Bulletin of the Seismological Society of America, Vol. 68, No. 4, pp. 1187–1190, August, 1978

LETTERS TO THE EDITOR

MONITORING SLIP ALONG MAJOR FAULTS IN SOUTHERN CALIFORNIA

BY R. P. KELLER, C. R. ALLEN, R. GILMAN, N. R. GOULTY, AND J. A. HILEMAN

Repeated surveys have been made of 16 small-scale theodolite alignment arrays in southern California. They span members of the Garlock, San Andreas, and San Jacinto fault systems (Figure 1 and Table 1), and were installed between 1967 and 1971. Results from surveys of six additional alignment arrays in the Imperial Valley have been included in a separate paper by Goulty *et al.* (1978).

The arrays span zones from 200 to 800 m wide perpendicular to the fault traces. Angles between targets are measured with a Wild T-2 Universal theodolite. The theodolite station at each array is a steel stake driven into the ground. Using the optical plumb, one may reposition the theodolite over a marker screwhead in the top of the stake to an accuracy of better than 1 mm. Most targets are specially inscribed nails in telephone poles, while a few are nails in trees or screwheads in the tops of other steel stakes driven into the ground flush with the surface. Very occasionally, a horizon reference target is used. Telephone-pole targets have proved surprisingly good in desert areas, but where there is irrigation, frequent rainfall or steep slopes, the data can be extremely noisy. When each array was installed, at least three targets were established on each side of the fault zone. Where possible, a reference target or targets were placed in directions parallel to the fault strike from the theodolite station. Targets have often been lost as telephone poles have been replaced, and our coverage of the San Jacinto fault system is poor because two complete arrays were destroyed.

Three alignment arrays cross the Garlock fault, and results from surveys of two of these are shown in Figure 2a. Rand is one of the arrays with lowest noise level and clearly shows no motion. Error bars represent the typical range of values of apparent slip parallel to the fault for the three targets on the far side of the fault with respect to reference targets on the same side of the fault as the theodolite station. The Christmas Canyon array is equally low noise, and also shows no significant left-lateral motion. Results from the Cameron array do show left-lateral motion, but it appears to be a distributed shear across the array. Accordingly, the plotted values are the sums of apparent left-lateral displacements of the targets most distant from the fault on either side, using a reference target in a direction parallel to the fault strike from the theodolite station. Errors in these values cannot be estimated as there is no redundancy in the measurements. If the motion observed at Cameron is a distributed shear, a larger array might have shown greater motion. Averaging over all the targets reduces the observed motion to about 2 cm over the 6 years of measurements. Miller (1976) has recorded left-lateral slip rates of 5 to 8 mm yr^{-1} 50 km farther southwest along the Garlock fault.

Alignment arrays spanning the "big bend" in the San Andreas fault between Una Lake and Santa Ana Wash (Figure 1) have failed to detect significant right-lateral motion above rather high noise levels equivalent to 2 mm yr^{-1} average slip rate. There is a suggestion of motion at the 1 mm yr^{-1} level at the Dever's Hill array across the Banning branch of the San Andreas fault. Further southeast, where the Banning and Mission Creek branches have rejoined, more definite indications of right-lateral motion have been observed (Figure 2b). At Indio Hills, we are again unable to estimate errors as there is only one surviving target on the far side of the

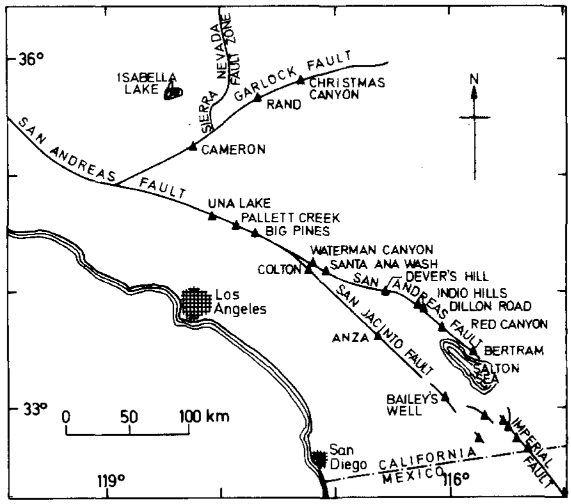

FIG. 1. Locations of theodolite alignment arrays in southern California.

