Geofísica Internacional (1990), Vol. 29, Num. 4, pp. 175-184

Paleomagnetic and tectonic constraints on the Late Cretaceous to early Tertiary northward translation of the Baja California peninsula

J. T. Hagstrum and P. E. Filmer
U. S. Geological Survey, and Dept. of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology

Received: April 24, 1990. Accepted: November 7, 1990.

RESUMEN

Los resultados paleomagnéticos del Cretáceo de Baja California y parte de California indican consistentemente un movimiento al norte y una rotación positiva de la región con respecto al craton de Norteamérica antes de la apertura del Golfo de California durante el Mioceno Tardío. La edad Cretácica de la magnetización se confirma por medio de estudios paleomagnéticos del Cretáceo Superior más recientes que el Supercrón Cretácico de Polaridad Normal (Aptio al Santoniano) y los registros paleomagnéticos para lavas del Mioceno Inferior a Medio indican que la California peninsular se encontraba en su posición "pre-Golfo" junto a la costa de Sonora durante gran parte del Mioceno. Las estimaciones de desplazamiento costero potencial con respecto al borde oeste de Norteamérica debido a subducción oblicua durante todo el Paleogeno, basadas en analogías de placa modernas y en reconstrucciones del movimiento de las placas Farallón y Kula + Farallón (≃1000-1200 km), corresponden aproximadamente al movimiento de la California peninsular hacia el norte que sugieren los resultados paleomagnéticos sobre el Cretáceo (≃900 km). Sin embargo, los estudios paleomagnéticos y geológicos más recientes indican que el desplazamiento ante-Mioceno de la California peninsular terminó antes del Eoceno Inferior. De este modo, el movimiento al norte debe haber ocurrido entre los Crones 32r y 23r, o sea entre ≃70 Ma y ≃52 Ma, y el movimiento costero de 900 km durante este tiempo se explica probablemente como movimientos transcurrentes paralelos al arco que pudieran estar relacionados con la subducción oblicua de la placa de Kula, aunque el movimiento al norte también pudiera haber ocurrido dentro de los límites del movimiento relativo de la placa de Farallón, basado en la alineación del margen norteamericano y la eficiencia del mecanismo de desplazamiento.

PALABRAS CLAVE: Paleomagnetismo; tectónica de placas; estructuras y procesos de margen de placa.

ABSTRACT

Cretaceous paleomagnetic data for the Baja California Peninsula (northwestern Mexico; southwestern California, U.S.A.) consistently indicate northward translation (≃8° in latitude or ~900 km) and clockwise rotation (≃20°) of the region relative to ancestral North America prior to opening of the Gulf of California in late Miocene time. Paleomagnetic and rock magnetic studies in Upper Cretaceous rocks younger than the Cretaceous Normal Polarity Superchron (Aptian to Santonian) confirm the age of the Cretaceous magnetization, and paleomagnetic data for early to middle Miocene lava flows indicate that peninsular California was near its pre-Gulf position against coastal Sonora during much of Miocene time. Estimates of potential coastwise displacement of crustal fragments along the western margin of North America by oblique subduction and arc-parallel strike-slip faulting for all of Paleogene time, based on modern analogs and plate reconstruction models of Farallon and Farallon + Kula plate motion (≃1000-2000 km), are roughly equivalent to the northward displacement of peninsular California indicated by the Cretaceous paleomagnetic data (≃900 km). However, current paleomagnetic and geologic studies indicate that the pre-Miocene displacement of peninsular California may have been completed by early Eocene time. The available paleomagnetic and paleontologic data constrain northward movement to have occurred between Chron 32r and Chron 23r, or between ≃70 Ma and ~52 Ma. Coastwise transport of 900 km during this time interval is most easily explained within the context of our model by arc-parallel strike-slip faulting related to oblique subduction of the Kula plate, although transport could also have occurred within the limits of relative motion of the Farallon plate depending on the trend of the North American margin and efficiency of the mechanism of transport.

KEY WORDS: Paleomagnetism; plate tectonics; plate margin structures and processes.

INTRODUCTION

Recent paleomagnetic studies of Upper Cretaceous rocks from the Baja California Peninsula, northwestern Mexico, and from southwestern California, U.S.A., have confirmed the conclusions of earlier studies and contributed to a growing body of data which consistently indicates that peninsular California (Fig. 1) was translated northward and rotated clockwise with respect to stable North America in Late Cretaceous and early Tertiary time. Other explanations of the paleomagnetic data, including long-term nondipole behavior of the ancient geomagnetic field and later widespread remagnetization, have been shown to be invalid. Unrecognized tilting of plutonic rocks (*e.g.*, Butler *et al.*, 1989) and concomitant inclination shallowing due to compaction in sedimentary rocks (*e.g.*, Arason and Levi, 1990) also have been proposed to explain the discordant data for the Baja California Peninsula (Butler *et al.*,1991).

