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December 14, 1984

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Commissioner Lando W. Zech, Jr.
US Nuclear Regulatory Commission
1717 H Street NW
Washington DC 20555

Re: Docket No. 50-275
Docket No. 50-323 /OC
Diablo Canyon Units 1 and 2

Gentlemen:

Enclosed for your information is a copy of a recent draft article prepared by two doctoral candidates at the California Institute of Technology proposing a new kinematic model for southern California. The article hypothesizes that there is a zone of active deformation in southern California which is interpreted to include the Western Transverse Ranges and northwest trending, predominantly strike-slip faults close to the coast north and south of the Transverse Ranges. Included among these faults is the Hosgri Fault. According to the article strain on this system is thought to account for about a third of the total North America-Pacific Plate motion.

We are reporting the article to you at this time in view of the motion pending before you to review ALAB-782. We remain confident that the seismic design of the Diablo Canyon facility is conservative and appropriate for

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the seismic conditions of the area. As with other papers and articles which have been published since the conclusion of the seismic hearings in February 1979, we and our consultants will continue to monitor and evaluate this article and others which may follow as a part of the Company's Long Term Seismic Program.

Very truly yours,

/s/ Philip A. Crane, Jr.

PHILIP A. CRANE, JR.

PAC:nl
Enclosure
cc w/encl:
Judge Thomas Moore
Judge W. R. Johnson
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Submitted to Tectonics

A Kinematic Model of Southern California

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Abstract

We propose a new kinematic model for southern California based on late Quaternary slip rates and orientations of major faults in the region. Internally consistent motions are calculated assuming that these faults bound rigid blocks. Relative to North America, most of California west of the San Andreas Fault is moving parallel to the San Andreas Fault in the big bend region, and not parallel to the motion of the Pacific Plate. This is accomplished by rotation of southern California around the big bend, and by the westward movement of central California north of the Garlock Fault. The velocity field distribution in southern California is calculated along several paths that begin in the Mojave Desert and end off the California coast. A path that crosses the western Transverse Ranges accumulates the accepted relative North America-Pacific Plate velocity while paths to the north and south suggest a significant missing component of motion. These results imply the existence of a zone of active deformation in southern California which is interpreted to include the western Transverse Ranges and NW trending, predominately strike-slip faults close to the coast north and south of the Transverse Ranges. Strain on this system is thought to account for about a third of the total North America-Pacific Plate motion.

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Introduction

Southern California is a tectonically active region, experiencing continental rifting, transform faulting, and small-scale collision. The forces that drive these processes are only partially understood, and despite a great deal of work even fundamental aspects of the kinematics are being debated. In this paper we have modeled the regional displacement field across southern California using available Quaternary slip rates for major faults. We propose a kinematic model that differs significantly from those presently published in the literature. We begin with the observation that little convergence occurs across the portion of the San Andreas Fault between the two bends of the big bend[1] (Figure 1). We use new data that indicate that the total shear rate between cratonic North America and the Pacific coastline is inadequate to account for the relative Pacific-North American Plate motion. Using the slip rates and trends of the major faults in southern California (Figures 1 and 2) we conclude that most of California west of the San Andreas Fault is moving parallel to the San Andreas Fault in the big bend region, and not parallel to the Pacific Plate motion or to the San Andreas Fault north of the big bend. Furthermore, major offshore right lateral faulting with a significant component of convergence is necessary across NW trending faults to account for the slip rates and trends of the major faults in California.

Problems with Previous Kinematic Models

The present tectonic regime is usually modeled with southern California attached to the Pacific Plate and moving about N35W relative to North America (e.g., Atwater, 1970; Anderson, 1971; Hill, 1982; Bird and Rosenstock, 1984). This motion is roughly parallel to the sections of the San Andreas Fault north and

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[1] The term 'big bend' is used to refer to the section of the San Andreas Fault that trends about N65W in the Transverse Ranges region. It lies between the 'north bend' and the 'south bend', two abrupt changes in the trend of the San Andreas Fault.

south of the big bend. The Transverse Ranges, which span the big bend region, are commonly attributed to compression in a zone of collision between the Pacific and North American Plates. Several serious problems with this interpretation are discussed below.

1) The net shear strain rate across southern California, determined from recently estimated slip rates on southern California faults, does not add up to the relative Pacific-North American plate velocity (Weldon and Sieh, *in press*; Sieh and Jahns, 1984). By our estimate, one third of the total plate velocity of 56 mm/yr (Minster and Jordan, 1978; 1984) is presently not accounted for by major onshore faults in southern California. Other workers (e.g., Bird and Rosenstock, 1984) have addressed the problem of total slip rate across southern California, and have produced solutions that yield the relative Pacific-North American Plate motion. Recent information on the slip rates of the southern San Andreas Fault (Weldon and Sieh, *in press*) and the San Jacinto Fault (Sharp, 1981), however, constrains each of these rates to be about 10 mm/yr less than previously thought. These slip rates, and the rates of the other major faults in southern California that are considered in our model, are shown in Figure 2.

2) A mass balance problem exists if southern California is moving with the Pacific Plate because the direction of motion would require a tremendous amount of convergence in the big bend region. A simple calculation for the amount of crust that would have encountered the big bend can be made. The width of the collision zone (normal to the relative plate motions) is about 150 km, and the amount of convergence is assumed to be equal to the offset on the San Andreas Fault, about 300 km. Using a crustal thickness of 25 km, a volume of crust greater than one million km^3 has to be accounted for. An unusually thin crust or a progressively widening big bend might reduce this volume, but it seems likely that at least one-half million cubic kilometers would have been

consumed if this convergence occurred. Volume estimates that include crustal thickening, east-west extension, material transport through erosion and deposition, and crustal "flow" around the big bend have been estimated to be less than a quarter million cubic kilometers (Humphreys, 1984).

3) There is little geologic support for large scale Quaternary convergence in the central Transverse Ranges, and what convergence there is can be attributed to the local geometry of the fault system (Weldon, 1984a). If California south of the Transverse Ranges were moving with the Pacific Plate, at least 20 mm/yr of convergence would have to occur everywhere across the Transverse Ranges. Most of the convergence across the central Transverse Ranges occurs on the Sierra Madre-Cucamonga Fault system (Figure 1). However, activity here is thought to vary between 1 and 6 mm/yr (Ziony and Yerkes, 1984) and this is the only structure upon which a significant amount of Quaternary shortening has been found. In the eastern Transverse Ranges considerable convergence can be assigned to the Banning strand of the San Andreas Fault (Matti et al., 1984). Between these two regions of thrusting lies a section of the San Andreas Fault 50 km in length along which little or no convergence can be documented (Figure 1). Despite local northeast dips of the San Andreas Fault in the area, features offset by the fault can be restored by pure strike slip motion (Weldon, unpublished mapping). In fact, extension is locally taking place on faults north (Weldon, 1984a) and south (Matti et al., 1984) of the San Andreas Fault in this area. It is impossible to appeal to simple northwest-directed collision between the North American and Pacific Plates to explain the Banning and Cucamonga thrusts without also having major convergence between them.

