Late Quaternary Faulting Along the Death Valley-Furnace Creek Fault System, California and Nevada

U.S. GEOLOGICAL SURVEY BULLETIN 1991

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By GEORGE E. BROGAN, KARL S. KELLOGG, D. BURTON SLEMMONS, and CHRISTINA L. TERHUNE

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Late Quaternary Faulting Along the Death Valley–Furnace Creek Fault System, California and Nevada

By George E. Brogan[1], Karl S. Kellogg, D. Burton Slemmons[2], and Christina L. Terhune

Abstract

The Death Valley–Furnace Creek fault system, in California and Nevada, has a variety of impressive late Quaternary neotectonic features that record a long history of recurrent earthquake-induced faulting. Although no neotectonic features of unequivocal historical age are known, paleoseismic features from multiple late Quaternary events of surface faulting are well developed throughout the length of the system. Comparison of scarp heights to amount of horizontal offset of stream channels and the relationships of both scarps and channels to the ages of different geomorphic surfaces demonstrate that Quaternary faulting along the northwest-trending Furnace Creek fault zone is predominantly right lateral, whereas that along the north-trending Death Valley fault zone is predominantly normal. These observations are compatible with tectonic models of Death Valley as a northwest-trending pull-apart basin.

The largest late Quaternary scarps along the Furnace Creek fault zone, with vertical separation of late Pleistocene surfaces of as much as 64 m (meters), are in Fish Lake Valley. Despite the predominance of normal faulting along the Death Valley fault zone, vertical offset of late Pleistocene surfaces along the Death Valley fault zone apparently does not exceed about 15 m.

Evidence for four to six separate late Holocene faulting events along the Furnace Creek fault zone and three or more late Holocene events along the Death Valley fault zone are indicated by rupturing of Q_{1B} (about 200–2,000 years old) geomorphic surfaces. Probably the youngest neotectonic feature observed along the Death Valley–Furnace Creek fault system, possibly historic in age, is vegetation lineaments in southernmost Fish Lake Valley. Near-historic faulting in Death Valley, within several kilometers south of Furnace Creek Ranch, is represented by (1) a 2,000-year-old lake shoreline that is cut by sinuous scarps, and (2) a system of young scarps with free-faceted faces (representing several faulting events) that cuts Q_{1B} surfaces.

INTRODUCTION

The Death Valley–Furnace Creek fault system of eastern California and western Nevada (fig. 1) is an active tectonic structure of regional significance that has had a profound influence on the geologic and geomorphic development of the western Great Basin. This fault system, more than 300 km (kilometers) in length, is the second longest fault system in California, surpassed in length only by the San Andreas fault system, and shows abundant geologic and geomorphic evidence of youthful surface rupture. However, no large historic earthquakes are known to be associated with faults in the system (Real and others, 1978; Ryall and others, 1966). All fault-related features, with one possible exception, are interpreted as prehistoric, although presently ongoing aseismic creep may be occurring in places (Burford and Harsh, 1980; Sylvester and Bies, 1986). For this reason, a scarp- or lineament-producing faulting event may be due to either an earthquake or a period of aseismic fault creep.

Movement along other faults in nearby areas has produced large earthquakes during historic time (Jennings and others, 1975; Ryall and others, 1966), and many of those faults have youthful fault-related features that are similar to features along the Death Valley–Furnace Creek fault system (Slemmons, 1967; Jennings and others, 1975). Examples include the 1872 Owens Valley earthquake, focused about 95 km west of Death Valley, and the 1932 Cedar Mountain earthquake, about 50 km north of Fish Lake Valley. As recently as 1986 in Chalfant Valley along the White Mountains, almost 25 km west of Fish Lake

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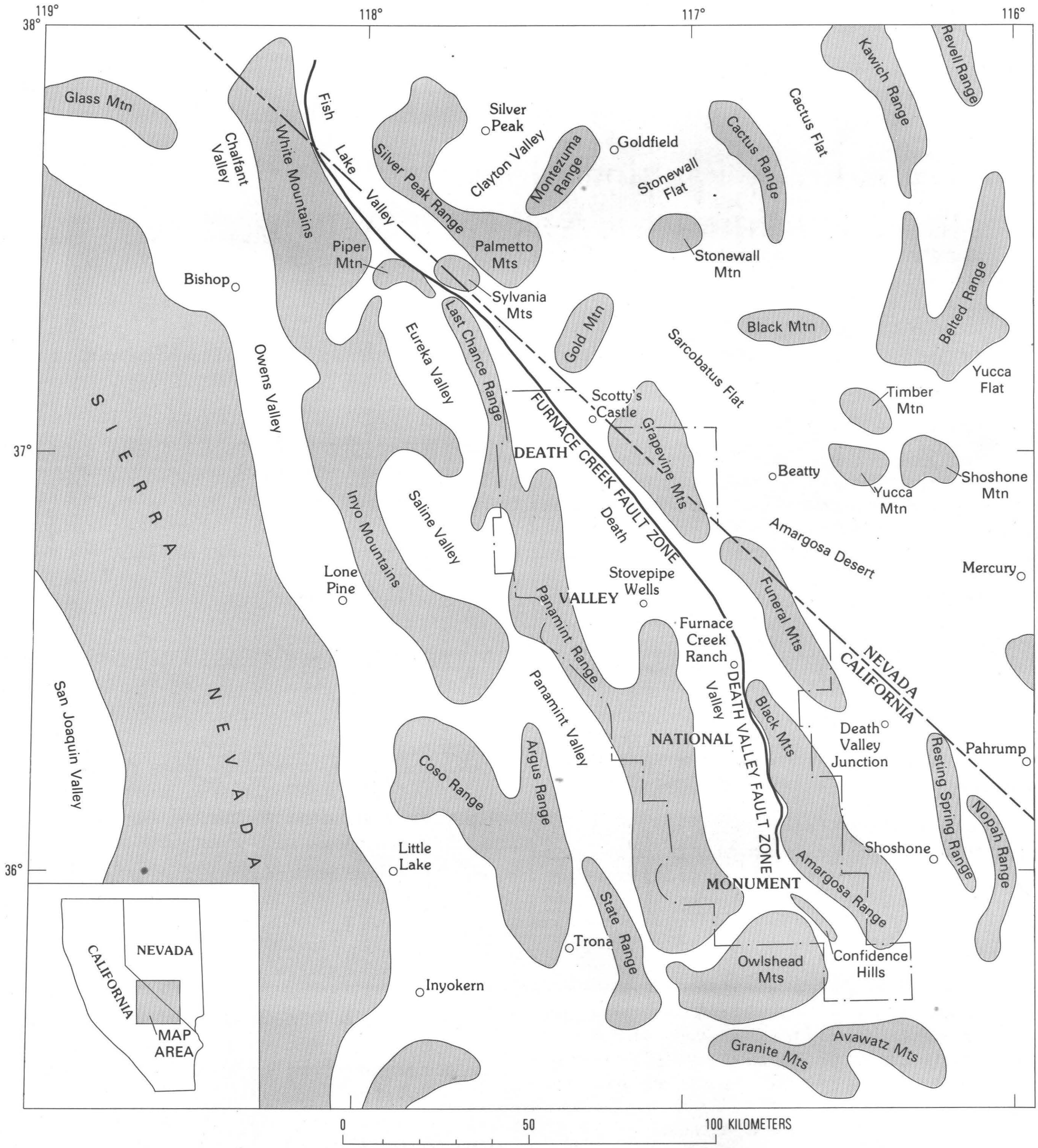

Figure 1. Map of the region surrounding the Death Valley–Furnace Creek fault system, showing major geographic features and trace of major faulting along fault system.

Valley, centimeter-scale scarps and cracks of tectonic origin formed during a moderate earthquake (dePolo, 1989). Accordingly, the Death Valley–Furnace Creek fault system is considered active and is a potential source of large earthquakes. The chronology of geologically recent faulting discussed in this report is therefore a useful background for assessing contemporary seismicity patterns and recurrence periods for large earthquakes on the fault system.

The Death Valley–Furnace Creek fault system may be viewed as part of a large, currently active, northwest-directed pull-apart zone, such that movement along the Furnace Creek fault zone is mostly strike slip and that along the north-trending Death Valley fault zone is mostly normal slip (Burchfiel and Stewart, 1966; Stewart, 1983). Estimates of right-lateral displacement along the Furnace Creek fault zone range between 40 and 100 km, but displacement is probably closer to 80 km (evidence summarized by Stewart, 1983); right-lateral displacement along the Death Valley fault zone was originally reported to be less than 8 km (Wright and Troxel, 1967) but was more recently estimated to be about 35 km (Butler and others, 1988).

The large component of normal offset along the Death Valley fault zone is a recent manifestation of the same general extensional processes that produced the impressive turtleback structures (denuded detachment surfaces on mostly Precambrian rock) in the Black Mountains (for example, Drewes, 1959; Hamilton, 1988). Stewart (1983) suggested that the Panamint Range may have originally resided atop the Black Mountains and subsequently slid 80 km to the northwest to its present location along the detachment (or several detachments) during middle to late Tertiary time. The gap or void created by ongoing extension between the Panamint Range and the Black Mountains is the site of the present Death Valley.

This report describes the Death Valley–Furnace Creek fault system between Wildhorse Flat (pl. 1*A*) at the north end of Fish Lake Valley, and Shoreline Butte (pl. 4) at the south end of Death Valley. Figure 1 shows the major ranges and valleys near the fault system. Faults along the main fault trace are mapped and described, and some of the faults subsidiary to the main fault system also are mapped. The mapped subsidiary faults include those in northern Fish Lake Valley between Indian and Marble Creeks (pl. 1*A*), in central Fish Lake Valley north of Oasis (pl. 1*A*), in the Oriental Wash area (pl. 1*B*), Ubehebe Crater area (pl. 1*C*), along the northwest side of Tucki Mountain (pl. 2), and along the west side of Death Valley (pls. 1*C*, 3, and 4).

The northwest-trending Furnace Creek fault zone, shown on plates 1 and 2, is the northern part of the Death Valley–Furnace Creek fault system and is subdivided for purposes of discussion into 12 sections (fig. 2). A neotectonic map of the Furnace Creek fault zone within California, based largely on the unpublished mapping of G.E. Brogan (the same data used for this report), was recently compiled (Bryant, 1988). The north-trending Death Valley fault zone, the southern part of the fault system, is subdivided into 11 sections (southernmost part of pl. 2 and pls. 3 and 4).

The term "section" rather than "segment" is used in this report because in the past decade the latter term has acquired a specific meaning in neotectonic studies (for example, Machette and others, 1991). A fault segment refers to a part of a fault zone or system that typically lies adjacent to a coherent or semicoherent block during a faulting event, so it commonly undergoes synchronous movement and has a map pattern that is distinct from that of adjacent fault segments. In this report, the subdivision of the fault system into sections is subjective and is based on changes in (1) trend of faults, (2) recency of faulting as expressed by the preservation of fault-related geomorphic features, (3) width of the fault zone, (4) consistency of fault patterns, and (5) proximity of the most recently active trace to adjacent range fronts and bedrock structures. Sections may, in fact, be segments, but that meaning is not necessarily implied in this report.

Acknowledgments

This report summarizes the principal findings of G.E. Brogan's study of the Death Valley–Furnace Creek fault zone, begun in 1969. He performed all of the original field work, aided by special low-sun-angle aerial photographs taken for this work. On the basis of additional aerial-photograph interpretation and limited field work, Kellogg and Terhune verified, revised, and condensed text and map information from the original report. Numerous localities were checked in March 1989 by M.D. Carr, K.F. Fox, Jr., K.S. Kellogg, D.W. Rankin, M.C. Reheis, J.C. Tinsley, and J.C. Yount. Thorough reviews of the manuscript were made by K.F. Fox, Jr., R.A. Thompson, and V.M. Glanzman. This work is part of the Yucca Mountain Program in cooperation with the U.S. Department of Energy (Interagency Agreement DE–AI08–78ET44802).