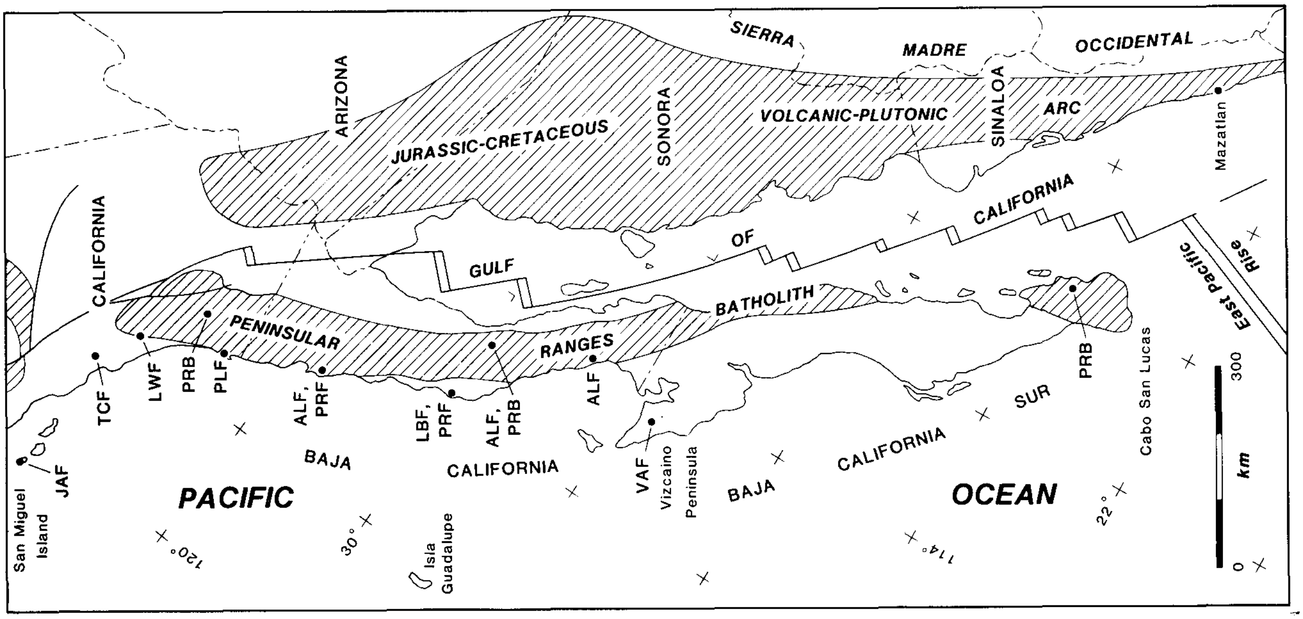

Fig. 1. Map of the Baja California Peninsula and the western Mexican mainland showing regional tectonic features and the approximate locus of the Jurassic and Cretaceous magmatic arc (ruled pattern). Dots indicate locations of paleomagnetic sampling sites and abbreviations are defined in Table 1.

These explanations require, however, that differential compaction in sedimentary rocks has had the same effect as tilting of plutonic rocks over a wide, tectonically variable area. As noted by Hagstrum *et al.* (1985) and Filmer and Kirschvink (1989), it appears more likely that the coincidence of paleomagnetic results for sedimentary and plutonic rocks from the Baja Peninsula indicates that neither of these errors has had a significant effect, and that the data can be most simply explained by northward translation and clockwise rotation of peninsular California. Current paleomagnetic (Flynn *et al.*, 1989) and geologic (Abbott and Smith, 1989) studies indicate that the pre-Miocene displacement of peninsular California may have been completed by early Eocene time. We present the large body of Cretaceous paleomagnetic data (Table 1) for the Baja California Peninsula, discuss the available early Tertiary paleomagnetic data for the Baja Peninsula, and examine how peninsular California could have been transported northward between latest Cretaceous and early Eocene time within the context of a tectonic model of the western North American margin based on examples of modern subduction zones (*i.e.*, Jarrard, 1986) and recent plate reconstruction models (*i.e.*, Engebretson *et al.*, 1985).

PREVIOUS WORK

Teissere and Beck (1973) first documented divergent paleomagnetic directions for the middle Cretaceous Southern California batholith (Fig. 1, Table 1) and suggested that these divergent directions were the result of a large-scale tectonic displacement with respect to cratonic North America. This displacement corresponds to a northward translation of about 12° in latitude (≃1330 km) and a clockwise rotation of 26° relative to North America. Erskine and Marshall (1980) also sampled the Southern California batholith at some K-Ar dated sites (115-90 Ma) and determined a 11° (≃1220 km) northward translation and 40° clockwise rotation for these rocks. Patterson (1984) undertook extensive sampling of the Cenomanian to Santonian Valle Formation on the Vizcaino Peninsula and Cedros Island in Mexico (Fig. 1) and reported a similar result (15° or ≃1670 km northward translation, 28° clockwise rotation). Hagstrum *et al.* (1985) contributed supporting data for the Peninsular Ranges batholith from along the length of the Baja California Peninsula and for the Valle Formation, in addition to data for the Turonian La Bocana Roja Formation. Based on a failed fold test and identical *in situ* directions, the Aptian to Albian Alisitos Formation was inferred to have been remagnetized by intrusion of the Peninsular Ranges batholith (Hagstrum *et al.*, 1985). Champion *et al.*(1986) provided data for Upper Cretaceous marine strata of the Jalama Formation on San Miguel Island (Fig. 1) in the Southern California borderland which indicate these rocks were translated 19° (≃2110 km) northward and rotated 50° clockwise. Although the available evidence implies that the characteristic magnetizations in Cretaceous rocks of the Baja California Peninsula were acquired mostly during the Cretaceous

