The Owens Valley Fault Zone, Eastern California, and Surface Faulting Associated with the 1872 Earthquake

U.S. GEOLOGICAL SURVEY BULLETIN 1982

THE OWENS VALLEY FAULT ZONE, EASTERN CALIFORNIA, AND SURFACE FAULTING ASSOCIATED WITH THE 1872 EARTHQUAKE

Frontispiece. View south-southeast down Owens Valley showing trace of strike-slip Owens Valley fault zone (arrows), which extends ~100 km along floor of Owens Valley from north of Big Pine to Owens Lake (in distance, beyond Lone Pine). Sierra Nevada and its active range-front faults along right side; faulted front of Inyo Mountains on left side. USGS aerial photograph USAF 018L-057, taken July 10, 1968, by U.S. Air Force from altitude of ~55,000 ft (16.8 km).

The Owens Valley Fault Zone, Eastern California, and Surface Faulting Associated with the 1872 Earthquake

By SARAH BEANLAND and MALCOLM M. CLARK

Estimates of slip and magnitude of the 1872 Owens Valley earthquake and estimates of late Quaternary slip, slip rate, and earthquake recurrence associated with the 100-km-long fault zone as determined at 40 sites

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The Owens Valley Fault Zone, Eastern California, and Surface Faulting Associated with the 1872 Earthquake

By Sarah Beanland[1] *and* Malcolm M. Clark[2]

Abstract

The right-lateral Owens Valley fault zone in eastern California extends north about 100 km from Owens Lake to beyond Big Pine. It passes through Lone Pine near the eastern base of the Alabama Hills and follows the floor of Owens Valley northward to the Poverty Hills, where it steps 3 km to the left and continues northwest across Crater Mountain and through Big Pine. The fault has an overall strike of 340° and dip of 80°±15° ENE. Surface ruptures formed along the entire length of the fault zone at the time of the 1872 earthquake. The right-lateral component of offset in 1872 averaged 6±2 m and reached a maximum of about 10 m at Lone Pine. The subordinate vertical component, generally normal and down to the east, averaged 1±0.5m. Average and maximum net oblique-slip of 6.1±2.1 m and 11 m, respectively, indicate a seismic moment of 1.8 to 4.4×10^{27} dyne cm and a moment magnitude of 7.5 to 7.7, slightly lower than previous estimates.

Data from one site suggest an average slip rate for the Owens Valley fault zone of 1.5±1 mm/yr since 300 ka. Several other sites yield an average Holocene net slip rate of 2±1 mm/yr. The Owens Valley fault zone apparently has experienced three major Holocene earthquakes. The minimum average recurrence interval is 5,000 years at the subsidiary Lone Pine fault, whereas it is 3,300 to 5,000 years elsewhere along the Owens Valley fault zone. The prehistoric earthquakes are not dated, so an average recurrence interval need not apply. However, approximately equal amounts of displacement happened during each Holocene earthquake.

The Owens Valley fault zone apparently accommodates some of the relative motion (dextral shear) between the North American and Pacific plates along a discrete structure. This shear occurs in the Walker Lane belt of strike-slip and normal faults within the mainly extensional Basin and Range Province. In Owens Valley, the displacement is partitioned between the Owens Valley fault zone and the nearby, subparallel, and purely normal range-front faults of the Sierra Nevada. Compared to the Owens Valley fault zone, these range-front normal faults are very discontinuous and have smaller Holocene dip-slip rates of 0.1 to 0.8 mm/yr. Contemporary activity on adjacent faults of such contrasting styles suggests large temporal fluctuations in the relative magnitudes of the maximum and intermediate principal stresses while the extension direction remains consistently east-west.

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INTRODUCTION

General

On March 26, 1872, at about 2:30 a.m., one of California's three largest historic earthquakes occurred in Owens Valley and was accompanied by surface rupture along the Owens Valley fault zone (Gilbert, 1884; fig. 1). Shaking intensities were greatest (MM X) at Lone Pine and Independence (Townley and Allen, 1939, p. 57–58), where most adobe and some brick buildings were destroyed. About 27 people died in Lone Pine, nearly 10 percent of the population (Whitney, 1872). Surface rupture extended about 100 km from Owens Lake to north of Big Pine, and ground-shaking effects were evident immediately after the event from Haiwee Meadows north to Big Pine (Whitney, 1872) and possibly to Bishop (Oakeshott and others, 1972). The earthquake was felt throughout most of California and Nevada, in Oregon and Arizona, and in Salt Lake City, Utah. Oakeshott and others (1972) derive a Richter magnitude of about 8 from their isoseismal map.

The Owens Valley fault zone extends from Owens Lake through Lone Pine near the eastern base of the Alabama Hills and then across the floor of Owens Valley to the Poverty Hills (fig. 2). It steps 3 km left across the Poverty Hills and continues northwest across Crater Mountain and through Big Pine. Surface ruptures associated with the 1872 earthquake followed preexisting north-to-northwest-trending fault traces of the Owens Valley fault zone such as ground-water barriers, simple scarps, echelon and side-stepping scarps, depressions, pressure ridges, and warped and tilted surfaces. Displacements in 1872 mimicked pre-1872 faulting and followed almost the total known length of the Owens Valley fault zone. Nearly all slip in 1872 and earlier was horizontal and dextral, and it reached a maximum of about 10 m near Lone Pine. Vertical slip was variable in sense and subordinate everywhere to horizontal slip.

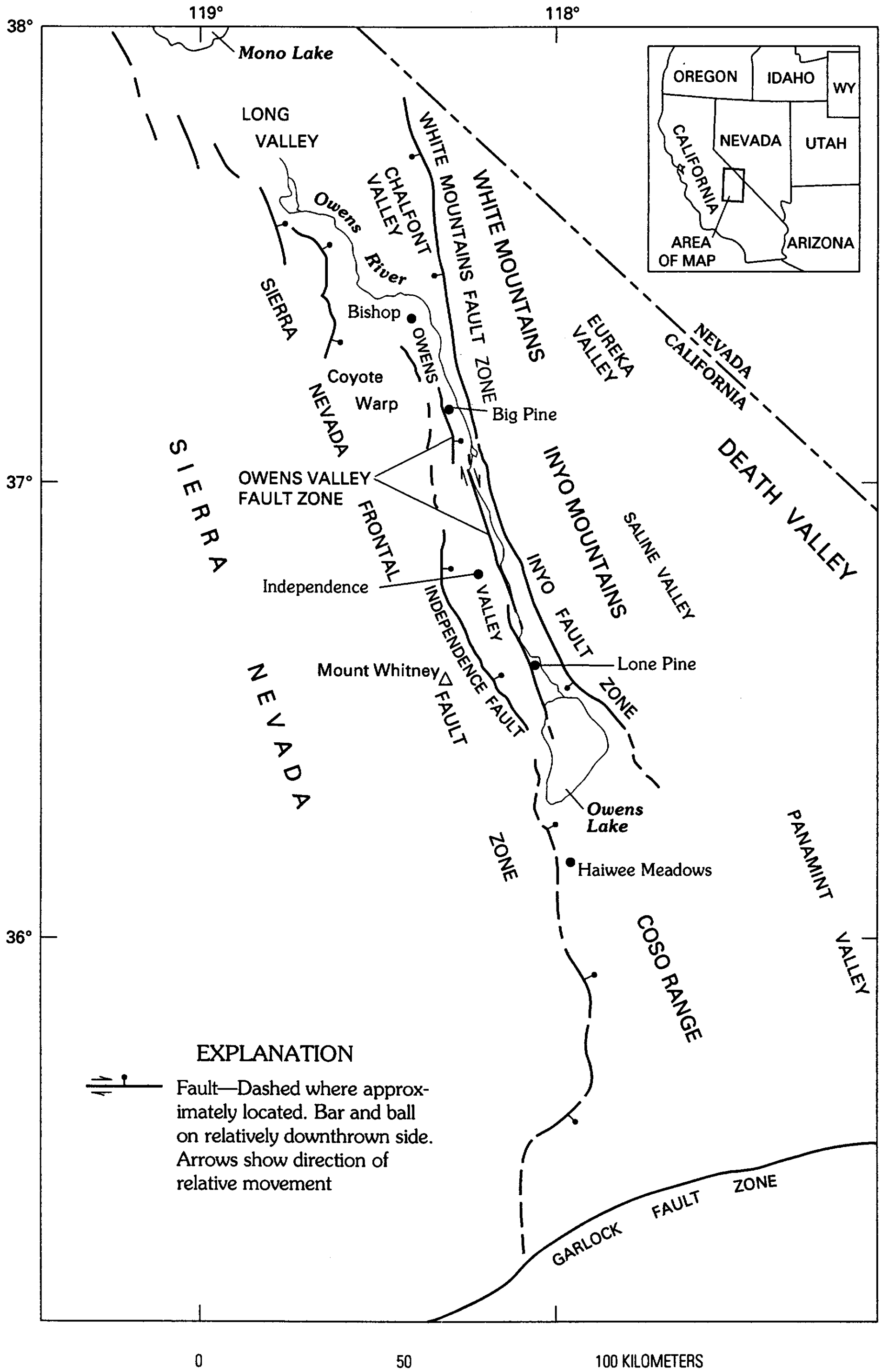


Figure 1. Location of Owens Valley fault zone, California. Owens Valley is bounded on west by frontal faults at base of Sierra Nevada and on east by frontal faults at base of Inyo and White Mountains. Faults generalized from Jennings (1975) and plates 1 to 3 of this report.

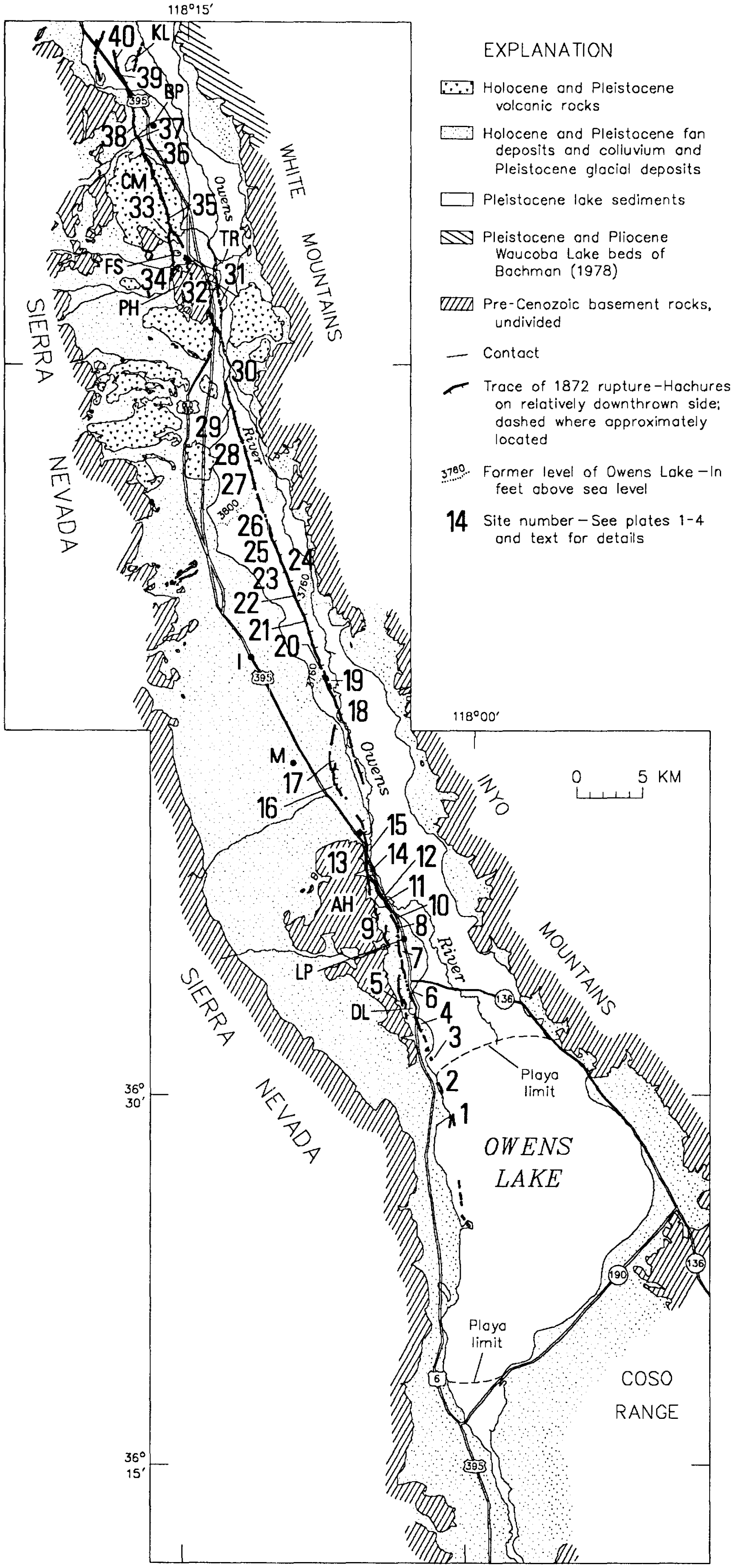


Figure 2. Generalized geology of Owens Valley, Calif., showing the 1872 rupture, sites 1 to 40, and geographic features mentioned in text. Geology simplified from plate 4. AH, Alabama Hills; BP, Big Pine; CM, Crater Mountain; DL, Diaz Lake; FS, Fish Springs cinder cone; I, Independence; LP, Lone Pine; KL, Klondyke Lake; M, Manzanar; PH, Poverty Hills; TR, Tinemaha Reservoir.

Earlier reports that emphasized the dramatic 7-m-high Holocene scarp of the subsidiary Lone Pine fault (for example, Gilbert, 1884; Hobbs, 1910; Townley and Allen, 1939; Richter, 1958) failed to note the dominantly strike-slip nature of both the 1872 earthquake and the Owens Valley fault zone. Although W.D. Johnson reported coseismic right-lateral slip of more than 4 m (Hobbs, 1910; Bateman, 1961), only recently has the dominance of strike slip at Lone Pine been documented (Beanland and Clark, 1987; Lubetkin and Clark, 1987, 1988). In this report we document the dominance of right-lateral strike slip along the entire length of the Owens Valley fault zone.

Our report further establishes that Owens Valley has at least two major independent but subparallel active faults only a few kilometers apart: The strike-slip Owens Valley fault zone near the middle of Owens Valley, and the Independence fault to the west at the base of the prominent Sierra Nevada escarpment (Gillespie, 1982). The Independence fault is a normal fault and shows no significant strike slip. How such subparallel faults can exist so close together in the Basin and Range Province and how they interact and influence each other are problems that have received attention recently (for example, Zoback and Beanland, 1986; Stewart, 1988, Hamilton, 1989).

Purpose of study

The main objectives of our study are to document the style of deformation and amount of slip in the 1872 earthquake and to assess the nature of late Quaternary movement on the Owens Valley fault zone. To do this, we have produced a strip map of the entire fault zone at a scale of 1:24,000 (pls. 1, 2, 3) and have selected specific sites for detailed study (table 3, on pl. 4). The geology of the region traversed by the fault is generalized in plate 4 and figure 2.

