DAVID BLOOM

TECTONICS, VOL. 3, NO. 2, PAGES 133-155, APRIL 1984

CORRELATION BETWEEN THE GEOLOGIC RECORD AND COMPUTED PLATE MOTIONS FOR CENTRAL CALIFORNIA

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Abstract. We have attempted to correlate geologic events in part of central California with computed motions of oceanic plates relative to cratonic North America. Three composite terranes are considered: (1) the Sierra Nevada, (2) the Coast Ranges northeast of the San Andreas fault, and (3) the Salinian block. In the Sierra Nevada, Jurassic plutonism (ending about 147 m.y. B.P.) and Cretaceous plutonism (120-80 m.y. B.P.) correlate with deduced Farallon-North America (FA:NA) convergence, as does the Nevadan orogeny (158-153 m.y. B.P.). However, the gap in plutonism 146-121 m.y. B.P. outlasted by far an apparent minimum in convergence (145-135 m.y. B.P.). Magmatism ceased in the Sierra and uplift slowed during the Laramide orogeny 75-45 m.y. B.P. when tectonic activity had moved east to the site of the Rockies, presumably because of a low angle of subduction, but volcanism resumed in the Sierra about 33 m.y. B.P., indicating that a steeper angle was reestablished. Apparently east-west compression slackened when the Pacific-North America (PA:NA) transform regime developed. Basalt was erupted in the southern Sierra 12-3 m.y. B.P., and during this same time, the range started its most rapid rise as a normal-fault-bounded block. The Coast Ranges northeast of the San Andreas fault are underlain by the Franciscan Complex. The older parts of the Complex were probably assembled in a subduction zone far south of their present location, but we believe that the same FA:NA convergence that was cited for Sierran plutonism was responsible, despite the disparity in latitude, as the Farallon plate was probably in contact with most of the western margin of North and South America. A perceived strong pulse in convergence 100-85 m.y. B.P. evidently produced the Coast Range thrust which on geologic grounds alone, most likely originated between 96 and 88 m.y. B.P. Some of the northwesterly transport of Franciscan rocks relative to North America is ascribed to oblique Kula-North America (KU:NA) convergence 85-43 m.y. B.P., during which period the Coast Range thrust was revived about 60 m.y. B.P. The Farallon plate again influenced the California margin after the Kula plate had moved northward, and FA:NA convergence caused the accretion of the Coastal Belt and King Range terranes of the neo-Franciscan. The advent of Pacific-North America (PA:NA) interaction was marked by local volcanism which advanced from the southeast toward the northwest in consonance with the passage of the Mendocino triple junction (Dickinson and Snyder, 1978). In the Salinian block, plutons 107-82

Paper number 3T1860.
0278-7407/84/003T-1860$10.00

m.y. old can be ascribed to the same FA:NA convergence as the contemporary Cretaceous plutons of the Sierra Nevada, although the Salinian intrusives originated much farther south. Paleomagnetic results (Champion et al., 1980) from the Salinian-related Pigeon Point Formation, 75-71(?) m.y. in age, suggest about 2500 km of poleward (essentially coastwise) movement. This postulated large movement during part (or all?) of the last 75 m.y. poses the greatest dilemma in our study. The Kula is the only known plate whose (computed) obliquely convergent motion is appropriate for the Late Cretaceous-Paleogene part of the migration, and even this motion is inadequate for the estimated transport within the most likely time window. Furthermore, the Farallon plate seems ideally suited for the Laramide orogeny 70-45 m.y. B.P. Both plates could not have been in contact with the same part of the margin at the same time. Oblique convergence of the Kula plate could possibly have caused large coastwise transport and also the Laramide orogeny. The Coast Ranges northeast of the San Andreas fault and the Salinian block both experienced strike slip faulting and en echelon folding correlative with PA:NA interaction, indicating that they were close together by Neogene time. Faulting and folding have been particularly marked since the inception of spreading in the Gulf of California and attachment of westernmost California to the Pacific plate about 4 m.y. B.P. The rise of individual coastal ranges, commencing 3-1 m.y. B.P., may possibly have been caused by slight convergence which appears in computed PA:NA relative motions from 5 m.y. B.P. to the present.

