Long dormancy, low slip rate, and similar slip-per-event for the Emerson fault, eastern California shear zone

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Abstract. Excavations in a playa along the 1992 rupture of the Emerson fault reveal evidence of two paleoseismic events, with only one large prehistoric rupture in the past 15 millennia. Accelerator mass spectrometer radiocarbon ages of charcoal from playa sediments and from fault-scarp colluvium directly beneath the playa beds indicate that the last large prehistoric slip event occurred about 9000 ka. Trench-wall exposures revealed clear evidence of at least one pre-9 ka rupture at the playa site. The event horizon of this earthquake is between two pedogenic carbonate layers that have radiocarbon ages of 14.8 ka and 24.1 ka, implying that the earthquake occurred about 20,000 years B.P. The actual bracketing ages for this rupture are likely a few thousand years older because of the mean residence time for the pedogenic carbonate and calibration of the ^{14}C ages by ^{230}Th dating. Despite the large uncertainties, a dormant period of at least 6 kyr to as much as 13 kyr separates the older event from the 9 ka event. Because the scarp formed by the penultimate event is similar in height to the scarp formed by the 1992 M_W 7.3 Landers earthquake, the penultimate rupture was, at least locally, similar in size to the most recent rupture. This similarity supports the concept of characteristic slip for the Emerson fault. Preliminary results from paleoseismic studies at other sites on the 1992 rupture suggest that large ruptures occurred on other nearby faults within a few hundred years of this penultimate event on the Emerson fault. The interseismic period that preceded the 1992 earthquake on the Emerson fault was about 40 times longer than the average interval between large events on the nearby San Andreas fault. Therefore, in comparison to events on the San Andreas fault, the 1992 Landers earthquake was an exceedingly rare event.

Introduction

The M_W 7.3 Landers earthquake of 1992 is one the largest magnitude strike-slip events to occur in the western hemisphere during the 20th century. The length of rupture is surpassed only by those of the 1906, 1948, 1958, and 1976 ruptures of the San Andreas, Queen Charlotte Islands, Fairweather, and Motagua faults. The amount of slip (as much as 6 m) is comparable to that produced those events. Also, the earthquake occurred in a region of relatively dense seismographic and geodetic instrumentation and in a populous state that many seismologists call home. Spectacular, well-exposed, surface faulting accompanied the event. Hence the earthquake attracted a great deal of attention and yielded an immense quantity of seismographic, geodetic, and geologic data that help understand the nature of the earthquake, its tectonic setting, and its implications for future activity in southern California. These data also stimulated wide-ranging discussions regarding the nature of seismicity and fault interactions [*Harris and Simpson*, 1992; *Harris et al.*, 1995; *Stein et al.*, 1992].

The Landers earthquake rupture occurred within an 80-km-wide belt of northwest striking, right-lateral slip faults in the central Mojave Desert, which comprise part of the eastern California shear zone (ECSZ) [*Dokka and Travis*, 1990]. This zone has only recently been widely recognized as an important element of the modern Pacific-North American plate boundary (Figure 1). Geodetic measurements across the ECSZ have shown that northwest trending dextral shear strain is accumulating at a rate of about a 10 mm/yr [*Sauber et al.*, 1986, 1994; *Savage et al.*, 1990]. Geological mapping documents tens of kilometers of post-middle Miocene dextral offset across the ECSZ [*Dokka*, 1983; *Dokka and Travis*, 1990]. Prior to 1992, several faults within the ECSZ were recognized as active and had been placed within legal Special Studies Zones by the California State Geologist [*Hart*, 1992]. Geological studies indicate a high probability of destructive earthquakes from faults within the ECSZ prior to the recent earthquake [*Wesnousky*, 1986].

The Landers earthquake generated slip on several north to northwest striking right-lateral faults within the ECSZ (Figure 1) [*Sieh et al.*, 1993]. Rupture of three, en echelon, right-stepping faults, the Johnson Valley, the Homestead Valley, and the Emerson faults, produced most of the earthquake's seismic moment (Figure 1). During the earthquake, rupture progressed as a northward propagating slip pulse [*Wald and Heaton*, 1994; *Cohee and Beroza*, 1994], but *Wald and Heaton's* [1994] inversion of geodetic and seismographic data reveals distinct retardations of the rupture front at two stepovers that separate the three major fault segments [*Spotila and Sieh*, 1995; *Zachariasen and Sieh*, 1995]. Hence each of the three major faults may have been the source of a temporally distinct subevent. Coseismic right-lateral slip on these faults was commonly greater than 2 m
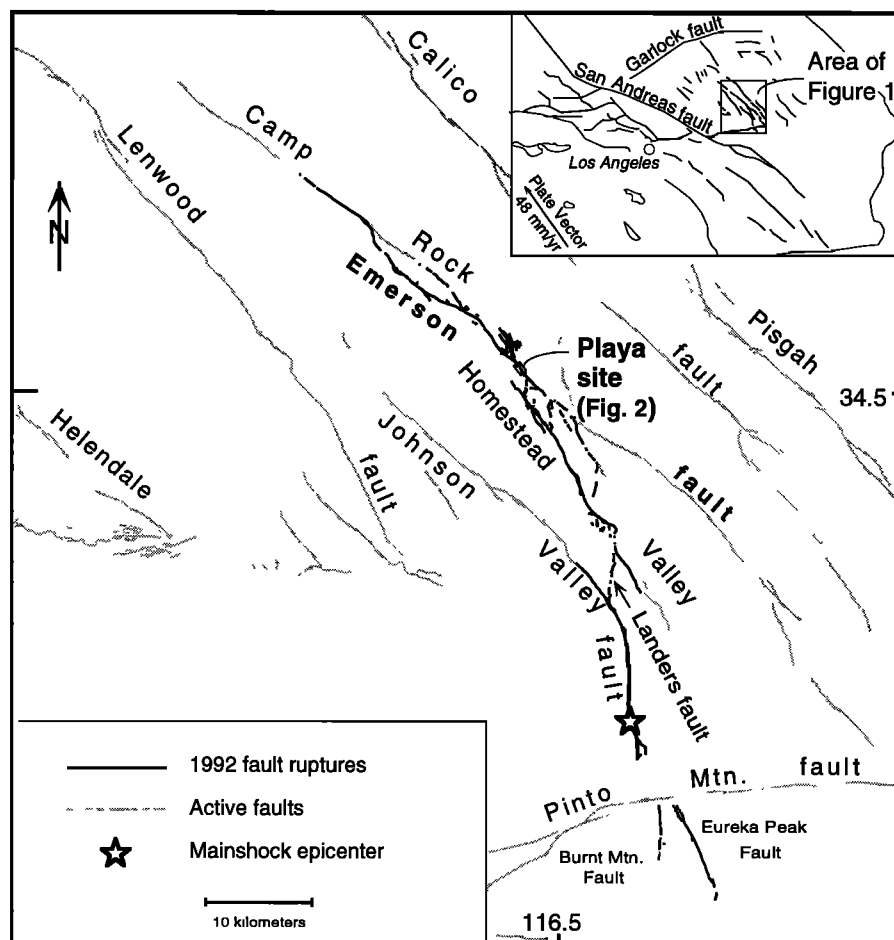
Figure 1. Map of the 1992 Landers earthquake surface rupture and faults of the central portion of the Eastern California shear zone (Mojave Desert) (modified from *Sieh et al.* [1993] and *Dokka and Travis* [1990]). Inset shows North American and Pacific plate boundary and major active faults. Fault map modified from *Dokka and Travis* [1990] and *Jennings* [1975]. Plate vector direction and rate from *DeMets et al.* [1994].

[*Sieh et al.*, 1993]. Another principal fault of the earthquake, the Eureka Peak fault, produced major aftershocks about 30 sec and about 3 min after the onset of the mainshock [*Hough*, 1994].

Important questions about the seismic behavior of the ECSZ and about earthquake processes have arisen from the phenomenology of the Landers earthquake. The role of geologic structure in the initiation, termination, and retardation of seismic rupture has been clarified by the earthquake, at a time when attempts to construct dynamic models of fault rupture have also proliferated [*Harris and Day*, 1993; *Ben Zion and Rice*, 1993; *Rice*, 1993]. The complexity of the 1992 rupture has renewed debate about the physics of the earthquake process. Why did several discrete faults fail in one earthquake? Why did some faults only break along part of their length? Why, for example, did the Johnson Valley fault rupture northward only to its intersection with the Landers/Kickapoo fault, rather than propagating rupture along its northern half? Similarly, why did the Emerson fault rupture only northward from near the termination of the Homestead Valley fault and not southward as well? And why did the Camp Rock fault only fail along a 10-km-long segment at the northern end of the 1992 rupture zone? The occurrence of the Landers earthquake also has raised questions concerning the likelihood of other large earthquakes within the ECSZ and on the nearby San Andreas fault [*Stein et al.*, 1992; *Harris and Simpson*, 1992; *Jaume and Sykes*, 1992].