Other geologic observations constrain the amount of convergence that has occurred across the Sierra Madre-Cucamonga and San Andreas Fault systems. The recognition of proximal early Pleistocene and late Pliocene sediments derived from the San Gabriel Mountains, both to the north (Barrows, 1979; Foster, 1980; Weldon, 1984b) and south (Matti and Morton, 1975; Morton and Matti, 1979) of these range bounding faults rules out large amounts of convergence. The detailed match of bedrock terranes, Tertiary deposits, and early Cenozoic structures across the San Andreas Fault zone in the Transverse Ranges (e.g., Ehlig, 1981; Ehlig et al., 1975; Crowell, 1981; Silver, 1982; Powell, 1981) argues strongly against "consumption" of significant volumes of material across the San Andreas Fault in the central and eastern Transverse Ranges since at least the Miocene.

4) It is physically difficult to understand how significant motion could occur on the southern San Andreas Fault if the material south of the big bend is moving parallel to the sections of the San Andreas Fault to the north and south of the big bend. The big bend forms an impediment to the northwestward transport of southern California, producing a situation in which other crustal fractures are more favorably aligned to accommodate the shearing motion (e.g., the San Jacinto and Elsinore Faults). Using a finite element method, Kosloff (1978) modeled the southern California crust as elastic blocks separated by relatively weak viscous faults. When driven by a far field shear oriented so as to drive NW directed right-lateral shear, he could not produce an active southern San Andreas Fault because the more favorably located faults relieved the stress. Kosloff (1978) and Humphreys and Hager (1984) have used this as evidence that the mantle must be contributing forces that drive the southern California crust towards the Transverse Ranges. With this new kinematic model, however, the magnitude of these forces are reduced.

5) Trilateration strain measurements (Savage, 1983) indicate nearly pure strike-slip motion occurring along the length of the San Andreas Fault in southern California. These data indicate that the strain field remains non-convergent

and rotates by the amount needed to keep it aligned with the local trend of the San Andreas Fault. The principal strain axes across the three southern Californian networks are shown in Figure 2. The lack of convergence is particularly striking in the central Transverse Ranges where the greatest amount of N-S strain accumulation would be predicted by existing models.

Overall, the evidence does not support Quaternary compression or geologic convergence in the central and eastern Transverse Ranges of large enough magnitude to be consistent with the current models of NW-directed motion of material south of the big bend. Local convergence does occur, but it can be attributed to either abrupt changes in fault trends or junctions between major faults. In fact, serious problems with the geology and the geodetic data arise if major regional convergence is assumed during the last few million years.

Proposed Model

The proposed model has two major new features. First, we suggest that the material between the big bend and the Pacific Coast is moving around the big bend by rotating in a counter-clockwise direction about a pole located approximately 650 km SW of the San Andreas Fault in the big bend region. This rotation allows movement along the San Andreas Fault to be strike-slip both in the Salton Trough and in the big bend (Figure 2), in agreement with the strain data of Savage (1983) and the geology discussed above. Note that except for a small step in the trend of the San Andreas Fault near the south bend, the San Andreas Fault fits remarkably well on a circular arc with its center at the proposed pole position. From the Salton Trough to the north end of the big bend, a distance of 400 km where we believe this rotation to be occurring, there are no deviations from the arc greater than three km other than the step at the Banning Fault. Furthermore, the velocity field presented by Savage (1983) for the trilateration network across the Salton Trough is itself suggestive of rotation about a pole located in approximately the predicted position (Figure 2).

The second feature of our model is that a significant amount of fault activity is taking place in southern California west of the Elsinore Fault. If the slip is occurring on NW trending faults like the Newport-Inglewood or other offshore faults, about 20 mm/yr of right lateral slip and 5 mm/yr of normal convergence is required. Other authors have proposed relatively large amounts of slip offshore (e.g., Anderson, 1977: ≥ 10 mm/yr) but our model is the first to integrate it into a complete description of the plate boundary.

A convenient way to test the internal consistency of this model is to perform line integrals of the strain rate between points of interest. If this is done between points on the stable North America Plate and the Pacific Plate, the total relative plate motion should be accumulated. This method has been described by Minster and Jordan (1984) and applied to a path across the Great Basin and central California. If all of the motion along any chosen path is considered, the results are independent of the path, and different paths connecting the same end points will yield the same results.

We have considered the four paths shown on Figure 3. When the path over which the integration is carried out encounters no rotation or distributed deformation of the blocks, the integral reduces to a simple sum of the relative slip rate vectors across each velocity discontinuity, generally a fault. Paths 1 and 2 have been integrated in this manner. Paths 3 and 4, which cross blocks rotating on a relatively small arc, requires accounting for continuous motion. For simplicity the overall deformation in the western Transverse Ranges is treated as though it were a single thrust fault parallel to the trend of the major faults and folds in the area. The effects of errors in the slip rates are discussed separately in the next section.

The paths begin in the Mojave Desert, which we believe is essentially part of the North American Plate. There are two reasons that lead us to believe that this is true. A path from cratonic North America to the Mojave Desert can be constructed south of the Great Basin that crosses very little significant Quaternary deformation (Figure 3). Also, there is recent evidence (Weldon et al., 1984; Dokka, 1983) that the Mojave region has not experienced the significant late Cenozoic rotations or deformations [illegible] t most previous models hypothesising an active Mojave require. Garfunkel [illegible]) and Calderone and Butler (1984) have proposed large scale counter-clockwise rotations, and Luyendyk et al. (1980) and Bird and Rosenstock (1984) have proposed large scale clockwise rotations within the Mojave Block, accompanied by major shear on the many NW trending faults that exist in the region. However, Dokka (1983) has demonstrated that these faults have not experienced enough total displacement to significantly deform the Mojave, and Weldon et al. (1984) have demonstrated paleomagnetically that the SW Mojave has rotated less than 4° since the middle Miocene. If the Mojave has not experienced significant internal deformation or rotation since the Miocene, and there is no major Quaternary structure separating it from North America, we feel that it can be considered a part of the North American Plate.

