LATE QUATERNARY SLIP RATE ESTIMATES FOR THE DEATH VALLEY AND FURNACE CREEK FAULTS, DEATH VALLEY, CALIFORNIA

Ralph E. Klinger and Lucille A. Piety

Seismotectonics and Geophysics Group

Bureau of Reclamation

ENCLOSURE 2

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ABSTRACT

Earlier published reports indicate that the slip rate for the Death Valley fault is on the order of 1-2 millimeters per year and that the slip rate for the Furnace Creek fault is on the order of 2-3 millimeters per year. However, geomorphic features associated with both faults indicate that numerous surface-rupturing earthquakes have occurred during the late Holocene and that 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 the site under consideration as a high-level nuclear-waste repository.

Along the Death Valley fault near Mormon Point, the surface of a middle to late Holocene alluvial fan is vertically displaced 10.5 meters. Preserved free-faces and inset terraces record the last three and possibly four events. Average vertical displacement per event at this location is interpreted to be about 2.1-2.6 meters. An approximate age of 2,000-4,000 years is estimated for the displaced geomorphic surface based on its surface characteristics. This yields an average vertical slip rate for the Death Valley fault of 3-5 millimeters per year.

Along the Furnace Creek fault near Red Wall Canyon, repeated movement has right-laterally offset latest Holocene channels and preserved evidence for the last three ground-rupturing events. Lateral displacement per event at this location is about 2.5-3.5 meters. Large drainages incised into the fan have also been offset and record the late Pleistocene slip history. Utilizing low-altitude aerial photography, a palinspastic reconstruction of the fan surface indicates that the large incised drainages are right-laterally offset 230-310 meters across the fault. An approximate age of 40,000 years, based on its surface characteristics, is estimated for the geomorphic surface into which the drainages are incised. This yields an average lateral slip rate for the Furnace Creek fault of 6-8 millimeters per year.

INTRODUCTION

The Death Valley-Furnace Creek fault system (DVFCFS) consists of several discrete faults that extend for over 350 kilometers (km) along the California-Nevada border. The Death Valley and Furnace Creek faults are the two dominant structures in the DVFCFS and together these two faults are the longest and most active faults in the region. Preliminary seismic risk studies indicate that the DVFCFS may be the controlling distant seismic source for the potential high-level nuclear-waste repository at Yucca Mountain. Therefore, an assessment of their Quaternary activity is important in the evaluation of Quaternary faults around Yucca Mountain. 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, return periods for large ground rupturing events, amount of displacement per event, lengths of individual surface-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 north-striking, high-angle, down-to-the-west normal fault that is located along the western flank of the Black Mountains (fig. 1). The Furnace Creek fault is the northwest-striking, right-lateral strike-slip fault that is located more or less along the axis of northern Death Valley and extends to the north along the Funeral Mountains (fig. 1). The two faults join near Furnace Creek Ranch in Death Valley, about 50 km from the potential repository site at Yucca Mountain. Field studies to evaluate the previous work along about 125 km of the Death Valley and Furnace Creek faults began early in 1993. The Death Valley fault was examined from Mormon Point to just north of Furnace Creek Wash (about 50 km) and the Furnace Creek fault was studied from its junction with the Death Valley fault northward to just south of Grapevine Canyon (about 75 km)(fig. 1). Abundant evidence for multiple late Holocene surface ruptures is well-preserved at numerous locations along both faults. Traditionally, much of the data regarding fault behavior is collected from trench excavations across the fault. However, because much of the DVFCFS lies within the Death Valley National Monument, these type of activities are not allowed. To improve our understanding of the DVFCFS, faults, associated surficial deposits, and tectonic features related to recent tectonic activity at specific sites were mapped at a scale of about 1:7,500. This paper documents some of the well-preserved evidence of past faulting and summarizes the findings of the reconnaissance studies undertaken during the 1993-94 field season and reports estimates of late Quaternary slip rates derived from mapping at two sites: one along the Death Valley fault near Mormon Point (fig. 2A) and one along the Furnace Creek fault north of Red Wall Canyon (fig. 2B).

FIGURE 1.--NEAR HERE

FIGURE 2.--NEAR HERE

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." In northern Death Valley, Curry (1938) reported abundant geomorphic evidence that suggested lateral displacement along the Furnace Creek fault. However, the role of these two faults in the development of Death Valley was not described until Burchfiel and Stewart (1966) presented their pull-apart basin hypothesis. Their model of right-lateral slip on the parallel northwest-striking Furnace Creek and southern Death Valley faults being translated to oblique-normal slip on the Death Valley fault (fig. 1), is now widely accepted. However, the relationship between these active faults and how they behave seismogenically remains unknown.

Hunt and Mabey (1966, p. A100) estimated that the most recent activity along the Death Valley fault is younger than about 2000 years, based on the relationship of the fault scarps in central Death Valley to late Holocene lake shorelines and archaeological artifacts. Clements (1954, p. 58-60), on the basis of newspaper accounts and other turn-of-the-century written records, speculated that the young scarps along the Death Valley fault were the result of the November 4, 1908, magnitude 6.5 earthquake reported by Stover and Coffman (1993, p. 75). Records for this particular earthquake, unfortunately, are not very good and the epicenter location is poorly located.

Curry (1938, p. 1875) implied that activity on the Furnace Creek fault was relatively young owing to the presence of "a churned-up furrow in recent alluvium." However, specific locations documenting young activity along the fault were not reported until Reynolds (1969, p. 238) noted that the margin of a Pleistocene alluvial fan north of Red Wall Canyon was right-laterally offset about 150 feet (ft). Reynolds also reported late Holocene activity along the Furnace Creek fault but interpreted the displacement of the fan margin as being middle to late Pleistocene. Bryant (1988, p. 8-9) reevaluated the age of the offset fan margin in order to develop the only published late Quaternary slip rate for the Furnace Creek fault in Death Valley. He acknowledged the 150 ft offset, but assumed that the stream incision that produced the fan margin occurred about 20,000 years before present (yrs B.P.) 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 that the estimated slip rate of 2.3 millimeters per year (mm/yr) was a crude minimum estimate. Most recently, Reheis (1994) reports that the lateral slip rate on the northern Furnace Creek fault in Fish Lake Valley is about 4-7 mm/yr, and may be as high as 12 mm/yr. This suggests that the minimum slip rate of 2.3 mm/yr for the Furnace Creek fault in Death Valley may underestimate the actual late Quaternary slip rate by at least a factor of two and perhaps by a factor of five.

In the most detailed study of the late Quaternary activity on the Death Valley and Furnace Creek faults, Brogan and others (1991) document the location of the major traces and prominent tectonic features along the length of the DVFCFS at a scale of 1:62,500. 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). While Brogan and others (1991) do not report any new slip rates for either fault, they acknowledge the minimum rate of 2.3 mm/yr reported by Bryan (1988) for the Furnace Creek fault. However, using the range of vertical separations for Holocene surfaces reported by Brogan and others (1991, p. 21), an average vertical slip rate of 0.2-2.5 can be estimated for the Death Valley fault.

QUATERNARY STRATIGRAPHY

The most extensive Quaternary stratigraphic work undertaken in Death Valley is the reconnaissance-level work of Hunt and Mabey (1966; 1:96,000). Their mapping remains the most comprehensive in regards to the Quaternary stratigraphy, but is confined to the southern half of Death Valley and lacks the detail needed to evaluate Quaternary faulting activity. More detailed mapping of the surficial deposits along the Furnace Creek fault was completed by Moring (1986; 1:62,500) in northern Death Valley and by Wright and Troxel (1993; 1:48,000) in central Death Valley. The work of Wright and Troxel (1993), although emphasizing the bedrock geology of the southern Funeral Mountains, extends into Death Valley and includes the surficial deposits along the southern end of the Furnace Creek fault.

Mapping of the surficial deposits in Death Valley, for the most part, remains areally limited and incomplete.

Because of the hyperarid environment in Death Valley and the accompanying lack of vegetation, age control utilizing conventional radiocarbon techniques has been difficult to obtain. Hence, the ages of alluvial surfaces presented by previous workers in Death Valley have been based on the archaeology and relative age criteria such as degree of desert pavement and varnish development, depth of stream incision, and relative topographic position. Other studies examining Quaternary processes such as alluvial fan deposition, pluvial lake history, and the effects of climatic change in the Death Valley area have obtained 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). Unfortunately, these ages are not tied to detailed maps and descriptions of the sampled surfaces that are needed to make correlations elsewhere do not exist. Only the recent work of Bull (1991, p. 86) has attempted to establish a stratigraphic framework for surficial deposits in the arid southwestern United States. Bull suggests that the alluvial sequences recognized throughout the region are related to major climatic changes. By using detailed descriptions of characteristics on geomorphic surfaces, soil developed on those surfaces, and numerical ages based on a variety of methods, he demonstrates that a regional correlation of these alluvial sequences is possible.

The ages of the faulted alluvial fans in Death Valley can be estimated not only from surface characteristics but also from the stratigraphic relationships between the alluvial fan deposits and deposits related to late Pleistocene pluvial Lake Manly. Our knowledge of Lake Manly is fragmentary (Blackwelder, 1933; 1954; Hooke, 1972; Dorn and others, 1990), but recent work by Ku and others (1994) indicates that the last perennial lake existed in Death Valley from about 30,000 to about 10,000 yrs B.P. Some late Pleistocene surfaces adjacent to the DVFCFS have strandlines that record former highstands of Lake Manly and at numerous locations in Death Valley alluvial deposits and older fault-line scarps are overlain by lacustrine deposits. Since the recession of Lake Manly, the larger drainages have incised the higher late Pleistocene surfaces and redeposited the sediment in younger alluvial fans downslope (fig. 2). Surface characteristics on the younger alluvial fans (table 1) suggest that the incision and deposition most likely occurred during the middle and late Holocene. Therefore, the scarps and offset drainages on these younger alluvial fans record the total slip that has occurred on the DVFCFS during the latter part of the Holocene.

TABLE 1.--NEAR HERE

METHODOLOGY

In this study, geomorphic surfaces on faulted alluvial fans were mapped on low altitude (~1:7,500) low-sun-angle photographs. Geomorphic surfaces were initially categorized on the basis of their tonal differences and surface textures. These characteristics relate directly to the degree of varnish development and desert pavement formation. The descriptions of these surfaces were later refined in the field by including characteristics such as bar-and-swale morphology, pavement packing, surface dissection, varnish development, and the degree of soil horizonation (table 1). Surface designations and preliminary age assignments used in this report were adapted from Bull (1991, p. 65, 74-76) and made by comparing surface characteristics described in Death Valley to the lower Colorado River region. All slip measurements and the scarp profile, with the exception of the longer offsets, were measured in the field with a tape and hand level. The longer offset distances were measured from the low altitude aerial photographs. In addition to the uncertainities inherit to the measurement of these morphologic features in coarse-grained alluvial fan deposits, additional error in slip measurements may have been incurred due to the questionable position of channel margins due to subsequent erosion and deposition or low angles of intersection between offset drainages and the fault. All scarp heights and scarp-slope angles were measured from a computer-generated plot of field data.

WILLOW CREEK

Young scarps are nearly continuous on Holocene alluvial surfaces along the Death Valley fault from Furnace Creek Ranch south to Shoreline Butte with the exception of a 13-to-14-km-long gap near Artists Drive (fig. 1). Where the fault rounds the northern end of the Mormon Point turtleback (fig. 1), the fault changes strike from north-northwest to east-northeast. In the embayment in the range near Willow Creek, the strike of the fault gradually changes back to a north-northwest direction where the fault lies along the western flank of the Copper Canyon turtleback (fig. 1). Pronounced triangular facets and fault-line scarps are preserved on older alluvial deposits in the area. Younger fault scarps parallel the triangular facets and a fault-line scarp and form the most recent active trace of the Death Valley fault. Correlative geomorphic surfaces on each side of the fault generally are poorly preserved. This complicates efforts to determine the style of deformation, slip per event measurements, and activity rates. Geomorphic surfaces on the hanging-wall side of most scarps have been modified either by erosion or by deposition from continued fan processes (fig. 3). However, approximately 700 meters (m) north of the mouth of Willow Creek, a late Holocene surface (Q3c; table 1) is preserved on both sides of the scarp (fig. 3). A scarp profile was measured at this location in order to resolve surface displacement across the fault during the time represented by the age of the surface (fig. 4).

FIGURE 3.--NEAR HERE

FIGURE 4.--NEAR HERE

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 implied that the overhanging scarps were evidence of local reverse faulting. In contrast, overhanging scarps are commonly associated with very young normal fault scarps in alluvium and represent an early stage of scarp degradation. Close examination in the field suggests that the original scarp morphology is being preserved by the case-hardening effect and cementation of the alluvial by chemical agents blowing off the playa. Cementation of the alluvium with sodium chloride salt was commonly observed as would be expected given the proximity of the scarps to the salt pan and the very low mean annual precipitation in this part of Death Valley (less than 40 mm/yr). The overhanging scarps along the Death Valley fault reflect a more resistant salt-impregnated "cap rock" portion of the alluvial surface which overlies erodible uncemented alluvium at the base of the scarp. Rather than following a slope decline model of fault-scarp degradation, as described by Wallace (1977), it appears that the scarps in Death Valley tend to follow a parallel retreat model as outlined by Young (1972). Some portion of most scarps along the length of the Death Valley fault were found to be vertical or near-vertical. Owing to the probable young age of the scarp and the complex factors controlling its degradation, in this instance, analysis of the scarp height and slope angle measurements was complicated. While 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.

The profile near Willow Creek was measured perpendicular to the scarp, but the scarp crosses the alluvial slope at this location at a high angle. Therefore, rills developed on the fan surface prior to faulting give the illusion of being laterally offset across the fault. However, no evidence for lateral displacement was recognized at this site. Also, due to the differential preservation of large bars and swales on the upper surface of the scarp, the overall height of the scarp, and the vertical slope angle of the scarp, measurement of the scarp height in the field was difficult. The total scarp height of 10.5 m was measured from a computer-generated plot of the profile (fig. 4) and is believed to approximate within about 0.5 m the total vertical displacement of the surface since its stabilization. Owing to its stratigraphic position relative to latest Pleistocene Lake Manly shorelines and surface characteristics (table 1), the faulted surface is correlated with the late Holocene Q3c surface of Bull (table 1). Therefore, based on the estimated age for the Q3c surface of 2-4 kiloannum (ka), a scarp height of 10.5 m yields an average late Holocene vertical slip rate of 3-5 mm/yr (table 2).

TABLE 2: LATE QUATERNARY SLIP RATE ESTIMATES

Fault	Locality	Displacement (m)	Time Period	Slip rate (mm/yr)
Death Valley	Willow Creek	10.5	~2-4 ka	3-5
Furnace Creek	Red Wall Canyon	230-310	~40 ka	6-8

Slope angles across the scarp range from the angle of repose at the toe to vertical at the crest (fig. 4). The two vertical sections of the profile shown in figure 4 are interpreted to represent preserved free faces formed by separate ground-rupturing events. This hypothesis is supported by the presence of inset terraces preserved on the footwall block near the mouth of Willow Creek that can be traced to the base of each free-face. Based on this relationship, the scarps near Willow Creek record at least three events in late Holocene Q3c deposits. Assuming that parallel retreat has dominated degradation of these scarps, then the height of preserved free faces approximate the amount of surface displacement resulting from each ground-rupturing event. The measured height of 2.1 and 2.6 m for the two relatively well preserved free faces would then represent the surface displacement per event. If the scarp represents three events, as suggested by the inset terraces associated with the scarp, then the total scarp height of 10.5 m indicates that average surface displacement per event is about 3.5 m. Assuming that the scarp represents four events, the average surface displacement per event is about 2.5 m. This is in close agreement with the heights 2.1 and 2.6 m for the preserved free faces. Additionally, assuming that minimal free-face degradation has occurred between events, it appears that the past several ground-rupturing earthquakes that have occurred along the Death Valley fault at this location have been of similar size.

RED WALL CANYON

As reported by Curry (1938), geomorphic features indicating young tectonic activity is both abundant and well preserved along the Furnace Creek fault. Between its junction to the south with the Death Valley fault and the Grapevine Canyon to the north, the Furnace Creek fault strikes generally northwest and its trace is linear with no evidence of large lateral steps or bends (fig. 1). Offset drainages along the length of the fault suggest that displacement is nearly pure lateral except in the vicinity of the Salt Creek Hills (fig. 1). The Funeral Formation of early Pleistocene (?) age (Wright and Troxel, 1993) is uplifted along the east side of the fault and folded in the northwest-trending Salt Creek anticline west of the fault (Hunt and Mabey, 1966). Late Pleistocene terraces and other geomorphic surfaces which overlie the Funeral Formation reflect this deformation and suggest that some transpression is occurring across the southern end of the Furnace Creek fault. North of the Salt Creek Hills, the Furnace Creek 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 those interpreted to be correlative with latest Holocene surfaces (Q4b; table 1). Along much of the fault, deposits of different ages are commonly juxtaposed across the fault making evaluation of the slip on the fault difficult. However, north of Red Wall Canyon, fan surfaces correlative with the late Pleistocene Q2c unit (table 1) are preserved along both sides of the fault and drainages that incised these surfaces record the late Pleistocene slip history (figs. 2B and 5).

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 in northern Death Valley (fig. 1). The fault at this location is expressed as a single dramatic trace nearly 1 km southwest of the range front (fig 2B). Numerous en echelon furrows, small closed depressions, shutterridges, notches, hillside troughs, and offset drainages indicate that deformation along the fault is confined to a relatively narrow zone (figs. 2B and 5). Small drainages offset along the fault indicate that slip has been predominately lateral. At a location about 250 m northwest of the offset fan margin recognized by Reynolds (1969)(site 4 in fig. 5), a small late Holocene drainage 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 then formed leaving the old channel margins and bar deposits preserved adjacent to the active channel. The timing between this sequence of faulting events is reflected in the successively greater degree of varnish developed on each successively older bar deposit. The progressive offset channel at this site provides excellent evidence of 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 lateral displacement per event ranged from 2.5 to 3.5 m.

FIGURE 5.--NEAR HERE

Large drainages which incised the late Pleistocene surface have also been offset across the fault (fig. 2B). In addition, there are numerous beheaded and mismatched channels along the fault (fig. 5). The current position of the larger drainages that are incised into the Q2c surface is interpreted to relate directly to the abandonment and stabilization of the surface. This interpretation is supported by the presence of several 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. Palinspastic reconstruction of the late Pleistocene surface using low-altitude (~1:7680) aerial photographs indicates that three of the incised older drainages have been right-laterally offset 230-310 m across the fault (fig. 5). The offset measurements for these larger drainages were derived from the aerial photography and are believed to approximate within about 10 m the total right-lateral displacement since the incision of the drainages into the late Pleistocene surface. Because the displacement of the drainages occurred following their initial incision, then the age of stabilization of the geomorphic 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.

Surface characteristics were described at several sites on the late Pleistocene surface (table 1; fig. 5). Geomorphic surfaces in the southwestern United States with similar characteristics have been estimated by Bull (1991) to have an age of 12-70 ka. The 230-310 m offset measured on the large drainages (fig. 5) divided by an the age estimate of 12-70 ka for the Q2c surface at Red Wall Canyon results in a poorly constrained slip rate of 3-26 mm/yr. However, based on comparisons to other geomorphic surfaces of known age in the region (Dorn, 1988; Wells and others, 1987; Taylor, written communication), an age of about 40 ka is believed to more closely approximate the age of the Q2c surface at Red Wall Canyon. Using this age estimate limits the average lateral slip rate to about 6-8 mm/yr (table 2). This rate is in agreement with the rate of 4-7 mm/yr estimated by Reheis (1994) for the Furnace Creek fault in Fish Lake Valley. Admittedly, age control on the faulted deposits at this site is not very precise, but the late Pleistocene displacement is much better constrained than previous measurements. Regardless of the large uncertainities in the age of the faulted deposits, it appears that the slip rate on the Furnace Creek fault may be several times greater than previously thought.

CONCLUSIONS

Detailed mapping of tectonic features and geomorphic surfaces along parts of the Death Valley and Furnace Creek faults indicate that the late Quaternary slip rate for both faults is significantly higher than has been previously reported. Scarps on late Holocene alluvial fans along the Death Valley fault at Willow record at least three, and probably four, ground-rupturing earthquakes. Slip per event on the order of 2.1-3.5 m can be estimated from the height of the scarp, preserved free-faces, and inset stream terraces. Using an age of 2-4 ka, estimated on the basis of relative age criteria, the vertical slip rate for the Death Valley fault at this location is about 3-5 mm/yr.

