Holocene slip rate of the central Garlock fault in Southeastern Searles Valley, California

McGill, Sally; Sieh, Kerry

1993

McGill, S., & Sieh, K. (1993). Holocene slip rate of the central Garlock fault in Southeastern Searles Valley, California. *Journal of Geophysical Research*, 98, 14217–14231.

<https://hdl.handle.net/10356/79869>

<https://doi.org/10.1029/93JB00442>

© 1993 American Geophysical Union. This paper was published in *Journal of Geophysical Research* and is made available as an electronic reprint (preprint) with permission of American Geophysical Union. The paper can be found at the following official URL: <http://dx.doi.org/10.1029/93JB00442>. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Downloaded on 26 Apr 2023 18:50:11 SGT

Holocene Slip Rate of the Central Garlock Fault in Southeastern Searles Valley, California

SALLY MCGILL¹ AND KERRY SIEH

Seismological Laboratory, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena

A Late Pleistocene shoreline at the overflow level of Searles Lake has been displaced 82 to 106 m (preferred value is 90 m) in a left-lateral sense and 2.5 m (net) north side up along the Garlock fault, at the southeastern corner of Searles Valley. Previously published radiocarbon dates from both surface and subsurface strata indicate that the most recent highstand of Searles Lake ended sometime between 10,000 and 13,800 ¹⁴C years ago. The maximum slip rate of the Garlock fault in southeastern Searles Valley is thus 11 mm/¹⁴C yr. If part of the offset of the shoreline occurred during older lakestands, then the slip rate may be somewhat less. A channel incised after the most recent highstand, however, is offset about 68 m, indicating that the minimum slip rate is 5 mm/¹⁴C yr. Subjective evaluation of the constraints on the offset and on the age of the shoreline yields a preferred rate of 6–8 mm/¹⁴C yr at this site. Assuming Bard et al.'s (1990) recent calibration of the radiocarbon time scale, the calibrated slip rate of the Garlock fault is between 4 and 9 mm/yr with a preferred value of 5–7 mm/yr. This estimate is similar to a previous estimate of the Holocene slip rate and is slightly less than an estimate derived from modelling of geodetic data. Extension north of the Garlock fault in Indian Wells and Searles valleys contributes no more than 3 mm/yr left slip to the Garlock fault.

INTRODUCTION

The Garlock fault is an active, left-lateral fault that extends about 250 km from its intersection with the San Andreas fault to the southern end of Death Valley, California (Figure 1). A total of 48–64 km of left slip across the fault has been documented [Smith, 1962; Smith and Ketner, 1970; Davis and Burchfiel, 1973]. Left-lateral slip on the Garlock fault may accommodate extension in the Basin and Range province north of the fault [Davis and Burchfiel, 1973].

Although the fault has not produced any large earthquakes historically, geomorphic and stratigraphic evidence indicates that it has done so in the past. The most recent surface-faulting event occurred after 890 ± 195 ¹⁴C yr B.P. at Twin Lakes, on the western Garlock fault [LaViolette et al., 1980] and after 1490 A.D. in Searles Valley, on the central Garlock fault [McGill, 1992]. Paleoseismic work suggests recurrence intervals ranging from 200 to 1700 years for surface-faulting events [Burke and Clark, 1978; LaViolette et al., 1980; Roquemore et al., 1982; McGill and Sieh, 1991]. Offset geomorphic features suggest left-lateral displacements of 2 to 10 m in individual slip events along various parts of the fault [Burke and Clark, 1978; Clark, 1970; Gupta et al., 1979; McGill and Sieh, 1991]. These displacements probably produced earthquakes of $M_w = 6.6$ to 7.8 [McGill and Sieh, 1991].

Several estimates of the slip rate of the Garlock fault have been made at various points along strike [LaViolette et al., 1980; Clark and Lajoie, 1974; Carter, 1980, 1982; Smith, 1975]. Better knowledge of the Holocene slip rate of the Garlock fault is important both for seismic hazard analysis and for improving our understanding of the Late Quaternary tectonics of the region. Some estimates of the recurrence interval are dependent on accurate knowledge of the slip rate at several places along strike

[McGill and Sieh, 1991]. Knowledge of the Garlock fault slip rate at several places along strike is also critical for understanding the tectonic role of the Garlock fault and its relation to the Basin and Range province north of the fault and to the proposed eastern California shear zone [Dokka and Travis, 1990]. Knowledge of the Garlock fault slip rate is also important for understanding how motion between the North American and Pacific plates is distributed [e.g., Weldon and Humphreys, 1986].

DESCRIPTION OF SITE

We base our estimate of the Garlock fault slip rate on the offset of a Late Pleistocene high shoreline of Searles Lake. Pleistocene Searles Lake was part of a chain of lakes that was fed by waters from the eastern flank of the Sierra Nevada via the Owens River [Gale, 1914; Smith, 1979]. Lacustrine sedimentation in Searles Valley began 3.18 m.y. ago, and lakes have occupied the valley intermittently since that time [Smith et al., 1983].

The overflow shoreline of Pleistocene Searles Lake crosses the Garlock fault in several places. The intersection of this shoreline and the fault is best preserved near the southwestern corner of the Slate Range, where the lake overflowed through Pilot Knob Valley. At this site, an abrasion platform and sea cliff have been cut by wave action into older alluvium and older lacustrine sediments. A 0- to 2-m-thick veneer of nearshore, lacustrine sands was deposited on this platform during the most recent highstands and pinched out against the sea cliff (Plate 1).

The shoreline angle, that linear feature formed by the intersection of the sea cliff and the abrasion platform, is offset in a left-lateral and vertical sense across two subparallel fault traces (Plate 1 and Figure 2), but the offset is difficult to measure precisely because the shoreline angle has been buried by colluvium. For this reason we had 20 backhoe trenches dug to locate the shoreline and the fault strands precisely (Figure 3). The relationships in the trench walls were documented by mapping the exposures at a scale of 1:20. The mapping was controlled by surveying to nails placed along the important contacts. Both walls of most trenches were mapped, but only one representative cross section is shown here. See McGill [1992] for the other cross sections.

¹Now at Department of Geological Sciences, California State University, San Bernardino.

