DAVID BLOOM

TECTONICS, VOL. 5, NO. 1, PAGES 49-64, FEBRUARY 1986

# MODEL FOR LATE MESOZOIC-EARLY TERTIARY TECTONICS OF COASTAL CALIFORNIA AND WESTERN MEXICO AND SPECULATIONS ON THE ORIGIN OF THE SAN ANDREAS FAULT

Myrl E. Beck, Jr.

Department of Geological Sciences,
Northwestern University, Evanston,
Illinois

Abstract. Cretaceous and early Tertiary arc and forearc rocks found along the coast in southern California and Baja California have been shown by paleomagnetic measurements to have originated many hundreds, or even several thousands, of kilometers south of their current locations. Northward transport also is found in Cretaceous batholithic rocks near the edge of the continent in Washington and British Columbia. The consistency of this pattern suggests that slices of arc and forearc rock originating on the western edge of North America have been translated along the coast by strike-slip faulting. Strike-slip faults are shown to be an expected response to north-oblique subduction of the Farallon and/or Kula plates. Faulting and subduction probably were concurrent activities; i.e., the arc and forearc grew and were displaced simultaneously. Because displacement was dominantly parallel to subduction-related lithic belts, arc and forearc rocks may have traveled large distances without producing either significant hiatuses in the rock record or conspicuous disruptions in the distribution of lithic belts. Subduction-related strike-slip faulting is shown to be favored by high angles of oblique convergence, shallow dip of the subducting slab, relatively easy slip on potential faults within the arc or forearc, and the existence of a place for the moving sliver to go. It is suggested that these conditions are not difficult to satisfy and that subduction-related strike-slip faulting may thus be a common feature of convergent orogens. The location of the San Andreas fault inboard from the continental margin may be attributable to localization of the Pacific-North American transform by a system of precollision subduction-related faults.

## INTRODUCTION

This paper is an attempt to answer three closely related questions:

1. Why does the California continental margin appear to some investigators to have been built dominantly in situ by subduction-related processes (e.g., Ernst, 1984), even though it is composed of rocks that, wherever studied paleomagnetically, appear to have moved many hundreds or even several thousand kilometers from their points of origin (e.g., Champion et al., 1984)?
2. According to plate tectonic theory the San Andreas transform forms the

---

Permanently at Department of Geology, Western Washington University, Bellingham.

Paper number 5T0689.
0278-7407/86/005T-0689$10.00

boundary between the Pacific and North American plates. Why, then, is it located entirely within North American continental crust?

3. What will happen to a crustal block (autochthonous, accreted, or otherwise) that finds itself trapped in a zone of oblique subduction?

## OUTLINE OF A TECTONIC MODEL

It is proposed that oblique subduction of the Farallon and/or Kula plates during Late Cretaceous and Paleogene time caused repeated detachment of thin strips or slivers from the leading edge of North America. The lateral dimensions of these slivers probably were of the order of tens of kilometers, up to a maximum of a few hundred kilometers, and their composition was dominantly that of forearc and magmatic arc rocks newly added to the western edge of the continent. Once detached, these slivers were transported northwestward along the continental margin Transport took place at plate tectonic velocities (around 1-10 cm/yr), and thus a detached block could move 1000 km or more in only a few tens of millions of years. Because transport was dominantly parallel to the trend of petrotectonic belts built by subduction along the continental margin, faulting left the margin ostensibly intact.

It is also proposed that detachment of these crustal slivers took place along faults or systems of faults developed to accommodate oblique convergence of the Farallon (or Kula) plate with North America, much as the Semangko fault of Sumatra takes up part of the oblique relative motion between the Indian and Asian plates today. From this it follows that the curious location of the modern Pacific-North America transform inboard from the edge of the North American continent may have been inherited from earlier subduction-related structures. Paleomagnetic evidence and consideration of the mechanics of detachment of crustal slivers suggest that the western margin of North America during Cretaceous and early Tertiary time may have been modified repeatedly by removal of successive slices from the outside in, with the outboard slices moving first and thus also moving furthest. Accreted exotic crustal blocks as well as autochthonous pieces of North American crust were both affected Thus in the western Cordillera, even bona fide North American crustal blocks must be suspected of being seriously allochthonous.

## WHY THE MODEL?

The distribution of rock types in the western United States has convinced many geologists that an active subduction zone occupied most of the western edge of North America for much, if not all, of late Mesozoic and Paleogene time. For example, Hamilton (1969, 1978b), Burchfiel and Davis (1972, 1975), Dickinson (1976), Davis et al. (1978), and Ernst (1970, 1984) have discussed aspects of Cordilleran tectonics in terms of a subduction model, in which the emphasis is placed on the age and present distribution of subduction-related petrotectonic elements. Several of these authors show diagrams depicting continuous or semicontinuous subduction zones lining the western edge of the North American plate for much of the Mesozoic and early Tertiary. None of these authors deny the existence or importance of displaced or exotic terranes, but clearly they see (or recently saw) the growth of western North America as fundamentally an autochthonous or parautochthonous, subduction-dominated process.

On the other hand, a few geologists have emphasized the importance of lateral ("coastwise") transport in shaping the western edge of the continent. For instance, Suppe (1970) invoked an episode of "proto-San Andreas" faulting to account for the doubling of Mesozoic terranes in coastal California. Page (1982), writing about the same region, called for Late Cretaceous or Paleogene northward transport of coastal rocks of the order of several thousands of kilometers. More recently, Cowan (1982) and Johnson (1984) have called for truncation of coastal rocks in the Pacific Northwest by dextral strike-slip faulting. There are still other examples that point to occasional episodes of strike-slip faulting subparallel to the continental margin. However, it is not clear from the geologic evidence alone whether these should be regarded as a major aspect of the tectonics of the last 100 m.y. or as merely a minor aberration.

Paleomagnetic evidence strongly supports a highly mobilistic point of view, in that it shows that western North America is mostly an assemblage of