Table 1

Cretaceous paleomagnetic directions and poles for the Baja California Peninsula

I	*D*	*N*	*R*	*k*	α_{95}	*Paleolat*	*Plat*	*Plong*	*Ref*
Point Loma Formation (PLF)									
38.5	30.4	26*	24.8520	22	6.2	18.1 ± 4.0	60.9	347.5	1
Punta Baja and Rosario Formations (PRF)									
45.2	3.8	23	22.1293	25	6.1	22.9 ± 4.4	85.3	17.8	2,3
Tuna Canyon Formation (TCF)									
46.9	73.2	12	11.9088	121	4.0	31.1 ± 3.2	28.4	315.1	3
Ladd and Williams Formations (LWF)									
45.1	323.6	20*	19.2310	25	6.7	17.5 ± 4.3	57.9	149.5	4
Jalama Formation (JAF)									
43.9	24.0	94*	91.0617	32	2.6	21.2 ± 1.8	67.6	345.2	5
La Bocana Roja Formation (LBF)									
52.1	12.0	3	2.9967	598	5.1	29.4 ± 4.4	79.5	316.6	6
Valle Formation (VAF)									
42.6	359.4	12	11.7176	39	7.0	22.8 ± 5.1	86.8	75.5	6,7
Peninsular Ranges Batholith (PRB)									
49.5	5.9	39	38.4492	69	2.8	29.4 ± 2.4	83.2	189.8	6,8
Alisitos Formation (remagnetized) (ALF)									
47.3	11.4	5	4.9654	115	7.2	25.2 ± 5.6	79.7	340.0	6,7

I, *D*, inclination and declination, in degrees; *N*, number of sites (*samples) analyzed; *R*, vector sum of *N* unit vectors; *k*, precision parameter for directions (Fisher, 1953); α_{95}, radius of 95% confidence for directions, in degrees; *Paleolat*, paleolatitude with 95% confidence limits, in degrees, calculated at 26°N, 248°E from virtual geomagnetic pole (VGP); *Plat*, *Plong*, latitude and east longitude of VGP, in degrees; *Ref*, references; 1, Bannon *et al.* (1989); 2, Filmer and Kirschvink (1989); 3, Morris *et al.* (1986); 4, Fry *et al.* (1985); 5, Champion *et al.* (1986); 6, Hagstrum *et al.* (1985); 7, Patterson (1984); 8, Teissere and Beck (1973).

Normal Polarity Superchron (Aptian to Santonian), their uniform normal polarity and similarity to present-day geomagnetic field directions are also possibly indicative of recent overprint magnetizations. However, paleomagnetic work on rocks younger than the Cretaceous Normal Polarity Superchron have provided the data necessary to dispel suspicion of recent remagnetization.

Fry *et al.* (1985) presented data showing both normal and reversed polarities for samples from the Turonian to Campanian Ladd and Williams Formations from the Santa Ana Mountains of southern California (Fig. 1), that are consistent in inclination with the other Cretaceous directions for the Baja California peninsula. These antipodal

Table 2

Average paleomagnetic poles and displacement parameters for the Baja California Peninsula

	N	R	K	A_{95}	*Paleolat*	*Plat*	*Plong*	*Ref*
				Miocene				
Baja California Peninsula	64	62.0968	22	3.8	25.0 ± 2.9	86.4	142.1	1
North America	18	17.8696	130	3.0	24.7 ± 2.3	87.4	129.7	2
Displacement at 26°N, 248°E:	poleward translation = -0.2 ± 3.8, clockwise rotation = -1.3 ± 4.2							
				Eocene				
Baja California Peninsula	42	40.4581	27	4.4	26.9 ± 3.6	77.6	165.4	3
North America	147	137.9458	16	3.0	27.3 ± 2.4	82.8	170.4	4
Displacement at 26°N, 248°E:	poleward translation = 0.4 ± 4.2, clockwise rotation = -5.9 ± 4.7							
				Cretaceous				
Baja California Peninsula	9		-49,-4	5.2,20.8	26.0 ± 4.1	80.8	335.7	5
North America	4	3.9915	352	4.9	36.4 ± 4.9	71.1	195.7	6
Displacement at 26°N, 248°E:	poleward translation = 10.4 ± 5.6, clockwise rotation = 28.8 ± 18.7							

Abbreviations as in Table 1. K, precision parameter for poles (Fisher, 1953); A_{95}, radius of 95% confidence for poles, in degrees; poleward translation and clockwise rotation with 95% confidence limits, in degrees. References: 1, Hagstrum *et al.* (1987); 2, Irving and Irving (1982) as modified by Hagstrum *et al.* (1987); 3, Flynn *et al.* (1989) omitting sites with $k<10$ or $\alpha_{95}>45°$; 4, Diehl *et al.* (1983); 5, this analysis (see Table 1); 6, Globerman and Irving (1988). Bingham statistics (Onstott, 1980) accompany the average Cretaceous pole for the Baja California Peninsula; R is not calculated, K_1, K_2 are the two Bingham concentration parameters, and A_1, A_2 are the two Bingham 95% confidence limits about the mean pole.

directions pass a reversal test and a fold test (Fry *et al.*, 1985), supporting the interpretation that they indeed record Late Cretaceous field directions and that the reversed directions correspond to the Chron 33r magnetozone. Morris *et al.* (1986) determined magnetization directions for samples of the Turonian to Maastrichtian Tuna Canyon Formation from the Santa Monica Mountains, California, and the Campanian to Maastrichtian Punta Baja and Rosario Formations near El Rosario, Baja California, which also pass both reversal and fold tests. Magnetizations measured by Bannon *et al.* (1989) in samples from the Campanian to Maastrichtian Point Loma Formation again pass both reversal and fold tests (Bannon *et al.*, 1989), and the authors correlate the reversed directions with Chron 32r. Filmer and Kirschvink (1989) also collected samples from the Rosario Formation at Punta