INTRODUCTION

If the geologic record is correctly understood, and if relative plate motions of the past have been correctly reconstructed, there should be a substantial correlation between the two. We have attempted a tentative correlation for west and central California, using the relative plate motions derived by Engebretson [1982]. The methods used for the analyses of the plate motions are described by Engebretson, et al. [this issue] in this volume. In the present study, the North American craton is "held still." Engraved upon it, so to speak, are today's coordinates of latitude and longitude, which have been held fixed throughout the passage of time. Thus whenever latitude and longitude are mentioned in this paper, they refer to the present North American grid. The latter can be imagined to resemble a wire net which is embedded in the rigid craton, but which extends loosely out over the active western continental margin, where allochthons of westernmost North America are free to move beneath the stationary net. Because North America is "held still", the earth's spin axis, mantle-related hot spots, and lithospheric plates (other than cratonic North America) appear to move relative to the craton and its present coordinates of latitude and longitude. For most of our purposes, the relative motions used are those which would be observed at latitude 37.5°N and longitude 122.5°W, near San Francisco. However, in treating the early history of the Salinian block, we have used relative motions at more southerly latitudes as well as the foregoing.

It must be emphasized that the motions of plates in the Pacific basin prior to 85 m.y. B.P. and especially those prior to 145 m.y. B.P. are poorly constrained, so our reconstructions and correlations for earlier events are tenuous, at best. However, we will include certain "milestone" events as far back as 150 or 160 m.y. B.P., in the hope that any positive correlations with plate motions will tend to strengthen weak reconstructions, and negative correlations may lead to improvements.

Much of western California has been pieced together by the accretion of terranes [Coney et al., 1980] , so the early history of any one part may not coincide with the histories of other parts. The individual histories should tend to merge somewhat for recent events, as many terranes of California had joined one another by the mid-Tertiary. We have divided the west and central part of the state as shown in Figure 1, mainly in consideration of late Mesozoic geology. For present purposes, we will choose just three composite terranes for attempted correlation of geologic events with plate motions: (1) the Sierra Nevada, (2) the Coast Ranges northeast of the San Andreas fault, and (3) the Salinian block.