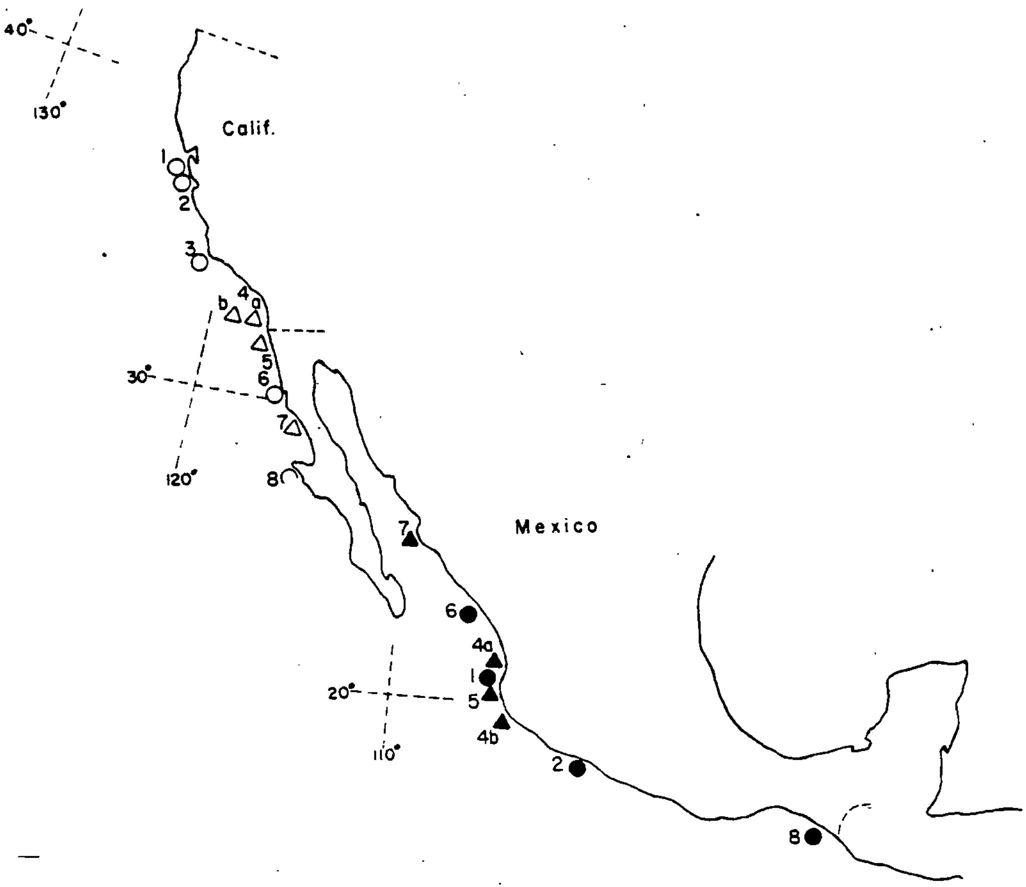

Fig. 1. Present locations (open symbols) and original locations (solid symbols) for Cretaceous and early Tertiary rocks from coastal California and Baja California. These reconstructions are based on the paleomagnetic data summarized in Table 1. Note that 95% confidence limits on paleolatitudes range up to 10° or more; the positions shown are the most probable locations. Circles denote forearc sedimentary rocks; triangles, arc rocks or sedimentary rocks overlying arc rocks. Rocks from study 3 "reconstruct" to a latitude south of the limits of the map.

allochthonous crustal blocks. Evidence on the subject published prior to about 1979 is reviewed by Irving (1979) and Beck (1980). Many papers bearing directly on the tectonics of California and western Mexico have been published since then, including those by McWilliams and Howell (1982), Champion et al. (1984), Beck et al. (1981a), Frei et al. (1984), Patterson (1984), Harbert et al. (1983), Hannah and Verosub (1980), and Kanter and McWilliams (1982). (Excluded from this list are paleomagnetic data for limestone blocks in the Franciscan material, ophiolitic material in Franciscan melange, and anything else that, if far-travelled, can most easily be interpreted to have ridden with an oceanic plate and not North America). Paleomagnetic data for California show the following (my interpretation):

1. Outboard subduction-related sedimentary terranes now located along the coast of central California south of Cape Mendocino formed far south of their present location relative to stable North America. Northward transport took place mainly in the Late Cretaceous and early Tertiary and amounted to several thousand kilometers in some cases.

2. Mesozoic volcanic, sedimentary, and plutonic rocks from Southern California and Baja California also have been translated northward in relation to the North American craton. However, they show less movement than the roughly coeval subduction-related sedimentary rocks now located further north.

TABLE 1. Approximate Latitudinal Displacements of Cretaceous and Early Tertiary Arc-Related Rocks of Coastal California and Mexico.

| Number | Formation | Age | $\Delta\gamma$, deg | Reference |
|---|---|---|---|---|
| 1 | Paleocene rocks at Point San Pedro, California | Paleocene | 19.0 | C |
| 2 | Pigeon Point formation | Late Cretaceous | 25.5 | C |
| 3 | Flysch near Figueroa Mountain, California | Late Cretaceous | 28.0 | M |
| 4a | Southern California batholith | mid-Late Cretaceous | 11.5 | B |
| 4b | San Marcos gabbro | late Early Cretaceous | 14.0 | H |
| 5 | Alistos formation | Early Cretaceous* | 11.5 | H |
| 6 | La Bocana Roja formation | early Late Cretaceous | 7.0 | H |
| 7 | Peninsular Ranges batholith | Late Cretaceous | 3.5*† | H |
| 8 | Valle formation | Late Cretaceous | 13.5 | H, P |

The numbers in the first column are keyed to the symbols in Figure 1. $\Delta\gamma$ is the approximate latitudinal shift indicated by paleomagnetic data taken from the reference cited in the last column. Note that these latitudinal shifts have 95% confidence limits ranging up to 10 or more degrees; the figures cited are the most probable values. References are as follows: C, Champion et al. (1984); M, McWilliams and Howell (1982); B, Beck et al. (1981a); H, Hagstrum et al. (1985); and P, Patterson (1984).

*Thought by Hagstrum et al. (1985) to have been remagnetized by intrusion of the Peninsular Ranges batholith in the Late Cretaceous.

†Recalculated from Hagstrum et al. (1985).

3. Mesozoic rocks of the Sierra Nevada and Great Valley are essentially in situ: northward transport of a few hundred kilometers is permitted by the paleomagnetic data but is not required.

Figure 1 and Table 1 illustrate these relationships for the coastal rocks. Figure 1 also shows that the transported arc-trench rocks in California and Baja California apparently originated at about the latitude of central Mexico. Marine geophysical studies by Karig et al. (1978) suggest that arc rocks and subduction complex rocks have been tectonically stripped from the continental margin along the central American coast; these may be remnants of Kariq's missing rocks (however, see Coney (1982) for an alternative interpretation).

## THE PLATE TECTONIC SITUATION

Figure 2 shows the configuration of plates in the eastern Pacific near the end of Cretaceous time, after Atwater (1970), Coney (1978), and Engebretson et al. (1985). There seems to be substantial agreement between these and other authors on the following points:

1. During the late Cretaceous and early Tertiary, at least two oceanic plates (Kula and Farallon) fronted North America on the west. These two plates were separated by a ridge, which intersected North America to form a triple junction (the Kula-Farallon-North America triple junction, hereafter TJ). The precise location of TJ at any given time is not well constrained, and the positions

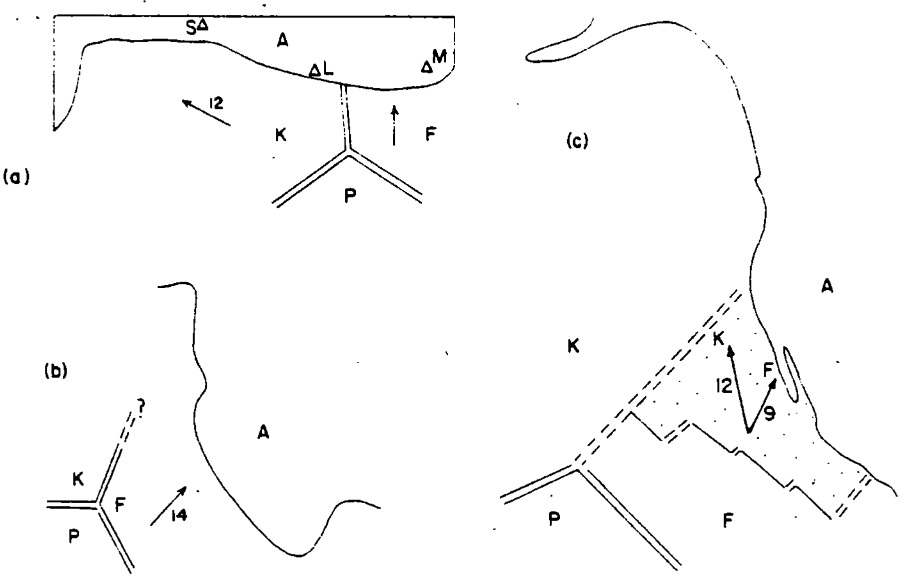

Fig. 2. Late Cretaceous and early Tertiary plate configuration of the eastern Pacific, after (a) Atwater (1970) (b) Coney (1978) and (c) Engebretson, et al., (1985). K,F,P, and A are the Kula, Farallon, Pacific, and North American plates respectively. Arrows show velocities of oceanic plates relative to North America, in cm/yr. In Figure 2a, S,L, and M are Seattle, Los Angeles, and Mazatlan, respectively. The stippled pattern in Figure 2c shows a region that could have been either Kula or Farallon plate.

shown in Figure 2 are largely conjectural.