Acknowledgments

Much of the work for this report was done by Sarah Beanland during a 1-year visit to the U.S. Geological Survey (USGS) in 1985–86 under a Study Grant from the New Zealand Geological Survey (Department of Scientific and Industrial Research, predecessor to the Institute of Geological and Nuclear Sciences). Mark Edgar worked full-time as surveyor and field assistant. S.K. Pezzopane, A.R. Gillespie, K.J. Kendrick, and S.G. Wesnousky contributed help in the field and many ideas. We had very helpful discussions with W.A. Bryant, G.A. Carver, C.M. dePolo, S.J. Martel, L.K. Lubetkin, G.R. Roquemore, D.B. Slemmons, and our USGS colleagues M.G. Bonilla, W.F. McCaffrey, M.L. Zoback, W.B. Hamilton, K.R. Lajoie, G.I. Smith, B.D. Turrin, and J.H. Stewart. M.G. Bonilla supplied his copy of Gilbert's 1883 notebook. J.C. Hamilton helped compile some of the maps, and Ray Eis and Susan Mayfield made the final versions of the figures and plates. Mark Ziegenbein of the Bishop office of the Bureau of Land Management (BLM) helped with information about field work and BLM aerial photographs. J.C. Eichelberger donated his excellent aerial photographs of Owens Valley to the USGS, and M.R. Garcia of the Los Angeles Department of Water and Power made available their vertical aerial photographs, including those taken for them by D.B. Slemmons in 1968 for his investigations of active faults of Owens Valley. The manuscript was greatly improved by the careful reviews of A.R. Gillespie and D.P. Schwartz and comments by many others.

HISTORICAL RECORDS AND PREVIOUS WORK

Newspapers throughout the Western United States reported the 1872 earthquake (Oakeshott and others, 1972). Particularly graphic newspaper accounts appeared in the *Inyo Independent* and *San Francisco Daily Evening Bulletin* (Hill, 1972). Other descriptions of the effects of the earthquake were presented by Mulholland (1894), Chalfant (1922), and Gunn (1941).

J.D. Whitney (1872), who went to Owens Valley after the earthquake, provided the first geologic report of the earthquake. Whitney considered faulting to be a secondary shaking effect. Although he did not describe the fault rupture specifically, he did describe the extent of ground cracking, fissuring, and ground-water changes. Joseph LeConte (1878) speculated that the Owens Valley earthquake represented a fraction of the ongoing uplift of Mt. Whitney and the Sierra Nevada.

G.K. Gilbert made the first careful description of the 1872 faulting during a visit to Lone Pine in August 1883. His unpublished field notes and sketches for August 17 near and south of Lone Pine (Bonilla, 1968; G.K. Gilbert, notebook no. 31 for Aug. 8–Sep. 2, 1883, from U.S. National Archives[3]) clearly describe both right-lateral displacement and vertical displacement. Gilbert inspected the fault from "2–3 miles north" of Lone Pine "as far south as the lake." In reference to his field sketch (fig. 3), Gilbert's shorthand notes [with our editing] read in part:

> A_1A is at the foot of the Alabama range * * * The old scarp shows a throw of 50 ft. or more, this [the Holocene scarp] of 2–20 ft. * * * [The scarp at] B is 10 ft. high with eastward throw. * * * [The scarps at] CC_1 have westward throw, the blocks between them and A_1A being depressed. * * * Along CC_1 the westward block has been carried north 10–15 ft.

[3]Gilbert's notebook No. 31 was lost in the mail in 1968. However, copies of the pages for August 16–18, 1883, are in the U.S. Geological Survey Field Records Library, Denver, CO 80225-0046.

Gilbert's notes indicate that he made no field inspection beyond the area of figure 3, but he did record the observations of others:

> Mr. Lyman Tuttle was [the Inyo County] surve[y]or [who reported that] fences etc. [were] offset up to 15 ft.[, the] west[ern] part going north. * * * The main fissure [the 1872 rupture] shows an old fault scarp, traced from 3–4 mi N. of Big Pine to Owens Lake—at least 40 miles[4]. The earthquake movement was chiefly on this line and followed it nearly the whole distance. * * *. The offset was quite general, having about the same amount at Big Pine as at Lone Pine.

Thus, unlike Whitney 11 years earlier, Gilbert recognized and clearly recorded both right-lateral and vertical slip along an older fault near Lone Pine, and he reported faulting from Big Pine to Owens Lake. Gilbert's 1883 field notes and sketches are the first documented and unequivocal description of right-lateral offset along the Owens Valley fault zone in 1872.

Unfortunately his subsequent published references to this faulting (Gilbert, 1884, 1890) did not report all of his recorded observations and were ambiguous about the sense of lateral slip (Bateman, 1961; Bonilla, 1968).

However, in 1907 W.D. Johnson made a detailed study of the fault near Lone Pine (Hobbs, 1910; Lubetkin and Clark, 1988). Although done 35 years after the earthquake, Johnson's measurements, maps, and photographs record the style and location of the 1872 surface ruptures near Lone Pine.

Subsequent workers who have discussed the Owens Valley fault zone include Knopf (1918), Bateman (1961), Pakiser and others (1964), Bonilla (1968), Slemmons and Cluff (1968), Carver and others (1969), and Hollett and others (1991). Hill (1972) published the small-scale mapping of D.B. Slemmons and his students. Bryant (1984a) mapped active traces northward from Crater Mountain (fig. 2) for hazard zoning. Detailed studies along the Owens Valley fault zone were done by Carver (1970) at Owens Lake, by Martel and others (1987) at Fish Springs cinder cone (fig. 2), and by Lubetkin and Clark (1988) at Lone Pine. The last two sites provide the best constraints for late Quaternary slip rates.

GEOLOGIC SETTING

Geology

Owens Valley is a major depression between the Sierra Nevada and the White and Inyo Mountains (fig. 1). Between Big Pine and Owens Lake the valley trends south-southeast. North of Big Pine it widens as the Sierran range front steps west, but it pinches closed at the north end of the White Mountains. South of Owens Lake it is closed off by the Coso Range. The crests of the Sierra Nevada and the Inyo Mountains are about 30 km apart. Owens Valley has been a closed drainage throughout most of Holocene time, but diversion of water early in this century to the Los Angeles Aqueduct has dried up Owens Lake during most years since then.

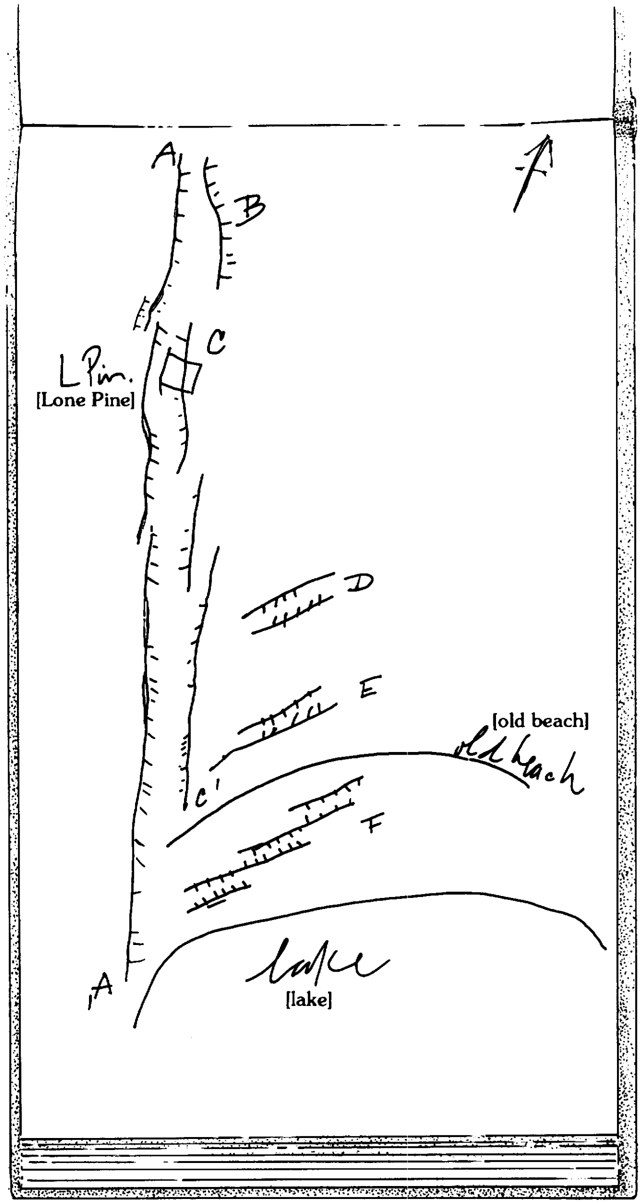


Figure 3. Redrafted sketch map from page 23 of G.K. Gilbert's notebook No. 31, for Friday, August 17, 1883. Letters show places Gilbert evidently visited that day. Hachured lines represent fault scarps. Bracketed type is added to clarify Gilbert's notations.

[4]Big Pine and Owens Lake are about 76 km (47 mi) apart. Gilbert might have been estimating the length of old scarps along this interval. We estimate that scarps extend along about 69 km (43 mi) of the 1872 trace.

The region is one of very high relief, particularly near Lone Pine, where Mt. Whitney rises more than 3,000 m above Owens Valley. The valley floor is generally broad and of low relief; it has scattered volcanic cones and lava flows south of Big Pine and is interrupted by rugged bedrock outcrops at the Alabama Hills near Lone Pine and the Poverty Hills, south of Big Pine (fig. 2; pl. 4). Ancient erosion surfaces are evident along the crests of the Sierra Nevada, the Coso Range, and the Inyo Mountains (Hopper, 1947).

Basement rocks of the Sierra Nevada near Owens Valley and the Alabama Hills are dominantly Mesozoic granitic plutons associated with pendants of Paleozoic and Mesozoic metasedimentary and volcanic rocks. The White and Inyo Mountains comprise a variety of Precambrian to Paleozoic metasedimentary rocks and Triassic to Jurassic metavolcanic rocks with some Mesozoic plutons (Matthews and Barnett, 1965; Streitz and Stinson, 1974). The Coso Range is mainly pre-Cretaceous metamorphic rocks and Mesozoic granitic plutons, Tertiary and Quaternary volcanic rocks, and Pliocene lake beds of the Coso Formation (Duffield and Bacon, 1981). The (informal) Waucobi Lake beds east of Big Pine (Bachman, 1978) are lithologically similar to the Coso Formation.

The floor of Owens Valley is dominated by Quaternary alluvial and lacustrine sediments and with Quaternary cinder cones and lava flows near Big Pine (pl. 4). Moraines from Pleistocene glaciers in the Sierra Nevada locally extend beyond the range front into Owens Valley. Vast coalescing alluvial fans from the Sierra Nevada extend more than half-way across Owens Valley. Outwash from the glacial advances is apparently correlative with major fan-building episodes along the range front (Gillespie, 1982). Smaller fans and colluvial slopes occur along the White and Inyo Mountains and the Alabama Hills.

Lacustrine sediments cover most of the flat floor of Owens Valley from the Owens Lake playa to north of Bishop (Hollett and others, 1991). Highstands of Owens Lake, marked by beach ridges, wave-cut shoreline angles, and lake sediments, are correlative with Pleistocene glacial cycles (see following section). Fluvial sediments occur along the Owens River meander belt (pl. 4) and along some side streams. The Owens River meander belt is incised approximately 10 m into Quaternary lake beds. Basaltic cinder cones and lava flows dominate the Big Pine volcanic field. Volcanism has been active throughout Quaternary time; some of the youngest lava may be Holocene in age (Gillespie, 1982).

History of Owens Lake and Age of Valley Fill

The history of Owens Lake is important to the study of the Owens Valley fault zone because it provides age constraints for many of the faulted sediments in the valley. When full, Owens Lake overflowed into a presently dry channel that lead to a series of lakes in the southern Great Basin as far as 80 km to the east (Smith and Street-Perrott, 1983). Overflow and filling of the downstream lakes apparently resulted from the wetter climate during the Pleistocene glaciations (Smith, 1979), and thus the ages of lake highstands and associated sediments are constrained.

Table 1. Approximate elevations of Owens Lake strandlines, eastern California

[ka, thousand years ago]

Strandline (pl. 4)	Elevation		Inferred age (see text)
	Feet	Meters	
A	3,880	1,183	>25 ka(?).
B	3,800	1,158	About 25 ka, early part of Tioga glaciation.
Outlet level	3,760	1,146	About 10 ka, overflow ceased.
C	3,720	1,134	7 to 2 ka(?), late Holocene glacial advance.
D	3,680	1,122	<7 to 2 ka(?).
E	3,630	1,107	<7 to 2 ka(?).
F (lowest)	3,597	1,097	<7 ka(?) to 1872.

The most recent overflow level of the Owens Lake basin is 1,146 m (table 1). This level would have flooded the valley at least as far upstream as the site of Independence today (fig. 2). This level implies that the lake sediments of the Owens Valley floor south of Independence date from at least the last period of sustained overflow and also that any fans or fluvial sediments that overlie or incise these lake sediments postdate the last overflow.

Evidence for former high lake levels of Owens Lake includes wave-cut shoreline angles and beach ridges (pl. 4; table 2). Strandlines lie above the outlet level along the northeast and southeast sides of the playa. Strandline A (pl. 4) is near 1,183 m, and strandline B is near 1,158 m. Without better elevation determinations it is unclear whether these two strandlines are faulted equivalents or if they represent separate highstands. Strandline B, at 1,158 m, may represent a highstand associated with the present outlet (1,146 m), if we assume approximately 12 m of downcutting during the overflow period. Below the present outlet level are the prominent strandline C on the east side of the lake, at about 1,134 m, and two sets of beach ridges at the south end of the lake, at 1,122 and 1,107 m (D and E, pl. 4). A set of nearly continuous beach ridges, strandline F, encircles the playa between about 1,097 and 1,100 m; the lowest ridge approximates the lake level of 1872 (Lee, 1912), before lowering of the lake by irrigation in Owens Valley and later by diversions into the Los Angeles Aqueduct. All shorelines lower than the outlet level presumably formed after the last significant overflow, although it is possible that rapid rise and fall of the water level, with brief overflow, happened but did not bury or erode older strandlines.

Ages of Owens Lake strandlines can be inferred by correlation with fluctuations downstream at Searles Lake (Smith, 1979, 1983; Smith and Street-Perrott, 1983; Benson and others, 1990) and with climatic chronologies. The last deep stage at Searles Lake occurred between 28 and 10 ka (Smith, 1979, fig. 41), which correlates with the latest Pleistocene Tioga glaciation in the Sierra Nevada (Burke and Birkeland, 1979). The deep stages of Searles Lake, which required overflow of Owens Lake, persisted until about 12.5 to 10 ka (Benson and others, 1990), when the level of Searles Lake dropped rapidly. This rapid drop of Searles Lake almost certainly resulted from cessation of overflow of Owens Lake but is not necessarily evidence for its desiccation or near desiccation. However, contemporary behavior of Mono Lake, in the next basin north of the Owens River drainage, suggests that the level of Owens Lake dropped far below overflow at the end of the Pleistocene epoch. Mono Lake rose to a late Pleistocene maximum at about 14 to 12 ka and then dropped rapidly to a much lower level (Lajoie and Robinson, 1982). The peak probably reflected a marked increase in rainfall during the warming period rather than simply ice melt, which would not account for the required volumes of water (Lajoie and others, 1983; K.R. Lajoie, oral commun., 1992).[5] Thus, Owens Lake likely overflowed throughout Tioga time until about 12 to 10 ka, when the water level probably dropped abruptly. Strandline B may have formed early during the Tioga highstand but was probably also occupied about 12 to 10 ka.