Fig. 1. Reference map shows locations mentioned in text. Carter, area in which Carter's [1980, 1982] 11-12 mm/yr slip rate was determined; CC, Christmas Canyon; Clark & Lajoie, site at which Clark and Lajoie's [1974] 5-8 mm/ ^{14}C yr slip rate was determined; CR, Coso Range; GF, Garlock fault; OLF, Owl Lake fault; PKV, Pilot Knob Valley; SAF, San Andreas fault.

Most trenches across the shoreline revealed moderately sorted to well-sorted, unconsolidated to poorly consolidated, medium to very coarse sand that pinched out against a sea cliff cut into older alluvium or that interfingered with colluvium derived from a sea cliff (Figures 4 and 5). Other trenches revealed beach sands truncated by fault strands (Figure 6). In most cases the upper part of these beach deposits (and occasionally the entire thickness) is poorly sorted because of bioturbation, which has mixed colluvium and eolian silt with the well-sorted beach sands.

After mapping the trench walls, we excavated by hand along the shoreline to find the precise intersection of the shoreline angle with most of the major fault strands and with many of the minor fault strands (Figure 7). Each three-dimensional excavation was mapped at a scale of 1:10 or 1:5, with control again provided by a number of surveyed points within each excavation (e.g., Figure 8).

OFFSET OF THE SHORELINE

The excavations revealed that the shoreline angle is left-laterally offset a total of 82-106 m, with a preferred value of 90 m (Table 1). A brief explanation of the offset measurements across each part of the fault zone is given below. Detailed justification of the measurements and uncertainties is given by McGill [1992]. Descriptions of the piercing points used are given in the appendix.

The shoreline angle is offset 37 ± 1 m across the southern fault zone (Figure 9). The preferred value (37 m) is based on projection of the shoreline angle from trenches 10 and 18 to the

northernmost strand of the southern fault zone at P5 and on the intersection of the shoreline angle with that same strand at P3, as exposed in a three-dimensional excavation west of trench 9. This three-dimensional excavation showed that the northernmost strand of the southern fault zone is the only strand within the southern fault zone that has significantly offset the shoreline.

The presence of a small (≈ 10 -cm-high) fault scarp north of trench 2 (Figure 9) suggests the possibility of additional offset of the shoreline between trenches 3 and 4 on an extension of this fault, or on other, concealed faults. The location and trend of the shoreline angle in trenches 3 and 4, however, suggest that little or no lateral offset of the shoreline has occurred between trenches 3 and 4 (P7 to P8), although any extrapolation over such a distance must be considered tenuous.

There are no faults visible at the surface between trenches 4 and 11, but projection of the shoreline northwestward from trench 4 and southeastward from a hand excavation southeast of trench 11 suggests that the shoreline may have been offset up to a few meters on concealed faults between these two trenches (P9 to P10, Figure 9).

A zone of many, closely spaced faults that offset the shoreline 3-14 m left laterally lies about 6 to 14 m south of the northern fault zone and is here called the north central shear zone. The offset of the shoreline across many of these minor faults was measured directly in three-dimensional excavations from either side of trenches 11, 12, 19 and 13 (Figures 8 and 10). The offset of the shoreline across concealed faults between these excavations

Plate 1. Simplified geologic map of site and locations of some trenches. See Figure 3 for locations of all trenches. Southwestern limit of Late Quaternary beach and nearshore sand (yellow) indicates location of shoreline. Solid squares mark piercing points used to measure offset of shoreline on the two main faults. Additional offset of shoreline has occurred on minor faults not shown here. Solid circles are piercing points used to measure offset of top edge of western side of channel incised into shoreline. Topography is from photogrammetry by Aerial Photometrics, Fresno, California. Elevations in meters. Contour interval 0.5 m. Geologic mapping by S. McGill and G. Roquemore.

Fig. 2. Stereo-pair aerial photographs of the Late Pleistocene shoreline of Searles Lake offset by two major strands of the Garlock fault zone. In the photo at right, faults are shown by solid lines, the geomorphic expression of the shoreline is shown by dots and the top edge of the western side of the offset channel is shown by dashed lines. Solid lines in the photo at left show the area of overlap with Plate 1 and Figure 3. North is approximately toward top of photos. Width of each photo is about 360 m. Taken from U.S. Geological Survey photos supplied by M. Clark.

was estimated by projecting the trend of the shoreline from places where it was exposed. The offset of the shoreline across various parts of the north central shear zone is summarized in Table 2.

The minimum estimates of the offsets in the north central shear zone generally represent slip on discrete faults, either measured directly as exposed in three-dimensional excavations or inferred from projections of the shoreline. Commonly, the trend of the shoreline bends and becomes more parallel to the fault strands within a meter or so of many of the fault strands (Figure 10). This suggests that the shoreline may have been warped left-laterally near some of the faults, adding an additional increment of left-lateral shear that is not included in the measurements of slip on discrete faults. The maximum estimates of the slip across various parts of the north central shear zone, therefore, were made by projecting the trend of the shoreline from farther away from individual fault strands in order to include possible warping in the offset measurement.

For example, in the vicinity of trench 11, the shoreline is offset 0.7 m on a fault exposed in a three-dimensional excavation just northwest of trench 11 (P12 to P13) and is offset an additional 0.1 m on another fault exposed in the excavations less than 1 meter farther northwest (Figure 10). The sum of these slips on two discrete faults represents the minimum offset of the shoreline near trench 11 (Table 2). The maximum offset (1.8 m; Table 2) was obtained by projecting the trend of the shoreline from farther away from the fault (P11 to P14).

The shoreline is offset 42–46 meters across the northern fault zone, with the preferred value being 46 meters (Figure 11). Three-dimensional excavations revealed the intersections of the shoreline with the northern and southern edges of the northern fault zone, but offsets across individual strands within the northern fault zone were not measured. The uncertainty in the offset results from uncertainty in the original trend of the shoreline across the northern fault zone, prior to any faulting or warping. The maximum offset value uses the trend of the shoreline in the northern part of the three-dimensional excavation north of trench 13 to approximate the most northerly original trend that is likely (P32 to P33). The minimum offset value uses the trend of the

shoreline in the southeastern part of the excavation east of trench 5 to approximate the most westerly original trend that is likely (P32 to P34). We prefer the maximum offset value because it is likely that the trend of the shoreline in the southeastern part of the excavation east of trench 5 has been modified by warping and that it does not represent the original trend of the shoreline.