The original investigation by Brogan was suggested by Slemmons of the Mackay School of Mines, University of Nevada at Reno, and was conducted under his overall guidance. Support for the original investigation was provided by the U.S. Atomic Energy Commission, the California Division of Mines and Geology, the National Science Foundation, Mackay School of Mines Foundation, Woodward-Clyde Consultants, and the U.S. Geological Survey. The people who contributed significant time and thought during the course of the original study include W.J. Carr, L.S. Cluff, B.W. Troxel, G.A. Carver, and C.E. Glass.

METHODS

Faults were mapped using stereoscopic pairs of low-sun-angle aerial photographs (approximate scale 1:12,000) and concentrated on interpreting geomorphic features and surfaces. Maps were compiled at scale 1:24,000, then recompiled for publication at a scale of 1:62,500. The low-sun-angle aerial photographs are most useful for interpreting scarp morphology in alluvial terrain where surfaces are of low relief. Consequently, faults in high-relief bedrock areas were not studied extensively. Fault scarps and other fault-related features subsequently were identified and studied in the field.

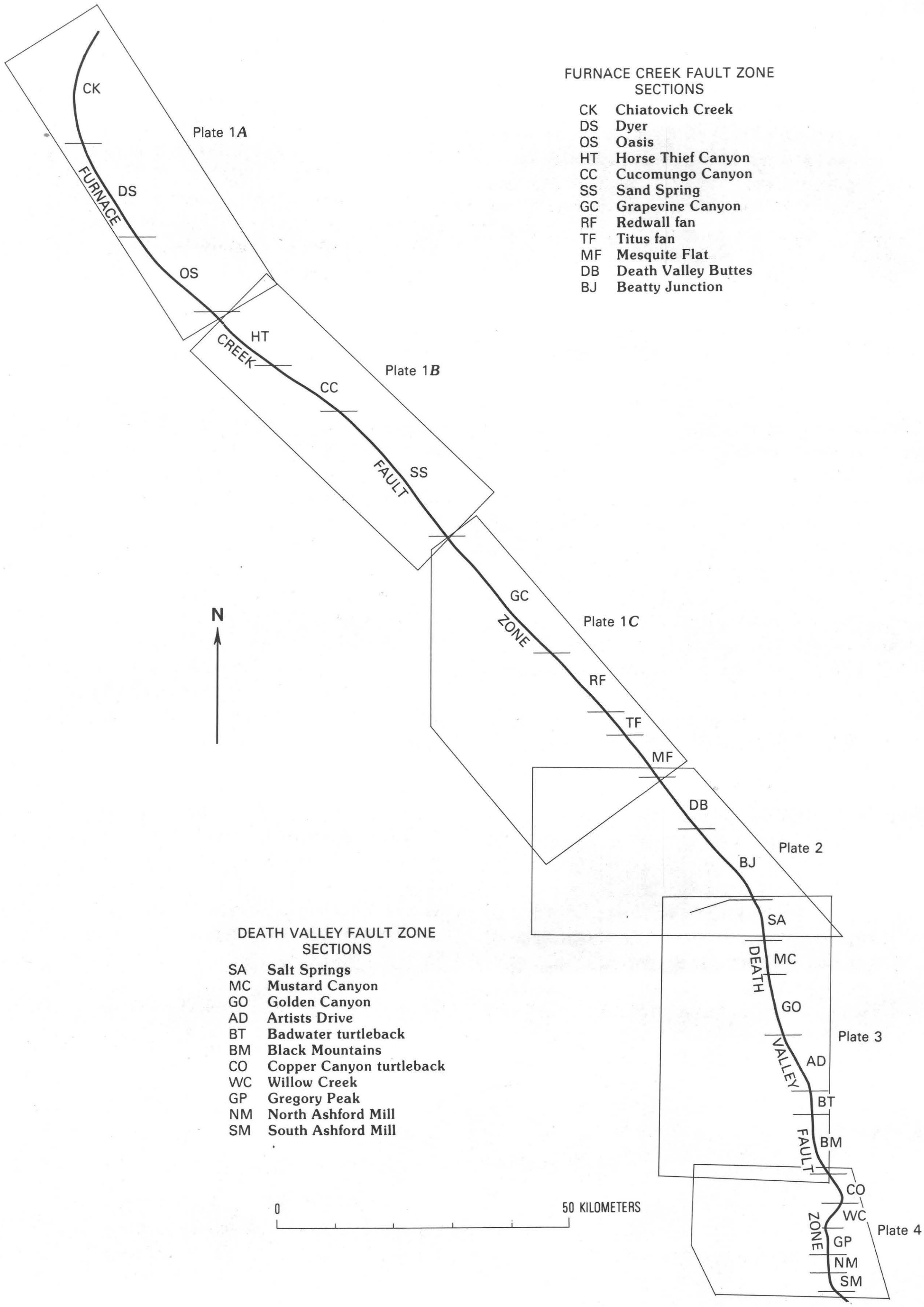

Figure 2. Reference map of the Death Valley–Furnace Creek fault system, showing the 12 sections of the Furnace Creek fault zone and 11 sections of the Death Valley fault zone.

Fault scarps were studied for evidence of recurrent displacement by means of fault-scarp morphologic techniques. The methods utilized for this fault-scarp study were developed and described by many workers (for example, Slemmons, 1977; Wallace, 1977, 1978; Bucknam and Anderson, 1979; and Pease, 1979). The geomorphic and structural nomenclature used herein also follows these sources, as well as some previous studies of a similar nature in other regions (for example, Clark, 1973; Brown and Wolfe, 1972; Ross, 1969; Vedder and Wallace, 1970; and Brown, 1970). Faults and fault-related features were classified according to a scheme originally compiled by Slemmons (1977) (table 1). Clark (1973) also described some of the features useful in identifying recent faulting.

Two methods were used to estimate the ages of faulting along the Death Valley–Furnace Creek fault system. One method involves the interpretation of fault-scarp morphology using the techniques of Slemmons (1977) and refined by Wallace (1977), who showed that slopes along fault scarps in alluvium are controlled successively by gravity-, debris-, and wash-related processes. The original surface of the fault scarp is replaced by an erosion surface and a debris slope; the slope of the erosion surface and debris slope gradually decline through time (fig. 3). The rate of slope decline depends on the process that controls the steepest slope on the scarp. By estimating the duration that each process controls the maximum slope angle, Wallace (1978, fig. 12) estimated the age of faulting that produced scarps (fig. 4). The estimated age appears to depend on climate, character and consolidation of the faulted material, orientation of the fault, and the height and slope of the original fault scarp (Wallace, 1978; Pease, 1979; and Pierce and Coleman, 1987). Low scarps decline in slope more rapidly than high scarps; thus, the original type and amount of dip slip are also important (Bucknam and Anderson, 1979).

The second method used to estimate the age of faulting events in the Death Valley area is based on interpreting the relative ages of fault-related features and successive geomorphic features. For example, at some localities a fault cuts an older alluvial surface or surfaces, whereas a younger surface remains undisturbed across the fault trace. At many localities, scarps in progressively older stratigraphic units and (or) geomorphic surfaces have progressively larger offsets, indicating that recurrent faulting occurred along the same trace.

We employed a four-fold classification for geomorphic surfaces along the Death Valley–Furnace Creek fault system (table 2), incorporating sparse age control from the Death Valley area; this classification is derived from similar classifications developed by Denny (1965), Hunt and Mabey (1966), Hooke (1972), and W.B. Bull (written commun., 1974). We consider the general chronology shown on table 2 to be a reasonable geomorphic tool useful for estimating the relative ages of surfaces in a small area; however, correlations from one area to another may not be accurate, and correlations between distant areas may be misleading. The correlation problem is paramount between Fish Lake Valley and Death Valley where the climates of the valleys and adjacent mountains differ widely. Consequently, the estimated ages for geomorphic surfaces cited in table 2 should be viewed as approximations requiring much refinement. Some refinement has occurred in Fish Lake Valley (Reheis, 1988; Sawyer and Slemmons, 1988).

FURNACE CREEK FAULT ZONE

This study evaluates the Furnace Creek fault zone from the north end of the zone near Chiatovich Creek in Fish Lake Valley (pl. 1*A*) to the mouth of Furnace Creek Wash, north of Texas Spring, in Death Valley (pl. 2). Geologic and geomorphic features express youthful faulting along much of this part of the fault zone, which is about 170 km long. The north end of the fault zone curves toward the northeast, where youthful scarps apparently die out. Right-lateral strike slip along the Furnace Creek fault zone is accommodated by normal movement along the northeast-trending faults. Other northeast-trending fault zones west of the Silver Peak Range have youthful scarps (Reheis, 1988; M.C. Reheis, U.S. Geological Survey, written commun., 1988), suggesting that the slip on the Furnace Creek fault is transferred to other northeast-trending faults in Fish Lake Valley. Southeastward, faults assigned to the Furnace Creek fault zone extend up Furnace Creek Wash (pl. 3) into the Amargosa Desert, where they appear to terminate (Wright and Troxel, 1967). A field reconnaissance of the fault zone in Furnace Creek Wash revealed little evidence of youthful faulting, although faults cutting Quaternary deposits were mapped by McAllister (1970); faults in Furnace Creek Wash are not shown on plate 3. An aerial reconnaissance of the Keane Wonder fault, which coincides with the southwestern base of the Funeral Mountains, revealed no geomorphic expression of youthful faulting, and that fault was not studied further.

Chiatovich Creek Section

The concave-eastward Chiatovich Creek section (CK; this symbol and those in subsequent discussions refer to fault sections shown on fig. 2 and on pls. 1–4) is the northernmost recently active part of the Furnace Creek fault zone. This section is further subdivided into a northern part, 7.6 km in length having a mean trend of N. 34° E., and a southern part, 11.5 km long with a mean trend of N. 30° W. The northern part curves away from the White Mountains range front near the mouth of Indian Creek and is defined by a series of discontinuous scarps in the Quaternary alluvial-

Table 1. Geomorphic features associated with active faults, ranked approximately by frequency of occurrence

[From Slemmons, 1977, and oral commun., 1979]

Rank	Geomorphic feature
	Strike-slip faults
1	Scarp, eroded scarp.
2	Bench.
3	Linear canyon, gully, gulch, swale, trench, trough, stream, or valley.
4	Pond, depression, swampy depression, sag, playa, sag pond, swampy trench, rhomb depression.
5	Lateral stream- or drainage-channel offset.
6	Fault gap, notch, or saddle.
7	Trench, wedge- or rhomb-shaped depression, elongate depression.
8	Offset ridgeline or hill.
9	Riedel shears, en echelon fissures.
10	Deflected or diverted drainage channel, valley axis, or stream line.
11	Linear or elongate ridge (pressure ridge), bulge or buckle, termination bulge.
12	Trough.
13	Ponded alluvium.
14	Aligned notch.
15	Shutterridge.
16	Swale.
17	Aligned vegetation or linear boundary.
18	Spring, elongate spring, marsh, ground-water barrier.
19	Lineament (lithologic, topographic, vegetation, mineralized, soil-contrast, and so forth).
20	Fault valley or graben (rift).
21	Fault trace.
22	Fault path or pebbly path.
23	Open crack or fissure.
24	Faceted ridge or spur, triangular facets.
25	Alignment of springs or very elongate springs.
	Normal-slip faults
1	Scarps (simple, fissure, trench or graben, longitudinal or step, subsidence).
2	Faceted spurs and ridges.
3	Over-steepened base of mountain fronts.
4	Rejuvenated valley floors with terraces upstream from fault scarp.
5	Zig-zag faults on conjugate sets of orthogonal fractures.
6	Arcuate scarps or sets of concentric scarps.
7	Wineglass-shaped canyons (as viewed from valley opposite canyon).
	Reverse-slip faults
1	Scarps.
2	Over-steepened base of mountain fronts.
3	Faceted spurs or ridges.
4	Mole-track or bulldozed scarps or traces.
5	Grabens or fissure swarms above main fault trace.