Strandlines of Owens Lake that are below the outlet level are presently under investigation (Orme and Orme, 1993), but evidence and details have not yet been published. We speculate that minor Holocene glaciations in the Sierra Nevada between approximately 7 and 2 ka (Yount and others, 1982) may have been associated with lake highstands, possibly with the wave-cut shoreline C[6]. Smith (1979) indicates that Searles Lake contained shallow water during that period, which suggests either brief or small overflow from Owens Lake. Other evidence for overflow as recently as 2 ka is provided by the chemical composition of sediments deposited after Owens Lake dried up in historic times (Smith, 1976, p. 99). Perhaps strandline C was followed by a brief overflow. Strandlines F around the playa are as much as 4 m above the 1872 water level and possibly represent high-water levels during the past 2,000 years or so. An Indian artifact from one of the higher beach ridges of strandline F is reported to be a few thousand years old (G.A. Carver, oral commun., 1985). These interpretations differ from those of Carver (1970), mainly because we now know that Owens Lake overflowed until 12 to 10 ka.

Much of the Owens Valley floor is flat and underlain by lake sediments; south of Independence the valley floor has an age close to 10 ka. Because the outlet level represents the minimum water level at 12 to 10 ka, it is reasonable to infer that the lake extended farther upstream during Tioga time. Indeed, surface and subsurface evidence suggest that deposits of Pleistocene Owens Lake extend north toward a dam of intercalated basalt flows and alluvium east of the Poverty Hills (Hollett and others, 1991). A separate late Pleistocene lake basin lay farther north in Owens Valley (Hollett and others, 1991). We infer that 12 to 10 ka is a good estimate of the age of the relatively flat surface throughout much of Owens Valley. Locally younger deposits overlie or are inset into the lake beds. Abundant sinuous sandy ridges on the surface of the lake sediments may represent deflation-resistant channel deposits that originally formed as the lake shore retreated southward after 12 to 10 ka. We estimate that deflation has removed about 2 m of sediment from the valley floor after the lake withdrew.

Most surfaces of alluvial fans that have fine distal parts extending out on the valley floor or that accumulated from steep hills (for example, along the Alabama Hills) were probably deposited in late Pleistocene to early Holocene time, when ample water was available to transport debris. Many fans represent long accumulation periods, but the ages of their surfaces or distal parts are probably about 10 ka. Colluvial slopes may be much younger, however.

South of Independence, the modern flood plain of the Owens River is incised as much as 10 m into the former lake bed. We infer that the incision of this belt of river meanders occurred rapidly after about 10 ka. The upper surface of the meander belt may have been approximately at its present level in early Holocene time; however the meanders show historic change (Whitney, 1872) and were probably very active during the middle to late Holocene glacial periods. The rise of Owens Lake to the level of strandline C would have flooded the valley floor as far upstream as the site of Mazourka Canyon Road (plate 1), and the meander belt would have been under water for some distance north of that point. Thus, the age of much of the meander belt surface might be less than 2 ka.

Quaternary deposits of plate 4 that we use to assess the history of faulting in Owens Valley are summarized in table 2.

Structural Setting of Owens Valley

Owens Valley is a major structural depression within the Inyo-Mono block of the Walker Lane belt (Stewart, 1988). The Walker Lane belt is a 100- to 300-km-wide zone

[5]Mono Lake did not rise high enough to overflow into the Owens River drainage during this latest Pleistocene highstand but may have during earlier pluvial periods (Russell, 1889; Putnam, 1949; Lajoie, 1968).

[6]Note added in proof: However, Clark and Gillespie (1994) date these minor glaciations as latest Pleistocene, not Holocene, in age. If this is correct, shorelines C, D, and E could still be Holocene in age but unrelated to Sierran glaciations.

Table 2. Summary of ages of upper Quaternary deposits in Owens Valley, eastern California

[Ma, million years ago; ka, thousand years ago]

Deposit	Age
Youngest set of beach ridges (strandline F)......	0.1 to 2 ka.
Older beach ridges and wave-cut shoreline angle.	Unknown.
Flood-plain deposits of Owens River meander belt.	Late Holocene: 2 ka.
Colluvial wedges at base of Alabama Hills and probably also Sierra Nevada and Inyo Mountains.	Late Holocene: 2 ka.
Younger fan deposits accumulated on valley floor.	10 ka.
Lake sediments of valley floor.........................	10 ka.
Older fan deposits, which probably represent a long part of the Pleistocene, including several glacial intervals. See Gillespie (1982).	50 to 500 ka (to perhaps 1 Ma).
Lava flows, various ages. Basalt and rhyolite ages distinguished on plate 4.	Holocene to early Pleistocene.

about 700 km long along the western Great Basin. It is marked by normal and strike-slip faulting and diverse topography. The Owens Valley fault zone represents concentrated strike-slip deformation in this region; north and south of the fault zone, horizontal deformation may be distributed across many smaller structures (see "Discussion").

Total vertical displacement across the Owens Valley fault zone, assessed from gravity data, is 2,500 m, east side down, at Owens Lake (Hollett and others, 1991). This 2,500 m and about 3,000 m of vertical displacement on the adjacent Sierra Nevada frontal fault zone (fig. 1) probably form the biggest range-to-basin displacement in the region. Vertical displacement on the Owens Valley fault zone decreases to about 500 m to the north near Tinemaha Reservoir, about 15 km south of Big Pine (fig. 2; Hollett and others, 1991). The fault zone steps left approximately 3 km across the uplifted Poverty Hills, which is consistent with right-lateral deformation. In contrast, the axis of Owens Valley steps right a few kilometers north of Poverty Hills, and deepens northward to about 1,500 m (Hollett and others, 1991).

Total horizontal offset of the Owens Valley fault zone has been estimated as only a few kilometers from the apparent correlation across the valley of the Independence dike swarm (Moore and Hopson, 1961) and of two Cretaceous plutons (Ross, 1962), both of which appear in the Sierra Nevada southwest of Big Pine and in the Inyo Mountains northeast of Independence. However, we suggest that 10 to 20 km of right slip is permitted by their data. Although not a large lateral offset compared with that of some other Californian faults (for example, the San Andreas fault), our estimate suggests the dominance of lateral over vertical displacement.

Lake beds of the Coso Formation and the Waucobi Lake embayment constrain the time that faulting started to form Owens Valley. Lake beds of the Coso Formation were accumulating by 6 Ma (Bacon and others, 1982), and the Waucobi Lake beds before 2.4 Ma (Bachman, 1978), presumably as a result of block faulting. The time of initiation of the Owens Valley fault zone itself is unknown.

DESCRIPTION OF THE OWENS VALLEY FAULT ZONE AND THE 1872 SURFACE RUPTURE

General Description

Our detailed mapping of the Owens Valley fault zone (pls. 1–3) locates recently active traces and identifies 40 sites where geomorphic and stratigraphic observations provide data on 1872 offsets and on late Quaternary deformation style and history. Data and interpretations from these key sites are summarized in table 3 (part of pl. 4), and supporting maps, profiles, and photographs are shown in figures 4 to 19. The sites are numbered from south to north.

The mapping that forms the basis of the strip map and the interpretation of style, amount, and history of deformation on the Owens Valley fault zone were done during 3 months in 1985, 113 years after the surface ruptured in 1872. Consequently, many features have been lost or modified. We use earlier observations where the same observations cannot be made today; the most valuable of these were made by W.D. Johnson (Hobbs, 1910).

The Owens Valley fault zone is a dominant Quaternary structure within Owens Valley. Other traces of recently active faults are present in the valley along the Independence fault, the White Mountains fault zone, the Inyo fault zone, the Coyote warp, and other faults scattered throughout the region (E. Vittori and D.B. Slemmons, written commun. 1990; Jennings, 1992). We conclude that most of these other faults had no displacement in the 1872 earthquake; only those with known or suspected 1872 surface rupture are included in the following discussion of the Owens Valley fault zone.

The Owens Valley fault zone extends nearly continuously from Owens Lake to north of Big Pine with an average strike of N. 20° W. The north end of the fault zone is well constrained near Klondyke Lake (fig. 2; pl. 3). Our investigation places the south end somewhere in the bed of historic Owens Lake (now a playa), but more recently Vittori and others (1993) report offset of Holocene shorelines at the south edge of the playa. Thus the total length of the fault zone is between 90 and 110 km. Surface rupture in 1872 extended the entire length of the fault zone.

Traces of the Owens Valley fault zone are marked by lineaments, ground-water barriers, simple scarps, echelon and side-stepping scarps, depressions, pressure ridges, and warped and tilted surfaces (pls. 1–3; figs. 4–7).

Some lineaments that appear as lines of vegetation and contrasts in surface color are related to differences in ground-water level across the fault. The east margin of the graben through Lone Pine (fig. 4), for example, is clearly marked by contrasts of vegetation and soil color, yet it has no topographic expression. Other ground-water effects include springs and their associated ponds, swamps, and vegetation, both in depressions and also along the downthrown side of scarps where the ground has been tilted toward the scarp to form a half graben (for example, through Big Pine, pl. 3). Lines of springs are also common along scarp faces and are abundant at the north end of the Alabama Hills (near site 15, pl. 1).

The most common type of fault trace is a simple scarp with several meters of vertical displacement. This displacement varies considerably within distances of only a few meters or tens of meters along strike, even across a single surface, and scarp heights given on the strip map (pls. 1–3) are representative but do not include every change. The direction of upthrown side also commonly changes along scarps; although most scarps face east, about 20 percent of them face west. For example, the upthrown side changes in several places between Diaz Lake near site 4 and Point Bartlett at site 1 (pl. 1).

We distinguish echelon from side-stepping scarps by the strike of the individual scarps. Echelon scarps are rotated clockwise from the average trend of the fault zone. They generally consist of several left-stepping scarps (compatible with right-lateral slip) and are not associated with topographic depression or uplift. An example is site 28 (pl. 2; table 3), north of Independence (fig. 2). Another well-developed series of echelon scarps lies east of the main fault zone and the Owens River north of Lone Pine (pl. 1).

In contrast to echelon scarps, side-stepping scarps parallel the average trend of the fault zone. All steps to the right are associated with topographic depressions (for example, sites 4, 19, 25, pls. 1, 2), and steps to the left are associated with uplift (for example, site 10, pl. 1); either side step may be associated with changes in upthrown side. All side steps along the Owens Valley fault zone have produced tectonic depression or uplift consistent with right-lateral deformation.

Sites 4 and 25 illustrate right steps. At site 4, 1 km south of Diaz Lake, a small right step of about 30 m and a change in upthrown side of the main scarp are associated with a 5-m-deep double depression (fig. 8) in the otherwise flat-lying lake beds. The depression is wider than the amount of side step. This site reveals the sensitivity of vertical tectonic movements to changes in fault attitude and position and illustrates dominant right-lateral deformation along the Owens Valley fault zone. Site 25 (fig. 9) also shows a typical sag pond related to a right step, and it documents constant displacement along both the scarp beyond the depression and the fault zone across the depression. In this example, the induced vertical deformation is relatively small (~2 m) and is constrained within the width of the side step (~60 m).

Point Bartlett at Owens Lake (site 1, pls. 1, 4; fig. 10) and the Poverty Hills (fig. 2) illustrate left steps. At Point Bartlett, lake sediments older than the playa surface are deformed into a dome within a left step of about 0.7 km. This uplift is shown by truncation of the deformed older lake strata by the playa surface and by southwestward-tilted fan deposits that overlie the lake beds. The 3-km left step that bounds the uplifted Poverty Hills is the largest one along the fault zone.

Most warped and tilted surfaces are too wide to be shown on plates 1–3. A small tilted surface occurs north of site 12, where the upthrown side bends up toward the scarp to form a ridge along the scarp crest (pl. 1). Half grabens represent tilting of the downthrown block toward a scarp and are common near Big Pine and Manzanar. Tilting of the floor of the graben near Lone Pine increases southward toward Diaz Lake. Broad tilting of Owens Lake (down to the west) was noted after the 1872 earthquake. Water levels along the west shoreline rose 2 ft relative to a jetty, and those along the east shoreline dropped (Whitney, 1872).

W.D. Johnson also reported fresh breaks along scarp faces or at the base of scarps (Hobbs, 1910), and steep parts of some scarps are still evident. Fresh breaks and steep parts of scarps record recent or episodic displacement. Progressive deformation is also suggested where scarps are eroded or channeled, especially where displacements occur in the eroded area. At some sites, deposits or surfaces of different ages are displaced by different amounts. Scarps that we infer to date solely from 1872 are generally lower than most along the main trace.

The Owens Valley fault zone is divided naturally into segments on the basis of continuity, strike, and style (fig. 2; pl. 4). Most segments are linked by throughgoing traces, and the only large discontinuity occurs at the Poverty Hills. The segments are most clearly defined on the basis of average strike, which varies between 325° and 360°. Deformation style is related to strike; the more northwesterly trending segments (near Owens Lake, Alabama Hills, Independence, and Crater Mountain) are associated with narrow linear traces, changes in upthrown side, fewer ground-water effects, and many side-stepping scarps (fig. 6). All of these features are consistent with strike-slip deformation. The more northerly trending segments (near Lone Pine, Manzanar, and Big Pine) are associated with wider fault zones, prominent ground-water effects, curving and east-facing scarps, and half-grabens (for example, the Lone Pine fault, fig. 4; pl. 1). Although lateral deformation also dominates on northerly fault trends, a significant dip-slip component is common.


HIGHWAY 395
11
0
1 KILOMETER
Approximate scale
10
LOS ANGELES AQUEDUCT
8
Alabama Hills
9
7
Lone Pine Creek

We measured fault dip at only three sites (14, 16, 18; table 3), but inferred it from the style of deformation at several others. For example, along linear scarps where the upthrown sides change, the fault plane presumably dips steeply (75° to 90°). Available dips support the general assumption that the more northwesterly strikes are associated with steeper faults. For example, compare site 14 (strike N. 5° W., dip 66° E.) with site 18 (strike N. 15° W., dip 85° W.). Although they are too few to be indicative, these attitudes are consistent with a larger proportion of normal, or extensional, deformation on the more northerly-striking fault segments.

Relation of the Owens Valley Fault Zone to Geologic Units

The generalized geologic map of Owens Valley (pl. 4) shows the map units that are offset by the fault zone. The ages of the units are discussed in a previous section and are summarized in table 2. Most of the deposits offset along the fault zone are lake sediments and alluvial fans that we assume have an age of about 10 ka. Younger faulted deposits include Owens Lake playa sediments and beach ridges (sites 2, 3), colluvial wedges (site 13), and deposits of the Owens River meander belt (site 18). Older Pleistocene faulted deposits and rocks include alluvium, cinder cones (site 33), and lava flows (site 34).

Fault traces are best preserved in lava, cinder cones, and alluvial fans but are commonly degraded in soft, fine-grained lake sediments. The relative scarcity of measurable displacement along the Independence segment is probably a result of rapid degradation of fault topography and the initially flat surface of the faulted lake-beds.

Displacement along the 1872 Surface Rupture

Displacement along the surface rupture of 1872 is still evident from site 2 to site 40 (pls. 1–3). W.D. Johnson in 1907 described fresh breaks along scarps near Lone Pine (Hobbs, 1910); he also measured right-lateral offsets of 4.9 m at a road and 2.7 m at a row of trees (sites 7, 8) (Bateman, 1961). Johnson made the only careful measurements of displacement during the first 90 years after the earthquake.