Because the answers to all of these questions hinge on understanding the spatial and temporal relationships of large earthquakes within the ECSZ, paleoseismic data are critical. The past rupture history of the faults and fault segments must be known in order to understand why the 1992 rupture proceeded along certain faults and fault segments and not others.

A comprehensive investigation of the paleoseismic history of the principal faults that ruptured during the 1992 Landers earthquake and of other faults in the ECSZ currently is underway. Several investigators are collaborating to piece together a record of surface rupture on the major faults in the ECSZ during the past few tens of thousands of years, and this paper focuses on the paleoseismic history at one site along the Emerson fault where surface rupture occurred in 1992.

The Playa Site

The 1992 rupture of the Emerson fault traverses sand and gravel alluvium along most of its length [*Bortugno and Spittler*, 1986]. Material suitable for radiocarbon dating is sparse in the coarse-grained alluvium, given the scant vegetation and rapid oxidation of organic matter in dry, porous deposits. To increase the chance of finding datable material, we selected a site along the 1992 rupture that traversed a small playa where fine-grained
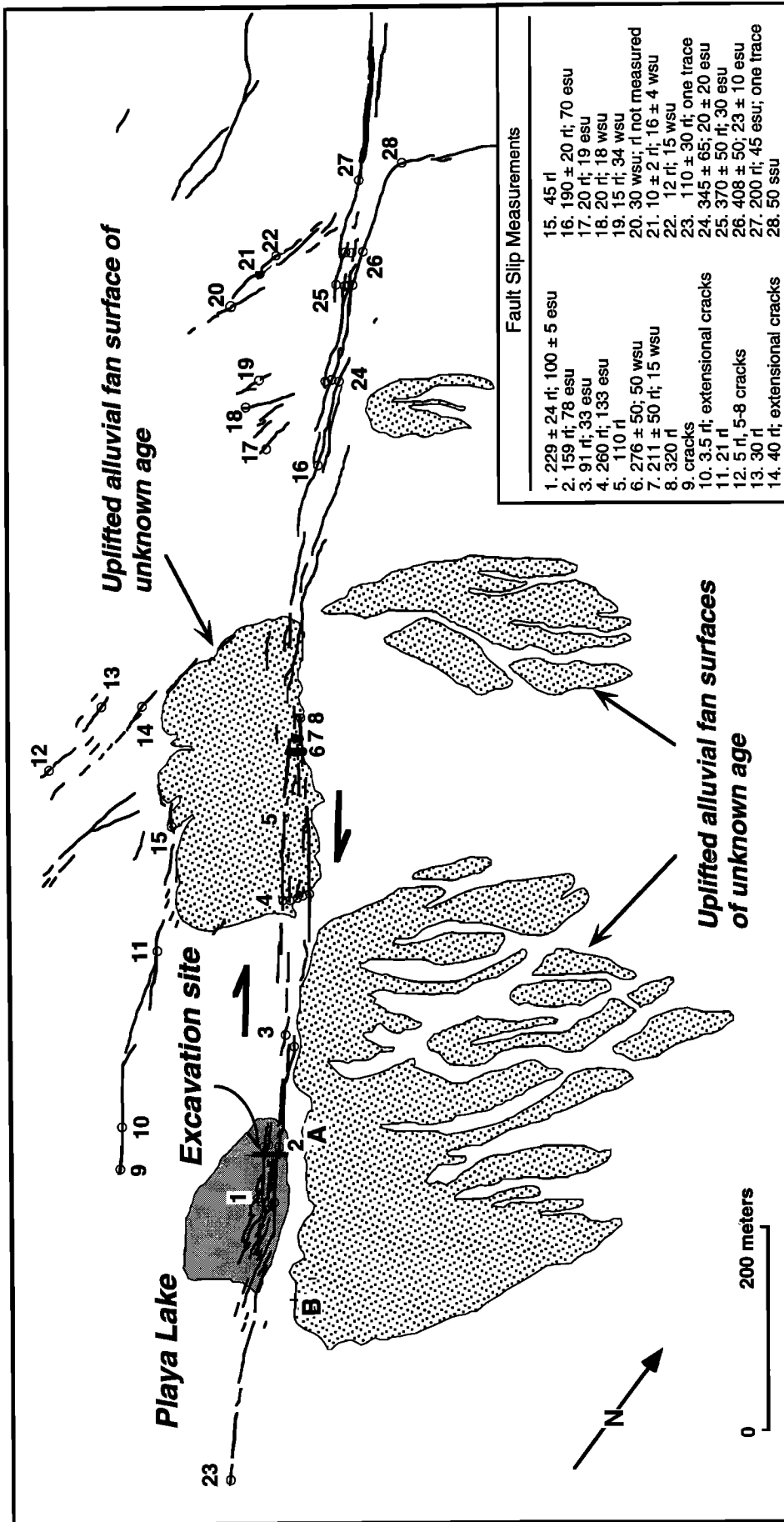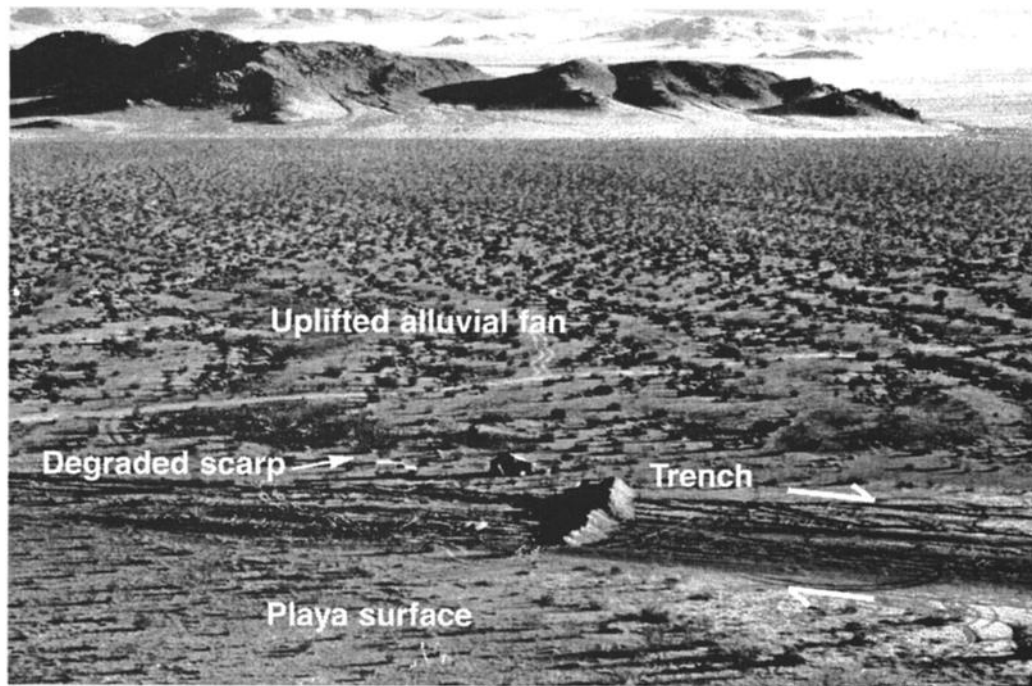
Figure 2. Schematic map of surface faults along the Emerson fault near the playa site, including measurements of 1992 offset [*Rubin and McGill*, 1992]. Solid circles, east-side-up (esu); solid circles, west-side-up (wsu); south-side-up, ssu; rl, right-lateral. A, soil site A; B, soil site B.

Figure 3. Oblique photograph of excavation at the playa site on the Emerson fault. Photograph taken from a hill to the west of the playa; view is to the east. Arrows indicate location and sense of slip on the Emerson fault.

lacustrine sediments favor preservation of detrital charcoal and offer a more complete depositional record (Figures 1, 2, and 3).

Deformation During 1992

The playa site is near the middle of the mapped length of the Emerson fault but near the southern end of the part that ruptured in 1992 (Figures 1 and 2). The amount of right-lateral slip reached a maximum value of about 6 m a few kilometers north-west of the site and diminished to the southeast and the northwest [*Rubin and McGill*, 1992]. The sense of vertical slip varied from east-side-up to west-side-up along the central section of the Emerson fault. The playa site is at a stepover between the Emerson to the Homestead Valley fault and *Zachariasen and Sieh* [1995] show a complete transfer of about 3 m of 1992 slip from the Homestead Valley to the Emerson fault *via* small, right-lateral faults in the stepover zone. Dextral slip on the Emerson fault decreases to the southeast as deformation is trans-ferred to small faults in the stepover region.

The amount of 1992 dextral and vertical slip along this stretch of the Emerson fault varies markedly [*Rubin and McGill*, 1992]. At the playa site, for example, offset motorbike tracks indicate 1.5 m of dextral slip, and about 50 m to the southeast, the dextral slip increases to about 2.3 m. The vertical offset at the excava-tion site is about 78 cm, east-side-up, and about 20 m to the southeast, vertical offset increases to about 100 cm, east-side-up.

