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LATE NEOGENE RELATIVE MOTIONS OF THE PACIFIC AND NORTH AMERICA PLATES

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Abstract. In this paper a new set of finite rotations describing the relative motion of the Pacific and North America plates during the last 10 m.y., incorporating recently published studies of the Pacific-Antarctic, Antarctic-Africa, and Africa-North America plate boundaries is presented. These finite rotations show that changes have occurred in Pacific-western North America motion at 2.48 Ma and between 3.40 and 3.9 Ma, resulting in increased compression along the Pacific-North America plate boundary. The most significant change in relative motion was of the latter age. During this change the predicted motion of the Pacific plate along the California coast changes from transform to transpressive, due to a clockwise rotation of the relative convergence vector by 12°. This timing of the onset of transpression agrees well with a variety of geologic data along the California plate boundary, including the onset of compressive deformation in onshore and offshore sedimentary basins, formation of reverse faults and anticlines (which are parallel to strike-slip faults of the previous, more westerly directed azimuth of relative motion), a change in the orientation of the San Andreas fault, and formation of a set of new, more northerly trending strike-slip faults. In this model this change in relative motion is caused by a change in the absolute motion of the Pacific plate, due to the detachment of a slab beneath the Fiji Basin between 3.4 and 3.9 Ma. The detachment of this slab and the resultant change in overall Pacific plate torque resulted in a noncollisional "orogeny" along the California plate boundary. This study shows that minor adjustments in the motion of large oceanic plates, such as the Pacific plate, can have profound consequences on the preserved geologic record.

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INTRODUCTION

The late Cenozoic tectonic history of coastal California has long been regarded as an example of transform tectonics [Atwater, 1970; Weldon and Humphreys, 1986; Sylvester, 1988]. Since the widespread acceptance of the plate tectonic paradigm in the late 1960s, this region has been interpreted with respect to patterns expected along a transform boundary between the Pacific and North America plates [Morgan, 1968; Atwater, 1970]. However, the complex patterns of fault geometry, late Cenozoic deformation of sedimentary basins, and recent seismic refraction experiments along coastal California showing Pacific oceanic crust underthrust beneath the continental shelf suggest a more complex interaction between these two plates during the last 10 m.y. [Howie and Savage, 1987] (Figure 1). In addition, VLBL (Very long base line) measurements of present-day deformation are becoming available to check the predictions of relative motion Euler poles of these two plates. Recently a detailed analysis of magnetic isochrons describing Pacific-Antarctic relative motion has been completed [Harbert and Cox, 1989]. This study, in combination with recent studies of North America-Africa [Klitgord and Schouten, 1986] and Africa-Antarctica [Molnar et

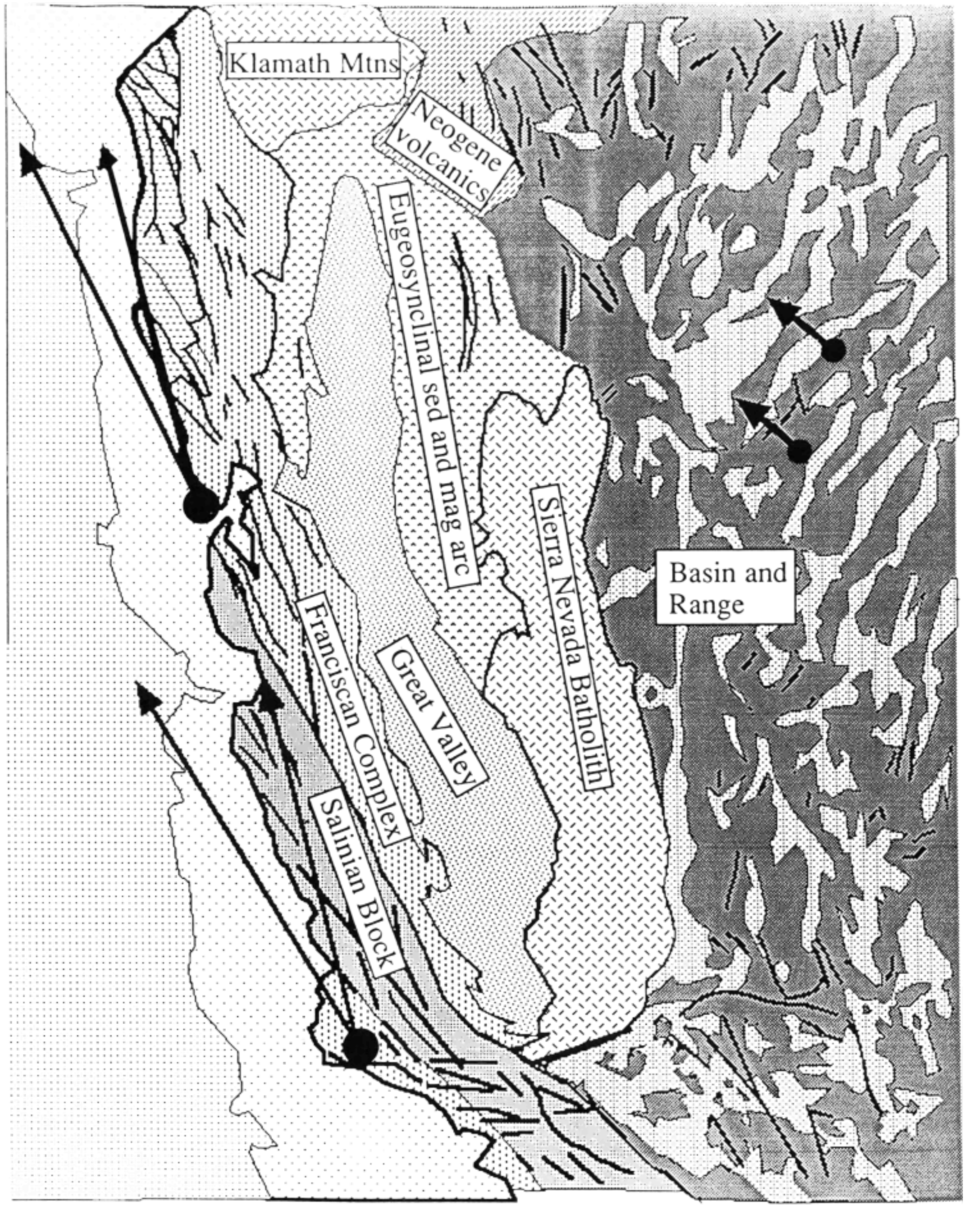


Fig. 1. Sketch of the California coast region, after Atwater [1970]. Features shown in this sketch are well represented in the digital residual gravity recently presented by Simpson et al. [1986]. Diffuse spreading of approximately 9 mm/yr N59°E occurs at present in the Basin and Range region (direction shown by short arrows) [Minster and Jordan, 1984]. At two points along coastal California, relative convergence vectors are shown for ages corresponding to between 0 and 3.4 Ma and between 3.9 and 10.0 Ma. The more northerly striking vectors represent the younger time interval. Each vector is scaled by the rate of relative motion between the Pacific and North America plates along this boundary. Estimation of the age of this transition in relative motion direction, the variability of the azimuth and rate of relative motion when calculated along this boundary, and the effect of Basin and Range spreading to relative motions are given in the text.

al., 1988], and present-day worldwide [DeMets et al., 1990] plate motions, provides a detailed record of Pacific-North America motion.

