scarps. The only units that appear to be unfaulted are less than several hundred years old. North of Red Wall Canyon, a late Pleistocene alluvial fan has been offset by the fault, and drainages that incised the alluvial fan surface record the late Pleistocene slip history (fig. 8). The fault is expressed on the fan by both east- and west-facing scarps, right laterally offset drainages, sediment-filled depressions, en echelon furrows, shutter ridges, and troughs.

The right laterally offset alluvial fan reported by Reynolds (1969, p. 238), and referred to as the Redwall fan by Brogan and others (1991, p. 12), is located about 2 km north of Red Wall Canyon (fig. 1) in northern Death Valley. The fault at this location is expressed as a single trace nearly 1 km southwest of the range front (fig. 8). Numerous en echelon furrows, small closed depressions, shutter ridges, notches, troughs, and offset drainages indicate that deformation along the fault is confined to a relatively narrow zone. Small drainages that were offset along the fault indicate that slip has been predominantly lateral. At a location about 250 m northwest of the offset fan margin recognized by Reynolds (1969), a small late Holocene drainage that formed on the late Pleistocene surface has been repeatedly offset. The southern channel margin on the uphill side of the fault has been progressively offset at least three times. Following each faulting event, a new channel margin formed, leaving the old channel margins and bar deposits preserved adjacent to the active channel (fig. 9). The timing of these faulting events is reflected in successively greater degrees of varnish developed on each successively older bar deposit. (See McFadden and others, 1989.)

The progressively greater offset channel also provides excellent evidence for the amount of slip for each of the last three ground-rupturing events. Measurements of lateral displacement from the original channel margin on the downhill side of the fault and between each of the offset margins on the uphill side indicate that the lateral displacement per event at this site ranges from 2.5 to 4.5 m. These values are consistent with measured offsets elsewhere along the Furnace Creek fault (fig. 10). An age of 2–4 ka is assigned to the main channel based on the degree of varnish development on the oldest offset channel margin, which is comparable with varnish formed on nearby late Holocene surfaces (Q3c; table 1). The total right-lateral offset of this channel across the fault is 12.2 m, which yields a late Holocene slip rate of 3 to 6 mm/yr. Evidence for at least the last three earthquakes provided by these repeatedly offset stream channels also indicates that the return period for ground-rupturing earthquakes on the Furnace Creek fault in northern Death Valley is between 700 and 1,300 years.

There are also numerous beheaded and mismatched channels along the fault (fig. 8). The presence of underfit channels on the uphill side of the fault that drain into wider or more deeply incised channels on the downhill side of the fault indicates that the larger drainages have been offset by the fault. The larger drainages are incised into a late Pleistocene surface