Path 1 begins by crossing the Garlock Fault and continues onto the Sierra block. We assume that the trend of the Garlock Fault west of the Owens Valley Fault (i.e., west of the Great Basin) indicates the direction of motion, S55W, and that the slip rate is 11 mm/yr (the best estimate of Carter, 1980; 1982). There is considerable uncertainty in the slip rate ascribed to the Garlock Fault, which will be addressed below. Though uncertainty exists, Carter's estimate provides the best constraint available today. From here the path heads west and crosses the San Andreas Fault, which contributes a vector parallel to the trend of the

San Andreas Fault (N40W) with a magnitude of 35 mm/yr (Sieh and Jahns, 1984). This results in a vector for the Salinia block (relative to North America) of 38 mm/yr that is directed N58W. This leaves a discrepancy of 23 mm/yr oriented N5W that is needed to bring the the net motion up to that of the Pacific Plate. The discrepancy vector is shown in Figure 3 as a "hollow" vector located at the end of path 1. The discrepancy vector is similar to the preferred discrepancy velocity vector of Minster and Jordan (1984), though our discrepancy vector predicts slightly more convergence in the region west of the San Andreas Fault as a result of the more southerly drift of the Sierra block in our model. As noted by Minster and Jordan (1984), much of the discrepancy vector may be taken up on the San Gregorio-Hosgri Fault system, and there is geologic support for this. Weber and Lajoie (1977) suggest a rate of 6-13 mm/yr of right-lateral slip for the fault, and Crouch et al. (1984) present evidence for considerable convergence across this and other faults west of the San Andreas Fault.

Path 2 follows path 1 across the Garlock and San Andreas Faults and then [illegible]s south through the western Transverse Ranges to the offshore area. Yeats (1983) calculates a rate of convergence across the Ventura Basin of 23 mm/yr for the last 200,000 years. More recent unpublished results from this area also give a high, though somewhat lesser rate of convergence (Rockwell, 1983: 17 ± 4 mm/yr). It is not yet known how the rate varies across the province or whether the numbers represent the total western Transverse Ranges. We have chosen to use Yeat's value, and we infer a direction of N5W, normal to the major faults and folds in the area (Figure 2). Path 2 results in a relative motion (55 mm/yr, N35W) indistinguishable from that of the Pacific Plate (as shown in Figure 3), suggesting that the borderland south of the western Transverse Ranges is moving with the Pacific Plate.

Path 3 crosses the San Andreas Fault east of the junction with the San Jacinto Fault and enters the Salton block, picking up a velocity of 25 mm/yr (Weldon and Sieh, *in press*) directed N55W, which is parallel to the tangent of the arc fit to the San Andreas Fault where path 3 crosses it. From here the path turns SW and heads directly towards the pole of rotation. By heading in this direction the only effect of block rotation is to decrease the magnitude of the velocity vector linearly in such a manner as to attain a value of zero at the pole. The faults that are encountered along the path are treated as translations that supply velocity vectors that are simply superimposed to determine a net slip rate for any point along the path. Path 3 crosses the San Jacinto Fault, picking up 10 mm/yr (the long term Quaternary slip rate of Sharp, 1981) directed parallel to the fault (N47W), and the San Andreas component decreases by 1.5 mm/yr due to the approach of the pole.* This results in a velocity vector for the Pomona block of 33 mm/yr oriented N52W. Continuing to the SW the Elsinore Fault is crossed next, adding about 2 mm/yr (constraints on this number are discussed in the next section) of right-lateral motion oriented N49W, and passes onto the Los Angeles block. Subtracting an additional 1.5 mm/yr from the San Andreas component of motion for the continued approach towards the pole yields a velocity vector of 33 mm/yr directed N53W. The path is finally brought offshore and another 2 mm/yr is removed from the San Andreas component, yielding a net relative velocity vector of 32 mm/yr pointing N50W. The discrepancy vector at the terminus of path 3 is indicated in Figure 3 with a "hollow" arrow that is 25 mm/yr pointing N11W.

If path 3 were to be continued to the terminus of path 2 a velocity vector would have to be included that nulls the discrepancy vector, implying the existence of a zone of significant dextral shear strain occurring between the Los Angeles block and the end of path 2. As the north-south directed compressive deformation in the western Transverse Ranges seems to decrease toward the central Transverse Ranges, the Newport-Inglewood Fault and/or other near-shore faults are thought to accommodate most of discrepancy vector 3.

Uncertainties in the Model

The description presented above is our best estimate, based on the data available, of the kinematics of southern California. The data are not well constrained in several critical areas. Possible sources of error include failure to consider strain resulting from smaller structures possessing unknown rates, and inaccurate parameterization of the structures treated. Ideally, uncertainties could be accumulated along the route of integration at the same time that the strain is calculated, so that at any point along the path an uncertainty could be given (relative to the beginning of the path). However, the nature of the uncertainties make them poorly suited to statistical treatment. The slip rates are the "best estimates" of the workers from their field areas, but the probability distribution of the estimates are often asymmetric and highly non-Gaussian. In lieu of a formal treatment of the error, we discuss probable sources and magnitudes of error and their quantitative effects on the block motions and on the overall kinematic model.

There is considerable uncertainty in both the magnitude and direction of motion of the Sierra block. Carter's slip rate of 11 mm/yr, that we use in deducing the motion of this block, is only absolutely constrained between 5 and 30 or more mm/yr (Carter, 1982). However, his best estimate of 11 mm/yr is based on several lines of geologic inference that we feel are quite good. Also, his rate is for the portion of the Garlock Fault to the east of the Owens Valley Fault, whereas path 1 crosses the fault west of of this fault. The Owens Valley Fault probably cannot contribute more than a few mm/yr even in its more active northern portion (Gillespie, 1982). We feel that the inactivity of the southern end of the Owens Valley Fault allows us to extend Carter's estimate across the fault and to the west. A related problem is that the Garlock Fault is quite curved. We have chosen S55W because it is the trend of the fault in the region where it separates the Mojave from the Sierra block, and therefore should best describe the block's local relative motion. Note that chosing this portion of the Garlock Fault yields a slip vector orientation that is pointing as far counterclockwise as the trace of the Garlock Fault will allow. If translation of the Sierra block is occurring in a more westerly direction, the motion of this block would be more in line with that chosen by Minster and Jordan (1984). The effect of increasing the slip rate on the Garlock Fault would be to increase the amount of convergence occurring offshore north of the Transverse Ranges and would be consistent with a component of left-lateral shear occurring across the western Transverse Ranges. However, if the Sierra block is moving westward by rotating about a pole located approximately 200 km to the southeast, as suggested by the curvature of the Garlock Fault, the relative velocity vector should be rotated counterclockwise 20–25° by the time the integration path reaches the San Andreas Fault. The possibility of this rotating movement is also suggested by the northward increase in activity across the Owens Valley Fault (Gillespie, 1982), and the presence of increasingly compressive faulting parallel to theGarlock Fault west of where our path crosses the Sierra block (Figure 3) (Davis and Lagoe, 1984).

