Very long baseline interferometry and active rotations of crustal blocks in the Western Transverse Ranges, California

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ABSTRACT

Changes in baseline vectors between very long baseline interferometry (VLBI) receiving stations in the Western Transverse Ranges imply that east-west blocks of crust in this region rotate clockwise about vertical axes with respect to the Pacific and North American plates. Minimum apparent rotations, given by the ratios between components of velocity perpendicular to baseline vectors and the lengths of the baselines, imply minimum current rotation rates of a few degrees per million years. The relevant VLBI receivers lie on different crustal blocks that are separated by major active faults. Both geologic and other geodetic observations imply north-south convergence between such blocks at several millimeters per year. Corrections to perpendicular components of velocity for such relative movements between blocks yield likely clockwise rotation rates of 6°/m.y. ± 2°/m.y., which are indistinguishable from the average rate inferred from paleomagnetic declinations of rocks in the Western Transverse Ranges with ages less than 15 m.y. Thus, rotation seems to have occurred continuously and apparently with only small variations in rate during a period when the tectonics of southern California changed dramatically. This apparent independence of the rotation rate on the changing surface kinematics is consistent (1) with such rotation being a manifestation of continuous deformation at depth in the lower crust and upper mantle, (2) with weak faults separating upper-crustal blocks, and (3) with the important resistance to continental deformation lying in the upper mantle and/or lower crust.

INTRODUCTION

The Western Transverse Ranges of California constitute an aberration in the overall right-lateral shear associated with relative motion between the Pacific and North America plates (Fig. 1). Strike-slip faulting on the northwest-trending San Andreas fault and parallel faults provides the dominant style of late Cenozoic and active deformation along most of the plate boundary. In the Transverse Ranges, however, the surface geology (Huftile, 1991a, 1991b; Namson and Davis, 1988, 1991; Yeats, 1983; Yeats and others, 1988), local geodetic surveys (Donnellan and others, 1993a, 1993b; Eberhart-Phillips and others, 1990), and seismicity (Boore and Stierman, 1976; Corbett and Johnson, 1982; Ekström and Dziewonski, 1985; Whitcomb and others, 1973; Yerkes and Lee, 1987) indicate north-south or northeast-southwest crustal shortening to be the dominant tectonic process. This crustal shortening has built the mountain range, which lies oblique to the direction of relative plate motion. The associated thrust faulting seems to pose the region's greatest seismic hazard. Right-lateral shear between the Pacific and North American plates during the past 10–20 m.y., however, seems to have been absorbed, at least in part, by clockwise rotations of crustal blocks about vertical axes (Hornafius, 1985; Hornafius and others, 1986; Kamerling and Luyendyk, 1979, 1985; Luyendyk, 1990, 1991). A basic question is whether such rotation continues or was a process associated with a tectonic regime different from that characterizing the past few million years. If rotation continues, it might be understood as the superficial response to continuous deformation at depth and distributed over a broad area (for example, Eberhart-Phillips and others, 1990; Jackson and Molnar, 1990). If it has stopped, its geodynamic significance could be quite different.

Clockwise rotation is implied by clockwise anomalies in paleomagnetic declinations in rocks with ages between about 5 and 20 m.y. (Hornafius, 1985; Hornafius and others, 1986; Kamerling and Luyendyk, 1979, 1985; Terres and Luyendyk, 1985). In the geologic history of California, 5 Ma is an important date. The Gulf of California began to open rapidly in a direction parallel to the San Andreas fault at about 5 Ma (Larson and others, 1968). Moreover, the 240 km of right-lateral slip on the San Andreas fault system south of the Transverse Ranges has accumulated since about 5 Ma (Crowell, 1962). Thus, it is logical to suspect that the declinations measured in rock older than 5 Ma may be unrelated to the tectonic processes that have occurred since 5 Ma, and therefore that these declinations reflect a style of deformation quite different from that occurring at present.

Revised ages assigned to the paleomagnetic samples from the western Transverse Ranges imply a relatively constant rotation rate of 6°/m.y. (±1°/m.y.), if rotation is assumed to have continued since 5 Ma (Fig. 2) (Luyendyk, 1990, 1991). These rotation rates were calculated assuming an axial geocentric dipole and thus are measured with respect to the north pole. Given the young ages, they apply to reference frames attached to the North American and Pacific plates. The inherent uncertainties in paleomagnetic measurements and inferences of geologic ages makes detecting rotations at this rate since 5 Ma virtually impossible. For instance, both detecting a declination anomaly of 12°, appropriate for samples with age of 2 Ma, and dating such young sedimentary rock so accurately are at the limits of resolution for both measurements. In fact, some studies of younger material in the Ventura Basin suggest that higher rotation rates might apply to the past few million years. Levi and others (1986) reported clockwise rotation of the eastern Ventura Basin of 30° ± 9° since about 2.5 Ma (the Saugus Formation). Liddicoat (1992) measured clockwise rotation 19.8° ± 9.0° for the Plio-Pleistocene Pico Formation.

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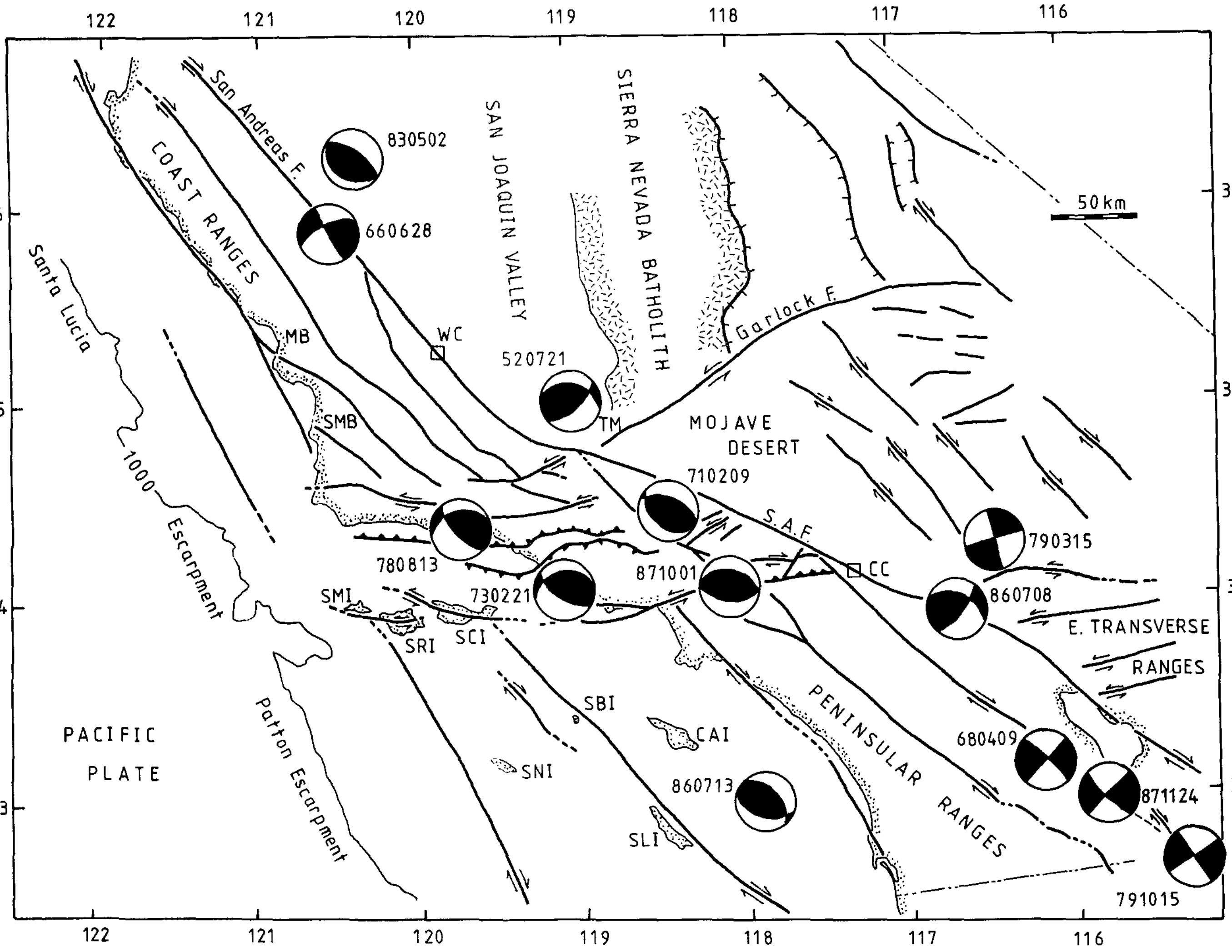


Figure 1. Map of southern California showing major faults and fault plane solutions of major earthquakes. In lower-hemisphere diagrams of the focal sphere, blackened areas contain compressional first motions and T-axes, and white areas contain dilatational first motions and P-axes. Six-digit numbers give the dates of earthquakes by year, month, and day. Abbreviations: CAI, Catalina Island; CC, Cajon Creek; MB, Morro Bay; S. A. F., San Andreas fault; SBI, Santa Barbara Island; SCI, Santa Cruz Island; SLI, San Luis Island; SMI, Santa Maira Island; SNI, San Nicolas Island; SRI, Santa Rosa Island; WC, Wallace Creek. (From Jackson and Molnar, 1990.)