Significant offset of the shoreline on secondary faults north of the northern fault zone or south of the southern fault zone is unlikely. The incised channel east of the offset shoreline is not noticeably offset on any faults other than the two main fault zones, precluding major displacement away from these two zones. The presence of minor faults in trenches 7 and 15 (Figure 12) and vertical warping of the shoreline north of the northern fault zone (Figure 13) suggests that a small amount of left-lateral offset and/or warping may have occurred in this area. A subjective, but reasonable, upper bound on the amount of possible left-lateral warping and offset between trenches 5 and 20 is about 3 m (P37 to P38 in Figure 12). This value is obtained by projecting the most northerly trend of the shoreline revealed in the excavation east of trench 5 to P37.

Net vertical displacement of the shoreline across the entire fault zone is 2.5 meters, north side up (Figure 13).

AGE OF THE SHORELINE AND SLIP RATE OF THE GARLOCK FAULT

Lakes occupying Searles Valley have reached the overflow level several times between about 10,000 and 24,000 ^{14}C yr B.P. [Stuiver and Smith, 1979; Benson *et al.*, 1990; G. I. Smith, written communication, 1991]. Searles Lake also overflowed between about 120 and 135 ka and possibly around 50 ka (G. I. Smith, written communication, 1991). The degree of soil development in the beach deposits suggests that the offset shoreline features studied in this paper formed during one of the most recent highstands of Searles Lake, between about 10,000 and 24,000 ^{14}C yr B.P., rather than during one of the older highstands (O. Chadwick, oral communication, 1991). The texture and calcium-carbonate stage of the soil developed on the Searles Lake

Fig. 3. Geologic map shows locations of trenches and of Figures 9-12.

Fig. 4. Photograph of trench 12 before three-dimensional excavations were done. Qb, unconsolidated, moderately well sorted, coarse sand interpreted as Late Quaternary beach deposits. The beach deposits are underlain by older Quaternary(?) lacustrine and alluvial deposits and are overlain by colluvium. Beach deposits are about 1 m thick here; width of trench is about 1 m.

shoreline are comparable to and the structure is weaker than on profiles SL85-1a and SL85-2c on alluvial fans draining towards Silver Lake, about 100 km east of the site discussed in this paper [McGill, 1992; Reheis *et al.*, 1989]. The latter two profiles are formed on fan surfaces estimated to be approximately 35,000 and 11,000 years old, respectively [Reheis *et al.*, 1989].

Further constraints on the age of the shoreline are provided by geological relationships at the site. The offset channel east of the shoreline (Plate 1 and Figure 2) must have incised after the most recent one of the 10,000- to 24,000-year-old highstands; otherwise, deposits from the most recent lakestand would have filled the channel. The geometry of the offset channel would have protected any lacustrine sediments that had been deposited on the western side of the channel and just north of either of the two main faults from stream erosion (Plate 1 and Figure 2). The lack of lacustrine sediments in the channel thus indicates that the channel incised after the most recent highstand of the lake.

Comparison of the offset of the channel with the offset of the shoreline suggests that the shoreline features on either side of the southern fault zone are about the same age as the channel. The channel is offset about 35 m across the southern fault zone and about 33 m across the northern fault zone and north central shear zone combined. Because the shoreline angle is offset approximately the same amount across the southern fault as is the channel, the shoreline features on either side of the southern fault must have formed during the most recent highstand and the channel must have incised immediately (within one or two earthquake cycles) after that shoreline was abandoned. Apparently, the most recent highstand of the lake in this area reworked the beach deposits of earlier highstands and further incised the preexisting sea cliff, thus obliterating the evidence of offset of any shoreline features from previous lakestands.

Offset of the shoreline across the northern fault zone and the north central shear zone, however, is 10-20 m larger than the offset of the channel across those zones. This suggests that the shoreline features on either side of the northern fault strand may have formed during an earlier highstand and may not have been completely reworked by the youngest highstand.

The slip rate calculations are summarized in Table 3 and are explained briefly below. In calculating the minimum slip rate of 5 mm/ ^{14}C yr, we use the minimum offset of the channel rather than the minimum offset of the shoreline because the channel clearly incised after the latest highstand, whereas the shoreline in the vicinity of the northern fault zone may have formed during an earlier highstand and may not have been completely reworked during the latest highstand. For this same reason, the maximum slip rate (11 mm/ ^{14}C yr) may substantially overestimate the true slip rate. The preferred slip rate values (6-8 mm/ ^{14}C yr) are obtained by dividing the preferred offset of the channel and shoreline by the preferred age of the latest highstand. Again, the offset of the channel is used in addition to the offset of the shoreline because of the possibility that the shoreline features near the northern fault zone may be older than the latest highstand.

The constraints on the age of the most recent highstand of Searles Lake come from radiocarbon dates on disseminated organic carbon and inorganic carbonate minerals from cores near the center of the basin [Stuiver and Smith, 1979] and on shells, oolites, tufa, and marl from lacustrine sediments exposed at the surface [Benson *et al.*, 1990]. The minimum age of abandonment of the most recent highstand is the age of the top of the Parting Mud layer in cores from the center of the basin. This is the uppermost layer associated with deep lakes in the cores. The average of seven radiocarbon dates from the top of the Parting Mud is $10,500 \pm 165$ years [Stuiver and Smith, 1979]. The age of the top of the Parting Mud is a minimum age for the abandonment of the latest overflow shoreline because the lake may have dropped below the overflow level long before deposition of mud at the center of the basin ceased.

The CO_2 in the lake water was probably not in equilibrium with the CO_2 in the atmosphere, however, making all dates on materials that derived their carbon from the lake water too old [Stuiver and Smith, 1979]. The magnitude of this disequilibrium was probably such that radiocarbon dates from Searles Lake are between 500 and 2500 years too old, depending on the depth, salinity and stratification of the lake [Stuiver and Smith, 1979]. Stuiver and Smith [1979] favor the smaller correction for the age

Fig. 5. Cross section along southern wall of trench 18 shows beach deposits (Qb) interfingering with colluvium (Qc) derived from the sea cliff. Tic marks on top and bottom of cross section are 1 m apart and correspond to tic marks along the edges of trench 18 in Figure 9. Elevations labelled on sides of cross section are in meters above sea level. Hc, Holocene colluvium; Hs, well-consolidated layer cemented by silt; Qbb, bioturbated beach deposits; Qoa5, older Quaternary(?) alluvium; uc, unconsolidated; pc, poorly consolidated; mc, moderately consolidated; wc, well consolidated; vwc, very well consolidated. Logged by S. McGill and M. Slates.

of the top of the Parting Mud because the youngest lakes were probably stratified. Therefore we use 10,000 ^{14}C yr B.P. as a minimum age for the latest highstand.