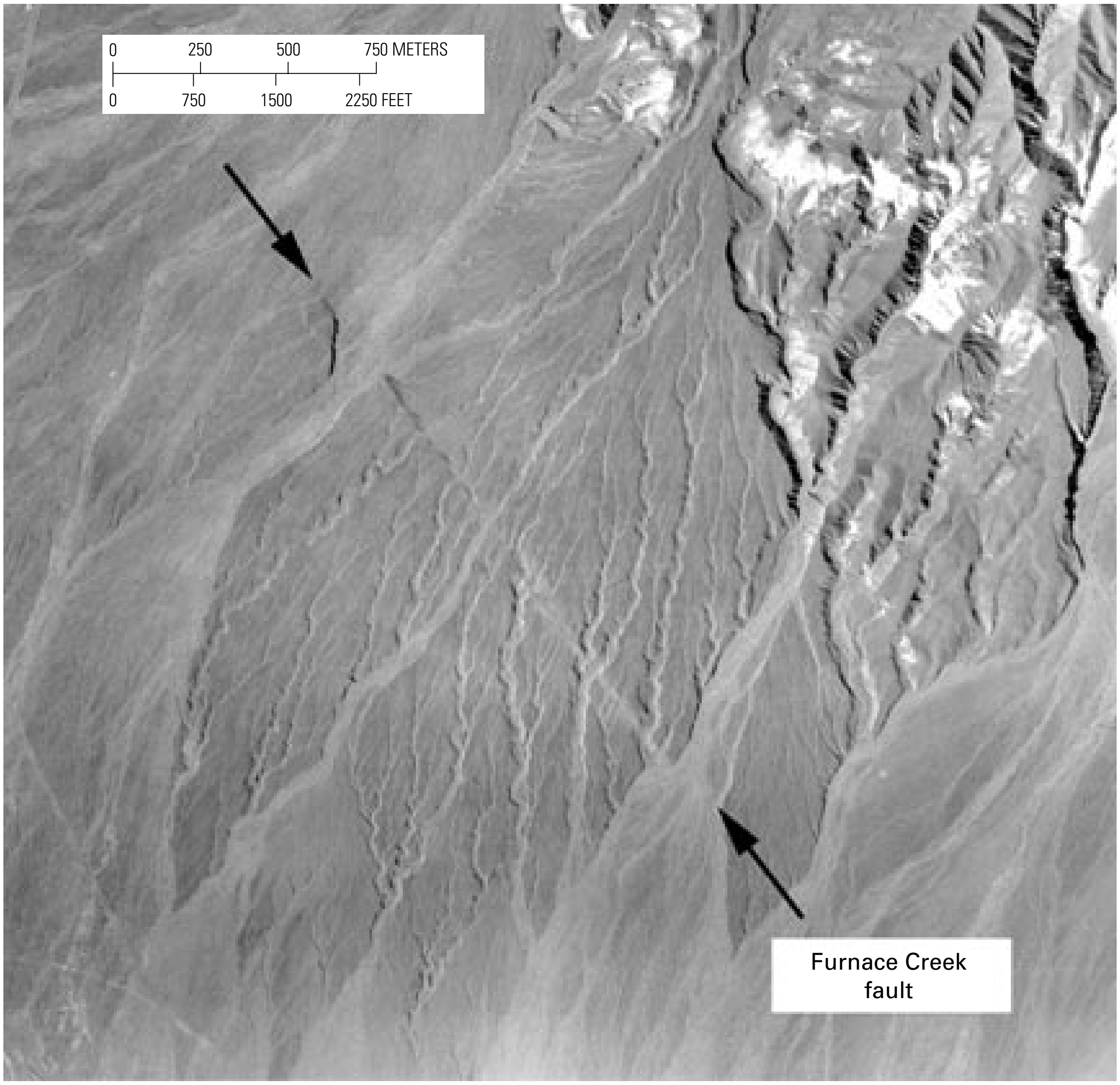

Figure 8. Vertical aerial photograph of a late Pleistocene alluvial fan faulted by Furnace Creek fault north of Red Wall Canyon in northern Death Valley.

whose age is estimated to be about 35–60 ka on the basis of (1) soil development (Q2c; table 1), and (2) the stratigraphic relation of correlative alluvial fan deposits to Lake Manly deposits (fig. 11).

The current position of the larger drainages that are incised into the late Pleistocene surface is interpreted to relate directly to total offset of the fault following the abandonment and stabilization of the alluvial fan surface. This interpretation is supported by a palinspastic reconstruction of the alluvial fan using low-altitude aerial photography (fig. 12). This reconstruction aligns three of the largest drainages (A, B, and C, fig. 12) that are incised into the late Pleistocene (Q2c) alluvial fan surface. These drainages moved progressively farther apart as a result of movement on the fault following stabilization of the alluvial fan surface and incision of the drainages. The right-lateral offset for these drainages now measures 248 m, 330 m, and 310 m for drainages A, B, and C (fig. 12), respectively. Because the displacement of the drainages occurred following their incision into the alluvial fan, the age of stabilization of the alluvial fan surface would approximate the age of the drainages. Therefore, the age of the geomorphic surface provides a maximum age for the total right-lateral displacement of the drainages and yields a slip rate of 4–9 mm/yr (table 2). This rate is in agreement with the late Pleistocene rate of 2–9 mm/yr estimated by Reheis and Sawyer (1997) for the Fish Lake Valley fault. This is also consistent with the late Holocene slip rate of 3–6 mm/yr provided by the offset late Holocene stream channels at the same location.