In our model the movement of the Sierra block is estimated by using information on the Garlock Fault. An alternative approach, chosen by Minster and Jordan (1984), is to consider a path that begins on stable North America and arrives at central California by crossing the Great Basin. Though uncertainties in the motions encountered along the path exist in both cases, we feel that there are fewer problems associated with the route we have chosen. This is due to the relatively large degree of uncertainty in the rate and orientation of extension across the Great Basin. Other workers have assumed that some of the motion on the Garlock Fault is due to deformation or rotation of the Mojave block relative to North America. We believe that it is entirely due to the opening of the Great Basin. The fact that the Garlock Fault does not span the entire southern margin of the Great Basin may be a problem. We feel, however, that an equally significant problem is produced by appealing to a mobile Mojave block; that is the apparent absence of deformation on the eastern margin of this block.

Strain along path 2 in the region of the western Transverse Ranges is assumed to be purely convergent normal to the major faults and folds, and ignores the left-lateral faults that combined are believed to accommodate less than 2 mm/yr (Clark et al., 1983). The resulting velocity vector for an arbitrary point south of the zone of convergence is very close to the velocity vector for the Pacific Plate (Minster and Jordan, 1978; 1984). This suggests that most of the California borderland west of the end of path 2 (Figure 3) is indeed part of the Pacific Plate.

Path 3 has the least amount of uncertainty associated with its relative velocity vectors. The rates and orientations of all three onshore strike slip faults crossed are fairly well constrained. For the San Andreas Fault we use Weldon and Sieh's (*in press*) estimated rate of 24.5 mm/yr ± 3.5 mm/yr and the orientation tangent to the circular arc shown in Figure 2 that produces pure strike-slip motion along the San Andreas Fault. Sharp (1981) has determined a rate of about 10 mm/yr on the San Jacinto Fault, and we have chosen an orientation that on average best describes that fault. Estimates of the slip rate across the Elsinore Fault vary from 1 mm/yr (Ziony and Yerkes, 1984) to 7 mm/yr (Kennedy, 1977). New work on the southern Elsinore Fault (~4 mm/yr: Pinault and

Rockwell, 1984) may help constrain the slip rate, but at the moment none of the estimates is as well constrained as the other slip rates encountered along path 3. In our model we arbitrarily chose 2 mm/yr to reflect the consensus that the northern Elsinore accommodates very little slip. If the lower estimate of 1 mm/yr is valid, it increases the discrepancy vector by a negligible amount. A rate of 7 mm/yr reduces the discrepancy vector to about 20 mm/yr, a change of only 20%. No reasonable slip rate on the Elsinore Fault can change the conclusion that a large fraction of the plate motion must be west of the Los Angeles block.

Another possible source of error in our model is the uncertainty of the pole position about which the blocks are rotating. This source of error must be small because the path covers less than 20% of the distance to the pole, and was chosen so that no change in orientation occurs. The uncertainty in the pole position can contribute only a few mm/yr of error to the total. If the Salton Trough is opening with a component normal to the San Andreas Fault, as has been suggested by Biehler (pers. comm., 1983), the pole may be farther away from the big bend region. This possible normal component in the Salton Trough, however, is not supported by Savage's (1983) strain data or by the arcuate fit of the San Andreas shown in Figure 2.

Another route similar to path 3 could be taken across the San Andreas Fault NW of the San Jacinto Fault, to the San Gabriel block, and then across the Sierra Madre-Cucamonga Fault to the Pomona block. This is shown on Figure 3 as path 4. Crossing the San Andreas Fault picks up 35 ± 5 mm/yr (Weldon, 1984b) parallel to the San Andreas Fault, N65W. This gives a velocity for the San Gabriel block which is similar to that found for the Salinia block with path 1. This is expected because there are no major active structures recognized between the two blocks. Rotating the Sierra block counterclockwise along the curved Garlock Fault (as discussed above) will result in Salinia moving with a magnitude and direction even more similar to that of the San Gabriel block. Crossing the Cucamonga Fault to the Pomona block adds 3 mm/yr (Matti et al., 1982; pers comm, 1984) to the relative velocity vector and rotates it clockwise about 15°. The resultant Pomona block vector (corrected for rotation accumulated by traversing the block to path 3) is virtually identical to that calculated with path 3. Again, the consistency of the results determined with different data sets along different paths tends to support the accuracy of the rates and the kinematic model. Also, since the Los Angeles block is moving parallel to the Pomona block, there remains about the same angular discordance between the San Gabriel block and the Los Angeles block as exists between the San Gabriel and Pomona blocks. The change in orientation of the Sierra Madre-Cucamonga Fault zone to the west will affect the relative amounts of convergence and lateral faulting along this boundary. Convergence on the Sierra Madre-Cucamonga Fault system is largely responsible for the current uplift of the central Transverse Ranges. In our model this is due to the slightly different direction of motion of the San Gabriel block with respect to those to the south, and not to simple convergence between the Pacific and North American Plates.

Implications

An important feature of our kinematic model is the prediction of a zone of very active deformation offshore. This is a consequence of the discrepancy vectors for paths 1, 3 and 4 and the convergence in the western Transverse Ranges all being nearly the same (vector diagrams, Figure 3). We propose that the discrepancy vectors for paths 1, 3 and 4 are accommodated on NW trending, predominately strike-slip faults near the coast, while convergence on E-W thrusts and folds in the western Transverse Ranges accommodate the same motion there. The style of activity varies because the elements differ in orientation. In this "coastal system" the western Transverse Ranges form a left step between the more NW trending offshore elements. Seismic studies support our model of a switch from predominately strike-slip motion on northwest trending faults in the borderland to essentially pure convergence in the western Transverse Ranges (e.g., Corbett, 1984). Unfortunately, the length of the seismic record is inadequate to estimate rates of deformation. The diminishing of convergent deformation to the east and west of the western Transverse Ranges places the site of the offshore faulting near the coastline both north and south of the Transverse Ranges. This arrangement of active features defines a coastal system of active boundaries that separate the Pacific Plate to the west from a slice of relatively intact continental material to the east.