San Jose and El Rosario along the western coast of Baja California. Biochemical investigations of the ammonites *Baculites inornatus* (Weiner and Lowenstam, 1980) from the Rosario Formation at Punta San Jose and X-ray, Mössbauer, and isothermal remanent magnetization (IRM) acquisition studies indicate that the sequence exposed at Punta San Jose has not been thermally or chemically altered and that the magnetic carrier is highly-stable single-domain magnetite (Filmer and Kirschvink, 1989). The normal-polarity samples of Campanian age sediments are inferred to have been deposited during Chron 33, and samples having reversed-polarity antipodal directions were collected from younger Maastrichtian sediments (Filmer and Kirschvink, 1989).

Extensive paleomagnetic data for Miocene lava flows sampled throughout the Baja California Peninsula yield a mean pole (Table 2) which is consistent with the North American reference pole indicating that peninsular California was near its pre-Gulf of California position against western Sonora (Fig. 1) by early Miocene time (Hagstrum *et al.*, 1987). Champion *et al.* (1986) reported paleomagnetic data for early and middle Eocene sedimentary rocks of the Ferello fan on San Miguel Island which imply a 20° (~2200 km) poleward translation and 50° to 80° clockwise rotation of peninsular California relative to North America since middle Eocene time. The normal polarity characteristic magnetization for the lower part of the section at Simonton Cove (Champion *et al.*, 1986), however, is similar in direction to that of nearby Late Oligocene and Early Miocene volcanic dikes (Kamerling and Luyendyk, 1985), indicating the likelihood of remagnetization. Kamerling and Luyendyk (1985) also sampled the Eocene sediments at Simonton Cove, and concluded that they were remagnetized by the middle Tertiary dikes. Furthermore, the two mean reversed-polarity directions for sites 3 and 4 were determined by Champion *et al.* (1986) primarily using remagnetization circle analysis, and are apparently an artifact of this analysis (see Champion *et al.*, 1986, Fig. 14); removal of a well-defined normal-polarity over-print magnetization will cause the remagnetization circles to intersect at its reversed-polarity antipode. A higher-coercivity reversed-polarity component of magnetization present in these rocks was isolated in four specimens from Simonton Cove that is similar in direction to the antipode of the normal polarity overprint (see Champion *et al.*, 1986). The middle Tertiary intrusive rocks also have both normal and reversed polarity magnetizations (Kamerling and Luyendyk, 1985) indicating that the Eocene host rocks could have been overprinted in both reversed and normal polarity fields as well.

Recently, Flynn *et al.* (1989) presented paleontologic and paleomagnetic data for early Eocene strata near Rosarito, Baja California, Mexico (Table 2). These data are consistent with the North American reference curve, implying that peninsular California had become attached to western Sonora by early Eocene time. Flynn *et al.* (1989) attempted to resolve the conflict between their data and those for San Miguel Island (Champion *et al.*, 1986) by suggesting that these data sets are for two previously independent terranes. However, lithologic correlations between Eocene strata on San Miguel Island and the San Diego region in southern California (Howell and Link, 1979) indicate that San Miguel Island was part of peninsular California in Eocene time. Due to the aforementioned problems associated with the Eocene paleomagnetic data for San Miguel Island (Champion *et al.*, 1986), we consider the paleomagnetic data of Flynn *et al.* (1989) to be more reliable.

DISCUSSION

Because of local vertical-axis rotations, related to Neogene strike-slip faulting in southern California (*e.g.*, Luyendyk *et al.*, 1985), the available Cretaceous paleomagnetic poles for the Baja California Peninsula are dispersed along a small-circle arc that is perpendicular to the paleomagnetic meridian for this terrane (Fig. 2, Table 1). Taken together, these paleomagnetic poles yield a mean Cretaceous pole for the Baja California Peninsula that is significantly different from a corresponding reference pole for ancestral North America (Table 2), and even the small circle dispersion from all possible local vertical-axis rotations is different from the reference pole at above the 95% confidence level. A comparison of the average poles indicates that peninsular California has moved northward approximately 10° in latitude (1110 km) and rotated 29° clockwise relative to North America since Late Cretaceous time. This displacement includes the opening of the Gulf of California which corresponds to about a 2° (≃220 km) northward translation and roughly 8° of clockwise rotation since Late Miocene time. Thus, the paleomagnetic data indicate that peninsular California moved northward approximately 8° (≃900 km) and rotated approximately 20° clockwise between Late Cretaceous and early Miocene time. The arrival of peninsular California in its pre-Gulf position prior to Miocene time is shown by the correspondence of paleomagnetic data for Miocene lava flows of the Baja Peninsula with coeval data for cratonic North America (Hagstrum *et al.*, 1987). In addition, these Miocene data for the Baja California Peninsula do not support either a long-period nondipole geomagnetic field in southwestern North America during Late Cretaceous to middle Tertiary time or tectonic movement of peninsular California greater than that associated with the opening of the Gulf of California since Miocene time (see Pischke *et al.*, 1986; Morris *et al.*, 1986).