Several single-event scarps across upper Holocene deposits evidently developed entirely in 1872. Those within the Owens Lake playa or that offset some of the beach ridges at the lake's northwest shore (sites 2, 3; fig. 10) clearly record only 1872 deformation, the vertical component of which is 0.3 to 0.5 m up to the east. Along the base of the Alabama Hills north of Lone Pine, very recent colluvium is displaced by a scarp whose steep face and nonrounded crest are characteristic of single-event scarps (site 13; fig. 11). This east-facing scarp records as much as 4.4 m of vertical displacement[6], the maximum anywhere along the fault zone, but is opposite a parallel, west-facing scarp that is 5 to 6 m high (1872 and earlier displacement). Net vertical displacement in 1872 across the fault zone here is therefore less than 4.4 m.

The most prominent single-event scarp (1872) is northeast of Manzanar where the south end of the Independence segment of the fault zone crosses the Owens River meander belt (site 18; fig. 12). This 400-m-long east-facing scarp represents vertical displacement of 0.5 to 1.0 m, and several abandoned stream channels record right-lateral offsets of 3 to 4 m. Two trenches that we excavated to study the fault confirmed that only one event (1872) is recorded at this site.

We also saw progressively greater deformation along the fault in older landforms or deposits. Surfaces, for example, are older than channels or other features that are eroded into them. We measured many sites where fault displacements of surfaces are greater than the displacements of the younger channels or eroded places that are cut into them. Such sites include 5, 9, 12, 17, 21, 26, 31, 33, 36–38, and 40, (table 3). Similarly, younger deposits that locally overlie the fault trace, and are displaced less than the older deposits along strike, also indicate progressive deformation (site 11). Vertical displacements at these sites are 1 m or less. Right-lateral displacements of 3 to 7 m, of probable 1872 origin, are recorded only at sites 9,

◄ **Figure 4.** Vertical aerial photograph of Owens Valley fault zone near Lone Pine showing locations of sites 7 to 11 (circled numbers). North at top. Fault zone details shown on figures 5, 15, 16, 17, and plate 1*B*. Fault acts as ground water barrier in Lone Pine, creating graben (dark tone) partly bounded by aligned vegetation west of Highway 395. Prominent scarp of Lone Pine fault crosses abandoned alluvial fan of Lone Pine Creek west of Lone Pine and Los Angeles Aqueduct near east base of Alabama Hills. Scarps of Owens Valley fault zone are visible north of Lone Pine and immediately west of Highway 395. Owens River meander belt incises older lake beds and eolian deposits in northeast part of U.S. Bureau of Land Management photograph CA01-77, 6-40-11, Oct. 8, 1977.

[6]The "vertical displacement" or "vertical deformation" of the text and "*V*" of the profiles in figures 9, 11–14, 16*B*, 17*B*, and 19 is, strictly, the vertical separation of the ground surfaces on either side of the scarp projected to the approximate center of the steepest part of the scarp. This vertical separation equals the vertical component of slip for vertical faults that pass through the point of measurement (ignoring effects of horizontal offset), but it may differ from the vertical component of fault slip for other possible locations of the fault plane, or for inclined faults, or for locations where horizontal offset influences vertical separation. Thus "*V*" of the profiles of fig. 16*B* will differ slightly from the vertical component of slip measured from other profiles of the same scarp in Lubetkin and Clark (1988).

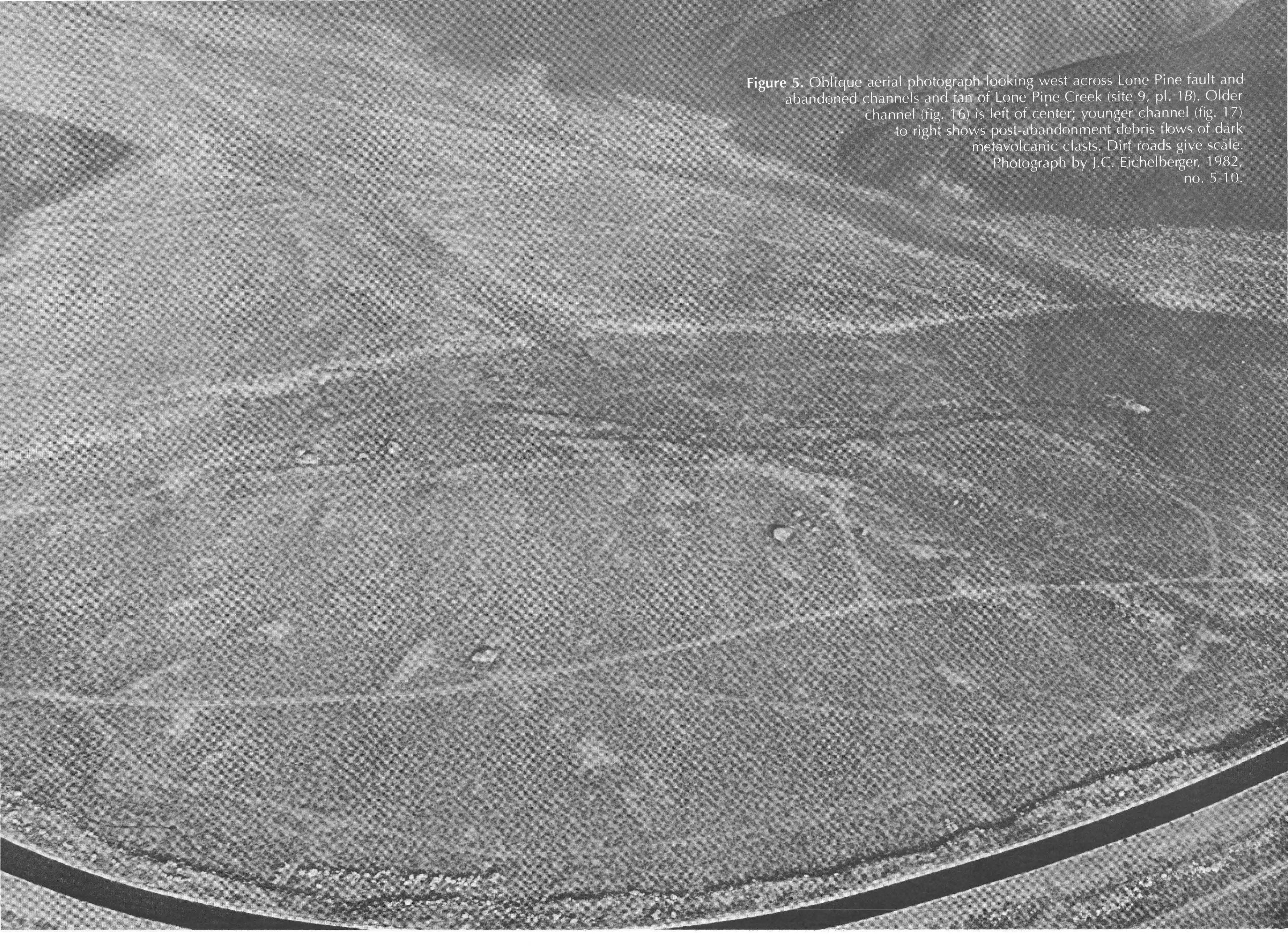


Figure 5. Oblique aerial photograph looking west across Lone Pine fault and abandoned channels and fan of Lone Pine Creek (site 9, pl. 1*B*). Older channel (fig. 16) is left of center; younger channel (fig. 17) to right shows post-abandonment debris flows of dark metavolcanic clasts. Dirt roads give scale. Photograph by J.C. Eichelberger, 1982, no. 5-10.

Figure 6. Oblique aerial photograph looking northwest along Owens Valley fault zone north of Independence between sites 27 and 28 (pl. *2D*). Shows linear nature of fault, low east-facing scarps, and wet areas in fault zone that are associated with right steps and bends of fault trace. Red Mountain in upper left, Crater Mountain and Poverty Hills in upper right center. One-lane dirt road west of fault gives scale. Photograph by J.C. Eichelberger, 1982, no. 3–13.

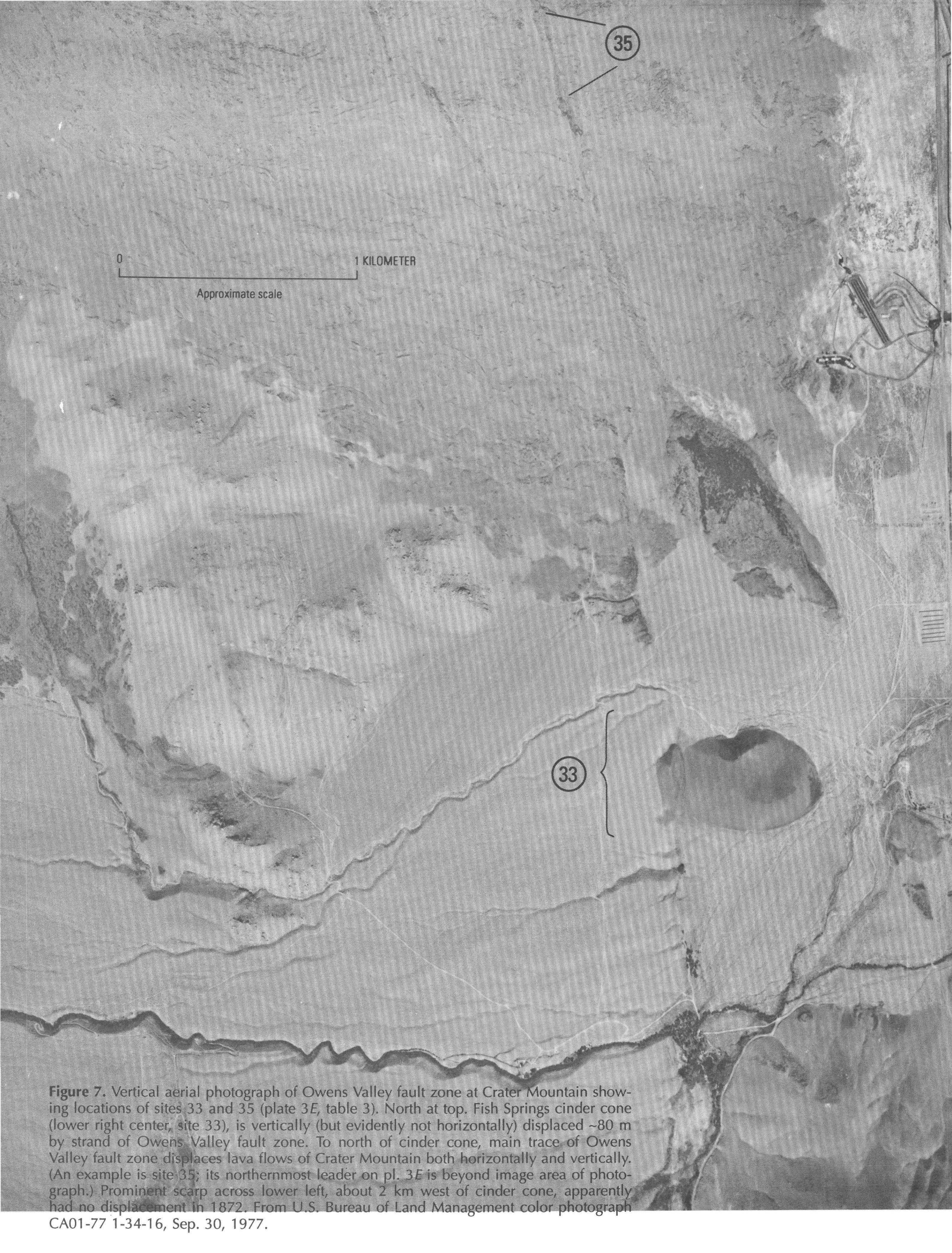


Figure 7. Vertical aerial photograph of Owens Valley fault zone at Crater Mountain showing locations of sites 33 and 35 (plate 3*E*, table 3). North at top. Fish Springs cinder cone (lower right center, site 33), is vertically (but evidently not horizontally) displaced ~80 m by strand of Owens Valley fault zone. To north of cinder cone, main trace of Owens Valley fault zone displaces lava flows of Crater Mountain both horizontally and vertically. (An example is site 35; its northernmost leader on pl. 3*E* is beyond image area of photograph.) Prominent scarp across lower left, about 2 km west of cinder cone, apparently had no displacement in 1872. From U.S. Bureau of Land Management color photograph CA01-77 1-34-16, Sep. 30, 1977.

21, 36, and 38 of these locations. For example, at site 21 (pl. 2; fig. 13) an abandoned stream channel records about 1 m of vertical and about 7m of right-lateral displacement. The surface of the lake beds on both sides of the channel along strike is displaced by a scarp about 4 m high, supporting the interpretation that the channel offset occurred in a single event, probably 1872.

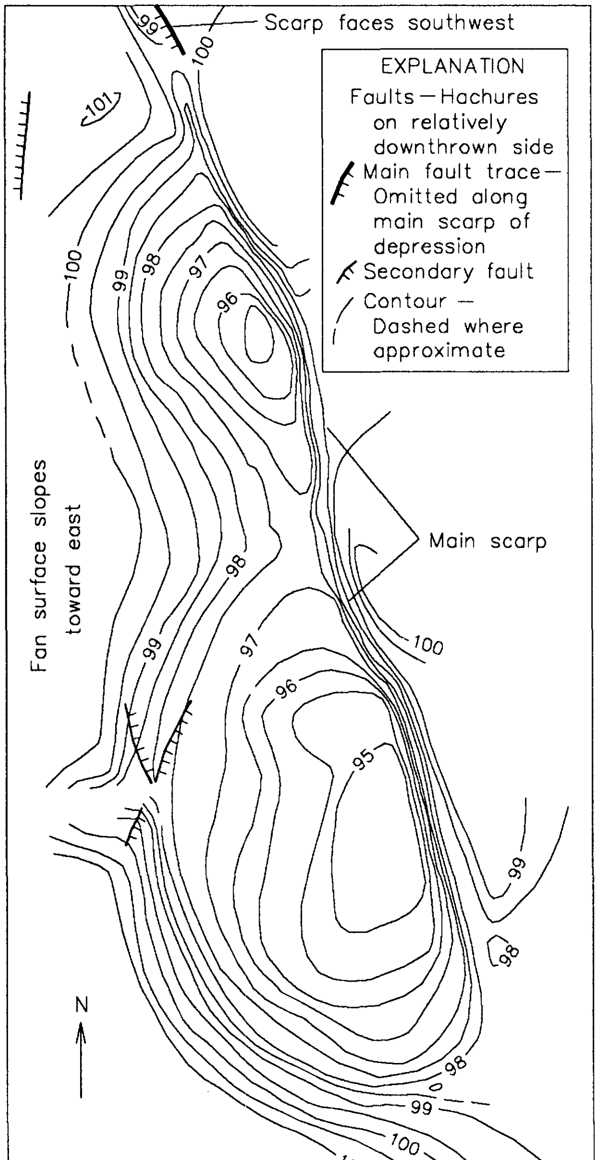


Figure 8. Tectonic depressions 1 km southeast of Diaz Lake (site 4; pl. 1, table 3). Owens Valley fault trace steps right about 30 m and reverses upthrown side across the depressions; consistent with right-lateral deformation and steep fault plane. Small subsidiary scarps also shown. Map area surveyed with self-reducing theodolite and moving staff, 1985. Contour interval 0.5 m on arbitrary datum of 100 m.

Near Big Pine, we identify a possible 1872 offset along a secondary fault scarp 0.25 km west of the main fault (site 38; fig. 14). Here, along a west-facing scarp that crosses an older fan surface (scarp ~8 m high) and a younger wash (scarp ~1 m high), a row of tree stumps, roughly normal to the fault and within the wash, is right-laterally offset about 3 m. We could not verify that the trees were planted before 1872, so we cannot be certain that this site records 1872 offset. If it does, the total right-lateral offset across the whole Owens Valley fault zone is probably more than 3 m. An alternative explanation for the offset row of trees is that they were planted in their present configuration.