2. Farallon-North America relative motion during Late Cretaceous and Paleogene time had an important element of convergence at all latitudes; Kula-North America interaction was more nearly oblique, and may have been transform (strike-slip) for part of the period.

3. The Kula-Farallon ridge moved generally northward along the North American coast, so that by mid-Tertiary time the Farallon plate was opposite western Mexico, California, and perhaps much of the Pacific Northwest as well. The manner in which the ridge and TJ migrated, however, is not known. It may have moved steadily or spasmodically, it may have reversed its direction (moved southward) one or more times, and it may have changed its position abruptly (as by ridge jumps).

4. During the middle Tertiary the Pacific-Farallon ridge gradually approached North America. This resulted in progressively younger oceanic plates, being subducted under North America. Eventually, the Farallon-Pacific ridge encountered the trench bordering North America, resulting in formation and growth of the Pacific-North American transform (San Andreas fault system), as was described by Atwater (1970).

As will be shown in the next section, the plate-tectonic situation described above is ideal for the development of strike-slip faults in the leading edge of the North American plate.

## STRIKE-SLIP FAULTS CAUSED BY OBLIQUE SUBDUCTION

Fitch (1972) seems to have been the first to point out a modern example (Sumatra) in which oblique subduction is accompanied by active strike-slip faulting in the overriding plate. In the Sumatran example the Indian plate (west of the Sunda strait) is underthrusting Asia at a convergence angle of about 45° (Figure 3). Apparently as a consequence, a crustal sliver comprising the leading edge of the Asian plate is moving relatively northwestward along the plate margin. The strike-slip fault that "decouples" the sliver from the Asian plate runs through the modern Sumatran magmatic arc (Hamilton, 1978a). In what follows, oblique convergence that results in a strike-slip fault/subduction zone pair

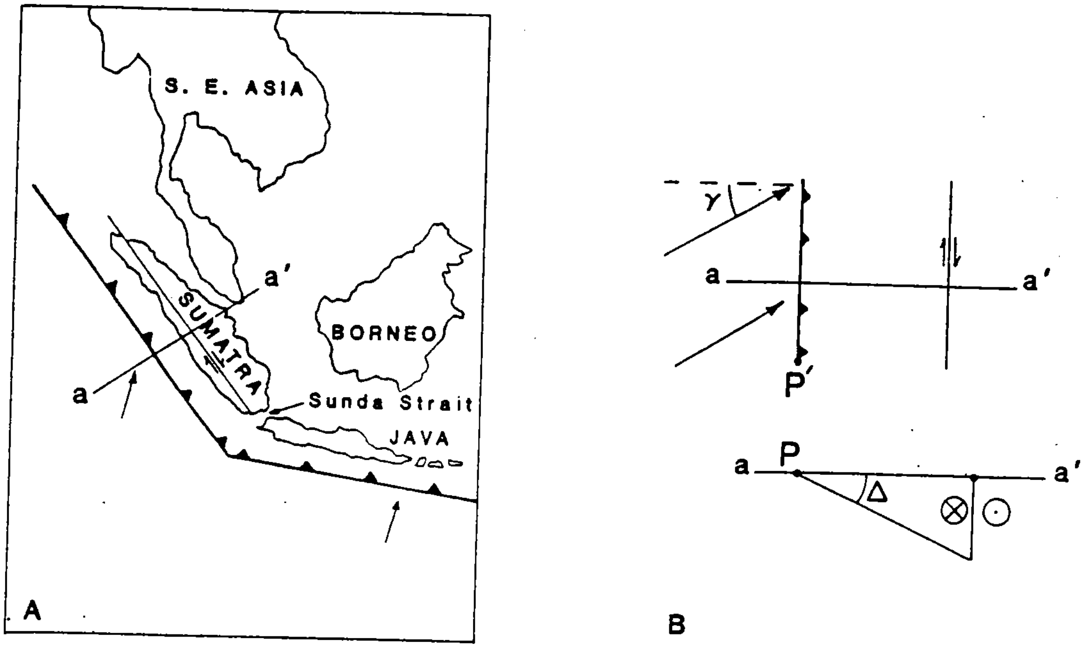

Fig. 3. (a) Simplified map and (b) schematic diagrams illustrating Sunda-style tectonics (modified from Fitch (1972) and Beck (1983)). The upper diagram in Figure 3b is a map view; the lower diagram is a cross section. Circled dots and crosses indicate motion out of and into the plane of the diagram, respectively.

will be referred to as "Sunda-style" tectonics.

Beck (1983) examined the dynamics of oblique convergence and (on minimum energy considerations) concluded that Sunda-style tectonics is favored over oblique subduction by the following conditions (Figure 3): (1) highly oblique convergence (large $\gamma$), (2) shallow dip of the subduction slab (small $\Delta$), and (3) relatively easy slip on the decoupling strike-slip fault.

The relationship (see the appendix) between these variables that assures that Sunda-style tectonics will be favored over oblique subduction is

$$\tan(\gamma/2) > \frac{r_f}{r_s} \tan\Delta \qquad (1)$$

in which $\gamma$ and $\Delta$ are as defined in Figure 3, and the expression $r_f/r_s$ is the ratio of resistance to slip on a vertical fault cutting the overriding plate ($r_f$) to resistance to slip on the subduction zone ($r_s$). This expression replaces inequality 3 of Beck (1983), which is incorrect. From (1), if the stresses required for slip on fault and subduction zone are roughly equal, shallow subduction (say, $\Delta = 20^{\circ}$) should favor Sunda-style tectonics wherever the angle of obliquity exceeds about $40^{\circ}$. It remains to examine controls on the variables in (1).

The angle of obliquity ($\gamma$) obviously depends on the relative velocity vector of the two converging plates and the trend of their common boundary. Both of these can vary significantly over distances of the order of a few hundred kilometers, and thus $\gamma$ also can be expected to vary significantly along most long plate margins. Several authors have shown that an important driving force for plate movements is the so-called "trench pull," which is the sum of several processes acting at subduction zones that tend to cause the subducting plate to move toward the trench. Thus because oblique subduction is energetically inefficient, trench pull probably tends to reduce the integrated value of $\gamma$ over any long plate margin. However, other significant forces also contribute to plate motion. Also, rarely if ever can $\gamma$ be zero everywhere along a long convergent margin with the normal amount of irregularity. Maps of present plate velocities (e.g., Addicott and Richards, 1981) show that although near-normal convergence is very common, values of $\gamma$ of $45^{o}$ or more are not particularly rare. This must have been the case during the past as well. For the Cordilleran example, Engebretson et al. (1985) show variable (often high) angles of obliquity for Farallon-North America and Kula-North America interaction during the late Cretaceous and early Tertiary.