As a maximum age for the most recent highstand of Searles Lake, we use the oldest radiocarbon date from deposits of the next previous highstand, 14,300 ^{14}C yr B.P. [Benson *et al.*, 1990]. Correcting this for disequilibrium between the CO_2 in the lake and the atmosphere yields a reservoir corrected maximum age of 13,800 ^{14}C yr B.P. Because the material dated came from deposits of the penultimate highstand, this date may considerably overestimate the age of the end of the latest highstand. On the other hand, radiocarbon dates on rock varnish on boulders at the overflow shoreline level are $13,610 \pm 110$ and $13,290 \pm 115$ ^{14}C yr B.P. [Dorn *et al.*, 1990], suggesting that the most recent shoreline may have been abandoned that early.

For our preferred age of the most recent highstand we use two radiocarbon dates on oolites and mollusks from surficial sediments of the most recent highstand. These dates are $11,730 \pm 350$ ^{14}C yr B.P. and $11,700 \pm 160$ ^{14}C yr B.P., respectively [Benson *et al.*, 1990; G. I. Smith, oral communication, 1991]. Following Stuiver and Smith [1979], we assume that only a minimal (500 years) correction for disequilibrium between the lake and the atmosphere need be made for the most recent highstand. We thus use 11,200 ^{14}C yr B.P. as the preferred age of the latest highstand.

Current efforts to calibrate the radiocarbon time scale with the U-Th time scale suggest that the radiocarbon dates used in calculating the slip rate may underestimate the true ages by 2000–3000 years [Bard *et al.*, 1990]. The slip rates reported in Table 3 are thus given in $\text{mm}/^{14}\text{C}$ yr and are appropriate for comparison with other slip rates based on radiocarbon dates. For some applications, however, an estimate of the slip rate in actual years is needed. If Bard *et al.*'s [1990] calibration is correct, then the slip rate values reported in Table 3 should all be reduced by about 1 mm/yr .

DISCUSSION

Comparison With Previous Estimates of the Slip Rate

The slip rate determined from the offset shoreline of Searles Lake is similar to (and much better documented than) the 5–8 mm/yr rate determined at Koehn Lake [Clark and Lajoie, 1974; Clark *et al.*, 1984]. Both of these slip rate estimates span roughly the same time period, that is, the past 10,000 to 15,000 years. Smith [1975] estimated a slip rate of about 1 mm/yr for the same time period at Christmas Canyon (Figure 1) on the basis of the 8-m offset of a channel incised into ~10,000-year-old lacustrine gravels. We regard this rate as a minimum, however, because the channel could have incised long after deposition of the ~10,000-year-old gravels. Carter [1980, 1982] reports an 11–12 mm/yr minimum slip rate on the basis of Pleistocene alluvial fans offset from their sources in El Paso Mountains. This suggests that the Garlock fault slip rate may have been higher during Pleistocene time than during Holocene time. Reevaluation of the fossils from which the age of the alluvial fans was estimated, however, suggests that the fans may be older than originally thought (D. Whistler, oral communication, 1992) and that the slip rate for the past 2.2 m.y. may have been as low as 7 mm/yr [McGill and Sieh, 1991, p. 21,618]. Thus there is no compelling evidence that the Garlock fault slip rate during late Pliocene and Pleistocene time was greater than the rate during Holocene time.

Carter [1982] cites separate evidence supporting an 11 mm/yr slip rate since middle Pliocene time, higher than most estimates of the Holocene slip rate. Documentation of this 11 mm/yr slip rate

Fig. 6. Late Quaternary beach deposits (Qb) truncated by faults in the eastern wall of trench 19. Ql, older Quaternary lacustrine deposits; Hc, Holocene colluvium. Faults 19C and 19D are also shown in Figure 8. White ruler is 15 cm long.

and discussion of its uncertainty have not been published, however.

Age of the Garlock Fault

The long-term slip rate of the Garlock fault has important implications for the age of the fault. If the slip rate of the fault since its inception has been comparable to the Holocene slip rate measured in Searles Valley (5–11 mm/ ^{14}C yr), then the ≈ 60 km of total left-lateral displacement across the fault must have begun between 12 and 5.5 m.y. ago (or between 15 and 6.5 m.y. ago if *Bard et al.*'s [1990] calibration of the radiocarbon time scale is correct). The evidence presented by *Carter* [1982] for a relatively high Pliocene slip rate (11 mm/yr) favors the younger end of this age range. On the other hand, sinistral rotation of the Ricardo Group, located just north of the Garlock fault and west of El Paso Mountains, began between about 11 and 9.5 Ma and ended by

about 7 Ma [*Burbank and Whistler*, 1987]. Perhaps an early period of left-lateral shear prior to formation of a throughgoing fault caused the sinistral rotations, and the cessation of rotation marks the onset of left-lateral translation along the newly formed Garlock fault. If this interpretation is correct, left-lateral slip on the Garlock fault began at about 7 Ma and the average slip rate since that time has been about 8 mm/yr, consistent with the estimates of the Holocene slip rate.

Comparison With Geodetic Measurements

Modeling of observations from a trilateration network across the Garlock fault suggests a slip rate of 12.7 ± 1.9 mm/yr at depth, if the locking depth is at the maximum depth of most historical seismicity on the fault (13 km) (M. Lisowski, written communication, 1991). This is somewhat higher than most geologic estimates of the slip rate, although it barely overlaps with

Fig. 7. Photograph of trench 11 after three-dimensional excavations were completed. Thin solid lines represent minor faults, thick dash-dotted lines represent the line along which moderately well sorted beach sand pinched out. Width of original trench is about 1 m.