Clear evidence for at least the last three ground rupturing earthquakes is also well preserved along the Furnace Creek fault. Repeatedly offset late Holocene channel margins indicate that lateral displacement per event ranged from 2.5 to 3.5 m. The right-laterally offset alluvial fan north of Red Wall Canyon records displacements that have occurred across the fault during the late Quaternary. Palinspastic reconstruction of the offset alluvial fan indicates that three large drainages incised into the fan surface are offset 230-310 m across the fault. An estimate of 40 ka for this geomorphic surface, which is based on relative age criteria, suggests that the slip rate on the Furnace Creek fault at this location is about 6-8 mm/yr.

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Table 1. DESCRIPTIONS OF QUATERNARY GEOMORPHIC SURFACES NEAR WILLOW CREEK AND RED WALL CANYON

			Clasts						Depth of	Varnish			
Geomorphic surface[1]	Inferred age (ka)	Locality	Size[2]	Lithology[3]	Orient.[4]	Form[5]	Pavement packing[6]	Bar/swale morphology[7]	dissection (m)[8]	Lithology[9]	Location[10]	Color[11]	Soil horizons[12]
Q4b/Q4a	<2						Includes active channels and bars related to the channels						
Q3c	2–4	15 on Fig. 3	Large cobbles and boulders	70% D, 13% M, 13% VT, 4% MV	--	--	--	Distinct	--	VT	Bottom Top surfaces Top depressions	5YR 6/8 5YR 6/8 5YR 5/8	--
Q3b	4–8	17 on Fig. 5	Large cobbles; pebbles and cobbles	43% L/D, 38% Q, 17% VT, 2% C	R to O	--	PP to MP	Subdued	≤0.5	Q	Bottom[13] Edge	5YR 5/8 7.5YR 3/0	Av/Bk (stage I)
Q3a	8–12	1 on Fig. 5	--	L/D, Q	--	--	--	Subdued	~2	Surface is dark, but clasts are predominately dark gray limestone and dolomite.			Av/B(z?)m/Bkb
Q2c	12–70	15 on Fig. 5	Boulders	Q, L/D, VT, CR	--	Many clasts cracked	[14]PP to WP	--	--	Most clasts have dark, red-brown varnish. Bottoms of some are bright red. Bottoms of others are light red.			--
		13 on Fig. 5	Boulders; pebbles	65% Q/S, 30% L/D, 5% VT, tr. SH	H	--	WP	None	--	Q VT	Bottom[13] Top surfaces Top depressions Bottom Top surfaces	2.5YR 4/8 2.5YR 5/8 2.5YR 2.5/0 2.5YR 4/8 2.5YR 2.5/2	Av/Av-Bwk/2Bk/2Bky (stage II+)
		18 on Fig. 5	Boulders; pebbles and cobbles	60% Q, 20% L/D, 20% S/C, 5% VT?, 5% CR	--	--	WP	None	--	Q	Bottom Edge Top surfaces	2.5YR 5/8 2.5YR 3/6 2.5YR 2.5/0	Avk/Btkz-Avb/2Bkyz (stage II+)
		2 and 3 on Fig. 5	--	--	--	--	MP to WP	Mature	--	Most clasts have dark varnish. Bottoms of quartzites are red or bright orange.			Av/Btk/Bkm (stage I+ to III)[15]
		4 on Fig. 5	Boulders	--	--	--	MP	Mature	--	Surface appears dark, but color is gray instead of brown (from dark-gray limestone and dolomite?). Bottoms of quartzites are moderately to slightly red. Tops of quartzites are dark red-brown.			Bk (stage II or III)
		16 on Fig. 5	Small boulders	42% L/D, 30% Q, 20% S, 5% VT, 3% C, tr. CR	O	--	MP	Mature	2 to 3	Q	Bottom[13] Edge[13]	2.5YR 5/8 to 4/8 5YR 2.5/1	Avk/Btkb/Bkb

Notes to accompany Table 1:

[1] Designations are from Bull (1991, table 2.2, p. 54) for alluvial geomorphic surfaces of the lower Colorado River region, which encompasses Death Valley.

[2] The entry before the semi-colon shows the maximum clast size (visually estimated). The entry after the semi-colon shows the dominant clast size (visually estimated). A single entry is for the maximum clast size. Size classes are as follows: Boulders, >256 mm; Cobbles, 64–356 mm; Pebbles, 2–64 mm.

[3] Lithology is the composition of the clasts. Where percentages are given, clast lithology was determined by identifying each clast located at 10-cm intervals along a 1.5-m-long measuring tape that was placed randomly on the surface. Abbreviations indicate the following lithology: C, chert; CR, carbonate rubble; D, diorite; L/D, limestone and dolomite (usually gray or dark gray; may include lenses of brown chert); M, metamorphic rocks, not specified; MV, metamorphosed volcanic rock; Q, quartzite (usually white, tan, or light pink); Q/S, quartzite and sandstone; S/C, sandstone and chert; SH, shale; VT, volcanic tuff. Where no percentages are given, clast lithology was noted by visual inspection and is listed in order of decreasing relative amounts of each lithology.

[4] Orient. is the orientation of the clasts in the pavement relative to the ground surface. Abbreviations are as follows. R, random; long axes of the clasts are random; no direction of orientation predominates. O, oblique; long axes of most clasts project at an oblique angle into the ground surface. H, horizontal; long axes of most clasts are parallel to the ground surface.

[5] Clast form includes changes to the clast condition or appearance that have occurred since deposition. These changes include physical abrasion into ventifacts, pitting and solution weathering, and cracking and disintegration resulting from thermal and chemical processes.

[6] Packing is how closely the clasts are organized on the surface. Abbreviations are as follows. PP, poorly packed; clasts are unorganized. MP, moderately packed; most clasts do not touch, and sand and silt are visible between the clasts. WP, well packed; clasts interlock or are nearly so, and little or no sand and silt visible between the clasts. Where two classes are given, the poorer packing refers to the pavement on bars and the better packing refers to the pavement in swales, unless otherwise noted.

[7] Bar and swale morphology is a measure of how much of the original depositional pattern remains on the surface. Property is dependent upon the original clast size and shape (e.g., pebbly surface may have little or no bar and swale topography initially). Terms are as follows. Distinct, contact between the bars and swales is clear and relief above the swale averages >50 cm. Subdued, relief above the swale averages between 25 and 50 cm. Mature, bars and swales are still visible but pavement development on bars is approaching or equivalent to that in the swales. None, bar and swale topography has been completely masked or was never present.

[8] Depth was visually estimated.

[9] Clast lithology on which varnish color was determined. Light-colored quartzites (Q) were used where available. Otherwise, light-colored volcanic tuffs (VT) were examined.

[10] Location of the varnish coat on which color was determined. Bottom is the portion of the clast below the ground surface. Edge is the portion of the clast that intersects the ground surface. Top is the portion of the clast above the ground surface. For the tops of clasts, varnish was noted on both the clast surface and in depressions, as indicated.

[11] Color was determined using Munsell notation.

[12] Soil horizons described according to Birkeland (1984, appendix 1, p. 353-361). Shown in parentheses is the stage of the maximum carbonate development in the Bk horizon (Birkeland, 1984, p. 358-359).

[13] Color is the maximum recognized by examining randomly selected clasts from the surface.

[14] Pavement is poorly packed near the fault scarp. Pavement is well packed on this surface further from the scarp (>100 m).

[15] Soil was noted only in a poor exposure, so that the maximum carbonate stage was dificult to estimate.

Figure 1. Map showing the location of the southern Death Valley, Death Valley, and Furnace Creek faults relative to the proposed repository site at Yucca Mountain (YM). Location of the faults taken from Reheis (1991a) and Brogan and others (1991). Stippled areas are the major mountain ranges adjacent to Death Valley. Letter abbreviations are locations described in this report: GC - Grapevine Canyon, RW - Red Wall Canyon, SCH - Salt Creek Hills, FCR - Furnace Creek Ranch, FCW - Furnace Creek Wash, AD - Artists Drive, CC - Copper Canyon, WC - Willow Creek, MP - Mormon Point, and SB - Shoreline Butte.

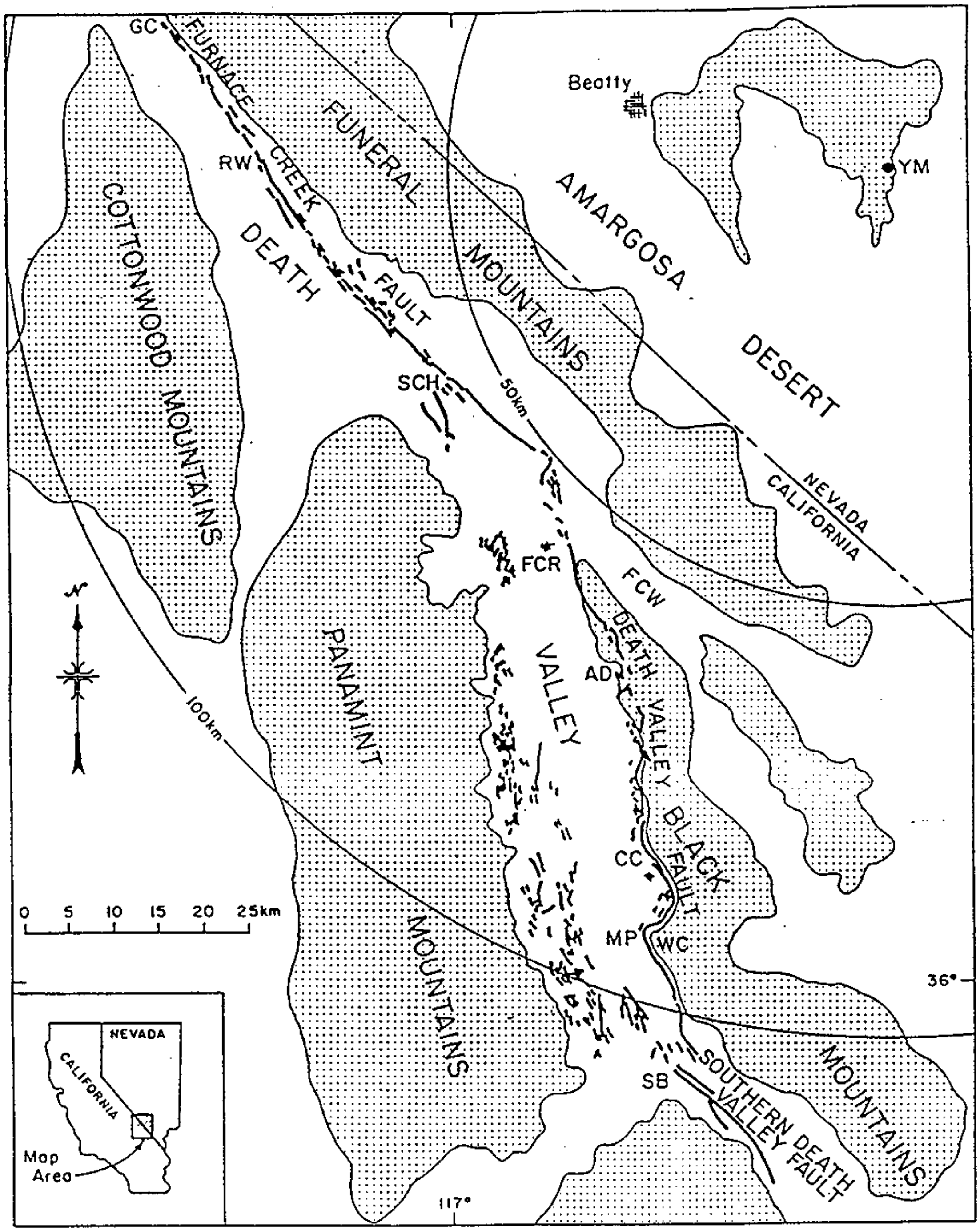
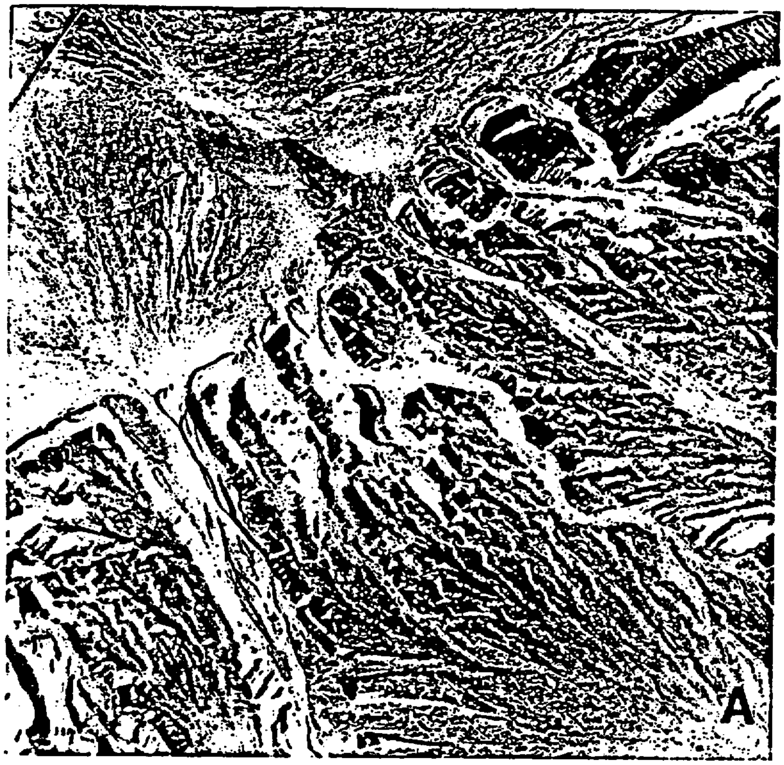

GC
FURNACE CREEK FAULT
FUNERAL MOUNTAINS
Beatty
YM
AMARGOSA DESERT
RW
COTTONWOOD MOUNTAINS
DEATH VALLEY
SCH
50km
NEVADA
CALIFORNIA
FCR
FCW
PANAMINT MOUNTAINS
DEATH VALLEY FAULT
AD
BLACK MOUNTAINS
100km
N
CC
MP
WC
0 5 10 15 20 25km
36°
SB
SOUTHERN DEATH VALLEY FAULT
117°
NEVADA
CALIFORNIA
Map Area

Figure 2. Vertical aerial photographs of faulted alluvial fans along A) the Death Valley fault near Willow Creek (GS-VFDT 7-209; approximate scale 1:20,000) and B) the Furnace Creek fault north of Red Wall Canyon (GS-VFDT 7-163; approximate scale 1:35,000).


A

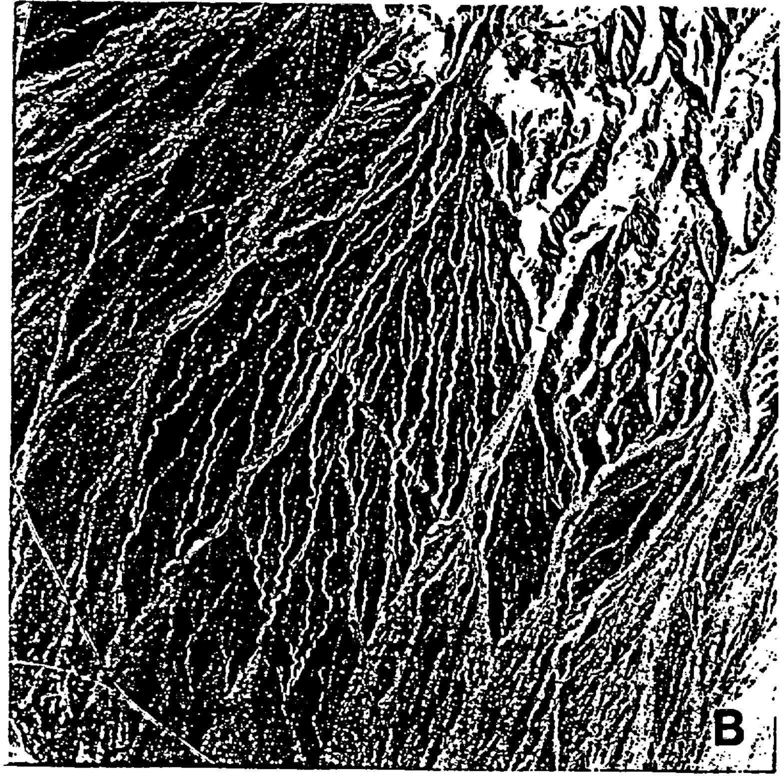

B

Figure 3 Surficial geologic map of the northeast-striking section of the Death Valley fault near Willow Creek (see fig. 2A). Numbered site locations, geomorphic surface designations, and criteria used to characterize and differentiate the surface units are outlined in table 1. A scarp profile was measured across the fault at site 15.

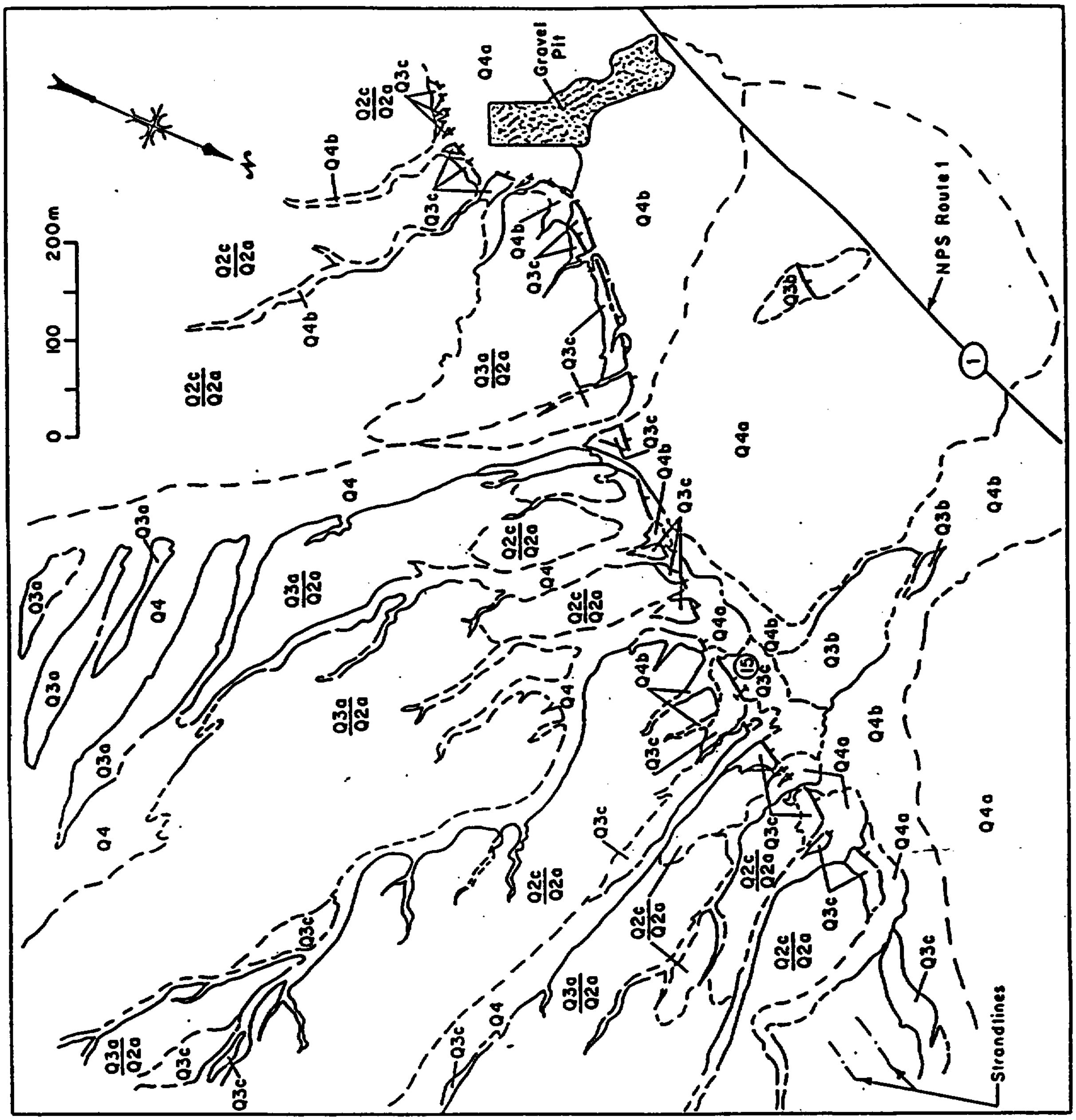

0
100
200m
Gravel Pit
NPS Route 1
1
15
Strandlines
Q4
Q4a
Q4b
Q3a
Q3b
Q3c
Q3a/Q2a
Q2c/Q2a

Figure 4. Scarp profile measured across the Death Valley fault near Willow Creek (site 15 in fig. 3). A scarp height of 10.5 m and a maximum scarp-slope angle of 90° were measured from the plot. The two near-vertical portions of the scarp near the crest (2.1 and 2.6 m high) are interpreted to be preserved free faces produced by past ground-rupturing earthquakes based on the relationship between the vertical portions of the scarp and adjacent inset stream terraces near the mouth of Willow Creek.