Factors that control $\Delta$ (the dip of the subducting slab) are more complicated. Controls on $\Delta$ have been the subject of several recent studies; Cross and Pilger (1982) provide a summary. Although the subject is far from simple, it seems likely that the following would promote shallow angles of subduction: (1) high rates of convergence between the subducting plate and the overriding plate, (2) rapid absolute motion of the overriding plate toward the trench. (3) subduction of young (and therefore hot and buoyant) lithosphere.

Cross and Pilger (1982) also suggest other factors that may be important. For instance, simple duration of subduction may play a role; because of the growth of the accretionary prism and other factors, old subduction zones seem to be accompanied by slabs with unusually shallow initial dips. Arrival of a buoyant "passenger" (for instance, an island arc, seamount chain, or other piece of thickened crust) at the subduction zone also seems to be a powerful factor tending to promote temporary shallowing of the dip of the slab (e.g., Isacks and Barazangi, 1977; Henderson et al., 1984).

Conditions were conducive to shallow subduction beneath western North America during much of the late Cretaceous and early Tertiary. Diagrams in the work of Engebretson et al. (1985) show North America moving westward (toward the trench) in an absolute framework during that time interval. The same authors also show that for most of the same period, the plate subducting beneath North America was young. Henderson et al. (1984) cite evidence suggesting that a buoyant aseismic ridge on the Farallon plate was subducted beneath North America from about 70 to 40 m.y. ago. Finally, the existence of plutons of Jurassic and Early Cretaceous age along the western edge of North America argues that the Cordilleran subduction zone already was old by Late Cretaceous time. Thus the subduction angle $\Delta$ should have been small for western North America, if the analysis of Cross and Pilger (1982) and the plate model of Engebretson et al. (1985) are correct. This conclusion is supported by Coney and Reynolds (1977), who deduced that a dramatic shallowing of the subduction angle occurred during the period 100 to 40 m.y. ago, from an analysis of the distribution of subduction-related volcanic rocks.

Note that it is the near-surface subduction angle that is important here; the angle at which the subducting slab finally plunges into the asthenosphere is of little significance. This is because in the calculation of work involved in unit slip, it was assumed that the overriding and subducting lithosphere slabs are everywhere in contact. Once contact is broken the downgoing plate can descend at any angle whatever. Thus the seismically determined subduction angle may not be the correct value of $\Delta$ to substitute into (1); it must often be too large.

The final factor that (according to (1)) should help determine whether oblique subduction or Sunda-type tectonics results from oblique convergence is $r_f/r_s$, the ratio of resistance to slip on a potential strike-slip fault cutting the arc-trench complex ($r_f$) to resistance to slip on the subduction zone ($r_s$). Beck (1983) discussed some factors that may help to determine $r_f$ and $r_s$. Resistance to slip on a fault or potential fault (including the plate-bounding "fault" of the subduction zone itself) must be a function of the physical properties of the rocks being deformed and the tectonic setting. For a fault or displacement zone that penetrates the entire lithosphere it seems likely that r has elements of both viscous and frictional resistance to slip. Thus a complete analysis of r should take into account such rock properties as the coefficients of friction and pseudo-viscosity and their variation with depth, cohesion (resistance to initial faulting), and the abundance of pore fluids and the resulting fluid pressure. Tectonic factors that might affect r include convergence velocity and any stress that may be transmitted across the subduction zone because of convergence. No doubt other factors also play a role, but with luck they will be minor. A complete discussion would require a long paper and one that I am not qualified to write. A few nonquantitative speculations follow:

1. Upon initiation of subduction beneath a continent, resistance to slip on

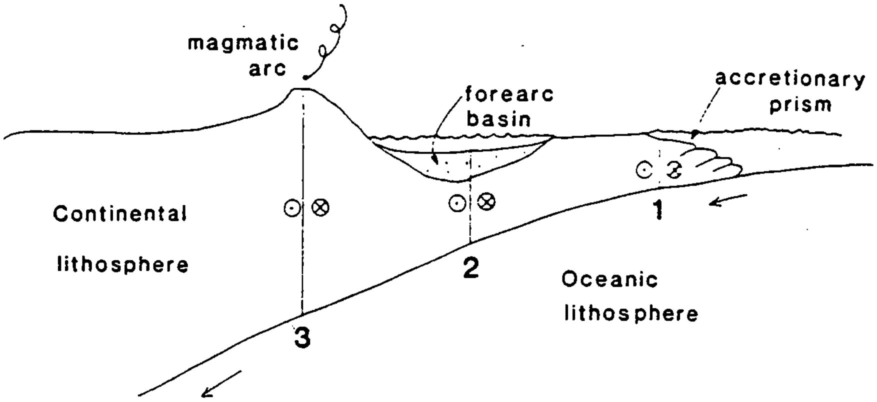

Fig. 4. A continental arc being dismembered by Sunda-style tectonics. Symbols are those in Figure 3. Faults 1 and 2 may move before fault 3. When fault 3 becomes active, faults 1 and 2 may cease movement.

potential strike-slip faults cutting the overriding lithosphere ($r_f$) presumably is quite high. This follows from the supposition that old, cold lithosphere has high cohesion. However, as magmatic fluids permeate upward, the overriding plate should warm up and soften, and $r_f$ should fall. For this reason, slip on Sunda-style faults cutting the magmatic arc is most likely some few tens of millions of years after subduction begins.

2. Resistance to strike-slip faulting is likely to be lower in the leading edge of the accretionary prism than elsewhere. This speculation is based on the premise that newly accreted sedimentary material ought to be full of water and that dewatering by subsequent compression and tectonic heating will reduce resistance to slip. Thus unless and until a "master fault" through the magmatic arc detaches the entire forearc region, strips of sedimentary material from the outer edge of the overriding plate are the best candidates for tectonic coastwise transport (Figure 4). The tendency for $\Delta$ to remain shallow after the subducting plate is initially overridden enhances this effect.

3. There seems to be no compelling reason why several parallel subduction-related strike slip faults cannot be active simultaneously. Given the thermal softening that is implied in some models for back arc spreading, there also seems to be no compelling reasons why Sunda-style faults could not detach and translate the entire magmatic arc.

4. If speculations 2 and 3 above are correct, then the more "outboard" the material in a growing continental arc and forearc, the further it will move. Because under suitable conditions of oblique subduction, material may be added to strips of lithosphere that already are detached and moving, age obviously is another factor: the older the rock, the further it is likely to have traveled.