In this paper I combine the plate motion studies described above to generate a series of western North America-Pacific plate finite rotations. These new finite rotations furnish a detailed history of the interaction of the Pacific plate and coastal California during the middle and upper Neogene. I then examine the relative motion of the Pacific and North America plates during the last 10 m.y.. These rotations show that an onset of transpression is predicted along coastal California beginning between 3.4 and 3.9 Ma. This shift from transform to transpressive relative plate motion is expressed by (1) A reorientation of the trace of the San Andreas fault to a more northerly strike near Point Arena, (2) formation of more northerly trending strike-slip faults east of the San Andreas fault, (3) widespread deformation and erosion of sedimentary basins along much of the California coast, and (4) initiation of fault normal compression along strike-slip faults, such as the San Andreas fault, that are oriented parallel to the previous, more westerly directed azimuth of Pacific-North America plate relative motion.

The change in Pacific-California motion apparently was caused by a jump in the plate torque vector of the Pacific plate, when a Pacific plate slab was detached in the southwestern Pacific Basin. This minor change in Pacific plate subduction geometry resulted in a period of deformation, uplift, and erosion; such phenomena are commonly interpreted in the geological record to show terrane collision or plate reorganization. This correlation in age of deformation and a change in Pacific-North America plate motion shows that deformation of Neogene age along the California coast is noncollisional in nature and is therefore unrelated to either terrane collision or major changes in oceanic or continental plate motion. Rather, this orogeny was caused by variations in the plate margin driving forces, which are influenced by changes in subduction geometry thousands of kilometers away from this focus of orogenic activity along the California coast.

CALCULATION OF NORTH AMERICA PACIFIC RELATIVE MOTION

Several recent studies allow accurate calculation of the motion of the Pacific plate relative to North America during the Neogene [Cox and Engebretson, 1985; Pollitz, 1986; Stock and Molnar, 1987, 1988; Pollitz, 1988; Harbert and Cox, 1989]. To calculate the total relative motion along this plate boundary, the paradigm of plate tectonics requires the addition of the relative plate motions across various spreading centers, including the Pacific-Antarctic, Antarctic-Africa, and Africa-North America, along which magnetic isochrons and transform faults record relative plate motion [Harbert and Cox, 1989; Molnar et al., 1988; Klitgord and Schouten, 1986]. In addition, to describe relative motion between the Pacific plate and coastal California, the displacement history of the western portion of the Basin and Range province with respect to the stable North America plate must be incorporated [Minster and Jordan, 1984].

Magnetic isochrons record recent changes in the relative motion of the Pacific-Antarctic and North America-Africa plate pairs. Velocity data from the Pacific-Antarctic rise [Harbert and Cox, 1989], when combined with the observation of deflections at the young end of hotspot tracks on the Pacific plate [Epp, 1984], show that between 3.4 and 3.9 Ma the absolute motion of the Pacific plate changed. In addition, the position of the North America-Africa Euler pole changed at 2.48 Ma [Klitgord and Schouten, 1986]. In contrast, the study of Africa-Antarctic relative motion by Molnar et al. [1988], which did not examine magnetic isochrons younger than magnetic isochron 5A, show no major changes in Euler pole location or spreading velocity when compared with present-day models of Antarctic-Africa (ANT-AFR) motion [Minster et al., 1974, Minster and Jordan, 1978; DeMets et al., 1990]. To calculate North America-Pacific (NAM-PAC) total reconstruction poles I have used PAC-ANT, ANT-AFR, and AFR-NAM finite rotations taken from the studies cited above.

Basin and Range extension is believed to have begun after 20 Ma [Anderson, 1971; Zoback et al., 1981; Henry, 1989]. A detailed analysis of Basin and Range extension during the Holocene is given by Minster and Jordan [1984], who calculated a Basin and Range-North America (BAR-NAM) relative motion pole that was located about 15° southwest of the Great Basin. If the BAR-NAM pole was moved to the northeast, a north to south increase in the rate of Basin and Range extension, and the curvature of faults along which BAR-NAM relative motion was taking place, that is, small circles about the relative motion pole, are predicted; neither of these phenomenon are observed today in the Basin and Range. Thus, while a small change in the Euler pole location towards the Great Basin produced a dramatic and unacceptable change in BAR-NAM relative motion, moving the Euler pole as much as 90° away from the Great Basin had little effect on the root mean square (rms) misfit between their model and the available relative motion data. This more remotely located BAR-NAM Euler pole differed from their best fit by only 1° of additional rms error. To estimate the effect of Basin and Range spreading on the finite rotations, I added this distant pole of relative BAR-NAM motion or their best fit BAR-NAM to finite rotations describing PAC-NAM relative motion. I favor the more distant BAR-NAM relative motion pole because it predicts a uniform direction and rate of Basin and Range spreading such as that observed in the Great Basin [Steward 1978; Zoback and Zoback, 1980; Minster and Jordan, 1987; Zoback, 1989].

The strain rate observed in the Basin and Range region was used to determine the rotation angle of relative motion about the BAR-NAM pole. I used a present-day rate that closely matched the integrated deformation rate vector given in model C of Minster and Jordan [1987]; that is, a BAR-NAM linear velocity of 10.1 mm/yr at an azimuth of N63°W for a reference point in the central Basin and Range [Minster and Jordan, 1984], closely matching the observed direction of extension that is between NW and N60°W [Zoback, 1989]. This rate of relative motion between cratonal and western north America is assumed to have been constant during the last 10 m.y. While variations in the rate of Basin and Range extension have been suggested [Zoback et al., 1981], the most likely displacement history [Wernicke et al., 1988], and the one used here, is that in which the rate of Basin and Range spreading is constant between 10 Ma and present.