At the excavation site, the 6-m-wide fault zone traverses the playa, and the northeastern shoreline deposits lap onto a low scarp (Figures 2 and 3). To the southeast near the edge of the playa, the fault zone widens and bends to the south. At this bend, the preearthquake playa shoreline is no longer horizontal, thus recording the coseismic deformation from the Landers event (Figure 4).

Geomorphic Setting and Evidence of Earlier Deformation

Evidence of prehistoric deformation along the northern Emerson fault consists principally of uplifted and truncated alluvial-fan surfaces of unknown age (Figure 2). The north-eastern shore of the playa overlies sandy, pebbly debris derived from a shallow, embayed slope on the southwestern flank of a truncated alluvial fan surface. The source of the fan lies in the hills to the southeast of the playa. Although no quantitative evidence for the age of these surfaces exists, soils underlying the surface have been described by W. B. Bull (written communi-cation, 1994). The fan surface is covered with a desert pavement of pebbles and cobbles, which is underlain by two distinct soils, each characterized by a well-developed (stage III) calcareous (K) horizon (Figure 5). Well-dated soils on similar substrates in arid environments elsewhere in the southwestern United States are between 20,000 and 50,000 years [*Bull*, 1991; *Machette*, 1985]. It is reasonable, therefore, to estimate that the age of this surface is 20-50 ka.

The total height of the scarp indicates uplift likely occurred during multiple previous events. The subdued nature of scarps and other small tectonic landforms along the fault, however, led *Sieh et al.* [1993] to conclude that the previous major surface rupture along the northern Emerson fault occurred at least several millennia prior to the 1992 event. Diffusion modeling of scarp profiles at "Stanford Hill," which is about 4 km northwest of the playa site, support the interpretation that the previous major ver-tical displacement occurred at least several thousand years ago [*Arrowsmith and Rhodes*, 1994].

Stratigraphic Relations in the Excavation

Our excavation crosses the Emerson fault near the northern edge of a small playa (Figures 2, 3, and 4). We mapped the
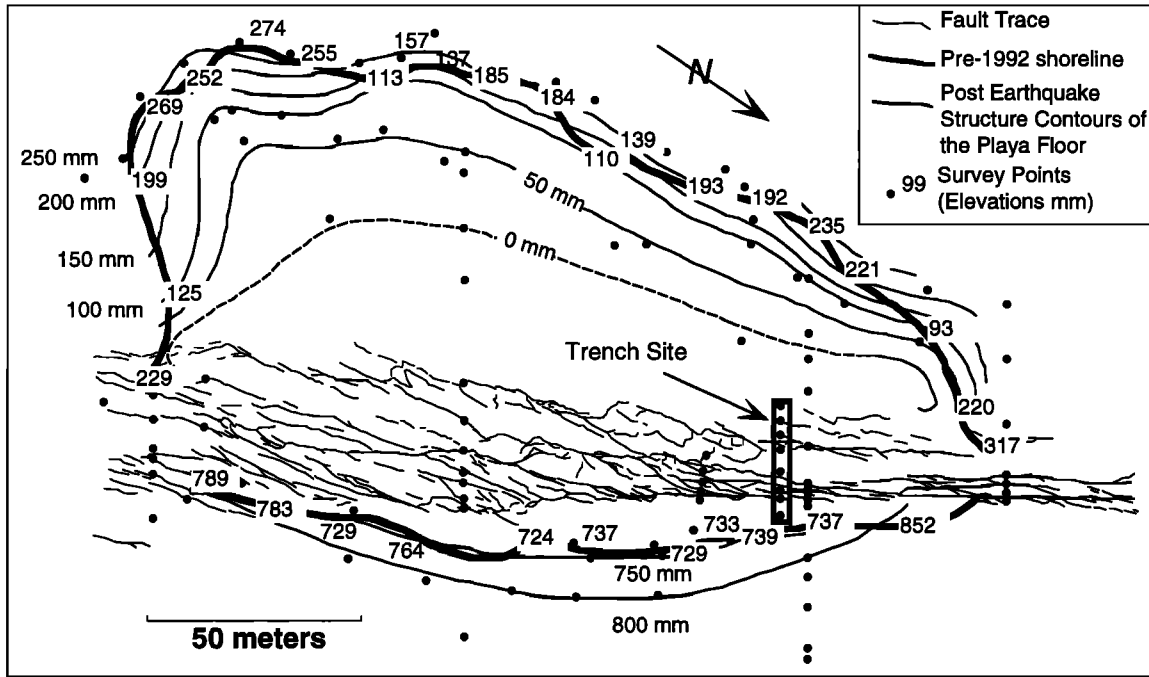
Figure 4. Detailed topographic map of the playa lake floor. Elevations of the pre-1992 shoreline, surveyed by an electronic EDM/theodolite indicate coseismic vertical deformation; arbitrary datum used. Southwest of the fault, shoreline has been vertically warped as much as 274 mm.
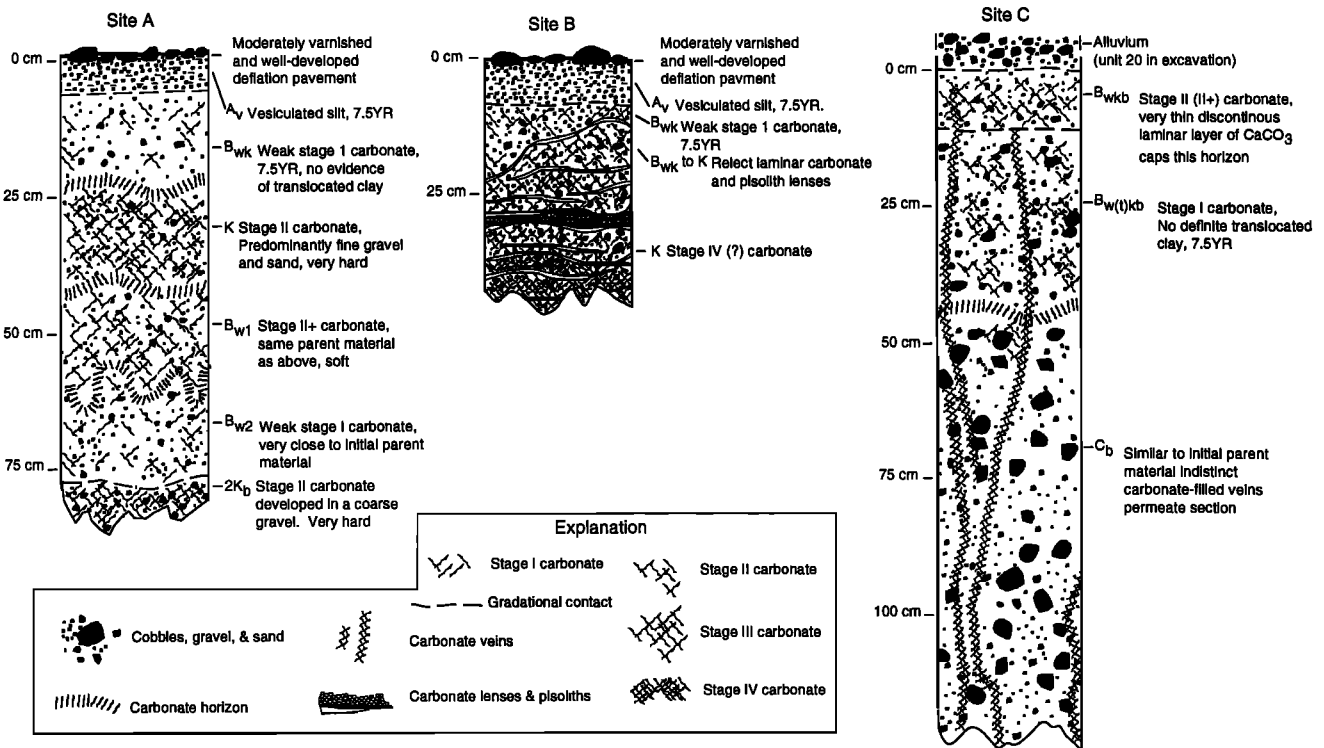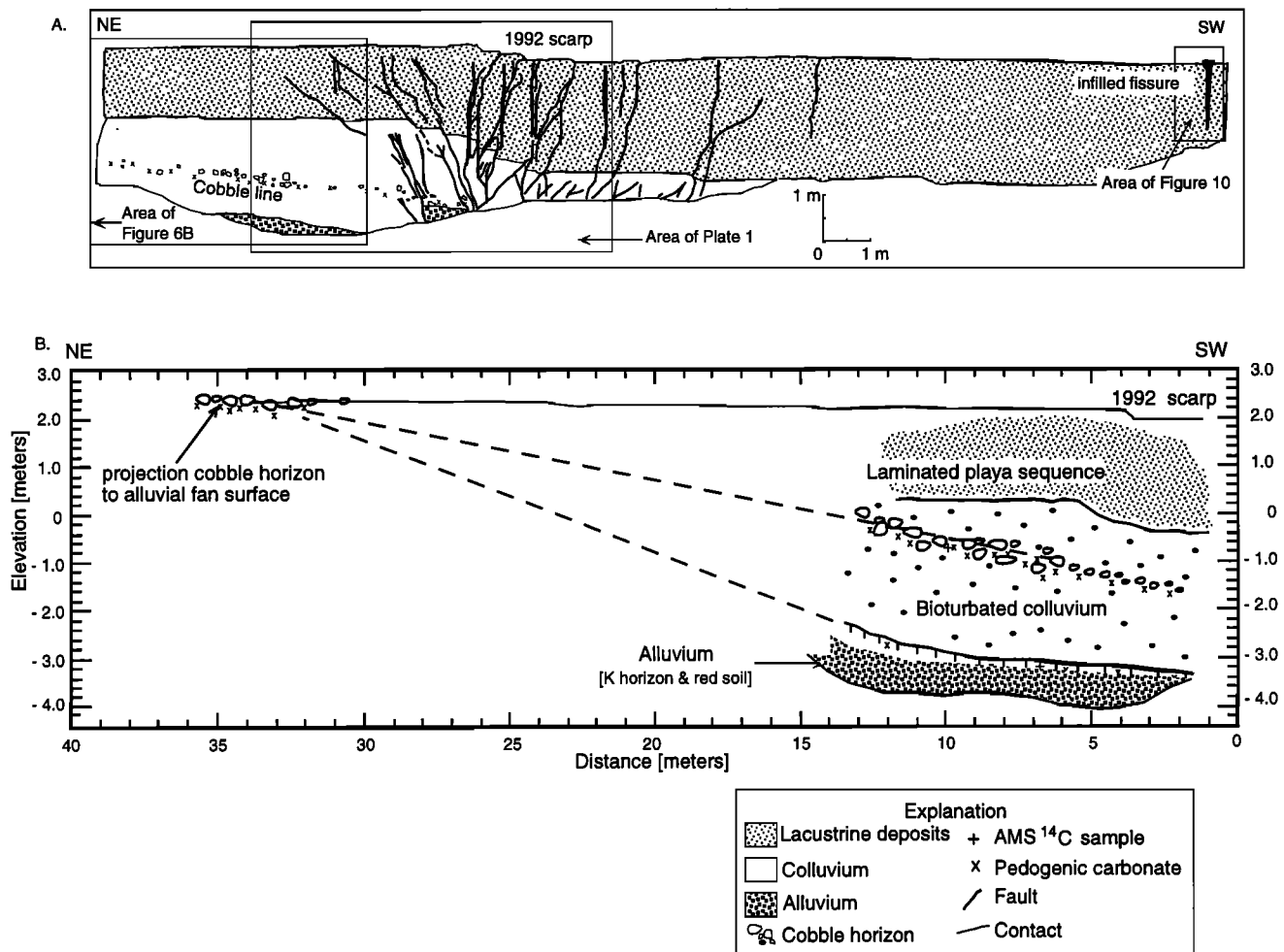