Fig. 8: Map of three-dimensional exposure documents 1.9- to 2.1-m-offset of shoreline in the vicinity of trench 19 (Table 2). Sand pinchout is offset at least 0.6 m along fault 19F (P20 to P27), about 1.1 m along fault 19D (P28 to P29) and about 0.2 m along fault 19C (P30 to P30b). An additional 0.2 m of left-lateral slip could conceivably have occurred as warping (P30b to P30c). Shaded area is former lake floor. Southern boundary of lake floor is defined by pinchout of beach sand against sea cliff in places and by truncation of beach sand by faults in other places. Structure contour lines show the elevation of the lake floor in meters above sea level. Contour interval is 10 cm. See Figure 10 for location of this map.

the rate documented in this paper. One reason for the discrepancy between the geologic and geodetic estimates is that the trilateration network spans a width of 15 km about the fault, whereas the geologic estimates are primarily calculated from slip on discrete faults within a zone about 100 m wide. In addition, the presence of other active faults within the trilateration network complicates interpretation of the geodetic data.

Evaluation of the Transform Model for the Garlock Fault

If the Garlock fault acts as a transform fault accommodating east-west extension north of the Garlock fault, as proposed by Davis and Burchfiel [1973], then the rate of slip along the Garlock fault would decrease eastward. The agreement between the preferred values of the slip rate in southeastern Searles Valley with the rate at Koehn Lake indicates that if extension north of the

Garlock fault between these two locations contributes to slip on the Garlock fault, any such contribution is within the uncertainty in the slip rate measurements. Several lines of evidence suggest that extension is occurring in this area. This evidence includes the many small, Quaternary faults in Indian Wells Valley and in the Coso Range (Figure 1) [Jennings *et al.*, 1962], aligned volcanic cones [Duffield *et al.*, 1980; Roquemore, 1980], the orientation of the minimum compressive axes of earthquake focal mechanisms [Sanders *et al.*, 1988; Walter and Weaver, 1980], and the presence of a magma body beneath Indian Wells Valley [Sanders *et al.*, 1988; Ho-Liu *et al.*, 1988]. However, this extension contributes no more than 3 mm/yr of left-lateral slip to the Garlock fault. (Three millimeters per year are the difference between the minimum slip rate in southeastern Searles Valley and the maximum slip rate at Koehn Lake.)

TABLE 1. Summary of Offset Across the Entire Fault Zone

Area	Preferred Value, m	Piercing Points Used	Minimum Offset, m	Piercing Points Used	Maximum Offset, m	Piercing Points Used
Southern fault	37.0	P3 to P5	36.0	P3 to P4 + P1 to P2	38.0	P3 to P5
Between trenches 3 and 4	0	P7 to P8	0	P7 to P8	3.0	P6 to P8
Between trenches 4 and 11	2.0	P9 to P10	0	P10 to P10	2.0	P9 to P10
North central shear zone	5.4	See Table 2	3.6	See Table 2	13.6	See Table 2
Northern fault	46.0	P31 to P32 + P33 to P36	42.1	P31 to P32 + P34 to P35	46.0	P31 to P32 + P33 to P36
North of northern fault	0	P38 to P38	0	P38 to P38	3.0	P37 to P38
Total	90		82		106	

See Figures 9-12 for locations of piercing points.

Seismic Hazard

The offset of the Searles Lake shoreline documented in this paper probably occurred seismically (by repeated, discrete displacements associated with earthquakes) rather than by aseismic creep. An alignment array at Christmas Canyon, 10 km west of the offset shoreline discussed in this paper, has not detected any aseismic creep since it was installed in 1971 [Louie *et al.*, 1985]. Similarly, U.S. Geological Survey quadrilaterals have not detected any aseismic creep along this or other parts of the fault (M. Clark, written communication, 1990). Thus there is no evidence that

aseismic creep has occurred on this part of the Garlock fault, although the occurrence of aseismic slip prior to the establishment of these arrays and quadrilaterals can not be ruled out.

CONCLUSIONS

A Late Pleistocene shoreline at the overflow level of Searles Lake has been left-laterally offset 82-106 m across the Garlock fault zone in southeastern Searles Valley. Although the lake has filled to its overflow level several times in Late Pleistocene time, relations between the offset shoreline and an offset channel that

Fig. 9. Map documents offset of shoreline across the southern fault zone and possible offset between trenches 3 and 11. Offset across southern fault zone is most likely 37 m (P3 to P5) but could be as little as 36 m (P3 to P4) or as large as 38 m (P3 to P5 plus P1 to P2). Offset of the shoreline between trenches 3 and 4 is most likely 0 m but could be up to about 3 m (P6 to P8). Offset of the shoreline between trench 4 and the excavation southeast of trench 11 is most likely 2 m but could be 0 m. See Figure 3 for location of this map. See appendix for description of piercing points.

Fig. 10. Map documents the 3.6- to 13.6-m-offset of the shoreline across the north central shear zone (Table 2). The location of the pinchout of well-sorted beach sand against a sea cliff was revealed in trenches 11, 12, 19 and 13 and in three-dimensional hand-excavations from these trenches. Labels 19B, 19C, 19D and 19F are faults that are also shown in Figure 8. See Figure 3 for location of this map. See appendix for descriptions of piercing points.

has incised the shoreline indicate that offset of the shoreline across the southern one of two main fault strands has occurred since the most recent highstand of Searles Lake. However, wave action during the most recent highstand may not have completely eroded

the offset of older shorelines across the northern fault. Therefore the 82-m minimum offset across the entire fault zone may not have all occurred since the most recent highstand. An offset channel, however, indicates that at least 68 m of left-lateral slip

TABLE 2. Summary of Offset Across the North Central Shear Zone

Area	Preferred offset, m	Piercing points used	Minimum offset, m	Piercing points used	Maximum offset, m	Piercing points used
Trench 11 hand excavations	0.8	P12 to P13 + 0.1 m on fault just NW of Trench 11	0.8	P12 to P13 + 0.1 m on fault just NW of Trench 11	1.8	P11 to P14
Between hand excavations from trenches 11 and 12	1.8	P15 to P16	0	P15 to P15	1.8	P15 to P16
Trench 12 hand excavations (east of P19c, Figure 10)	0.8	P18 to P19 + 0.1 m on fault 12D	0.8	P18 to P19 + 0.1 m on fault 12D	2.8	P17 to P19b
Between hand excavations from trenches 12 and 19 (P19c to P20, Figure 10)	0	P20 to P20	0	P20 to P20	2.0	P19c to P20
Trench 19 hand excavations	1.9	P20 to P27 + P28 to P29 + P30 to P30b	1.9	P20 to P27 + P28 to P29 + P30 to P30b	2.1	P20 to P27 + P28 to P29 + P30 to P30c
Between hand excavations from trenches 19 and 13	0.1	on a fault just south of Trench 13	0.1	on a fault just south of Trench 13	3.1	P21 to P22
Total	5.4		3.6		13.6	

See Figures 8 and 10 for locations of piercing points.