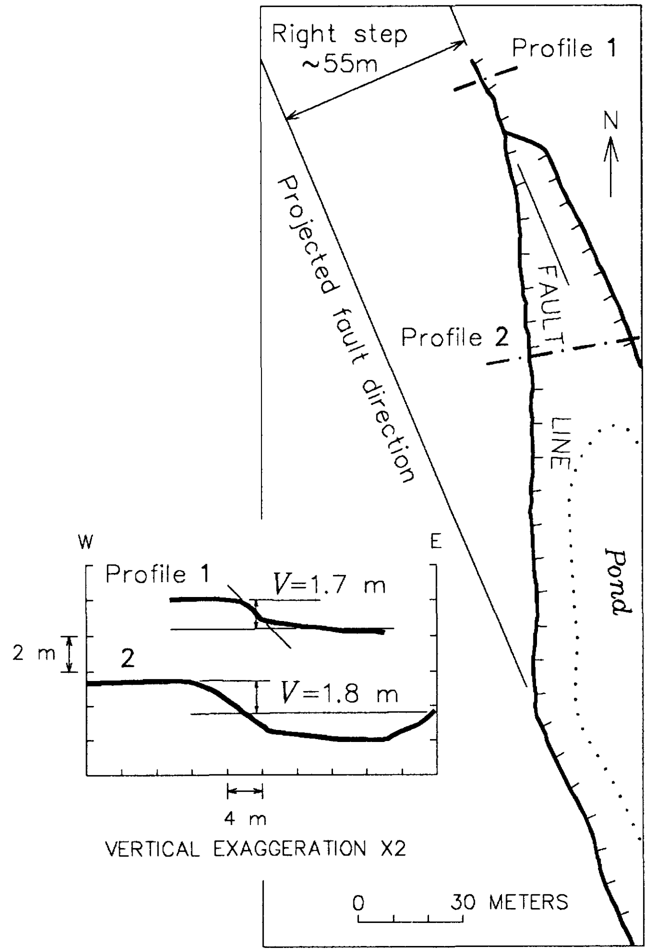
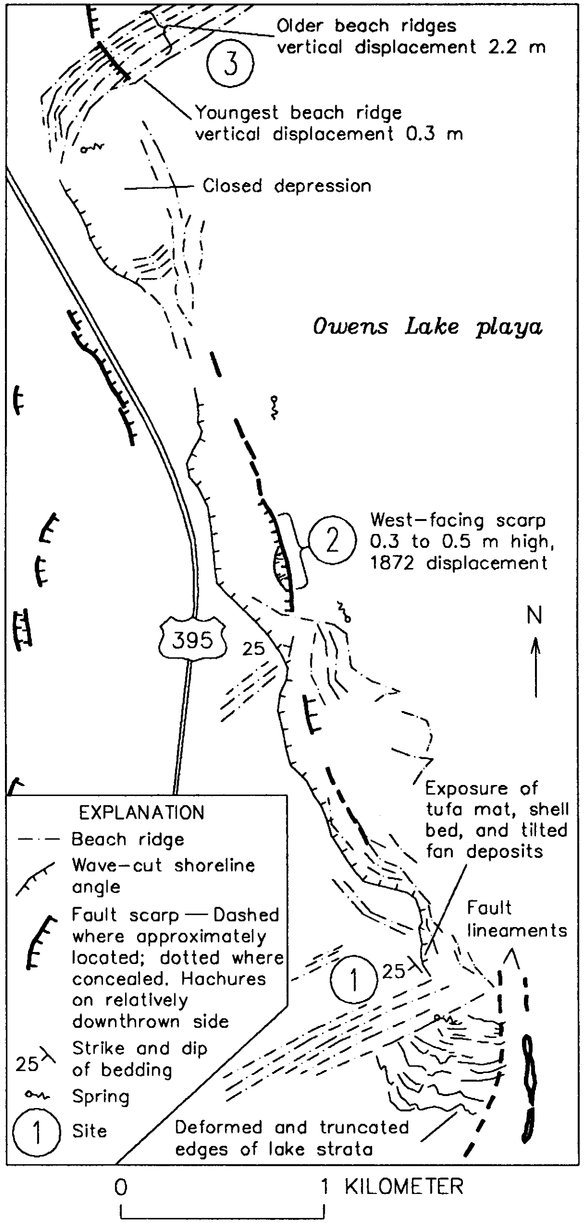


Figure 9. Right step and associated depression along Owens Valley fault zone 7 km northeast of Independence (site 25; pl. 2, table 3). Profiles show that net vertical offset is approximately equal across and north of step. At deepest part of depression (pond), west-facing scarp changes to west-dipping surface that faces half graben. *V* is vertical separation of fan surfaces projected (lightweight lines) to approximate center of steepest part of scarp face (see text). Map and profiles surveyed with self-reducing theodolite and moving staff, 1985.



◄ **Figure 10.** Deformation features of Owens Valley fault zone along and near northwest shore of Owens Lake (sites 1 to 3; pl. 1, table 3). Fault zone steps left about 0.7 km across Point Bartlett (site 1); deformed lake and fan sediments represent uplift (bulging) in the step-over, consistent with right-lateral deformation. Beach ridges are along lowest strandline (F, pl. 4). Base from plate 1.

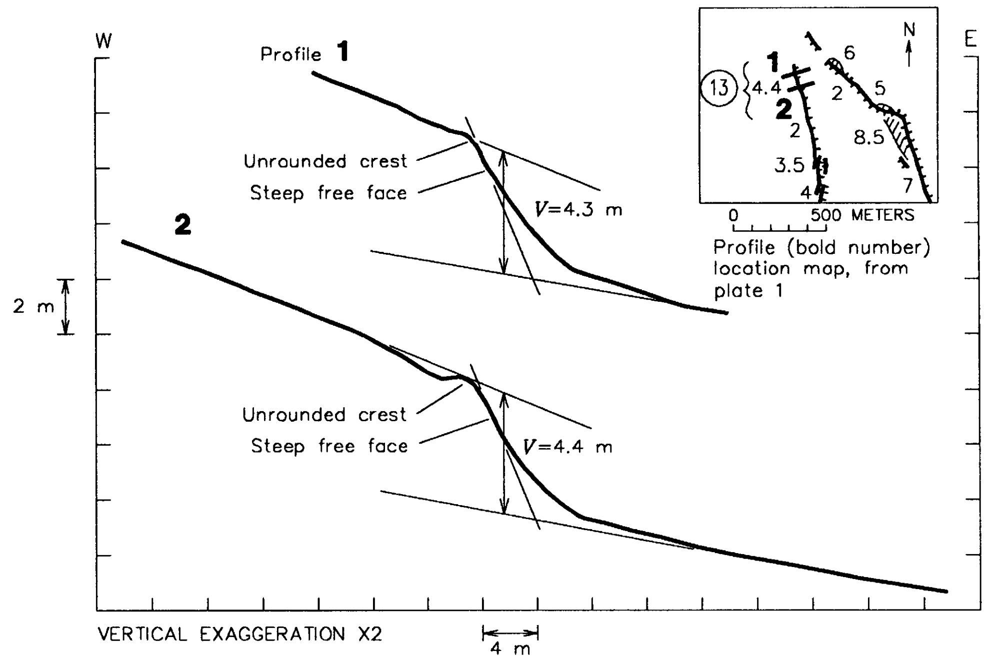


Figure 11. Representative profiles of fault scarp across young colluvial slopes at base of Alabama Hills (site 13; pl. 1, table 3). Profiles show characteristics of single-event scarps (Wallace, 1977) and, combined with apparently young age of the displaced deposits, suggest record of one event only (1872). *V* is vertical separation of fan surfaces projected (lightweight lines) to approximate center of steepest part of scarp face (see text).

From the data above, we assess average and maximum displacements for the 1872 rupture. Vertical displacement for 1872 is 1 m or less at all except two sites—9 and 13. However, both these sites lie west of west-facing Holocene scarps (a 1-m scarp near site 9, and a 5- to 6-m scarp near site 13), thus net vertical displacement across the fault zone is less. We estimate an average vertical displacement of 1 m and note that the possible maximum of 4.4 m occurred at site 13.

Average and maximum right-lateral offsets for 1872 are less reliable because data are so few. The value of 3 to 4 m at site 18 is a good measurement, about 7 m at site 21 is reliable, and so is about 4 m at site 36. The best measurements are from sites 7, 8, and 9: 4.9, 2.7, and 6 m, respectively. However, the scarp at site 9 on the Lone Pine fault is along a graben that is parallel to, and bounded on the east by, the main fault trace at sites 7 and 8; offsets on these two fault strands should be summed to give 8.7 to 10.9 m, or approximately 10 m. These limited data indicate that the average right-lateral offset in 1872 was about 6 m, and the maximum was about 10 m.

We combine the vertical and right-lateral displacement to estimate an average net displacement at the surface in 1872 of about 6 m, and a maximum of about 11 m. We also assess the ratio of horizontal to vertical displacement in the 1872 surface rupture. The average displacements suggest 6:1, and the maximum displacements suggest 2.3:1. Because the maximum vertical displacement is so unrepresentative of the fault zone as a whole, we consider that the actual ratio at Lone Pine, 10:1, is probably a fair assessment of the maximum ratio.

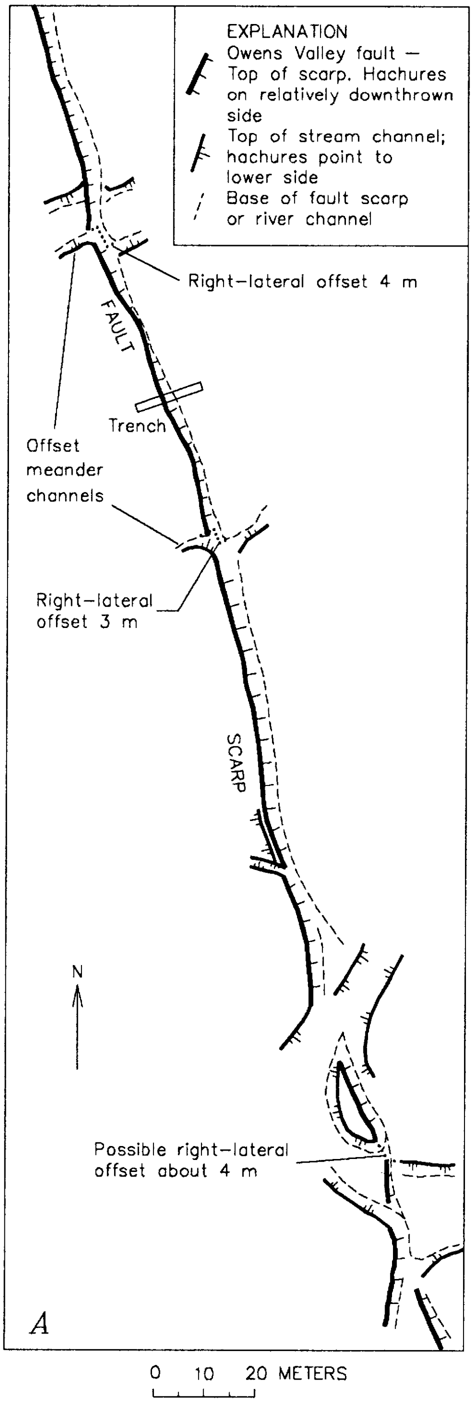
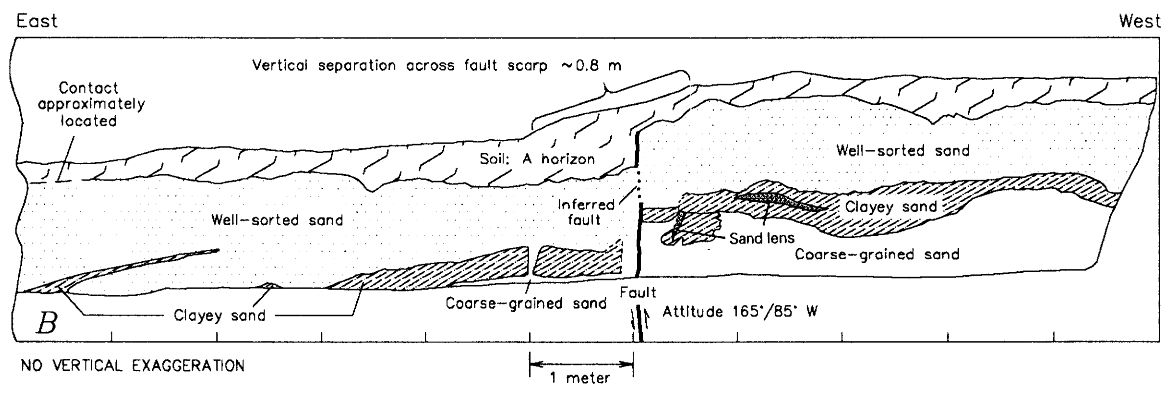


Figure 12. Map, *A*, and sketch, *B*, of Owens Valley fault zone where it crosses upper Holocene flood-plain deposits of Owens River meander belt (site 18; pl. 2, table 3). Map also shows location of trench excavated across fault in 1985. Area surveyed with self-reducing theodolite and moving staff, 1985. Sketch shows south wall of trench. Fault attitude is averaged from both sides of trench. Site 18 records only 1872 displacement; vertical component about 1 m, horizontal component, 3 to 4 m.



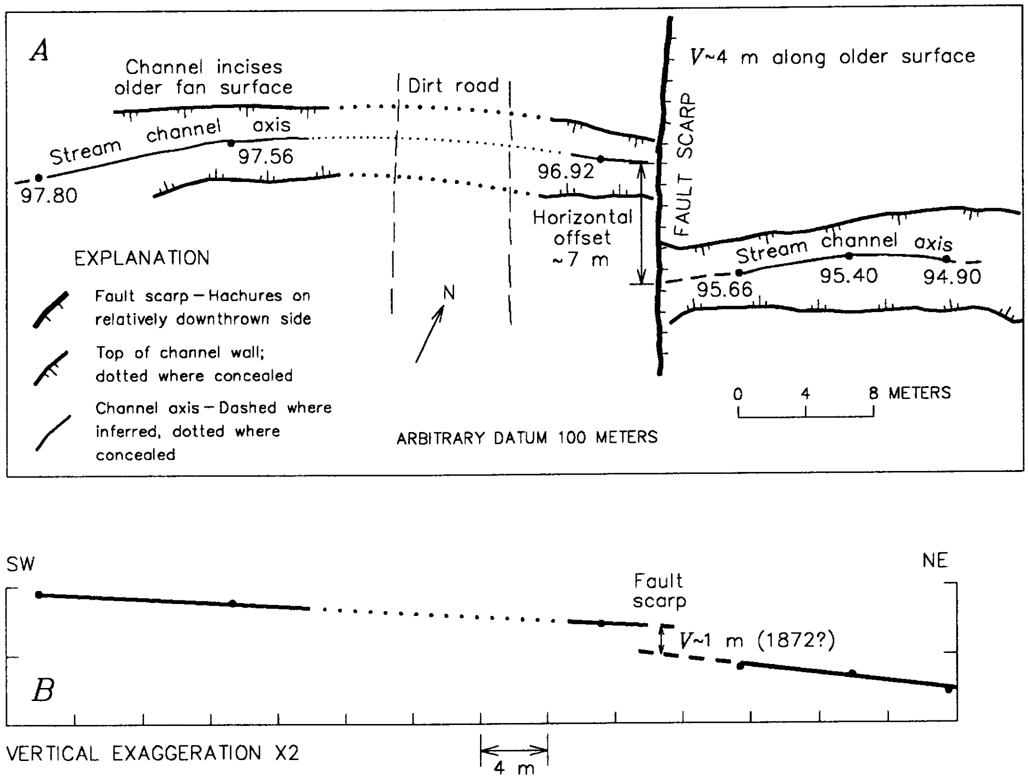


Figure 13. Offset stream channel at Owens Valley fault zone 5 km northeast of Independence (site 21; pl. 2, table 3). *A*, Map showing about 7 m of right-lateral offset of channel, probably in 1872. *B*, Channel profile showing vertical displacement *V* of about 1 m (1872?); adjacent older fan surface incised by channel is vertically displaced about 4 m, indicating progressive displacement. *V* is vertical separation of fan surfaces projected (dashed lines) to approximate center of steepest part of scarp face (see text). Map and profile surveyed with self-reducing theodolite and moving staff, 1985. Elevations of survey points (solid circles) are relative to arbitrary datum of 100 m.