Figure 5. Schematic diagram of soil profiles at sites A and B from the area near the playa site (W. B. Bull, written communication, 1994). Site locations A and B are shown in Figure 2; site C is a soil pit in the bottom of the excavation.

Figure 6. (a) Generalized cross-section across the southeastern wall of the trench, which was approximately perpendicular to the fault zone. Surface offset from the 1992 earthquake is 71 ± 2 cm. (b) Topographic profile and geologic cross section across the Emerson fault at the playa showing relations between various units and the alluvial fan surface. Because the dendro-corrected ages are not available for samples older than 10,000 years, samples in units 20 and 10 are reported as ^{14}C years ago before 1950.

entire southeast wall of the excavation at a scale of 1:20. Unstable walls and slumping of beds below the playa deposits in the central one-third of the excavation prevented us from completely documenting the disruption associated with the principal fault zone.

Lacustrine, colluvial, and alluvial deposits exposed in the excavation were extensively to slightly modified by biogenic and pedogenic processes. The oldest exposed unit is a red soil developed on a pebble- and cobble-bearing sand (same as alluvium shown on Figure 6). A radiocarbon analysis of soil carbonate within this bed yielded a nominal radiocarbon age of about 24,000 years. Overlying the red soil is a thick, massive, bioturbated pebbly silty sand (same as bioturbated colluvium shown on Figure 6). This sand unit contains a cobbly calcareous horizon that dips gently to the southwest, which yielded a nominal radiocarbon age of 14.8 ka. Both the cobbly horizon and the soil project northeastward to the surface of the old alluvial fan, described above (Figure 6). Northeastward thinning, laminated, silt deposited in the playa overlie and lap onto the massive sand (Plate 1). Radiocarbon analyses of detrital charcoal in these laminated playa beds yield calendric ages of 7.8 to 9.0 ka.

Major stratigraphic units exposed in the excavation are numbered in ascending stratigraphic order (Plate 1). The oldest exposed unit 10 is a red, silty, sandy calcareous gravel. The upper part of the gravel contains a stage II to II+, B_{wkb} horizon topped by thin, laminar layers of calcium carbonate (W. B. Bull, written communication, 1994) (Figure 5). The horizon is distinctly red but contains little evidence of translocated clay, similar to several well-dated soils in arid settings in southern California [*Machette*, 1985]. The duration of pedogenesis in these similar soils commonly is several thousand years. The upper surface of the soil projects to, and thus appears to be correlative with, the top of the old alluvial fan (Figure 6b). The alluvial fan surface exposed in the excavation originally sloped northeastward, but has been tilted several degrees about a horizontal axis parallel to the fault and now dips southwestward toward the playa. A greater amount of K horizon development on the exposed alluvial fan surface to the east is consistent with the interpretation that gravel unit 10 is its downdropped correlative.