The uncertainties in the resultant finite rotations are difficult to estimate accurately. In order the

TABLE 1. Finite Rotations Used to Calculate Relative Motion Poles for the North America-Pacific Plate Pair

Ref	P1	P2	A1	A2	λ	ϕ	ω	Type
1	BAR	NAM	10.00	0.0	-43.00	200.00	-0.80	DP
1	BAR	NAM	10.00	0.0	+26.00	235.00	-3.40	BF
2	ANT	AFR	3.40	0.0	6.00	-39.30	0.48	BF
2	ANT	AFR	3.40	0.0	5.60	-39.20	0.44	NUVEL-1
3	ANT	AFR	3.40	0.0	7.93	-38.72	0.50	BF
3	ANT	AFR	3.40	0.0	9.46	-41.70	0.51	RM-2
4	ANT	AFR	10.59	0.0	11.72	-43.84	1.55	BF
2	AFR	NAM	2.70	0.0	73.70	94.80	-0.59	BF
2	AFR	NAM	2.70	0.0	78.80	38.30	-0.68	NUVEL-1
3	AFR	NAM	2.70	0.0	82.68	-17.68	-0.68	BF
3	AFR	NAM	2.70	0.0	80.43	56.36	-0.64	RM-2
5	AFR	NAM	9.67	0.0	79.08	77.95	-2.41	BF
6	ANT	PAC	3.40	0.0	64.00	276.00	-3.16	BF
6	ANT	PAC	3.90	3.4	64.00	276.00	-0.46	BF
6	ANT	PAC	11.09	3.9	71.05	298.00	-5.98	BF

Ref refers to the appropriate reference for each finite rotation (see below), λ and ϕ describe the position (north latitude and east longitude) and ω describes the reconstruction angle (in degrees) used to reconstruct the plate pair P1 and P2 between ages A1 and A2. Type, for the Basin and Range poles of Minster and Jordan [1984] are BF, best fitting, or DP, a finite rotation located approximately 90° from the Basin and Range region, in constrast to a best-fitting finite rotation between a plate pair; RM-2 and NUVEL-1 refer to finite rotations determined as part of a geohedron in the model given in the appropriate reference. The Pacific-Antarctic-Africa-North America-Basin and Range (western North America) (PAC-ANT-AFR-NAM-BAR) circuit was completed using the finite rotations labelled above as 1, Minster and Jordan [1984]; 2, DeMets et al. [1990]. 3, Minster and Jordan [1978]; 4, Klitgord and Schouten [1986]; 5, Molnar et al. [1988]; and 6, Harbert and Cox [1989]. To allow for Basin and Range-North America plate motion, the plate circuit Pacific-Antarctic-Africa-North America-Basin and Range was completed using one of two finite rotations presented in Minster and Jordan [1984] that described Basin and Range spreading. These two poles differed in rms error, when compared with the available relative motion data, by only 1°. The first of these two is quite distant from the Basin and Range and shows a consistent direction and rate of relative BAR-NAM motion, the second is the best-fitting pole and is located much closer to the Basin and Range. This latter finite rotation suggests a somewhat variable direction and rate of predicted spreading within this region. The order of summation of these poles is given in Table 2, and the resulting finite rotations describing relative North America-Pacific or western North America (incorporating a model of Basin and Range spreading) - Pacific plate motionis given in Table 3.

calculate these uncertainties after summing finite rotations along a plate circuit, the equivalent uncertainties in both Euler pole location and angular velocity must be known. For NAM-AFR finite rotations, no uncertainty regions or uncertainties in reconstruction angles are given [Klitgord and Schouten, 1986]. For AFR-ANT finite rotations, Stock and Molnar [1988] have described their method of uncertainty estimation. However, these authors do not derive statistically rigorous 95% confidence bounds; instead, they describe "reasonable estimates....consistent with the quality of magnetic anomalies and fracture zones" [Stock and Molnar, 1988, p.1344-1345]. For PAC-ANT motion, Harbert and Cox [1989] used a modified χ squared test to estimate 95% confidence bounds for both finite rotation pole location and reconstruction angle. Their method was computer intensive, in that estimates of spreading velocity and associated uncertainties from each marine magnetic profile were reprojected about each trial pole location and goodness of fit and error parameters were calculated. In the study of BAR-NAM motion, rigorous uncertainties were not calculated because of the relatively sparse data available. However, Minster and Jordan [1984] give two widely spaced finite rotations that differed in misfit by only 1° in the rms sense. Models of present-day instantaneous plate motions give rigorous 95% uncertainty estimates for Euler pole locations and angular velocities [Minster and Jordan, 1978; DeMets et al., 1990]. Because of this difficulty in combining these different, or nonexistent, estimates of uncertainty, I chose to generate seven models of relative plate motion along the California coastal region. Together, these different combinations of finite rotations give an estimation of the variation in models describing Pacific-western North America relative motion. Data from Table 1 are combined as shown in Table 2 to produce the finite rotations describing Pacific-western North America shown in Table 3; graphic data are presented in Figure 2.

The finite rotations additions are summed in the order listed below (from left to right).

$$ {}_{NAM}^{\;0}R_{PAC}^{T} = {}_{ANT}^{\;0}R_{PAC}^{T} + {}_{AFR}^{\;0}R_{ANT}^{T} + {}_{NAM}^{\;0}R_{AFR}^{T} $$

$$ {}_{BAR}^{\;0}R_{PAC}^{T} = {}_{ANT}^{\;0}R_{PAC}^{T} + {}_{AFR}^{\;0}R_{ANT}^{T} + {}_{NAM}^{\;0}R_{AFR}^{T} + {}_{BAR}^{\;0}R_{NAM}^{T} $$

In this notation the first finite rotation R is labeled to show that the Antarctic plate is fixed and the Pacific plate is rotated in a clockwise sense from time 0 to time T [Cox and Hart, 1986] (see Table 1 for references for finite rotations and Table 3 for calculated NAM-PAC and BAR-PAC Euler poles). Both this study and those of Engebretson et al. [1984], Cox and Engebretson [1985], Pollitz [1986], Stock and Molnar [1988] and Harbert and Cox [1989] suggest a significant change in relative motion between the Pacific and North America plates during the Neogene. Each of these five models describing western North America-Pacific relative motion show that the onset of transpression along the coastal California plate margin began between 3.4 and 3.9 Ma. This age agrees with those calculated by examining the deflection in the azimuthal trends of

TABLE 2. Sequences Used to Derive the Seven Models and Their Finite Rotations

Plate Pair	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
${}_{BAR}^{\;0}ROT_{NAM}^{10.6}$	RM(DP)	RM(BF)	RM(BF)	RM(DP)	RM(DP)	RM(DP)	RM(DP)
${}_{AFR}^{\;0}ROT_{NAM}^{2.7}$	RM(BFP)	RM(BFP)	RM(BFP)	RM(BFP)	NV(BFP)	NUVEL-1	NUVEL-1
${}_{AFR}^{2.7}ROT_{NAM}^{19.9}$	KS(86)	KS(86)	KS(86)	KS(86)	KS(86)	KS(86)	KS(86)
${}_{ANT}^{\;0}ROT_{AFR}^{3.4}$	RM(BFP)	RM(BFP)	NV(BFP)	NV(BFP)	NV(BFP)	NV(BFP)	NUVEL-1
${}_{ANT}^{3.4}ROT_{AFR}^{10.6}$	MEA(88)	MEA(88)	MEA(88)	MEA(88)	MEA(88)	MEA(88)	MEA(88)
${}_{ANT}^{\;0}ROT_{PAC}^{10.6}$	M372	M372	M372	M372	M372	M372	M372

The seven models and their corresponding finite rotations, which describe relative plate motion along the California coastal region, were derived by combining the finite rotations listed in Table 1 in the sequences shown above. Each model's finite rotations, shown in Table 3, were calculated by summing the finite motions given in the corresponding column of this table. The following abbreviations are used: RM(DP), Minster and Jordan [1984] distant Basin and Range finite rotation; RM(BF), Minster and Jordan [1984] best-fit Basin and Range finite rotation; RM(BFP), Minster and Jordan [1978] best-fitting finite rotation; NV(BFP), DeMets et al. [1990] best-fitting finite rotation; NUVEL-1, DeMets et al. [1990] Nuvel-1 model finite rotation; KS(86), Klitgord and Schouten [1986] finite rotation; MEA(88), Molnar et al. [1988] finite rotation; and M372, Harbert and Cox [1989] finite rotations. As in Table 1, these are total reconstruction poles. The models 1 through 6, produced by summing different combinations of finite rotations independently calculated in the studies cited above, were quite similar, suggesting that a change from transform to transpressive relative motion occurred between 3.4 and 3.9 Ma along the California coast.