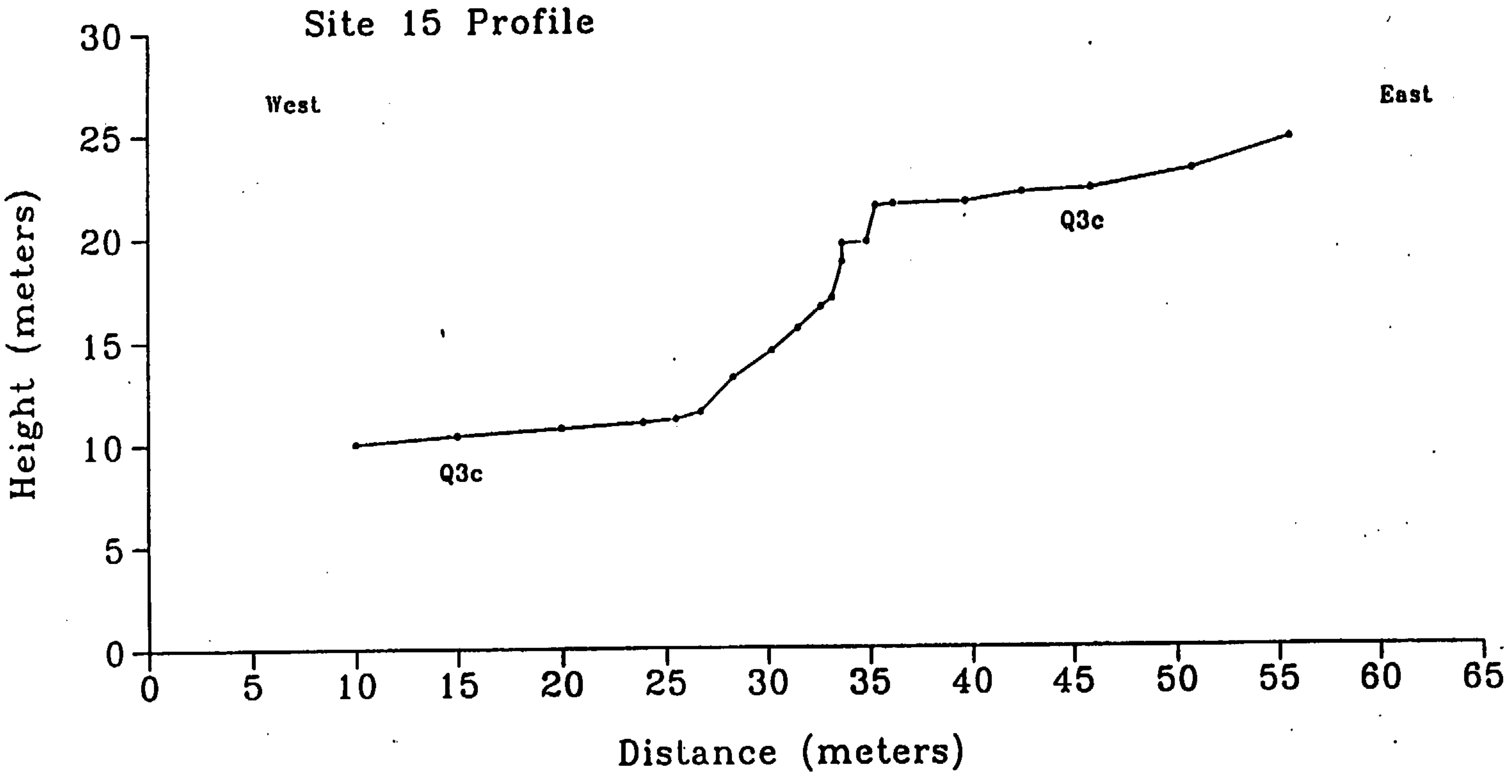
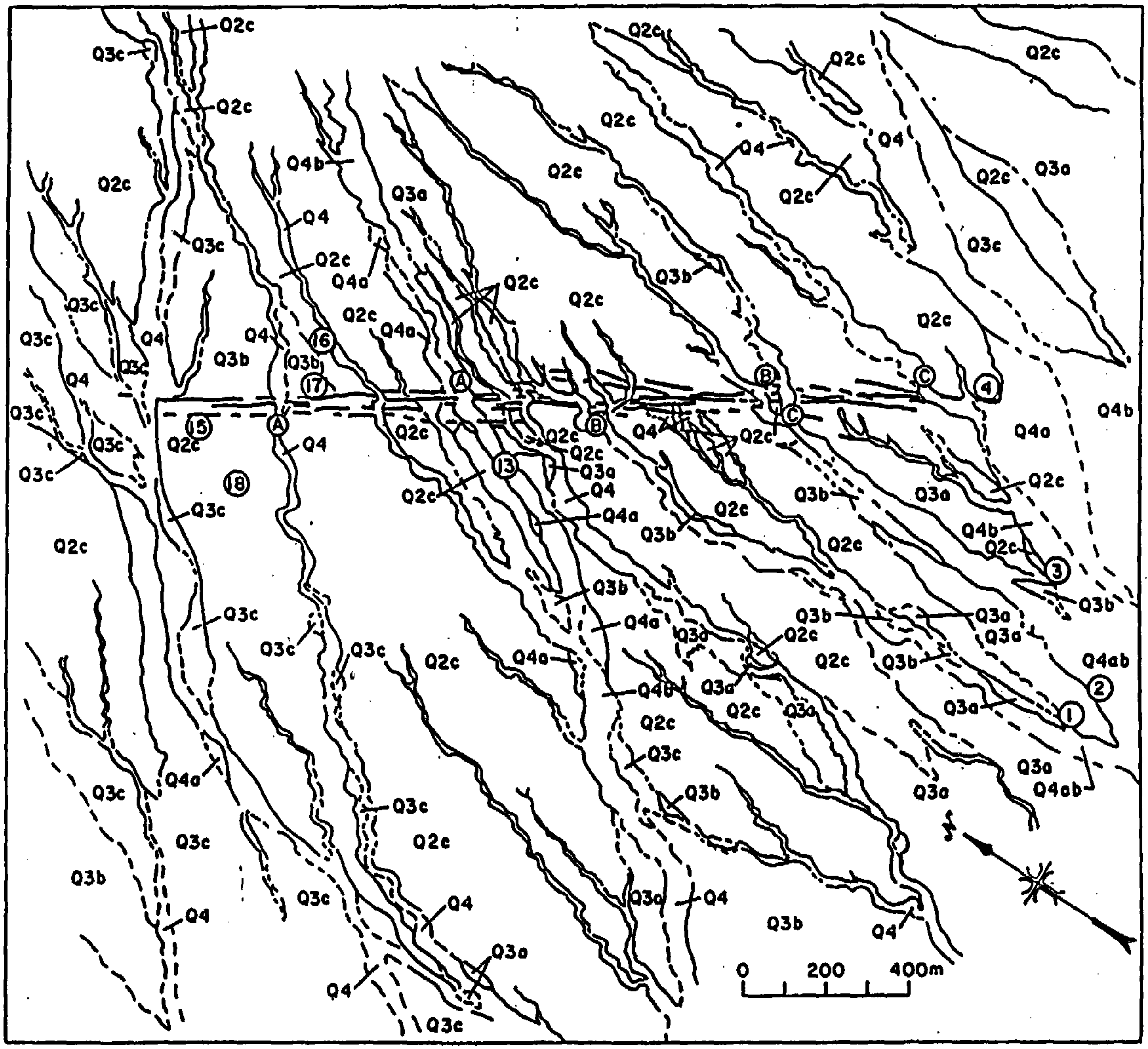
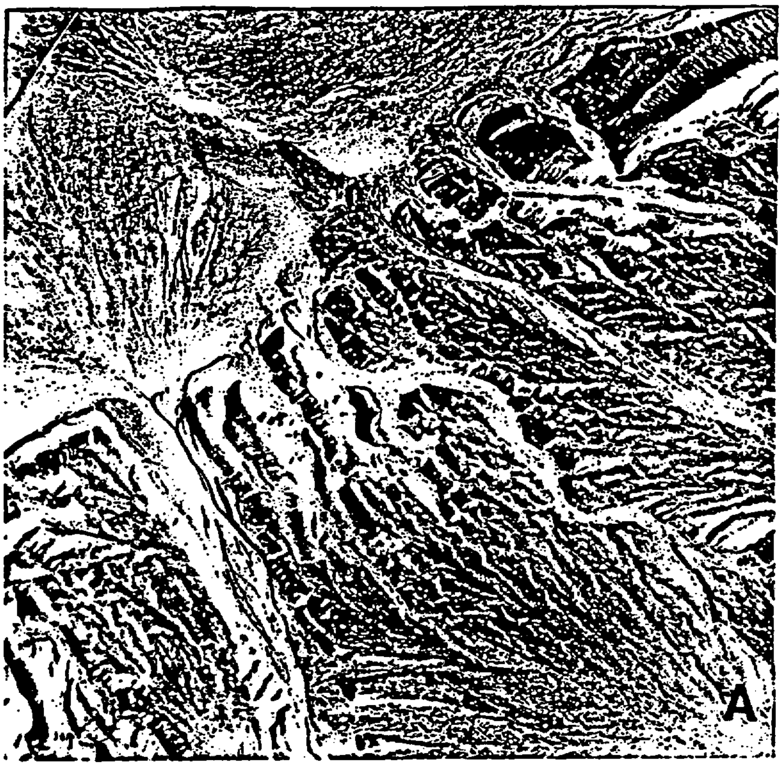
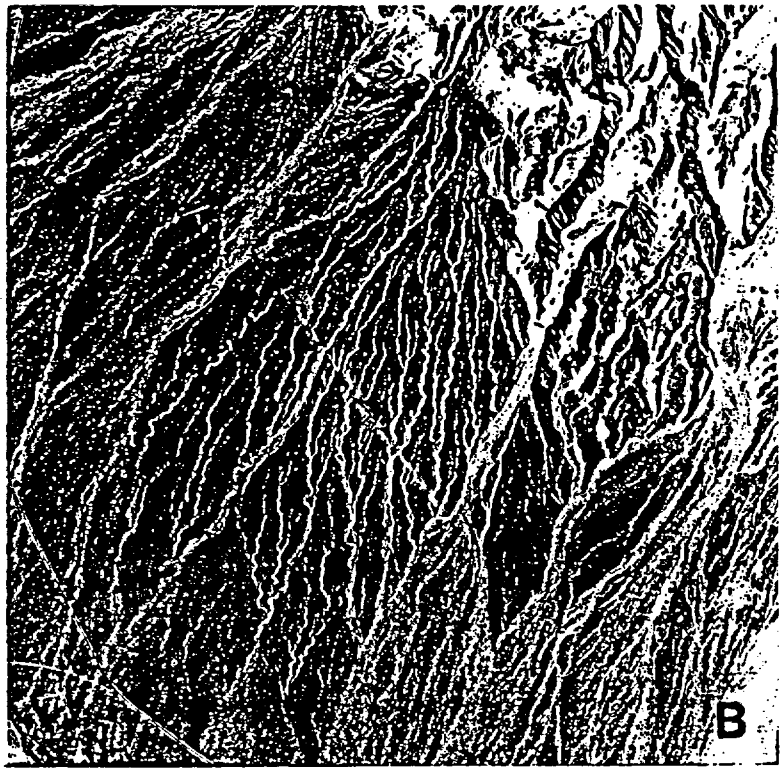

Site 15 Profile
West
East
Q3c
Q3c
Height (meters)
Distance (meters)
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65

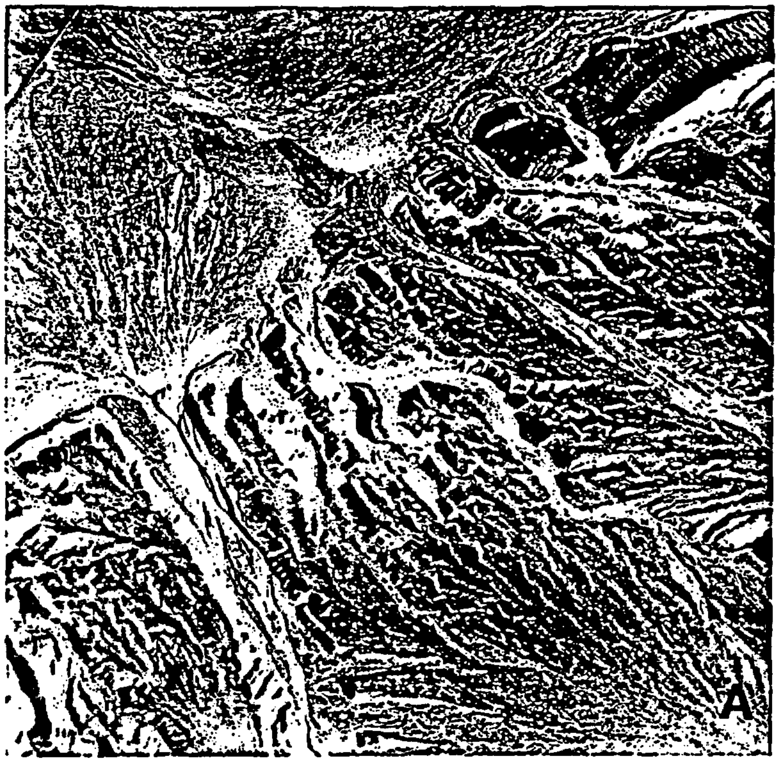
Figure 5. Surficial geologic map of a part of the alluvial fan adjacent to the Furnace Creek fault near Red Wall Canyon (see fig. 2B). Numbered site locations, geomorphic surface designations, and criteria used to characterize and differentiate the surface units are outlined in table 1. The 360-480 m right-lateral offset across the fault was measured between the drainages denoted by letters.



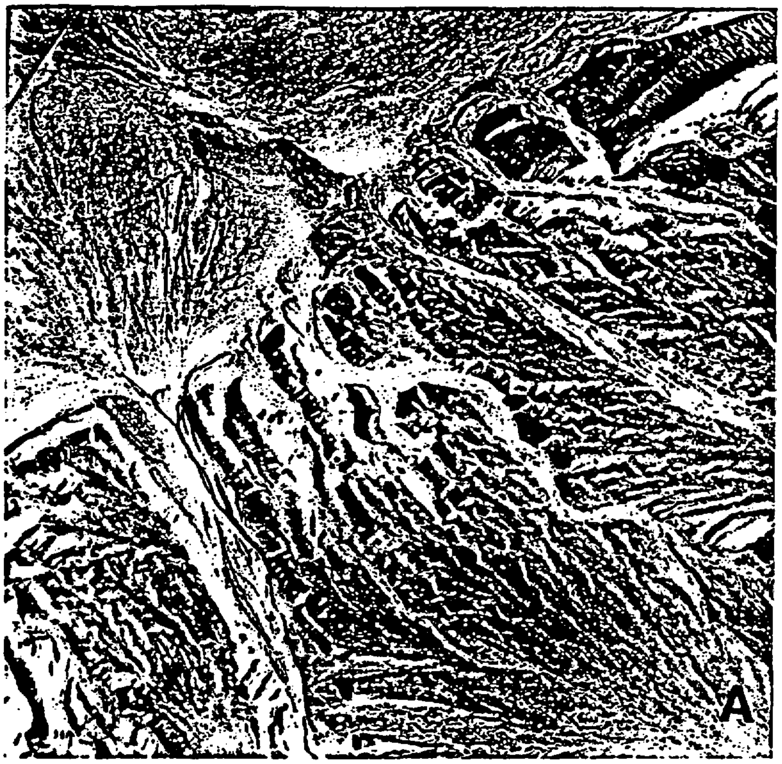
Q2c
Q3c
Q2c
Q2c
Q2c
Q2c
Q4
Q4
Q2c
Q3a
Q4b
Q3a
Q4
Q2c
Q3c
Q3b
Q2c
Q4a
Q2c
Q2c
Q3c
Q4
Q3b
Q4
⑯
Q4a
Ⓐ
Ⓑ
Ⓒ
④
Q4b
Q3c
Q3c
Q3b
⑰
⑮
Ⓐ
Q2c
Q4
Q2c
Ⓑ
Q4
Q2c
Ⓒ
Q4a
Q3c
⑱
⑬
Q2c
Q3a
Q4
Q4a
Q3b
Q3a
Q2c
Q2c
Q3c
Q2c
Q3b
Q2c
Q4b
Q2c
③
Q3b
Q3c
Q3c
Q3c
Q3b
Q4a
Q3a
Q3a
Q3a
Q2c
Q4a
Q2c
Q3a
Q2c
Q3b
Q4ab
②
Q4b
Q2c
Q3a
①
Q3c
Q3c
Q3c
Q3c
Q3b
Q3a
Q4ab
Q3a
Q2c
Q3b
Q4
Q3a
Q4
Q3b
Q4
Q3a
Q4
Q3c
0
200
400m

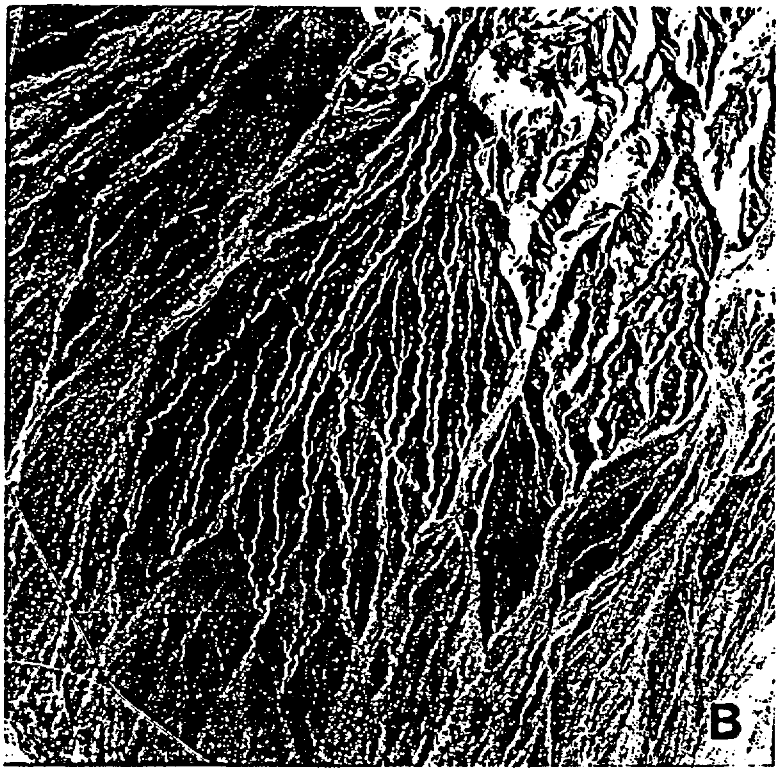

A


B


A


B


A


B

PRELIMINARY EVALUATION OF THE BARE MOUNTAIN FAULT ZONE, TARANTULA CANYON, NYE COUNTY, NEVADA

Larry W. Anderson and Ralph E. Klinger
Seismotectonics and Geophysics Group
Technical Service Center
Bureau of Reclamation
Denver, Colorado

~~9507250025~~

ENCLOSURE 1

Figure 1. Map showing the location of the Bare Mountain fault zone.

faulting calcic horizon development in the faulted fluvial gravel and along the fault surface provide evidence indicating that this faulting event occurred early in the late Pleistocene.