Although these studies strongly suggest that rotation has continued since 5 Ma, perhaps at a rate faster than that for the earlier period, the uncertainties are too large to allow the rate to be defined precisely.

Jackson and Molnar (1990) argued that the horizontal components of slip associated with earthquakes in the Western Transverse Ranges (Fig. 1), which are aligned approximately perpendicular to the local orientation of the San Andreas fault, imply continued clockwise rotations of east-west–trending blocks in the Western Transverse Ranges. One could concoct schemes without rotations to account for such orientations, but an orientation perpendicular to the boundary of an obliquely convergent (or divergent) boundary is consistent with simple mechanisms causing rotations of blocks within a broad shear zone (McKenzie and Jackson, 1983, 1986).

Perhaps more important evidence for ongoing rotation was provided by relative displacements between two receiving stations for Very Long Baseline Interferometry (VLBI); those at Vandenberg Air Force Base (VNDN) and the Jet Propulsion Laboratory (JPL) (Fig. 3). The relative movement between VNDN and JPL throughout a period of 5 years of duration was approximately perpendicular to the orientation of slip vectors for earthquakes occurring on the boundaries of crustal blocks in the Western Transverse Ranges. The simplest interpretation is that the blocks rotate clockwise (Jackson and Molnar, 1990), with respect to a frame of reference attached, for instance, to rigid North America. Here, we discuss VLBI data spanning a longer duration and including baselines between additional stations. These data confirm the existence of clockwise rotation. Moreover, by recognizing that the VLBI sites lie on different crustal blocks, we show that the rotation rates are greater than Jackson and Molnar (1990) had deduced, but are comparable with the average rates interpreted from paleomagnetic declinations. Hence, the geodetic data suggest that rota-

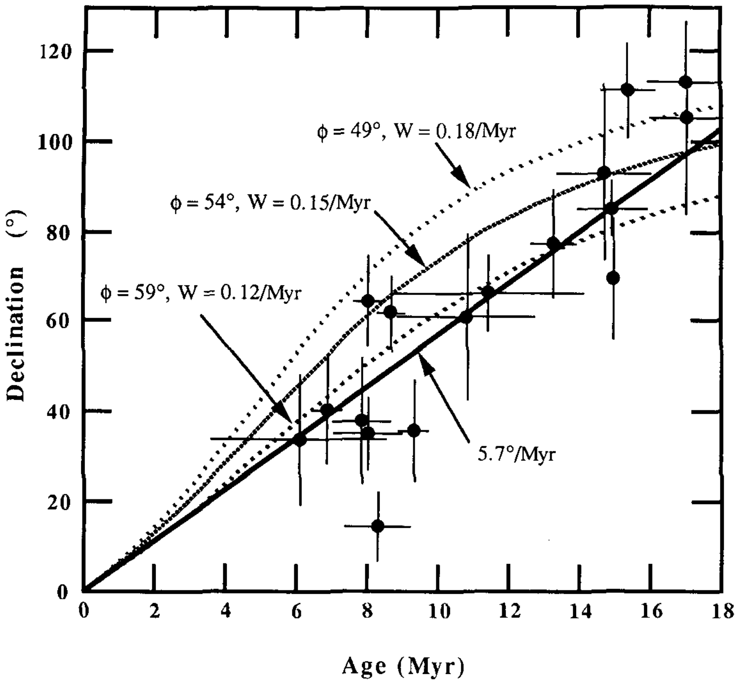


Figure 2. Plot of paleomagnetic declinations for samples in the Western Transverse Ranges as a function of age. Data are from the compilation and redating of Luyendyk (1990, 1991). The straight line of 5.7°/m.y. describes the trend, but theoretical curves using equation 4 do so also. For these, W is the velocity gradient, and ϕ_0 is the present orientation of the blocks with respect to the boundary of the region.

tion in the Western Transverse Ranges has continued without an important change in rate, while the distribution of major faults and the configuration of crustal blocks changed considerably.

MEASUREMENTS OF VELOCITIES USING VLBI

A global network of permanent receivers plus a few mobile receivers routinely record microwave signals from extragalactic sources (Caprette and others, 1990). During a single VLBI measurement, two or more receivers simultaneously record microwave radiation from several extragalactic radio sources in sequence. After the experiment, these signals are cross-correlated to determine the relative arrival times ("delays") of the signals between different pairs of receivers. In the absence of noise, discussed briefly below, the delay is proportional to the projection of the baseline vector between the receiving sites onto the unit vector in the direction of the microwave source. By measuring delays from sources in many directions, the relative positions of the receivers can be determined.

Several sources of noise contaminate measurements of delays. Dispersion of microwaves passing through the ionosphere can be determined, and hence compensated for, by recording signals at two frequencies. Additional delays depend on the temperature, pressure, and humidity of the atmosphere through which the microwaves pass. A common assumption is that the excess line-of-sight atmospheric delay is related to the atmospheric zenith delay by a simple mapping function that depends on the local meteorological parameters and the elevation of the observation. The validity of this approximation has been tested using radiosondes and performing ray-trace analysis. The excess zenith delay is conveniently divided into two parts: the hydrostatic delay, which depends only on temperature and pressure, and the "wet" delay, which is more variable and depends on the water-vapor content of the atmosphere. The wet zenith delay can be treated as a stochastic process. Its value can be found by using a Kalman filter (Herring and others, 1990) or by fitting it to a simple time-varying function (Ma and others, 1990). Drifts of the oscillators in the clocks at each site are also assumed to be stochastic and are treated similarly to the atmospheric delay.

Because VLBI observations are by nature differential, it is impossible to determine absolute positions of the stations. A simultaneous spatial translation of all stations will not affect the data. Thus, a serious issue in VLBI is the reference frame used to analyze the measurements. Furthermore, the rate of rotation and the orientation of the Earth's rotation axis change with time. Unless care is taken, these changes will manifest themselves as a rotation of the VLBI network and as incorrectly inferred relative velocities of the receivers, even if changes in the baseline lengths were estimated accurately. To fix the reference frame, constraints, which are not unique, must be imposed on solution for positions and velocities of receiver sites. In some cases *a priori* information, and in others the nature of the information sought, determine the particular constraints.

We are interested in the motion of parts of California relative to a frame of reference attached to either the North American or the Pacific plate. Because most of the region is far from the stable part of the North American plate but close to that of the Pacific plate, we find it useful to work in a reference frame where the Pacific plate is fixed. Relative to the stable parts of North America, Vandenberg (VNDN) moves northwest essentially parallel to, and as fast as, the Pacific plate (Argus and Gordon, 1990; Clark and others, 1987). The discrepancy between average plate motions since 2 Ma and VLBI-based velocities for 5–10 yr is only a few mm/yr, approximately the same as the uncertainty in each. Although some folding has been detected west and offshore from VNDN, the estimated average rates of movement across this zone time are 0.1 mm/yr since Pliocene time (Clark and others 1991) and less than 0.5 mm/yr since mid-Miocene time (Meltzer and Levander, 1991). Thus, it is reasonable to treat the station at VNDN as lying on the Pacific plate. To define movement of the other sites with respect to the Pacific plate, we imposed the following constraints on the VLBI solution. (1) The position of Vandenberg is held fixed. This eliminates the translational degrees of freedom. (2) The azimuth between Vandenberg and Kauai, Hawaii, is held fixed. This eliminates two of the rotational degrees of freedom. (3) The elevation of Westford, Massachusetts, is held fixed. This eliminates the remaining rotational degree of freedom (about the Kauai-Vandenberg axis) and, incidentally, ensures that local vertical co-ordinates in California will take on reasonable values.