The fan surface exposed in the excavation was buried after some degree of pedogenesis. Local erosion of some of the alluvial fan surface resulted in burial of the fan surface and rede-
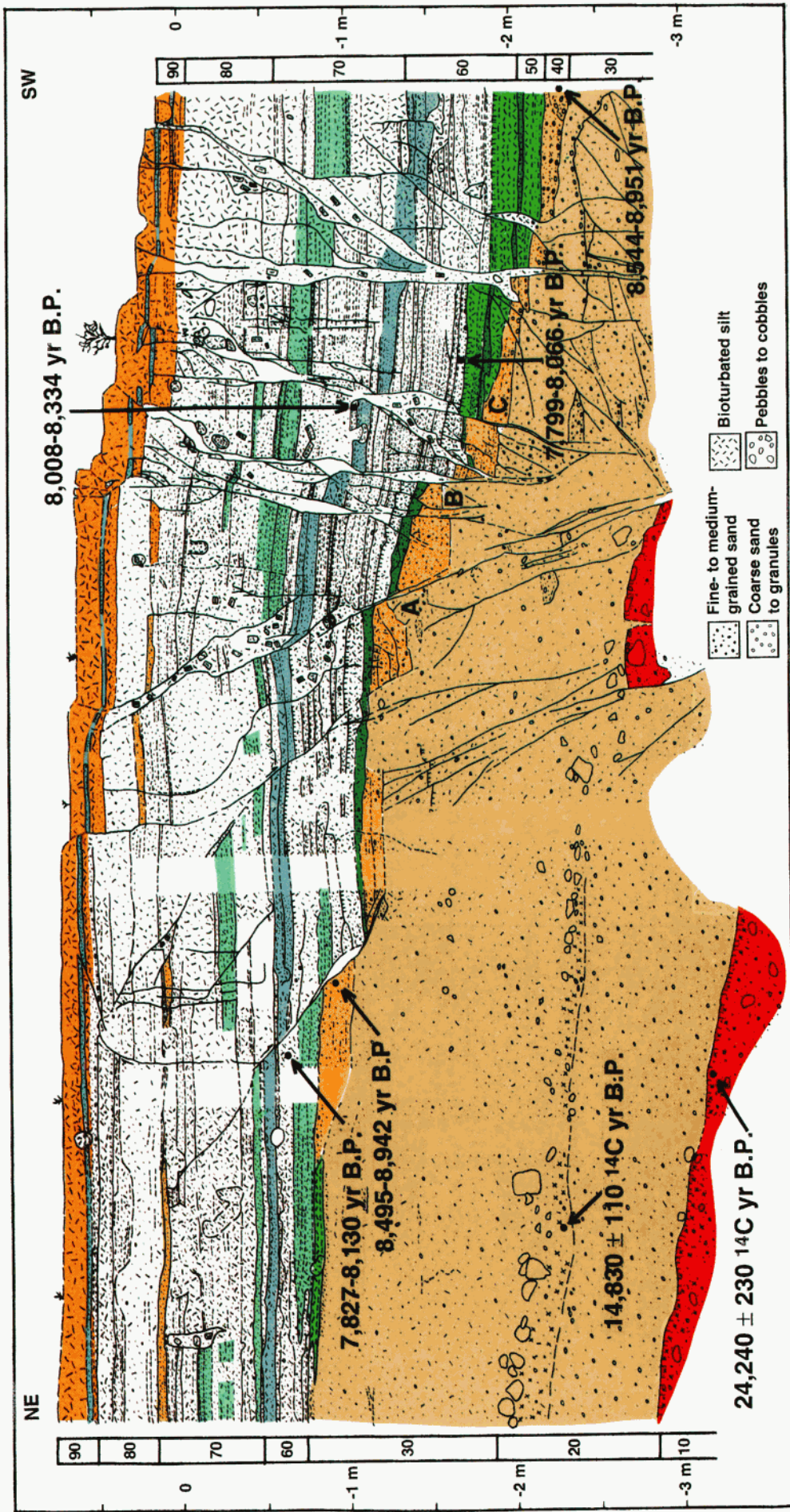
Plate 1. Detailed map of southeastern wall of the trench across the Emerson fault zone. The excavation was approximately perpendicular to the fault zone. Key units related to faulting history are colored. Area of Plate 1 shown in Figure 6. Evidence of two faulting events prior to the 1992 event are present in the section, one between units 10 and 30 and another at the top of unit 30. No vertical exaggeration.
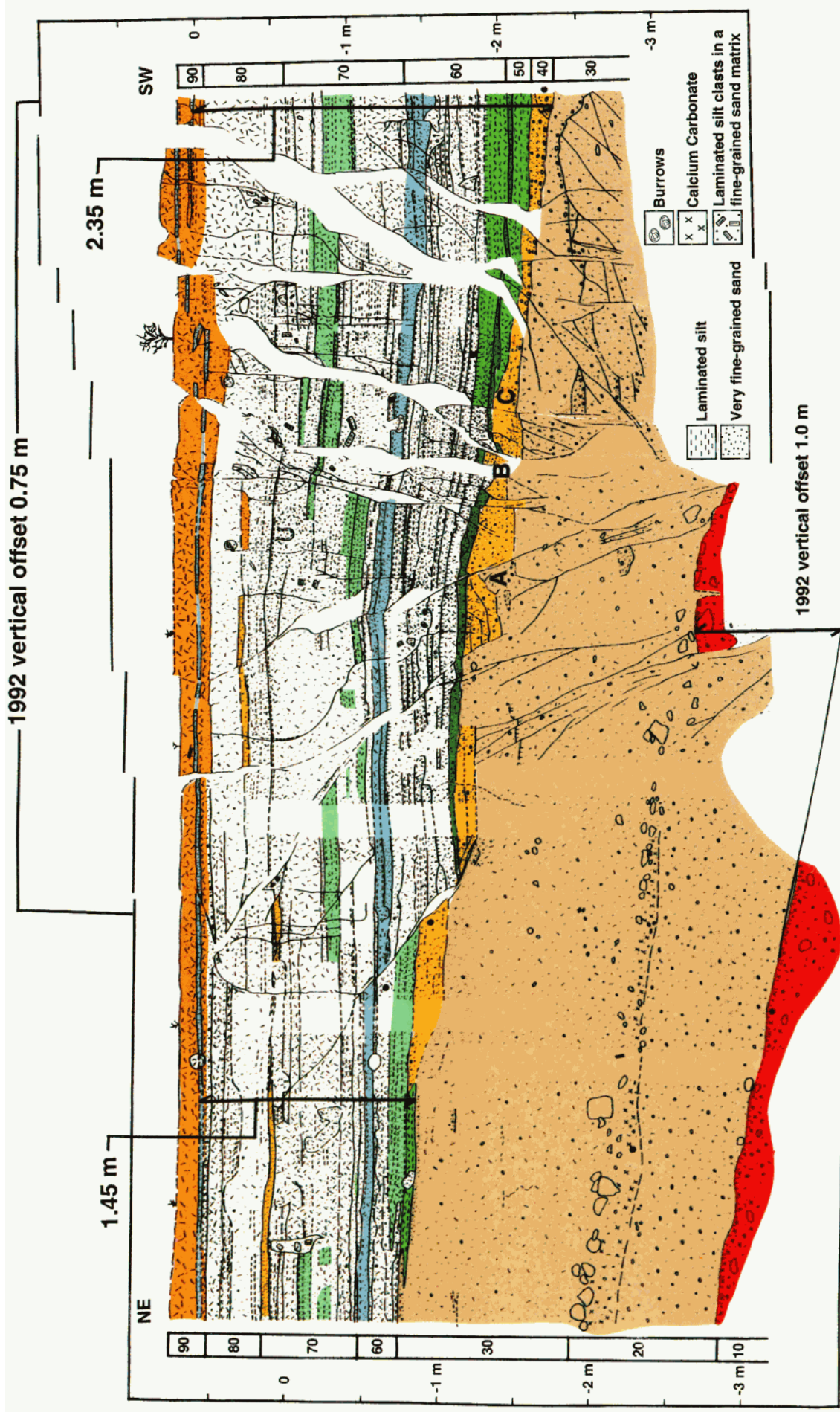
Plate 2. Palinspastic reconstruction of the strata in the trench wall prior to the 1992 Landers earthquake reveals topography on base of the playa beds associated with an older fault scarp. Units 40-80 change thickness across the scarp by about 100 ± 2 cm. No vertical exaggeration.

position of these alluvium in the adjacent playa, which is now preserved as units 20 and 30 directly above unit 10. Units 20 and 30 are poorly sorted, massive, silty, pebbly to cobbly sands (Plate 1). Although the units are massive, the proportion of fine sediment varies locally, so that the unit has a heterogeneous texture. The top of unit 20 is distinguished by a calcareous (stage II) matrix and a concentration of pebbles and cobbles, many of which have $CaCO_3$ coatings. This unit dips about 5° toward the playa and away from the alluvial fan surface (i.e., similar to underlying red soil).

The only plausible source for the large clasts is the uplifted alluvial fan to the northeast of the playa (Figure 6). The lack of an impermeable layer beneath the calcareous member of unit 20 suggests that the carbonate did not form by the advection of water through the unit. The horizon is more likely a pedogenic feature, formed by the downward migration of carbonate into the unit, when it was at the ground surface. The amount of calcium carbonate is evidence of a substantial period of pedogenesis during which the colluvial surface was neither aggrading nor eroding rapidly. Radiocarbon dates on calcium carbonate in the colluvium of unit 20 provide an estimate of the duration of pedogenesis, which is no more than a few thousand years.

The massive but heterogeneous character of units 20 and 30 are typical of highly bioturbated alluvial and colluvial sediments in southern California [e.g., *Sieh and Jahns*, 1984; *Grant and Sieh*, 1994; *Yeats et al.*, 1997]. The wedge-shaped geometry of the units and their southwestward dip (Plate 1) suggest that they are a colluvial deposit formed from erosion of the alluvial fan to the northeast. Although the unit might have formed as thinly bedded sheets or channelized flow of pebbly sand washed off the sloping alluvial fan surface, bioturbation by animals or plants could have destroyed the bedding. The absence of burrows in the calcareous cobbly stratum suggests that unit 20 was thoroughly churned prior to deposition of unit 30. Furthermore, the abrupt upper contact of unit 30 is a clear indication that bioturbation occurred prior to burial by overlying units.

Unit 40 is a discontinuous, loose, poorly sorted, sandy deposit, with minor amounts of silt and small pebbles. Subjacent unit 30 is distinctly less friable due to a higher percentage of silt. The presence of discontinuous laminae of silt and sand within unit 40 indicates that, unlike unit 30, it has not been extensively bioturbated. Both upper and lower contacts of unit 40 are sharp and dip southwestward. In the center of Plate 1, the unit rests upon a faulted, irregular upper surface of unit 30. Farther southwest the unit is wedge-shaped, thinning to the southwest.