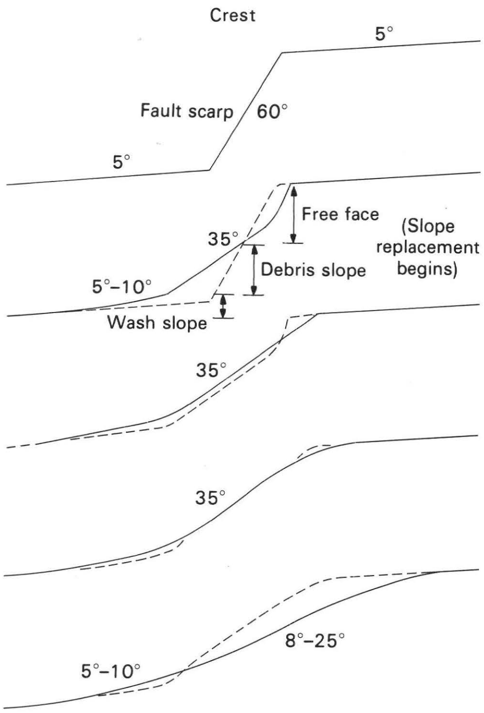

Figure 3. Profiles of successively older fault-scarp morphology. From Wallace (1977). Erosional slopes along fault scarps in alluvium are controlled successively by gravity-, debris-, and wash-related processes. Dashed line represents outline of previous profile.

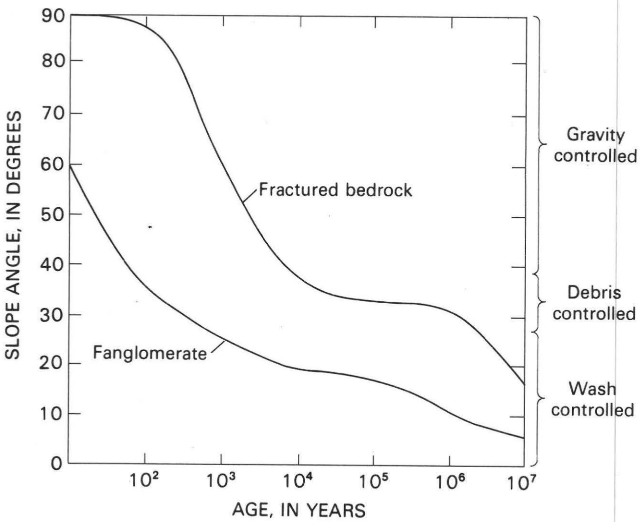

Figure 4. Slope angle versus age for fault scarps in bedrock and fanglomerate determined from north-central Nevada. Modified from Wallace (1978).

fan deposits of Fish Lake Valley. The southern part coincides with the eastern front of the White Mountains from Indian to Busher Creeks. A series of scarps and benches having a more northerly trend than the range-front fault splits away from the main fault trace north of Busher Creek. This splay of the Furnace Creek fault zone ends to the south in a prominent set of northward-trending scarps in alluvial-fan deposits east of the main fault trace between Marble and Indian Creeks. Earlier mapping that covers the Chiatovich Creek section was published by Albers and Stewart (1965), Krauskopf (1971), and Robinson and Crowder (1973).

Late Quaternary and Holocene fault-related features in the Chiatovich Creek section include both eastward- and westward-facing fault scarps, grabens, offset streams, and shutterridges. Offset shutterridges and drainages indicate a predominant component of right-lateral strike slip along north- or northwest-trending parts of this section of the fault zone.

Q_{1B} surfaces are faulted in two places and probably by three separate events between Indian and Marble Creeks (M.C. Reheis, U.S. Geological Survey, written commun., 1989). Just south of Indian Creek, a 24-m-high east-facing scarp in deposits underlying an inferred mid-Pleistocene (Q_2) surface contains a slight but distinct bench. Along trend with the bench to the north is a small scarp with 3.3 m of relief on an inferred older Holocene (Q_{1C}) surface near the mouth of Indian Creek. The beveled profile of the higher scarp and the superposition of two scarps are interpreted as evidence of recurrent faulting.

The sinuous scarp that cuts the alluvial-fan deposits at the mouth of Leidy Creek shows greater relief where it cuts an inferred Pleistocene (Q_2) surface than it does where it cuts younger surfaces. Scarps cutting the inferred Pleistocene surface range in height from several meters to as many as several tens of meters in the most dissected deposits. In a surface believed to be early Holocene (Q_{1C}), evidence of faulting varies from faint lineaments to scarps as much as several meters high. No fault-related features were recognized in alluvial deposits of either Q_{1A} or Q_{1B} age near Leidy Creek.

Dyer Section

The Dyer section (DS, pl. 1*A*), 10.4 km in length with a mean trend of N. 22° W., coincides with the White Mountains range front between Busher and Toler Creeks. Scarps in poorly consolidated alluvial deposits at the mouth of Perry Aiken Creek near the middle of the Dyer section have the greatest relief of any scarps along the Furnace Creek fault zone (fig. 5). The largest scarps face eastward, sloping uniformly at about 30° and having as much as 64 m of relief. The zone of surface rupture in the Dyer section ranges in width from that of a single scarp to nearly 1 km. Earlier mapping of the Dyer section was published by Bryson (1937), Strand (1967), Krauskopf (1971), and Albers and Stewart (1965).

The faulted fan deposits near Perry Aiken Creek (fig. 5) are of inferred Pleistocene age (Q_2). No fault-related features are recognized with certainty in units younger than

Table 2. General characteristics of geomorphic surfaces, Death Valley–Furnace Creek Fault system, California and Nevada

[m, meter; >, more than; —, not applicable]

Surface	Desert varnish	Death Valley surface	Fish Lake Valley surface	Approximate relief above Q_{1A} surface	Estimated age[1]
Q_{1A}	None	Active bars and channels	Active channel.............	—	0–200 years; historic.
Q_{1B}	None to light	Inactive bar and channel.	Abandoned channels and surfaces	0–3 m	200–2,000 years; late Holocene[2].
Q_{1C}	Medium to dark...........	Subdued bar and swales.	Subdued lobes and swales.	0–12 m	2,000–10,000 years; Holocene.
Q_2	Heavy	Smooth, with pavement; eroded by Lake Manly shorelines.	Rounded steps.............	0–60 m	>10,000 years; Pleistocene (predates Lake Manly).

[1]Ages estimated on the basis of the 2,000-year-old shoreline of Hunt (1960) and Hunt and Mabey (1966) and an inferred high stand of Lake Manly 10,000 years B.P. (Hooke, 1972).

[2] ^{14}C dates on "Q_{1B}-type surfaces" from Fish Lake Valley range from about 650 to 2,170 years B.P. (Sawyer and Slemmons, 1988).

Q_2 in this area. Profiles across the scarps near Perry Aiken Creek do not show evidence of beveled crests. Possible evidence of younger faulting, expressed by discontinuous, subdued scarps(?) and linear, tonal contrasts on inferred younger Holocene surfaces (Q_{1B}), occurs at two localities within the Dyer section (pl. 1*A*). A broad break in slope on an inferred Q_{1B} surface at the mouth of McAfee Creek may be a subtle fault scarp. Possible subdued scarps in undissected Q_{1B}(?)-age deposits also were recognized in several ravines about 0.6 km south of Busher Creek.

Oasis Section

The Oasis section (OS, pl. 1*A*), which has a fault length of 22.8 km and a mean trend of N. 42° W., contains three distinct zones of fault-related features. The western zone is a series of discontinuous scarps that follow the White Mountains range front. A central zone of scarps appears to be the modern trace of the Furnace Creek fault zone. The central and western zones merge and follow the range front near the north end of the Oasis section, but in the southern part of the Oasis section, the central zone is as much as 1.6 km east of the range front. The eastern zone consists of discontinuous vegetation lineaments in the southern part of the Oasis section and extends southward into the Horse Thief Canyon section. A prominent set of vegetation lineaments also occurs south of the Lookout Mine on the east side of Fish Lake Valley adjacent to the Oasis section. Previous maps covering the Oasis section were published by Strand (1967), Ross (1967), McKee and Nelson (1967), Reynolds (1969), Krauskopf (1971), and Stewart and others (1974).

Features indicative of recent faulting along the Oasis section include scarps with sinuous traces, en echelon scarps, conjugate scarps, vegetation lineaments, stream offsets, linear ridges, sags, ponded alluvium, and trenches. Between Toler and Wildhorse Creeks, the fault trace follows the curvilinear range front and is defined by a series of prominent en echelon fault scarps; no continuous surface rupture is recognized along this reach of the fault zone. The scarps appear only to cut the Pleistocene (Q_2-age) deposits. Younger alluvial deposits pond locally along the bases of westward-facing scarps.

South of Wildhorse Creek, the main (central) zone of scarps trends away from the range front. A prominent set of fault scarps cuts an inferred Pleistocene (Q_2) surface south of the mouth of Furnace Creek, defining sags and linear ridges. Nearly 20 m of relief was measured on an eastward-facing scarp in Q_2 deposits in this area, whereas a southwest-facing scarp in inferred older Holocene (Q_{1C}) deposits has only about 1 m of relief. Younger surfaces (Q_{1B} and Q_{1A}) do not appear to have been faulted.

Two prominent scarps that bound a sag along the main (central) fault trace just south of Furnace Creek offset three abandoned drainages. The southernmost drainage is offset about 62 m, the middle drainage is offset 69 m, and the northern drainage is offset successively across the two scarps in steps of 54 and 66 m for a total of 120 m of right-lateral displacement. Right-lateral strike slip