Figure 9. Right laterally offset stream channel margins (arrows). Distance between arrows is approximately 3 m. Dashed line, approximate location of Furnace Creek fault.

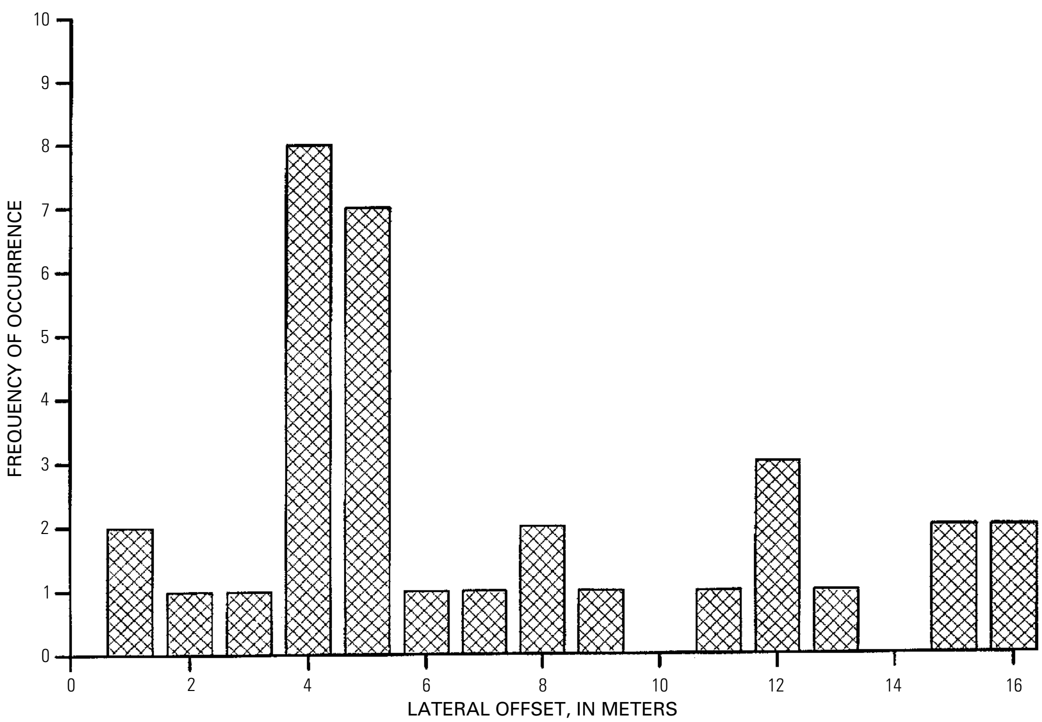

Figure 10. Frequency plot of right-lateral offsets of late Holocene geomorphic features, as measured along Furnace Creek fault (n=33).