TABLE 3. Total Reconstruction Poles Derived in This Study

Model	Plate Pair	T	λ	φ	ω
7	${}^{0}_{BAR}ROT^{T}_{PAC}$	2.70	-45.4	94.6	2.075
		3.40	-45.1	95.2	2.628
		3.90	-44.9	95.5	3.038
		9.67	-48.7	103.9	7.493
		10.42	-49.0	103.8	8.032
		10.59	-48.7	103.6	8.010
6	${}^{0}_{BAR}ROT^{T}_{PAC}$	2.70	-45.0	95.4	2.095
		3.40	-44.7	96.0	2.654
		3.90	-44.6	96.1	3.063
		9.67	-48.7	103.9	7.497
		10.42	-49.0	103.8	8.033
		10.59	-48.7	103.6	8.010
5	${}^{0}_{BAR}ROT^{T}_{PAC}$	2.70	-45.0	99.3	2.236
		3.40	-44.8	98.8	2.781
		3.90	-44.7	98.4	3.179
		9.67	-48.8	104.0	7.497
		10.42	-49.1	103.9	8.033
		10.59	-48.8	103.7	8.010
4	${}^{0}_{BAR}ROT^{T}_{PAC}$	2.70	-47.0	96.8	2.016
		3.40	-46.1	97.0	2.583
		3.90	-45.7	96.9	2.997
		9.67	-48.7	103.8	7.497
		10.42	-49.1	103.7	8.033
		10.59	-48.7	103.5	8.010
3	${}^{0}_{BAR}ROT^{T}_{PAC}$	2.70	-45.6	85.3	2.841
		3.40	-45.0	85.7	3.621
		3.90	-44.8	85.8	4.189
		9.67	-47.9	90.0	10.353
		10.42	-48.1	89.8	11.114
		10.59	-47.9	89.5	11.146
2	${}^{0}_{BAR}ROT^{T}_{PAC}$	2.70	-45.7	85.7	2.855
		3.40	-45.2	86.1	3.639
		3.90	-44.9	86.1	4.206
		9.67	-47.9	90.0	10.355
		10.42	-48.1	89.8	11.114
		10.59	-47.9	89.5	11.146
1	${}^{0}_{BAR}ROT^{T}_{PAC}$	2.70	-47.1	97.3	2.033
		3.40	-46.2	97.5	2.6030
		3.90	-45.8	97.3	3.0160
		9.67	-48.7	103.9	7.4998
		10.42	-49.1	103.7	8.0326
		10.59	-48.7	103.5	8.0098

Poles derived in this study for 0 to 10.59 Ma. These poles are derived by combining the Euler poles listed in Table 1 in the sequence shown in Table 2. They give the relative motion of the Pacific plate (PAC) with respect to the the western North America (western Basin and Range, BAR). As in Table 1, these are total reconstruction poles. The Euler pole location and ω value describe the rotation of the plate on the right with respect to the plate on the left of the rotation tensor. As in Table 1, λ and φ are the north latitude and east longitude of the Euler pole; ω is the rotation angle in degrees.

young ends of hotspot tracks on the Pacific plate [Epp, 1984; Pollitz, 1986]. The deflection being evidence for a change in the absolute motion of the Pacific plate [Epp, 1984; Cox and Engebretson, 1985; Pollitz, 1986]. This was substantiated by investigating young marine magnetic anomalies of the Pacific-Antarctic ridge that showed a change in relative motion between the Pacific and Antarctic plates between 3.4 and 3.9 Ma [Harbert and Cox, 1989].

Two important points are demonstrated by the results shown in Table 3. First, between 3.4 and 3.9 Ma there was a change in the location of the PAC-ANT pole. When included in the plate circuit, this shift in Euler pole position correlates with in an increased angle of relative convergence. The angle of relative convergence is simply the angle the relative motion vector makes with the boundary between the overriding and underthrusting plates, in this case the Pacific and western North America plates. Between 10.3 Ma and the middle Pliocene the convergence angle between these two plates had been parallel to the trend of the San Andreas fault. After the end of the early Pliocene, as a result of this change in BAR-PAC Euler pole location, the style of convergence along this margin changed from transform to transpressive. Second, the relative motion of the Basin and Range and North America plates implies a linear velocity along the San Andreas fault that closely matches those measured in recent VLBL studies (Figures 3 and 4). VLBL data from the California coast region suggest linear velocities of between 32 ± 4 and 48 ± 5 mm/yr [Kroger et al., 1987], similar to recent direct measurements of San Andreas motion of 32.1± 7.4 mm/yr [Savage and Burford, 1973; Thatcher, 1979; Prescott et al., 1981; Sieh and Jahns, 1984]. The result of adding BAR-NAM finite rotations to NAM-PAC finite rotations is to decrease slightly, by about 4 mm/yr, the amount of expected relative movement along the California plate boundary and rotate clockwise approximately 3° the direction of relative motion. Both BAR-NAM and PAC-NAM convergence directions are very nearly parallel to the strike of the San Andreas fault. However, earlier in the Neogene, plate velocities along the margin were probably higher than present-day rates, suggesting a wider, more diffuse region of transform motion in the early Neogene [Atwater, 1970]. The results of this onset of transpression after 3.9 or 3.4 Ma are well recorded in the coastal California region.