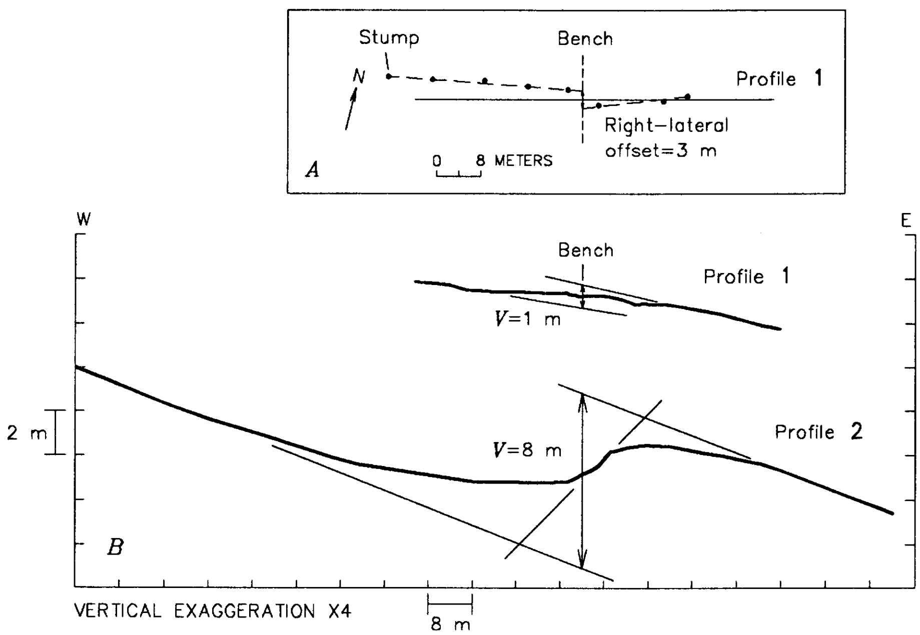


Figure 14. Offset row of stumps of planted trees at colinear bench and west-facing scarp along secondary fault trace 0.5 km west of main strand of Owens Valley fault zone near Big Pine (site 38; pl. 3, table 3). *A*, Map showing row of stumps that is right-laterally offset about 3 m, possibly in 1872; however, trees may have been planted in this arrangement. *B*, Profiles across fault trace. Profile 1 is next to row of stumps across topographic bench; profile 2 is 60 m south of stumps, across scarp. *V* is vertical separation of fan surfaces projected (lightweight lines) to approximate center of steepest part of scarp face (see text). Map and profiles surveyed with self-reducing theodolite and moving staff, 1985.

HISTORY OF ACTIVITY ALONG THE OWENS VALLEY FAULT ZONE

Abundant evidence of progressive deformation and cumulative right-lateral offset marks the Owens Valley fault zone (table 3). Only three sites (9, 33, 35), however, provide specific, reliable data for slip rates or recurrence intervals. At site 9 two channels and their deposits record a history of repeated earthquakes along the Lone Pine fault, 1 km west of the main trace of the Owens Valley fault zone (figs. 4, 5, 15). This site has received detailed study (Lubetkin, 1980; Lubetkin and Clark, 1987, 1988), and here we summarize this work and supply some additional observations (figs. 16 and 17).

The Lone Pine fault scarp reaches 6.5 m high across an abandoned outwash fan of the Tioga (latest Pleistocene) glaciation (fig. 5). Scarp profiles along an incised channel at the abandoned south channel and along the youngest debris flow at the north channel indicate a 1- to 2-m component of dip slip in 1872 (figs. 16 and 17). However, each of these sites also records average right-lateral offsets of 4 to 6 m for 1872 and earlier earthquakes. At the north channel, an older debris flow that is displaced 2.2 m vertically and about 12 m right laterally (fig. 17) suggests two 1872-type events. At the southern channel, an intermediate terrace is apparently displaced 4 m vertically and its margins 12 or 8 m right laterally (the 8-m value may reflect erosion of the terrace riser). At this channel, the original fan surface is displaced 6 to 6.5 m vertically and 10- to 18-m right laterally (fig. 16). Together, these data indicate that three 1872-type events created the scarp. Support for this interpretation is also gained from desert-varnish patterns on boulders in the fault scarp, by scarp morphology, and by sediments near the fault (Lubetkin and Clark, 1988).

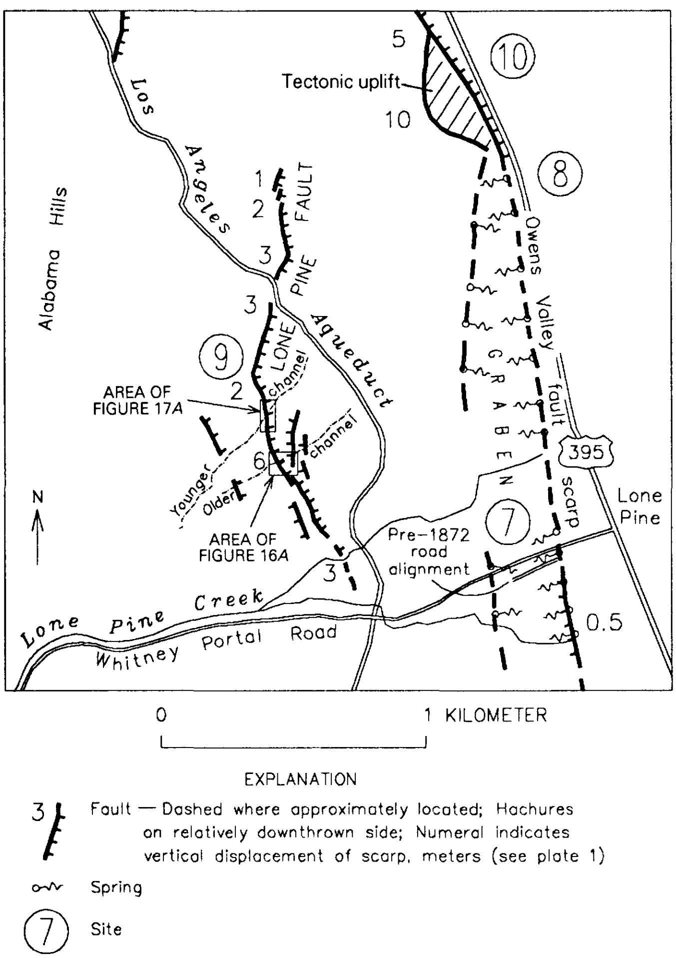


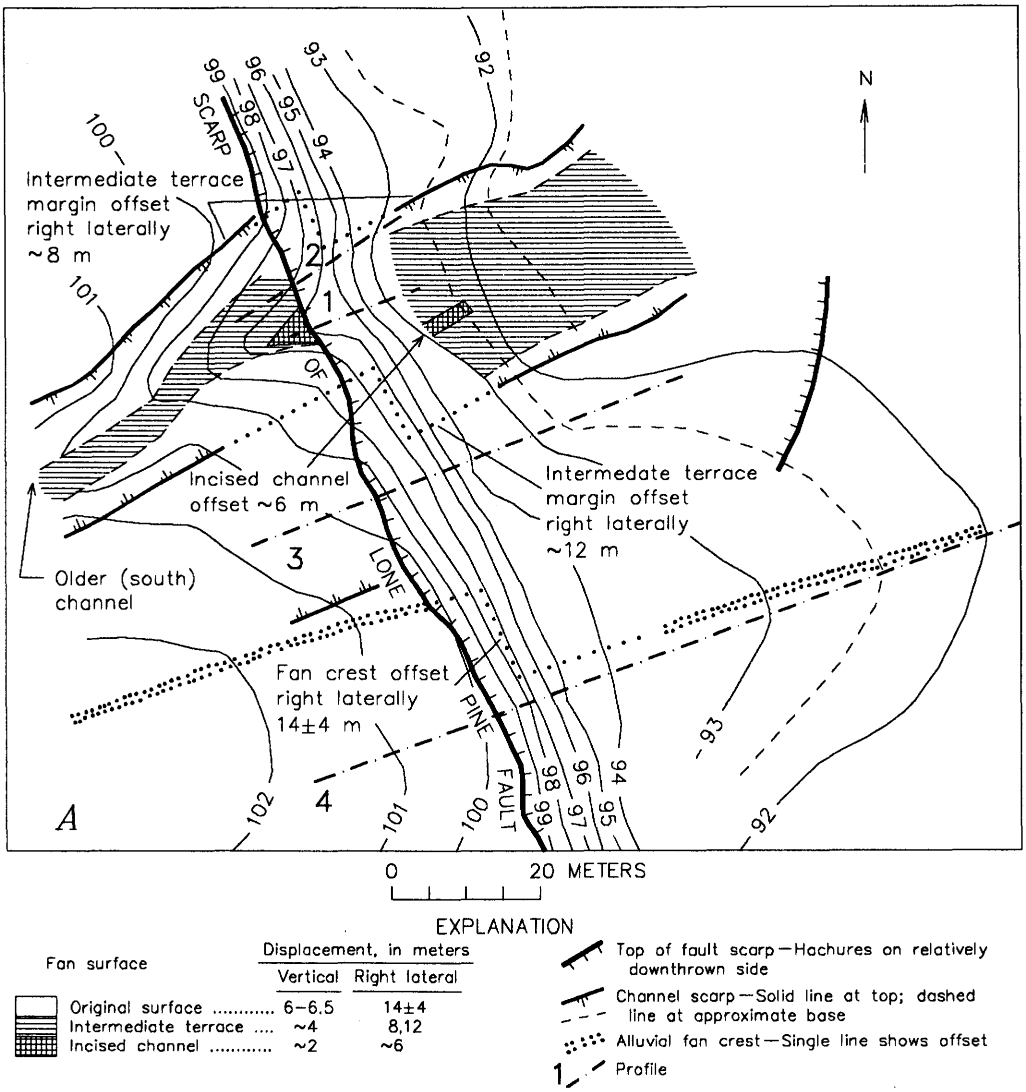
Figure 15. Owens Valley fault zone near Lone Pine (sites 7 to 10; pl. 1, table 3). Main fault zone forms graben having poorly defined west boundary. Lone Pine fault offsets abandoned channels and fan of Lone Pine Creek (figs. 16, 17) near base of Alabama Hills. Base from plate 1.

Average right-lateral offset for each earthquake is 4 to 6 m, and net slip averages 4.3 to 6.3 m. When combined with the age range of the fan surface, 21 to 10 ka (Lubetkin and Clark, 1988), these values give a latest Quaternary slip rate of 0.4 to 1.3 mm /yr. If these data are combined with the 1872 offsets measured nearby along the subparallel main trace of the Owens Valley fault zone, 2.7 to 4.9 m, the horizontal-slip component for 1872 is between about 7 and 11 m, and the latest Quaternary slip rate for the Owens Valley fault zone is 0.7 to 2.2 mm/yr. The average recurrence interval derived from these data for three earthquakes is 5,000 to 10,500 years (Lubetkin and Clark, 1988).

The Fish Springs fault (pl. 3) has the best and longest available record of faulting along the Owens Valley fault zone. At site 33 (fig. 7) a cinder cone, outwash fans of the Tahoe and Tioga glaciations, and a stream channel are vertically displaced across this north-striking dip-slip fault. Detailed work by Martel (1984), and Martel and others (1987) provides the following displacements and slip rates. The cinder cone, 314±36 ka in age, is vertically displaced 78±6 m, indicating a late Quaternary vertical slip rate of 0.25±0.03 mm/yr. The Tahoe and Tioga fans are displaced 31±3 m and 3.3±0.3 m, respectively. The age of the Tahoe glaciation is uncertain but probably corresponds to the age of marine oxygen isotope stage 4 and (or) 6 [65–75 ka and (or) 128–195 ka, respectively]. Martel and others (1987) discuss the implications of either age assignment: Stage 4 yields a much faster than average late Quaternary slip rate for the fault, while a constant slip rate suggests the fan is 124 ka in age, and probably represents stage-6 deposition. Displacement of the Tioga fan (age 10–26 ka) is consistent with the average slip rate (Martel and others, 1987).

A channel incised into the Tioga fan surface just north of the cinder cone has been vertically displaced about 1 m, probably in 1872. This displacement is consistent with the interpretation of three similar Holocene events after abandonment of the Tioga fan surface about 10 ka.