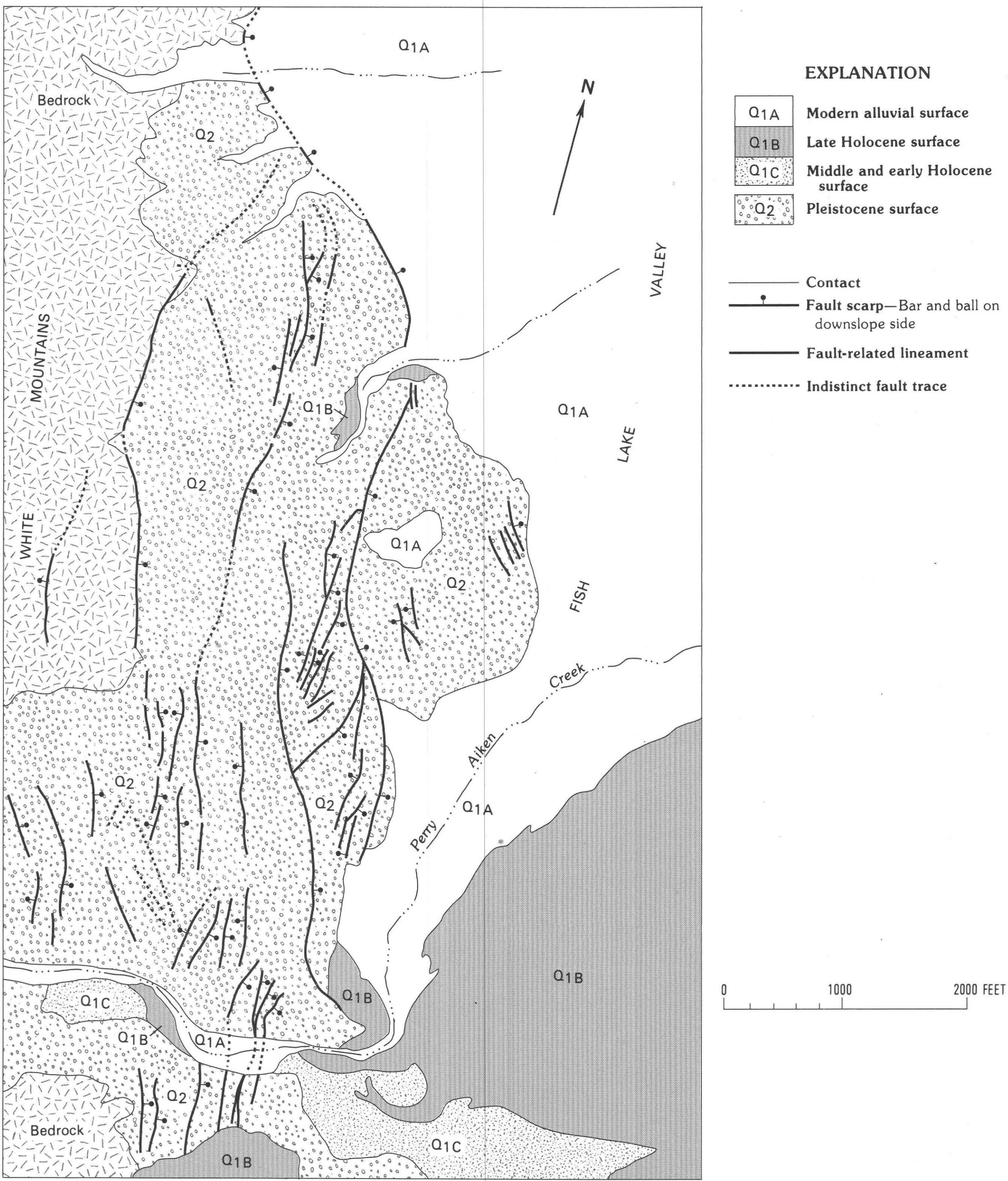

Figure 5. Surficial geologic sketch map showing complex scarp pattern and Quaternary units in part of the Dyer section of the Furnace Creek fault zone. Bedrock is pre-Pleistocene in age. Map drawn directly from aerial photograph. Location of sketch map is shown on plate 1*A*.

apparently exceeds northeast-side-down normal displacement in this area.

The vegetation lineament that ends on the north about 3.5 km northwest of Oasis marks the northern end of a 13.7-km-long zone of young features, possibly as young as Q_{1A} in age, that extends into the Horse Thief Canyon section to the south. This zone may represent the youngest faulting along the Furnace Creek fault zone. Several days after a severe summer storm in 1969 a 10.8-m-long fissure zone formed in modern playa deposits near the mouth of Furnace Creek. However, it was not possible to demonstrate if the fissure was tectonic in origin.

Geomorphic relationships several kilometers west of Oasis are shown on figure 6. The western scarps cut Q_2 surfaces, slope approximately 22°, and have about 1.5 m of vertical separation. The eastern scarps truncate Q_2 surfaces, are several tens of meters high, and are as steep as 21°. Both the eastern and western scarps within the area of figure 6 appear older than Q_{1B} surfaces.

Horse Thief Canyon Section

The Horse Thief Canyon section (HT, pls. 1*A*, 1*B*), with a fault length of 14.5 km and a mean trend of N. 40° W., extends from near the mouth of Cottonwood Creek to Willow Wash at the south end of Fish Lake Valley (pls. 1*A*, 1*B*). Previous mapping of the Horse Thief Canyon section was published by Ross (1967), Strand (1967), and McKee and Nelson (1967). Other studies of the Horse Thief Canyon section were published by McKee (1968) and Reynolds (1969).

Distinct vegetation lineaments continuous with the eastern zone of lineaments and small scarps in the southern part of the Oasis section are the principal indicators of youthful faulting along the northernmost 8 km of the Horse Thief Canyon section. These lineaments appear as vegetation lineaments in young alluvial deposits and may be of nearly historic (Q_{1A}) age. Some of the vegetation lineaments may be cultural in origin, but those of northwest trend that coincide with boundaries of vegetation contrast are judged to be tectonic.

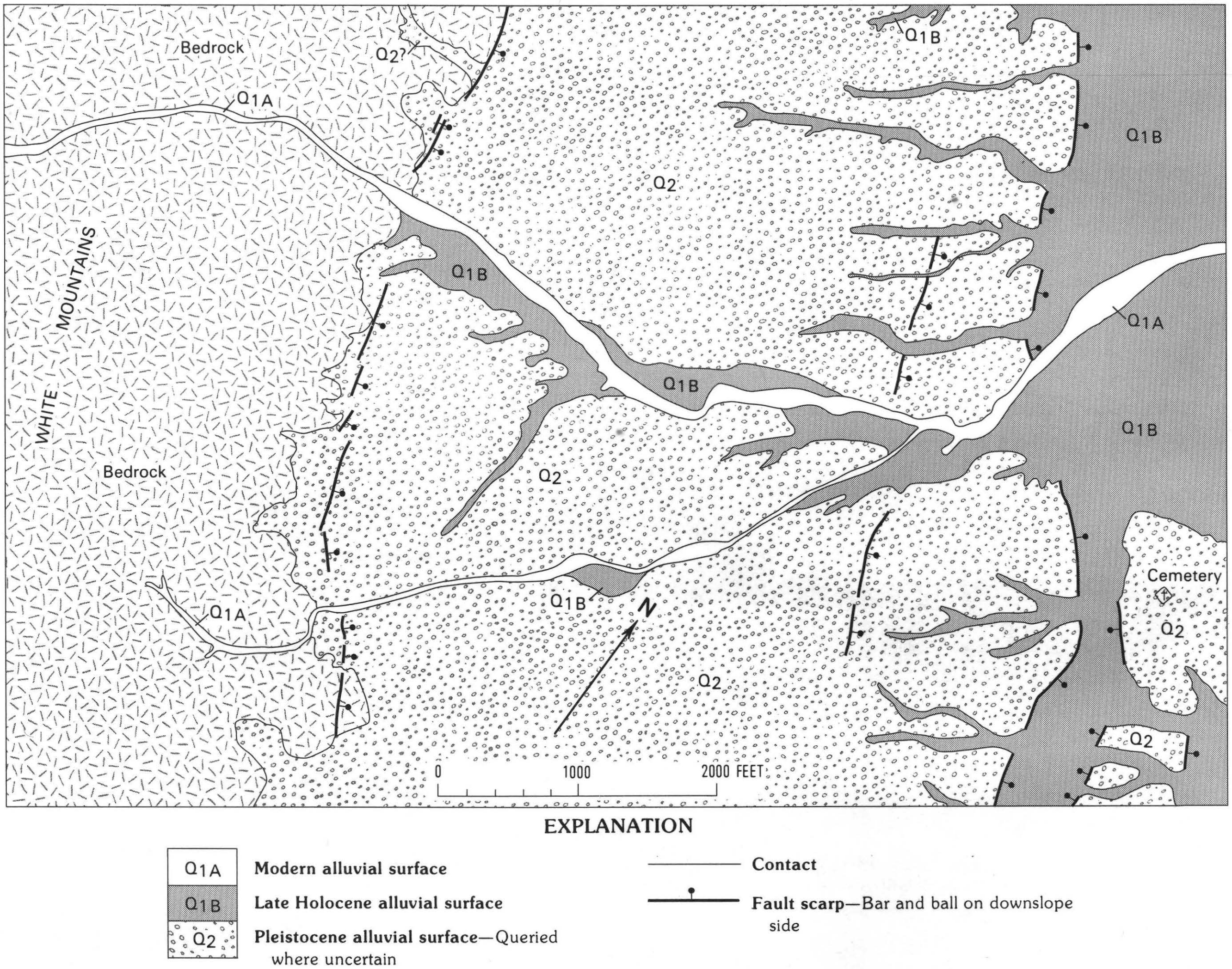

Figure 6. Surficial geologic sketch map showing scarp pattern and Quaternary units in part of the Oasis section of the Furnace Creek fault system. Bedrock is pre-Pleistocene in age. Map drawn directly from aerial photograph. Location of map is shown on plate 1*A*.

The most prominent fault-related feature in the southern part of the Horse Thief Canyon section is a discontinuous, southwest-facing linear scarp cutting an inferred Pleistocene (Q_2) surface. The scarp is eroded extensively, and younger deposits in the cross-cutting drainage channels do not appear to be faulted. A few small, isolated, northeast-facing scarps occur along the range front in the southern part of the Horse Thief Canyon section, and several other small scarps cut alluvial deposits in the adjacent valley. Three drainages with right-lateral offset near the south end of the section (not shown on pl. 1*B*) show no evidence of a dip-slip component.

Cucomungo Canyon Section

The Cucomungo Canyon section (CC, pl. 1*B*), 16.2 km in length with a mean trend of N. 55° W., is the only part of the Furnace Creek fault zone located almost entirely in bedrock within mountainous terrain. In Willow Wash, aligned valleys follow the same northwest trend as scarps in the Horse Thief Canyon section. The fault zone turns abruptly to a west-northwest trend in lower Cucomungo Canyon, then gently curves back to a northwest trend as it is traced southeast up the southwest side of Cucomungo Canyon and down the southwest side of Last Chance Canyon into Death Valley. Previous maps of the Cucomungo Canyon section were published by Strand (1967), Ross (1967), McKee and Nelson (1967), and McKee (1985). McKee (1968) estimated the long-term average rate of right-lateral movement for the Furnace Creek fault zone to be on the order of 0.25 mm (millimeter) per year on the basis of his correlation and interpretation of offset drainages and bedrock features across the Cucomungo Canyon section. This is an order of magnitude slower than the slip rate estimated by Bryant (1988) for late Quaternary faulting in the Redwall fan section, and about 13–25 percent of the lateral slip rate of 1.0 to 1.8 mm/yr, inferred in Fish Lake Valley by Sawyer (1988).

The Furnace Creek fault zone is exposed in bedrock near the head of Last Chance Canyon, where it strikes N. 60° W., and individual fault surfaces range in dip from 60° SW to vertical. As it is traced southward from Fish Lake Valley through the Cucomungo Canyon section into Death Valley, the Furnace Creek fault zone bends eastward and steps eastward. In concert with right-lateral strike slip along the fault system as a whole, this bend produces significant compression across the more westerly trending parts of the Cucomungo Canyon section; components of reverse dip slip have, in fact, been recognized along west-northwest-trending faults cutting bedrock within the Cucomungo Canyon section (M.C. Reheis, U.S. Geological Survey, written commun., 1989).

Geomorphic features indicative of youthful faulting are abundant in the Cucomungo Canyon section and include small scarps, shutterridges, trenches, notches, benches, diverted drainages, linear valleys, and various lineaments of unknown origin. Faults cut surfaces as young as Q_{1B} in age. One kilometer west of Willow Spring, three drainages developed on Q_{1B} surfaces show right-lateral offset of 4.6 to 6.4 m.

Sand Spring Section

The Sand Spring section (SS, pl. 1*B*), 24.7 km in length with a mean trend of N. 36° W., extends from the mouth of Last Chance Canyon to about 1 km north of the northern boundary of Death Valley National Monument, along the base of the Grapevine Mountains. Northwest of Little Sand Spring the fault zone is marked by a series of en echelon, elongate ridges; these ridges trend approximately 15° more west than the trend of the fault zone. The fault is further marked by aligned valleys and notches. South of Little Sand Spring, subdued, isolated scarps reflect recent faulting over a broad zone. Discontinuous scarps are mapped as far as 7 km northeast of the main fault near Oriental Wash. Previous maps of the Sand Spring section were published by Strand (1967), Reynolds (1969), McKee (1985), and Moring (1986).