Throughout this paper, geologic

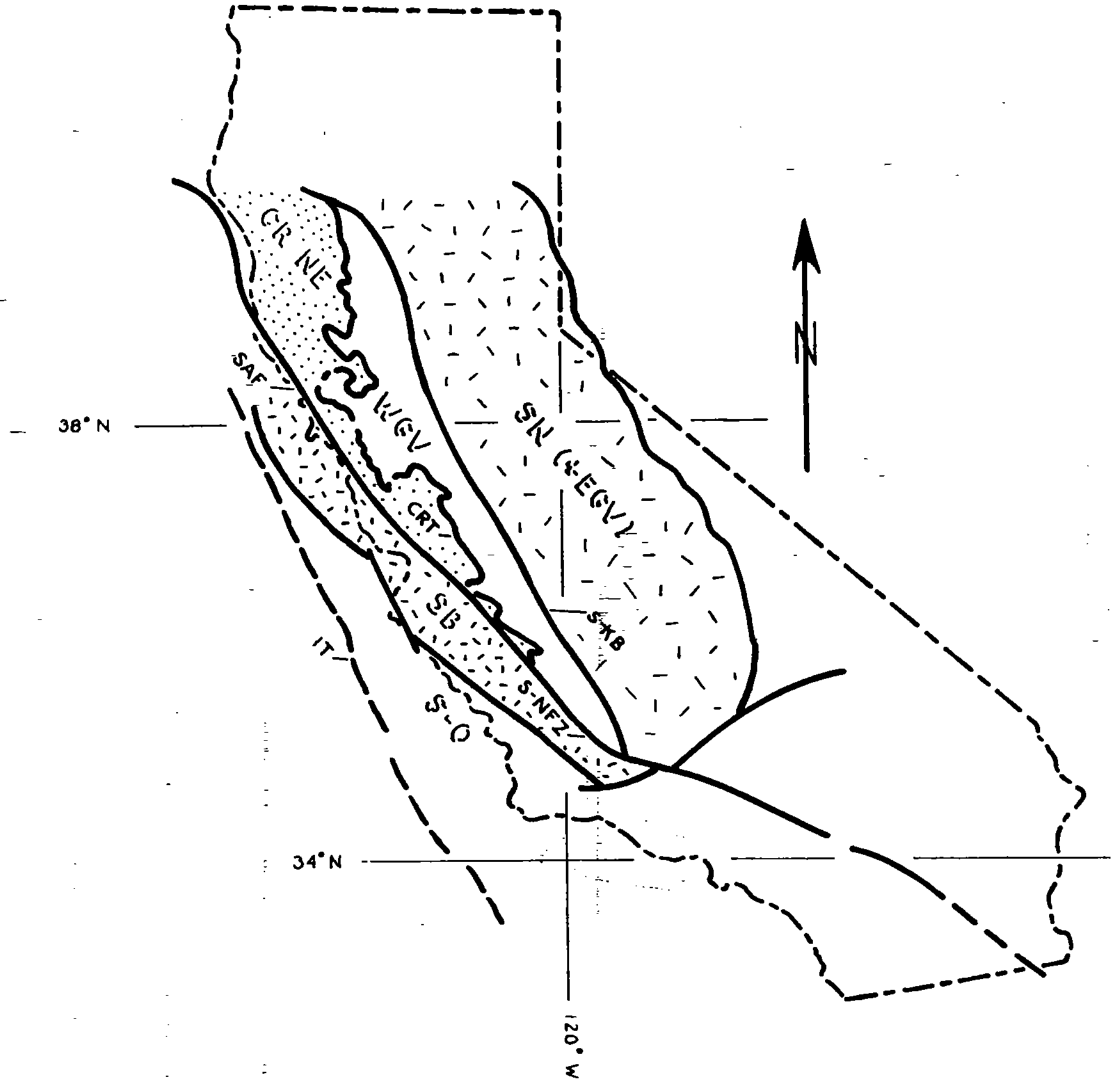


Fig. 1. Map of late Mesozoic terranes, west and central California. Terranes which are patterned are discussed in text. Most are composite, and consist of sub-terranes. Explanation of block letters: CR NE, Coast Ranges northeast of San Andreas fault; SE, Salinian Block; SN (+EGV), Sierra Nevada, plus basement beneath east part of Great Valley; S-O, Sur-Obispo Belt; WGV, west part of Great Valley. Tectonic boundaries: CRT, Coast Range thrust; IT, inactive trench; SAF, San Andreas fault; S-KB, boundary of Sierran-Klamath basement rocks (largely buried); S-NFZ, Sur-Nacimiento fault zone.

periods, epochs, and stages have been assigned ages (in millions of years before the present, m.y. B.P.) on the basis of the time scale of Harland et al. [1982] .

SIERRA NEVADA

The Sierra Nevada should be somewhat more favorable than coastal regions for attempted correlation of the geologic record with plate motions, as the Sierra have been comparatively stationary relative to cratonic North America. Paleomagnetic results show no compelling evidence for a large change in latitude or rotation relative to cratonal North America, at least since about 85 m.y. B.P. [Gromme and Merrill, 1965; Frei et al., 1982; Hannah and Verosub, 1980;