In southern California the coastal system is only exposed onshore in the western Transverse Ranges. Measurements of the rate and direction of convergence across the western Transverse Ranges at various longitudes may provide a direct means of quantifying the location, rate, and style of motion on the NW trending elements of the system that are not exposed onshore. We have calculated that the end of path 2 is moving with the Pacific Plate, but the distribution of activity on the faults within the borderland between the end of path 2 and the Los Angeles block cannot be determined until the distribution of the convergent activity in the Transverse Ranges east of path 2 has been worked out in detail, or until the slip rates of the underwater faults are determined. Another area where constraint on the activity of the coastal system may exist is Baja California. Allen et al. (1960) report Quaternary deformation on the Agua Blanca Fault that indicates up to centimeters/year of activity joining the Gulf of California with the California borderland. Yeats and Haq (1981) also describe active features that run down the western length of Baja, suggesting that some of the Pacific-

North American plate motion never enters the Gulf of California.

Another important consideration is the relation between the offshore activity and the value for the Pacific-North American Plate relative motion. We accept the plate motion value determined by Minster and Jordan (1978; 1984) and compare our integrated velocity to theirs. The motion on the NW trending elements of the coastal system is determined by assigning the difference between the integrated strain and the Pacific-North American Plate motion on these features. We feel justified in doing this because it is consistent with the slip estimates determined by the extension of paths 1, 3 and 4 to the end of path 2, which is a purely internal determination. While the acquisition of the Pacific Plate velocity by the end of path 2 supports the Pacific-North American Plate rates of Minster and Jordan (1978; 1984), we do not intend for this to be taken as strong evidence for the accuracy of their value. This is because we have accumulated an unknown amount of uncertainty along path 2, and because their rates are based on a 3 my average while ours are late Quaternary estimates. It is not yet known whether our model is valid for the tectonics prior to the late Quaternary. If the actual Pacific-North American Plate rate differs somewhat from the value determined by Minster and Jordan (1978; 1984), an internally consistent model could be produced by only adjusting the model convergence rate in the western Transverse Ranges. The quality of the data from the western Transverse Ranges, however, probably does not allow one to alter the model very much.

We agree with the conclusion of Minster and Jordan (1984) that the convergence across the Pacific-North American plate boundary is due to the westward motion of central California in response to the opening of the Great Basin, and not due to the geometry of the San Andreas system. We feel that our rate and direction of motion for the Sierra block (11 mm/yr and S55W) are better constrained than theirs. Further, if the Sierra block is rotating west, as suggested by the curvature of the Garlock Fault, the convergence in the Transverse Ranges near the junction of the Garlock Fault with the San Andreas Fault can be explained by the impingment of the SW corner of the Sierra block into the Salinia-San Gabriel block. We feel that this satisfies the geology (Davis and Lagoe, 1984) better than appealing to the geometry of the San Andreas-Garlock junction.

Finally, our model suggests origins for the activity in the Transverse Ranges that differ from previous accounts. These ranges have long been taken as evidence for southern California, as part of the Pacific Plate, to be colliding into North America in the big bend region. However, our model (Figure 4) produces uplift in the eastern Transverse Ranges with convergence across a step in the otherwise arcuate and strike-slip southern San Andreas Fault. The convergence across this small step is 25 mm/yr oriented N50W. The central Transverse Ranges are being uplifted by the Sierra Madre-Cucamonga Fault system. Convergence across this boundary is due to the different directions of motion of the San Gabriel block and the blocks to the south. As shown in Figure 4, this geometry requires about 3 mm/yr of convergence across this zone. Activity in the western Transverse Ranges is due to a left step in the "coastal system", and is probably unrelated to the San Andreas Fault. Corbett (1984) notes that all well located earthquakes that occurred deeper than 20 km, and most that occurred deeper than 15 km (from 1971-1981), were either in the Banning Pass area or in the western Transverse Ranges. This is thought to be due to the existence of cold, brittle material at an unusually great depth as a result of the exceptional degree of convergence at these locations. This is supported by the anomalously high seismic velocity of the deep crust in the same locations (Humphreys, 1984)

We feel that the major uncertainties in the tectonics of southern California are external to the region modeled. The opening of the Great Basin appears to control the motion of the Sierra block, which in turn controls the amount of convergence near and off of the central California coast. It is also felt that the similarity in motion of the Salinia block with that of the San Gabriel block suggests that the extension in the Great Basin (which controls the motion of the Salinia block) is related to the rotation of southern California (which controls the motion of the San Gabriel block). Furthermore, the degree to which the Mojave block is part of North America directly affects the amount of activity required offshore to satisfy the plate boundary conditions. The value chosen for the instantaneous plate velocity affects the estimates of offshore activity in a completely analogous way. In spite of these external uncertainties, it is the internal consistency of the model, which includes the coastal system through the activity documented in the western Transverse Ranges, that suggests to us that the kinematics of southern California are now reasonably well understood. The single tie across the western Transverse Ranges to the borderland leaves the coastal system as the least certain past of the model, but the agreement of the velocity at the end of path 2 (which crosses the western Transverse Ranges) with the externally derived value for the velocity of the Pacific Plate (Minster and Jordan, 1978; 1984) lends additional support for the nature of the coastal activity. The magnitude of the offshore activity implies that the region between the San Andreas Fault and the coastal system may be thought of as a mini-plate that is neither part of the North American Plate or the Pacific Plate.

Acknowledgements

This paper is based on the field work and thoughts of innumerable people who have worked in southern California. We would like to acknowledge all of those workers referenced in the bibliography and to especially thank those who have freely shared their unpublished data and ideas upon which our model is based. We are particularly grateful to Leon Silver, Clarence Allen, Brad Hager, Kerry Sieh, Kris Meisling and Steve Wesnousky, who lent critical discussion and/or detailed reviews of the first draft of this manuscript. We thank Jan Mayne for assistance in the preparation of the figures.