Small scarps on the Oriental Wash fan cut inferred Pleistocene deposits but are extensively eroded and cut by channels. All of these scarps slope less than 15°. Most faulting in the Sand Spring section appears to be older than that along adjacent sections of the fault zone, although Holocene deposits are offset near the southern end of the Sand Spring section (M.C. Reheis, U.S. Geological Survey, written commun., 1989).

Grapevine Canyon Section

The Grapevine Canyon section (GC, pl. 1*C*), 25.8 km in length with a mean trend of N. 38° W., comprises two distinct zones of fault-related features extending from near the northern boundary of Death Valley National Monument to Bighorn Gorge in the Cottonwood Mountains. Prominent scarps mark the main trace of the fault along the range front of the Grapevine Mountains. Strands of the main fault zone are exposed in bedrock along parts of the Grapevine Mountains. A second zone of fault-related features, starting about 1 km southwest of the main fault trace in the northern part of the Grapevine Canyon section, extends from 2 km south of the northern section boundary at least to the road to Ubehebe Crater. In the southern 2 km of the Grapevine Canyon section, a cluster of scarps on the west side of Death Valley continues southward into the Redwall fan and Titus fan sections. Fault scarps are sparse in this southwestern strand of the fault zone; a gap in the surface expression of the fault extends from the area of Ubehebe Crater to

Bighorn Gorge, a fault length of about 15 km. Previous maps of the Grapevine Canyon section area were published by Strand (1967), Reynolds (1969), Streitz and Stinson (1977), and Moring (1986).

The Grapevine Canyon section has abundant, well-developed features indicative of youthful faulting, including linear ridges and valleys, diverted and displaced channels, ponded alluvium, trenches, benches, notches, shutterridges, sags, springs, vegetation lineaments, en echelon scarps and benches, and beheaded channels. Immediately south of the site of the old Grapevine Ranger Station, displaced drainages indicate right-lateral slip of 12 to 21 m, with no obvious dip-slip component; a large shutterridge is also here.

In the northern part of the Grapevine Canyon section, prominent scarps cut Pleistocene (Q_2) deposits, and smaller scarps cut deposits inferred to be as young as early Holocene (Q_{1C}). Youthful (Holocene?) scarps about 2 km south of Ubehebe Crater are mantled by unfaulted ash deposits. Scarps in Q_2 surfaces typically have separations of about 15 m, whereas the separation on corresponding scarps in inferred Q_{1C} units generally is less than 1.5 m. Surfaces younger than Q_{1C} do not appear to be faulted. Disruption of deposits assigned a Q_{1C} age was identified for about 23.8 km along this section of the Furnace Creek fault zone.

Redwall Fan Section

The Redwall fan section (RF, pl. 1*C*), 13 km long with a mean trend of N. 33° W., encompasses a single well-developed scarp, separated into four colinear parts by erosion and (or) buried by younger alluvial deposits. Previous maps covering the Redwall fan section were published by Reynolds (1969) and Streitz and Stinson (1977).

The northernmost part of the Redwall fan section consists of a 1.9-km-long, northeast-facing scarp cutting a Q_2 surface with relief as great as 23 m and a slope as steep as 33°. En echelon furrows (Reidel shears) trend north-northwest across the crest of the scarp. The next set of scarps to the south displaces distributary channels in an inferred Q_{1C} surface. The right-slip component ranges from 0.2 to 2.7 m, and relief on the scarps is 0.2 to 2 m. Scarps in a Q_2 surface are 2.4 to 5 m high, suggesting recurrent faulting. The next series of scarps toward the south is mostly in dissected alluvium of suspected Q_2 age; a distinct furrow and bench appear to represent the most recent surface rupture in this area. Farther south, the fault zone diverges from the range front of the Grapevine Mountains. The southern end of the Redwall fan section is marked by several northeast-facing scarps. These are separated from the next set of scarps to the north by more than 3 km. Q_{1C} surfaces are the youngest geomorphic units believed to be faulted in the Redwall fan section.

Within the Redwall fan section, an approximate late Quaternary right-lateral slip rate of 2.3 mm/yr (millimeters per year) for the Furnace Creek fault zone was calculated by Bryant (1988). The calculation assumed that an alluvial fan surface, older than Q_{1C} and whose edge is offset right laterally by 46 m, is about 20 ka.

Titus Fan Section

The Titus fan section (TF, pl. 1*C*), along the foot of the alluvial fan issuing from Titus Canyon, is 4.9 km long and has a mean trend of N. 31° W. This section is characterized by multiple northeast-facing scarplets. Previous maps of the Titus fan section were published by Reynolds (1969) and Streitz and Stinson (1977).

Surfaces assigned to unit Q_{1C} clearly are faulted along the Titus fan section, and Q_{1B} surfaces are disrupted. Scarps in inferred Q_{1B} surfaces are small, typically less than 0.5 m high, and locally appear as linear traces of surface disruption (mole tracks) rather than as distinct surface scarps. Immediately south of the Titus Canyon road, several faults, with as much as about 0.5 m down-to-the-east dip separation, are exposed in a barrow pit. Faults in this section are not known to disrupt modern (Q_{1A}-age) alluvial deposits. Scarps cutting Q_{1B} surfaces extend almost continuously for about 13 km southwest of the Titus Canyon section (to the middle of the Death Valley Buttes section).

Mesquite Flat Section

The Mesquite Flat section (MF, pl. 1*C*), 8.1 km long with a mean trend of N. 36° W., extends from the southern part of the Titus Canyon fan to Triangle Spring. Previous maps covering the Mesquite Flat section were published by Hunt and Mabey (1966), Reynolds (1969), and Streitz and Stinson (1977).

Like the Titus fan section to the north, the Mesquite Flat section is not along a mountain front but is on an alluvial plain several kilometers west of the front. The fault zone is expressed mainly as vegetation lineaments and eroded scarplets. Northeast-facing scarplets as high as 1.8 m cut inferred Q_{1B}-age alluvial deposits in the southern part of the Titus Canyon fan. The local drainage has modified virtually all of these scarps. In Mesquite Flat, the fault zone is defined by sharp vegetation contrasts, aligned dunes, and tonal lineaments in playa deposits, but it is not known whether the playa deposits are actually faulted. The dunes are colinear with many of the vegetation lineaments and may have been localized by the stabilizing action of plants growing along the fault trace.

Death Valley Buttes Section

The Death Valley Buttes section (DB, pls. 1*C*, 2), 9.1 km long with a mean trend of N. 46° W., extends from Triangle Spring to 2.0 km northwest of Mud Canyon. Previous maps covering the Death Valley Buttes section were published by Hunt and Mabey (1966), Reynolds (1969), and Streitz and Stinson (1977).

The northernmost 5.0 km of the Death Valley Buttes section has a nearly continuous, southwest-facing scarp cut along the base of a slope developed on Tertiary strata. The fault scarp generally is less than 1 m high. In addition, a series of north- to northwest-trending en echelon graben structures are northeast of the main fault, and cut geomorphic surfaces Q_2 and Q_{1B}. Tertiary strata are strongly folded along this part of the fault zone. Instead of continuous scarp in the southern part of the Death Valley Buttes section, the fault zone has a series of westward-facing scarplets that appear to form a north-trending set of en echelon tension gashes.

The youngest faulting appears to involve unit Q_{1B} along the northern 5 km of the Death Valley Buttes section. Farther south, unit Q_{1C} is the youngest unit thought to be faulted.

Beatty Junction Section

The Beatty Junction section (BJ, pl. 2), 19.5 km long with a mean trend of N. 50° W. stretches from the Stovepipe Wells area to the sharp southward bend in the trace of the active fault system north of Salt Springs. It is the southernmost section of known active faulting along the Furnace Creek fault; no evidence of late Pleistocene or Holocene faulting was discovered along the southeastward projection of the Furnace Creek fault in Furnace Creek Wash. Previous maps showing the Beatty Junction section were published by Noble and Wright (1954) and Hunt and Mabey (1966).

The northern part of the Beatty Junction section is marked by both northeast- and southwest-facing scarps. In this area, the youngest faulted deposits are assigned to unit Q_{1B}. Locally, there is progressively greater offset of older (Q_{1C}? and Q_2) units that suggest recurrent Quaternary displacements.

Farther south toward Beatty Junction, scarps are discontinuous, generally facing southwestward with less than 1.0 m of relief. More than 50 percent of the fault trace in this area is covered by undisturbed alluvial deposits. Only one low (less than 1 m), discontinuous scarp was recognized from Beatty Junction to the southeast end of the Beatty Junction section; vegetation lineaments are the principal indicator of young faulting in this part of the fault zone.

DEATH VALLEY FAULT ZONE

The Death Valley fault zone is structurally distinct from the Furnace Creek fault zone; the former strikes generally north and is characterized by a large, probably predominant component of normal slip. The fault zone was studied between the mouth of Furnace Creek, north of Texas Spring in central Death Valley, and Shoreline Butte at the south end of Death Valley (southernmost part of pl. 2 and pls. 3 and 4). Evidence of youthful faulting persists throughout nearly all of this zone. The main fault zone extends along the east side of Death Valley, but geomorphic evidence of youthful faulting also can be seen along the west side of the valley. Only the main fault zone is described in this report.

South of Shoreline Butte, the Death Valley fault zone changes from a sinuous, north-trending fault to a linear, northwest-trending fault. This southern extension of the Death Valley fault zone was referred to as the Confidence Hills fault zone by Hunt and Mabey (1966). The late Cenozoic history of the southern Death Valley fault zone recently has been described by Butler and others (1988).

Salt Springs Section

The Salt Springs section (SA, pl. 2), 4.4 km in length, extends from about 1 km north of Salt Springs to the mouth of Cow Creek. Excepting the sinuous northern 1.5 km of the section, the average trend is about N. 10° W. The section is marked by discontinuous, sinuous small scarps cutting alluvial fans of sediments shed from the Funeral Mountains. Previous maps covering the Salt Springs section were published by Hunt and Mabey (1966) and Streitz and Stinson (1977).

The Salt Springs section consists of a northern sinuous but generally northeast-trending breached scarp and a southern set of north to northwest-trending discontinuous scarps. The northern sinuous scarp cuts through Salt Springs and is west facing for a mapped length of 2.3 km; this fault may extend further south-southwest into the valley, but was mapped only for the length covered by low-sun-angle aerial photographs. Relief along this scarp is as great as 3.0 m between Salt Springs and State Highway 190 but diminishes in either direction from that point; maximum slope angle of the scarp is 31°. This fault displaces a lake shoreline (fig. 7) that existed briefly in Death Valley about 2,000 years ago (Hunt, 1960; Hunt and Mabey, 1966). The southern set of scarps is discontinuous, with trends ranging from N. 8° W. to N. 25° W., and relief of generally less than 0.5 m. These scarps are not aligned with one another and locally tend to produce trenches.