Fig. 11. Map documents 42- to 46-m-offset of the shoreline across the northern fault zone. The shoreline is probably warped within about 0.7 m north of the northern edge of the northern fault zone, in which case the offset is 46 m (P33 to P36 plus P31 to P32). The minimum offset is 42 m (P34 to P35 plus P31 to P32) and would apply if the current trend of the shoreline within 0.7 m north of the northern edge of the northern fault zone represents the original trend of the shoreline across the northern fault zone. See Figure 3 for location of this map. See appendix for descriptions of piercing points.

Fig. 12. Locations of shoreline features in trenches north of the northern fault zone. There is no evidence of significant offset of the shoreline north of the northern fault zone, but up to about 3 m of left-lateral warping could conceivably have occurred (P37 to P38). Warping may be responsible for the more westerly trend of the shoreline angle in trench 7. See Figure 3 for location of this map. See appendix for descriptions of piercing points.

Fig. 13. Elevation of the shoreline angle (base of sea cliff) as a function of distance perpendicular to the fault zone. Dashes show actual measurements of shoreline elevation. Triangles show elevation of an older shoreline (Qob, in Figure 12).

has occurred across the Garlock fault zone since the end of latest highstand of Searles Lake (10,000 to 13,800 ^{14}C yr B.P.), yielding a minimum slip rate of 5 mm/ ^{14}C yr. Dividing the maximum offset of the shoreline by the minimum age of the end of the latest highstand yields a maximum slip rate of 11 mm/ ^{14}C yr.

TABLE 3. Slip Rate of the Garlock Fault

Preferred slip rate	Maximum slip rate	Minimum slip rate
preferred offset of channel and = <u>shoreline</u> preferred age of latest highstand	maximum offset = <u>of shoreline</u> minimum age of latest highstand	minimum offset = <u>of channel</u> maximum age of latest highstand
= $\frac{68 \text{ to } 90 \text{ m}}{11,200 \text{ }^{14}\text{C yr}}$	= $\frac{106 \text{ m}}{10,000 \text{ }^{14}\text{C yr}}$	= $\frac{68 \text{ m}}{13,800 \text{ }^{14}\text{C yr}}$
= 6-8 mm/ ^{14}C yr	= 11 mm/ ^{14}C yr	= 5 mm/ ^{14}C yr

Considering that the most recent highstand may not have completely destroyed the offset of older shorelines, the true offset of the shoreline of the most recent highstand is most likely between the preferred offset of the channel (68 m) and the preferred offset of the shoreline (90 m). Dividing these values by the preferred age of the end of the latest highstands (11,200 ^{14}C yr) suggests that the slip rate of the Garlock fault in southeastern Searles Valley is most likely between 6 and 8 mm/ ^{14}C yr. Assuming Bard et al.'s [1990] calibration of the radiocarbon time scale, the calibrated slip rate is between 4 and 9 mm/yr and most likely is between 5 and 7 mm/yr.

The Holocene slip rate in Searles Valley is similar to the Holocene slip rate at Koehn Lake [Clark and Lajoie, 1974], indicating that extension in Indian Wells Valley and Searles Valley has contributed no more than 3 mm/yr of left slip to the Garlock fault. The 7 Ma age of the Garlock fault inferred from paleomagnetic observations [Burbank and Whistler, 1987] is consistent with a constant slip rate equal to the Holocene slip rate. Modeling of trilateration measurements suggests a slightly higher slip rate than the geologic estimates, but this is probably due to the wider distance perpendicular to the fault that is spanned by the trilateration network.

APPENDIX: DESCRIPTION OF PIERCING POINTS

Southern Fault Zone (Figure 9 and Table 1)

P1. Subjective estimate of the eastern limit at which shoreline is likely to intersect southern edge of southern fault zone. An intersection farther east would require an unlikely bend in the shoreline.

P2. Projection of shoreline from trench 9 to southern edge of southern fault zone. The fact that the trend of the shoreline in trenches 1 and 17 projects to the same point suggests that the shoreline is not offset between trench 9 and the southern edge of the southern fault zone.

P3. Intersection of base of sea cliff with northernmost strand of southern fault zone, as exposed in a three-dimensional excavation.

P4. Projection of trend of base of sea cliff in trench 18 to northernmost strand of southern fault zone.

P5. Projection of visual best-fit line to trend of base of sea cliff in trenches 10 and 18 to northernmost strand of southern fault zone.

Between Trenches 3 and 4 (Figure 9 and Table 1)

P6. Projection of visual best fit line to shoreline in trenches 10 and 18 to possible westward extension of fault that has produced a small scarp north of trench 2. Represents eastern limit at which shoreline is likely to intersect the extension of this fault.

P7. Projection of 690.1-m structure contour on lake floor in trench 3 to a possible westward continuation of the fault expressed as a small scarp north of trench 2. There is no sea cliff in trench 3; the beach sands thin and pinchout against a gently sloping lake floor. Because the base of the sea cliff in trench 10 is at an elevation of 690.1 m, we correlate the 690.1-m structure contour on the lake floor in trench 3 with the base of the sea cliff in trenches 10 and 18.

P8. Projection of base of sea cliff from trench 4 to possible continuation of the fault expressed as a small scarp north of trench 2. Trend of shoreline in trench 4 is assumed to be parallel to the geomorphic break-in-slope east of trench 4 that is related to the shoreline.

Between Trenches 4 and 11 (Figure 9 and Table 1)

P9. Projection of shoreline from trench 4 to a hypothetical fault. Trend of shoreline is assumed to be parallel to the geomorphic break in slope east of trench 4 that is related to the shoreline.

P10. Projection of shoreline from three-dimensional excavation southeast of trench 11 to hypothetical fault.