TABLE 1

ALIGNMENT ARRAYS ACROSS MAJOR FAULTS IN SOUTHERN CALIFORNIA

Array Name	Fault	Lat. N.	Long. W.	Initial Survey Date	No. of Surveys to 24 Sept 1977	Summarised Results
Anza	San Jacinto	33°34.0′	116°37.8′	6 Aug 1970	5	Possible creep episode with 11 cm r-l. slip between Aug 1970 and Jan 1973.
Bailey's Well	Coyote Creek	33°06.2′	116°03.6′	15 Mar 1969	12	Continued afterslip following Borrego Mtn. earthquake totaling 66 mm in 8.5 yr.
Bertram	San Andreas	33°24.7′	115°47.5′	5 May 1968	11	No detectable slip above high-noise level equivalent to 2.5 mm/yr slip rate.
Big Pines	San Andreas	34°22.7′	117°41.4′	7 May 1970	5	No detectable slip above high-noise level equivalent to 2 mm/yr slip rate.
Cameron	Garlock	35°05.7′	118°18.3′	20 Jan 1971	7	5 ± 2 mm/yr l-l. slip distributed across array. Poorly constrained.
Christman Canyon	Garlock	35°31.5′	117°21.7′	21 Jan 1971	7	No slip.
Colton	San Jacinto	34°04.8′	117°18.3′	29 Apr 1970	12	No detectable slip above noise level equivalent to 1 mm/yr slip rate.
Dever's Hill	Banning	33°55.8′	116°34.6′	28 Apr 1970	3	Suggestion of r-l. slip at the average rate of 0.75 ± 1mm/yr.
Dillon Road	San Andreas	33°43.7′	116°10.2′	17 Apr 1970	3	R-l. slip of 3 ± 1.5 mm/yr.
Indio Hills	San Andreas	33°46.0′	116°13.0′	16 Apr 1970	4	R-l. slip of 1 mm/yr. Poorly constrained.
Pallett Creek	San Andreas	34°27.5′	117°53.6′	18 Feb 1970	5	No detectable slip above high-noise level equivalent to 2 mm/yr slip rate.
Rand	Garlock	35°26.8′	117°40.4′	21 Jan 1971	7	No slip.
Red Canyon	San Andreas	33°37.6′	116°02.9′	11 May 1967	13	R-l. slip of 3 ± 1.5 mm/yr.
Santa Ana Wash	San Andreas	34°06.2′	117°06.4′	18 Jan 1971	3	Indication of r-l. slip at the average rate of 1 ± 1 mm/yr.
Una Lake	San Andreas	34°33.1′	118°06.8′	16 Feb 1970	7	No detectable slip above high noise level equivalent to 2 mm/yr slip rate.
Waterman Canyon	San Andreas	34°10.5′	117°16.6′	30 Apr 1970	5	No slip.

fault. Error bars plotted for Dillon Road, only 6 km southeast of Indio Hills, show the range of values obtained from all three targets on the far side of the fault. An average slip rate of 3 ± 1.5 mm yr^{-1} was observed. At Red Canyon, the error bars show the range of apparent parallel slip for only two targets on the far side of the