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FIGURE CAPTIONS

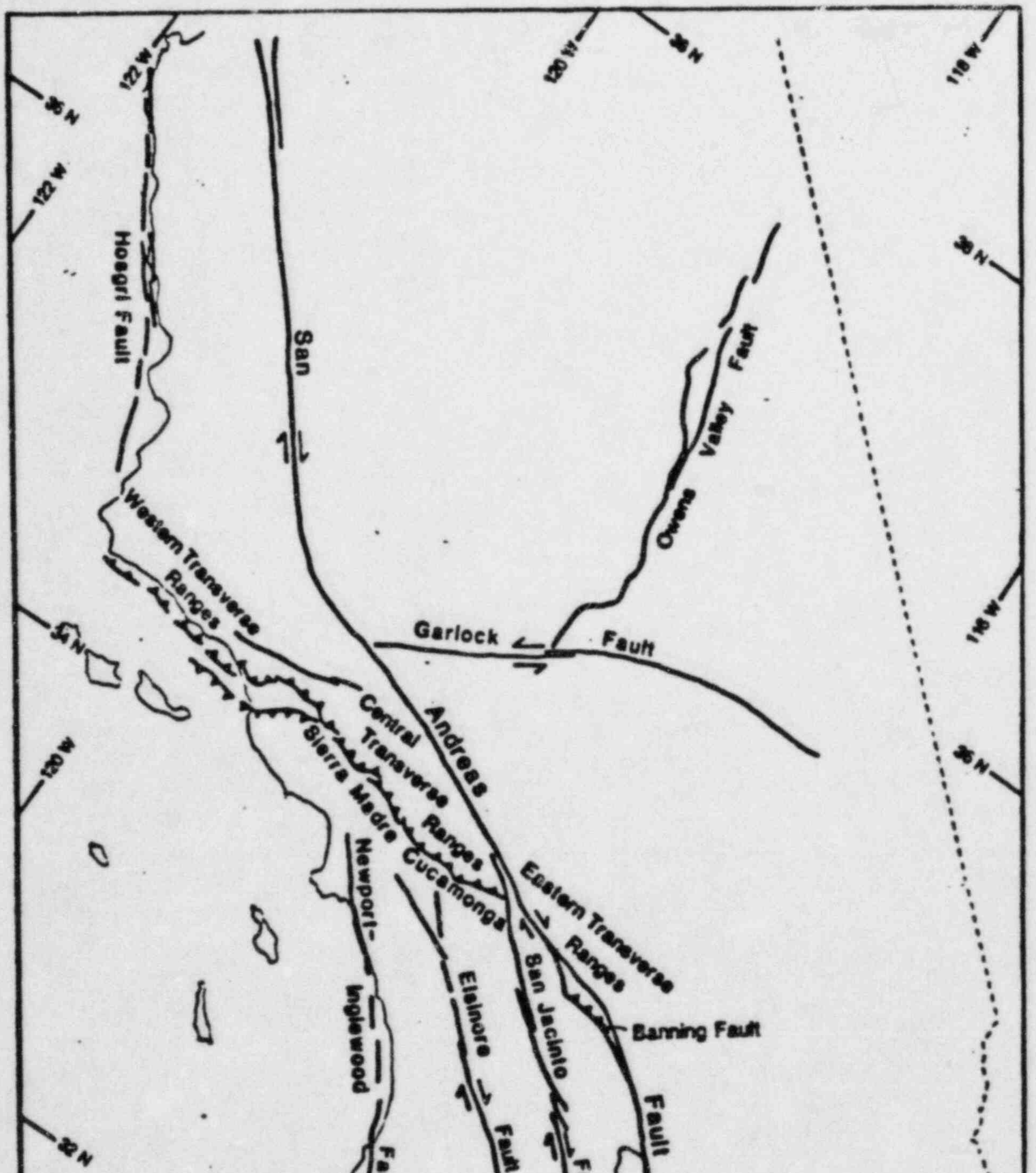
Figure 1 - The principle faults of southern California and the subdivisions of the Transverse Ranges used in this paper. These faults are assumed to bound essentially rigid blocks that are modeled as moving in directions consistent with the faults that bound them. The broad deformation associated with the western Transverse Ranges is modeled as a simple boundary, parallel to the zone.

Figure 2 - The major blocks in southern California and the data used to calculate their velocities relative to North America. The arcs have been fit to the trend of the San Andreas fault to determine the direction of motion of southern California west of the fault. Only the area between the northern big bend, the Salton trough and the Pacific coast is rotating along the arcs. The principle strain rates from 3 trilateration networks in southern California and the average velocity field across the Salton network (Savage, 1983) are included to demonstrate the consistency of this data with the curvature of the fault. The slip rates (mm/yr) used in the model are located where the integration paths (Fig. 3) cross the faults. The letters associated with the rates are the references from which the rates were chosen: a) Sieh and Jahns, 1984; b) Carter, 1980; 1984; c) Weldon, 1984; d) Weldon and Sieh, 1984; e) Sharp, 1981; f) Matti et al, 1982; g) see text; h) Yeats, 1983.

Figure 3 - Integration paths and slip vectors for the major blocks in southern California. The solid arrows are the velocity vectors relative to North America for points along the paths and the vector diagrams show the data used to construct these vectors. Because the southern California blocks are rotating about a relatively close pole, the velocity vectors vary by a small but significant amount across the blocks (see text). The corrections

are included in the vector diagrams as vectors with points instead of heads. The "hollow" arrows at the end of Paths 1, 3 and 4 (on both the map and the vector diagrams) are the discrepancy vectors, the motion necessary to bring the path up to the relative plate motion between the Pacific and North American plates (Pacific-North American plate motion form Minster and Jordan, 1984). Only Path 2 yields the total plate motion, indicating that more than 1/3 of the plate motion is accommodated by structures close to or off of the California coastline (see text).

Figure 4 - Schematic representation of the active deformation in the Transverse Ranges. The eastern Transverse Ranges are being uplifted by convergence across a step in the San Andreas fault, indicating a rate of convergence of 25 mm/yr oriented N50W. The western Transverse Ranges are being compressed by a similar left step in the hypothesized coastal system, at a rate of 23 mm/yr oriented about N5W. The central Transverse ranges are only experiencing minor uplift, due to the difference in direction of motion of the San Gabriel block and southern California. The direction and magnitude of this compression is difficult to determine from the model alone. If the rates of motion are the same and all of the convergence is due to the difference in direction, the model suggests a rate of 3 mm/yr oriented N25E. However, small changes in the relative magnitudes of the motions change the orientation of the convergence by large amounts. There is about 11 mm/yr of convergence perpendicular to the San Andreas fault and the Pacific margin north of the Garlock fault due to the opening of the Great Basin. If the Sierra block is rotating west, as the curvature of the Garlock implies, there should be 3-5 mm/yr of NS convergence where the SW corner of the Sierra block impinges on the Salinia-San Gabriel block.