EARLY PLIOCENE NONCOLLISIONAL OROGENY: COASTAL CALIFORNIA

Today the Pacific-North America plate boundary is a rather wide belt along coastal California, both onshore and offshore, from the northern end of the Gulf of California to Cape Mendocino [Atwater,

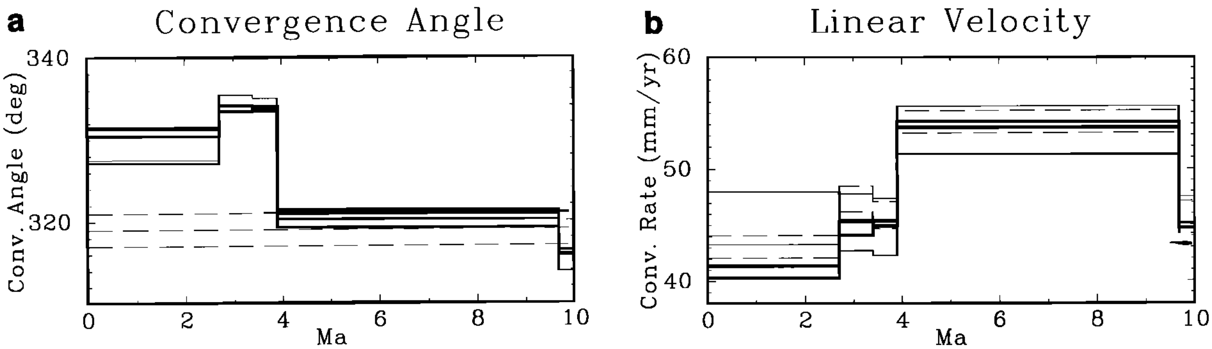


Fig. 2. Linear velocities calculated at the point 36.5°N, 238.9°E, near the intersection of the San Andreas and Hayward faults. These figures show (a) the azimuth and magnitude of the relative motion vector between the two plates in degrees east of north and (b) relative motion in millimeters per year. Seven sets of finite rotations are calculated in order to estimate the variability of predicted motions along the coastal California plate boundary. The basis finite rotations used in the seven finite rotation models are presented in Table 1, the differences between the various models are presented in Table 2, finite rotations calculated for the coastal California boundary are presented in Table 3, and linear velocities are given in Table 4. The numeric data used in this figure are given in Table 4. The dashed lines show the azimuth of the San Andreas fault, 319°N, taken from Minster and Jordan [1984]. Note that in each model significant compression, and a slowing of relative motion, begins at about 3.9 Ma.

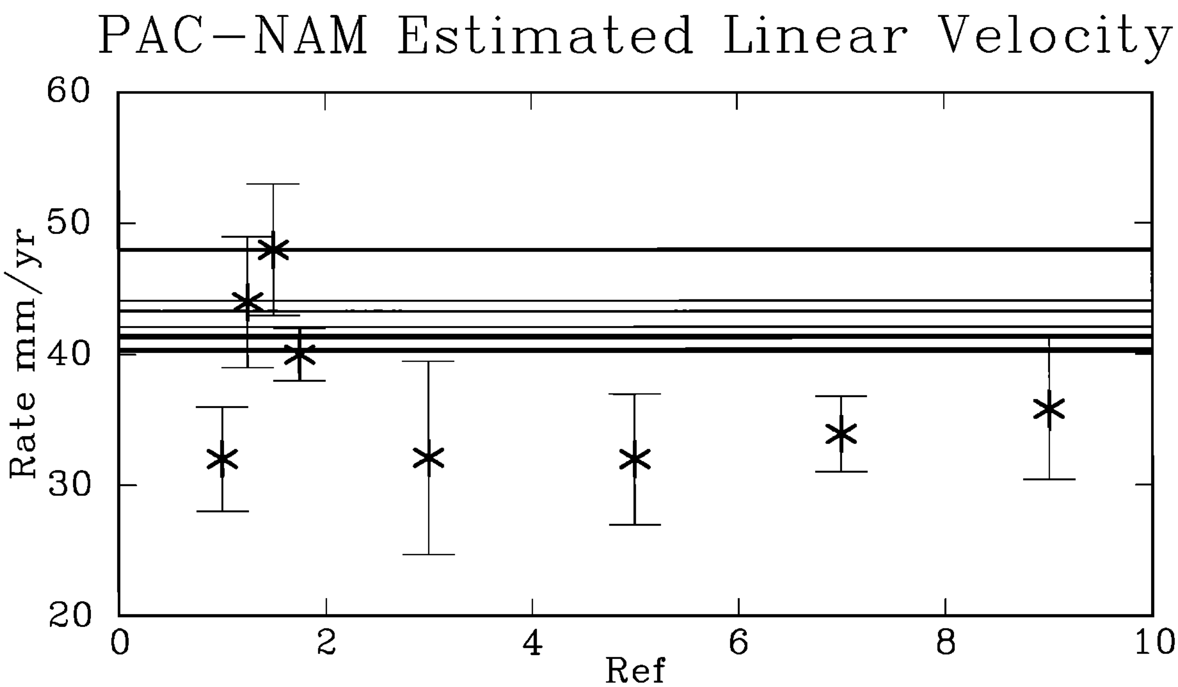


Fig. 3. Comparison of the present-day relative motion velocities with those measured in the coastal California region. Previously calculated models of finite motion had yielded predicted relative motions higher than those measured in the coastal California region. The convergence data given in Figure 2b were projected onto the strike of the San Andreas fault to yield the amount of predicted present-day motion parallel to this orientation and compared with measured values from the following sources: reference 1 and 2, VLBL measurements from Kroger et al. [1987]; 3, Prescott et al. [1981]; 5, Savage and Burford [1973]; 7 and 9 Sieh and Jahns [1984]; and 11, Thatcher [1979]. In each case predicted model velocities, shown as horizontal lines in this figure, are slightly higher than observed. Model 7, a model which includes Basin and Range relative motion agrees with recent VLBL measurements to a greater degree than models 1 through 6.