The VLBI solution presented here (Fig. 3) is a "Global" solution; it is a combination of

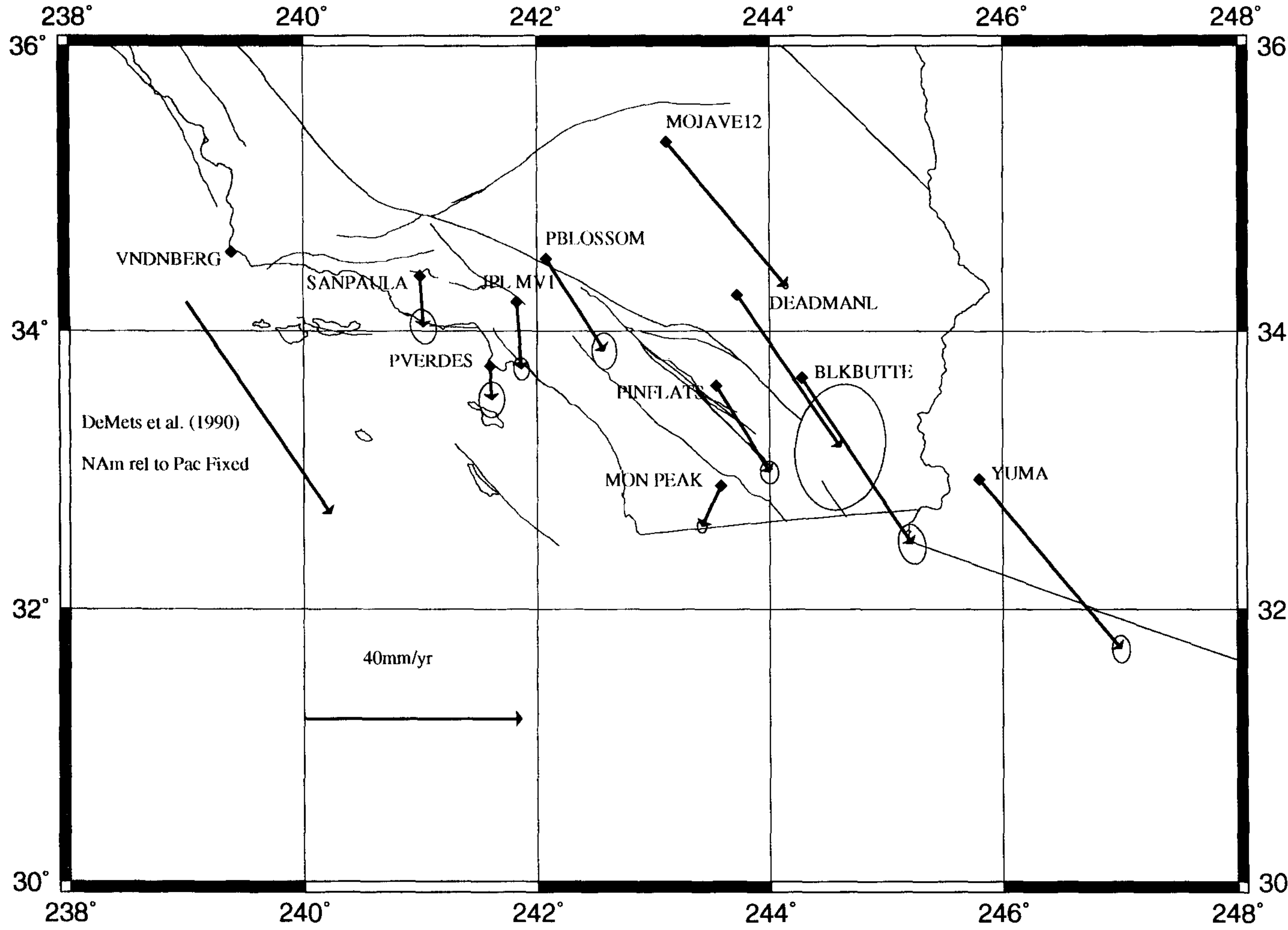


Figure 3. Map of southern California and surroundings showing locations of VLBI sites and velocities relative to the Pacific plate. The reference frame used to define the Pacific plate assumes that VNDN lies on the Pacific plate; that the direction to Kauai, Hawaii, is fixed; and that the elevation at Westford, Massachusetts, also is fixed.

~2,000 VLBI experiments commencing in 1979 and ending in June 1992. The constraints noted above were imposed on this data set. With a few exceptions, positions of receivers have been assumed to vary linearly with time throughout the period of observation. Exceptions include cases where an earthquake caused a sudden displacement of a station position. In such cases, the station position was allowed to change at the time of the earthquake, but the velocity before and after the earthquake was assumed to be constant. Measured changes in relative positions support the assumption that velocities are essentially constant (Fig. 4).

Because it includes more data, the Global solution for a given baseline is more accurate than that based solely on the data from the receivers defining the baseline (Fig. 4). The relative positions of two stations can be indirectly inferred from a series of experiments that share several stations in common. For example, if the position of JPL relative to Vandenberg is known from one experiment, and that for Santa Paula relative to Vandenberg is known from another experiment, the position of JPL relative to Santa Paula can be inferred. This assumes, of course, that care is taken to put the results of both VLBI experiments in the same reference frame. Unless noted otherwise, all uncertainties in VLBI-determined velocities quoted below are 1 σ.

VLBI-MEASURED VELOCITIES FOR THE WESTERN TRANSVERSE RANGES

Besides VNDN, there are two other VLBI sites spread across the Western Transverse Ranges (Santa Paula and JPL) and two others of interest nearby (Pearblossom and Palos Verdes) (Fig. 3). All of the velocities imply regional right-lateral shearing of California west of the San Andreas fault. Relative to VNDN and the Pacific plate, these four sites move south-southeast (Table 1). Pearblossom moves parallel to the North American plate (144°), and lying farther northeast than the others, it moves the fastest. The movement of Palos Verdes suggests that right-lateral strike slip in the California borderland, south of Santa Cruz island, is significant. The more south-southeastward directions of the velocities of Santa Paula, JPL, and Palos Verdes than the southeastward (144°) movement of the North American plate suggest that clockwise rotation about a vertical axis is a possible mechanism for accomplishing this shearing.

For the baseline between Santa Paula and VNDN (Figs. 3 and 4a), there is only a relatively slow change in distance (= 150 km) be-