Truncation of the continental margin along the northern Middle America Trench (Fig. 2) by right-lateral offset in early Tertiary time (Karig *et al.*, 1978), and the suggestion that Precambrian and Mesozoic basement rocks in this region are possible source rocks for continentally-derived detritus on the Vizcaino Peninsula (Kimbrough *et al.*, 1987), are also consistent with the tectonic displacement of peninsular California indicated by the paleomagnetic data. Modern analogs imply that

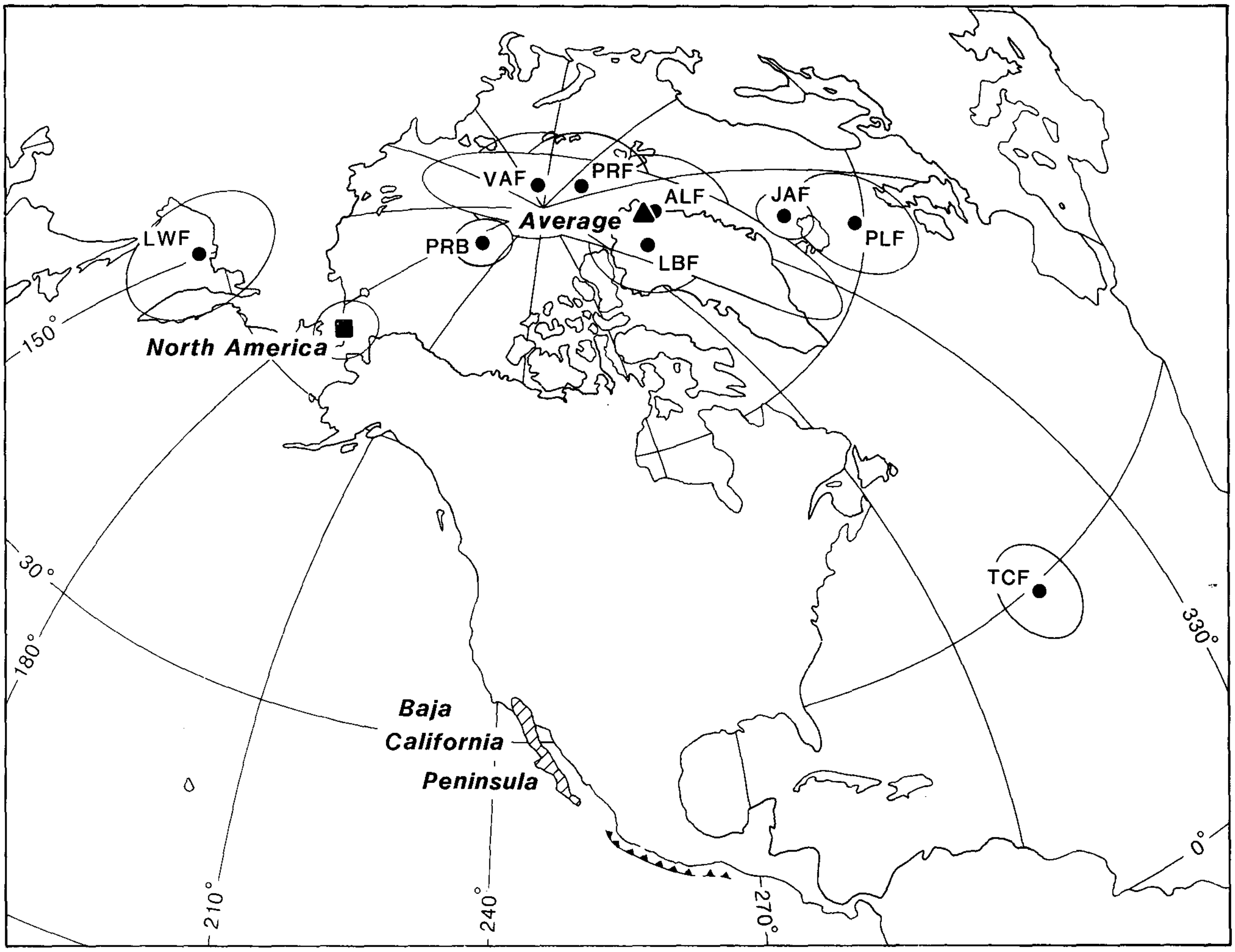

Fig. 2. Unit-mean paleomagnetic poles (circles) and average pole (triangle) for Cretaceous rocks of peninsular California (shaded region) and the Cretaceous reference pole for North America (square) with 95% confidence limits. Data and abbreviations for unit names are given in Table 1. The northern portion of the Middle America Trench (sawtoothed line) is shown along the southern margin of Mexico. Equal-area map projection is centered at 26°N, 248°E.

the northward displacement of peninsular California along the ancient convergent margin of North America could have been accomplished by oblique subduction and concurrent arc-parallel strike-slip faulting (*e.g.*, Beck, 1983). Jarrard (1986) observed that there are active arc-parallel strike-slip faults behind two-thirds of modern subduction zones with overriding continental crust, and that these faults tend to form 100 to 300 km inland from the trench, near or within the magmatic arc, where the overriding plate is weakest. Reconstructions of plate motions along the western margin of North America in Late Cretaceous and early Tertiary time (Engebretson *et al.*, 1985) show significant components of northward motion for the Farallon and Kula plates relative to North America (Table 3). The exact position of the Kula-Farallon ridge is unknown, so it is uncertain which plate was subducted beneath western North America at a particular latitude in Late Cretaceous and early Tertiary time.