The coarseness of unit 40 indicates transport, either by alluvial or colluvial processes. The southwestward sloping base of the unit suggests a source to the northeast, and the onlapping
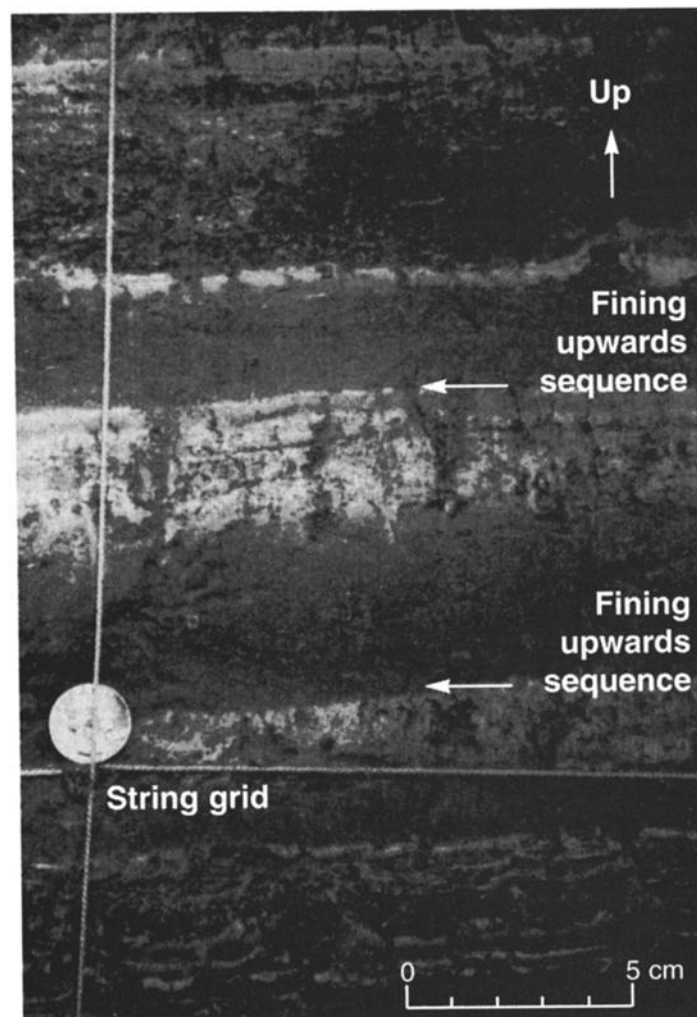
Figure 7. Photograph of bioturbated, planar laminated, normally graded bedding within the playa sequence. Individual fining upward sequence represent settling of suspended load during individual inundations of the playa.

and interfingered lacustrine sediment directly above unit 40 demonstrates that this slope is an original depositional slope, not a consequence of tectonic deformation. Thus unit 40 was probably derived from the gentle colluvial slope that flanks the playa (Figures 3 and 6b). The rapidly thinning geometry of unit 40 is additional evidence that the deposit had a local source.

Well-laminated, but locally bioturbated, silt and very fine sand overlie colluvial units 30 and 40 and comprise most of the sediment in the upper part of the excavation. These fine-grained deposits dominate units 50 through 90 and are shown in green and blue on Plate 1. The laminated beds are normally graded (Figure 7).

Bedding shape, grain size, and sedimentary structures of the laminated beds indicate a lacustrine origin; the normal grading and distribution of grain sizes are typical of suspended sediment deposited in standing water [Reading, 1986]. The lack of ripple marks or scour-and-fill is additional evidence of deposition in quiet water. Planar-laminated beds are wedge-shaped and exhibit pronounced thinning or pinchout toward the colluvial slope to the northeast. These deposits thicken toward the center part of the playa where the water was deeper and persisted longer.

Locally, coarse beds occur within units 50 through 90. They are poorly sorted, fine to coarse sand that contain rare granules. These beds are best preserved in units 50 and 60 and thin slightly southwestward, downslope and toward the center of the modern playa. Units 50 and 60 interfinger with the silt and fine-sand lacustrine beds but are too coarse-grained to be suspended load. We interpret these deposits as thin sheets of debris that were eroded from the gentle slope on the northeast side of the modern playa surface. The fine to coarse sand deposits appear to have been buried soon after deposition by suspended sediment during subsequent floods in the playa.

Most of the uncolored parts of units 50 through 90 are silt to fine sand that contain scarce coarse sand to small pebbles (Plate 1). Generally these units are not well laminated or normally graded. Their upper and lower contacts are commonly discontinuous, which indicates extensive bioturbation. The bioturbation increases upward, which implies either a decreasing rate of deposition or more vigorous bioturbation. Roots are probably the principal bioturbation agent. The paucity of circular or arcuate features (i.e., Krotovina) within the bioturbated layers suggests that burrowing animals did not play a major role in homogenizing the sediment.

Geochronology

Units 10 and the upper part of unit 20 contain pedogenic carbonate, and units 40 and 60 contain fragments of detrital charcoal; therefore all four units are datable by radiocarbon analysis. Radiocarbon dating, performed by G. Burr at the National Science Foundation University Arizona Accelerator Mass Spectrometer (AMS) Facility (Table 1), yielded ages that, within formal error, are stratigraphically consistent and indicate that units 10 through 30 are latest Pleistocene in age and that units 40 through 90 are early to late Holocene in age.

Detrital charcoal from undisturbed parts of unit 60 yielded three radiocarbon ages, within a calendric range of 7800 - 8340 years B.P. (Table 1 and Plate 1). These charcoal fragments were probably derived from burned plants on the adjacent alluvial or bedrock surface that were carried into the playa by runoff. Two samples from lower unit 60 yielded nearly identical age ranges of 7827 - 8130 and 7799 - 8066 years B.P., whereas the uppermost bed of unit 60 yielded a slightly older age of 8008 - 8334 years B.P. Although the mean ages of these samples are out of stratigraphic order by about 100 years, the ages are stratigraphically consistent at the 95% confidence level.

Detrital charcoal provides a maximum age estimate of the strata that contain it. The charcoal, although friable, could be a century or more older [e.g., Grant and Sieh, 1994] than the deposit. In this case, the small discrepancy in detrital radiocarbon ages is most easily understood if we assume that the ^{14}C date from uppermost unit 60 is from a sample that is about a century older its depositional age, indicating an age of about 7908 - 8234 years B.P. for the uppermost unit 60.

Two radiocarbon analyses on small fragments of charcoal constrain the time of deposition of unit 40. The cell structure of these charcoal pieces indicates that they were probably derived from plants. The proximity of the source of unit 40 suggests that these plants were growing on the nearby colluvial surface. The two date ranges are nearly identical: 8544 - 8951 years B.P., and 8495 - 8942 years B.P. We interpret that these samples as establishing a maximum age for the initiation of playa deposition across the scarp. This age range for the unit 40 charcoal is statistically distinct from that of overlying unit 60. The radiocarbon dates indicate that the main phase of playa deposition began between about 7.8 ka and 8.9 ka.

Geochronologic constraints on the age of colluvial units 20

Table 1. Radiocarbon Analyses

Sample[*]					
Lab	Field	Stratigraphic Unit[†]	$\delta^{13}C$, ‰	^{14}C Age,[‡] years B.P.	Calendar Ages,[§] B.P.
AA10785	EFPS-C23	60	-25	7145 ± 65	7799-8066
AA10778	EFPS-C6	60	-25	7210 ±80	7827-8130
AA10776	EFPS-C2	upper 60	-25	7425 ±60	8008-8334-
AA10781	EFPS-C16	40	-22.9	7860 ± 40	8495-8942
AA10775	EFPS-C1	40	-21.9	7905 ± 40	8544-8951
AA10784	EFPS-C22[#]	20	-3.7	14,830 ± 110	
AA10783	EFPS-C21[#]	10	-3.5	24,240 ± 230	

[*] Samples listed in stratigraphic order.

[†] Units are labeled in Figure 7.

[‡] Reported ^{14}C ages use Libby's half-life (5568/years); sample and standard ^{13}C values are normalized to -25‰ except where indicated. Analytical uncertainties are 1 standard deviation.

[§] Calendar ages from program of Stuiver and Reimer [1993]. Method B, 20 yr. calibration curve, and 2 standard deviation uncertainty. Because the dendro-corrected ages are not available for samples older than 10 kyrm , samples C21 and C22 are reported as ^{14}C years B.P.

[#] Samples EFPS-C21 and C22 are pedogenic carbonate, other samples are detrital charcoal.

and 30 are less certain than those for the playa sediments because they are derived from pedogenic carbonate. The nominal age of the carbonate in upper unit 20, which was from sandy, $CaCO_3$-rich matrix in the cobble horizon, is about 14,800 ^{14}C years B.P. (Plate 1 and Table 1).

Three principal difficulties arise in using the radiocarbon date to assign an age to the cobble bed. First, the carbonate cement formed after deposition of the cobble bed. If the carbonate cement precipitated from advecting groundwater, then the radiocarbon date could be substantially younger than the cobble horizon. If the carbonate formed pedogenically, then it is slightly younger than the cobble horizon but older than overlying unit 30. The second uncertainty in interpreting the radiocarbon analysis is the origin of the carbon. Unlike the carbon in the detrital charcoal, it is unclear if the carbon in the carbonate was in equilibrium with the atmosphere at the time of its deposition. In the vicinity of the playa, however, incorporation of "dead" carbon is unlikely because calcareous bedrock is not present in the drainage of the playa, and no calcareous clasts are present in the alluvial fan from which the cobble line is derived. Furthermore, no clasts of pedogenic carbonate from the underlying red soil were recognized in unit 20. The third problem concerns the calibration of radiocarbon ages with calendric ages. The ratio of radiocarbon to stable carbon in the atmosphere has varied significantly with time, creating a "reservoir effect" [Stuiver and Pollach, 1977]. Precise corrections currently are not possible for late Pleistocene samples, but recent comparisons of radiocarbon and U/Th ages suggest that late Pleistocene radiocarbon ages are two to three thousand years younger than the actual age of the sample [Edwards et al., 1993]. If the pedogenic carbonate in unit 20 formed when the cobble bed was a few tens of centimeters beneath the ground surface, then its age would postdate deposition of the bed. If we adopt a 2 kyr reservoir correction and then add about 3 kyr for the time to bury the cobble horizon and allow calcium carbonate to accumulate through pedogenesis, then the calendric age of the cobble bed is about 20,000 years B.P.