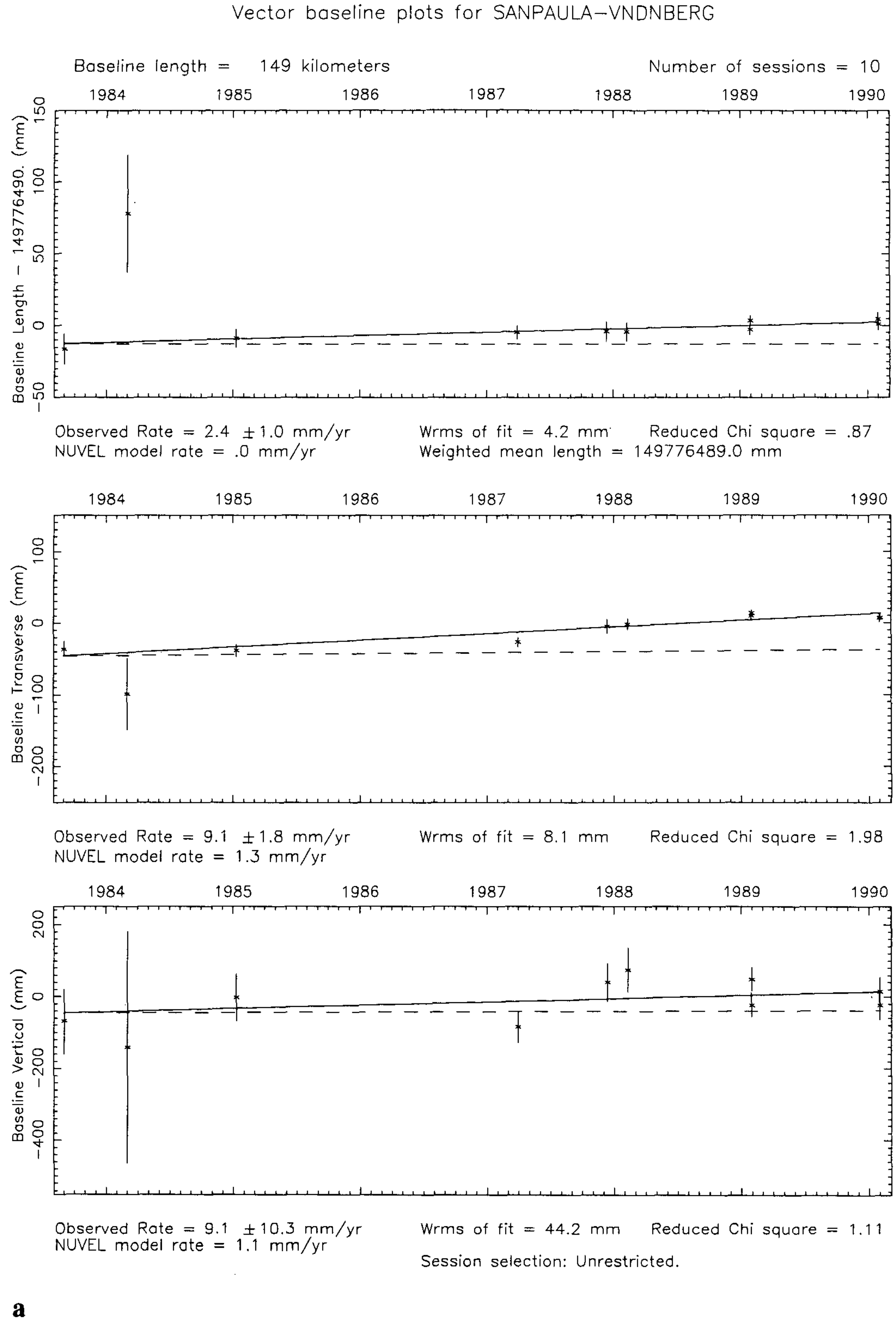
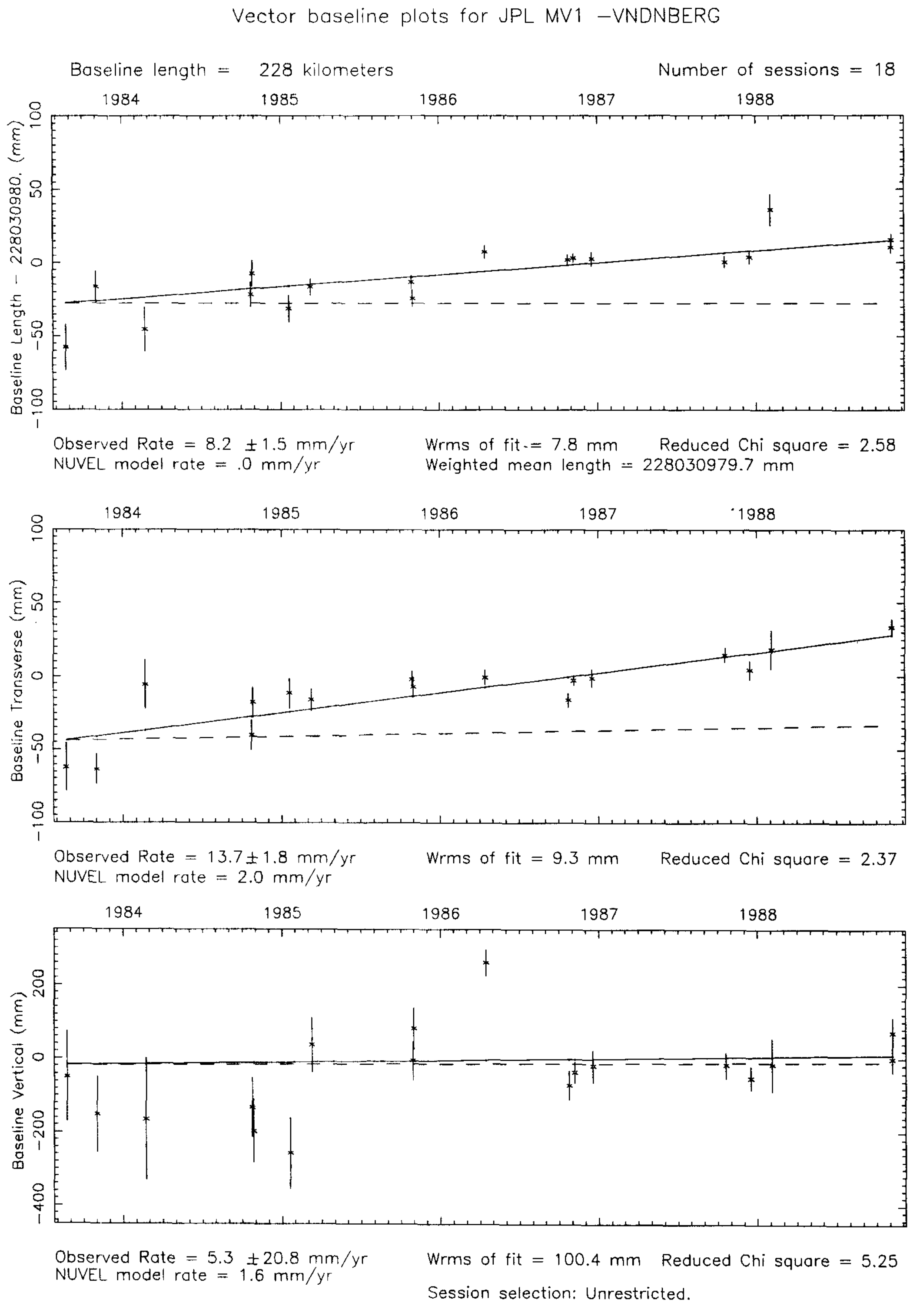


Figure 4. Changes in the baseline vectors (a) between Santa Paula and Vandenberg (VNDN) and (b) between JPL MV1 and VNDN. Components parallel to the baseline vector (baseline length), perpendicular and horizontal, and vertical are shown. These components are measured at the midpoints of the baselines. The vertical component of displacement is measured in the direction from the center of the Earth to the center of the baseline. The transverse component is that perpendicular to both the *a priori* vector between the two sites and the vertical co-ordinate. Only data recorded by these two stations were used to obtain the components of velocity. These plots give some indication of the scatter of individual VLBI measurements, but the vector velocities shown here differ slightly from those in Table 1 and Figure 3. In addition, a value of χ-squared has been estimated to measure the extent to which errors are normally distributed. Thus, in principle, to determine the uncertainty that defines the 67% confidence region, one should multiply σ by χ.



b

Figure 4. (*Continued*).

TABLE 1. VELOCITIES OF VLBI SITES RELATIVE TO VANDENBERG (VNDN)

Site	Speed (mm/yr)	Azimuth (°)
Pearblossom	20.8 ± 0.9	144 ± 2
Santa Paula	10.5 ± 1.0	172 ± 4
JPL	12.6 ± 0.7	165 ± 2
Palos Verdes	6.2 ± 0.9	157 ± 7

tween them: 2.6 ± 0.8 mm/yr (Table 1), consistent with only minor left-lateral slip on the east-west–trending Santa Ynez fault (Fig. 1) (Sylvester and Darrow, 1979). The (approximately southward) perpendicular speed of Santa Paula of 10.2 ± 0.9 mm/yr corresponds to an *equivalent* clockwise rotation of Santa Paula about VNDN of 6.8 (±0.6) × 10^{-8}/yr, or 3.9°/m.y. (±0.3°/m.y.). As discussed in more detail below, because these two sites lie on different crustal blocks, this rate is a lower limit for the clockwise rotation rate.

The Santa Paula receiving site lies between the San Cayetano and Oak Ridge thrust faults, which bound the Ventura Basin (Fig. 5). Therefore it does not lie on the block of crust containing VNDN. Slip on the San Cayetano fault should bring the site at Santa Paula and the block of crust to the north toward one another. Correcting for deformation near these faults is complicated by the likely accumulation of compressive elastic strain near the two faults (Donnellan, 1991; Donnellan and others, 1993a, 1993b), which presumably will be relieved in the future. Accordingly, the measured component of velocity perpendicular to the baseline vector should be an underestimate of the corresponding long-term, approximately southward, velocity between the material north of the San Cayetano fault and VNDN, two areas that seem to lie on the same crustal block.

