Reports

North American–Pacific Relative Plate Motion in Southern California from Interferometry

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Very long baseline interferometry measurements of baselines crossing the San Andreas fault zone in southern California have provided observational constraints on rates of elastic tectonic strain accumulation. The single site located near this fault (the Jet Propulsion Laboratory site) moves in a direction concordant with the Pacific plate motion vector but at approximately half the net rate relative to North America. This motion agrees approximately in amount with geologically determined displacement rates on the San Andreas fault alone but not with the local strike of the fault. When considered together with complementary geodetic data, these results suggest a complex relation between the short-term accumulation of elastic strain and its permanent accommodation on existing faults.

Very long baseline interferometry (VLBI) has developed in recent years into a valuable technique for the acquisition of precise geodetic data (*1*). VLBI measurements of baselines have been made during the past decade under the auspices of the National Aeronautics and Space Administration Crustal Dynamics Project. The goals of this work include the elucidation of present-day plate tectonic motions and the better characterization of crustal deformation zones at plate boundaries. The utility of the VLBI technique for measuring baselines of 100 to 1000 km makes it complementary to conventional geodesy for such studies.

VLBI measurements of baselines that cross the San Andreas fault system in California during the interval 1980 through 1984 have yielded signatures of substantial tectonic motion. We present here the most recent summary of the relevant VLBI measurements and discuss these data in relation to other geodetic and geologic data. These results provide new constraints on the distribution of strain in this well-studied region.

The VLBI technique uses fixed or mobile radio telescope receivers at two or more sites, which simultaneously record the microwave emissions of selected compact extragalactic sources. Subsequent correlation of these signals allows the estimation of parameters describing the position and motion of the receiving stations in inertial space (*2*). After the removal of signatures due to the motion of the earth through space, propagation delays, and other pertinent effects, estimates of the vector baseline components in an earth-fixed reference frame are obtained. Since 1980, the techniques used for the elimination of systematic errors due to atmospheric and ionospheric path delay have allowed baseline determinations with typical length uncertainties on the order of 2 cm. The VLBI data acquired between 1980 and now are of comparatively uniform quality and temporal distribution and therefore form the basis of the present discussion.

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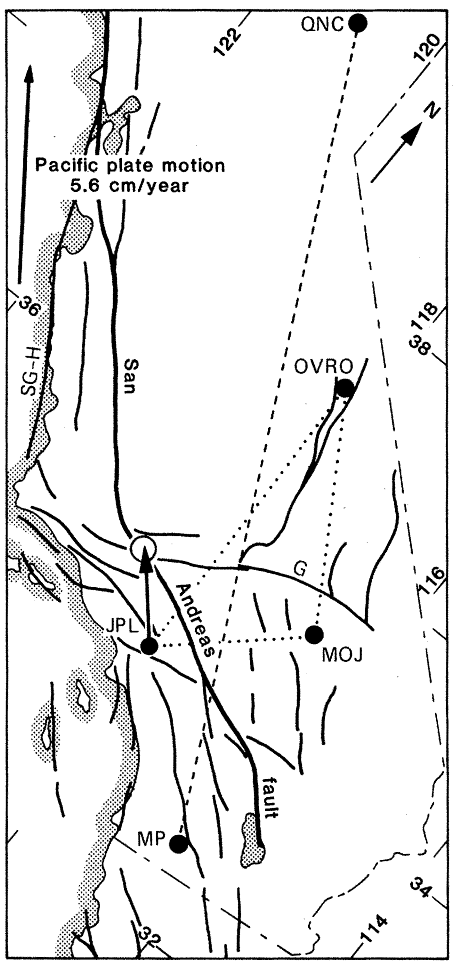

Fig. 1. Fault map of southern and central California showing space geodetic sites, measured baselines, and the direction of motion of the Pacific plate with respect to North America. The San Andreas fault forms the nominal boundary between the Pacific and North American plates. The major restraining bend ("the Big Bend") lies between the Salton Sea in southeastern California and central California. VLBI measurements of the baselines between Owens Valley Radio Observatory (OVRO), Mojave Base Station (MOJ), and the Jet Propulsion Laboratory (JPL) yield a velocity for JPL of 2.5 ± 0.4 cm/year in the direction N40°W ± 7° relative to the other two sites. This motion and its uncertainty are indicated by the arrow and the small ellipse at its tip. Satellite laser ranging results (*16, 17*) for the baseline from Monument Peak (MP) to Quincy (QNC) have yielded conflicting rates of shortening. Other important features are the San Gregorio–Hosgri (SG-H) and Garlock (G) faults.