We also have a radiocarbon analysis of pedogenic carbonate in the red soil, unit 10. That analysis yielded a radiocarbon age of about 24.2 kyr. If we adopt the same 2 kyr reservoir correction and add a few thousand years for pedogenic accumulation of calcium carbonate, then we estimate that the old soil formed about 28 ka.

Evidence of a Previous Earthquake

A 6-m-wide zone of complex faults and fractures (Figure 6) defines the Emerson fault in the trench. Based on the dextral offset associated with the 1992 earthquake, most local faults accommodated right-lateral slip in addition to the vertical motion displayed in the trench wall. Mismatches in the thickness of beds across many of the faults is evidence of this lateral slip. The playa surface at the top of the excavation was vertically offset about 80 cm, which is similar to the values measured near the trench soon after the earthquake.

Restoration of the dip slip on the 1992 faults reveals the approximate geometry of the playa beds prior to the earthquake (Plate 2). Voids and vertical mismatches in the restored cross section result from restoring only the vertical motion on irregularly shaped faults in the oblique-slip fault zone. Because the surface of the excavation was disturbed by the backhoe, the laterally continuous and undisturbed unit 60 was used to restore 1992 motion across the trench.

Despite minor mismatches, all of the beds in the playa sequence are nearly contiguous when the 1992 vertical offset is restored, which implies that no vertical offsets as large as that of 1992 has occurred across this fault zone since deposition of the playa beds began about 7.8 to 8.9 ka. Although minor mismatches may imply minor events, two other lines of evidence demonstrate that no centimeter-scale or larger offsets have occurred in the past 8.9 kyr. First, where beds are well preserved adjacent to fault planes, no fault-scarp colluvial wedges are present on either side of the fault. Furthermore, we did not find sloping erosional unconformities that would mark the upper part of an eroded scarp. If faults had moved more than a few centimeters during the past 8.9 kyr, then such erosion and deposition would be apparent in the laminated playa sediment adjacent to the faults. Only in the heavily bioturbated parts of units 70 and 80 would such evidence be impossible to detect.

Abrupt thickening of individual playa beds is also potential evidence of syndepositional faulting. Given the shallowness of the playa, a scarp a few tens of centimeters high would have created a significant difference in the depth of water across the fault. This would lead to abrupt changes in bed thickness across the fault scarp and draping of units over a paleoscarp. Such features are not present in the section.

Evidence for a major faulting event is present in the colluvium directly below the playa beds. Several minor faults, which were not reactivated in 1992, are truncated at the base of unit 40. This is evidence of faulting prior to deposition of unit 40. At one location ("A" in the center of Plate 2), the base of unit 40 has an irregular slope, suggesting that it was deposited upon a northeast-facing fault scarp. Further, the steepness of this slope (about 40°) indicates that unit 40 buried the scarp before degradation occurred. Observations of historical scarps suggest at gravitational collapse may occur within a few decades of an earthquake [Clark, 1972], and we suspect that this small scarp was buried quickly before it was extensively eroded.

The wedge-shaped geometry of unit 40 adjacent to two other faults that slipped in 1992 ("B" and "C" in Plate 2) is evidence of a nearby fault scarp that was at least as high as the thickness of unit 40. These scarps degraded and produced colluvial debris soon after scarp formation. The actual scarp from which the wedge formed is not present in the plane of the trench wall, so it must have been moved out of the plane of the exposure by dextral slip in 1992.

Based upon well-documented historical examples, colluvial wedges forming at the base of fault scarps in materials as erodable as unit 30 develop much of their total thickness in just a few years to decades [Clark, 1972; Machette, 1975; Wallace, 1977; Lubetkin and Clark, 1988]. On this basis, we suspect that the faulting event probably occurred within the age ranges of the two charcoal samples from unit 40, that is, between about 8.5 and 9.0 ka. A minimum estimate of the scarp height from this paleoseismic event can be made by adding the differential thickness of each colluvial wedge; this yields a minimum height of about 85 cm.

The difference in thickness of the playa beds across the paleoscarp provides an independent scarp-height estimate. The restored cross section (Plate 2) shows that the playa units thicken southwestward across the fault zone and that most of this thickening is in the lower part in the playa section. The thickening does not occur abruptly at individual faults but occurs gradually across a distance of many meters. Several individual beds are associated with small notches in the uppermost colluvial beds and even interfinger with the uppermost colluvium. These

relationships provide evidence that the playa beds were deposited adjacent to a gentle colluvial slope, which was steepest in the vicinity of the fault zone.

The minimum height of the paleoscarp was 90 cm, based on the thickness differences in playa sediments across the fault zone; this is consistent with the estimate based on thickness of colluvial wedges. The thickness of the playa sediments directly northeast of the fault zone is about 1.45 m, whereas the thickness of the sediments southwest of the fault zone is about 2.35 m (Plate 2). The difference in thickness of these two sections, about 90 cm, closely approximates the height of the paleoscarp calculated above from differential thickness of colluvial wedges.

Speculation on Another Holocene Event

Despite the lack of evidence for a significant amount of surface rupture along the active fault trace during the last 8.9 kyr, possible evidence of a younger event is present a few meters west the fault zone. Here, a fissure, infilled with younger playa sediment, intersects the southwestern trench wall and clearly breaks the playa sediments between depths of about 0.4 to about 1.7 m (Figure 8). The fissure is not present (at least in the plane of the trench wall) more than 1.7 m below the present ground surface nor is it present in the northwestern trench wall. The formation and filling of the fissure were contemporaneous with deposition of beds about 0.4 m below the present surface of the playa. Beds adjacent to the fissure are not noticeably deformed, so the feature must have formed by erosion along a thin crack. If so, the eroded material must have been carried downward or laterally out of the plane of the trench.

Using an average rate of playa sediment accumulation, we estimate that the fissure is about 1,300 years B.P. The date of the fissure-forming event could be slightly older than our estimate, if the more extensive bioturbation of the upper playa beds implies that the upper section of the playa beds accumulated at a slower rate than the lower section.
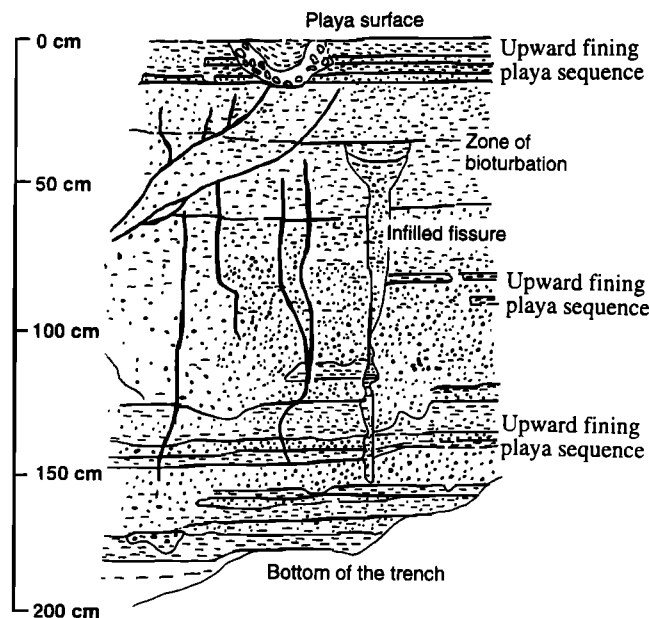
Figure 8. Sketch of infilled fissure, which may have formed from seismic shaking produced by a rupture of a nearby fault. Location of fissure in trench is shown in Figure 6. Dots indicate sand; dashes indicate silt; circles indicate pebbles. Playa deposits shown here correspond to units 60-90 in Plate 1.

Whether the fissure is evidence of a previous earthquake is uncertain. It is not associated with any recognizable scarp nor is it associated with disruptions in the principal fault zone. Fissuring and related collapse pits are common in the arid regions of the North American southwest, and in many cases they can be related to deformation and cracking in areas of historical groundwater pumping [*Pampeyan et al.*, 1988]. In other cases, they form by downward flow of water into cracks and faults that are related to recent earthquakes [*Clark*, 1972; *Holzer and Clark*, 1993]. Both of these explanations are improbable in this case. Groundwater has not been withdrawn from this remote location in historic times, and the lack of filled fissures within the fault zone strongly argues against this fissure forming along a tectonic fracture. In addition, there is no underlying fracture beneath the fissure, as shown in Figure 8.

Although minor rupture on the Emerson fault at the playa site cannot be ruled out, we do not believe the paleofissure is a tectonic feature because contemporaneous filled fissures are not present within the fault zone. The linearity of the fissure rules out an origin as an infilled root channel from a large plant. The filled fissure may have initiated as a crack that resulted from seismic shaking produced by rupture of a nearby fault.