The displacements of forearc slivers between the trench and strike-slip fault depend on the obliquity of plate convergence, the degree of interplate coupling, and the strength of the overriding plate (Beck, 1986; Jarrard, 1986). Based on the available data for modern subduction zones, Jarrard (1986) derived the following equation for

Table 3

Latest Cretaceous and Paleogene reconstruction parameters for the Farallon and Kula plates relative to North America at 26° N, 248°E

Age From (Ma)	To	Azimuth (degree)	Obliquity (degree)	Speed (km/Ma)	Strike-slip velocity (km/Ma)	Coastwise displacement (km)
			Farallon (56 to 28 Ma)			
28	37	52	23	86	17	153
37	43	56	19	128	26	156
43	48	62	13	163	32	160
48	56	56	19	160	32	256
			Farallon (66 to 56 Ma)			
56	61	60	15	140	28	140
61	66	58	17	132	26	130
				Total Farallon (66 to 28 Ma):		995
			Kula (66 to 56 Ma)			
56	61	44	31	85	40	200
61	66	33	42	106	51	255
			Total (56 to 28 Ma) + Kula (66 to 56 Ma):			1180
			Farallon (74 to 66 Ma)			
66	74	61	14	112	22	177
			Kula (74 to 66 Ma)			
66	74	22	53	111	57	456

Azimuth and speed (V) for time intervals are from Engebretson *et al.* (1985), Table 5, Baja California site (26°N, 248°E). Obliquity values (ϕ) are based on a 345°-trending North American plate margin in latest Cretaceous and Paleogene time. Strike-slip velocity (V_{ss}) calculated using equation (1) and assuming slip vector residuals (θ) of 11.4±17.5 and 27.9±5.8 for the Farallon and Kula plates, respectively (see text).

the rate of strike-slip motion (V_{ss}) of a forearc sliver with respect to the overriding plate

$$V_{ss} = V \tan\theta / (\sin\phi \tan\theta + \cos\phi) \qquad (1)$$

where V is the convergence rate between the major plates, θ is the slip vector residual, and ϕ is the obliquity of convergence. Obliquity values for the Farallon and Kula plates (Table 3) are calculated using the convergence azimuths of Engebretson *et al.* (1985) and assuming an orientation of 345° for the North American margin. This azimuth is parallel to the present trend of the Cretaceous Sierra Nevada batholith which is inferred, based on modern examples, to have been approximately parallel to the ancient convergent plate margin (Jayko and Blake, unpublished data, 1989). These obliquity values for the Farallon and Kula plates are roughly equivalent to those for the Ecuador and Colombia subduction zone and the Sumatra subduction zone, respectively (see Jarrard, 1986). Thus, we have used the slip vector residuals (the differences between observed slip vector azimuths of shallow thrusting earthquakes and the expected azimuths from known plate motions) for these two modern subduction zones (Jarrard, 1986) in equation (1) to calculate potential coastwise displacements of peninsular California along the North American margin due to strike-slip faulting in Late Cretaceous and early Tertiary time (Table 3). The total coastwise displacement relative to North America at 26°N, 248°E during Paleogene time would be approximately 1000 km for Farallon plate motion, and about 1200 km for Farallon + Kula plate motion. The northward components for these estimates of coastwise displacement (960 km, Farallon; 1140 km, Farallon + Kula) between 66 Ma and 28 Ma are similar to the northward displacement for peninsular California (≃900 km) inferred from the Cretaceous paleomagnetic data (Table 2).

However, the paleomagnetic data for early Eocene rocks of the Baja California Peninsula (Flynn *et al.*, 1989) indicate that the Paleogene northward translation of peninsular California was completed by early Eocene time (Table 2). Additionally, Abbott and Smith (1989) have confirmed their previous geochemical correlation between Eocene Poway Conglomerate clasts in southern California and Baja California and source rocks near El Plomo in northwestern Sonora. This correlation also indicates that peninsular California was adjacent to Sonora by Eocene time. Taken together the available paleomagnetic, paleontologic, and geologic data imply that peninsular California was displaced northward along the North American margin between Chron 32r (Bannon *et al.*, 1989) and Chron 23r (Flynn *et al.*, 1989), or between ≃70 Ma and ≃52 Ma (Harland *et al.*, 1982). The total northward component of strike-slip displacement between 70 and 52 Ma based on our model is ≃470 km for Farallon plate motion and is ≃810 km for Kula plate motion (Table 3). Thus, most, if not all, of the pre-Miocene northward movement of the Baja California Peninsula (≃900 km) could be accounted for by strike-slip faulting associated with north-oblique subduction of the Kula plate.

Studies of Pacific and Farallon plate motions (Rosa and Molnar, 1988) and models of deformation in the Cordillera related to horizontal-slab subduction (*e.g.* Dickinson and Snyder, 1978; Bird, 1988), however, imply that it was the Farallon plate subducted beneath most of western North America during Late Cretaceous through Eocene time. Although our model for strike-slip displacement between 70 and 52 Ma indicates only ≃470 km of coastwise displacement associated with subduction of the Farallon plate, the assumed trend of the North American margin and efficiency of coupling between the downgoing slab and displaced terrane strongly influence this result. *In situ* stress and heat flow investigations of the San Andreas fault (*e.g.*, Zoback *et al.*, 1987) and geodetic surveys of strain rates in the plate boundary zone of New Zealand (Walcott, 1984) imply that this coupling could have been quite efficient and that estimates of terrane displacement based on seismic slip indicators are minimum estimates. Within the framework of our model, varying the margin's trend from 345° to 0° would increase the magnitude of the coastwise displacement from ≃70 km to ≃510 km with 20% of the convergence velocity converted into strike-slip displacement, and increase the displacement from ≃690 km to ≃1270 km if 50% (maximum value) of the convergence velocity were used. Thus, northward transport of peninsular California between latest Cretaceous and early Eocene time is within the limits of relative motion of the Farallon plate depending on the trend of the North American margin and efficiency of the mechanism of transport.