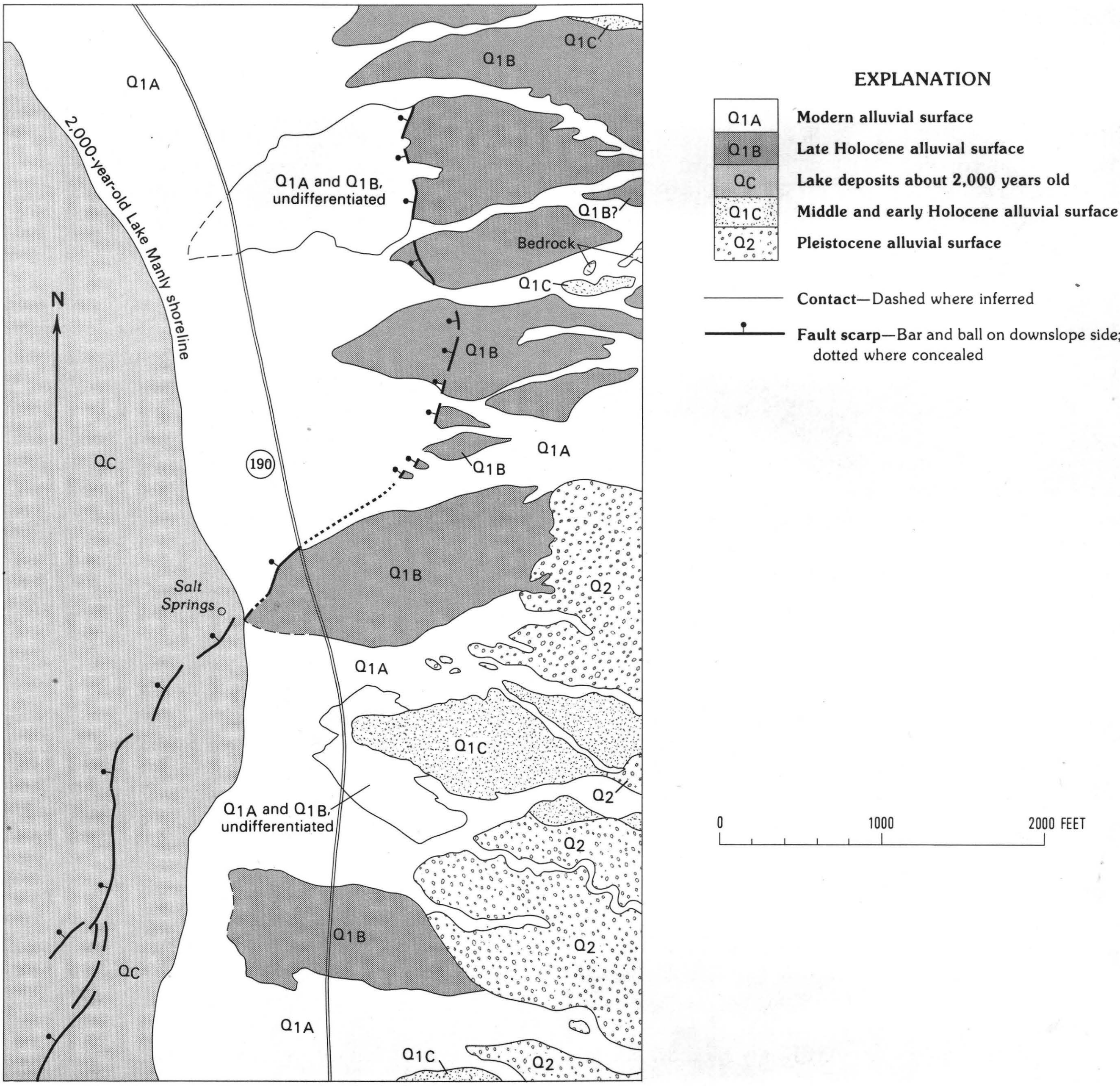

Figure 7. Surficial geologic sketch map showing scarp pattern and Quaternary units in part of the Salt Springs section of the Death Valley fault zone. Map drawn directly from aerial photograph. The 2,000-year-old Lake Manly shoreline of Hunt (1960) has been downdropped about 0.5 m or less on the northwest side of the fault zone. Bedrock is pre-Pleistocene in age. Location of sketch map is shown on plate 2.

Mustard Canyon Section

The Mustard Canyon section (MC, pl. 3) is 3.1 km long and is between the mouth of Cow Creek and BM –221 on State Highway 190. Earlier mapping of the Mustard Canyon section was published by Noble and Wright (1954), Hunt and Mabey (1966), and McAllister (1970).

The Mustard Canyon section is distinctive for three reasons: (1) it is not along a range front, (2) no geomorphic evidence of recent fault activity was observed on low-sun-angle aerial photographs, and (3) the most prominent topographic trends are approximately N. 55° W. rather than north. The prominent northwestern topographic trends of this section, such as the southwest-facing slope along the southern flank of the hills surrounding Mustard Canyon, are probably fault controlled, as they are about parallel to northwest-trending faults cutting nearby bedrock mapped by Hunt and Mabey (1966). The main trend of the Death

Valley fault zone is not offset across the Mustard Canyon section, so the relationship of the northwest-trending faults to the Death Valley fault zone is obscure.

Golden Canyon Section

The Golden Canyon section (GO, pl. 3) is 8.7 km long and has a mean trend of N. 22° W. Most of the section is expressed as a west-facing scarp along the western side of the northern Black Mountains. In addition, a 2-km-wide zone of east- and west-facing scarps cuts the alluvial fans of Tucki and Blackwater washes on the west side of Death Valley. Earlier mapping of the Golden Canyon section was published by Noble and Wright (1954), Hunt and Mabey (1966), and McAllister (1970).

The main trace of the Golden Canyon section, along the east side of Death Valley, consists of three parts. The northern 2.1-km-long part trends N. 32° W., and is characterized by several north-trending trenches developed within 0.8 km west of the frontal fault, which is discontinuously exposed. These trenches are mainly in an older surface developed on the Pliocene and Pleistocene(?) Funeral Formation; they are of variable but significant relief, with side slopes inclined generally less than 20°. The southern two parts of the section contain Holocene or late Pleistocene scarps associated with the frontal fault, exposed more or less continuously as a single west-facing fault scarp, which continues into the Artists Drive section to the south at the base of the Black Mountain range front.

The central 3.8-km-long reach of this section, extending southward from just north of Furnace Creek Ranch, trends about N. 11° W. and consists mostly of a west-facing scarp ranging from 0.2 m to 2.3 m high with free-face slopes as steep as 57°, although undercutting by modern alluvial erosion may have oversteepened some slopes. Slopes of scarps in this part of the fault range from 23° to 30°, and from 46° to 57°. These two ranges in slope may represent two faulting events, separated by enough time for the slopes to decline on the older set before the younger set formed.

Careful geodetic leveling across two scarps in this central part of the section, 1.5 km south of Furnace Creek Wash, showed significant vertical creep across the scarps (Sylvester and Bies, 1986); between 1970 and 1985, scarp height on the eastern scarp increased by 7 mm and that on the western scarp by 2 mm.

The southern part of the Golden Canyon section trends linearly N. 30° W. in unconsolidated deposits for 3.2 km. Relief on west-facing scarps is as great as 2.1 m. A few scarps west of the main fault trace define small grabens.

The youngest faulting in the Golden Canyon section, possibly the youngest clearly fault related feature of the Death Valley–Furnace Creek fault system, displaces alluvium that is interpreted to be of late Holocene (Q_{1B}) age. The youngest faulted alluvium is not varnished, contains scarps with free faces, and grades into recent unfaulted alluvium. According to Wallace (1977, 1978), scarps with free faces persist only a few hundred to a few thousand years in central Nevada.

Artists Drive Section

The Artists Drive section (AD, pl. 3) is 13.1 km long with a mean trend of N. 26° W. This section extends from 0.7 km east of the mouth of Desolation Canyon on the north to 0.7 km northwest of Natural Bridge on the south. Earlier mapping of the Artists Drive section was published by Noble and Wright (1954), Hunt and Mabey (1966), and Streitz and Stinson (1977).

This section defines the eastern margin of the Artists Drive fault block of Hunt and Mabey (1966), who mapped the Artists Drive section as continuous with the Golden Canyon section to the north and the Badwater turtleback section to the south. The Artists Drive section is the only section of the Death Valley fault zone that has mainly exposed bedrock west of the most recently active fault trace. Consequently, geomorphic features produced by recent fault activity are not well preserved; scarps within this section offset upper Tertiary volcanic rocks of the Artists Drive Formation of Hunt and Mabey (1966), which are mantled by Tertiary and Quaternary gravels and typically do not have a free face exposed. The north end of the section consists of east-facing scarps in alluvium and bedrock, and at the mouth of Desolation Canyon a short, west-facing scarp has relief of 0.8 m.

The central part of this section consists of a west-facing scarp in unconsolidated gravels with relief of 0.8 m to 3.4 m. A complex trench or graben as wide as 800 m is west of the main scarp, indicating extension normal to the main fault trace. In the southern part of the section, the fault cuts exposed bedrock, and traces indicating recent fault activity are not preserved, even in colluvial gravel deposits along the western margin of the fault. Along the west side of Death Valley, about 12 km west of the faults cutting the west side of the Black Mountains, a series of scarps trending about N. 13° E. defines a complex trench.

The most recent faulting event in the Artists Drive section appears to displace alluvium believed to be of Q_{1B} age with a scarp 0.8–1.2 m high; older alluvium inferred to be of Q_{1C} age has a scarp as high as 5 m. Scarps on an older, Q_2, surface are large (as much as 4.8 m of relief) and rounded. These three distinct sets of scarps appear to depict at least three faulting events along the Artists Drive section.

Badwater Turtleback Section

The Badwater turtleback section (BT, pl. 3) is 6.5 km long, has a mean trend of N. 6° W., and extends from 0.7 km northwest of Natural Bridge on the north to 0.4 km east-northeast of Badwater. Earlier mapping of the Badwater turtleback section has been published by Curry (1954), Drewes (1963), and Hunt and Mabey (1966).

Scarps in unconsolidated deposits face mainly westward; many branch scarps or secondary scarps occur in the downthrown block west of the main scarp at the base of the mountain front. The trends of scarps are generally north, but one prominent trench 1 km north of Badwater trends N. 52° W. The predominant type of displacement appears to be down-to-the-west normal faulting. The slopes of scarps within this section are as steep as about 35°, although below an elevation of -260 ft they appear to be modified and oversteepened, probably by lakeshore erosion when ancient Lake Manly reached this elevation about 2,000 years ago (Hunt, 1960). Scarps mapped with slopes of 34°–36° above -260 ft but below sea level are topographically below lake deposits that may correlate with a 10,000 to 11,000-year-old stand of Lake Manly identified by Hooke (1972). These relationships suggest that most scarps within the Badwater turtleback section are between 10,000–11,000 years and 2,000 years old (Q_{1C} age).

Some faults cut deposits inferred to be as young as Q_{1B}. A discontinuous east-facing scarp about 30 m west of the 2.0-m-high east-facing scarp, about 1 km south of the section's northern boundary, cuts surfaces of two ages: (1) a surface on a narrow bar of well-varnished gravel (inferred unit Q_{1C}), south of the road to Natural Bridge, containing two scarps, each with about 0.5 m of relief, and (2) a raised surface to the north covered by unvarnished gravel (inferred unit Q_{1B}) containing a scarp with 0.15 m of relief.

Two faulting events were also identified west of the main fault trace about 1 km north of the section's southern boundary. Here, an older faulted surface shows little varnish and probably represents unit Q_2 that was covered by Lake Manly. The maximum slope of a scarp cutting this surface is 12° with relief of 0.7 m. A younger surface at this locality (probably unit Q_{1B}) on premodern alluvium with no varnish is partly obscured by modern Q_{1A}-age alluvium. A scarp cutting the inferred Q_{1B} surface has relief of about 0.2 m.

Black Mountains Section

The Black Mountains section (BM, pl. 3) is 11.2 km long, has a mean trend of N. 4° W., and extends southward from near Badwater to the mouth of Copper Canyon. Earlier mapping of the Black Mountains section was published by Curry (1954), Drewes (1963), Noble and Wright (1954), and Hunt and Mabey (1966).