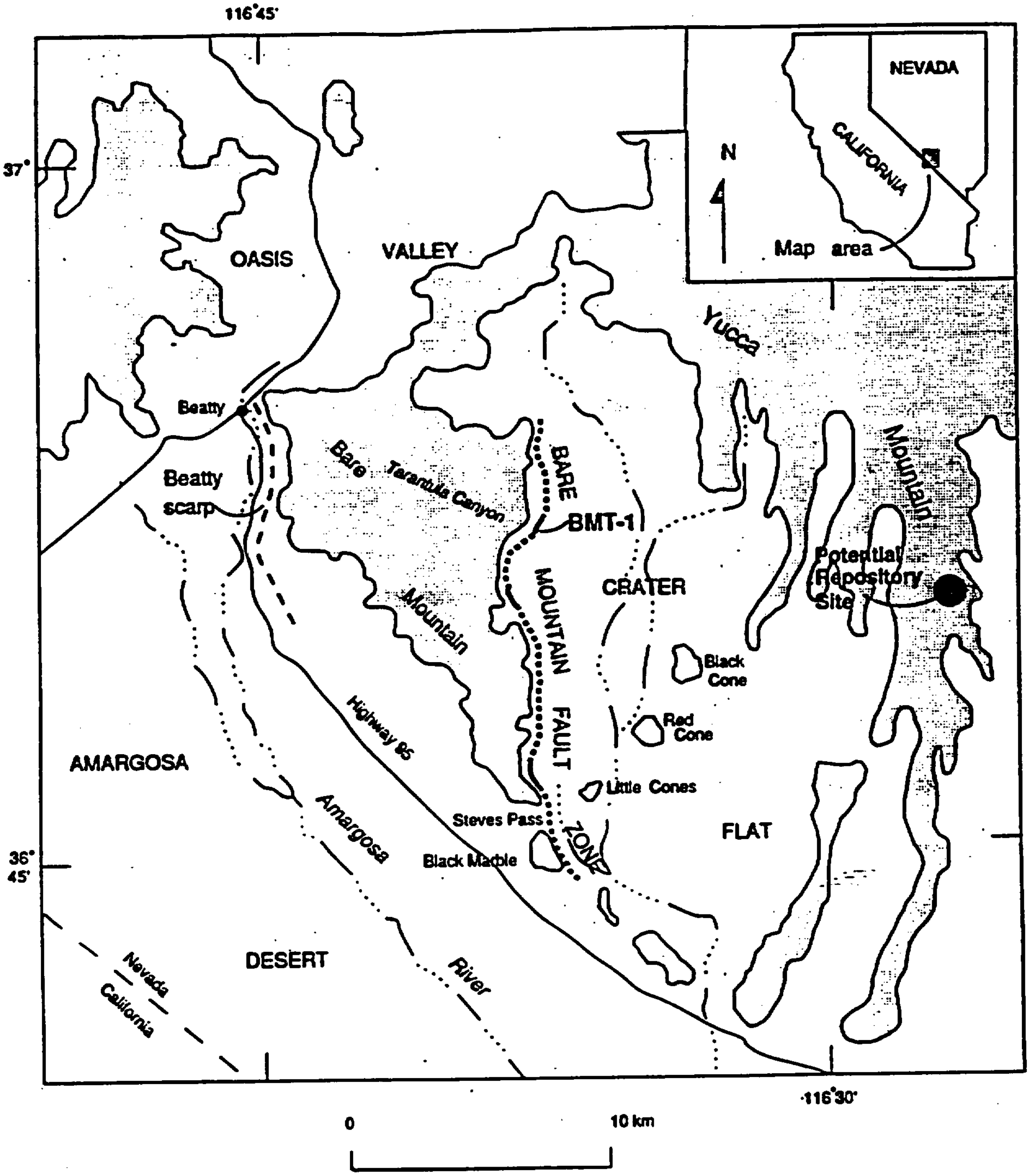
On the basis of the apparent age of the most recent faulting event, age of the deposits displaced, and the amount of displacement observed from the single event in the Tarantula Canyon trench, the slip rate for the Bare Mountain fault appears to be about 0.015 millimeters per year or less and the recurrence interval for surface faulting events appears to be at least 100,000 years.

INTRODUCTION

The Bare Mountain fault zone lies along the east side of Bare Mountain in Nye County, Nevada, approximately 15 km west of the potential nuclear waste repository at Yucca Mountain (fig. 1). Because of its proximity and the belief that this fault could be a potential source for significant future ground motions at the repository site, this fault zone was identified for detailed analysis in the Yucca Mountain Site Characterization Plan (U.S. Department of Energy, 1988).

FIGURE 1.--NEAR HERE

Cornwall and Kleinhampl (1961) were the first to recognize the presence of a major



EXPLANATION

Fault scarps in younger (upper Pleistocene?) deposits, fault dotted where concealed

BMT-1 Tarantula Canyon site

range-bounding structure along the east side of Bare Mountain. They also inferred Quaternary activity on this fault owing to the sharp, relatively straight range front and the small, relatively undissected alluvial fans along the east side of the range. Swadley and others (1984) were the first to refer to this structure as the Bare Mountain fault zone. Later mapping by Swadley and Parrish (1988) shows the range-front fault cutting early Pleistocene deposits but being buried by younger, early to middle Pleistocene, deposits. In contrast, Reheis (1988) and Monsen and others (1992) indicate that deposits as young as Holocene are faulted at several locations along the range. The reconnaissance work by Reheis (1988) specifically addressed the Quaternary faulting history along the eastern side of Bare Mountain. Surficial mapping and observations made in several mine exploration pits led Reheis (1988, p. 105) to report that there is abundant evidence for recurrent Quaternary activity along the eastern side of Bare Mountain. This paper takes exception to the earlier conclusions of Reheis (1988). It concludes that at the Tarantula Canyon site on the Bare Mountain fault zone, the late Quaternary rate of faulting is very low, and the age of the most recent surface faulting event is older than previously reported.

Acknowledgments

This work was supported by the U.S. Department of Energy, Yucca Mountain Project Office. Reviews of this paper were made by Dan Ponti, Alan Ramelli, and Mary-Margaret Coates.

DETAILED STUDIES AT TARANTULA CANYON

Detailed study of the Bare Mountain fault zone began in 1993. Work has consisted of analysis of aerial photographs, surficial geologic mapping, profiling of suspected fault scarps, description of soil development on geomorphic surfaces at several locations, and analysis of geologic relationships exposed in one trench and one large test pit excavated across the trace of the fault zone. Most of this work has been concentrated in the Tarantula Canyon area. In the following sections, preliminary results from the studies at Tarantula Canyon are presented.

Mapping

The Bare Mountain fault zone extends from about 5 km north of Tarantula Canyon to the southeastern end of Black Marble, a distance of approximately 17 km (fig. 1). Low-sun-angle (afternoon sun), 1:12,000 scale, vertical aerial photographs, flown by the State of Nevada in 1987, were analyzed in conjunction with field work to identify possible tectonic features, verify previous mapping, and further delineate Quaternary unit characteristics and contacts. Stratigraphic units defined by geomorphic surfaces and possible tectonic features (scarps and lineaments) identified on the aerial photographs and by previous workers were field checked, and preliminary criteria for the subdivision of these stratigraphic units along the range front were established; the basic criteria used were desert pavement and desert varnish development, soils, and topographic position.

The preliminary subdivision of surficial deposits and geomorphic surfaces is shown in table 1. All of the characteristics are readily observable in the field and easily recognized on aerial photographs. These characteristics are similar to those described by Hoover and others (1981), Swadley and others (1984), and Taylor (1986) for the surficial deposits in the region. Numeric ages have been obtained for geomorphic surfaces in the Amargosa Desert and Crater Flat areas (Peterson and others, 1995). Surface characteristics, soil development, and other relative age criteria were examined at these sites in order to further evaluate our age assignments for the Quaternary units along Bare Mountain.

TABLE 1.--NEAR HERE

Results of mapping for this study suggest no evidence of Holocene movement on the Bare Mountain fault zone. In addition, surficial evidence for late Quaternary faulting on the Bare Mountain fault zone continuing to the southeast into the Amargosa Desert does not exist. For most of its 17 km length, the Bare Mountain fault zone is marked by a linear contact between alluvium and resistant bedrock. In prospect pits, particularly along the northern part of the range, the fault contact is characterized by abundant and usually sheared carbonate material in alluvium and colluvium of unknown age. Along most of the range, however, the fault typically is concealed by young alluvial fan deposits and colluvium; only in a few areas is displacement of late Quaternary deposits readily recognized. Alluvium estimated to be late to middle Pleistocene in age is broken by what appear to be fault scarps at only three locations along the range front (shown as solid line segments in figure 1). The length of these scarps is 100 to 400 m and the height is 0.5 to 2 m. At several other locations, possible scarps or lineaments are present on middle or early Pleistocene deposits or at what appears to be the contact (fault line scarp?) between older and younger surficial deposits. At or near several localities where late Pleistocene or Holocene activity has been previously reported, deposits that appear to be older than those reported to be faulted apparently are not displaced.

The Tarantula Canyon site is the only location along the Bare Mountain range front where a fault scarp crosses a relatively flat Q2 alluvial fan (fig. 2; see table 1 for generalized unit descriptions, characteristics, and possible ages). The scarp is about 110 m long and up to 2.4 m high and is located above the projection of a carbonate-cemented shear or fault zone on the south side of the wash that was described by Reheis (1988). No scarp is present north of Tarantula Canyon wash apparently because the fault is buried by a slightly younger Q2 or an older Q3 deposit (mapped as Q3? on figure 2). South of Tarantula Canyon wash, the fault is buried by Q4 (early to middle Holocene) and Q3 deposits (late Pleistocene?; fig. 2). The fan with the fault scarp was mapped in this study as a Q2 fan (middle to late Pleistocene). However, in the area of the scarp and adjacent to the range front, the Q2 fan is buried by a thin veneer (< 50 cm) of younger alluvial, colluvial, and eolian material. This veneer is probably equivalent to Q4 deposits and probably is no older than latest Pleistocene.

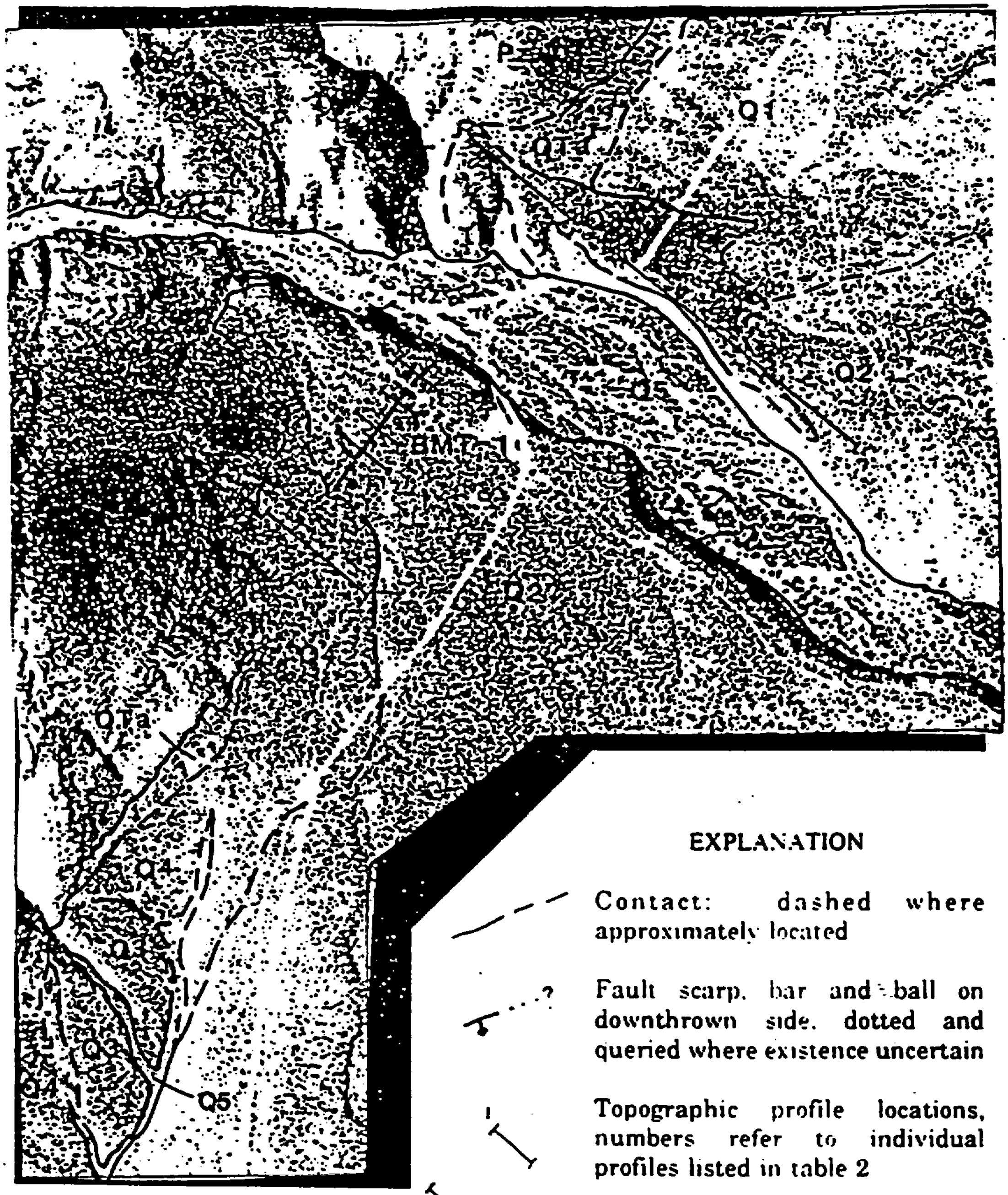
FIGURE 2.--NEAR HERE

Scarp Profiles

To estimate the age of the fault scarp at Tarantula Canyon, topographic profiles were measured across the scarp. Topographic profiling has been widely used in the western United States to approximate the ages of fault scarps (Wallace, 1977, 1980; Bucknam and Anderson, 1979; Nash, 1980, 1984; Machette and Personius, 1984). The method is based on the assumption that a scarp developed in unconsolidated materials (regardless of its origin) will degrade in a relatively predictable manner. Nash (1986) provides a good review of the technique.

Nine profiles were measured at the mouth of Tarantula Canyon (fig. 2). On the south side of the wash, seven profiles (1-7) were measured across the scarp on the Q2 surface. Further south, one profile (8) was measured on a Q4 surface across a photolineament that trends south along strike of the scarp. On the north side of the wash one 220-m-long profile (9) was measured across the projection of the fault zone and scarp from the south side of the wash. Three of the scarp profiles (1, 3, and 5) were measured using a tape, stadia rod, and hand level; the remaining profiles (2, 4, and 6 to 9) were measured using an electronic surveying instrument (total station). A topographic profile

Figure 2. Surficial geologic map of the Tarantula Canyon site.



Base from enlarged low-sun-angle aerial photograph taken in 1987 (State of Nevada, Yucca Mountain Low Sun Angle Project, Photo 4-1a-10)

0 100m

EXPLANATION

Contact: dashed where approximately located

Fault scarp, bar and ball on downthrown side, dotted and queried where existence uncertain

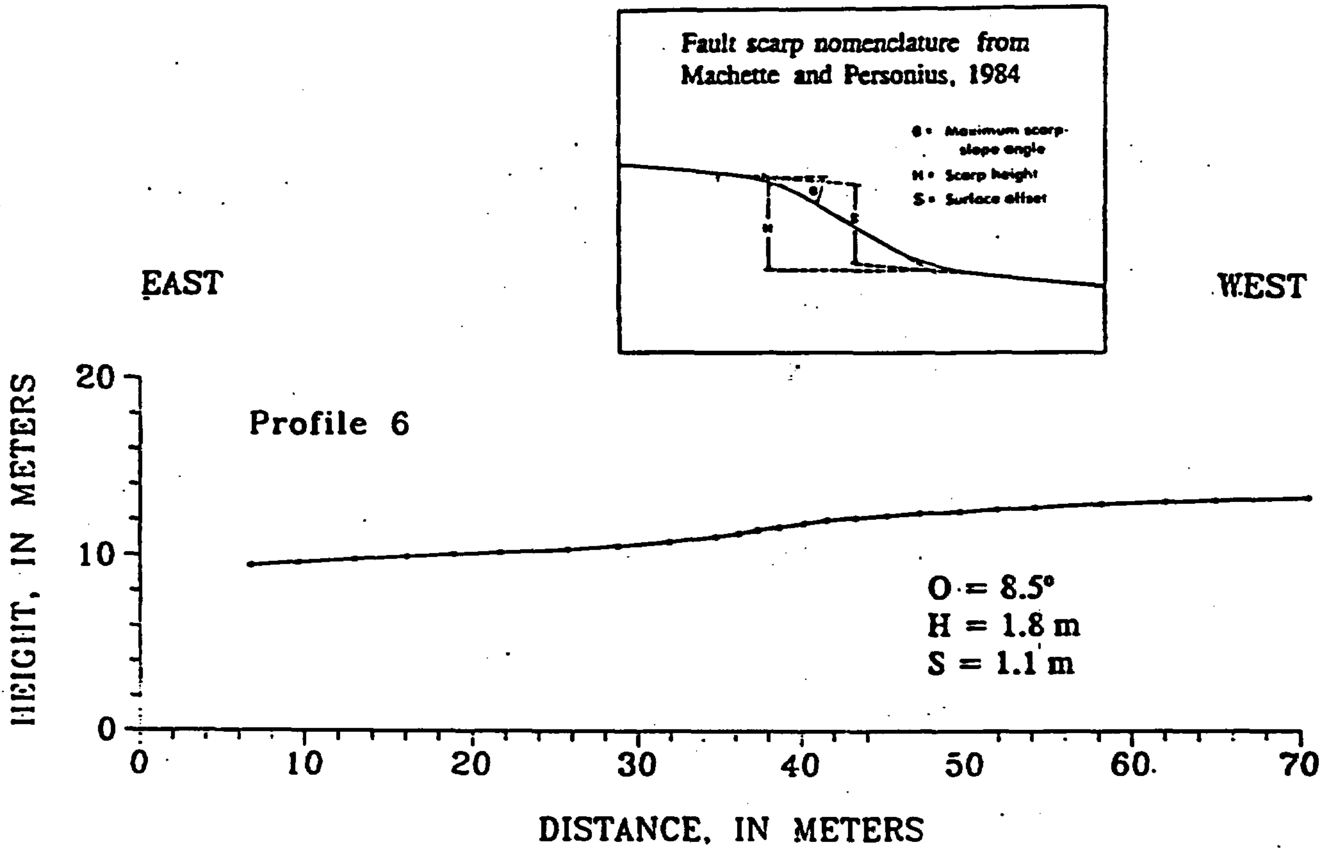
1 Topographic profile locations, numbers refer to individual profiles listed in table 2

BMT-1 Trench locations

Pz Paleozoic bedrock

Q1 Surficial units, numbered oldest (Q1) to youngest (Q5). See table 1 for generalized unit descriptions, characteristics, and possible ages

Figure 3. Topographic profile (Profile 6) across the Bare Mountain fault zone at Tarantula Canyon. Location of profile shown on figure 2.