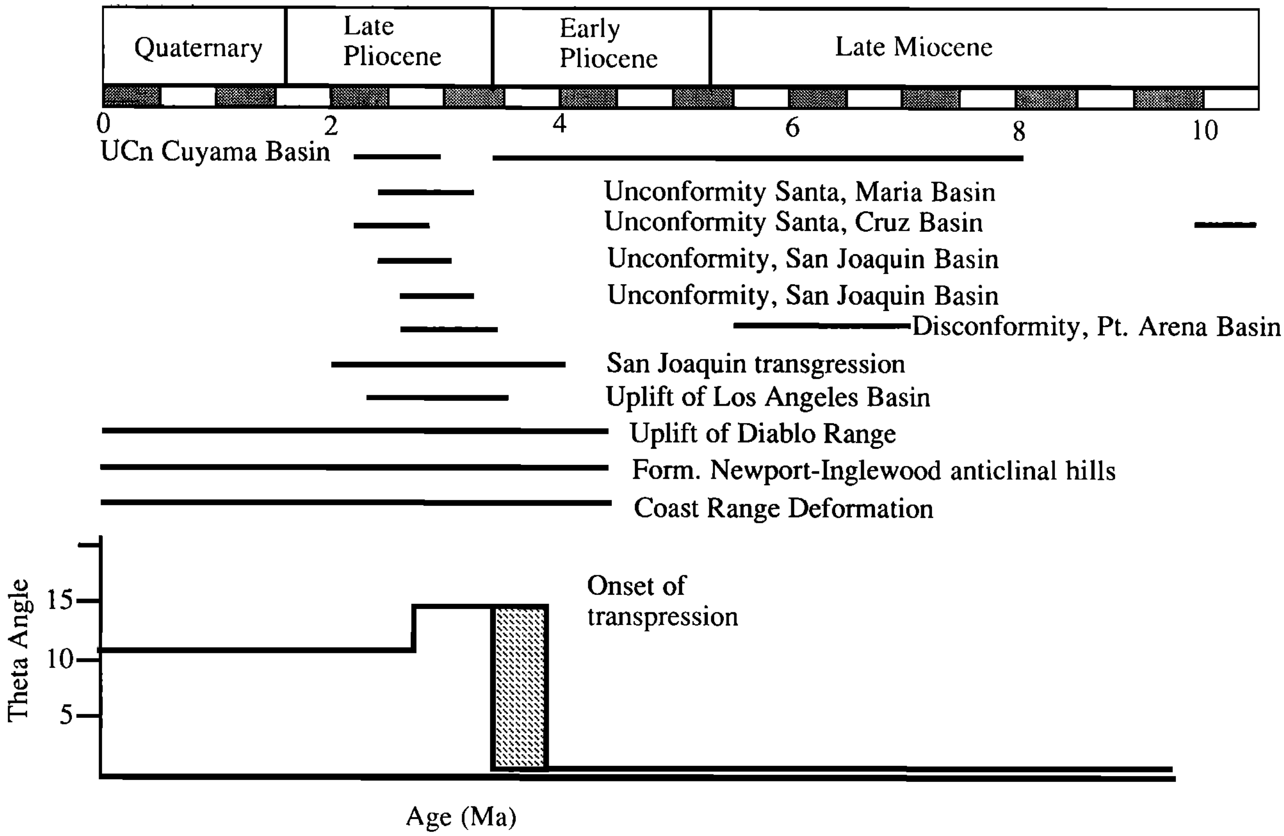


Fig. 4. Summary of tectonic history proposed in this paper for the California coastal region comparing a theta angle and the tectonic events described in the text. Note the correlation between the change in convergence angle, plotted as the dot product between the linear velocity vector and the strike of the San Andreas fault, and deformation and uplift along much of coastal California.

1970; Minster and Jordan, 1984, 1987]. The calculated finite rotations presented in this paper suggest that the onset of transpressive motion along this plate margin occurred between 3.9 and 3.4 Ma. There are two expected results of this change in relative motion. First, compression should occur along strike-slip faults that form in response to and are parallel with the earlier direction of relative motion, and second, new, more northerly trending transform faults should form to accommodate the new direction of motion along the plate boundary. In the geologic record of California, compression of the appropriate age is recorded by (1) unconformities in sedimentary basins, (2) compression-related structures, such as anticlines and reverse faults, and (3) uplift and erosion. Each of these suggests a middle Pliocene orogeny along the California Pacific-North America plate boundary.

Sedimentary basins both onshore and offshore of the California coast record a compressive event beginning in the early to middle Pliocene. Unconformities or disconformities in the Cuyama, Santa Maria, Santa Cruz, San Joaquin, San Joaquin, and Point Arena basins occurred between 4 and 2.4 Ma [Bartow, 1987; Bachman and Crouch, 1987; Crouch and Bachman, 1987; Crowell, 1987; Graham, 1987; Mayer, 1987]. No similar simultaneous deformation is present in late Miocene or early Pliocene units. In addition to basin deformation, onset of compression in the middle Pliocene is also recorded by the uplift of the Diablo, Santa Cruz, and Santa Lucia Ranges, Los Angeles block, and formation of Newport-Inglewood anticlinal hills between 5 and 3 Ma [Page, 1966, 1977, 1981; Dibblee, 1976; Crouch et al., 1984, Harwood, 1984; Nilsen and Clark, 1987]. Pliocene development of thrust faults in the San Francisco Bay area suggests an onset of compression between the Pacific and North America plates between 5 and 3 Ma. Today, along strike-slip faults such as the San Andreas, fault parallel compression is observed [Crouch et al.,

TABLE 4. Linear Velocities Calculated for the Seven Models

Model	P1	P2	A1	A2	Velocity	Azimuth	V_N	V_E
7	BAR	PAC	2.70	0.00	40.3	330.4	35.0	-19.9
	BAR	PAC	3.40	2.70	44.1	333.4	39.5	-19.7
	BAR	PAC	3.90	3.40	45.4	334.0	40.8	-19.9
	BAR	PAC	9.67	3.90	54.2	321.3	42.3	-33.9
	BAR	PAC	10.42	9.67	45.1	316.4	32.6	-31.1
6	BAR	PAC	2.70	0.00	41.4	331.3	36.3	-19.9
	BAR	PAC	3.40	2.70	45.3	334.1	40.7	-19.8
	BAR	PAC	3.90	3.40	44.9	333.7	40.3	-19.9
	BAR	PAC	9.67	3.90	53.7	320.9	41.7	-33.9
	BAR	PAC	10.42	9.67	44.7	315.8	32.0	-31.1
5	BAR	PAC	2.70	0.00	48.0	331.5	42.2	-22.9
	BAR	PAC	3.40	2.70	42.7	334.1	38.4	-18.6
	BAR	PAC	3.90	3.40	42.3	333.6	37.9	-18.8
	BAR	PAC	9.67	3.90	51.3	320.2	39.4	-32.8
	BAR	PAC	10.42	9.67	44.7	315.8	32.0	-31.1
4	BAR	PAC	2.70	0.00	41.3	327.5	34.8	-22.2
	BAR	PAC	3.40	2.70	45.5	335.4	41.3	-18.9
	BAR	PAC	3.90	3.40	45.0	335.0	40.8	-19.0
	BAR	PAC	9.67	3.90	53.6	322.0	42.2	-33.0
	BAR	PAC	10.42	9.67	44.7	315.8	32.0	-31.1
3	BAR	PAC	2.70	0.00	43.3	327.1	36.4	-23.5
	BAR	PAC	3.40	2.70	47.8	334.4	43.1	-20.6
	BAR	PAC	3.90	3.40	47.4	333.4	42.4	-21.2
	BAR	PAC	9.67	3.90	55.6	320.1	42.7	-35.6
	BAR	PAC	10.42	9.67	47.5	313.5	32.7	-34.4
2	BAR	PAC	2.70	0.00	44.1	327.0	37.0	-24.0
	BAR	PAC	3.40	2.70	48.5	334.1	43.7	-21.2
	BAR	PAC	3.90	3.40	47.1	333.5	42.1	-21.0
	BAR	PAC	9.67	3.90	55.2	320.1	42.4	-35.4
	BAR	PAC	10.42	9.67	47.1	313.5	32.4	-34.2
1	BAR	PAC	2.70	0.00	42.1	327.3	35.4	-22.7
	BAR	PAC	3.40	2.70	46.2	335.2	41.9	-19.4
	BAR	PAC	3.90	3.40	44.7	335.1	40.5	-18.8
	BAR	PAC	9.67	3.90	53.2	322.0	41.9	-32.8
	BAR	PAC	10.42	9.67	44.2	315.8	31.7	-30.8

Linear velocities calculated about stage poles calculated from the finite rotations, models 5 through 1, given in Table 3 for a point near the intersection of the San Andreas and Hayward faults, latitude = 36.5°N, longitude = 238.9°E. Seven models are presented, of which model 7 (BAR-PAC) is favored in this report. Together, these various combinations of previously published finite rotations give a sense of the uncertainity in determining Pacific-western North America relative motion. These vectors describe the motion of the Pacific plate (PAC) with respect to the North America margin, excluding Basin and Range motion (NAM-PAC relative motion), and including the Basin and Range (BAR-PAC relative motion), between two ages, A1 and A2. Relative motion is described by the convergence vector whose length is given in millimeters per year; azimuth is expressed in degrees east of north. In addition, this relative convergence vector is given in terms of a northerly (V_N) and easterly (V_E) velocity.