North Central Shear Zone (Figures 8 and 10 and Tables 1 and 2)

P11. Projection of shoreline (sand pinchout against sea cliff) from southeastern end of three-dimensional excavation southeast of trench 11 to fault just northwest of trench 11.

P12. Projection of shoreline (sand pinchout) from northwestern part of three-dimensional excavation southeast of trench 11 to fault northwest of trench 11.

P13. Intersection of shoreline (sand pinchout) with fault just northwest of trench 11, as exposed in a three-dimensional excavation.

P14. Projection of shoreline (sand pinchout) from northwestern part of three-dimensional excavation northwest of trench 11 to fault just northwest of trench 11.

P15. Location of shoreline (sand pinchout) at northwestern edge of three-dimensional excavation northwest of trench 11.

P16. Projection of shoreline from eastern end of excavation east of trench 12 to hypothetical fault at northwestern edge of excavation northwest of trench 11.

P17. Projection of shoreline (sand pinchout) from eastern part of excavation east of trench 12 to fault 12E.

P18. Projection of shoreline (sand pinchout) from western part of excavation east of trench 12 to fault 12E.

P19. Intersection of shoreline (sand pinchout) with fault 12E, as exposed in a three-dimensional excavation.

P19b. Intersection of fault 12E with a line parallel to the trend of the shoreline in the eastern part of the excavation east of trench 12 and passing through the shoreline at the western edge of the excavation west of trench 12.

P19c. Location of shoreline (sand pinchout) at western edge of three-dimensional excavation west of trench 12.

P20. Location of truncation of beach sands by fault 19F at eastern edge of three-dimensional excavation east of trench 19. Trend of shoreline at P19c also projects to P20, suggesting no offset between P19c and P20. However, the shoreline is so nearly parallel to the fault zone at P19c that the shoreline could be offset the entire distance (2 m) from P19c to P20.

P21. Location of shoreline at western edge of three-dimensional excavation west of trench 19.

P22. Intersection of line parallel to the trend of the shoreline away from faults (in the excavation north of trench 13) and passing through the location of the shoreline in the southern wall of trench 13 with a hypothetical fault. Used to estimate the amount of possible warping of the shoreline between trenches 13 and 19.

P27. Intersection of shoreline (sand pinchout) with fault 19F; exposed in a three-dimensional excavation.

P28. Intersection of shoreline (sand pinchout) with fault 19D; exposed in a three-dimensional excavation.

P29. Intersection of shoreline (sand pinchout) with fault 19D; exposed in a three-dimensional excavation.

P30. Intersection of shoreline (sand pinchout) with fault 19C; exposed in a three-dimensional excavation.

P30b. Intersection of shoreline with fault 19C; exposed in a three-dimensional excavation.

P30c. Intersection of fault 19C with a line parallel to the trend of the shoreline between P27 and P28 and passing through location of shoreline at western edge of excavation west of trench 19.

Northern Fault Zone (Figure 11 and Table 1)

P31. Intersection of shoreline (sand pinchout) with southernmost strand of northern fault zone. Exposed in a three-dimensional excavation.

P32. Intersection of shoreline (sand pinchout) with southernmost strand of northern fault zone. Exposed in a three-dimensional excavation.

P33. Projection of shoreline from P32 to northern edge of northern fault zone.

P34. Intersection of northern edge of northern fault zone with a line parallel to the trend of the shoreline (sand pinchout) in the southeastern part of the excavation east of trench 5 and passing through P32. The line between P32 and P34 represents the most westerly trend that the shoreline is likely to have had across the northern fault zone prior to any faulting and warping.

P35. Intersection of the shoreline (sand pinchout) with the northernmost strand of the northern fault zone. Exposed in a three-dimensional excavation.

P36. Projection of shoreline from northwestern part of excavation east of trench 5 to northern edge of northern fault zone.

North of Northern Fault Zone (Figure 12 and Table 1)

P37. Projection of the most northerly trending portion of the shoreline (base of sea cliff) in excavation east of trench 5 to a reference line parallel to the fault zone. Line from shoreline in trench 5 to P37 represents the most northerly orientation that is likely for the original trend of the shoreline in this area.

P38. Location of shoreline (base of sea cliff) in southeastern wall of trench 20.

Acknowledgments. We thank the China Lake Naval Weapons Center for allowing access and for permitting the excavations, and we thank Allan Katzenstein for acting as our sponsor with the Naval Weapons Center. Mike Slates, Steve Bryant, Glenn Roquemore, and Linda Maepa assisted with the field work. Malcolm Clark provided USGS aerial photographs of the site. We also thank George I. Smith for sharing his unpublished mapping of and dates for deposits of Searles Lake. Oliver Chadwick provided descriptions of the soils. Lisa Grant assisted with drafting of figures. Two anonymous reviewers made suggestions that significantly improved the manuscript. This work was supported by USGS Earthquake Hazards Reduction Program grant 14-08-0001-G1789 and by a Koons Field Research Fellowship. Trenches were surveyed with a Wild TC-2000 total station purchased with funds from the W. M. Keck Foundation and by USGS Earthquake Hazards Reduction Program grant 14-08-0001-G1177. California Institute of Technology, Division of Geological and Planetary Sciences contribution 5246.