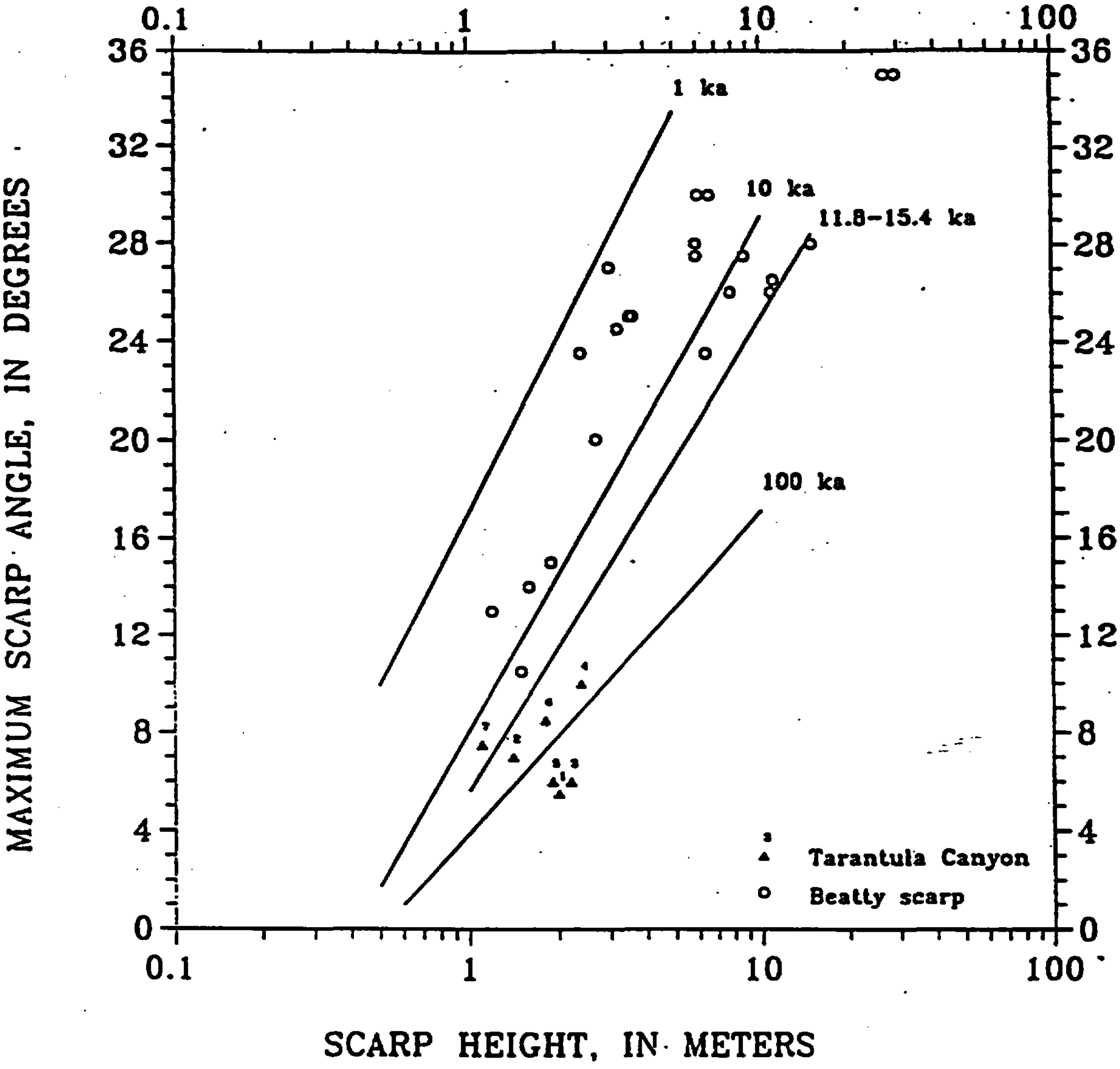

Fault scarp nomenclature from Machette and Personius, 1984
θ = Maximum scarp-slope angle
H = Scarp height
S = Surface offset
θ
H
S
EAST
WEST
Profile 6
HEIGHT, IN METERS
DISTANCE, IN METERS
0
10
20
0
10
20
30
40
50
60
70
θ = 8.5°
H = 1.8 m
S = 1.1 m

between 8,300 and 10,000 years (Swadley and others, 1988; Anderson, this volume).

FIGURE 4.--NEAR HERE

The Tarantula Canyon scarp profile data also were compared to a series of regressions developed by Bucknam and Anderson (1979) for scarps of known age in the Great Basin Province (fig. 4). Data derived from the three profiles measured manually (1, 3, and 5) cluster together and plot lower on the graph than do the profiles measured electronically with the total station, even though profiles 1, 3, and 5 were measured along essentially identical transects as profiles 2, 4, and 6, respectively [the Bucknam and Anderson (1979) profiles were measured manually]. This suggests that profiles measured by hand result in profiles with lower maximum scarp-slope angles than do profiles measured by instrument. It is believed that the data collected manually, owing to the fewer number of data points and the greater distance between measurements, produces profiles that are artificially smoothed. Regardless of the slight differences in the scarp data, the Tarantula Canyon scarps are clearly much older than the Beatty scarp based on their dramatically lower maximum scarp-slope angles. In addition, a comparison of the scarp heights and maximum scarp-slope angles for the Tarantula Canyon scarp to the data for the Panguitch fault scarps in southwestern Utah reported by Bucknam and Anderson (1979) suggests that the Tarantula Canyon fault scarp may be about 100,000 years old.

Figure 4. Plot of scarp height versus maximum scarp-slope angle for profiles measured across the Bare Mountain fault zone at Tarantula Canyon (table 2) and the Beatty scarp (Anderson, this volume), compared to regression lines for scarps of known age in the Basin and Range (modified from Bucknam and Anderson, 1979).


0.1
1
10
100
36
32
28
24
20
16
12
8
4
0
1 ka
10 ka
11.8–15.4 ka
100 ka
▲ Tarantula Canyon
○ Beatty scarp
MAXIMUM SCARP ANGLE, IN DEGREES
SCARP HEIGHT, IN METERS

Trench BMT-1

In September 1993, a 43-m-long trench (BMT-1) was excavated across the scarp at Tarantula Canyon (fig. 1 and 2). A portion of the trench log for BMT-1 is presented in figure 5.

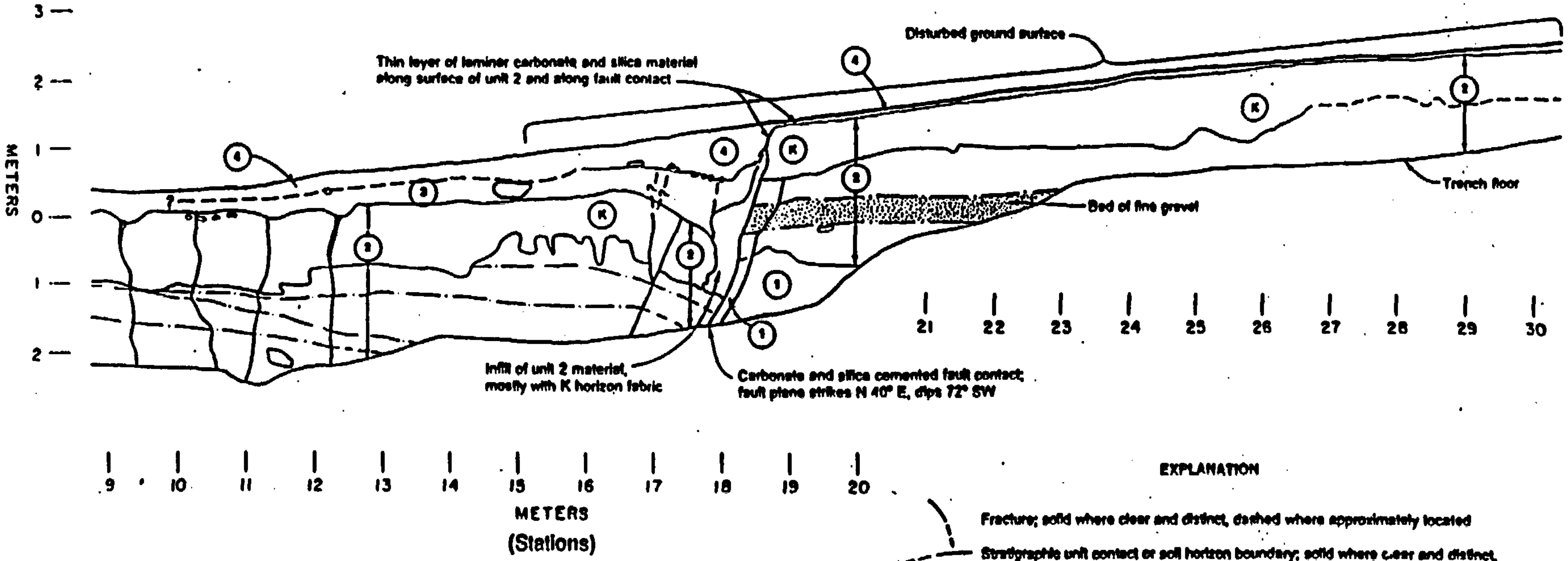
FIGURE 5.--NEAR HERE

Unit 1, the lowermost unit recognized, is known to be present only in the west-central portion of the trench (the top of unit 1 may be present in the floor of the trench at station 11). This fairly resistant sandstone and conglomerate unit is probably equivalent to the QTa unit of Swadley and Parrish (1988), based on its degree of induration and relationship to overlying units. A clear unconformity separates unit 1 from unit 2.

Unit 2 is a crudely stratified sandy gravel. A well-developed calcic horizon (stage IV-IV+), 0.7-1.5 m thick, is present in the upper part of this unit (fig. 5; soil profile nomenclature from Birkeland, 1984). Unit 3, a gravelly silt, is preserved only in the eastern part of the trench (between stations 9 and 18), and it appears to be the argillic horizon (Bt) associated with the calcic horizon formed in unit 2. While unit 2 is a fluvial gravel deposited on the Tarantula Canyon alluvial fan, unit 3 consists of both finer grained fluvial deposits and eolian material that was deposited following abandonment and stabilization of the fan surface. Although differing from each other both texturally

Figure 5. Portion of trench log for south wall of BMT-1, Tarantula Canyon site.

SOUTH WALL



EXPLANATION

Fracture; solid where clear and distinct, dashed where approximately located

Stratigraphic unit contact or soil horizon boundary; solid where clear and distinct, dashed where approximately located or gradational

Bedding

Ⓚ K fabric (horizon of stage IV-IV+ carbonate or carbonate-silica accumulation)

Cobbles and boulders

④ Holocene colluvium, light brown gravelly silt

③ Pleistocene colluvium, light brown gravelly silt

② Pleistocene alluvium, white to very pale brown sandy gravel with stage IV-IV+ calcic horizon development

① Pleistocene-Pliocene(?) alluvium, light gray to very pale brown, well cemented, gravelly sand

and by their mode of deposition, units 2 and 3 appear genetically related by soil development suggesting that their ages are similar.

Trench units 2 and 3 are considered the equivalent of map unit Q2, and the well-developed pedogenic carbonate (stage IV-IV+) present in the upper part of trench unit 2 suggests some antiquity for these deposits (Bull, 1991, chap. 2). As map unit Q2 is probably equivalent to unit Q2c of Swadley and others (1984), which has an estimated age of 270-800 ka, or to the Early Black Cones unit of Peterson and others (1995), which has an estimated age of >159->201 ka (table 1), these age estimates apply also to trench units 2 and 3. Thus, trench units 2 and 3 are at least 100,000 years old, and probably much older.

The uppermost and youngest unit in the trench, unit 4, is a massive, gravelly silt considered the equivalent of map unit Q2. An archeological survey of the trench site prior to excavation recovered artifacts reportedly 7,000 years old from this unit (Paul Buck, Desert Research Institute, oral commun., 1993). Based on the degree of soil profile development (no textural B horizon, stage I-II carbonate morphology), the maximum age for trench unit 4 is probably latest Pleistocene.

A prominent fault is exposed in the trench between stations 18 and 19, coincident with the base of the surface scarp (fig. 5). The fault clearly displaces trench units 1, 2, and 3. Although unit 4 thickens east of the fault on the south wall of BMT-1, it appears to be unfaulted. The thickening appears to be the result of pre-unit 4 erosion at the base of the fault scarp. The interpretation that unit 3 is the argillic (Bt) horizon associated with unit 2 is supported by the presence of shearing extending into unit 3 from unit 2, which in turn is overlain by unsheared unit 4. Unit 3 also thickens where it overlies the fissure fill (unit 2?) adjacent to the fault (station 18) and is present only in the eastern part of the trench where unit 2 has been backtilted. No buried soil horizons, stone lines, texturally different infill units, or colluvial wedges are present that would indicate multiple displacements of unit 2 and 3. The fissure fill composed of unit 2 material suggests only a single surface-faulting event. Backtilting and fissure filling like that observed between stations 9 and 13 are features commonly observed in trench exposures across Quaternary normal faults and are associated with historic normal faulting earthquakes in the Basin and Range (Nelson, 1992; McCalpin and others, 1994). Vertical separation across unit 2 also is uniform across the fault without progressive increase downward in the trench. These observations indicate that the Tarantula Canyon site has experienced only one surface-rupturing event since deposition of units 2 and 3.

The backtilting of units 2 and 3 on the hanging wall is particularly pronounced between stations 16 and 18, but is present in the trench eastward to at least station 5 (not shown in figure 5). To compensate for the backtilting, vertical separation resulting from the faulting event was measured by projecting the nearly flat surface of the calcic horizon from both ends of the trench to the fault. Total vertical separation of unit 2 across the fault is 1.5 m. No indications of lateral or oblique slip were observed in the trench. Slickensides with near-vertical rakes on bedrock and on silica-carbonate cemented material along the fault at other locations along the Bare Mountain fault zone indicate that past displacement on the fault has been nearly pure normal.

DISCUSSION

Although study of the Bare Mountain fault zone is still in progress, several conclusions can be drawn from the work conducted to date. Unit 4 is the only unfaulted deposit in trench BMT-1. Therefore, the age of this unit provides the minimum age of the most recent faulting event at Tarantula Canyon. However, evidence both within the trench and from surrounding geologic relationships indicates that the age of this faulting event is much greater than the probable maximum age of unit 4 (latest Pleistocene). First, a distinct laminar carbonate layer, 0.5-1.5cm thick, is present at the contact between units 2 and 4 on the footwall block (stations 18-30+ in figure 5). This laminar carbonate layer seemingly postdates the most recent faulting event as it drapes the 72°-dipping fault plane, coating cobbles and pebbles along the fault surface, and extends nearly to the bottom of the trench, becoming thinner with depth. The carbonate layer retains its laminar character and is not brecciated, fractured, or striated as would be expected if the layer had been faulted. This laminar carbonate is not present between trench stations 8 and 18 where unit 2 has been backtilted and where unit 3 is preserved. A similar carbonate layer occurs in the eastern part of the trench up to station 8 and alternately truncates and infills fractures in unit 2. The fractures generally occur only in the hanging wall and are believed to be the result of the faulting event that offset unit 2, backtilted units 2 and 3, and produced the scarp. Thus, it appears that development of the 0.5- to 1.5-cm-thick laminar carbonate layer, followed by deposition of unit 4, more precisely constrains the age of faulting and suggests an age of at least several tens of thousands of years.

An additional line of evidence that supports an age of some antiquity for the faulting event is the topographic profiles of the scarp. As discussed previously, the profile data indicate that the scarp at Tarantula Canyon is significantly older than the Beatty scarp and could have an age of about 100 ka. Also, no bevels or compound scarps are present on the scarp profiles, and surface offsets measured from the profiles at the trench site (table 2) are consistent with the separation of strata measured in the trench and indicate only one surface-rupturing event.

Finally, the deposit mapped north of Tarantula Canyon Wash (Q3? in figure 2) is a small alluvial fan that originated from a side drainage and was deposited on the Q2 alluvium. This Q3? deposit postdates the surface-faulting event exposed in the trench and expressed by the fault scarp, as no fault scarp is present on the ground or in the topographic profile (profile 9) across this surface. The alluvial fan deposit that buries the fault has a well-developed soil with argillic and stage II+ carbonate horizons, suggesting it is at least several tens of thousands of years old, certainly much older than trench unit 4.

EARTHQUAKE HAZARD

Generally, estimates of fault-slip rates and recurrence intervals are based on evidence for more than a single faulting event. However, the age of displaced deposits and the amount of slip exhibited at the Tarantula Canyon site do provide some age constraints on the late Quaternary activity of the Bare Mountain fault zone. Assuming a minimum age of 100 ka for trench unit 2 and given the vertical separation of 1.5 m, a late Quaternary slip rate of 0.015 mm/yr for the Bare Mountain fault zone at Tarantula Canyon is estimated. Considering that unit 2 is probably much older than 100 ka, a slip rate much less than 0.015 mm/yr is possible. Likewise, if one accepts that unit 2 is at least 100,000 years old and has been faulted only once, then the recurrence interval for surface-rupturing earthquakes on the Bare Mountain fault zone could be on the order of 100,000 years or more.

Fracturing of unit 1, which is truncated by unit 2, suggests an earlier, pre-unit 2 faulting event or events. In addition, stratigraphic relationships of the carbonate deposits filling some fractures in unit 2 suggest the possibility that unit 2 may have been fractured either before or after the 1.5-m surface-faulting event. If a fracturing event or events occurred, no measurable displacement has been noted. Thus, if an earthquake other than the 1.5-m surface-rupturing event occurred on the Bare Mountain fault and produced some of the fractures in unit 2, the magnitude of that earthquake was below the threshold of surface rupture. In the Basin and Range Province, this threshold is believed to be about M_W 6.5 (dePolo, 1994). From the work of dePolo and Wells and Coppersmith (1994), it follows that the earthquake magnitude for the event that produced the 1.5 m of displacement was probably greater than M_W 6.5.

CONCLUSIONS

On the basis of work to date, clear evidence of Holocene or latest Pleistocene faulting along the Bare Mountain fault zone is not present. The activity rate of the Bare Mountain fault zone appears to be very low, about 0.015 mm/yr, and the age of the most recent surface-faulting event is significantly older than previously thought. Topographic profile data suggest that the scarp associated with the most recent faulting event at Tarantula Canyon could be about 100,000 years old. The fault scarp profiles and preliminary results from the trench also indicate that a single surface-faulting event, characterized by approximately 1.5 m of displacement, has occurred at the Tarantula Canyon site in the late Quaternary.

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Table 1. Surface characteristics utilized for the preliminary subdivision of surficial deposits and geomorphic surfaces along the Bare Mountain fault zone along with estimated age [The characteristics listed in this table may not depict the age of underlying deposits or reflect sedimentological properties related to its depositional history]

Unit	Age	Soil	Pavement	Desert Varnish	Topography
Q5	Historic-Late Holocene	May have weak A/C profile; A_v < 1 cm thick	Generally absent; local incipient packing and horizontal orientation of clasts	None	High-relief bar and swale
Q4	Holocene-Late Pleistocene	Thin A_v horizon (several cm thick)	Poorly packed	Weakly developed on quartzite clasts	Bar and swale is distinct but subdued; bars are coarser grained than adjacent swales.
Q3	Late to Mid-Pleistocene	Moderately developed A_v horizon (5-10 cm thick)	Moderately to well packed on bars	Moderately developed on quartzite clasts	Bar and swale subdued; transition between bars and swales diffuse
Q2	Mid- Pleistocene	Well developed A_v horizon (< 10 cm thick)	Moderately to well packed pavement; $CaCO_3$ rinds and fragments common on surface clasts	Well developed on surface clasts	Little or no evidence of bar and swale
Q1	Mid-to Early Pleistocene	A_v horizon may or may not be present depending on topographic position	Moderately to well packed; pavement is being degraded; underlying petro-calcic horizon is locally exposed	Moderately to well developed on some surface clasts; sometimes lacking	Surface is dissected; small rills and drainages common
QTa	Pleistocene-Pliocene	Gravel completely cemented with carbonate or silica, or both; in places veneered by younger unconsolidated deposits	None	None	No original surfaces preserved

Table 2. Bare Mountain fault zone profile data, Tarantula Canyon site

[Scarp height, surface offset, and maximum scarp angle measured from computer generated plots of the profiles. Profiles 1, 3, and 5 measured with hand level and stadia rod, other profiles measured with electronic surveying instrument (total station). No scarp observable in profiles 8 and 9. Profile 3 measured along axis of trench BMT-1 before excavation. Profile 4 measured immediately south of BMT-1. See figure 2 for approximate profile locations]

Profile	Scarp height (meters)	Surface offset (meters)	Maximum scarp-slope angle (degrees)
1	1.9	1.5	6.0
2	1.4	0.9	7.0
3	2.2	1.5	6.0
4	2.4	1.9	10.0
5	2.0	1.6	5.5
6	1.8	1.1	8.5
7	1.1	0.4	7.5
8	-	-	-
9	-	-	-

LATE QUATERNARY SLIP RATE ESTIMATES FOR THE DEATH VALLEY AND FURNACE CREEK FAULTS, DEATH VALLEY, CALIFORNIA

Ralph E. Klinger and Lucille A. Piety

Seismotectonics and Geophysics Group

Bureau of Reclamation

ENCLOSURE 2

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LATE QUATERNARY SLIP RATE ESTIMATES FOR THE DEATH VALLEY AND FURNACE CREEK FAULTS, DEATH VALLEY, CALIFORNIA

Ralph E. Klinger and Lucille A. Piety
Seismotectonics and Geophysics Group
Bureau of Reclamation

ABSTRACT

Earlier published reports indicate that the slip rate for the Death Valley fault is on the order of 1-2 millimeters per year and that the slip rate for the Furnace Creek fault is on the order of 2-3 millimeters per year. However, geomorphic features associated with both faults indicate that numerous surface-rupturing earthquakes have occurred during the late Holocene and that 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 the site under consideration as a high-level nuclear-waste repository.