122 W
36 N
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Hosgri Fault
San
Andreas
Owens Valley Fault
Garlock Fault
Western Transverse Ranges
Central Transverse Ranges
Sierra Madre Cucamonga
Eastern Transverse Ranges
Newport-Inglewood Fault
Elsinore Fault
San Jacinto Fault
Banning Fault
Fault
N
0 kilometers 100

Figure 1

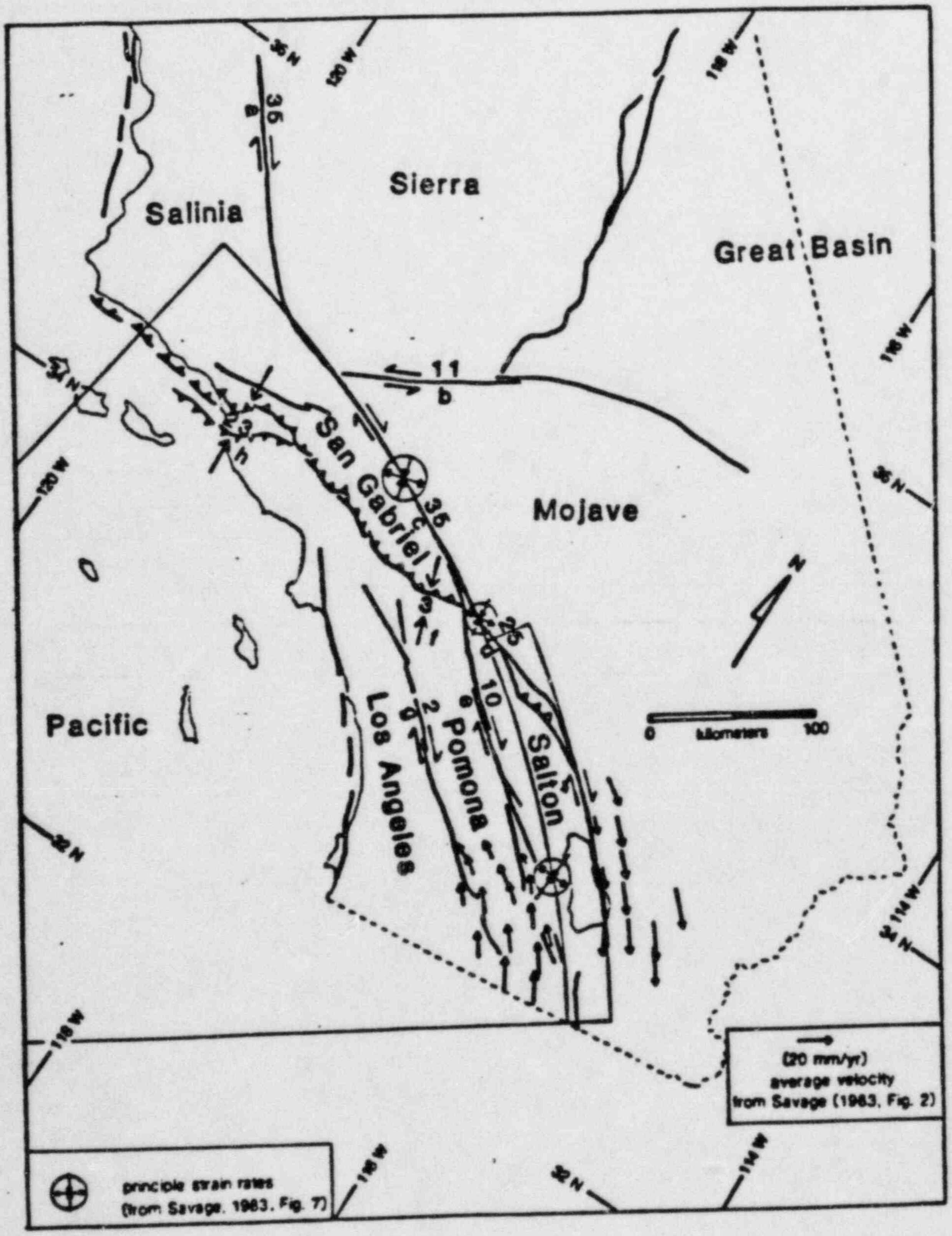
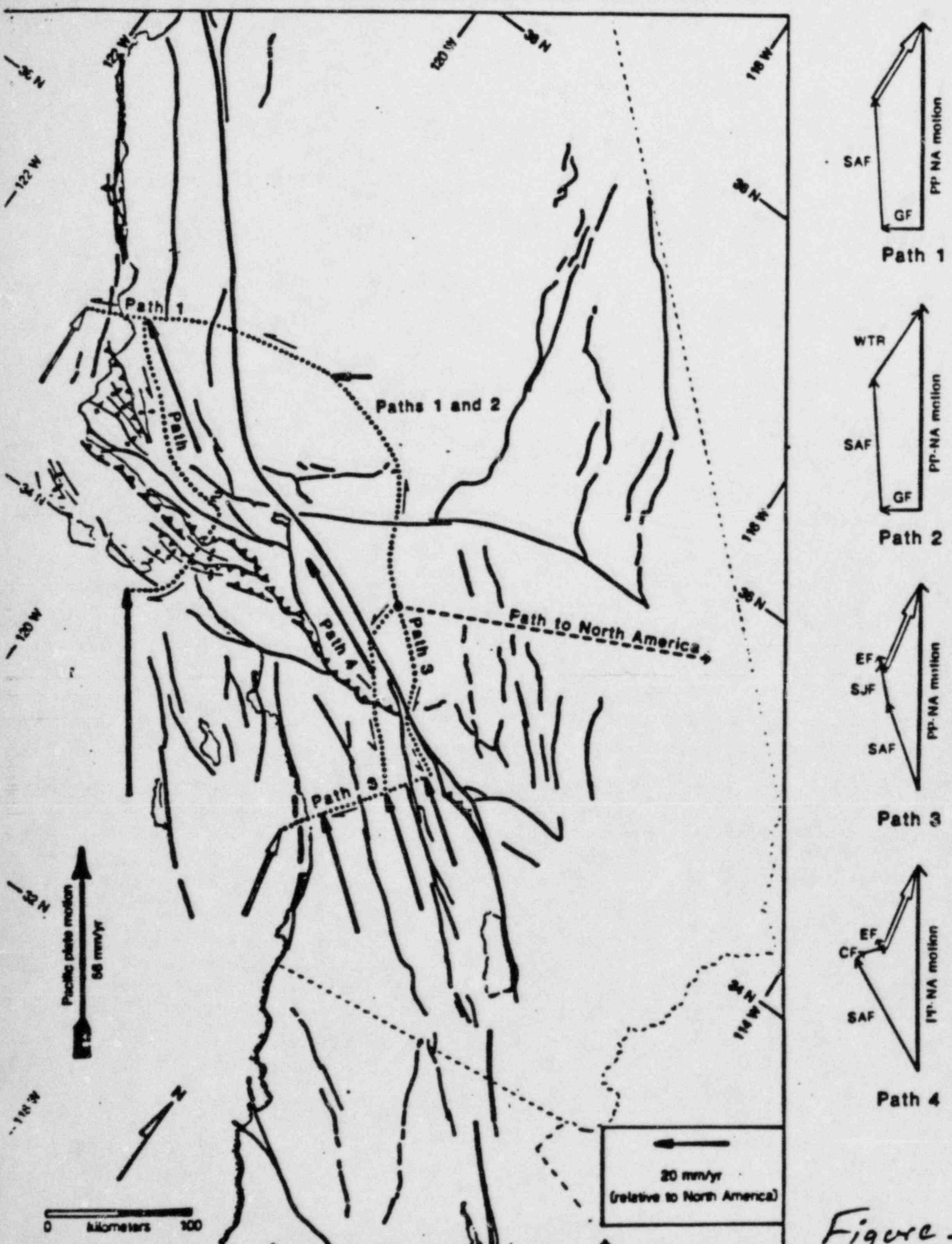