Five years of measurements using Global Positioning System (GPS) satellites and receivers indicate localized strain accumulation across the Ventura Basin (Donnellan, 1991; Donnellan and others, 1993a, 1993b). Sites 20 km apart have moved toward one another at 7 ± 2 mm/yr, and sites somewhat farther apart have converged more rapidly, implying overall convergence at 11 ± 2 mm/yr. Donnellan and others (1993b) showed that this strain can be matched by slip on thrust faults that are locked only at depths less than 5 km.

Geological investigations of the region surrounding the San Cayetano and Oak Ridge faults also call for rapid convergence across this region (Huftile, 1991a, 1991b; Namson and Davis, 1988, 1991; Rockwell, 1988; Rockwell and others, 1988; Yeats, 1983, 1988; Yeats and others, 1988). Let us assume that convergence across this region, averaged over thousands to millions of years, occurs at about 10 mm/yr, as Molnar (1992) inferred from a synthesis of this published work. Let us also assume, arbitrarily, a 2-σ error of 5 mm/yr in the rate. Santa Paula lies between the San Cayetano and Oak Ridge faults where they reach the surface only a few kilometers apart (Fig. 5). Thus, elastic strain apparently accumulates as convergence at ~5 (±2 σ = 2.5) mm/yr is absorbed both north and south of Santa Paula. Accordingly, the area north of the San Cayetano fault moves approximately south with respect to Santa Paula at 5 mm/yr. We may treat the orientation of convergence at the San Cayetano and Oak Ridge faults as indistinguishable from that perpendicular to the VNDN–Santa Paula baseline. Hence, the sum of 10.2 + 5 mm/yr (= 15.2 ± 1.5 mm/yr) divided by the distance between Santa Paula and VNDN gives an apparent clockwise rotation of 10.1 (±1.0) × 10^{-8}/yr, or 5.8°/m.y. (±0.6°/m.y.) (1-σ uncertainties). If the area north of Santa Paula lies on the same block as VNDN, that block rotates with respect to the Pacific plate at about 6°/m.y., which is indistinguishable from the average since 5–15 Ma deduced paleomagnetically (Fig. 2).

The baseline between JPL and VNDN (length = 228 km) has been lengthening at 5.2 ± 0.5 mm/yr (Table 1). As discussed below, elastic strain accumulation associated with slip at depth on the San Andreas fault could contribute 2–4 mm/yr to this divergence.

The perpendicular, south-southwesterly speed of 11.5 ± 0.7 mm/yr of JPL with respect to VNDN can be understood as an equivalent clockwise rotation of JPL about VNDN of 5.0 (±0.3) × 10^{-8}/yr, or 2.9°/m.y. (±0.2°/m.y.). Again this is a minimum rate, because it ignores JPL and VNDN lying on different crustal blocks. If we add to this measured speed the full 10 ± 5 mm/yr (2 σ), suggested above for the convergence across the San Cayetano and Oak Ridge faults, the corresponding southward rate for area north of JPL with respect to VNDN itself is 21.5 ± 2.6 mm/yr. This corresponds to an apparent rotation rate of 9.4 (±1.1) × 10^{-8}/yr, or 5.4°/m.y. (±0.7°/m.y.) (1 σ). Again, if this area north of JPL lies on the same block as VNDN, the rotation rate for that block is indistinguishable from the paleomagnetically determined average rate since 5–15 Ma.

Other recent geodetic surveys using GPS satellites and receivers also suggest a comparable rate of rotation for parts of the Western Transverse Ranges. The analysis of subnetworks surrounding the Ventura Basin (Fig. 5) for a 4.6-yr period by Donnellan and others (1993a) yields clockwise rotation rates of 4°–7°/m.y. for different subnetworks and 8° ± 1°/m.y. for the subnetwork south of the basin (Donnellan and others, 1993b). Similarly, Feigl (1991) analyzed GPS measurements made over a 4-yr period just north and east of VNDN, across Santa Maria Basin. In a reference frame fixed to VNDN, the network has been rotating clockwise with rates defined by subnetworks of 3 or 4 sites between 0.4 × 10^{-7}/yr and 1.0 × 10^{-7}/yr (between 2°/m.y. and 6°/m.y.). The most rapid rate applies to the area east of VNDN.

The average rate of 6°/m.y. given by paleomagnetic declinations of rocks with ages of 5 to 15 m.y. agrees with the two calculated rotation rates based on 10 yr of VLBI data and the GPS results of Donnellan and others (1993a, 1993b) and of Feigl (1991), for 3 and 5 yr, respectively. Because the corrections made to the VLBI results for the deformation near the San Cayetano and Oak Ridge faults are somewhat arbitrary and cannot be assigned statistical errors, the uncertainties based on the VLBI results quoted above are probably underestimates. Thus, it probably is wisest to conclude that the apparent rotation rates are 6°/m.y. ± 2°/m.y. The obvious, simple conclusion is that the rotations have continued since about 15 Ma until 1990.

Other possible interpretations, at least of the VLBI data, must assign this agreement of paleomagnetically and geodetically determined rates to coincidence. If the region between JPL and VNDN consisted of several blocks, separated by northwest-trending faults, the measured motions of VLBI sites would not require rotation of the blocks. The absence of obvious evidence for such faults in east-west–trending belts of rock that clearly have undergone extensive deformation of other kinds since 5 Ma and the evidence of active rotations shown by GPS surveys (Donnellan, 1991; Donnellan and others, 1993a, 1993b; Feigl, 1991) permit us to ignore this possibility. Alternatively, the apparent rotations might arise from elastic strain in the upper crust associated with continuous slip at depth, but not at the surface, along the San Andreas fault.

POSSIBLE EFFECTS OF ELASTIC STRAIN ACCUMULATION ASSOCIATED WITH SLIP ON THE SAN ANDREAS FAULT

There is no doubt that a sufficiently complicated model with enough faults can yield an elastic strain field that matches the relative velocities of Santa Paula and JPL with re-