The VLBI sites (Fig. 1) considered here are located at the Jet Propulsion Laboratory (JPL) in Pasadena, California, at the Mojave Base Station (MOJ) located south of the Garlock fault in the northeastern Mojave desert, and at the Owens Valley Radio Observatory (OVRO). During the interval 1980.0 to 1984.8, the OVRO-MOJ baseline was measured 43 times. The JPL-OVRO and JPL-MOJ baselines were measured 22 and 16 times, respectively, during the same period. Lyzenga *et al.* (*3*) give a more detailed description of the temporal distribution and uncertainties of these measurements.

The VLBI measurements resulting from a given experiment consist of the three-dimensional position vectors between observing stations. Because the vector components are obtained in an earth-fixed reference frame, repeated measurements of a VLBI network afford determinations not only of changes in shape and scale but also of orientation. Thus, the triangular net considered here yields unambiguous relative vector displacements, directly interpretable in terms of plate tectonic motions. The horizontal components (east and north) of these baseline vectors are plotted as a function of measurement time in Fig. 2.

This data set has been used to obtain a least-squares estimate for average strain and rotation rates across the triangle. The resulting rate of dextral engineering shear strain is 0.17 ± 0.02 microstrain/year, along an azimuth of N33°W ± 3°. The nondeformational rotation rate is 0.16 ± 0.02 μrad/year, in a clockwise sense. The estimate for the rate of network dilatation is 0.04 ± 0.02 microstrain/year. The uncertainties quoted here for strain estimates represent 1 SD, propagated through the least-squares estimation process. The uncertainties in the baseline component rates of change (Fig. 2)

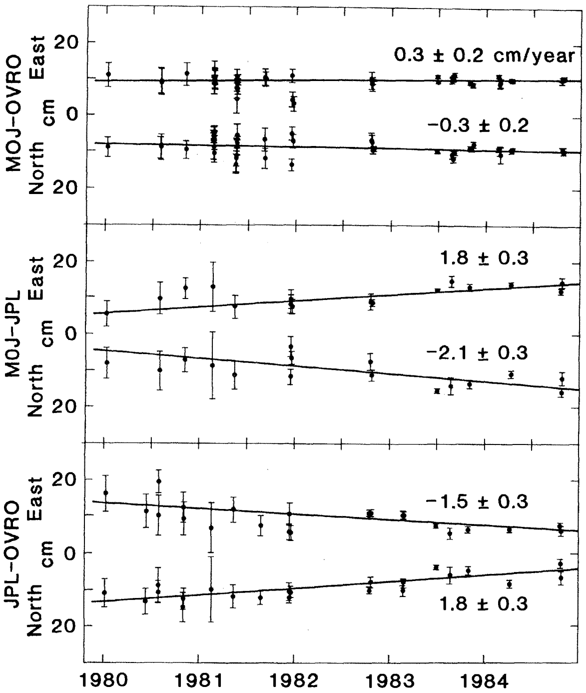

Fig. 2. Plots of changes in the horizontal components of the three California VLBI baselines during 1980 through 1984. The baseline vectors are resolved into local east and north components, which are plotted minus arbitrary constant distances. Plotted points represent the results of individual VLBI experiments, with error bars reflecting VLBI uncertainties of 1 SD. The solid lines are derived from the least-squares strain rate estimate, which enforces triangular velocity vector closure among the three baselines. The slope uncertainties also represent 1-SD limits. These mutually determined rate estimates are in good agreement with the rates of baseline change that would be obtained for the individual baselines independently.

reflect the same SD. The root source of these error estimates is in the original VLBI measurement (*4*).

These results indicate very little motion between OVRO and MOJ but show a significant northwestward motion of JPL with respect to the other two sites. If we average between the OVRO and MOJ rates, the JPL site is found to move with respect to eastern California at a rate of 2.5 ± 0.4 cm/year, in a direction of N40°W ± 7° (Fig. 1).