To summarize the foregoing discussion in geological terms, given an angle of obliquity ($\gamma$) of more than a few tens of degrees (probably a common situation), Sunda-style tectonic displacement will be energetically favored if the angle of subduction ($\Delta$) is small and if resistance to slip on faults or potential faults cutting the overriding lithosphere is comparable to resistance to slip on the "fault" representing the subduction zone itself. Small values of $\Delta$ probably accompany relatively rapid subduction of young lithosphere; aging of the subduction zone and absolute motion of the overriding plate toward the trench also may help. Ease of slip on faults cutting the overriding plate probably depends mainly on the physical properties of the rocks involved. Slip should be easiest on faults within the accretionary prism during the early stages of oblique subduction, but if the overriding plate becomes thermally softened by magmatism, a decoupling fault may develop within or behind the magmatic arc. The plate reconstructions cited in the last section suggest that conditions for Sunda-style faulting were satisfied along stretches of the western North American coast during much of Late Cretaceous and early Tertiary time. Intuition argues that they must be

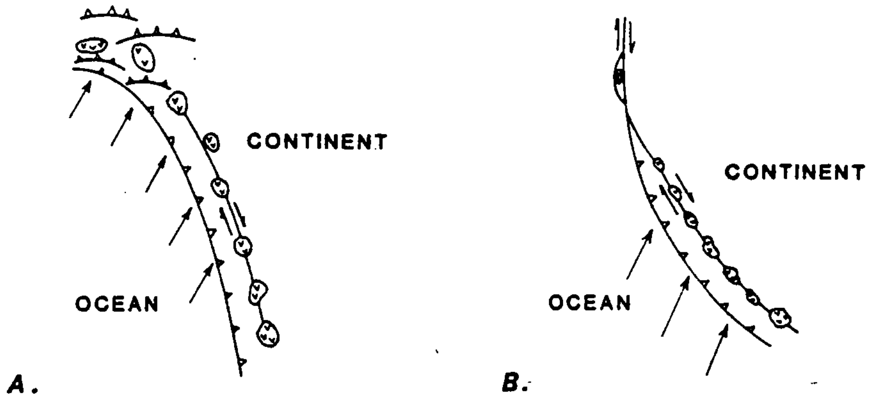

Fig. 5. The buttress effect. (a) A sliver of overriding lithosphere has been detached by Sunda-style tectonics, but a buttress of undetached continental lithosphere prevents large amounts of displacement. (b) The buttress effect is absent, and large displacements are possible. The checked pattern signifies igneous rocks of the magmatic arc. Open teeth indicate the subduction zone (note that subduction is strongly oblique); teeth shown within continent are thrust faults and other compressive structures in the continental lithosphere.

satisfied rather commonly. What prevents Sunda-style faults from disrupting most convergent margins? The answer probably lies in the buttress effect, discussed in the next section. Strike-slip faulting can displace a sliver of lithosphere parallel to the plate margin only if the sliver has somewhere to go.

## THE BUTTRESS EFFECT AND TECTONIC TRANSPORT

Figure 5 illustrates a two-plate model, showing two very similar cases of oblique subduction beneath a continent. In Figure 5a, suggested by a possible scenario for pre-Miocene South America, a sliver of lithosphere has been detached from the continent by oblique subduction, in the case shown by development of a strike-slip fault aligned with the magmatic arc. However, large-scale tectonic transport is prevented by a buttress of continental rock, and the sliver has nowhere to go. In such a situation, displacements of more than a few hundred kilometers would require severe crumpling of the buttress and/or sliver, and displacements of thousands of kilometers would seem to be impossible. Figure 5b, on the other hand, suggests a mechanism for translating pieces of crust through large distances along the continental margin. This is one possible scenario for the southwestern United States and western Mexico during the Late Cretaceous and early Tertiary.

If the Kula-Farallon ridge intersected North America as far south as southern Mexico during the Late Cretaceous (one possible interpretation of the anomaly record (Engebretson et al., 1985), then several three-plate models which fit the paleomagnetic data very well also become possible. Some of these have been discussed by Beck et al. (1981a). Figure 6a illustrates the plate configuration. The assumptions underlying these models are the following:

1) Although the Kula and Farallon both converged with North America in a north-oblique sense during most of the period in question (say, 90 to 40 m.y. B.P.), Farallon relative motion tended to be more nearly normal, whereas for much of the period Kula relative motion was so highly oblique as to be essentially transform. Thus Farallon-North America interaction was an excellent instrument for creating subduction-related continental margin rocks, whereas Kula-North America interaction was better suited for transporting them.

2. Conditions opposite the Farallon plate during this period often were such that slivers of North America were effectively detached by incipient Sunda-style faults. However, much of the time, these slivers were prevented from moving by the presence of a buttress, consisting of an undetached segment of coastal North

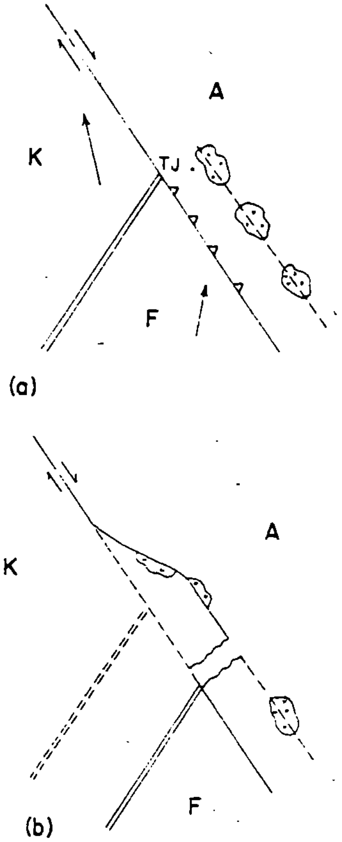

Fig. 6. Plate configuration for southwestern North America during Late Cretaceous-early Tertiary time, and one scenario for Sunda-style NW transport of slivers of coastal North America. (a) Plate configuration, with transport prevented by presence of a buttress of undetached crust opposite the Kula plate. K, F, and A are as in Figure 2. TJ is the Kula-Farallon-North America triple junction. Arrows show motion of oceanic plates relative to North America and are schematic only; F-A relative motion is right-oblique, but with sufficient normal component to build arc-forearc rocks on the leading edge of North America. K-A relative motion is so strongly oblique as to be essentially transform. The checked pattern indicates the magmatic arc built by Farallon subduction; the dashed line shows a potential Sunda-style fault upon which movement would be possible if the buttress were removed. (b) Removal of the buttress by southeastward displacement of TJ. Here retrograde (southward) movement of TJ has placed a piece of previously detached sliver opposite the Kula plate. Cross faults shown for detachment of the moving sliver are completely schematic. The change of position of the K-F ridge depicted here is by means of a ridge-jump; spreading merely died out at the position shown by dashed lines and commenced in a new location.

America north of TJ, opposite the Kula plate (Figure 6a).

3. Throughout the period there was a general tendency for TJ to move northwestward along the North American continental margin. However, at times TJ moved in the opposite direction (to the southeast), either discretely (as by a ridge jump or subduction of a transform fault; Figures 6b and 7a) or by steady retrograde motion caused by slight changes in relative plate velocities (Figure 7b). At such times, pieces of coastal North America that had been effectively detached from the continent by oblique subduction of the Farallon plate became attached to the Kula plate, with resulting rapid transport northward (Figure 6b). Cross faults needed to transfer these pieces from the North American to the Kula plate were not difficult to produce, because the detached sliver was narrow, thin, and subject to large tractions from the motion of neighboring large plates.