Along the Death Valley fault near Mormon Point, the surface of a middle to late Holocene alluvial fan is vertically displaced 10.5 meters. Preserved free-faces and inset terraces record the last three and possibly four events. Average vertical displacement per event at this location is interpreted to be about 2.1-2.6 meters. An approximate age of 2,000-4,000 years is estimated for the displaced geomorphic surface based on its surface characteristics. This yields an average vertical slip rate for the Death Valley fault of 3-5 millimeters per year.

Along the Furnace Creek fault near Red Wall Canyon, repeated movement has right-laterally offset latest Holocene channels and preserved evidence for the last three ground-rupturing events. Lateral displacement per event at this location is about 2.5-3.5 meters. Large drainages incised into the fan have also been offset and record the late Pleistocene slip history. Utilizing low-altitude aerial photography, a palinspastic reconstruction of the fan surface indicates that the large incised drainages are right-laterally offset 230-310 meters across the fault. An approximate age of 40,000 years, based on its surface characteristics, is estimated for the geomorphic surface into which the drainages are incised. This yields an average lateral slip rate for the Furnace Creek fault of 6-8 millimeters per year.

INTRODUCTION

The Death Valley-Furnace Creek fault system (DVFCFS) consists of several discrete faults that extend for over 350 kilometers (km) along the California-Nevada border. The Death Valley and Furnace Creek faults are the two dominant structures in the DVFCFS and together these two faults are the longest and most active faults in the region. Preliminary seismic risk studies indicate that the DVFCFS may be the controlling distant seismic source for the potential high-level nuclear-waste repository at Yucca Mountain. Therefore, an assessment of their Quaternary activity is important in the evaluation of Quaternary faults around Yucca Mountain. 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, return periods for large ground rupturing events, amount of displacement per event, lengths of individual surface-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 north-striking, high-angle, down-to-the-west normal fault that is located along the western flank of the Black Mountains (fig. 1). The Furnace Creek fault is the northwest-striking, right-lateral strike-slip fault that is located more or less along the axis of northern Death Valley and extends to the north along the Funeral Mountains (fig. 1). The two faults join near Furnace Creek Ranch in Death Valley, about 50 km from the potential repository site at Yucca Mountain. Field studies to evaluate the previous work along about 125 km of the Death Valley and Furnace Creek faults began early in 1993. The Death Valley fault was examined from Mormon Point to just north of Furnace Creek Wash (about 50 km) and the Furnace Creek fault was studied from its junction with the Death Valley fault northward to just south of Grapevine Canyon (about 75 km)(fig. 1). Abundant evidence for multiple late Holocene surface ruptures is well-preserved at numerous locations along both faults. Traditionally, much of the data regarding fault behavior is collected from trench excavations across the fault. However, because much of the DVFCFS lies within the Death Valley National Monument, these type of activities are not allowed. To improve our understanding of the DVFCFS, faults, associated surficial deposits, and tectonic features related to recent tectonic activity at specific sites were mapped at a scale of about 1:7,500. This paper documents some of the well-preserved evidence of past faulting and summarizes the findings of the reconnaissance studies undertaken during the 1993-94 field season and reports estimates of late Quaternary slip rates derived from mapping at two sites: one along the Death Valley fault near Mormon Point (fig. 2A) and one along the Furnace Creek fault north of Red Wall Canyon (fig. 2B).

FIGURE 1.--NEAR HERE

FIGURE 2.--NEAR HERE

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." In northern Death Valley, Curry (1938) reported abundant geomorphic evidence that suggested lateral displacement along the Furnace Creek fault. However, the role of these two faults in the development of Death Valley was not described until Burchfiel and Stewart (1966) presented their pull-apart basin hypothesis. Their model of right-lateral slip on the parallel northwest-striking Furnace Creek and southern Death Valley faults being translated to oblique-normal slip on the Death Valley fault (fig. 1), is now widely accepted. However, the relationship between these active faults and how they behave seismogenically remains unknown.

Hunt and Mabey (1966, p. A100) estimated that the most recent activity along the Death Valley fault is younger than about 2000 years, based on the relationship of the fault scarps in central Death Valley to late Holocene lake shorelines and archaeological artifacts. Clements (1954, p. 58-60), on the basis of newspaper accounts and other turn-of-the-century written records, speculated that the young scarps along the Death Valley fault were the result of the November 4, 1908, magnitude 6.5 earthquake reported by Stover and Coffman (1993, p. 75). Records for this particular earthquake, unfortunately, are not very good and the epicenter location is poorly located.

Curry (1938, p. 1875) implied that activity on the Furnace Creek fault was relatively young owing to the presence of "a churned-up furrow in recent alluvium." However, specific locations documenting young activity along the fault were not reported until Reynolds (1969, p. 238) noted that the margin of a Pleistocene alluvial fan north of Red Wall Canyon was right-laterally offset about 150 feet (ft). Reynolds also reported late Holocene activity along the Furnace Creek fault but interpreted the displacement of the fan margin as being middle to late Pleistocene. Bryant (1988, p. 8-9) reevaluated the age of the offset fan margin in order to develop the only published late Quaternary slip rate for the Furnace Creek fault in Death Valley. He acknowledged the 150 ft offset, but assumed that the stream incision that produced the fan margin occurred about 20,000 years before present (yrs B.P.) 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 that the estimated slip rate of 2.3 millimeters per year (mm/yr) was a crude minimum estimate. Most recently, Reheis (1994) reports that the lateral slip rate on the northern Furnace Creek fault in Fish Lake Valley is about 4-7 mm/yr, and may be as high as 12 mm/yr. This suggests that the minimum slip rate of 2.3 mm/yr for the Furnace Creek fault in Death Valley may underestimate the actual late Quaternary slip rate by at least a factor of two and perhaps by a factor of five.

In the most detailed study of the late Quaternary activity on the Death Valley and Furnace Creek faults, Brogan and others (1991) document the location of the major traces and prominent tectonic features along the length of the DVFCFS at a scale of 1:62,500. 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). While Brogan and others (1991) do not report any new slip rates for either fault, they acknowledge the minimum rate of 2.3 mm/yr reported by Bryan (1988) for the Furnace Creek fault. However, using the range of vertical separations for Holocene surfaces reported by Brogan and others (1991, p. 21), an average vertical slip rate of 0.2-2.5 can be estimated for the Death Valley fault.

QUATERNARY STRATIGRAPHY

The most extensive Quaternary stratigraphic work undertaken in Death Valley is the reconnaissance-level work of Hunt and Mabey (1966; 1:96,000). Their mapping remains the most comprehensive in regards to the Quaternary stratigraphy, but is confined to the southern half of Death Valley and lacks the detail needed to evaluate Quaternary faulting activity. More detailed mapping of the surficial deposits along the Furnace Creek fault was completed by Moring (1986; 1:62,500) in northern Death Valley and by Wright and Troxel (1993; 1:48,000) in central Death Valley. The work of Wright and Troxel (1993), although emphasizing the bedrock geology of the southern Funeral Mountains, extends into Death Valley and includes the surficial deposits along the southern end of the Furnace Creek fault.

Mapping of the surficial deposits in Death Valley, for the most part, remains areally limited and incomplete.

Because of the hyperarid environment in Death Valley and the accompanying lack of vegetation, age control utilizing conventional radiocarbon techniques has been difficult to obtain. Hence, the ages of alluvial surfaces presented by previous workers in Death Valley have been based on the archaeology and relative age criteria such as degree of desert pavement and varnish development, depth of stream incision, and relative topographic position. Other studies examining Quaternary processes such as alluvial fan deposition, pluvial lake history, and the effects of climatic change in the Death Valley area have obtained 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). Unfortunately, these ages are not tied to detailed maps and descriptions of the sampled surfaces that are needed to make correlations elsewhere do not exist. Only the recent work of Bull (1991, p. 86) has attempted to establish a stratigraphic framework for surficial deposits in the arid southwestern United States. Bull suggests that the alluvial sequences recognized throughout the region are related to major climatic changes. By using detailed descriptions of characteristics on geomorphic surfaces, soil developed on those surfaces, and numerical ages based on a variety of methods, he demonstrates that a regional correlation of these alluvial sequences is possible.

The ages of the faulted alluvial fans in Death Valley can be estimated not only from surface characteristics but also from the stratigraphic relationships between the alluvial fan deposits and deposits related to late Pleistocene pluvial Lake Manly. Our knowledge of Lake Manly is fragmentary (Blackwelder, 1933; 1954; Hooke, 1972; Dorn and others, 1990), but recent work by Ku and others (1994) indicates that the last perennial lake existed in Death Valley from about 30,000 to about 10,000 yrs B.P. Some late Pleistocene surfaces adjacent to the DVFCFS have strandlines that record former highstands of Lake Manly and at numerous locations in Death Valley alluvial deposits and older fault-line scarps are overlain by lacustrine deposits. Since the recession of Lake Manly, the larger drainages have incised the higher late Pleistocene surfaces and redeposited the sediment in younger alluvial fans downslope (fig. 2). Surface characteristics on the younger alluvial fans (table 1) suggest that the incision and deposition most likely occurred during the middle and late Holocene. Therefore, the scarps and offset drainages on these younger alluvial fans record the total slip that has occurred on the DVFCFS during the latter part of the Holocene.

TABLE 1.--NEAR HERE

METHODOLOGY

In this study, geomorphic surfaces on faulted alluvial fans were mapped on low altitude (~1:7,500) low-sun-angle photographs. Geomorphic surfaces were initially categorized on the basis of their tonal differences and surface textures. These characteristics relate directly to the degree of varnish development and desert pavement formation. The descriptions of these surfaces were later refined in the field by including characteristics such as bar-and-swale morphology, pavement packing, surface dissection, varnish development, and the degree of soil horizonation (table 1). Surface designations and preliminary age assignments used in this report were adapted from Bull (1991, p. 65, 74-76) and made by comparing surface characteristics described in Death Valley to the lower Colorado River region. All slip measurements and the scarp profile, with the exception of the longer offsets, were measured in the field with a tape and hand level. The longer offset distances were measured from the low altitude aerial photographs. In addition to the uncertainities inherit to the measurement of these morphologic features in coarse-grained alluvial fan deposits, additional error in slip measurements may have been incurred due to the questionable position of channel margins due to subsequent erosion and deposition or low angles of intersection between offset drainages and the fault. All scarp heights and scarp-slope angles were measured from a computer-generated plot of field data.

WILLOW CREEK

Young scarps are nearly continuous on Holocene alluvial surfaces along the Death Valley fault from Furnace Creek Ranch south to Shoreline Butte with the exception of a 13-to-14-km-long gap near Artists Drive (fig. 1). Where the fault rounds the northern end of the Mormon Point turtleback (fig. 1), the fault changes strike from north-northwest to east-northeast. In the embayment in the range near Willow Creek, the strike of the fault gradually changes back to a north-northwest direction where the fault lies along the western flank of the Copper Canyon turtleback (fig. 1). Pronounced triangular facets and fault-line scarps are preserved on older alluvial deposits in the area. Younger fault scarps parallel the triangular facets and a fault-line scarp and form the most recent active trace of the Death Valley fault. Correlative geomorphic surfaces on each side of the fault generally are poorly preserved. This complicates efforts to determine the style of deformation, slip per event measurements, and activity rates. Geomorphic surfaces on the hanging-wall side of most scarps have been modified either by erosion or by deposition from continued fan processes (fig. 3). However, approximately 700 meters (m) north of the mouth of Willow Creek, a late Holocene surface (Q3c; table 1) is preserved on both sides of the scarp (fig. 3). A scarp profile was measured at this location in order to resolve surface displacement across the fault during the time represented by the age of the surface (fig. 4).

FIGURE 3.--NEAR HERE

FIGURE 4.--NEAR HERE

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 implied that the overhanging scarps were evidence of local reverse faulting. In contrast, overhanging scarps are commonly associated with very young normal fault scarps in alluvium and represent an early stage of scarp degradation. Close examination in the field suggests that the original scarp morphology is being preserved by the case-hardening effect and cementation of the alluvial by chemical agents blowing off the playa. Cementation of the alluvium with sodium chloride salt was commonly observed as would be expected given the proximity of the scarps to the salt pan and the very low mean annual precipitation in this part of Death Valley (less than 40 mm/yr). The overhanging scarps along the Death Valley fault reflect a more resistant salt-impregnated "cap rock" portion of the alluvial surface which overlies erodible uncemented alluvium at the base of the scarp. Rather than following a slope decline model of fault-scarp degradation, as described by Wallace (1977), it appears that the scarps in Death Valley tend to follow a parallel retreat model as outlined by Young (1972). Some portion of most scarps along the length of the Death Valley fault were found to be vertical or near-vertical. Owing to the probable young age of the scarp and the complex factors controlling its degradation, in this instance, analysis of the scarp height and slope angle measurements was complicated. While 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.

The profile near Willow Creek was measured perpendicular to the scarp, but the scarp crosses the alluvial slope at this location at a high angle. Therefore, rills developed on the fan surface prior to faulting give the illusion of being laterally offset across the fault. However, no evidence for lateral displacement was recognized at this site. Also, due to the differential preservation of large bars and swales on the upper surface of the scarp, the overall height of the scarp, and the vertical slope angle of the scarp, measurement of the scarp height in the field was difficult. The total scarp height of 10.5 m was measured from a computer-generated plot of the profile (fig. 4) and is believed to approximate within about 0.5 m the total vertical displacement of the surface since its stabilization. Owing to its stratigraphic position relative to latest Pleistocene Lake Manly shorelines and surface characteristics (table 1), the faulted surface is correlated with the late Holocene Q3c surface of Bull (table 1). Therefore, based on the estimated age for the Q3c surface of 2-4 kiloannum (ka), a scarp height of 10.5 m yields an average late Holocene vertical slip rate of 3-5 mm/yr (table 2).

TABLE 2: LATE QUATERNARY SLIP RATE ESTIMATES

Fault	Locality	Displacement (m)	Time Period	Slip rate (mm/yr)
Death Valley	Willow Creek	10.5	~2-4 ka	3-5
Furnace Creek	Red Wall Canyon	230-310	~40 ka	6-8

Slope angles across the scarp range from the angle of repose at the toe to vertical at the crest (fig. 4). The two vertical sections of the profile shown in figure 4 are interpreted to represent preserved free faces formed by separate ground-rupturing events. This hypothesis is supported by the presence of inset terraces preserved on the footwall block near the mouth of Willow Creek that can be traced to the base of each free-face. Based on this relationship, the scarps near Willow Creek record at least three events in late Holocene Q3c deposits. Assuming that parallel retreat has dominated degradation of these scarps, then the height of preserved free faces approximate the amount of surface displacement resulting from each ground-rupturing event. The measured height of 2.1 and 2.6 m for the two relatively well preserved free faces would then represent the surface displacement per event. If the scarp represents three events, as suggested by the inset terraces associated with the scarp, then the total scarp height of 10.5 m indicates that average surface displacement per event is about 3.5 m. Assuming that the scarp represents four events, the average surface displacement per event is about 2.5 m. This is in close agreement with the heights 2.1 and 2.6 m for the preserved free faces. Additionally, assuming that minimal free-face degradation has occurred between events, it appears that the past several ground-rupturing earthquakes that have occurred along the Death Valley fault at this location have been of similar size.

RED WALL CANYON

As reported by Curry (1938), geomorphic features indicating young tectonic activity is both abundant and well preserved along the Furnace Creek fault. Between its junction to the south with the Death Valley fault and the Grapevine Canyon to the north, the Furnace Creek fault strikes generally northwest and its trace is linear with no evidence of large lateral steps or bends (fig. 1). Offset drainages along the length of the fault suggest that displacement is nearly pure lateral except in the vicinity of the Salt Creek Hills (fig. 1). The Funeral Formation of early Pleistocene (?) age (Wright and Troxel, 1993) is uplifted along the east side of the fault and folded in the northwest-trending Salt Creek anticline west of the fault (Hunt and Mabey, 1966). Late Pleistocene terraces and other geomorphic surfaces which overlie the Funeral Formation reflect this deformation and suggest that some transpression is occurring across the southern end of the Furnace Creek fault. North of the Salt Creek Hills, the Furnace Creek 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 those interpreted to be correlative with latest Holocene surfaces (Q4b; table 1). Along much of the fault, deposits of different ages are commonly juxtaposed across the fault making evaluation of the slip on the fault difficult. However, north of Red Wall Canyon, fan surfaces correlative with the late Pleistocene Q2c unit (table 1) are preserved along both sides of the fault and drainages that incised these surfaces record the late Pleistocene slip history (figs. 2B and 5).

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 in northern Death Valley (fig. 1). The fault at this location is expressed as a single dramatic trace nearly 1 km southwest of the range front (fig 2B). Numerous en echelon furrows, small closed depressions, shutterridges, notches, hillside troughs, and offset drainages indicate that deformation along the fault is confined to a relatively narrow zone (figs. 2B and 5). Small drainages offset along the fault indicate that slip has been predominately lateral. At a location about 250 m northwest of the offset fan margin recognized by Reynolds (1969)(site 4 in fig. 5), a small late Holocene drainage 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 then formed leaving the old channel margins and bar deposits preserved adjacent to the active channel. The timing between this sequence of faulting events is reflected in the successively greater degree of varnish developed on each successively older bar deposit. The progressive offset channel at this site provides excellent evidence of 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 lateral displacement per event ranged from 2.5 to 3.5 m.

FIGURE 5.--NEAR HERE

Large drainages which incised the late Pleistocene surface have also been offset across the fault (fig. 2B). In addition, there are numerous beheaded and mismatched channels along the fault (fig. 5). The current position of the larger drainages that are incised into the Q2c surface is interpreted to relate directly to the abandonment and stabilization of the surface. This interpretation is supported by the presence of several 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. Palinspastic reconstruction of the late Pleistocene surface using low-altitude (~1:7680) aerial photographs indicates that three of the incised older drainages have been right-laterally offset 230-310 m across the fault (fig. 5). The offset measurements for these larger drainages were derived from the aerial photography and are believed to approximate within about 10 m the total right-lateral displacement since the incision of the drainages into the late Pleistocene surface. Because the displacement of the drainages occurred following their initial incision, then the age of stabilization of the geomorphic 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.

Surface characteristics were described at several sites on the late Pleistocene surface (table 1; fig. 5). Geomorphic surfaces in the southwestern United States with similar characteristics have been estimated by Bull (1991) to have an age of 12-70 ka. The 230-310 m offset measured on the large drainages (fig. 5) divided by an the age estimate of 12-70 ka for the Q2c surface at Red Wall Canyon results in a poorly constrained slip rate of 3-26 mm/yr. However, based on comparisons to other geomorphic surfaces of known age in the region (Dorn, 1988; Wells and others, 1987; Taylor, written communication), an age of about 40 ka is believed to more closely approximate the age of the Q2c surface at Red Wall Canyon. Using this age estimate limits the average lateral slip rate to about 6-8 mm/yr (table 2). This rate is in agreement with the rate of 4-7 mm/yr estimated by Reheis (1994) for the Furnace Creek fault in Fish Lake Valley. Admittedly, age control on the faulted deposits at this site is not very precise, but the late Pleistocene displacement is much better constrained than previous measurements. Regardless of the large uncertainities in the age of the faulted deposits, it appears that the slip rate on the Furnace Creek fault may be several times greater than previously thought.