Faults cutting inferred Q_{1B} surfaces are the youngest along this section, similar to the youngest faults observed in the three sections to the north. A spectacular example of youthful faulting is near the mouth of a wineglass canyon in the center of the Black Mountains section, where inferred Q_{1B}-age alluvium contains east-facing scarps with about 0.2 m of relief. The same ruptures cut an older alluvial unit thought to be of Q_{1C} age, where the relief on the scarps is 0.5 to 1.5 m. These relationships suggest at least two events, one older and one younger than 2,000 years.

A main west-facing frontal scarp is mapped discontinuously at the base of the Black Mountains, and a few east- and west-facing scarps occur in the alluvium west of the frontal scarp. Fissures of unknown origin are along the margins of all of the fans of this section, as well as along the southern margin of the Copper Canyon fan just south of this section. The most recent scarps along the Black Mountains section are commonly west of the frontal scarp, and they may be as steep as 34° to 61° with as much as several meters of vertical offset. Many of the scarps cutting surfaces inferred to be older than Q_{1B} (2,000 years) have free-face slopes steeper than 34°, and slopes of 50° or more are common.

Several grabens are oriented adjacent and roughly parallel to the west side of the main frontal scarp. Additional geomorphic trenches are west of the main scarp near the base of several alluvial fans and define arcuate patterns concentric to the fans. These unusual patterns suggest that fan morphology governs trench geometry and that the trenches are probably caused by compaction of fine-grained deposits at the toe of the fans due to alluvial loading.

Copper Canyon Turtleback Section

The Copper Canyon turtleback section (CO, pl. 4) is 5.8 km long and has a mean trend of N. 28° W. The northern 3.3 km has a mean trend of N. 38° W., and the southern 2.5 km has a mean trend of N. 17° W. The section is between the mouths of Copper Canyon on the north and Sheep Canyon on the south. Earlier mapping of the Copper Canyon turtleback section was published by Curry (1954), Noble and Wright (1954), Wright and Troxel (1954), Drewes (1959), and Hunt and Mabey (1966).

Scarps in unconsolidated deposits in the Copper Canyon turtleback section are predominantly west facing; a few branch faults with east-facing scarps define trenches with the predominant west-facing scarps. The southwest side of the turtleback, a domed and erosionally exposed fault surface separating Tertiary rocks above the surface from Precambrian rocks below (Hunt and Mabey, 1966), trends approximately N. 38° W., and is marked by a discontinuously exposed frontal fault scarp separating Precambrian rock to the northeast from alluvium to the southwest. Many of the scarps have relief in excess of 4 m, and virtually all of the scarps have free-face slopes in excess of 40°. The steepness of the slopes may be related to the bouldery talus present along the base of the range.

Four trenches are identified along this section; three trend north and are on the downthrown block immediately west of the main west-facing scarp. The fourth trench is 490 m wide and trends N. 49° E.

At least three faulting events, the oldest thought to be older than 10,000 years, are preserved at several localities along this section. At a locality 1.6 km north of the mouth of Sheep Creek, a large west-facing scarp with a free face offsets a probable Q_2 surface. A smaller scarp, also with a free face, generally follows the trace of the older, larger scarp and displaces a bouldery deposit that shows a well-developed varnish (Q_{1C} age?); the scarp also displaces a Q_{1B} surface by a lesser amount. West of the smaller scarp at this locality is another young scarp that displaces a coarse debris flow interpreted to be Q_{1B} in age. Near the head of the Copper Canyon fan, Q_{1C}-age alluvium is cut by a prominent west-facing scarp, although about 80 m southwest of this scarp, another scarp cuts alluvium of probable Q_{1B} age.

Willow Creek Section

The Willow Creek section (WC, pl. 4) is 5.5 km long with a mean trend of N. 53° E. The section extends from Sheep Canyon southwestward to Mormon Point. Earlier mapping of the Willow Creek section was published by Curry (1954), Drewes (1959), Hill and Troxel (1966), and Hunt and Mabey (1966).

This section is characterized by Quaternary faults that trend northeast, about 60° to the general trend of the Death Valley fault zone. The youngest scarps within the section displace Q_{1B}-age alluvial deposits. All scarps are higher in elevation than the 2,000-year-old Lake Manly shoreline of Hunt and Mabey (1966), so the relative age of faulting to that shoreline is unknown. Most scarps face northwest, although a few face southeast, so that faulting along this section is predominantly down to the northwest, with no evidence observed of a lateral component of slip. Relief on scarps is as much as 9.4 m, with maximum slopes ranging from 21° to overhanging, suggesting local reverse faulting. All scarps are dissected by stream channels filled with unfaulted alluvium. Beveled scarps at two localities within the section are weak evidence for more than one faulting event; at one locality the upper and lower beveled surfaces slope 22° and 70°, whereas at the other locality they slope 40° and 70°. The great heights (as much as 9.4 m) of some scarps of the section also suggest that more than one faulting event occurred along the section; extreme northwest-southeast extension in the Death Valley region (Burchfiel and Stewart, 1966) would logically produce large normal faults along this northeast-oriented section.

Gregory Peak Section

The Gregory Peak section (GP, pl. 4) is along the western base of Smith Mountain from Mormon Point to a location 8.9 km to the south. The mean trend of the section is about N. 28° W. Earlier mapping within the section was published by Hunt and Mabey (1966) and Noble and Wright (1954).

Scarps within the section generally face westward, with secondary and branch scarps facing both eastward and westward. Relief on scarps interpreted as the main range-front fault is as high as 8.8 m. Measured maximum slopes on all scarps vary from 25° to 52°; this wide range in slope angles suggests more than one period of faulting.

No distinct evidence for lateral slip was found along the Gregory Peak section, although at the southern end of the section incised streambeds are faulted with scarp geometry that could be ascribed to normal slip combined with right slip. Also, en echelon northeast fault trends in the southern part of the section may be Reidel fractures associated with a component of right slip.

Four prominent trenches and two prominent branch scarps occur in the downthrown block of the Gregory Peak section west of the main, west-facing range-front fault. The trenches trend north-south to N. 30° W., and the two prominent branch scarps trend north-south to N. 20° E.

Scarps cut alluvium younger than 2,000-year-old lake deposits; the youngest surface faulted appears to be unit Q_{1B}. A well-developed west-facing scarp near the southern border of the section cuts an inferred Q_{1C} surface. A northward extension of the scarp, 0.7 km north of the southern end of the section, has distinctly lower relief where it cuts a Q_{1B}(?) surface and is in part buried by modern (Q_{1A}-age) alluvium.

North Ashford Mill Section

The north Ashford Mill section (NM, pl. 4) is 5.8 km long and has a mean trend of N. 13° W. The northern end of the section is at the northern limit of outcrop of a wedge of Pliocene and Pleistocene(?) Funeral Formation where it is in fault contact with Precambrian rocks on the west side of the Mormon Point turtleback (Nobel and Wright, 1954). At the south end of the section, a 2.2-km-wide zone of outcrop of Funeral Formation separates the Death Valley fault zone and the exposed turtleback surface. Earlier mapping of this section was published by Noble and Wright (1954) and Noble (1941).

This section follows a dissected west-facing fault scarp along the mountain front that has as much as 200 m of relief; the fault displaces interbedded volcanics and fanglomerate of the Funeral Formation (Noble, 1941). Younger east- and west-facing scarps in alluvium along the base of the scarp generally face westward and have as much as 6.6 m of relief; most scarp faces slope between 35° and 40°.

The most recent faults in this section cut Q_{1B} surfaces and are similar in age to the most recent faulting in the Gregory Peak section. No lateral component of movement was noted in the section.

South Ashford Mill Section

The south Ashford Mill section (SM, pl. 4), 2.7 km long, marks the southern extent that was studied along the Death Valley fault zone. The south Ashford Mill section is characterized by a sinuous fault pattern that trends between N. 10° W. and N. 40° W., and extends southward to the southern limit of mapping, about 1 km northwest of Ashford Mill. The fault zone probably extends southward beneath the modern alluvium of the Amargosa River. Earlier mapping of the south Ashford Mill section was published by Noble (1941).

The section crosses the base of an alluvial fan at the mouth of Ashford Canyon and mostly consists of isolated, subdued, rounded scarps in alluvium. In the northern 0.8 km of the section, older scarps with about 80 m of relief displace interlayered basalt, breccia, and fanglomerate of Pliocene(?) age (Noble, 1941). A scarp in Quaternary deposits with 0.3 m of relief is 18 m west of the larger, older scarps. Another discontinuously expressed fault trace trends about N. 10° W. for 2.7 km near the Amargosa River. Scarps along this trace face westward, have relief varying from less than 0.3 m to as much as 0.6 m, and are breached by streams containing unfaulted alluvium. Scarps of this trace also are oriented in a series of en echelon, left-stepping sections, suggesting a component of right slip.

CHRONOLOGY OF LATE QUATERNARY FAULTING

The Death Valley–Furnace Creek fault system shows evidence of multiple late Quaternary faulting events. The oldest faulting considered in this study is interpreted to be late Pleistocene in age. Holocene faulting events also are well documented, although possible historic faulting has been tentatively identified at only one locality.

Faulting thought to be late Pleistocene (Q_2 age) occurs along the entire Death Valley–Furnace Creek fault system, and evidence for faulting believed to be Holocene was recognized in all sections of the fault system except the Salt Spring and Mustard Canyon sections of the Death Valley fault zone. Furthermore, along the Furnace Creek fault zone, right-lateral separation of geomorphological features thought to be late Pleistocene or younger is, in most places, greater than dip separation and was identified in all but the Sand Spring and Mesquite Flat sections. In contrast, along the Death Valley fault zone, small right-lateral separations were identified only on the Badwater turtleback and Copper Canyon sections.

Faulting Inferred to be late Pleistocene to middle Holocene (Q_2 and Q_{1C} age; older than 2,000 years)

Large, apparently continuous scarps, believed to be mostly Pleistocene in age, persist along the eastern base of the White Mountains from Indian Creek southward to Oasis (pl. 1*A*). North of Indian Creek, the most recently active fault traces diverge eastward from the range front into the basin of Fish Lake Valley. The range front north of Indian Creek is linear and may have been the locus of surface faulting during Pleistocene time, although large scarps in Holocene material have not been mapped in this area.

The largest scarps in inferred Pleistocene materials along the Furnace Creek fault zone are within the Dyer section (pl. 1*A*). These large scarps probably developed during several faulting events during late Pleistocene time, although direct evidence of multiple faulting has not been identified.

From Oasis southward to Sand Spring, the fault trace is well defined in the valley between the Last Chance Range and the Sylvania Mountains (pl. 1*B*); mountain fronts bordering the fault are interpreted to represent fault scarps that are probably as old as Tertiary.

In northern Death Valley, surface faulting along the main trend of the Furnace Creek fault zone is poorly defined in the Sand Spring section, although faults to the east of the trend of the main fault zone appear to displace late Pleistocene (Q_2) surfaces. Holocene faulting may not have occurred within the northern Sand Spring section.

The Furnace Creek fault zone adjacent to and west of the Grapevine and Funeral Mountains (pls. 1*C*, 2) appears to have been faulted extensively during late Pleistocene time; fault-related features of inferred Holocene age are also common.

The Death Valley fault zone also appears to have been active during late Pleistocene time. High fault scarps modified by Lake Manly shorelines, which reached their high point about 10,000 years ago, attest to late Pleistocene fault activity in Death Valley. Faulting of inferred Holocene age appears to have continued along most of the Pleistocene fault scarps, except possibly in the Mustard Canyon section and along the western range front of the Black Mountains in the Artists Drive section (pl. 3) where scarps may be entirely of Pleistocene age.