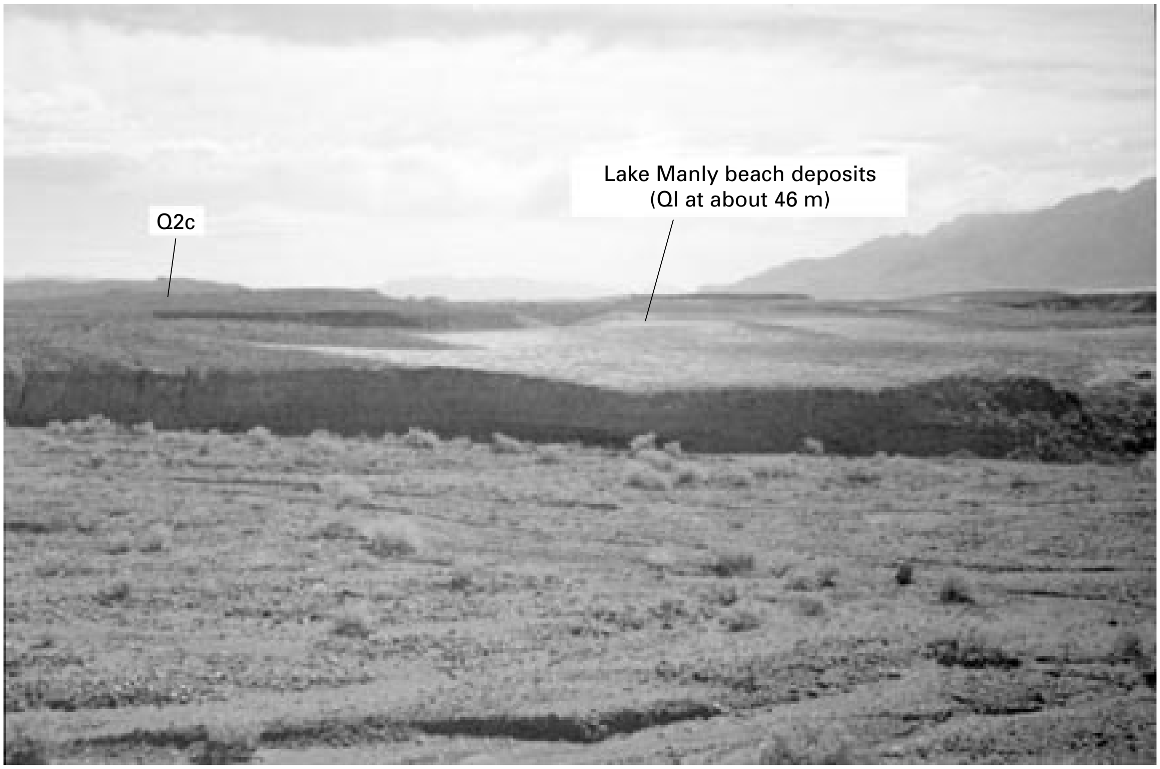

Figure 11. Stratigraphic relationship between late Pleistocene alluvial fan deposits (Q2c) and the overlying late Pleistocene Lake Manly deposits (Ql) at the 46-m shoreline near Triangle Spring. The lacustrine deposits are correlated to the 10–35 ka highstand of Li and others (1997).

Conclusions

Mapping of tectonic features and geomorphic surfaces along parts of the Death Valley and Furnace Creek faults, combined with detailed stratigraphic work, indicates that the late Quaternary slip rate for both faults is significantly higher than has been previously reported. Scarps on Holocene alluvial fans along the Death Valley fault near Mormon Point record at least the last three (and perhaps as many as four) ground-rupturing earthquakes. A net slip-per-event value on the order of 2.6 m can be estimated from the total height of the Willow Creek scarp, preserved single-event free faces, and uplifted stream terraces. Based on an estimated age of 4–8 ka for the faulted alluvial fan, the vertical slip rate on the Death Valley fault at this location is about 1–3 mm/yr. Assuming that the Willow Creek scarp represents the last four events, a return period of 1–2 k.y. for ground-rupturing earthquakes along the Death Valley fault can be estimated. However, given a slip rate of 1–3 mm/yr, and assuming surface displacements on the order of 2.6 m per event, a recurrence interval of 870–2,600 years can be estimated.

Clear evidence for at least the last three ground-rupturing events is also well preserved along the Furnace Creek fault near Red Wall Canyon. A repeatedly offset, late Holocene channel indicates that right-lateral displacement for the last event ranges from 2.5 to 4.5 m. A measurement of 12.2 m total right-lateral offset of the stream channel yields a late Holocene slip rate of 3–6 mm/yr on the Furnace Creek fault at this location. Also, assuming that the offset channel represents the last three events, a late Holocene return period of 700–1,300 years can be estimated for ground-rupturing earthquakes along the Furnace Creek fault in northern Death Valley. A right laterally displaced alluvial fan also records the total right-lateral offset that has occurred across the fault during the latest Pleistocene. Palinspastic reconstruction of the offset alluvial fan indicates that the large drainages incised into the alluvial fan surface have been offset 250–330 m across the fault. An age estimate of 35–60 ka for this geomorphic surface yields a slip rate on the Furnace Creek fault at this location of about 4–9 mm/yr. These rates indicate that the late Pleistocene slip rate is at least a factor of two greater than previous estimates for the Furnace Creek fault in northern Death Valley.