CONCLUSIONS

Detailed mapping of tectonic features and geomorphic surfaces along parts of the Death Valley and Furnace Creek faults indicate that the late Quaternary slip rate for both faults is significantly higher than has been previously reported. Scarps on late Holocene alluvial fans along the Death Valley fault at Willow record at least three, and probably four, ground-rupturing earthquakes. Slip per event on the order of 2.1-3.5 m can be estimated from the height of the scarp, preserved free-faces, and inset stream terraces. Using an age of 2-4 ka, estimated on the basis of relative age criteria, the vertical slip rate for the Death Valley fault at this location is about 3-5 mm/yr.

Clear evidence for at least the last three ground rupturing earthquakes is also well preserved along the Furnace Creek fault. Repeatedly offset late Holocene channel margins indicate that lateral displacement per event ranged from 2.5 to 3.5 m. The right-laterally offset alluvial fan north of Red Wall Canyon records displacements that have occurred across the fault during the late Quaternary. Palinspastic reconstruction of the offset alluvial fan indicates that three large drainages incised into the fan surface are offset 230-310 m across the fault. An estimate of 40 ka for this geomorphic surface, which is based on relative age criteria, suggests that the slip rate on the Furnace Creek fault at this location is about 6-8 mm/yr.

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Table 1. DESCRIPTIONS OF QUATERNARY GEOMORPHIC SURFACES NEAR WILLOW CREEK AND RED WALL CANYON

			Clasts							Varnish			
Geomorphic surface[1]	Inferred age (ka)	Locality	Size[2]	Lithology[3]	Orient.[4]	Form[5]	Pavement packing[6]	Bar/swale morphology[7]	Depth of dissection (m)[8]	Lithology[9]	Location[10]	Color[11]	Soil horizons[12]
Q4b/Q4a	<2		Includes active channels and bars related to the channels										
Q3c	2–4	15 on Fig. 3	Large cobbles and boulders	70% D, 13% M, 13% VT, 4% MV	--	--	--	Distinct	--	VT	Bottom Top surfaces Top depressions	5YR 6/8 5YR 6/8 5YR 5/8	--
Q3b	4–8	17 on Fig. 5	Large cobbles; pebbles and cobbles	43% L/D, 38% Q, 17% VT, 2% C	∩ to O	--	PP to MP	Subdued	≤0.5	Q	Bottom[13] Edge	5YR 5/8 7.5YR 3/0	Av/Bk (stage I)
Q3a	8–12	1 on Fig. 5	--	L/D, Q	--	--	--	Subdued	~2	Surface is dark, but clasts are predominately dark gray limestone and dolomite.			Av/B(z?)m/Bkb
Q2c	12–70	15 on Fig. 5	Boulders	Q, L/D, VT, CR	--	Many clasts cracked	[14]PP to WP	--	--	Most clasts have dark, red-brown varnish. Bottoms of some are bright red. Bottoms of others are light red.			--
		13 on Fig. 5	Boulders; pebbles	65% Q/S, 30% L/D, 5% VT, tr. SH	H	--	WP	None	--	Q VT	Bottom[13] Top surfaces Top depressions Bottom Top surfaces	2.5YR 4/8 2.5YR 5/8 2.5YR 2.5/0 2.5YR 4/8 2.5YR 2.5/2	Av/Av-Bwk/ 2Bk/2Bky (stage II+)
		18 on Fig. 5	Boulders; pebbles and cobbles	60% Q, 20% L/D, 20% S/C, 5% VT?, 5% CR	--	--	WP	None	--	Q	Bottom Edge Top surfaces	2.5YR 5/8 2.5YR 3/6 2.5YR 2.5/0	Avk/Btkz-Avb/ 2Bkyz (stage II+)
		2 and 3 on Fig. 5	--	--	--	--	MP to WP	Mature	--	Most clasts have dark varnish. Bottoms of quartzites are red or bright orange.			Av/Btk/Bkm (stage I+ to III)[15]
		4 on Fig. 5	Boulders	--	--	--	MP	Mature	--	Surface appears dark, but color is gray instead of brown (from dark-gray limestone and dolomite?). Bottoms of quartzites are moderately to slightly red. Tops of quartzites are dark red-brown.			Bk (stage II or III)
		16 on Fig. 5	Small boulders	42% L/D, 30% Q, 20% S, 5% VT, 3% C, tr. CR	O	--	MP	Mature	2 to 3	Q	Bottom[13] Edge[13]	2.5YR 5/8 to 4/8 5YR 2.5/1	Avk/Btkb/Bkb

Notes to accompany Table 1:

[1] Designations are from Bull (1991, table 2.2, p. 54) for alluvial geomorphic surfaces of the lower Colorado River region, which encompasses Death Valley.

[2] The entry before the semi-colon shows the maximum clast size (visually estimated). The entry after the semi-colon shows the dominant clast size (visually estimated). A single entry is for the maximum clast size. Size classes are as follows: Boulders, >256 mm; Cobbles, 64–356 mm; Pebbles, 2–64 mm.

[3] Lithology is the composition of the clasts. Where percentages are given, clast lithology was determined by identifying each clast located at 10-cm intervals along a 1.5-m-long measuring tape that was placed randomly on the surface. Abbreviations indicate the following lithology: C, chert; CR, carbonate rubble; D, diorite; L/D, limestone and dolomite (usually gray or dark gray; may include lenses of brown chert); M, metamorphic rocks, not specified; MV, metamorphosed volcanic rock; Q, quartzite (usually white, tan, or light pink); Q/S, quartzite and sandstone; S/C, sandstone and chert; SH, shale; VT, volcanic tuff. Where no percentages are given, clast lithology was noted by visual inspection and is listed in order of decreasing relative amounts of each lithology.

[4] Orient. is the orientation of the clasts in the pavement relative to the ground surface. Abbreviations are as follows. R, random; long axes of the clasts are random; no direction of orientation predominates. O, oblique; long axes of most clasts project at an oblique angle into the ground surface. H, horizontal; long axes of most clasts are parallel to the ground surface.

[5] Clast form includes changes to the clast condition or appearance that have occurred since deposition. These changes include physical abrasion into ventifacts, pitting and solution weathering, and cracking and disintegration resulting from thermal and chemical processes.

[6] Packing is how closely the clasts are organized on the surface. Abbreviations are as follows. PP, poorly packed; clasts are unorganized. MP, moderately packed; most clasts do not touch, and sand and silt are visible between the clasts. WP, well packed; clasts interlock or are nearly so, and little or no sand and silt visible between the clasts. Where two classes are given, the poorer packing refers to the pavement on bars and the better packing refers to the pavement in swales, unless otherwise noted.

[7] Bar and swale morphology is a measure of how much of the original depositional pattern remains on the surface. Property is dependent upon the original clast size and shape (e.g., pebbly surface may have little or no bar and swale topography initially). Terms are as follows. Distinct, contact between the bars and swales is clear and relief above the swale averages >50 cm. Subdued, relief above the swale averages between 25 and 50 cm. Mature, bars and swales are still visible but pavement development on bars is approaching or equivalent to that in the swales. None, bar and swale topography has been completely masked or was never present.

[8] Depth was visually estimated.

[9] Clast lithology on which varnish color was determined. Light-colored quartzites (Q) were used where available. Otherwise, light-colored volcanic tuffs (VT) were examined.

[10] Location of the varnish coat on which color was determined. Bottom is the portion of the clast below the ground surface. Edge is the portion of the clast that intersects the ground surface. Top is the portion of the clast above the ground surface. For the tops of clasts, varnish was noted on both the clast surface and in depressions, as indicated.

[11] Color was determined using Munsell notation.

[12] Soil horizons described according to Birkeland (1984, appendix 1, p. 353-361). Shown in parentheses is the stage of the maximum carbonate development in the Bk horizon (Birkeland, 1984, p. 358-359).

[13] Color is the maximum recognized by examining randomly selected clasts from the surface.

[14] Pavement is poorly packed near the fault scarp. Pavement is well packed on this surface further from the scarp (>100 m).

[15] Soil was noted only in a poor exposure, so that the maximum carbonate stage was difficult to estimate.

Figure 1. Map showing the location of the southern Death Valley, Death Valley, and Furnace Creek faults relative to the proposed repository site at Yucca Mountain (YM). Location of the faults taken from Reheis (1991a) and Brogan and others (1991). Stippled areas are the major mountain ranges adjacent to Death Valley. Letter abbreviations are locations described in this report: GC - Grapevine Canyon, RW - Red Wall Canyon, SCH - Salt Creek Hills, FCR - Furnace Creek Ranch, FGW - Furnace Creek Wash, AD - Artists Drive, CC - Copper Canyon, WC - Willow Creek, MP - Mormon Point, and SB - Shoreline Butte.

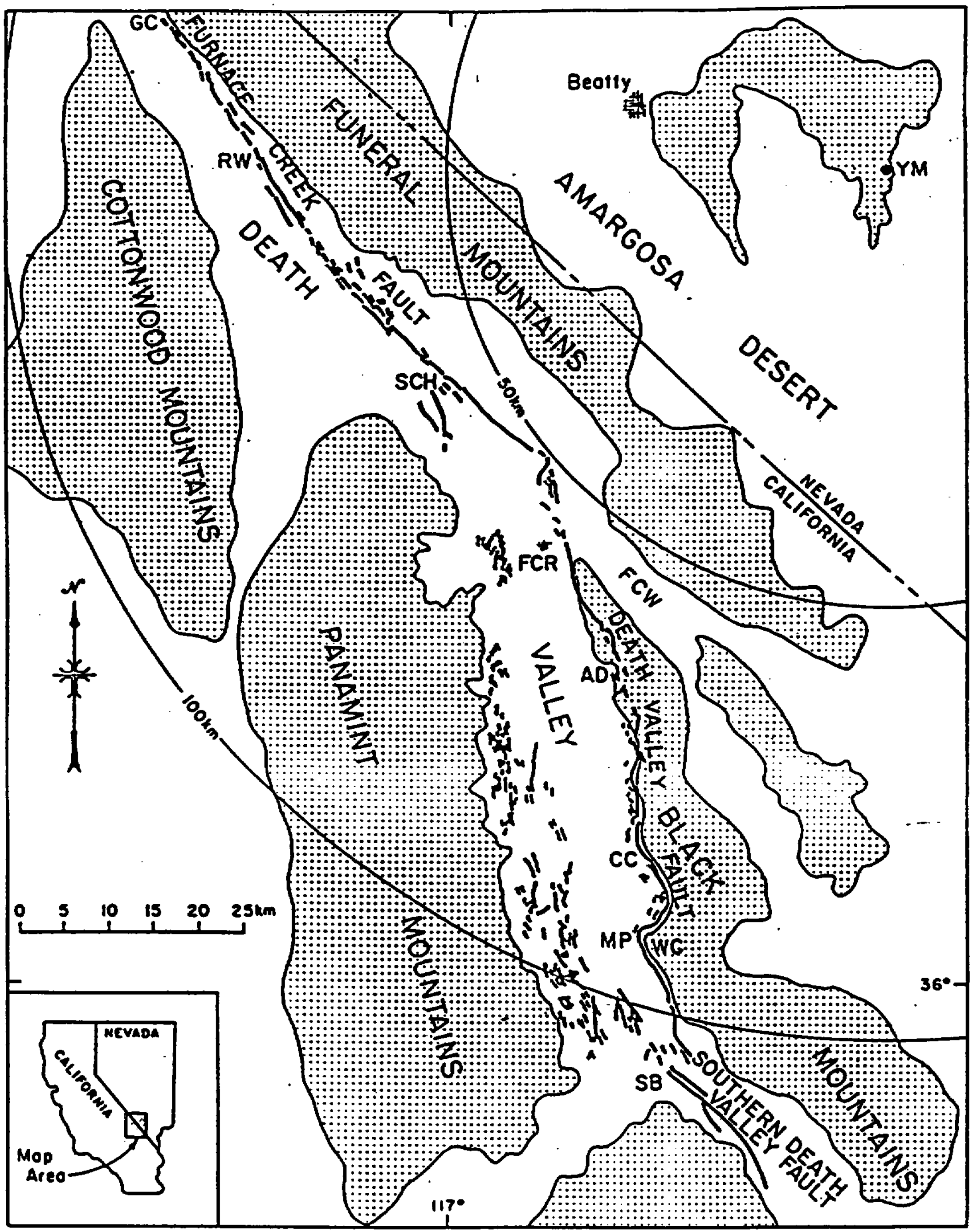

GC
FURNACE CREEK FAULT
RW
FUNERAL MOUNTAINS
AMARGOSA DESERT
Beatty
YM
COTTONWOOD MOUNTAINS
DEATH VALLEY
SCH
50km
NEVADA
CALIFORNIA
FCR
FCW
DEATH VALLEY FAULT
AD
PANAMINT MOUNTAINS
BLACK MOUNTAINS
CC
MP
WC
100km
36°
SB
SOUTHERN DEATH VALLEY FAULT
117°
0 5 10 15 20 25km
N
NEVADA
CALIFORNIA
Map Area

Figure 2. Vertical aerial photographs of faulted alluvial fans along A) the Death Valley fault near Willow Creek (GS-VFDT 7-209; approximate scale 1:20,000) and B) the Furnace Creek fault north of Red Wall Canyon (GS-VFDT 7-163; approximate scale 1:35,000).


A

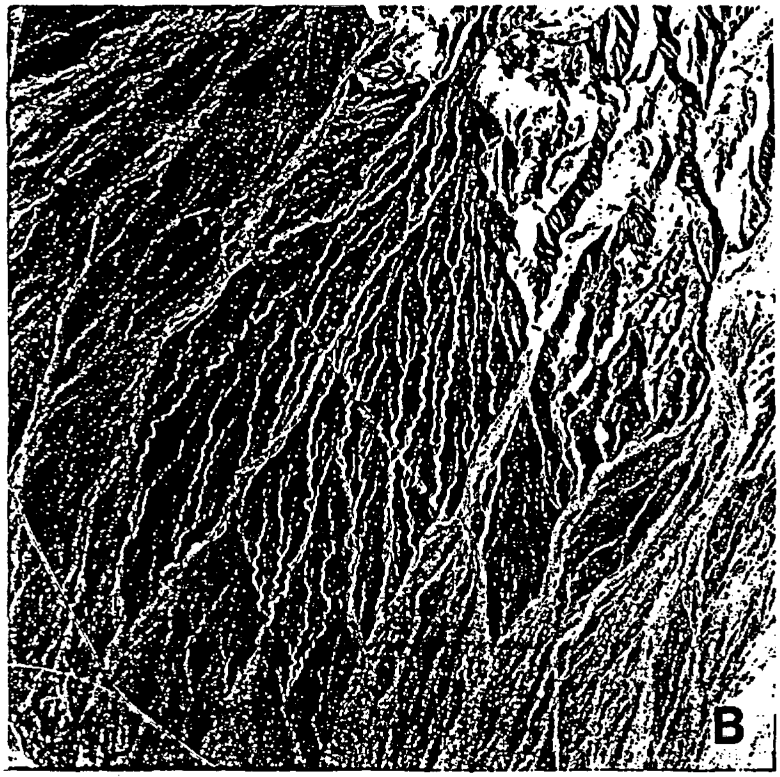

B

Figure 3 Surficial geologic map of the northeast-striking section of the Death Valley fault near Willow Creek (see fig. 2A). Numbered site locations, geomorphic surface designations, and criteria used to characterize and differentiate the surface units are outlined in table 1. A scarp profile was measured across the fault at site 15.

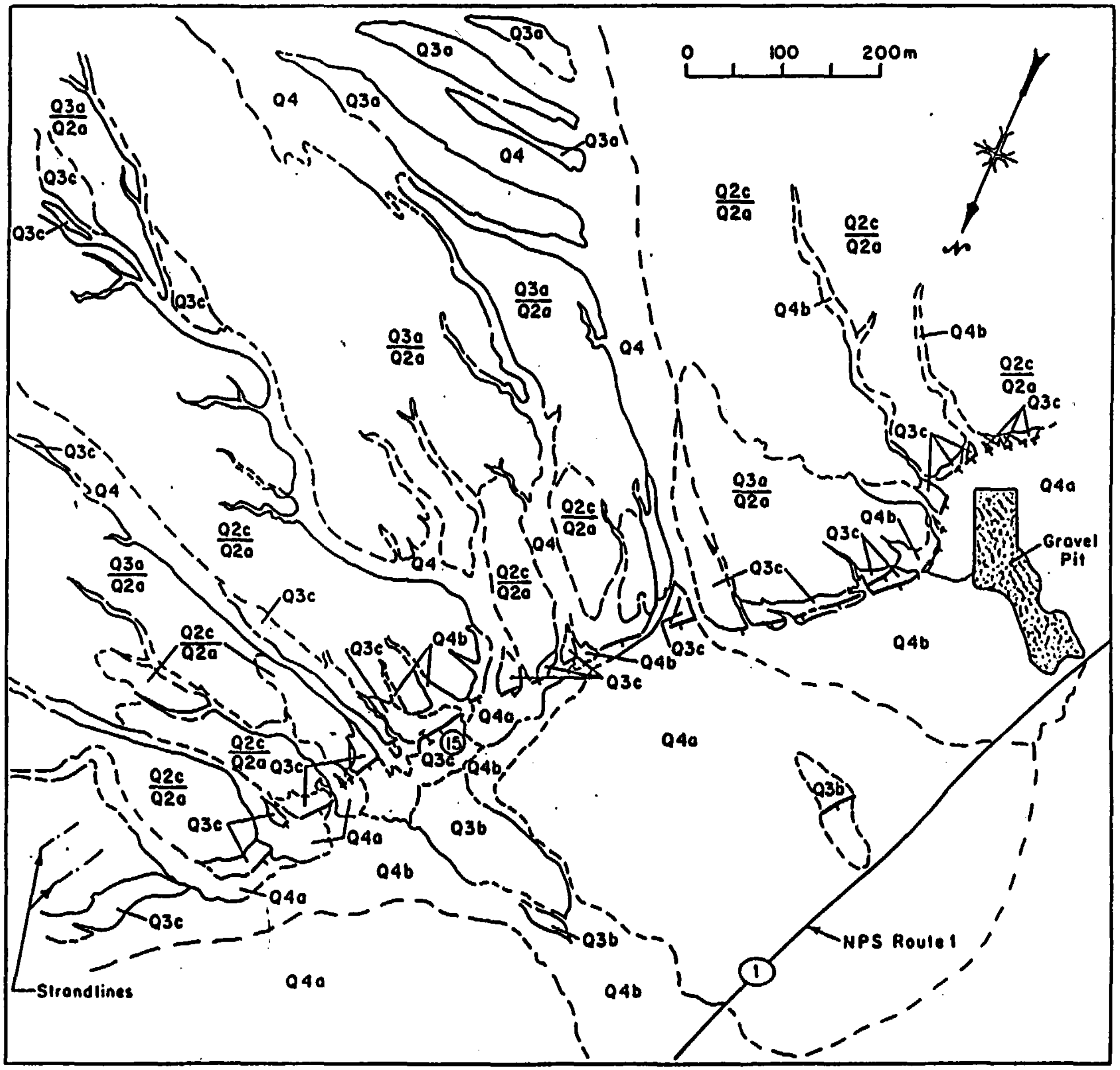

0
100
200m
Q3a
Q3a
Q4
Q3a
Q4
Q3a
Q3a
Q2a
Q3c
Q3c
Q3c
Q2c
Q2a
Q2c
Q2a
Q3a
Q2a
Q3a
Q2a
Q4
Q4b
Q4b
Q2c
Q2a
Q3c
Q3c
Q3c
Q4
Q3a
Q2a
Q2c
Q2a
Q2c
Q2a
Q4
Q4a
Q3c
Q4b
Q2c
Q2a
Q4
Q3a
Q2a
Q3c
Q3c
Gravel Pit
Q2c
Q2a
Q3c
Q4b
Q4b
Q3c
Q4b
Q3c
Q4a
15
Q3c
Q4b
Q4a
Q2c
Q2a
Q3c
Q2c
Q2a
Q3b
Q3c
Q4a
Q3b
Q4b
Q4a
Q3c
Q3b
NPS Route 1
1
Strandlines
Q4a
Q4b

Figure 4. Scarp profile measured across the Death Valley fault near Willow Creek (site 15 in fig. 3). A scarp height of 10.5 m and a maximum scarp-slope angle of 90° were measured from the plot. The two near-vertical portions of the scarp near the crest (2.1 and 2.6 m high) are interpreted to be preserved free faces produced by past ground-rupturing earthquakes based on the relationship between the vertical portions of the scarp and adjacent inset stream terraces near the mouth of Willow Creek.