1984; Mount and Suppe, 1987; Zoback et al., 1987].

On a regional scale the California Pacific-North America plate boundary clearly records compression and shortening normal to the boundary between the North American and Pacific plates beginning in the middle Pliocene. The amount of shortening in the Coast Ranges region has been estimated [Namsen and Davis, 1988] as 33 km in the last 3 Ma. Using the finite rotations given in Table 3, our calculation of 35 and 42 km of convergence normal to the trend of the San Andreas fault beginning between 3.9 to 3.4 Ma closely matches this estimate (Table 4).

Many of the faults that make up the plate boundary between the Pacific and North America plates have a trend of about 319°E [Minster and Jordan, 1984], similar to that of the San Andreas. However, more northerly trending faults are observed along the California plate margin, including the Greenville, Green Valley and Concord, Calaveras, San Gregorio, San Simeon, Hosgri, and Santa Lucia Bank faults. The more northerly trending Hayward-Calaveras and Hosgri faults appear to have been formed at about 3 Ma [Bartow, 1987]. Also, the trend of the San Andreas fault changes to a more northerly strike in the region of Point Arena, which is near the position of the Pacific-Gorda-North America triple junction at 3.4 Ma as calculated using the model 5 BAR-PAC finite rotations. The more northerly trend of the San Andreas north of this point is consistent with the relative motion of the Pacific and North America plates from 3.4 Ma to present. Bolt et al. [1968] and Herd [1978] have suggested that more northward trending strike-slip faults have formed east of the present transform system. If this is occurring, then the California coast is a plate-tectonic boundary in an intermediate state of tectonic development. Specifically, it is intermediate in the sense that strike-slip motion along transform faults, whose orientation reflects an older (10.3-3.6 Ma; 319.5°E) azimuth of Pacific-North America motion, along which fault parallel compressional deformation is occurring, still account for most of the strike-slip motion along the boundary. Inboard of these faults, a younger set of strike-slip faults, parallel to the present-day direction of relative motion (2.7-0 Ma; 331.5°), are being formed intermittently today (Figure 5). This change in Euler pole location appears to be unrelated to tectonism, terrane region. This change from transform to transpressive motion appears to have been rapid. As noted earlier, the Pacific plate appears to have changed its relative motion with respect to both the North America plate and the hotspot framework. I will briefly review models that describe the driving mechanisms of large oceanic plates in order to understand the cause of this jump in Euler pole location.

CHANGE IN PACIFIC PLATE SUBDUCTION GEOMETRY AT 3-4 MA

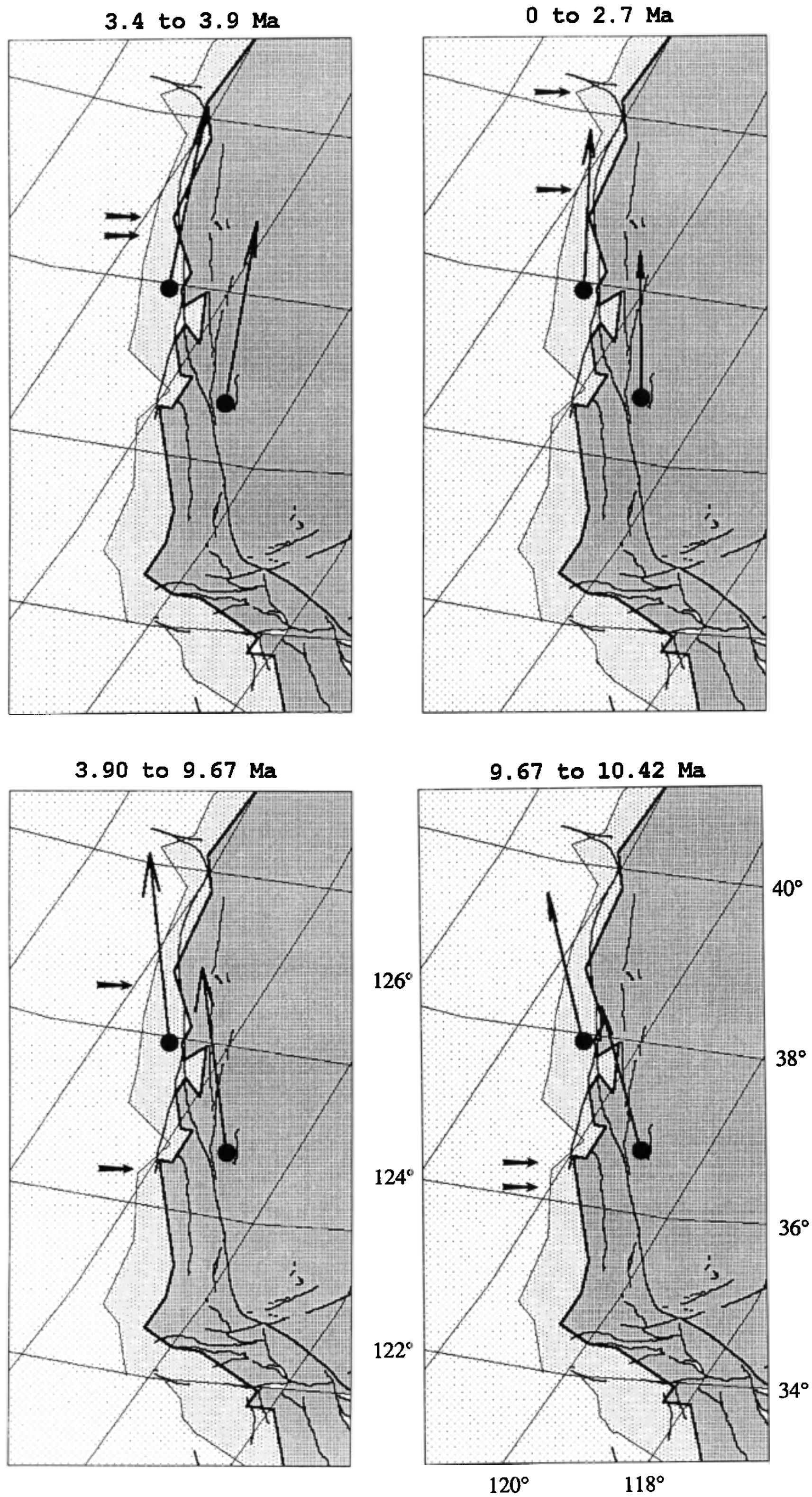
The location of present-day instantaneous rotation poles for oceanic plates can be accurately modelled with respect to a hotspot reference frame by measuring the percentage of plate boundary that is occupied by subduction zones [Peterson, 1985]. Major shifts in a plate torque vector correspond to changes in the location of subduction zones along the plate boundary [Solomon and Sleep, 1974; Forsyth and Uyeda, 1975; Solomon et al., 1975, 1977; Jarrard, 1986]. The position of the Euler pole describing the relative motion of an oceanic plate with respect to the hotspot reference frame can also be accurately calculated by modelling the torque of the subducting slab [Peterson and Seno, 1983; Peterson, 1985].