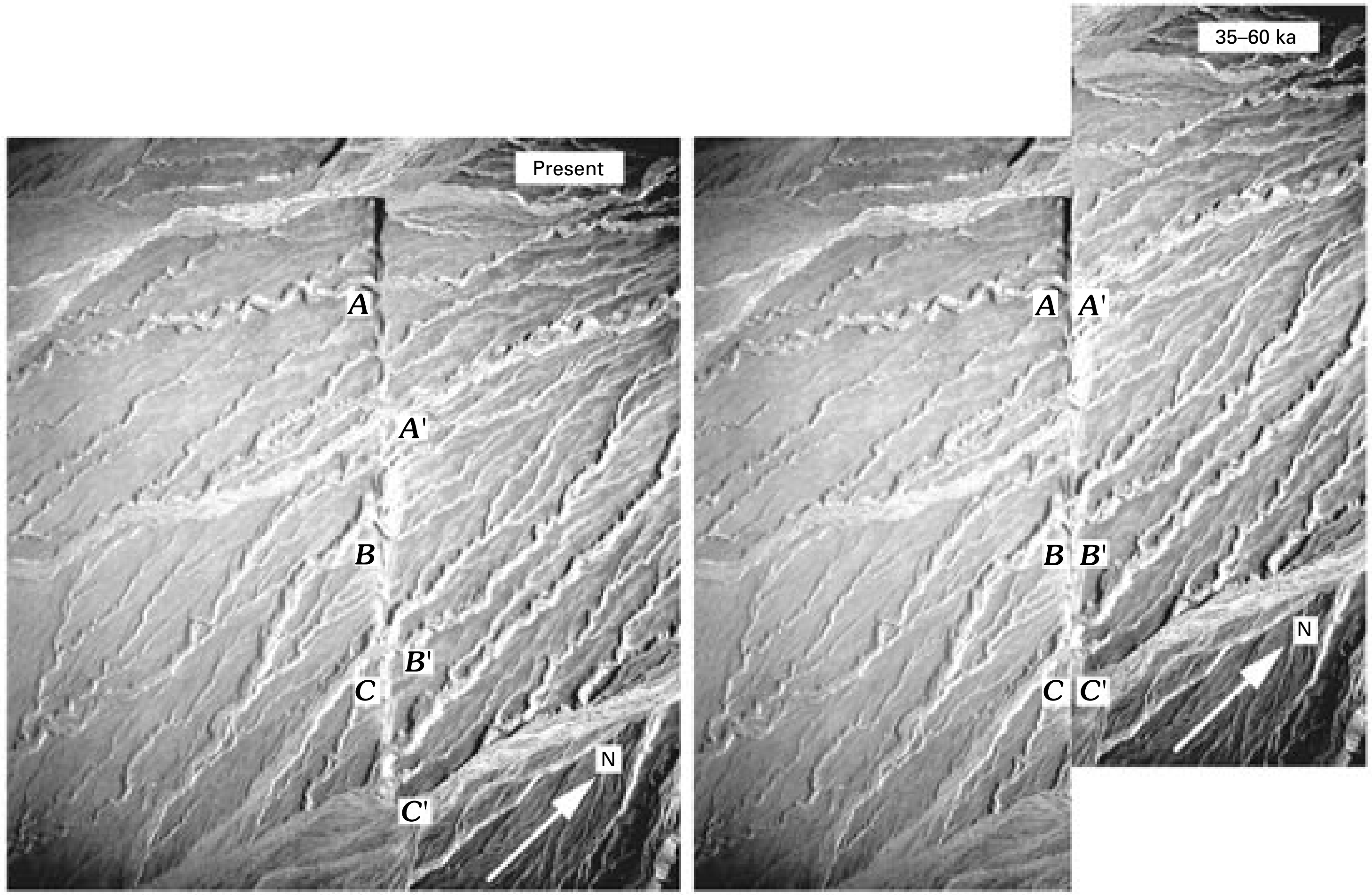

Figure 12. Palinspastic reconstruction of a late Pleistocene alluvial fan north of Red Wall Canyon in northern Death Valley.

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