CONCLUSIONS

The paleomagnetic data for Upper Cretaceous rocks from Baja California and Baja California Sur, Mexico, and southern California, U.S.A., consistently indicate that peninsular California was translated northward approximately 8° in latitude (≃900 km) and rotated clockwise (≃20°) relative to stable North America during Late Cretaceous and early Tertiary time. Apparently, subsequent vertical-axis rotations in southern California related to Neogene strike-slip faulting have obscured early Tertiary rotations of some of these rocks (Fig. 2, Table 1).

Eocene paleomagnetic (Flynn *et al.*, 1989) and geologic (Abbott and Smith, 1989) evidence indicates that peninsular California was near its pre-Gulf position against coastal Sonora (Fig. 1) by early Eocene time. Thus, the available paleomagnetic and paleontologic data constrain northward movement of peninsular California to have occurred between approximately Chron 32r and Chron 23r, or between ≃70 Ma and ≃52 Ma.

A simple model of the western margin of North America in Late Cretaceous and early Tertiary time, based on plate reconstruction models (Engebretson *et al.*, 1985) and modern subduction analogs (Jarrard, 1986), indicates that peninsular California could have been transported northward the ≃900 km required by the paleomagnetic data between 70 and 52 Ma most easily by strike-slip faulting related to oblique subduction of the Kula plate, but also by faulting related to subduction of the Farallon plate if the margin were near N-S in trend and if most of the tangential component of convergence were converted into northward displacement.

ACKNOWLEDGEMENTS

The authors thank A. S. Jayko and M. C. Blake, Jr. for a preprint of their work, and R. F. Butler, D. E. Champion, C. S. Gromme, and E. A. Mankinen for constructive comments on an earlier version of the manuscript.

BIBLIOGRAPHY

ABBOTT, P. L., and T. E. SMITH, 1989. Sonora, Mexico, source for the Eocene Poway Conglomerate of southern California. *Geology, 17,* 329-332.

ARASON, P., and S. LEVI, 1990. Compaction and inclination shallowing in deep-sea sediments from the Pacific Ocean. *J. Geophys. Res., 95,* 4501-4510.

BANNON, J. L., D. J. BOTTJER, S. P. LUND and L. R. SAUL, 1989. Campanian/Maastrichtian stage boundary in southern California: Resolution and implications for large-scale depositional patterns. *Geology, 17,* 80-83.

BECK, M. E., Jr., 1983. On the mechanism of tectonic transport in zones of oblique subduction. *Tectonophys., 93,* 1-11.

BECK, M. E., Jr., 1986. Model for late Mesozoic-early Tertiary tectonics of coastal California and western Mexico and speculations on the origin of the San Andreas fault. *Tectonics, 5,* 49-64.

BIRD, P., 1988. Formation of the Rocky Mountains, western United States: A continuum computer model. *Science, 239,* 1501-1507.

BUTLER, R. F., G. E. GEHRELS, W. C. McCLELLAND, S. R. MAY, and D. KLEPACKI, 1989. Discordant paleomagnetic poles from the Canadian Coast Plutonic complex: Regional tilt rather than large-scale displacement? *Geology, 17,* 691-694.

BUTLER, R. F., W. R. DICKINSON, and G. E. GEHRELS, 1991. Paleomagnetism of coastal California and Baja California: Alternatives to large-scale northward transport. *Tectonics,* in press.

CHAMPION, D. E., D. G. HOWELL, and M. MARSHALL, 1986. Paleomagnetism of Cretaceous and Eocene strata, San Miguel Island, California, Borderland and the northward translation of Baja California. *J. Geophys. Res., 91,* 11,557-11,570.

DICKINSON, W. R., and W. S. SNYDER, 1978. Plate tectonics of the Laramide orogeny. *Geol. Soc. Am. Mem. 151,* 355-366.

DIEHL, J. F., M. E. BECK, Jr., S. BESKE-DIEHL, D. JACOBSON, and B. C. HEARN, Jr., 1983. Paleomagnetism of the Late Cretaceous-early Tertiary north-central Montana alkalic province. *J. Geophys. Res., 88,* 10,593-10,609.

ENGEBRETSON, D. C., A. COX, and R. G. GORDON, 1985. Relative motions between oceanic and continental plates in the Pacific basin. *Geol. Soc. Am.* Spec. Pap. 206, 59 pp.

ERSKINE, B., and M. MARSHALL, 1980. A paleomagnetic and rock magnetic investigation of the northern Peninsular Ranges batholith, southern California. *Eos Am. Geophys. Union Trans.* 61, 948.

FILMER, P. E., and J. L. KIRSCHVINK, 1989. A paleomagnetic constraint on the Late Cretaceous paleoposition of northwestern Baja California, Mexico. *J. Geophys. Res., 94,* 7332-7342.

FISHER, R. A., 1953. Dispersion on a sphere. *R. Soc. London Proc.,* A217, 295-305.

FLYNN, J. J., R. M. CIPOLETTI and M. J. NOVACEK, 1989. Chronology of early Eocene marine and terrestrial strata, Baja California, Mexico. *Geol. Soc. Am. Bull.,* 101, 1182-1196.