Results from the VLBI measurements yield a short-term displacement rate on the southern San Andreas transform that is similar to displacement rates derived from geologic and local geodetic network information. Geologic estimates (~3 cm/year), based on the offset of Tertiary geologic units on either side of the fault, show a displacement of roughly 300 km in the past 10×10^6 years (*5*). These long-term slip rates are similar to estimates of recent activity across the fault based on the displacement of Holocene geomorphic landforms and deposits (*6*) and on strain rates from local geodetic networks (*7*). Geodetic networks spanning tens of kilometers, however, indicate a direction of maximum strain more nearly parallel to the local fault strike than the plate motion vector. These rates of motion (~3 cm/year) are about half of that expected from the study of ocean-floor magnetic lineations in the Pacific, which indicate a relative motion of about 6 cm/year between the Pacific and North American plates in California. The first analysis of magnetic anomalies in the Pacific suggested a relative plate motion of ~6 cm/year (*8*), and this rate was confirmed by analysis of magnetic anomalies at the mouth of the Gulf of California (*9*), which lies at one end of the San Andreas transform. These magnetic lineations show that spreading in the gulf began about 4×10^6 years ago, and, when coupled with geologic estimates of about 300 km of opening (*10*), give similar spreading rates. The above estimates agree with a global inversion for plate motion rates that indicates a local velocity of ~5.6 cm/year between the Pacific and North American plates (*11*).

Resolving the discrepancy between a net relative plate rate of motion of 6 cm/year and a rate of motion on the principal transform (the San Andreas fault) of only ~3 cm/year has remained an enigmatic problem. A feasible resolution of this problem involves relegating some of the motion to the slowly opening northern Basin and Range Province within the North American plate and some to other faults in the California borderland near the edge of the Pacific plate (*12*), of which the San Gregorio–Hosgri fault may be the most active (*7, 13*). A vector summation of the best estimates for recent slip rates and directions encompassing the San Andreas, northern Basin and Range, and California borderland faults appears to account reasonably well for the relative Pacific–North American plate motion (*14*).

Because the San Andreas fault is locked in the region of the Big Bend (*15*), the VLBI measurements reported here probably reflect recoverable elastic strain in the crust, as opposed to permanent deformation caused by seismic or aseismic slip. In view of the fact that the measured rate of motion is closely comparable to the San Andreas displacement rates recorded by geologic and local geodetic networks, the following explanations are possible. (i) All of the elastic strain recorded by VLBI can be accounted for in the long term by motion on the San Andreas fault, which is manifested in periodic large earthquakes (*6*); no additional strain then remains to be released on faults other than the San Andreas within the vicinity of the VLBI net. (ii) The similarity in geologic and VLBI estimates may be coincidental, given the broad observed distribution of elastic strain in the deformation zone between the Pacific and North American plates; the ~3 cm/year VLBI rate may then reflect nothing more fundamental than that the JPL site is located near the center line of an approximately homogeneous deformation zone. The determination of which of these alternatives is correct depends upon the degree to which interseismic elastic strain is concentrated near major fault zones. Some elastic strain "peaking" over faults is evident in the region, but a significant component is distributed over a relatively broad zone (*7*). It is also possible that the VLBI motion may be influenced by postseismic rebound (for example, from the 1952 Kern County or 1971 San Fernando earthquakes). Such phenomena, however, might be expected to exert their greatest effect on smaller geodetic nets within short distances from the epicenters (comparable to the rupture dimensions). This may in fact account for the tendency of the smaller scale geodetic strains to align with the local fault strike, in contrast to the VLBI result.

A further constraint on elastic strain accumulation in southern California comes from satellite laser ranging (SLR) determinations of baseline lengths between Quincy and Monument Peak (Fig. 1). Early reports indicated a rate of baseline shortening of ~6.5 cm/year (*16*). Subsequent SLR reports indicated a rate of ~3 cm/year (*17*). At this time, it is unclear whether this represents a real change in the rate of tectonic motion or is an effect of observational errors. The few available VLBI measurements (*18*) of this baseline yield rates of 4 to 5 cm/year, but these values have uncertainties of as much as ±2 cm/year. Although the possibility of temporal variability in strain is intriguing, the currently available data do not require it. We therefore center our discussion on the spatial distribution of tectonic motion.