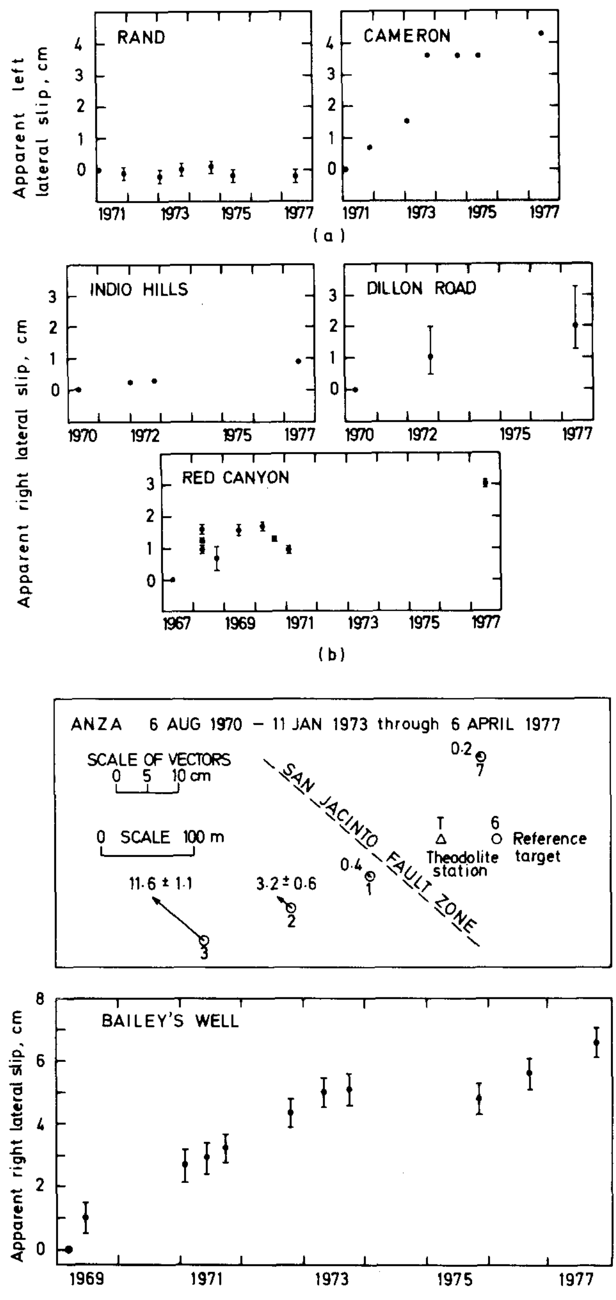

FIG. 2. (a) Results from Rand and Cameron alignment arrays on the Garlock fault. (b) Results from Indio Hills, Dillon Road, and Red Canyon alignment arrays on the San Andreas fault. (c) Results from Anza alignment array on the San Jacinto fault and Bailey's Well alignment array on the Coyote Creek fault.

fault. The results of three surveys in early 1968 demonstrate that they are not a realistic estimate of the true errors. The array shows right-lateral motion at an average rate of 3 mm yr^{-1} with an estimated error of 1.5 mm yr^{-1}.

Our most surprising data are from the array at Anza, which spans the San Jacinto fault. A map of the array is shown in Figure 2c with vectors indicating the observed amounts of slip. This motion had essentially accumulated by January 11, 1973, with three subsequent surveys to April 6, 1977 showing no significant further change. These four surveys were averaged to give the vectors shown, and the errors given for targets 2 and 3 are the ranges of values from them. The measurements show 11 cm of apparent right-lateral motion across the array. Some of the targets were visibly tilted in 1970, and for fear of further tilts having taken place or freak errors in theodolite readings during the 1970 survey, we cannot assert that this is a valid result.

The Bailey's Well alignment array spans the Coyote Creek fault, and was established in March 1969 across the central break of the Borrego Mountain earthquake of April 9, 1968. Results of the surveys are shown in Figure 2c, with error bars indicating the typical spread of values from four targets on the far side of the fault from the theodolite station. Of course, we are unable to determine whether slip was steady or episodic between surveys, but slip appears to have occurred steadily at an average rate of 10 ± 1 mm yr^{-1}, except for the period between surveys of September 27, 1973 and October 27, 1975. This quiescent period shows up consistently using any combination of targets. The observed motion presumably represents afterslip due to the blanket of sediment, about 3 km thick, covering basement rocks at this locality (Burford, 1972).

In conclusion, we have a strong indication of left-lateral slip at the west end of the Garlock fault, at an average rate of 5 ± 2 mm yr^{-1}. Along the Banning branch of the San Andreas fault, there is a suggestion of right-lateral slip at the 1 mm yr^{-1} level. Between Thousand Palms and Mecca, the San Andreas fault has been creeping at an average rate of 3 ± 1.5 mm yr^{-1}. A surprisingly large creep episode with 11 cm of slip may have occurred on the San Andreas fault near Anza between August 1970 and January 1973. Afterslip on the central break of the Borrego Mountain earthquake has continued at a rate of about 10 mm yr^{-1}, except for a pause in activity between September 1973 and October 1975.

Acknowledgment

This study was funded by the U.S. Geological Survey, recently under Contract 14-08-0001-15860.

References

Burford, R. O. (1972). Continued slip on the Coyote Creek fault after the Borrego Mountain earthquake, *U.S. Geol. Survey, Profess. Paper 787*, 105–111.

Goulty, N. R., R. O. Burford, C. R. Allen, R. Gilman, C. E. Johnson, and R. P. Keller (1978). Large creep events on the Imperial fault, California, *Bull. Seism. Soc. Am.* **68,** 517–521.

Miller, R. W. (1976). Results of triangulation-trilateration for earth-movement study at California aqueduct fault crossing sites, Section IV: Sandberg to Wheeler Ridge, Supplement No. 8, Sites; Ranch Tejon and Meade, U.S. Dept. of Commerce, National Ocean Survey, Rockville, Maryland, 35 pp.

Seismological Laboratory
California Institute of Technology
Pasadena, California (R.P.K., C.R.A., R.G., J.A.H.)
Division of Geological and Planetary Sciences
Contribution No. 3023

Department of Geophysics and Planetary Physics
School of Physics
The University
Newcastle Upon Tyne NE1 7RU England
(N.R.G.)

Manuscript received January 16, 1978