Late Pleistocene Faulting at the Playa Site

Collapsing of the trench walls prevented us from completely exposing the red soil, cobble layer, and colluvial units 10 and 20 in most of the trench. Hence we could only partially document the record of late Pleistocene faulting. Furthermore, the generally massive character of colluvial units 20 and 30 made it difficult to distinguish colluvial packages events that might be present in these deposits. Nevertheless, we recognize evidence of at least one large prehistoric event within these units.

At the northeastern edge of the fault zone, the red soil has an east-side-down separation of 1 m, whereas the cobble line in unit 20 has a west-side-down separation of less than 0.3 m (Plate 1). The cobble horizon is a diffuse bed, so its separation cannot be restored precisely. If the 1992 separation of the base of the playa is restored, however, the cobble line across the fault has little or no separation (Plate 2), which contrasts with the separation of ~75 cm on the red soil in this restoration.

We interpret this separation on the top of unit 10 as strong evidence of at least one major slip event between formation of the red soil and deposition of the cobble layer. If the discrepancy between the vertical separations of the red soil and the cobble horizon is the result of a single event, then slip during that event was large. We estimate that the scarp would have been about 1 m high, which is slightly larger than and opposite in throw to the 1992 scarp. The massive character of unit 20 makes it difficult to determine if this throw occurred in one event or more than one event.

The lack of erosion of the red soil from the upthrown block is notable and implies that the uplifted red soil was buried by at least a meter of colluvium prior to the event. Furthermore, the fault juxtaposes massive, bioturbated colluvium against the red soil and underlying alluvium, suggesting that the event occurred after deposition and bioturbation of the unit 20 colluvium. Thus the offset must have occurred after formation of the red soil and shortly before deposition of the cobble layer. In this scenario, disruption occurred closer to our 20 ka estimate for the cobble layer than to the 28 ka estimate for the soil.

No clear evidence from the trench indicates deformation between this event and the last prehistoric event of 8.9 ka. We

cannot rule out the possibility, however, of large ruptures between about 20,000 and 8,900 years B.P on the principal faults of the 1992 zone. The faults in colluvium at the lower right of Plate 1 are most likely related to the 8.9 ka event but could be interpreted as evidence for an older event. These faults dip steeply southeastward into the trench wall, away from the viewer. Thus we could determine whether or not they extended up to the base of unit 40 (horizon of the 8.9 ka event) or terminate beneath it.

Discussion

Holocene Slip Rate for the Emerson Fault and Tectonic Implications

Paleoseismic data presented here indicate a low slip rate for the Emerson fault at the playa site, although the average slip rate for the fault is difficult to calculate due to its long recurrence interval and the variable amount of slip along strike. The average lateral slip rate for the Emerson fault at the playa site during the most recent earthquake cycle is about 2 m over 9 kyr or ~0.2 mm/yr. Approximately 6 km to the north on the fault where 1992 offsets were 6 m, extensively degraded fault scarps and uplifted alluvial deposits suggest similarly long recurrence intervals. There, stream gullies across the Emerson fault scarp are subdued and have low gradients [Arrowsmith and Rhodes, 1994]. Thus the recurrence interval determined at the playa site may be similar to that 6 km to the north. There, 1992 dextral offsets were as large as 6 m, so the average slip rate calculated there for the fault is ~0.7 mm/yr (6 m over 9 kyr). Because the playa site is near the stepover between the Emerson and Homestead Valley faults, other faults may accommodate some of the slip, thus the 0.2 mm/yr slip rate at the playa should be a minimum value. The 0.7 mm/yr rate determined farther north may be a better estimate for the main fault.

In addition to the Emerson fault, other crustal faults in the ECSZ, including the Helendale, Lenwood, Johnson Valley, Camp Rock, Calico, and Pisgah-Bullion Mountain faults, contribute motion to the strain budget across the Pacific-North American plate boundary (Figure 1) [Dokka and Travis, 1990]. The long recurrence interval for the Emerson fault at the playa site indicates that one or more of the other six major fault zones of the ECSZ must slip much more rapidly than the Emerson in order to accommodate the reported geodetically determined rate of 7-12 mm/yr [Sauber et al., 1986, 1994]. If this rate is divided by the seven major faults, then the average rate is 1-1.7 mm/yr, which is higher than the rate we propose for the Emerson fault. This average slip rate also is supported by the distribution of the total slip on each of these faults. Dokka and Travis [1990] estimate a total of ~65 km of net right-lateral slip across the entire ECSZ, but only 1.5-4 km of this slip has occurred across the Emerson-Camp Rock fault [Dokka, 1983; Dokka and Travis, 1990]. If the modern role of individual faults in the ECSZ reflects their relative importance throughout shear zone development, then the total geologic offset across the ECSZ and the Emerson fault can be used to estimate the proportion of slip that is accommodated by the Emerson fault . If the maximum geologic offset on the Emerson fault is 4 km and the total offset across the ECSZ is about 65 km, then the Emerson fault accommodates about 6% of the total offset. Six percent of the 7-12 mm/yr geodetically determined rate across the ECSZ yields a rate of about 0.4-0.7 mm/yr for the Emerson fault, which is comparable to the paleoseismic rate of 0.2-0.7 mm/yr. The age of the Emerson fault can be estimated by dividing total geologic

offset of 1.5-4 km by the paleoseismic rate of 0.2-0.6 mm/yr, which yields an estimate of 2.5-20 m.y. old.

Seismic Implications of Faulting in the Eastern California Shear Zone

The complex rupture pattern of the 1992 Landers earthquake sparked questions regarding the recurrence intervals of these faults and the validity of the characteristic earthquake hypothesis. Our paleoseismic studies, along with similar studies along the 1992 Landers earthquake rupture (e.g., northern Johnson Valley, Homestead Valley, and Lenwood faults), provide basic information on the behavior of these faults and indicate recurrence intervals of the order of thousands of years [Hecker et al., 1993; Herzberg and Rockwell, 1993; Rockwell et al., 1993; Padgett and Rockwell, 1994]. The last prehistoric rupture on the Homestead Valley fault may have been coeval with that on the northern Emerson fault, or may have been as much as a 3 kyr later.

The interval between these prehistoric events and 1992 is more than an order of magnitude longer than recurrence intervals for the San Andreas fault [Sieh et al., 1989; Sieh, 1986]. During the Holocene epoch, for example, large earthquakes produced by the Emerson fault appear to have occurred about forty times less frequently than on the nearby San Andreas fault. Thus the 1992 event was an exceedingly rare event, with respect to faulting on the San Andreas fault.

The last events on the northern Johnson Valley and northern Emerson faults produced a scarp, similar in width and vertical displacement of the 1992 rupture [Herzberg and Rockwell, 1993]. The timing of the last earthquake on the northern Johnson Valley fault is nearly indistinguishable from the time of the last large earthquake on the northern Emerson fault, as well as the penultimate prehistoric earthquake on the Homestead Valley fault [Hecker et al., 1993]. The Lenwood fault also ruptured in the same time period [Padgett and Rockwell, 1993]. If major prehistoric earthquakes occurred about 9 ka on the northern Emerson, northern Johnson Valley, and Lenwood faults and were no more than a few hundred years apart, then it is possible that these faults rupture in temporal clusters, similar to the pattern of normal-fault ruptures observed this century in the Central Nevada Seismic belt [Wallace, 1978, 1984, 1987].

Conclusions

Paleoseismic excavations along the 1992 rupture of the Emerson fault record only one prehistoric rupture in at least the last 15 kyr, and the last prehistoric rupture occurred about 9 ka. Because the scarp that formed during this prehistoric event is similar in height to the scarp formed during the 1992 M_w 7.3 Landers earthquake, the penultimate rupture was similar, at least locally, to the 1992 rupture. This similarity supports the concept of characteristic slip for the Emerson fault. The playa site also provided clear evidence of at least one pre-Holocene major rupture, about 20,000 years B.P. Despite the large uncertainties in the actual bracketing ages, a dormant period of at least 6 kyr separates this event from the 8.9 ka event.

The most recent interseismic period for the Emerson fault at the playa site is about 40 times longer than the average interval between large events on the nearby San Andreas fault. Thus the 1992 Landers earthquakes was a rare event compared to the frequency of large earthquakes produced by the San Andreas.

The local slip rate of the Emerson fault at the playa site is

only about 0.2 mm/yr, but the actual long-term rate of the Emerson fault is probably closer to 0.7 mm/yr. This rate is only one-tenth to one-twentieth of the geodetically determined inter-seismic rate of strain accumulation across the entire ECSZ; thus the Emerson fault contributes relatively little to overall strain accumulation across the ECSZ. A similarly low ratio of total geologic slip across the Emerson fault to total estimated slip across the ECSZ demonstrates that the current minor role of the Emerson fault is also representative of its long-term role.

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