Neither the cinder cone nor other features are horizontally offset across the Fish Springs fault (fig. 7). The



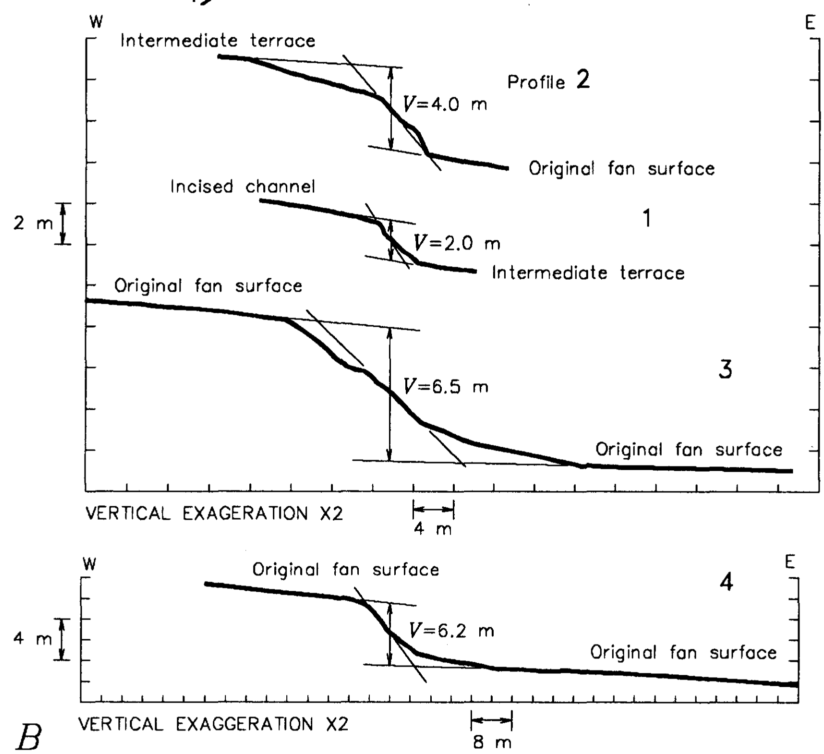
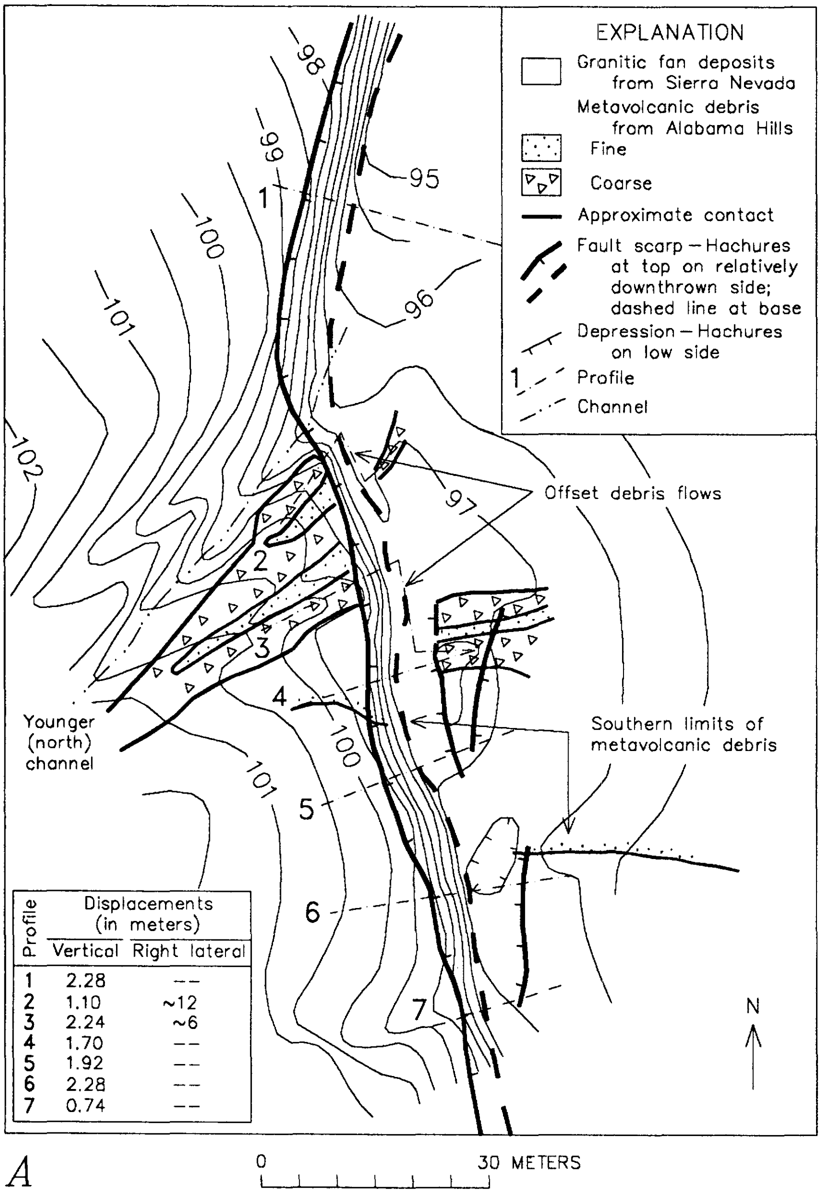


Figure 16. Older (south) abandoned channel of Lone Pine Creek where it crosses Lone Pine fault (site 9; pl. 1, table 3). Incised channel, intermediate terrace, and original fan surface and crest all show increasing vertical and right lateral displacements with increasing age (progressive displacement). Data suggest three Holocene earthquakes, each having displacement similar to that produced in 1872—approximately 2 m vertical and 4 to 6 m right lateral. *A*, Contour map; surveyed with self-reducing theodolite and moving staff, 1985. Contour interval 1 m, intermediate contours dashed at 0.5 m interval; arbitrary datum 100 m. *B*, Scarp profiles. Complex shape of some profiles records earlier earthquakes (see Lubetkin and Clark, 1988). Profiles numbered in order of increasing surface age. *V* is vertical separation of fan surfaces projected (lightweight lines) to approximate center of steepest part of scarp face (see text).

fault is secondary to the main Owens Valley fault zone, branching south from the main fault zone at the south end of Crater Mountain (pl. 3). The main fault lies almost 1 km east of the cinder cone, trends more northwest, and extends across Crater Mountain as a linear feature. It exhibits characteristics of strike-slip faults, such as changes in upthrown side. At least three lava ridges appear to be right-laterally offset across the trace (site 35). We interpret the Fish Springs fault as a splay that records only vertical displacement, whereas the main Owens Valley fault zone trace immediately east of the cinder cone is a linear feature that shows essentially no vertical displacement. The two components of displacement appear to have been partitioned at this latitude.

About 1.5 km north of the cinder cone, the main fault trace bends left and is associated with large uplift and a scarp about 100 m high. This style of deformation is consistent with right-lateral offset. Farther north the lava ridges at site 35 have apparently been offset about 30 m to the right. Crater Mountain is probably a composite cone, and the age of its lava is unknown. Only two ages are available (B.D. Turrin, oral commun., 1992): 290±40 ka from the west side of the mountain, and about 80 ka from an unknown location. Until better lava ages are available, we are reluctant to use the slip rate implied by these values. However, the scarp across Crater Mountain may yield slip rates in the future.

A large number of sites along the Owens Valley fault zone show geomorphic evidence of progressive deformation. Site 5 (fig. 18) is an example of a younger fan that is vertically displaced less (1 m) than the original fan surface (>4.8 m), but no reliable data on the timing of the displacements are available. The riser between the original and the young fans is also apparently right laterally offset by 13 m.



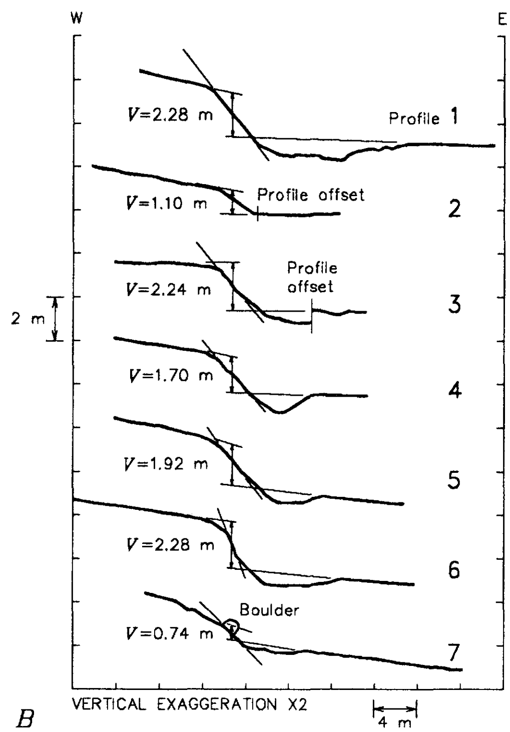


Figure 17. Younger (north) abandoned channel of Lone Pine Creek where it crosses Lone Pine fault (site 9; pl. 1, table 3). Granitic fan deposits from Sierra Nevada and younger metavolcanic debris-flow deposits from Alabama Hills record 1872 and earlier faulting. For detailed study of this site see Lubetkin (1980) and Lubetkin and Clark (1988). *A*, Contour map; surveyed with self-reducing theodolite and moving staff, 1985. Contour interval 0.5 m, arbitrary datum 100 m. *B*, Profiles. *V* is vertical separation of fan surfaces projected (lightweight lines) to approximate center of steepest part of scarp face (see text).

Because of its size, this apparent offset suggests multiple events, but its origin could be erosional rather than tectonic.

Better data on progressive displacement come from several sites (17, 26, 37, and 40; table 3) where the fault offsets deposits dated as approximately 10 ka and where eroded parts of the scarp, such as channels, show vertical displacements that are about one-third of the total local scarp height. At site 17 (fig. 19), stream channels in a distal fan surface show less vertical displacement (about 1 m) than the adjacent fan surface (>2.5 m). Furthermore, the scarp across one channel itself shows evidence of two displacement events (profile 3, fig. 19), because the middle of the scarp slope is distinctly steeper. This scarp suggests that the vertical displacement in 1872 was about 0.8 m, that two events have produced a cumulative displacement of 1.35 m, and that three events have produced 2.6 to 2.7 m of vertical displacement. Because the ages of the distal fan deposits are about 10 ka, these data suggest three Holocene events, including that in 1872. This is consistent with the conclusions reached at the Fish Springs fault and may be compatible with those at the Lone Pine fault (see "Discussion").

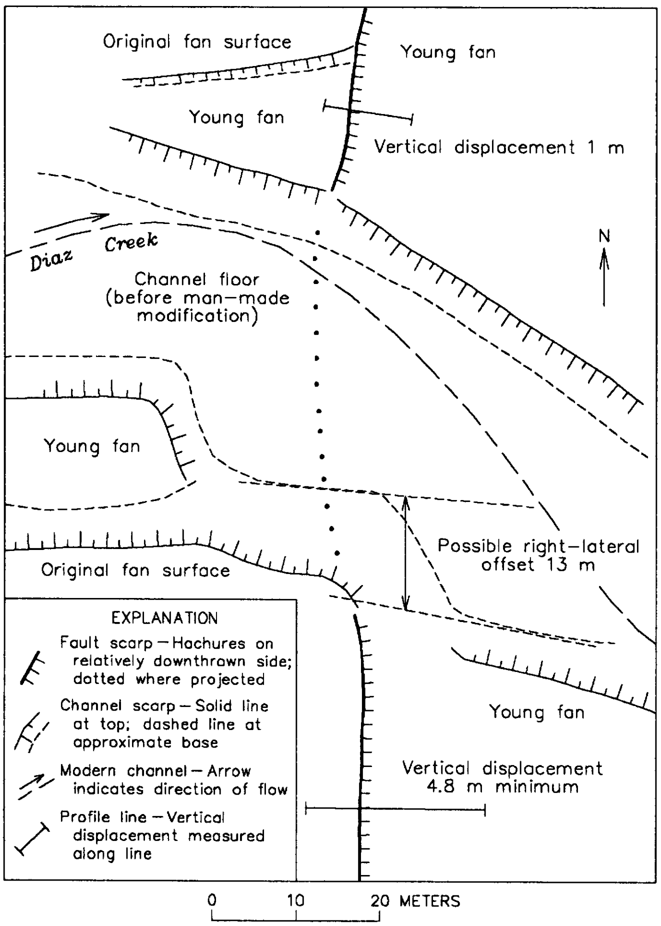


Figure 18. Erosion and displacement across Owens Valley fault zone at Diaz Creek (site 5; pl. 1, table 3). Younger surfaces show less displacement than original surface, indicating progressive displacement. Origin of 13-m right-lateral separation of channel at fault might be tectonic, but could also be either partly or entirely erosional. Map area surveyed with self-reducing theodolite and moving staff, 1985.

DISCUSSION

Displacement and Magnitude of the 1872 Earthquake

From the data presented in this report, we can assess the main displacement parameters of the 1872 earthquake on the Owens Valley fault zone. First, the surface rupture has a mapped length of 90 to 110 km, which we express as 100±10 km. The uncertainty lies in the unknown position of the southern end of the rupture in the playa of Owens Lake.

Second, right-lateral offset probably averaged about 6 m, with a maximum of about 10 m at Lone Pine. The error on the average value cannot be rigorously assessed, as it is based on sparse data scattered on both primary and secondary fault strands along a fault zone of variable offset. Measurement error is minor considering that we do not know how representative each measurement is. We consider the error on this average to be ±2 m.

Third, vertical displacement probably averaged about 1±0.5 m, mostly down to the east, but varied in sense along the fault zone. Measured vertical displacement ranged from zero to 4.4 m maximum.

Fourth, the dip of the fault plane is relevant because it helps refine our estimate of net slip. North-northwest-trending fault segments appear to have steeper dips (75°–90°, generally ENE. to E.) than the more north-trending segments (about 60°–75° E.). Few measurements are available, however, to substantiate these figures. Overall, the fault strike averages 340°, suggesting that at depth the fault dip is generally steep, perhaps dipping 80°±15° ENE. In particular, splay faults and secondary faults may diverge from this steep dip. Using 80°±15°, we derive an average net oblique slip of 6.1±2.1 m in 1872.

Fifth, we estimate a maximum net slip in 1872 at Lone Pine. Summing the displacement on all strands and accounting for fault dip, we suggest that perhaps 11 m of oblique slip occurred. We are not certain that this is a true maximum because there are so few appropriate data along the fault zone, but we accept it as the demonstrated maximum.

From these values we can assess the seismic moment (M_o) and moment magnitude (M_w) of the 1872 earthquake. Seismic moment is the product of the shear modulus (μ), average slip at depth ($\ddot{u}$), and area of the fault plane (A): $M_o = \mu \ddot{u} A$ (modified from Hanks and others, 1975). We obtain A from fault length of 100±10 km and fault width (depth along slope) of 10 to 12 km, the measured maximum depth range of earthquakes in the region (D.P. Hill, oral commun., 1992). The average values, $\mu = 3 \times 10^{11}$ dyne-cm, $\ddot{u} = 6$ m, and

$A=10^3$ km², give an average seismic moment $M_0=1.8\times10^{27}$ dyne-cm. Maximum values $\bar{u}$ =11 m and $A=1.32\times10^3$ km² give a maximum seismic moment of 4.4×10^{27} dyne-cm.

Using the formula of Hanks and Kanamori (1979) for moment magnitude, $M_w=\frac{2}{3}\log M_0-10.7$, we derive an average value of $M_w=7.5$ and a maximum of $M_w=7.7$ for the 1872 earthquake. These are slightly lower than the value of $M_w=7.8$ estimated by Hanks and others (1975) or the magnitude assessments of about 8 (from intensity distribution) or not less than 8.25 (from comparisons with other earthquakes) given by Oakeshott and others (1972).

With a seismic moment of 1.8 to 4.4×10^{27} dyne-cm, the 1872 earthquake apparently is the third, or perhaps second, largest historic California earthquake, after those of 1857 ($M_0=9\times10^{27}$ dyne-cm) and 1906 ($M_0=4\times10^{27}$ dyne-cm) on the San Andreas fault (Hanks and Kanamori, 1979).

Late Quaternary Slip Rates and Recurrence Intervals for the Owens Valley Fault Zone

In this section we use data collected both by us during this study and by others from the Lone Pine and Fish Springs faults to determine average late Quaternary and Holocene slip rates and an average Holocene recurrence interval for the Owens Valley fault zone.

The Fish Springs fault has an average vertical slip rate of 0.2±0.03 mm/yr since 314±36 ka (Martel and others, 1987). By assuming that the adjacent main fault trace accommodates all of the strike-slip deformation at this position along the fault zone and by taking an average ratio of 6:1 for horizontal to vertical slip, we suggest a net average slip rate for the whole fault zone here of 1.5 mm/yr for late Quaternary time. We acknowledge the very large uncertainty in this derived slip rate. Although it is based on a vertical slip component that varies greatly in both magnitude and sense along the strike of the fault, the 1872 vertical displacement of the Fish Springs fault was the same as the average vertical displacement for the entire fault zone. The uncertainty on this value is probably at least 1 mm/yr.