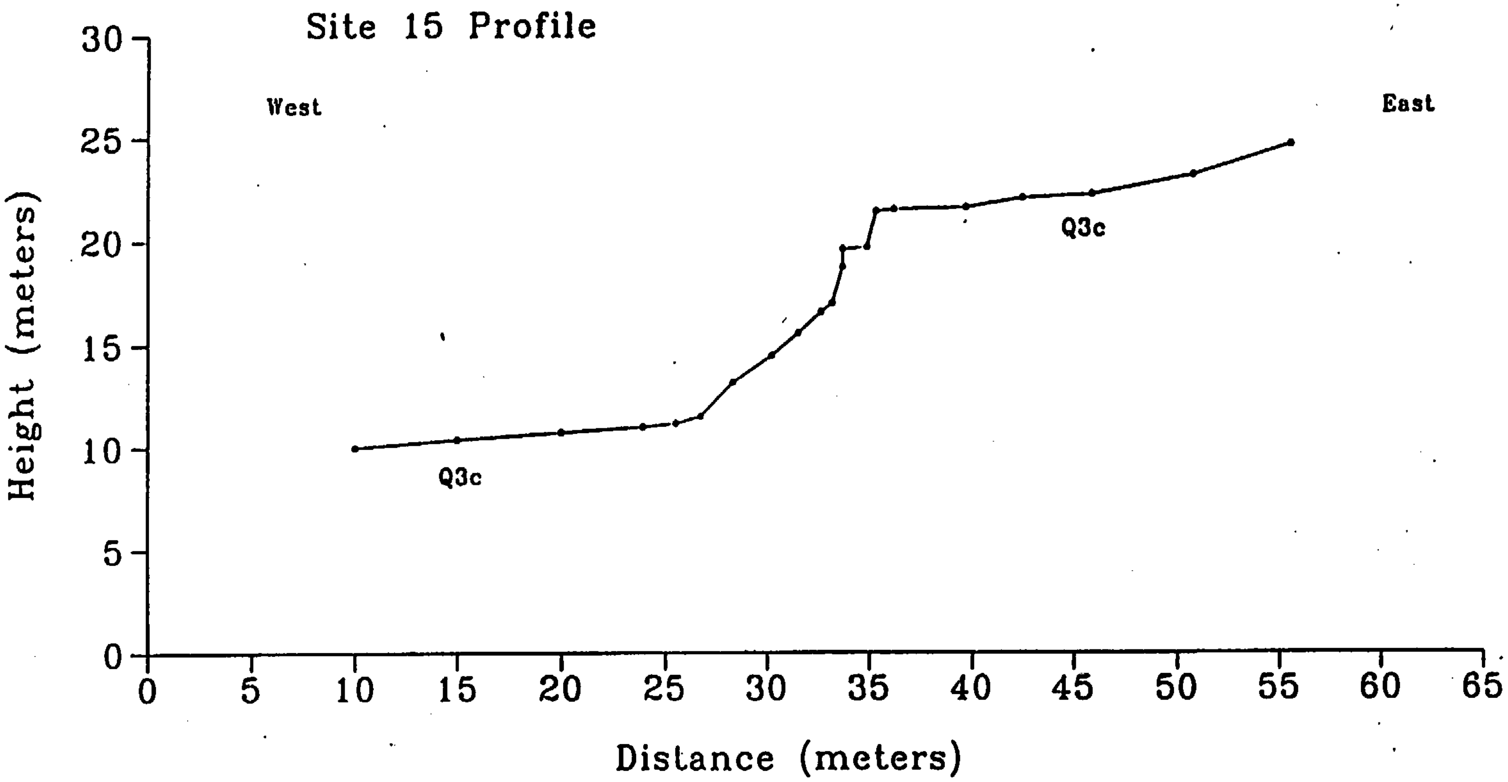
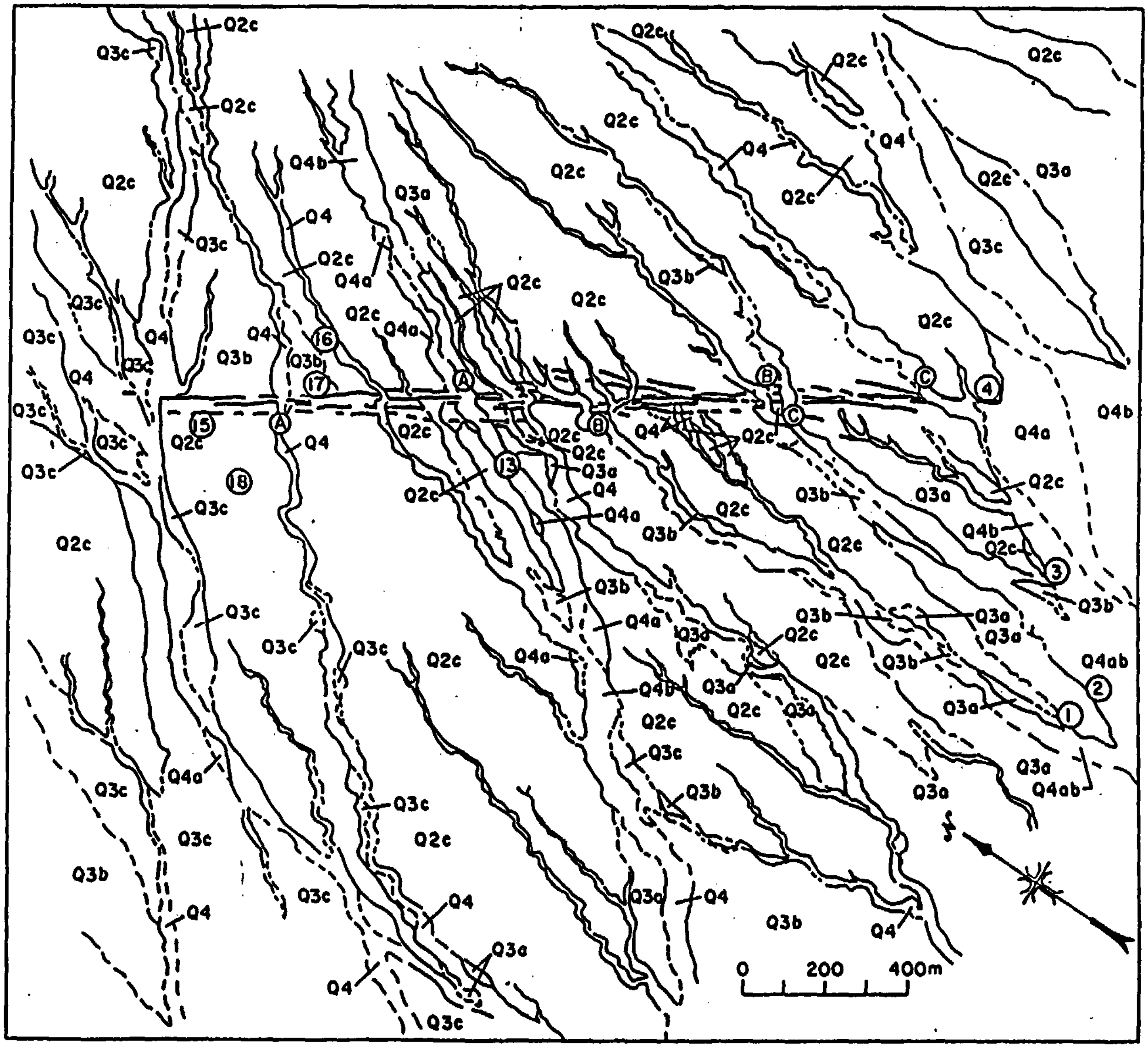

Site 15 Profile
West
East
Q3c
Q3c
Height (meters)
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Distance (meters)

Figure 5. Surficial geologic map of a part of the alluvial fan adjacent to the Furnace Creek fault near Red Wall Canyon (see fig. 2B). Numbered site locations, geomorphic surface designations, and criteria used to characterize and differentiate the surface units are outlined in table 1. The 360-480 m right-lateral offset across the fault was measured between the drainages denoted by letters.


Q2c
Q3c
Q2c
Q2c
Q2c
Q2c
Q4
Q2c
Q4
Q2c
Q4b
Q3a
Q2c
Q2c
Q3a
Q4
Q3c
Q2c
Q3c
Q4a
Q3b
Q2c
Q2c
Q2c
Q3c
Q4
Q2c
Q4a
Q3c
Q4
Q3b
Q4
16
Q3b
17
A
A
B
C
B
C
4
Q4b
Q3c
15
A
Q4
Q2c
Q2c
Q2c
Q4
Q2c
Q4a
Q3c
Q3c
Q2c
Q3c
Q3a
13
Q4
Q3b
Q3a
Q2c
18
Q2c
Q4a
Q2c
Q3b
Q4b
Q2c
Q3c
Q2c
Q2c
3
Q3b
Q3b
Q3a
Q3c
Q4a
Q3a
Q2c
Q3a
Q3c
Q3c
Q2c
Q4a
Q2c
Q3b
Q4ab
Q4b
Q3a
2
Q2c
Q2c
Q3a
Q3a
1
Q3c
Q4a
Q3c
Q3b
Q3a
Q3c
Q3c
Q2c
Q3a
Q4ab
Q3b
Q4
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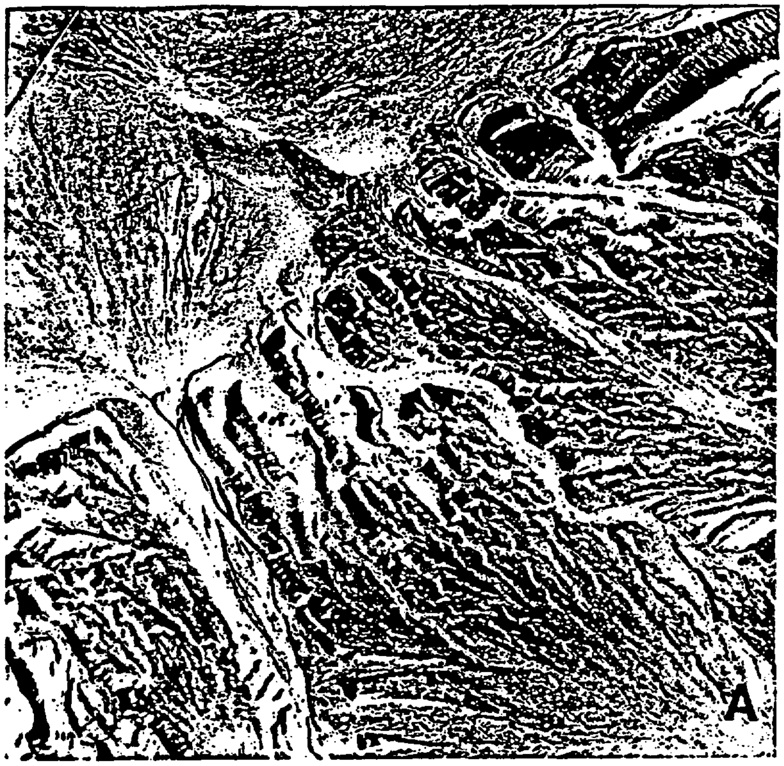
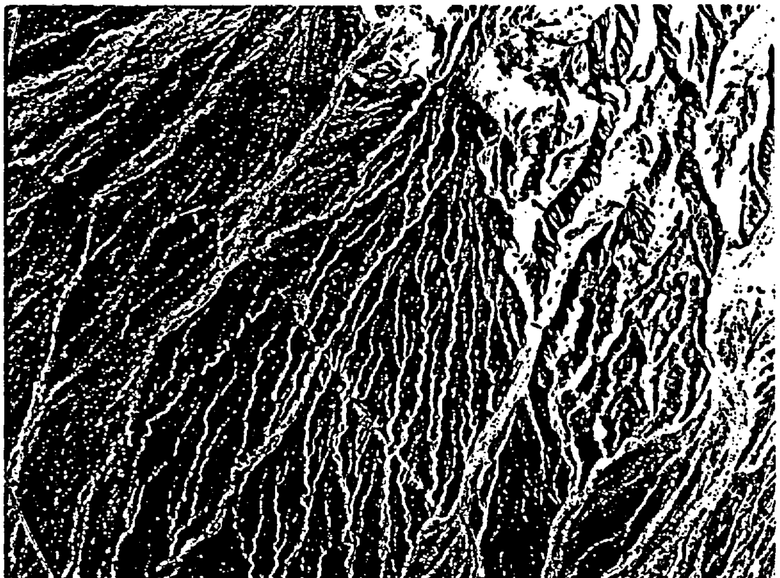
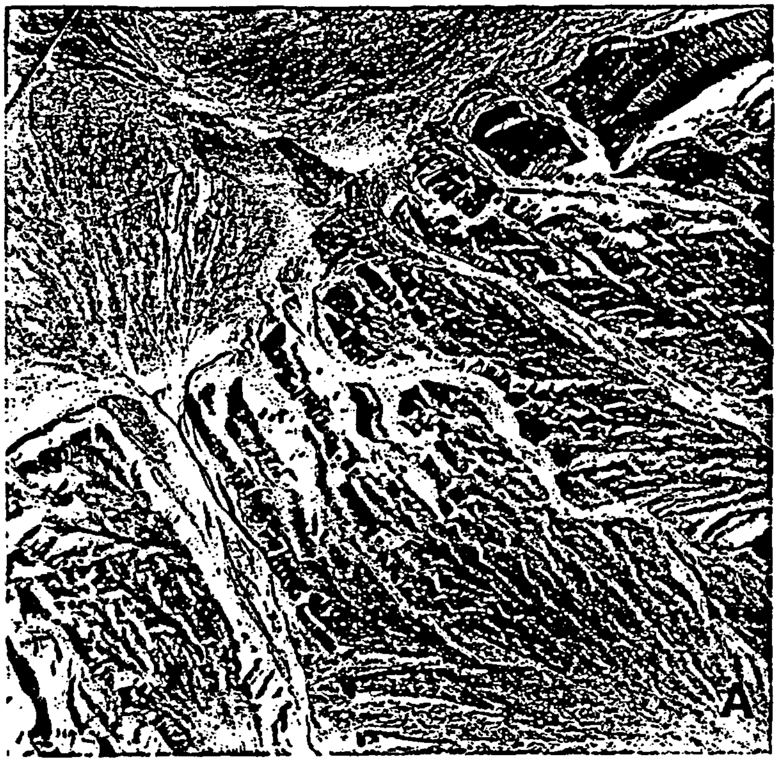
Q4
Q3a
Q4
Q3b
Q4
Q3a
Q4
Q3c
0
200
400m


A


B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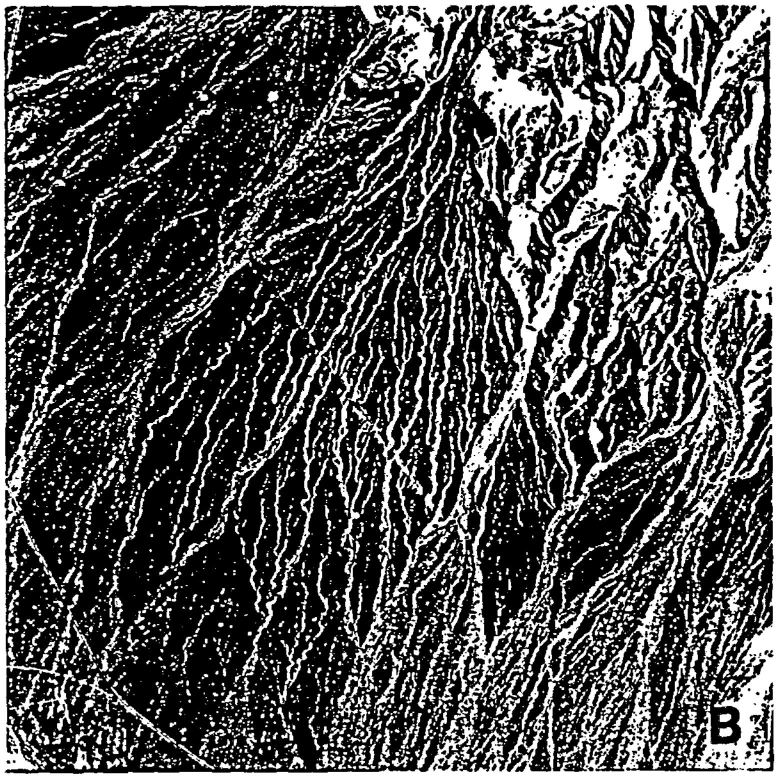
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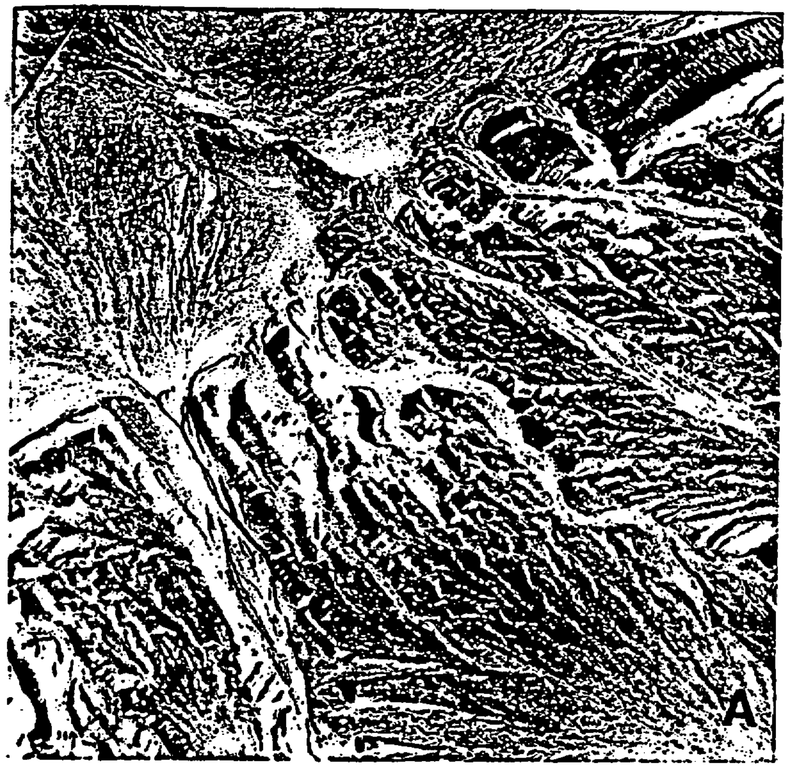
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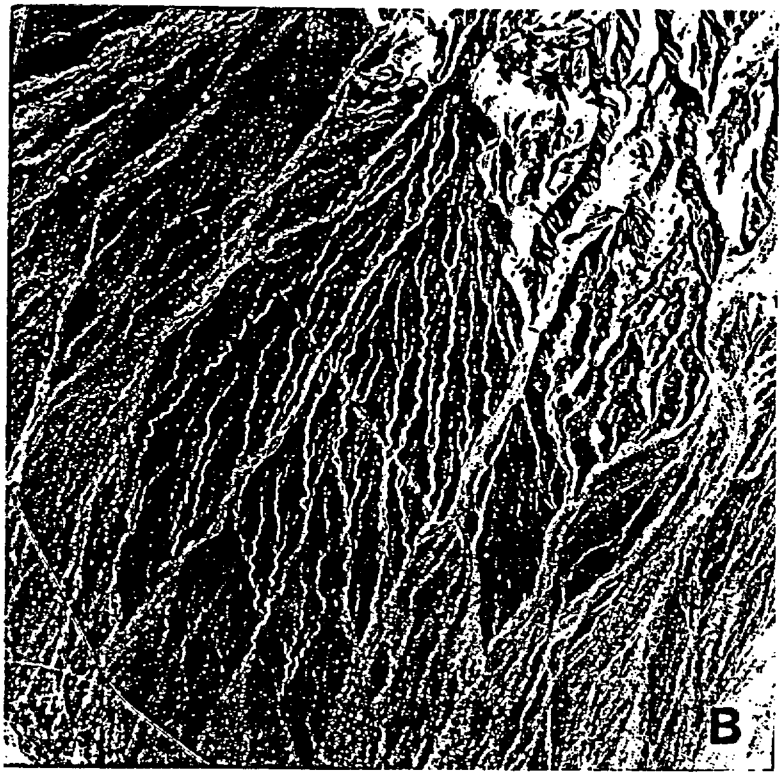
B