Peterson and Seno [1983] and Peterson [1985] deduced the present Pacific hotspot (HSP) Euler pole by calculating a torque vector for the Pacific plate in which incremental torques along the edge of the plate are weighted by the square of the age of the subducting crust. This method, as presented by Peterson and Seno [1983] and Peterson [1985], relates the torque direction that the plate is assumed to be moving in response to (τ) to the incremental torques along different segments (l) of a plate's subduction zones (τ (l)), with a weighting factor of the square of the age of the plate subducting in this incremental zone (the square of a(l)). These relations may be written simply as

$$\hat{\tau} = \int \hat{\tau}(l)\, a^2(l)\, dl$$

$$\tau \cong \sum_{i=0}^{N} \tau_i\, a_i^2\, \Delta l_i$$

Fig. 5. Linear velocities calculated from the model 7 finite rotations presented in this paper, plotted during four intervals. In these four figures, linear velocities at two locations of the California coast (solid circles) are shown along with the estimated position of the Mendocino triple junction at the beginning and end of each time interval (horizontal arrows). The more northerly arrow corresponds to the triple junction location at the older time, and the southerly horizontal arrow corresponds to the triple junction location at the younger time. The change from transform to transpressive convergence along this plate boundary occurs between 3.4 and 3.9 Ma.


3.4 to 3.9 Ma
0 to 2.7 Ma
3.90 to 9.67 Ma
9.67 to 10.42 Ma
126°
124°
122°
40°
38°
36°
34°
120°
118°

This second equation is important because it relates the change in location of the Euler pole of an oceanic plate directly to an observable change in a single, or combination of plate subduction parameters. The shift in the PAC-ANT Euler pole appears to be an abrupt event, expressed by a discreet jump in HSP-PAC Euler pole location. I prefer the model of Peterson and Seno because it relates an abrupt, discontinuous mechanism, that is the discreet change in subduction geometry or sudden changes in the age of subducting crust, to changes in Euler pole location.

Using Peterson and Seno's model, the change in BAR-PAC and NAM-PAC Euler pole locations between 3.4 and 3.9 Ma correlates with a change in the subduction geometry of the Pacific plate. Cox and Engebretson [1985] and Harbert and Cox [1989] correlate the changes in Euler pole locations with the detachment of a Pacific plate slab beneath the North Fiji Plateau between 3.4 and 3.9 Ma [Kroenke, 1972; Coleman and Kroenke, 1981; Kroenke et al., 1986; Cooper and Taylor, 1987]. The age of detachment is constrained by both paleomagnetic and geochemical observations in the Fiji Basin region [Gill et al., 1984; Malahoff et al., 1982]. When the incremental torque vector (τ) is calculated before and after detachment of a slab, the change in Euler pole location is similar to that calculated from the marine magnetic isochrons from the Pacific-Antarctic ridge [Harbert and Cox, 1989]. Detachment of the slab beneath the North Fiji plateau is also constrained by abrupt change near 3 Ma in magmatic composition at Fiji and initiation of rotation of Fiji and Vanuatu. Gill et al. [1984] have related this change to tapping of a deeper magma source, the loss of a subduction-related component, or arrival of mantle magma from the north. Paleomagnetic rotations also constrain the change in plate geometry. Clockwise rotation of Vanuatu and the New Hebrides arc began between 6 and 3 Ma, whereas counterclockwise rotation of Fiji began near 3.5-4.5 Ma [Malahoff et al., 1982; Gill et al., 1984]. The geochemical changes in magma composition at Fiji and the poorly constrained timing of rotations suggest that detachment of the Pacific plate slab beneath the North Fiji plateau may have occurred between 3.4-3.9 Ma. The formation of compressive structures along the North America-Pacific plate boundary in California, such as anticlines and reversed faults, coincided with the 3.4-3.9 Ma detachment of the Pacific plate slab beneath the North Fiji Plateau. Thus it seems likely that the orogeny along the California coast was caused by detachment of a slab far removed from the North America-Pacific plate boundary.

CONCLUSIONS

This study highlights the correlation between a relatively minor change in relative plate motion and the widespread occurrence of certain tectonic events in California. Calculation of the PAC-NAM and PAC-BAR motions by use of a plate circuit for the relative motions of PAC-ANT-AFR-NAM and PAC-ANT-AFR-NAM-BAR shows significant changes in motion at 2.48 and between 3.4 and 3.9 Ma. When a Basin and Range-North America plate Euler pole is included, linear velocities along the San Andreas fault are closer to those observed in recent VLBL measurements. A change in AFR-NAM motion at 2.48 Ma resulted in a decrease in relative motion between the plate pair along the California plate boundary. Between 3.4 and 3.9 Ma, increased compression occurred along much of the Pacific-North America plate margin. The amount of normal convergence along the trace of the San Andreas fault increased from 1.4 mm/yr between 10.0 and 3.9 Ma to 13.0 mm/yr beginning between 3.9 and 3.4 Ma. In addition, the azimuth of relative motion changed from 319.5°E, parallel to the trend of the San Andreas fault, to 331.5°E. The result was a change from transform to transpressive motion between the plates. This transpression is recorded by erosional or disconformable contacts in sedimentary basins, fault-normal compression along strike-slip faults, formation of more northerly trending strike-slip faults parallel to the present-day azimuth of relative motion, and widespread compressive deformation, both onshore and offshore. This case history of coastal California underscores the importance of understanding regional plate tectonics when interpreting complex geological structures along an active plate boundary. It also suggests that complex structures should be carefully interpreted before they are incorporated into geologic models. Erosion, uplift, and compressive deformation may be caused by a noncollisional, transpressive mechanism unrelated to either terrane accretion or major plate reorganization. Although the previous statement may appear to be reminiscent of geosynclinal theory, this deformation along the California coast is related to a variation in relative plate motion.

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