The reason that three-plate models are preferable to the two-plate model illustrated in Figure 5b is simply that the paleomagnetic evidence shows rather convincingly that Mesozoic batholiths now located along the western edge of North America from Mexico to northern British Columbia all formed south of about (present) latitude 40° N. This includes several plutons in British Columbia (Irving et al., 1985), and the Mount Stuart batholith in northwestern Washington (Beck et al., 1981b). Subduction-related sedimentary rocks apparently obey the same rule. To my knowledge, no exceptions have been found; that is, no subduction-related late Mesozoic or early Tertiary (pre-Eocene) rock unit on the western edge of the continent has been shown to have originated north of about the present-day California-Oregon border. It is easiest to account for this apparent southern provenance of arc and forearc rocks with a three-plate model, by attributing their creation to the Farallon plate, and their transport to the Kula plate. However, simple curvature of the continental margin

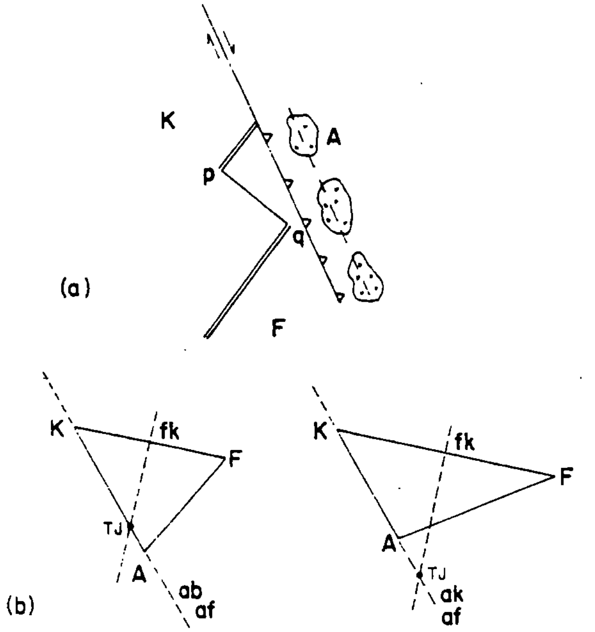

Fig. 7. Two more ways to move the K-F ridge. (a) Subduction of a transform fault. Symbols are those used in previous illustrations. As North America rides westward over the oceanic plates, transform fault pq will be gradually consumed, in effect jumping TJ southeastward down the continental margin. (b) Velocity triangles illustrating conditions for steady retrograde (SE) movement of TJ, after McKenzie and Morgan (1969). Sides of velocity triangles give relative velocities of indicated plates. Dashed lines labeled with lowercase letters give a frame of reference in which each two-plate margin does not change. For a stable triple junction to exist, dashed lines must intersect at a point TJ. The location of TJ gives the velocity of the triple junction relative to each plate. In the left-hand diagram, TJ migrates NW along the North American plate margin; this is assumed to have been the usual situation in the Late Cretaceous and early Tertiary. The right-hand diagram shows a situation in which TJ moves SE relative to North America. Note that fairly trivial changes in relative velocity are sufficient to change one case into the other.

might accomplish the same thing using only two plates. For instance, given the arrangement of continental margin and the direction of relative plate motions shown in Figure 5b, one might expect creation of arc and forearc rocks to occur mainly in the south, because subduction is most nearly normal there.

This discussion of processes and scenarios for Sunda-style coastwise transport of crustal blocks has been placed in the context of the North American Cordillera, but it is obvious that much of it may apply to other convergent continental margins as well.

## ORIGIN OF THE SAN ANDREAS FAULT

It is commonly accepted that the San Andreas fault is a transform boundary between the North American and Pacific plates. There also seems to be general agreement that the San Andreas fault grew out of a collision of the Pacific-Farallon ridge with the Farallon-North America trench some time in the middle Tertiary. The plate geometry, after Atwater (1970) and McKenzie and Morgan (1969), is shown in Figure 8; Figure 8a shows the situation just before the Pacific plate came into contact with North America, and Figure 8b shows it some few millions of years later. In Figure 8b the San Andreas transform system is growing as triple junctions M and R migrate in opposite directions along the continental margin.

One puzzle left unresolved by this picture is why the San Andreas fault cuts North American crust. At the time of impact of the Pacific plate with North America the two plates were separated by an active subduction zone. This subduction zone should have constituted an

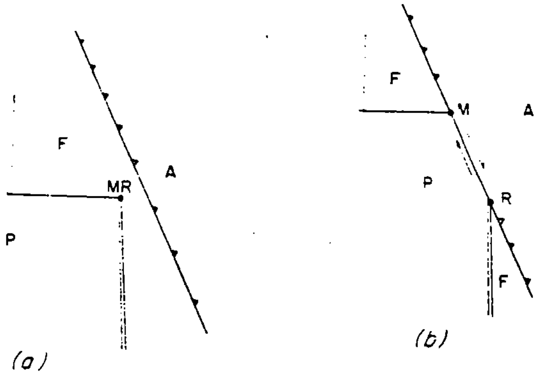

Fig. 8. Probable plate configuration along western North America immediately (a) before and (b) after collision of the Pacific plate with North America. M and R are Medocino and Rivera triple junctions.

excellent "zone of weakness," and thus ought to have provided an ideal location for the new transform. Why then did it choose to cut inland through thick continental lithosphere?

Atwater (1970) first considered this problem. She noted an apparent lag in time between collision of ridge and trench (creating the San Andreas transform) and commencement of faulting inland (for instance, the beginning of opening of the Gulf of California). During this period, she felt, motion between the Pacific and North American plates was taken up on a fault along the continental margin (the "zone of weakness" of the previous paragraph). In her model, faulting on the San Andreas proper was delayed until the Pacific lithosphere had cooled, thickened, strengthened, and somehow welded itself tightly to the edge of North America. However, it is difficult to see how an actively deforming Pacific-North America "join" could ever have become stronger than unfractured North American lithosphere. Presumably, the edge of North America was already weak.

Garfunkel (1973) also was puzzled by the location of the San Andreas inland from the continental margin and assumed (I believe correctly) that it was localized by a precollision fracture zone. He cited geological evidence showing that movement on the San Andreas fault in central California began well before collision of the Pacific plate with North America. In Garfunkel's model, as in Atwater's, a growing transform fault along the continental margin is the initial product of elimination of the Farallon plate. However, Garfunkel saw attachment of the sliver of North America to the Pacific plate as a gradual process: as the offshore fault grew by migration of the Mendocino and Rivera triple junctions, slip was gradually transferred from the offshore fault inland until eventually the offshore fault became completely inactive. Thus any slip required by the plate motions but not found along the San Andreas transform can be attributed to slip on the now inactive continent-bordering fault. By Garfunkel's estimate the amount of such slip should be large. Finally, to account for the existence of a precollision San Andreas fault, Garfunkel drew an analogy with modern Sumatra.

Dickinson and Snyder (1979) offered a different explanation for the location of the San Andreas fault. In their paper they presented explanations for many features of California coastal geology in terms of tectonic effects caused by migration of the triple junctions at either end of the San Andreas transform. As was first shown by McKenzie and Morgan (1969), triple junctions M and R (Figure 8) would have been stable only if the continental margin was straight. (In terms of the geometry of features on the surface of a sphere, "straight" can be translated as "forming part of a small circle about a single pole ). Slight departures from straightness are found along any continental margin, and no doubt the Tertiary California coast had them also. Dickinson and Snyder (1979) analyzed the tectonic consequences of the passage of triple junctions past minor irregularities in the California coastline. According to their diagrams, one result of migration of a triple junction past a convex irregularity might be to cause the transform fault to step inland; in effect, to deal with the irregularity by slicing it off. Dickinson and Snyder suggested that the current inboard location of the San Andreas may be a response to triple-junction instability on a grand scale: the San Andreas currently is straightening the California coastline by removing a very large bulge.

Dickinson and Snyder (1979) also noted the "curious and important coincidence," previously pointed out by McKenzie and Morgan, that the slip vector between the Pacific and North America plates at the time of impact lay along the Farallon-North America trench. In fact, this phenomenon may not have been a coincidence, but it was certainly important: stability of the Mendocino and Rivera triple junctions, and thus to a considerable extent the history of the San Andreas fault, depended on colinearity of the transform fault (the direction of relative motion between the Pacific and North American plates) and the trench (the precollision continental margin).