FRY, J. G., D. J. BOTTJER and S. P. LUND, 1985. Magnetostratigraphy of displaced Upper Cretaceous strata in southern California. *Geology, 13,* 648-651.

GLOBERMAN, B. R., and E. IRVING, 1988. Mid-Cretaceous paleomagnetic reference field for North America: Restudy of 100 Ma intrusive rocks from Arkansas. *J. Geophys. Res., 93,* 11,721-11,733.

HAGSTRUM, J. T., M. McWILLIAMS, D. G. HOWELL, and S. GROMME, 1985. Mesozoic paleomagnetism and northward translation of the Baja California Peninsula. *Geol. Soc. Am. Bull., 96,* 1077-1090.

HAGSTRUM, J. T., M. G. SAWLAN, B. P. HAUSBACK, J. G. SMITH, and C. S. GROMME, 1987. Miocene paleomagnetism and tectonic setting of the Baja California Peninsula, Mexico. *J. Geophys. Res., 92,* 2627-2639.

HARLAND, W. B., A. V. COX, P. G. LLEWELLYN, C. A. G. PICKTON, A. G. SMITH, and R. WALTERS, 1982. A geological Time Scale, Cambridge University Press, New York, 131 pp.

HOWELL, D. G., and M. H. LINK, 1979. Eocene conglomerate sedimentology and basin analysis, San Diego and the southern California borderland. *J. Sediment. Petrol., 49,* 517-540.

IRVING, E., and G. A. IRVING, 1982. Apparent polar wander paths, Carboniferous through Cenozoic, and the assembly of Gondwana. *Geophys. Surv., 5,* 141-188.

JARRARD, R. D., 1986. Relations among subduction parameters. *Rev. Geophys., 24,* 217-284.

KAMERLING, M. J., and B. P. LUYENDYK, 1985. Paleomagnetism and Neogene tectonics of the northern Channel Islands, California. *J. Geophys. Res., 90,* 12,485-12,502.

KARIG, D. E., R. K. CARDWELL, G. F. MOORE, and D. G. MOORE, 1978. Late Cenozoic subduction and continental margin truncation along the northern Middle America Trench. *Geol. Soc. Am. Bull., 89,* 265-276.

KIMBROUGH, D. L., J. J. HICKEY, and R. M. TOSDAL, 1987. U-Pb ages of granitoid clasts in upper Mesozoic arc-derived strata of the Vizcaino Peninsula, Baja California, Mexico. *Geology, 15,* 26-29.

LUYENDYK, B. P., M. J. KAMERLING, R. R. TERRES, and J. S.HORNAFIUS, 1985. Simple shear of southern California during Neogene time suggested by paleomagnetic declinations. *J. Geophys. Res., 90,* 12,454-12,466.

MORRIS, L. K., S. P. LUND, and D. J. BOTTJER, 1986. Palaeolatitude drift history of displaced terranes in southern and Baja California. *Nature, 321*, 844-847.

ONSTOTT, T. C., 1980. Application of the Binghan distribution function in paleomagnetic studies. *J. Geophys. Res., 85,* 1500-1510.

PATTERSON, D. L., 1984. Paleomagnetism of the Valle Formation and the Late Cretaceous paleogeography of the Vizcaino basin, Baja California, Mexico, *in* V. A. Frizzell, Jr., ed., Geology of the Baja California Peninsula, Society of Economic Mineralogists and Paleontologists, Pacific Section, 39, 173-182.

PISCHKE, G., G. GASTIL, and M. MARSHALL, 1986. Mesozoic paleomagnetism and northward translation of the Baja California Peninsula: Discussion. *Geol. Soc. Am. Bull., 97,* 1279-1280.

ROSA, J. W. C., and P. MOLNAR, 1988. Uncertainties in reconstructions of the Pacific, Farallon, Vancouver, and Kula plates and constraints on the rigidity of the Pacific and Farallon (and Vancouver) plates between 72 and 35 Ma. *J. Geophys. Res., 93*, 2997-3008.

TEISSERE, R. F., and M. E. BECK,Jr. 1973. Divergent Cretaceous paleomagnetic pole position for the southern California batholith, U.S.A. *Earth Planet. Sci. Lett., 18,* 296-300.

WALCOTT, R. I., 1984. The kinematics of the plate boundary zone through New Zealand: A comparison of short- and long-term deformations. *Geophys. J. R. Astr. Soc.*, 79, 613-633.

WEINER, S., and H. A. LOWENSTAM, 1980. Well preserved fossil mollusk shells: Characterization of mild diagenetic processes, *in* P. E. Hare, ed., Biochemistry of Amino Acids, John Wiley and Sons, New York, 95-114.

ZOBACK, M. D., M. L. ZOBACK, V. S. MOUNT, J. SUPPE, J. P. EATON, J. H. HEALY, D. OPPENHEIMER, P. REASENBERG, L. JONES, C. B. RALEIGH, I. G. WONG, O. SCOTTI, and C. WENTWORTH, 1987. New evidence on the state of stress of the San Andreas Fault system, *Science*, 238, 1105-1111

J. T. Hagstrum,
U. S. Geological Survey, Menlo Park,
California 94025, U.S.A

P. E. Filmer,
Dept. of Earth, Atmospheric and Planetary Sciences,
M. I. T., Cambridge, Mass. 02139, U.S.A.