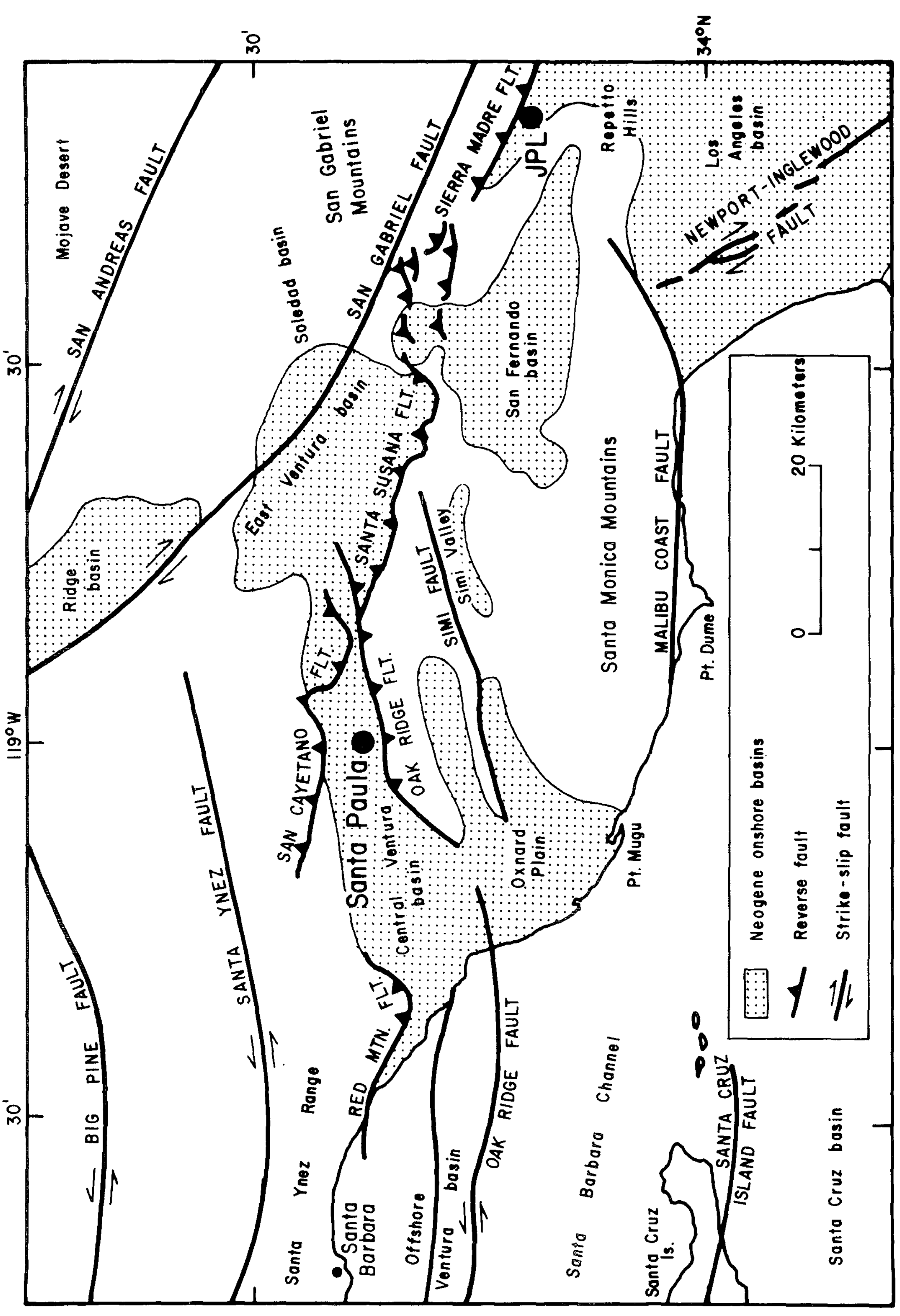


Figure 5. Map of the Ventura Basin and surroundings, showing locations of VLBI sites at Santa Paula and JPL, active faults, late Cenozoic basins, and mountain ranges. (Redrawn from Yeats, 1983, Fig. 1.)

spect to VNDN. Rather than search among the infinite space of such models, we confine our attention to simple cases and use the equation for displacement at the surface of a halfspace cut by an infinitely long, vertical strike-slip fault that is locked from the surface to a depth, h. The velocity of a point at a distance x from the fault with respect to points infinitely far from it on one side is given by

$$u(x) = U/2 - (U/\pi) \arctan (x/h) \quad (1)$$

where U is the relative velocity between areas on opposite sides of the fault and far from it (for instance, King and others, 1987). Let U = 35 mm/yr, the rate of slip on the San Andreas fault in central California measured geologically and geodetically (King and others, 1987; Lisowski and others, 1991; Sieh and Jahns, 1984). The sites at VNDN, Santa Paula, and JPL lie about 100 km, 40 km, and 35 km from the San Andreas fault.

Consider two locking depths: 16 km, appropriate for central California (King and others, 1987), and 25 km, an extreme suggested by Eberhart-Phillips and others (1990) to account for strain in the Western Transverse Ranges measured using laser geodesy. Ignoring the bend in the San Andreas fault, elastic strain should contribute right-lateral slip, with respect to the rigid interior of the Pacific plate, and parallel to the fault. For a locking depth of 16 km, speeds of VNDN, Santa Paula, and JPL would be 1.8 mm/yr, 4.2 mm/yr, and 4.8 mm/yr, respectively. For 25 km, the corresponding speeds are 2.7 mm/yr, 6.2 mm/yr, and 6.9 mm/yr, respectively. Clearly, the differences in speeds between VNDN and the other two sites can account for a lengthening of the VNDN–Santa Paula and VNDN–JPL baselines. The magnitudes of these differences, plus the orientations of the calculated relative velocities being more nearly parallel than perpendicular to the baseline vectors, however, make elastic strain for either locking depth insufficient to account for more than a small fraction of the apparent rotations. Moreover, for a slip rate of only 25 mm/yr, which we suggest below is more appropriate for the segment of the San Andreas fault in the Mojave region than 35 mm/yr, speeds calculated from equation 1 would be correspondingly smaller. A more complex configuration of faults is necessary to account for the perpendicular components in terms of elastic strain.

IMPLICATIONS OF ACTIVE AND FINITE ROTATIONS

We proceed with the conviction that clockwise rotation with respect to the Pacific and North American plates continues in the Western Transverse Ranges at a rate of about 6°/m.y. ± 2°/m.y., or $1.0 \pm (0.3) \times 10^{-7}$/yr, and is not a transient associated with the earthquake cycle. Let us examine the implications of this ongoing rotation for the present-day kinematics of deformation in southern California and for the possible mechanisms that impart such a rotation.

Implications for the Kinematics of Deformation

Suppose that the movement of the area north of Santa Paula and JPL with respect to VNDN and the Pacific plate applies to the San Gabriel Mountains, which lie south of the San Andreas fault in the Mojave region. In simple terms, this area can be thought of as constituting the eastern end of a block of crust containing VNDN at its western end (Figs. 1 and 6). In such a case, this block of crust would extend as much as 200–250 km eastward from VNDN. Relative to the Pacific plate, the eastern end of the block should move due south at a rate given by the product of the rotation rate and the distance from the edge of the Pacific plate: $1.0 (\pm 0.3) \times 10^{-7}$/yr × 225 (±25 km) = 22.5 ± 7.3 mm/yr, which is essentially the estimated rate based on the change in baseline vector between JPL and VNDN and corrections for active tectonics.

Consider the vector triangle for relative velocities among the Pacific plate, the San Gabriel Mountain block, and the Mojave Desert block (Fig. 6). The North American plate moves at 48 mm/yr in the direction 144° with respect to the Pacific plate (DeMets and others, 1990). Several geologic and geodetic studies in the eastern part of the Mojave Desert suggest right-lateral shear approximately parallel to the San Andreas fault at about 8 mm/yr (Dokka, 1983; Dokka and Travis, 1990; Sauber and others, 1987; Savage and others, 1990). Accordingly, suppose that the western part of the Mojave region (the Mojave Desert block) moves at 40 mm/yr in the direction 144° with respect to the Pacific plate. The movement of the San Gabriel Mountains with respect to the western Mojave Desert, however, should be parallel to the San Andreas fault in that area, 295° or 115°. We leave the rate of slip on that fault segment unspecified and determine it from vector addition. Finally, suppose again that the San Gabriel Mountains move nearly due south with respect to the Pacific plate, as the inference of rotation suggests. The vector diagram for the Pacific plate and the Mojave and San Gabriel blocks (Fig. 6) yields a rate of southward movement of the San Gabriel Mountains with respect to the Pacific plate of 21.3 mm/yr, which is virtually identical to that estimated for the area north of JPL and well within the range of 22.5 ± 7.3 mm/yr estimated in the preceding paragraph from the apparent rotation rate. This comparison provides a test, if not an overwhelmingly convincing one, of the suggestion that the San Gabriel Mountains lie on the eastern end of the block containing VNDN and rotating clockwise with respect to the Pacific plate.

This analysis is crude in part because of the large uncertainties in the requisite parameters. Moreover, if the San Gabriel Mountains were, in fact, part of the block that includes VNDN, the southward velocity of this block with respect to the Pacific plate should vary from east to west. Notice, however, that the vector diagram in Figure 6 does not depend on the assumption of a single, rotating block of crust. It is implied by the measured change in baseline vector between JPL and VNDN and the geologic and geodetic evidence of crustal shortening northwest of JPL.

In the vector triangle in Figure 6, the calculated slip rate on the San Andreas fault in the Mojave region is less than 35 mm/yr, the rate farther north in central California (King and others, 1987; Lisowski and others, 1991; Sieh and Jahns, 1984). The calculated rate of 25.9 mm/yr is well within the range of 24.5 ± 3.5 mm/yr obtained by Weldon and Sieh (1986) from offsets of late Quaternary landforms in the region near Cajon Pass. This analysis, therefore, suggests that right-lateral slip of ~10 mm/yr (Sharp, 1981) on the San Jacinto fault should not be added to Weldon and Sieh's (1986) 24.5 mm/yr to estimate the rate for the San Andreas fault in the Mojave region, as for instance Jackson and Molnar (1990) and Weldon and Humphreys (1986) assumed. The ~10 mm/yr of slip on the San Jacinto fault probably is absorbed by thrust faulting along the southern edge of the San Gabriel Mountains.

The suggested variation in the slip rate along the San Andreas fault emphasizes that, no matter how continuous the trace of an intracontinental strike-slip fault might be, slip on that fault need not be, and in general is not, constant along it. Intracontinental strike-slip faults, in general, are not transform faults.