My model for the origin of the San Andreas fault is very similar to Garfunkel's (1973). Immediately prior to its impact with the Pacific plate, the western edge of North America probably was already sliced through by a network of strike-slip faults or potential strike-slip faults that had formed because of oblique subduction of the Farallon plate. Similar faults probably had existed since at least the Late Cretaceous and had been active intermittently, whenever conditions permitted slip to occur. Thus the coastline of North America already was detached and ready for strike-slip displacement when it first came into contact with the Pacific plate. In such a case, transfer inboard of slip between the Pacific and North America should have presented no particular problem.

This still leaves unexplained the surprising agreement between the direction of Pacific-North America relative motion before the two plates came into contact (the direction of the future transform) and the precollision trend of the continental margin. However, perhaps this agreement was only partly coincidence and partly a natural consequence of collision-induced changes in the forces controlling plate motions. Because absolute plate velocities are very small, even huge plates (for instance, the Pacific) have very little momentum. This means that, theoretically, plate motions can respond quickly to changes in driving forces. If it is assumed that there were existing strike-slip faults roughly parallel to the North American continental margin immediately prior to collision, then perhaps forces exerted by the two plates on one another readjusted their relative velocity to take advantage of those faults. For this mechanism to be valid, a slight change in Pacific-North American relative velocity must have occurred. Calculations (for the latitude of Los Angeles) using the stage poles of Engebretson (1983) indicate that Pacific-North American relative motion changed direction from N30°W to N54°W, roughly during the interval 40 to 25 m.y. ago. This is in the right sense to convert transpression (intuitively a high-energy form of plate interaction) into transform motion parallel to the continental margin. Unfortunately, I can find no convincing evidence for an episode of transpression at this time in the California geological literature. However, mid-Tertiary California geology is complicated enough to accommodate a great many tectonic models, possibly including the one suggested here.

## SUMMARY AND CONCLUSIONS

1) Oblique subduction can cause the detachment and removal of slices of the leading edge of an overriding plate. Detachment is along strike-slip faults within the forearc or arc that roughly parallels the continental margin. Tectonic transport requires that the buttress problem be overcome, in effect, that the slices have somewhere to go.

2) Under conditions that may be common in zones of oblique subduction, strike-slip faulting will develop first in the forearc region and later possibly migrate into the arc. Forearc rocks thus travel farther than arc rocks. Transport is subparallel to the trend of subduction-related lithic belts, and therefore even very substantial faulting may leave the continental margin looking superficially intact.

3) Conditions along the western edge of North America during Late Cretaceous and early Tertiary time were conducive to northward transport of slices of North American arc and forearc. Paleomagnetic evidence from California, Baja California, and elsewhere argues that such transport did occur.

4) The San Andreas fault may have been localized by preexisting fractures produced by oblique subduction of the Farallon plate. North American and Pacific motions may have adjusted slightly at contact to accommodate transform interaction between the two plates.

5) The model developed here is general enough so that it should be applicable to other convergent orogens.

## APPENDIX: DERIVATION OF INEQUALITY (1)

Figure 9 shows a block diagram and several sections of a simplified subduction zone. Convergence is in the direction shown (Figure 9b), in a direction making an angle $\gamma$ with the normal to the overriding plate. Assume that the subducting and overriding plates are in contact everywhere along the inclined face labeled "slant section" in Figure 9c. The energy required, per unit length of trench, to accomplish one unit of convergence by oblique subduction is then

$$S'(\cos \gamma')\, r_s$$

where $S'(\cos \gamma')$ is the area of a diagonal strip of length $S'$ running from P to D (Figure 9c), and $r_s$ is resistance to slip on the subduction zone ($r$ has the dimensions of stress). However, $S'(\cos\gamma') = S$. Alternatively, convergence could

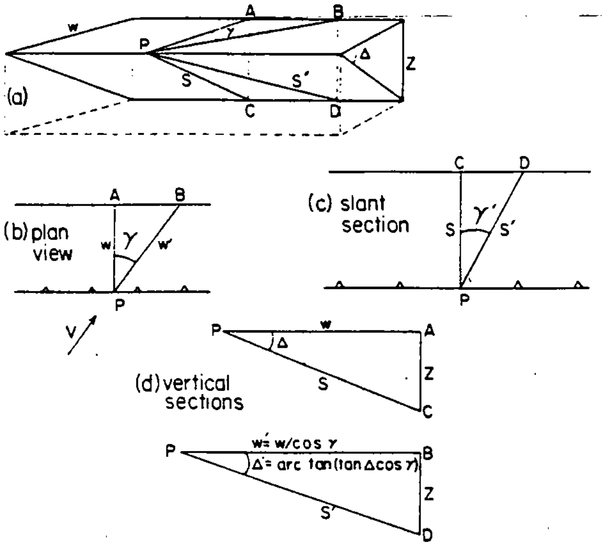

Fig. 9. Simplified block diagram of a subduction zone, illustrating alternative modes of oblique convergence. Convergence can be accommodated by oblique subduction along path S' or by normal subduction along path S combined with slip on fault plane ABCD to take up the margin-parallel component. Convergence is at velocity V, making an angle $\gamma$ with the normal to the trench. The angle $\Delta$ is the angle of subduction, measured in a plane normal to the trench. W is the width of the potential "sliver." See the Appendix.

take the place by slip of $\cos\gamma'$ along line segment S, accompanied by movement (opposed by resistance $r_f$) of the entire block (of height Z) by a distance $\sin\gamma'$. The energy required to accomplish unit convergence by this (Sunda-style) tectonic arrangement is $S(\cos\gamma')r_s + Z(\sin\gamma')r_f$. Thus if Sunda-style tectonics is to require less energy than oblique subduction,

$$Sr_s > S(\cos\gamma')\,r_s + Z(\sin\gamma')r_f$$

Making use of the trigonometric relationships shown in Figure 9 and noting that

$$\tan\ \gamma' = \cos\Delta\ \tan\gamma$$

inequality (1) can be obtained.

Acknowledgments. D. Champion, D. Engebretson, and R. Speed ruthlessly criticized an early version of this manuscript, which did it a lot of good. They would ~~not agree with~~ everything in this version either, however. C. Allen, B. Luyendyk, and B. Page suggested further improvements. M. McWilliams provided a uniquely perceptive review. Special thanks are due to K. Pine and D. Engebretson, each of whom found an error in my mathematics. I also thank Northwestern University and its geology department for stimulating discussions and a place to house my word processor while this paper was being prepared.

## REFERENCES

Addicott, W. O., and P. W. Richards, Plate tectonic map of the circumpacific region, Am. Assoc. Pet. Geol., Tulsa, Okla., 1981.

Atwater, T., Implications of plate-tectonics for the Cenozoic tectonic evolution of western North America, Geol. Soc. Am. Bull., 81, 3513-3536, 1970.

Beck, M. E., Jr., Paleomagnetic record of plate-margin tectonic processes along the western edge of North America, J. Geophys. Res., 85, 7115-7131, 1980.

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

Beck, M. E., Jr., R. F. Burmester, D. C. Engebretson, and R. Schoonover, Northward translation of Mesozoic batholiths, western North America: Paleomagnetic evidence and tectonic significance, Geofis. Int., 20, 143-162, 1981a.

Beck, M. E., Jr., R. F. Burmester, and R. Schoonover, Paleomagnetism and tectonics of the Cretaceous Mt. Stuart batholith of Washington: translation or tilt?, Earth Planet. Sci. Lett., 56, 336-342, 1981b.