At the south end of Death Valley (pl. 4), inferred Pleistocene faulting occurred as far south as the south Ashford Mill section of the study area and continued south along the Confidence Hills south of Shoreline Butte, beyond the area studied for this investigation.

Late Holocene Faulting (Q_{1B} and Q_{1A} age; younger than 2,000 years)

Several discrete faulting events inferred to be of late Holocene age are identified along the Death Valley–Furnace Creek fault system, although evidence for historic faulting remains equivocal. Evidence for four to six separate late Holocene faulting events along the Furnace Creek fault zone and three or more late Holocene events along the Death Valley fault zone are indicated by rupturing of Q_{1B} surfaces. Most of these events cannot be correlated from one section to another, but events in the Horse Thief Canyon section of the Furnace Creek fault zone and the Golden Canyon section of the Death Valley fault zone appear to be younger than those in other sections.

Along the Furnace Creek fault zone, late Holocene faulting is believed to have occurred in all but the Chiatovich Creek, Sand Spring, Grapevine Canyon, and Redwall fan sections, and possibly the Oasis section. Geomorphically fresh features in the Horse Thief Canyon section are thought to be the youngest unequivocally fault induced features in the Furnace Creek fault zone. Small fissures found in 1969 in a manmade playa in the Oasis section may be related to faulting, although they did not form in association with a known seismic event.

Late Holocene faulting has certainly occurred along the Death Valley fault zone. In the Salt Springs area (pl. 3), a scarp displaces a lake shoreline that is approximately 2,000 years old. The full length of the faulting is unknown; only 2.3 km of the young scarp has been mapped, although it may extend for a length of 10 km into the salt pan west of Furnace Creek Ranch. The sinuous nature at the north end of the scarp suggests predominantly dip-slip movement.

In the Golden Canyon section (pl. 3) of the Death Valley fault zone, low scarps have free faces, probably representing at least two faulting events, in unvarnished alluvial materials interpreted as unit Q_{1B}. These scarps are probably the youngest clearly fault related features of the Death Valley–Furnace Creek fault system and may be nearly historic. The system of young scarps has been mapped northward as far as Furnace Creek Ranch.

South of the Golden Canyon section along the western front of the Black Mountains, faulting of Q_{1B}-age alluvium extends about 60 km to the south border of the study area. Scarps in inferred Q_{1B} surfaces range in relief from less than 0.3 m to 1.5 m.

CONCLUSIONS

Although no major seismic activity has been recorded during historic time along the Death Valley-Furnace Creek fault system, many youthful geomorphic features related to active faulting are present along this zone. Recent leveling experiments (Sylvester and Bies, 1986) suggest that aseismic creep may be as important as earthquakes in scarp development.

Late Pleistocene and Holocene faulting along the Furnace Creek fault zone is predominantly strike slip with a local, subordinate dip-slip component (table 3), which is possibly due to local changes in strike of the fault zone. The geomorphically sharpest fault-related features are in the Horse Thief Canyon area, although small fissures in a manmade playa near Oasis may represent historic displacement. Many sections of the Furnace Creek fault zone show evidence of multiple periods of faulting, although the number of inferred Holocene events appears to increase (to as many as four) southward along the zone.

Fault displacement along the Death Valley fault zone is predominantly dip slip (table 4), with only a minor component of right slip observed locally. The contrasting styles of faulting between the Furnace Creek and Death Valley fault zones (predominantly strike slip along the former and dip slip along the latter) well supports the rift model for the formation of Death Valley first suggested by Burchfiel and Stewart (1966). In this model, right-lateral motion along the Furnace Creek fault zone and along a northwest-trending southern extension of the Death Valley fault zone created an intervening zone of tension in which the north-trending graben of Death Valley formed.

The youngest discrete faulting event along the Death Valley fault zone, possibly near historic in age, occurred in the Golden Canyon area, although evidence for multiple Holocene faulting events is better exposed along the southern part of the Death Valley fault zone.

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Table 3. Summary of Quaternary faulting along the Furnace Creek fault zone, California and Nevada

[Inferred geomorphic surfaces are described in table 2. n.o., none observed; —, value is unknown; >, more than; <, less than]

Fault-section abbreviation (fig. 2)	Oldest unfaulted surface	Surface faulted	Scarp		Maximum right-lateral separation (m)	Length of continuous surface breakage in section (km)	Remarks
			Maximum slope angle	Maximum vertical separation (m)			
CK	Q_{1A}	Q_{1B}	—	—	—	—	Q_{1B} faulted at two localities and by three separate events (M.C. Reheis, written commun., 1989).
	Q_{1A}	Q_{1C}	20°	1.8	15	19.1	Scarps define broad zone of faulting curving in trend from N. 30° W. on south to N. 34° E.
	Q_{1A}	Q_2	32°	21.5	132	19.1	Slopes of about 17° and 8° above face of scarp suggest multiple faulting events.
DS	Q_{1A}	Q_{1B}	—	—	n.o.	—	Minor fault scarps at the mouth of McAfee Creek and near the mouth of Busher Creek; may represent different faulting events.
	Q_{1A}	Q_2	30°	64	n.o.	10.4	Section contains scarps with largest vertical separation along Furnace Creek fault zone.
OS (eastern zone)	$Q_{1A?}$	$Q_{1A?}$	8°	1.4	n.o.	>6	Continuous with youngest faults in the Horse Thief Canyon section.
OS (central zone)	$Q_{1B?}$	Q_{1C}	—	0.9	n.o.	8.7	Main fault trace. Scarps in Q_2 extend northward into the Chiatovich Creek section. Historic fissures may be fault related.
	$Q_{1B?}$	Q_2	33°	30	120	11.8	
OS (western zone)	Q_{1A}	$Q_{1B?}$	22°	1.5	n.o.	5.5	Q_{1B} is not present at fault scarps, but prominence of scarps suggests faulting occurred after Q_{1B} was deposited.
	Q_{1A}	Q2	27°	21	n.o.	7.0	
HT	None?	Q_{1A}	—	n.o.	n.o.	7.7	Vegetation lineaments continue an additional 6 km north into Oasis section.
	None?	Q_2	—	—	n.o.	>6.0?	West-facing breached small scarps; appears to continue into the Cucomungo Canyon section.
CC	Q_{1A}	Q_{1B}	—	1.5	6.4	<10	Fault surface exposed in bedrock dips 60–90° SW.
	Q_{1A}	Q_2	15°	4.8	46	>10?	
SS	$Q_{1B?}$	Q_{1C}?	—	—	—	—	Faulting appears to be distributed over a broad zone; many small scarps are east of main trace, cutting Q_2 surface on Oriental Wash fan. Holocene (Q_{1C}?) surface offset at south end of section (M.C. Reheis, written commun., 1989).
	$Q_{1B?}$	Q_2	<15°	3.0	n.o.	24.7	
GC	Q_{1B}	Q_{1C}	10°	1.5	8.5	23.8	Dip slip is about 10 percent of right slip.
	Q_{1B}	Q_2	—	20	21	>23.8	
RF	Q_{1B}	Q_{1C}	—	2.0	2.7	>13.0	Dip slip is about one-third of right slip.
	Q_{1B}	Q_2	33°	23	n.o.	>13.0	
TF	Q_{1A}	Q_{1B}	—	.5	n.o.	4.9?	Mole tracks.
	Q_{1A}	Q_{1C}	32°	.9	1.2	>4.9	Multiple parallel scarps.
MF	Q_{1A}	Q_{1B}	—	1.8	n.o.	8.1	Mainly vegetation lineaments.
DB	Q_{1A}	Q_{1B}	27°	1.5	<.6	>5.0	Continuous north into MF section.
	Q_{1A}	Q_{1C}	—	—	n.o.	4.1	Continuous to south in BJ section. Unit Q_2 has larger scarps than unit Q_{1C}.
BJ	Q_{1A}	Q_{1B}	—	.3	1.8	>7.8	May extend into DB section.
	Q_{1A}	Q_{1C}	24°	.3	1.5	>11.7	At least three events; may extend into SA section to south.
	Q_{1A}	Q_2	—	2.4	7.3	>19.5	Two events noted.

Table 4. Summary of Quaternary faulting along the Death Valley fault zone, California

[Inferred geomorphic surfaces are described in table 2. n.o., none observed; —, value is unknown; >, more than; <, less than; , about]

Fault-section abbreviation (fig. 2)	Oldest unfaulted surface	Surface faulted	Scarp: Maximum slope angle	Scarp: Maximum vertical separation (m)	Maximum right-lateral separation (m)	Length of continuous surface breakage in section (km)	Remarks
SA	Q_{1A}	Q_{1B}	31°	3.0	n.o.	2.3	Displaces 2,000-year-old shoreline.
MC	Q_{1C}	n.o.	n.o.	n.o.	n.o.	n.o.	No distinct faulting in section.
GO	Q_{1A}	Q_{1B}	57°	2.3	n.o.	8.7	Possibly two faulting events in Q_{1B}.
AD	Q_{1A}	Q_{1B}	22°	1.2	n.o.	13.1	Appears older than faulting in GO section.
	Q_{1A}	Q_{1C}	48°	5.0	n.o.	13.1	
	Q_{1A}	Q_2	—	4.8	n.o.	—	Large, rounded scarps.
BT	Q_{1A}	Q_{1B}	—	.15	n.o.	—	On main fault trace.
	Q_{1A}	Q_{1C}	32°	2.7	n.o.	6.5	On main fault trace.
	Q_{1A}	Q_2	—	9.0	n.o.	6.5	On main fault trace.
	Q_{1A}	Q_{1B}	—	.2	n.o.	—	On branch fault.
	Q_{1A}	Q_{1C}	—	.5	.2	6.5?	On branch fault.
	Q_{1A}	Q_2	12°	.7	n.o.	6.5?	On branch fault.
BM	Q_{1A}	Q_{1B}	32°	.2	n.o.	11.2?	On main fault.
	Q_{1A}	Q_{1C}	~50°	1.5	n.o.	—	On main fault.
	Q_{1A}	Q2	90°	10.4	n.o.	11.2	On main fault.
	Q_{1A}	Q_{1B}	64°	—	n.o.	—	On branch faults at base of alluvial fans.
	Q_{1A}	Q_2	—	1.2	n.o.	1.2	On branch fault.
CO	Q_{1A}	Q_{1B}	—	0.6	n.o.	5.8?	On main fault trace.
	Q_{1A}	Q_{1C}	—	4.5	n.o.	5.8	On main fault trace.
	Q_{1A}	Q_2	90°	15	n.o.	5.8	On main fault trace.
	Q_{1B}	Q_{1C}	—	1.5	3.6	—	On branch fault.
WC	Q_{1A}	Q_{1B}	—	<.9	n.o.	—	On secondary fault.
	Q_{1A}	Q_{1C}	70°	2.4	n.o.	5.5?	On main fault trace.
	Q_{1A}	Q_2	>90°	>9.0	n.o.	5.5	On main fault trace.
GP	Q_{1A}	Q_{1B}	52°	1.5	n.o.	8.9?	On main fault trace.
	Q_{1A}	Q_{1C}	37°	4.5	n.o.	8.9	On main fault trace.
	Q_{1A}	Q_2	34°	8.8	n.o.	8.9	On main fault trace.
NM	Q_{1A}	Q_{1B}	38°	1.5	n.o.	—	
	Q_{1A}	Q_2	40°	6.6	n.o.	5.8	On main fault trace.
SM	Q_{1A}	Q_{1B}	22°	.6	n.o.	—	
	Q_{1A}	Q_{1C}	27°	2.7	n.o.	2.7	

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