Implications for Mechanisms Imparting Rotations

Two simple, end-member mechanisms generate rotations of crustal blocks about

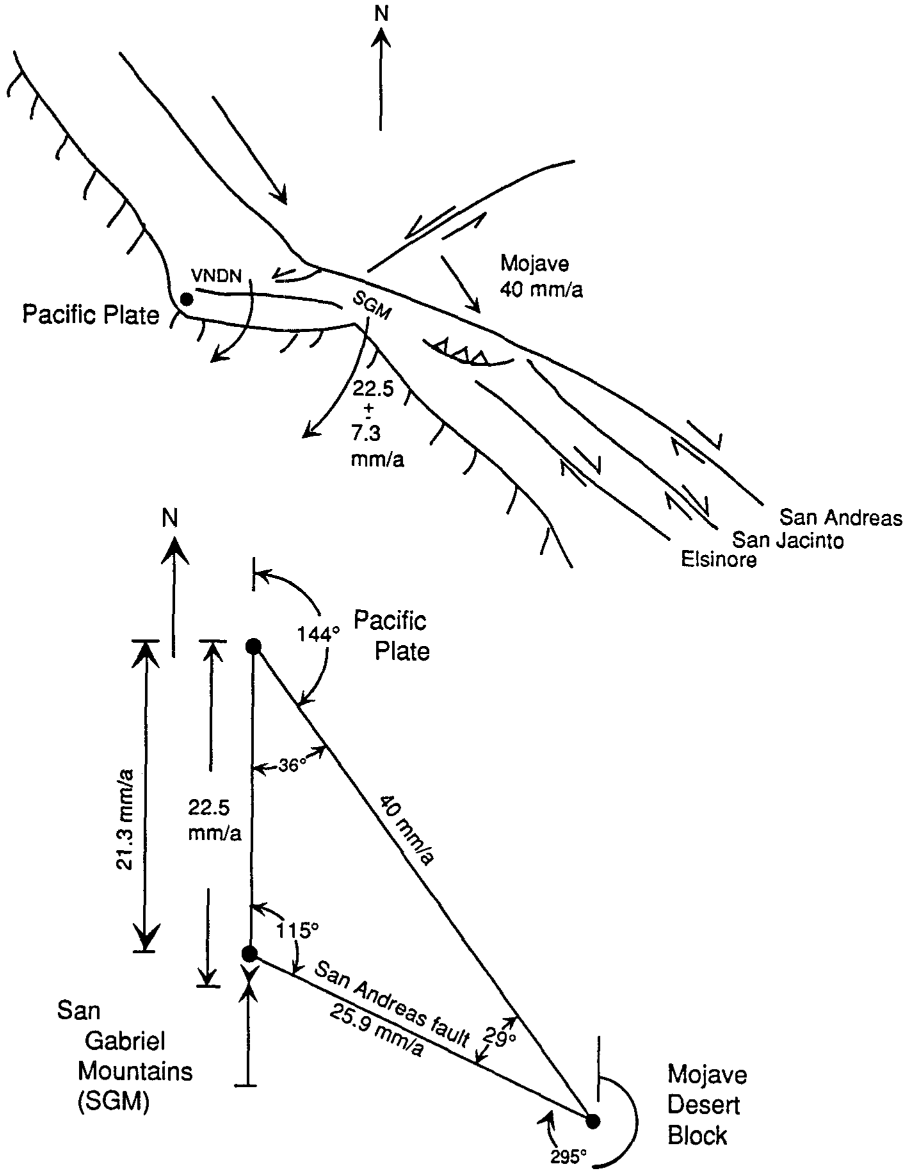


Figure 6. Simplified map of southern California and velocity space for the relative motions among the Pacific plate, the western Mojave block, and the San Gabriel Mountains (SGM). The Western Transverse Ranges and the San Gabriel Mountains seem to rotate about an axis near VNDN. For this simple hypothesis, the San Gabriel Mountains move nearly due south with respect to the Pacific plate at 22.5 ± 7.3 mm/yr. We assume that, of the 48 mm/yr of right-lateral shear between the Pacific and North American plates, 8 mm/yr is absorbed in the eastern Mojave area. Then, the western Mojave block moves southeast at about 40 mm/yr with respect to the Pacific plate. Assuming (1) southward movement of the San Gabriel Mountains with respect to the Pacific plate and (2) slip between the San Gabriel Mountains and the western Mojave block parallel to the San Andreas fault between them, the calculated rates of relative movement are 21.3 mm/yr and 25.9 mm/yr, respectively.

vertical axes (McKenzie and Jackson, 1983, 1986). Friction on the lateral margins of blocks might cause them to rotate. Alternatively, vorticity within a continuously deforming substratum might impart rotations to blocks carried by the substratum. Jackson and Molnar (1990) used the evidence for ongoing rotations in the Western Transverse Ranges and estimates of the rotation rate to test these simple models, and they found only the second to be acceptable. Two aspects of the newer VLBI results, however, render their tests unconvincing. First, the rotation rates for the blocks in the Western Transverse Ranges seem to be distinctly faster than Jackson and Molnar (1990) had inferred. Second, the suggestion that the slip on the San Andreas fault across the Mojave is slower than farther north in central California permits calculated rotations, using either mechanism, that are faster than Jackson and Molnar had considered.

To examine these mechanisms, assume that, in a frame of reference attached to the Pacific plate, shear arising from relative plate motions is parallel to the plate boundary, which lies near the coast of California. Consider two simple, if extreme, cases: the "pinned-block model," in which crustal blocks are pinned to the margins of the deforming zone; and the "floating-block model," in which blocks rotate in response to a homogeneously deforming fluid substratum (McKenzie and Jackson, 1983, 1986).

As applied to the Mojave region, the literal definition of pinned blocks must be relaxed. At the western end of the Western Transverse Ranges, blocks appear to be, nearly at least, pinned to the Pacific plate. At their eastern ends, such blocks are bounded by the San Andreas fault, where slip occurs, but they are not strictly pinned to another large block to the east. Nevertheless, if their relative motions with respect to one another and to the Pacific plate result from simple, uniform boundary conditions on the ends of the blocks, then their relative motions will obey the same mathematical relations as strictly pinned blocks. For blocks behaving as if pinned, the movement of the bounding rigid plates or blocks (or, in this case, the trace of the San Andreas fault) must be perpendicular to the orientation of the pinned blocks (McKenzie and Jackson, 1983). For east-west blocks in the Western Transverse Ranges, their eastern ends in the Mojave region must move southward with respect to the Pacific plate. Thus, the pinned-block model, if appropriate, implies that the San Andreas fault in the Mojave region is becoming more nearly parallel to Pacific–North America plate motion and hence more nearly aligned with its trace farther north.

Following McKenzie and Jackson (1983), the component of velocity between the bounding blocks is given by $W \cdot a$, where W is a velocity gradient, and a is the width of the deforming zone. For the Western Transverse Ranges, the width, a, is the distance from the Pacific plate to the San Andreas fault in the Mojave region, measured perpendicular to the edge of the Pacific plate, ~150 km. Mc-

TABLE 2. AMOUNTS OF ROTATION FOR DIFFERENT PRESENT-DAY ROTATION RATES

Age	Present-day rotation rate*		
	6.8°/m.y.	5.7°/m.y.	4.6°/m.y.
5 m.y.	46° (34°)	37° (28°)	29° (23°)
10 m.y.	83° (68°)	74° (57°)	61° (46°)
15 m.y.	99° (92°)	93° (85°)	83° (69°)
20 m.y.	106° (134°)	102° (114°)	95° (92°)

*Values in parentheses were calculated assuming a constant rotation rate.

Kenzie and Jackson (1983) showed that the rotation rate, R, for pinned blocks is simply W. Hence, with W = 1.0 (±0.3) × 10^{-7}/yr, the component of velocity of the San Gabriel Mountains parallel to the plate boundary should be 15 ± 5 mm/yr. This is clearly reasonable and is implicit in the analysis of kinematics given above. Moreover, this velocity is not very different from that measured between VNDN and the VLBI site at Pearblossom (Table 1), which lies adjacent to a locked portion of the San Andreas fault in the Mojave region. Thus, we cannot use the present rotation rate to reject the suggestion that the blocks are driven by shear on their margins.

For floating blocks, we use the formula derived by Lamb (1987, p. 78) for the rotation of an ellipsoidal block submerged in a fluid undergoing homogeneous shear. We may consider the case in which the fluid is sheared parallel to its boundaries, without a component of convergence or divergence between the boundaries. For a block much longer than it is wide, Lamb's (1987) equation 7 reduces to

$$R = W \sin^2 \phi \qquad (2)$$

for the (clockwise) rotation rate. Again W is the (right-lateral) velocity gradient across the zone, and ϕ is the angle between the strike of the deforming zone and the long axis of the block. Assuming east-west blocks and shear parallel to relative plate motion (144°), ϕ = 54°. Thus, the estimate of R given above yields, via equation 2, W = 1.75 (±0.5) × 10^{-7}/yr.