REFERENCES

- Bard, E., B. Hamelin, R. G. Fairbanks, and A. Zindler, Calibration of the C-14 time scale over the past 30,000 years using mass-spectrometric U-Th ages from Barbados corals, *Nature*, **345**, 405-410, 1990.
- Benson, L. V., D. R. Currey, R. I. Dorn, K. R. Lajoie, C. G. Oviatt, S. W. Robinson, G. I. Smith, and S. Stine, Chronology of expansion and contraction of four Great Basin Lake systems during the past 35,000 years, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **78**, 241-286, 1990.
- Burbank, D. W., and D. P. Whistler, Temporally constrained rotations derived from magnetostratigraphic data: Implications for the initiation of the Garlock fault, *Geology*, **15**, 1172-1175, 1987.
- Burke, D. B., and M. M. Clark, Late Quaternary activity along the Garlock fault at Koehn Lake, Fremont Valley, California (abstract), *Eos Trans. AGU*, **59**, 1126, 1978.
- Carter, B. A., Quaternary displacement on the Garlock fault, California, in *Geology and Mineral Wealth of the California Desert*, edited by D. L. Fife and A. R. Brown, pp. 457-466, South Coast Geological Society, Santa Ana, California, 1980.
- Carter, B., Neogene displacement on the Garlock fault, California (abstract), *Eos Trans. AGU*, **63**, 1124, 1982.
- Clark, M. M., Some characteristics of the most recently active traces of the Garlock fault, *Geol. Soc. Am. Abstr. Programs*, **2**, 82, 1970.
- Clark, M. M., et al., Preliminary slip-rate table and map of Late Quaternary faults of California, *U. S. Geol. Surv. Open File Rep.*, **84-106**, 12 pp., 1984.
- Clark, M. M., and K. R. Lajoie, Holocene behavior of the Garlock fault, *Geol. Soc. Am. Abstr. Programs*, **6**, 156-157, 1974.
- Davis, G. A., and B. C. Burchfiel, Garlock fault: An intracontinental transform structure, southern California, *Geol. Soc. Am. Bull.*, **84**, 1407-1422, 1973.
- Dokka, R. K., and C. J. Travis, Late Cenozoic strike-slip faulting in the Mojave Desert, California, *Tectonics*, **9**, 311-340, 1990.
- Dorn, R. I., A. J. T. Jull, D. J. Donahue, T. W. Linick, and L. J. Toolin, Latest Pleistocene lake shorelines and glacial chronology in the Western Basin and Range Province, U. S. A.: Insights from AMS radiocarbon dating of rock varnish and paleoclimatic implications, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **78**, 315-331, 1990.

- Duffield, W. A., C. R. Bacon, and G. B. Dalrymple, Late Cenozoic volcanism, geochronology, and structure of the Coso Range, Inyo County, California, *J. Geophys. Res.*, **85**, 2381-2404, 1980.
- Gale, H. S., Salines in the Owens, Searles and Panamint basins, southeastern California, *U.S. Geol. Surv. Bull.*, **580-L**, 251-323, 1914.
- Guptill, P., D. Collins, and E. Heath, Quaternary displacements on the south branch of the Garlock fault, Tehachapi Mountains, California, *Geol. Soc. Am. Abstr. Programs*, **11**, 81, 1979.
- Ho-Liu, P., H. Kanamori, and R. W. Clayton, Applications of attenuation tomography to Imperial Valley and Coso-Indian Wells region, southern California, *J. Geophys. Res.*, **93**, 10,501-10,520, 1988.
- Jennings, C. W., J. L. Burnett, and B. W. Troxel, Geologic map of California, Trona sheet, Calif. Div. of Mines and Geol., Sacramento, 1962.
- LaViolette, J. W., G. E. Christenson, and J. C. Stepp, Quaternary displacement on the western Garlock fault, southern California, in *Geology and Mineral Wealth of the California Desert*, edited by D. L. Fife and A. R. Brown, pp. 449-456, South Coast Geological Society, Santa Ana, California, 1980.
- Louie, J. N., C. R. Allen, D. C. Johnson, P. C. Haase, and S. N. Cohn, Fault slip in southern California, *Bull. Seismol. Soc. Am.*, **75**, 811-833, 1985.
- McGill, S. H. F., Paleoseismology and neotectonics of the central and eastern Garlock fault, California, Ph.D. dissertation, Calif. Inst. of Technol., Pasadena, 1992.
- McGill, S. F., and K. E. Sieh, Surficial offsets on the central and eastern Garlock fault associated with prehistoric earthquakes, *J. Geophys. Res.*, **96**, 21,597-21,621, 1991.
- Reheis, M. C., J. W. Harden, L. D. McFadden, and R. R. Schroba, Development rates of Late Quaternary soils, Silver Lake Playa, California, *Soil Sci. Soc. Am. J.*, **53**, 1127-1140, 1989.
- Roquemore, G., Structure, tectonics and stress field of the Coso Range, Inyo County, California, *J. Geophys. Res.*, **85**, 2434-2440, 1980.
- Roquemore, G. R., P. E. Smith, and E. W. Banks, Holocene earthquake activity of the eastern Garlock fault in Christmas Canyon, San Bernardino County, California, *Geol. Soc. Am. Abstr. Programs*, **14**, 228, 1982.
- Sanders, C., P. Ho-Liu, D. Rinn, and H. Kanamori, Anomalous shear wave attenuation in the shallow crust beneath the Coso volcanic region, California, *J. Geophys. Res.*, **93**, 3321-3338, 1988.
- Smith, G. I., Large lateral displacement on Garlock fault, California, as measured from offset dike swarm, *Am. Assoc. Pet. Geol. Bull.*, **46**, 85-104, 1962.
- Smith, G. I., Holocene movement on the Garlock fault, *U.S. Geol. Surv. Prof. Pap.*, **975**, p. 202, 1975.
- Smith, G. I., Subsurface stratigraphy and geochemistry of Late Quaternary evaporites, Searles Lake, California, *U.S. Geol. Surv. Prof. Pap.*, **1043**, 130 pp., 1979.
- Smith, G. I., and K. B. Ketner, Lateral displacement on the Garlock fault, southeastern California, suggested by offset sections of similar metasedimentary rocks, *U.S. Geol. Surv. Prof. Pap.*, **700-D**, D1-D9, 1970.
- Smith, G. I., V. J. Barczak, G. F. Moulton, and J. C. Liddicoat, Core KM-3, a surface-to-bedrock record of Late Cenozoic sedimentation in Searles Valley, California, *U.S. Geol. Surv. Prof. Pap.*, **1256**, 24 pp., 1983.
- Stuiver, M., and G. I. Smith, Radiocarbon ages of stratigraphic units, in *Subsurface Stratigraphy and Geochemistry of Late Quaternary Evaporites, Searles Lake, California*, edited by G. I. Smith, *U.S. Geol. Surv. Prof. Pap.*, **1043**, 130 pp., 1979.
- Walter, A. W., and C. S. Weaver, Seismicity of the Coso Range, *J. Geophys. Res.*, **85**, 2441-2458, 1980.
- Weldon, R., and E. Humphreys, A kinematic model of southern California, *Tectonics*, **5**, 33-48, 1986.

S. McGill, Department of Geological Sciences, California State University, 5500 University Parkway, San Bernardino, CA 92407-2397.

K. Sieh, Seismological Laboratory, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125.

(Received September 19, 1991;
revised February 8, 1993;
accepted February 18, 1993.)