At Fish Springs, the vertical slip rate since 10.6 to 26 ka is 0.1 to 0.3 mm/yr (Martel and others, 1987). Applying the 6:1 ratio as above gives a net average post-Tioga slip rate of 0.6 to 1.8 mm/yr. The net average slip rate derived at Lone Pine is 0.7 to 2.2 mm/yr since 10 to 21 ka (Lubetkin and Clark, 1988). These estimates for the Owens Valley fault zone, from the Lone Pine and Fish Springs faults, which are about 55 km apart, are surprisingly consistent,

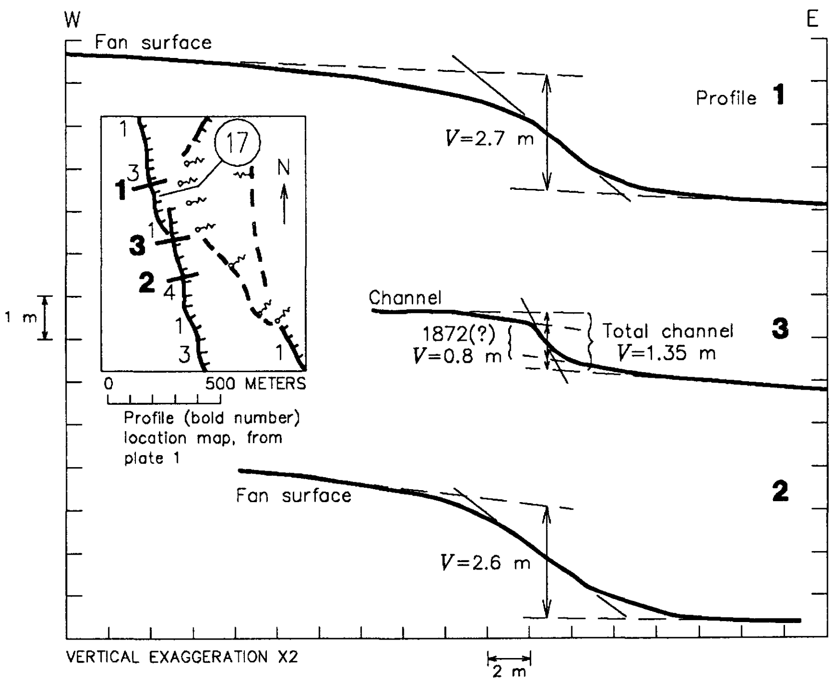


Figure 19. Representative profiles of fault scarps across ~10-ka fan surface near Manzanar (site 17; pl. 1, table 3). Channels that dissect fan and scarp (for example, profile 3) show less vertical displacement than do adjacent fan surfaces (profiles 1 and 2), and hence are younger, indicating multiple events. If shape of profile 3 records two events, then site 17 apparently records three events. *V* is vertical separation of fan surfaces projected (lightweight lines) to approximate center of steepest part of scarp face (see text).

given the tenuous nature of the Fish Springs estimate. Taken together they suggest an overall average net Holocene slip rate of 0.6 to 2.2 mm/yr, a range consistent with the late-Quaternary rate above for Fish Springs fault of 1.5±1 mm/yr since 314 ka.

No specific dates are available to refine the slip rates presented here; however, we think that most of the offset surfaces and deposits described as latest Pleistocene to Holocene in age are, in fact, close to 10 ka in age. Shoreline data from Owens Lake indicate that the lake overflowed until about 10 to 12 ka. The lake level at that time was about 1,146 m (3,760 ft), and the up-valley contour of that elevation is marked on plate 4. At least three sites below the 1,146-m contour show evidence for progressive deformation, and the latest vertical displacement at these sites is about one-third of the total vertical displacement (sites 11, 12, 17). This suggests that for the scarps to have been preserved, about three displacement events postdate about 10 ka. Because these latest and total displacements are very similar to those measured on outwash of the Tioga glaciation at the Lone Pine and Fish Springs faults, we suggest that the younger age limits given for those places may apply elsewhere. These age limits would imply that the fan surfaces date from the end of the Tioga glacial interval, which is reasonable. Thus, average net Holocene slip rates for the Owens Valley fault zone are probably at the faster end of the slip-rate ranges, 1.8 or 2.2 mm/yr. The small number of Holocene events places large uncertainties on these assessments, and 2±1 mm/yr is probably a fair assessment of the Holocene slip rate.

Lubetkin and Clark (1988) noted that the relation between the Tioga outwash fan and the Lone Pine fault scarp indicates three faulting events of roughly equal displacement, the first of which happened shortly before abandonment of the fan near the end of the Tioga glaciation, at least 10,000 years ago. Because the third event was that of 1872, the resulting minimum average recurrence interval was 5,000 years for the Lone Pine fault. The work of Martel and others (1987) on the Fish Springs fault and our own data from elsewhere in Owens Valley, however, allow a shorter average recurrence interval for the Owens Valley fault zone.

Several of our sites, including site 33 on the Fish Springs fault, indicate three post-Tioga, or post-10-ka, earthquakes as discussed above. Because the last event happened in 1872, and the earliest may have occurred close to 10 ka, the maximum recurrence interval for these sites is 5,000 years. But if a fourth event that is not detected in the Holocene record happened immediately before 10 ka, the minimum interval allowed by these data is 3,300 years.

We see two obvious explanations for these different minimum recurrence intervals calculated for the Owens Valley fault zone. The simplest is that the true average recurrence intervals at all sites is 5,000 years, the only value permitted by the data at all sites. It is the minimum interval at the Lone Pine fault and the maximum elsewhere. This explanation assumes that all the data are compatible; for instance, the Lone Pine fan was abandoned soon after drying of Pleistocene Owens Lake started. This sequence of events requires the age of the first of the three earthquakes to be very close to 10 ka, after significant lowering of Owens Lake, but just before Lone Pine Creek switched to its present channel. Lubetkin and Clark (1988), however, argued that the Lone Pine fan was probably abandoned before the end of the Tioga glaciation, when Lone Pine Creek was still sufficiently competent to excavate its present channel. The timing and large discharges envisioned in their conjecture would be incompatible with the drying of Owens Lake. But we think that post-Tioga abandonment of the Lone Pine fan could still be possible if episodic early Holocene floods were able to cut the new channel of Lone Pine Creek. Later abandonment would mean that the three events recorded along the Owens Valley fault zone could be the same as the three recorded in the scarps of the Lone Pine fault. Our explanation seems plausible and is permitted by the small number of ages available; more ages are needed, however, to either prove or deny this idea.

Another explanation is that the Lone Pine fault, a secondary fault, slipped in 1872 but not during each previous earthquake, including one or more since 10 ka. According to this explanation, minimum average recurrence interval for most of the Owens Valley fault zone is 3,300 years, but it is 5,000 years for the Lone Pine fault. This possibility, of course, raises disturbing questions about the validity of our assumptions of uniform recurrence and uniform (characteristic) behavior during successive earthquakes, assumptions we must make to predict anything about earthquakes and fault behavior along the Owens Valley fault zone from our sparse data.

Indeed, our data do not date individual earthquakes, thus we cannot test the validity of the average recurrence interval assessment. The three earthquakes may in fact have clustered quite closely in time; our age determinations could not distinguish such a group. What our observations do support, albeit qualitatively, is the recurrence of approximately equal displacement in each event. The Lone Pine data, in particular, support the characteristic earthquake model (Schwartz and Coppersmith, 1984), at least with respect to displacement.

Significance of Strike-Slip Motion on the Owens Valley Fault Zone

Along the Owens Valley fault zone the horizontal component of slip is dominant. The vertical component is subordinate, variable in sense, and locally absent. This and deformation style indicate that the Owens Valley fault zone is a steeply dipping strike-slip structure. The northwest strike of the fault zone is within 20° of that of the San

Andreas fault. Because of its style and location, the Owens Valley fault zone appears to be a part of the Pacific–North American plate boundary zone through California, of which the San Andreas fault is the main component. Although the slip rate of the Owens Valley fault zone is one-tenth or less of that of faults of the San Andreas system, the Owens Valley fault zone accommodates a significant component of dextral shear on a relatively discrete structure.

Owens Valley lies within the Inyo-Mono block proposed by Stewart (1988) as an element of his Walker Lane belt of the western Basin and Range province. The Inyo-Mono block includes major northwest-trending dextral strike-slip and normal faults. It is bounded to the north by the east-west trending left-lateral Excelsior-Coaldale structure, which apparently interrupts the Owens Valley–White Mountain fault system about 75 km north of Bishop. To the south this block is bounded by the Garlock fault (fig. 1).

From our present knowledge of the Inyo-Mono block, the Owens Valley fault zone stands out as the most simple and possibly the dominant strike-slip structure of the block. Along strike to the north, the White Mountain fault zone is more complex and includes both right-slip and normal faults (dePolo, 1988; Lienkaemper and others, 1987). Along strike to the south, continuity with the shorter and less well expressed Airport Lake fault (Roquemore, 1983) and Little Lake fault (Roquemore and Zellmer, 1986) south of the Coso Mountains has not yet been established (Roquemore, 1988). The discontinuous expression of these faults, however, implies that their late Quaternary slip rates are significantly less than that of the Owens Valley fault. Subparallel active strike-slip faults also lie to the east in the Inyo-Mono block in Eureka, Saline, Panamint, Fish Lake, and Death Valleys in Nevada and California (fig. 1), but all appear to be much more closely associated with normal faults than is the Owens Valley fault zone. Indeed, these other strike-slip systems have been identified as directly related to detachment faults of large displacement that are the down-dip expression of associated normal faults at the surface (MIT 1985 Field Geophysics Course and Biehler, 1987; Wernicke and others, 1988; Hamilton, 1989), an association that has been neither demonstrated nor proposed for the Owens Valley fault zone and its nearby, but separate, normal faults.

The right-lateral faults of the Inyo-Mono block may be part of the postulated eastern California shear zone (Dokka and Travis, 1990; Savage and others, 1990). This zone of right-lateral faults has been identified in the central and eastern Mojave Desert, south of the Garlock fault, and some of its faults project toward Owens Valley (Roquemore and Simila, 1993, for example). Savage and others (1990) show that deformation of geodetic nets that cross this proposed shear zone in the Mojave Desert is similar to that of such networks in Owens Valley. Although deformation across the Owens Valley fault zone is compatible with that across the eastern California shear zone in the Mojave Desert, no one has yet demonstrated a direct connection of any individual north- to northwest-striking fault of the Mojave Desert to the Owens Valley fault zone across the active Garlock fault. The Garlock fault has a Holocene slip rate many times greater than that known for any fault of the proposed eastern California shear zone (Clark and others, 1984; McGill and Sieh, 1991, 1993) and does not appear to be offset by any discrete crossing structure. Dokka and Travis (1990) suggest rather that Cenozoic southward bending of the Garlock fault transfers right-lateral shear from strike-slip faults of the shear zone in the Mojave Desert to those of the Inyo-Mono block north of the Garlock fault.

We also note significant changes in the character of faulting northwest of Owens Valley near the east boundary of the Sierra Nevada (fig. 1). Significant strike-slip faulting is apparently absent within at least 70 km of the range front for at least 300 km northwest of Owens Valley. Furthermore, maximum late Quaternary dip-slip rates to the northwest are much higher: 1.7 mm/yr at McGee Creek at Long Valley, and 2 to 2.5 mm/yr at Lundy Creek next to Mono Lake (Clark and others, 1984). It is interesting that late Quaternary dip-slip rates along the Sierra Nevada front northwest of Bishop are comparable to strike-slip rates along the Owens Valley fault zone.

Studies of seismicity in the western Basin and Range Province indicate nearly equal components of horizontal extension and horizontal shear; the shear component, on a vertical plane striking N. 10° W., reflects a large strike-slip displacement in almost every historic event in this region (Ellsworth, 1990). In Owens Valley, the regional combination of strike-slip and extensional deformation appears to have been to some extent partitioned, with the strike-slip component concentrated on the Owens Valley fault zone.

Approximately parallel to and within 15 km of the Owens Valley fault zone is the major Sierra Nevada range-front fault zone of purely normal faults. This zone consists of the Independence fault (Gillespie, 1982) and other subparallel and discontinuous faults to the north and south along the west side of Owens Valley (Jennings, 1992). Compared to the Owens Valley fault zone, these range-front faults show more variable strike, have much more discontinuous surface traces, and have lower Late-Quaternary slip rates: About 0.1 mm/yr on the Independence fault west of Independence, and 0.6 to 0.8 mm/yr on a fault west of Fish Springs at Birch Creek (Clark and Gillespie, 1993). Not enough slip rates are known on these range-front faults to determine any relation between their slip rates and the vertical slip rates on adjacent parts of the Owens Valley fault zone.

Similar pairs of strike-slip and normal faults have been recognized in this region: For example, near Cedar Mountain in Stewart's (1988) Walker Lake block about 150 km to the north (Gianella and Callaghan, 1934; Bell, 1988), in Chalfant Valley (fig. 1; Lienkaemper and others, 1987; dePolo and Ramelli, 1987), in Saline Valley (fig. 1; Zellmer, 1983), in Panamint Valley (fig. 1; MIT Field Geophysics Course and Biehler, 1987; Burchfiel and others, 1987; Zhang and others, 1990), in Death Valley (fig. 1; Burchfiel and Stewart, 1966; Hamilton, 1989; Brogan and others, 1991), and near Little Lake (fig. 2; Roquemore, 1988).

Some of these paired faults could be related to simple pull-apart basins (Aydin and Nur, 1982), and hence slip could occur simultaneously on both styles of fault. Such faults are proposed for Saline-Panamint Valleys (fig. 1; Burchfiel and others, 1987) and for Death Valley (fig. 1; Burchfiel and Stewart, 1966; Hamilton, 1989; Brogan and others, 1991).

But other pairs, including that of Owens Valley, may not be related to pull-apart structures. We have found no evidence that suggests simultaneous rupture of the Sierran range-front and Owens Valley faults. Compared to faults of the Owens Valley fault zone, the range-front faults evidently did not move in 1872, they show little or no evidence for more than one Holocene displacement, and they have distinctly lower slip rates.

Explanations for such co-existence of contrasting fault styles unrelated to pull-apart basins have been suggested by Zoback and Beanland (1986), Stewart (1988), and Jones and Wesnousky (1993). Analysis of stress and slip directions indicates that the contrasting styles may best be explained by large temporal fluctuations in the relative magnitude of the maximum horizontal stress, S_{Hmax} (but see Jones and Wesnousky, 1993, for a different view). For the Independence fault, S_{Hmax} must be close in magnitude to the minimum horizontal stress, S_{Hmin}, whereas for the Owens Valley fault zone S_{Hmax} and the vertical stress, S_V, must be approximately equal. Presently, the principal stress S_{Hmax} on this fault pair is close in magnitude to S_V, and is oriented about north-south, favoring strike-slip motion of northwest-trending structures. Both faults indicate a regional S_{Hmin} orientation of about N. 80° W., consistent with local focal mechanisms for smaller events (D.D. Given, written commun., 1989). In detail, deformation style along the Owens Valley fault zone itself conforms to an east-west extension direction. North-trending fault segments show more prominent normal-fault characteristics (half grabens, east-facing scarps), whereas northwest-trending segments show fewer of these and more prominent strike-slip features (linear scarps and changes in upthrown side).

The cause of the proposed temporal shifts in relative stress magnitudes is as yet unknown, but it may be related to stress relaxation or changes following significant bursts of tectonic activity. It will be interesting to find out which style of deformation fills the White Mountains seismic gap (Wallace, 1984). Although it lies between the sites of the 1872 Owens Valley strike-slip event to the south and the 1932 Cedar Mountain, dominantly strike-slip event 150 km to the north, this gap also includes normal faults, and historic normal faults are dominant farther to the north. The seismic belt in which this gap lies cuts across tectonic province boundaries and includes both normal and strike-slip events during the past 120 years. We have not been able to determine whether stress perturbations can occur within such a time span or whether some other mechanism explains the Owens Valley faulting.

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