The average velocity gradient should be approximately equal to the ratio of the velocity describing right-lateral displacement across the region divided by the width of the region. For a velocity of 40 mm/yr and W = 1.75 (±0.5) × 10^{-7}/yr, the width should be approximately 230 ± 70 km, which is clearly reasonable (Fig. 1). Thus, the "floating-block model," in its simplest form of homogeneous shear of the underlying material, also passes the test imposed by the measured rotation rate.

Implications of Finite Rotations for Crustal Dynamics

The two basic mechanisms for imparting rotations differ in one fundamental, if qualitative, aspect that is important for finite deformation and finite rotations. For blocks that rotate in response to stresses imposed on their lateral margins, the geometry of faults and blocks should affect the local stress field, the partitioning of slip onto different faults, and consequently the rotations of the blocks. For blocks carried by a continuously deforming substratum, the orientations of the blocks are of secondary importance to the regional velocity field of the substratum. Thus, if rotation is the response to stresses on the margins of the blocks, erratic changes in rotation rates should occur as the geometry of the blocks changes. Alternatively, if relative plate motion is steady, and blocks are carried by continuous flow in a wide deforming zone, rotation rates are likely to vary only slowly in time. Whereas instantaneous rotation rates do not permit rejection of either extreme, pinned, or floating blocks, consideration of finite rotations provides a discriminant of these simple mechanisms.

Recall that paleomagnetic declinations call for rotations of 80° to 100° since 15 Ma. For the "pinned-block model" to be strictly applicable, the boundaries of the deforming zone must move in a direction perpendicular to the orientation of the blocks. At 15 Ma, when the blocks presumably were oriented north-south, instead of east-west, the area east of the blocks would have moved *east*, not southeast, with respect to the Pacific plate. This seems unlikely, even allowing for variations in the relative motion between the Pacific and North American plates (Stock and Molnar, 1988). Although rejecting this literal version of the "pinned-block model" may be like "knocking down a straw person," testing simple and interesting variants of it does not appear to be easy.

At a qualitative level, the evolving tectonic history of western North America in the past few million years seems inconsistent with the basic assumption underlying the "pinned-block model," that rotation is imparted by stress on the margins of the blocks. The opening of the Gulf of California and the creation of the San Andreas fault in southern California indicate a very large change in the configuration of crustal blocks at about 5 Ma. Yet, because rotation has continued at essentially a uniform rate, this change seems to have had no effect on rotation. The rotating blocks seem to be insensitive to the most dramatic changes in southern California's late Cenozoic tectonics, suggesting that such rotation is relatively independent of the distribution and configuration of the faults and blocks.

For the "floating-block model" to operate, the rotation rate should change steadily with time, as is clear from equation 2. Such a variation in time might seem to contradict the claim that the present rate determined using VLBI measurements and the average since 15 Ma are essentially the same. In fact, we can show that Luyendyk's (1990, 1991) synthesis of paleomagnetic declinations and inferred history of rotations agrees as well with the history expected from a varying orientation of blocks as with a constant rotation rate.

We derive a formula for the variation in time of declinations based on the assumption of a constant velocity gradient, W, but such that the rotation rate changes with time as the orientation of the block changes, as equation 2 requires. Let ϕ and ϕ_0 be orientations of the blocks relative to the orientation of plate motion, with ϕ_0 the present orientation. (We will use $\phi_0 = 54° \pm 5°$.) Let $\Phi = \phi - \phi_0$ define the orientation of the block relative to its present orientation; at t = 0, $\Phi = 0$. Thus, Φ measures the (future) change in orientation since the present time. Conversely, for a negative value of time, corresponding to an age = −t, Φ gives the present magnetic declination of a rock with that age. Given the rotation rate, $R = d\Phi(t)/dt$, we have from equation 2:

$$d\Phi(t)/dt = W \sin^2 [\Phi(t) + \phi_0] \qquad (3)$$

which can be integrated to yield

$$\Phi(t) = (\pi/2 - \phi_0) - \arctan [Wt + \tan (\pi/2 - \phi_0)]. \qquad (4)$$

Consider the calculated amount of rotation versus time for present-day rotation rates of 1.2, 1.0, and 0.8 × 10^{-7}/yr (or 6.8°/m.y., 5.7°/m.y. and 4.6°/m.y.). For ϕ_0 = 54° in equation 4, these correspond to W = 1.8, 1.5, and 1.2 × 10^{-7}/yr. For ages since 15 Ma, equation 4 yields calculated declinations that vary smoothly, but that do not differ much from those obtained assuming a constant rotation rate (Table 2). In particular, calculated declinations using equation 4 and present-day rotation rates between 4.6°/m.y. and 5.7°/m.y. fit Luyendyk's (1990, 1991) plot of declination versus age for ages younger than 15 m.y. as well as a constant rate (Fig. 2). Moreover, calculated rotations for the period earlier than about 15 Ma are small. Paleomagnetic declinations from Oligocene strata in the Santa Ynez Mountains (Sespe Formation), indeed show little difference from those of middle Miocene rocks. From these results, Liddicoat (1990) suggested that significant rotation began only at about 15 Ma. Thus, the present active rotation rate and the paleomagnetic declinations are consistent with long blocks rotating in response to vorticity in an underlying continuously deforming substratum.

CONCLUSIONS

Apparent rotations calculated from measured components of velocities perpendicular to baseline vectors between VNDN and both Santa Paula and JPL suggest that crustal blocks within the Western Transverse Ranges rotate about vertical axes at rates of at least 5×10^{-8}/yr (3°/m.y.). Elastic strain associated with slip at depth on the San Andreas fault cannot explain the measured relative velocities between sites. In fact, because these three sites lie on different blocks of crust where overall north-south convergence across the Western Transverse Ranges characterizes the local tectonics, these rotation rates are probably underestimates. A rotation rate of about $1.0 (\pm 0.3) \times 10^{-7}$/yr, or 6°/m.y. (±2°/m.y.) applies to an east-west block that includes VNDN. This latter present-day rate is indistinguishable from the average rate since 15 Ma.

If such present-day rates apply to blocks extending from the margin of the Pacific plate to the San Andreas fault, then rotation absorbs a significant fraction of right-lateral shear between North America and the Pacific plate at the latitude of the Transverse Ranges. If a large component of shear is accommodated by such a rotation, the slip rate on the San Andreas fault in the Mojave region might be distinctly smaller than that measured along the same fault in central California. The deficit, transferred westward by rotation in the Western Transverse Ranges, should be absorbed by the thrust faulting south of the San Gabriel Mountains. A rate of underthrusting there at about 10 mm/yr seems quite reasonable.

The present-day rates of rotation are consistent either with long east-west–trending blocks being driven by friction on their lateral margins (the Pacific plate and the Mojave region) or by blocks being carried by continuous deformation of a viscous substratum deforming in response to the Pacific–North American relative plate motion. The large finite rotations measured paleomagnetically seem, at least to us, to be more easily understood as the response to a deforming viscous substratum than as the result of friction applied to the ends and sides of crustal blocks within an evolving shear zone along the Pacific–North American plate boundary.

Rotations caused by friction on the lateral margins of blocks depend critically on the orientations of blocks and slip rates on the bounding faults. When the blocks in the Western Transverse Ranges rotated with an average rate of about 6°/m.y. between 15 Ma and 5 Ma, there was no San Andreas fault comparable with that of today in southern California. The entire configuration of faults and blocks must have been very different from that characterizing the period since the Gulf of California began to open rapidly at about 5 Ma. Yet, rotation since 15 Ma seems to have been remarkably steady.

In contrast, rotations of blocks immersed in, or floating on, a continuously deforming substratum depend largely on the rate and orientation of that deformation, which in turn depends primarily on the speed and direction of relative plate motion. Although the average relative velocity between the Pacific and North American plates since 10 Ma has been somewhat faster than that between 20 and 10 Ma (Stock and Molnar, 1988), changes since 10 Ma seem to have been small. Thus, the continuity of rotation, while the tectonics of the upper crust underwent a major change, suggests that rotation is relatively independent of the complexities of surface tectonics and instead results from processes at depth (England and Wells, 1991; Jackson and Molnar, 1990; Sonder and others, 1986). Accordingly, relative plate motion seems to be resisted more by continuous deformation of the underlying substratum than by slip on faults in the upper crust.

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