Salinia
Sierra
Great Basin
Mojave
San Gabriel
Pacific
Los Angeles
Pomona
Salton
36 N
120 W
118 W
116 W
35 N
34 N
32 N
114 W
36
11
35
25
10
2
3
a
b
c
d
e
f
h
N
0 kilometers 100
(20 mm/yr) average velocity from Savage (1983, Fig. 2)
principle strain rates (from Savage, 1983, Fig. 7)

Figure 2



36 N
122 W
122 W
120 W
36 N
118 W
36 N
Path 1
Paths 1 and 2
Path 2
34 N
116 W
36 N
120 W
Path to North America
Path 4
Path 3
Path 5
32 N
34 N
114 W
118 W
N
Pacific plate motion
56 mm/yr
0 kilometers 100
20 mm/yr
(relative to North America)
SAF
GF
PP NA motion
Path 1
WTR
SAF
GF
PP-NA motion
Path 2
EF
SJF
SAF
PP-NA motion
Path 3
EF
CF
SAF
PP-NA motion
Path 4

Figure 3

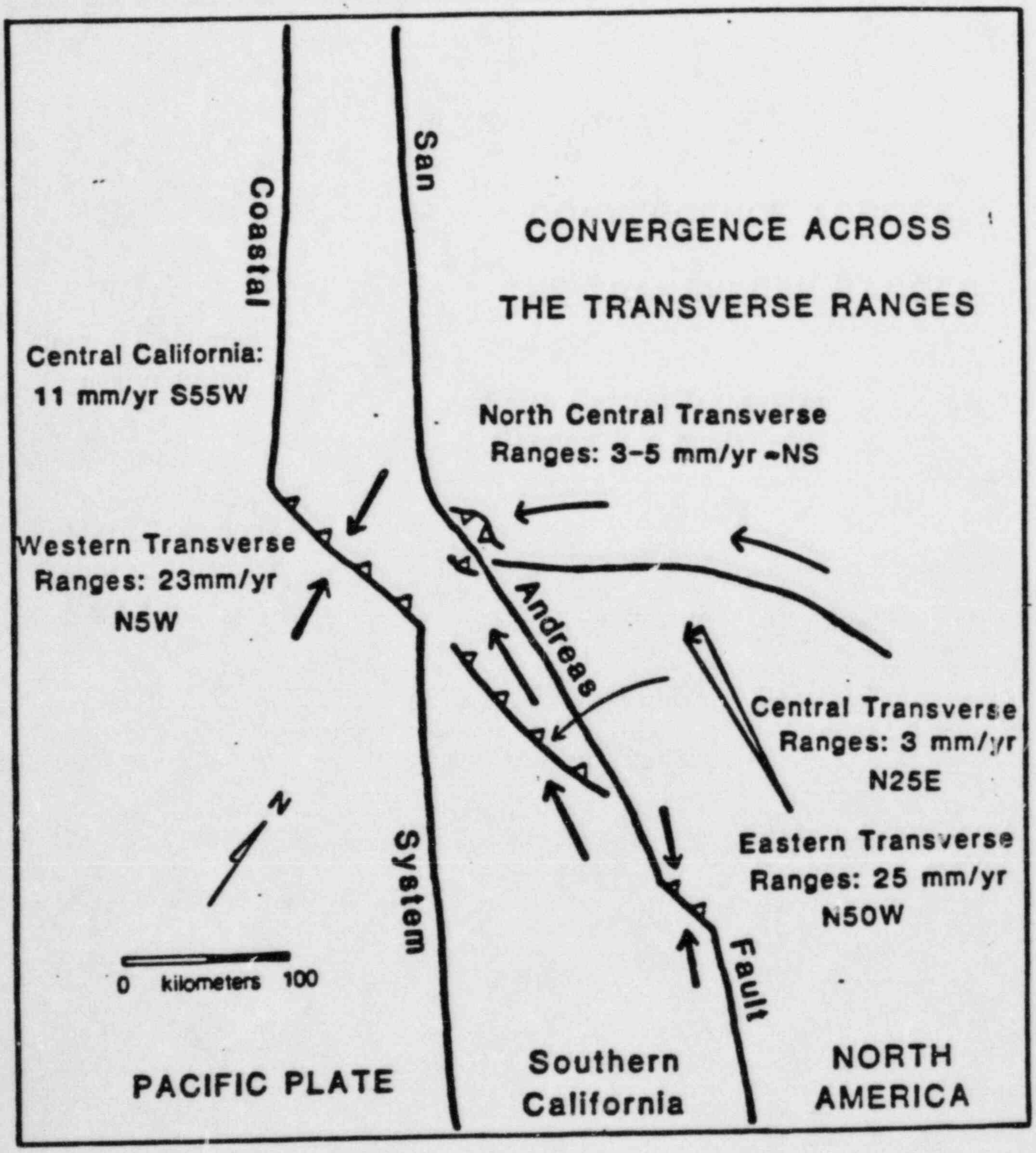

CONVERGENCE ACROSS
THE TRANSVERSE RANGES
Coastal
San
Central California:
11 mm/yr S55W
North Central Transverse
Ranges: 3-5 mm/yr ≈NS
Western Transverse
Ranges: 23mm/yr
N5W
Andreas
Central Transverse
Ranges: 3 mm/yr
N25E
Eastern Transverse
Ranges: 25 mm/yr
N50W
N
System
Fault
0 kilometers 100
PACIFIC PLATE
Southern
California
NORTH
AMERICA

Figure 4