Given the lack of strong evidence for contemporary shortening between OVRO and Quincy, any discrepancy between the SLR and VLBI results is most likely accommodated between JPL and Monument Peak. This presents a problem in that JPL and Monument Peak lie on roughly the same small circle (Fig. 1) about the pole of relative plate motion (*11*). This finding suggests a left-stepping kink in the locus of elastic strain accumulation, roughly coincident with the location of the Big Bend and Transverse Ranges. Although the inferred JPL–Monument Peak relative motion is lessened by the most recent SLR findings, even a modest discrepancy of 1 cm/year results in similar conclusions. Such a distribution of elastic strain could be relevant to suggestions of local reorientation of the Pacific–North American plate slip direction in southern California (*19*). However, such "microplate" activity is not reflected directly in the present short-term measurements, which show a direction of motion parallel to the overall plate boundary.

The explanation of such an offset shear zone may depend on the nature of the forces that drive plate motions at the boundary. It has been suggested (*20*) that active convective downwelling in the mantle beneath the Transverse Ranges exerts tractions on the base of the lithosphere in this region. Alternatively, complex block motions within the transpressive restraining bend of the San Andreas (*14*) may elastically redistribute the strain. In this case, mantle convergence and downwelling beneath the Transverse Ranges kink assumes a more passive role.

Resolution of these questions must await more complete geodetic strain data and a more comprehensive understanding of the forces that drive short-term deformation of the crust and mantle. In particular, the rates of motion between OVRO, Monument Peak, and Quincy, upon which much of the above hypothesis rests, must be better determined before either the kinematics or the dynamics become well defined. It is expected that continuing measurements by VLBI (and other space-based geodetic techniques) incorporating more sites than those discussed here, coupled with conventional geodetic data, will further improve our understanding of strain accumulation and tectonic motion in western North America.

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Colors of Objects in the Field of the Double Quasi-Stellar Object 1146+111B,C

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Color images of faint objects were used to test two hypotheses for the quasi-stellar object (QSO) pair 1146+111B,C: gravitational lens or massive string. Blue, red, and near-infrared CCD (charge-coupled device) images of the field of this QSO pair were examined for gravitational lens multiple-image candidates for all four QSO's in the field (B, C, D, and E). No third image of 1146+111B,C was found, down to 4 magnitudes fainter than BC. This result implies a compact lens mass distribution, if B and C are images of the same QSO. C appears to be redder than B in the wavelength region from 700 to 1100 nanometers. This raises the question of whether B and C are images of the same QSO. Three blue stellar objects of unusual color were found at plausible locations for multiple images of the other two QSO's in the field. A very red object was found at a plausible lens position. Under the hypothesis that B and C are lensed images, these color data severely restrict the possible lens models and imaged QSO multiplicities. One possibility is a compact lens mass of 4×10^{15} solar masses at a redshift of 0.8. Another is an S-shaped massive string. If the spectrum of any of the three anomalous blue objects were available, it would be possible to distinguish between these two models. However, it is difficult to fit the color and intensity data reported here to either simple string or black hole models. Overall, the simplest model consistent with all the data is the no-lens, no-string hypothesis: B and C probably are separate QSO's, but with some spectral similarities.

The field 1146+111 is unusual in at least two respects. It contains an excess number of quasi-stellar objects (QSO's), and two of them have nearly identical redshifts. These two QSO's, B and C, are separated on the sky by 157 arc sec. Is it possible that light from a QSO has traveled on two gravitationally deflected paths around a massive foreground object, giving rise to the dual images B and C? Until now, seven such "gravitational lenses" with multiple QSO image separations of less than 8 arc sec have been discovered. These image separations are consistent with the idea that massive galaxies are the gravitational light deflectors. An image separation of 157 arc sec, if gravitational in origin, would imply a much more massive foreground object.

On the basis of spectra around 600 nm, Turner *et al.* (*1*) report a confirmation of Paczynski's (*2*) suggestion that the double QSO 1146+111B,C found by Hazard, Arp,

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