Burchfiel, B. C., and G. A. Davis, Structural framework and evolution of the southern part of the Cordilleran orogen, western United States, Am. J. Sci., 272, 97-118, 1972.

Burchfiel, B. C., and G. A. Davis, Nature and controls of Cordilleran orogenesis, western United States: Extensions of an earlier synthesis, Am. J. Sci., 275-A, 363-396, 1975.

Champion, D. E., D. G. Howell, and C. S. Gromme, Paleomagnetic and geologic data indicating 2500 km of northward displacement for the Salinian and related terranes, California, J.

Geophys. Res., 89, 7736-7752, 1984.

Coney, P. J., Mesozoic-Cenozoic Cordilleran plate tectonics, Mem. Geol. Soc. Am. 152, 33-50, 1978.

Coney, P.J., Plate tectonic constraints on the biogeography of Middle America and the Caribbean region, Ann. Mo. Bot. Gard., 69, 432-443, 1982.

Coney, P. J., and S. J. Reynolds, Cordilleran Benioff zones, Nature, 270, 403-406, 1977.

Cowan, D. S., Geological evidence for post-40 m.y. B. P. large-scale northwestward displacement of part of southeastern Alaska, Geology, 10, 309-313, 1982.

Cross, T. A., and R. H. Pilger, Jr., Controls of subduction geometry, locations of magmatic arc and back-arc region, Geol. Soc. Am. Bull., 93, 545-562, 1982.

Davis, G. A., J. W. H. Monger, and B. C. Burchfiel, Mesozoic construction of the Cordilleran "collage," central British Columbia to central California, in Mesozoic Paleogeography of the Western United States, edited by D. Howell and K. McDougall, pp. 1-32, Society of Economic Paleontologists and Mineralogists, Pacific Section, Los Angeles, Calif., 1978.

Dickinson, W. R., Sedimentary basins developed during evolution of Mesozoic-Cenozoic arc-trench system in western North America, Can. J. Earth Sci., 13, 1268-1287, 1976.

Dickinson, W. R., and W. S. Snyder, Geometry of triple junctions related to San Andreas transform, J. Geophys. Res., 84, 561-572, 1979.

Engebretson, D. C., Relative motions between oceanic and continental plates in the Pacific basin, Ph. D. thesis, 211 pp., Stanford Univ., Stanford, Calif., 1983.

Engebretson, D. C., R. G. Gordon, and A. Cox, Relative motions between oceanic and continental plates in the Pacific basin, Spec. Pap. Geol. Soc. Am.,1985.

Ernst, W. G., Tectonic contact between the Franciscan melange and the Great Valley sequence: Crustal expression of a Late Mesozoic Benioff zone, J. Geophys. Res., 75, 886-901, 1970.

Ernst, W. G., Californian blueschists, subduction, and the significance of tectonostratigraphic terranes, Geology, 12, 436-440, 1984.

Fitch, T. J., Plate convergence, transcurrent faults, and internal deformation adjacent to Southeast Asia and the western Pacific, J. Geophys. Res., 77, 4432-4461, 1972.

Frei, L. S., J. R. Magill, and A. Cox, Paleomagnetic results from the central Sierra Nevada: Constraints on reconstructions of the western United States, Tectonics, 3, 157-177, 1984.

Garfunkel, Z., History of the San Andreas fault as a plate boundary, Geol. Soc. Am. Bull., 84, 2034-2042, 1973.

Hagstrum, J. T., M. McWilliams, D. G. Howell, and C. S. Gromme', Mesozoic paleomagnetism and northward translation of the Baja California peninsula, Geol. Soc. Am. Bull., 96, 1077-1090, 1985.

Hamilton, W., Mesozoic California and the underflow of the Pacific mantle, Geol. Soc. Am. Bull., 80, 2409-2430, 1969.

Hamilton, W., Tectonic map of the Indonesian region, Map I-8775-D, U.S. Geol. Surv., Reston, Va.. 1978a.

Hamilton, W., Mesozoic tectonics of the western United States, in Mesozoic Paleogeography of the Western United States, edited by D. Howell and K. McDougall, pp. 33-70, Society of Economic Paleontologists and Mineralogists, Pacific Section, Los Angeles, Calif., 1978b.

Hannah, J. L., and K. L. Verosub, Tectonic implications of remagnetized Upper Paleozoic strata of the northern Sierra Nevada, Geology, 8, 520-524, 1980.

Harbert, W. P., R. J. McLaughlin, and W. V. Sliter, Paleomagnetism of the Parkhurst limestone, Coastal Belt Franciscan, northern California (abstract), ES Trans. AGU, 64, 868, 1983.

Henderson, L. J., R. G. Gordon, and D. C. Engebretson, Mesozoic aseismic ridges on the Farallon plate, and southward migration of shallow subduction during the Laramide orogeny, Tectonics, 3, 121-132, 1984.

Irving, E., Paleopoles and paleolatitudes of North America and speculations about displaced terranes, Can. J. Earth Sci., 16, 669-694, 1979.

Irving, E., G. Woodsworth, P. Wynne, and A. Morrison, Paleomagnetic evidence for displacement from the south of the Coast Plutonic Complex, British Columbia, Can. J. Earth Sci., 22, 584-598, 1985.

Isacks, B. L., and M. Barazangi, Geometry of Benioff zones: Lateral segmentation and downward bending of the subducted lithosphere, in Island Arcs, Deep Sea Trenches, and Back-Arc Basins, Maurice Ewing Ser., vol. 1., edited by M.

Talwani and W. C. Pitman, pp. 99-114, A.G.U., Washington, D. C., 1977.

Johnson, S. Y., Evidence for a margin-truncating transcurrent fault (prelate Eocene) in western Washington, *Geology*, *11*, 538-541, 1984.

Kanter, L. R., and M. O. McWilliams, Rotation of the southernmost Sierra Nevada, California, *J. Geophys. Res.*, *87*, 3819-3830, 1982.

Karig, D. E., R. F. Cardwell, G. F. Moore, and D. G. Moore, Late Cenozoic subduction and continental margin truncation along the northern Middle America trench, *Geol. Soc. Am. Bull.*, *89*, 265-276, 1978.

Magill, J. R., A. Cox, and R. Duncan, Tillamook volcanic series: Further evidence for tectonic rotation of the Oregon Coast Range, *J. Geophys. Res.*, *86*, 2953-2970, 1981.

McKenzie, D. P., and W. J. Morgan, The evolution of triple junctions, *Nature*, *224*, 125-133, 1969.

McWilliams, M. O., and D. G. Howell, Exotic terranes of western California, *Nature*, *297*, 215-217, 1982.

Page, B. M., Migration of Salinian composite block, California, and disappearance of fragments, *Am. J. Sci.*, *282*, 1694-1734, 1982.

Patterson, D. L., Paleomagnetism of the Valle formation of the Late Cretaceous paleogeography of the Vizcaino basin, Baja California, in *Geology of the Baja California Peninsula*, edited by V. A. Frizzell, Jr., pp. 173-182, Society of Economic Paleontologists and Mineralogists, Pacific Section, Los Angeles, Calif., 1984.

Suppe, J., Offset of Late Mesozoic basement terrains by the San Andreas fault system, *Geol. Soc. Am. Bull.*, *81*, 3253-3258, 1970.

---

M. E. Beck, Jr., Department of Geology, Western Washington University, Bellingham, WA 98225.

(Received April 23, 1985;
revised August 21, 1985;
accepted August 21, 1985.)