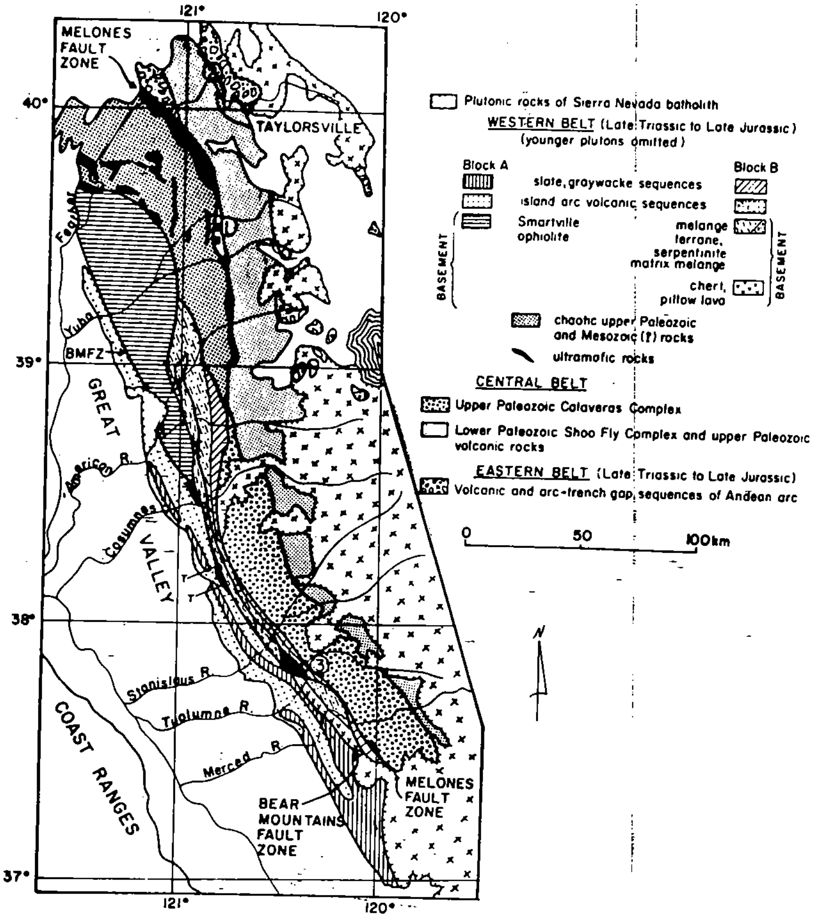


Fig. 2. Geologic map of part of western Sierra Nevada, from Schweickert, 1981a, slightly modified; courtesy of Prentice-Hall, Inc.

Bogen et al., 1983], although the data are permissive of circa 300 km of poleward motion (A. Cox, informal communication, 1983). The Sierra probably moved westward in response to extension in the Basin and Range province, and this may have affected certain Neogene events, but we will not explore this possibility in the present discussion.

Highlights of Sierran geology and history. The Sierra Nevada, including the High Sierra, foothills, and Sierran basement beneath the east edge of the Great Valley, is a vast and complex composite terrane. References helpful for present purposes include the following: Schweickert and Cowan [1975]; Schweickert [1981a, b] ; Clark [1976] ; Duffield and Sharp [1975]; Saleeby [1981]; Bateman [1979]; Kistler and Peterman [1973]; Stern et al., [1981]; Chen and Moore [1982]; Bateman and Wahrhaftig [1966]; Rinehart and Ross [1964]. These papers provide many additional references.

A simplified geologic map from Schweickert [1981] is shown in Figure 2. The major geologic events will now be scanned very briefly.

The prebatholithic rocks are arranged in subparallel NNW trending belts which are separated by tectonic boundaries. One of the important boundaries is the Melones fault zone--probably an east dipping thrust. East of the Melones fault zone in the "Central Belt" of Figure 2 are deformed Paleozoic complexes (Shoo Fly and Calaveras) which are largely clastic sediments and chert-rich sequences, but which include some mafic and intermediate volcanics. West of the Melones fault zone in the "Western Belt" of Figure 2 are accreted melanges, Jurassic island arc assemblages, and ophiolites. In the northwestern part of this belt, twin island arc assemblages are separated by the Smartville ophiolite [Cady, 1975; Xenophontos and Bond, 1978], whose age is approximately 160 m.y. In the southern foothills (not shown in Figure 2), there is a serpentine matrix melange which may have evolved while in oceanic transit prior to accretion and which subsequently became the basement upon which certain Sierran sediments were deposited [Saleeby, 1979]. The various prebatholithic assemblages are mildly to intensely metamorphosed, and they exhibit preintrusive structures such as faults, tight mesoscopic folds, and (in the case of fine-grained rocks) pervasive cleavage which generally strikes NNW.

Schweickert and Cowan [1975] proposed that an east facing Jurassic island arc approached the continent from the west. The arc split, and the Smartville ophiolite formed by interarc spreading between the two halves. The composite arc terrane collided with the continent, and at least part of the Melones fault zone represents the suture. Schweickert and Cowan [1975] suggested that the collision caused the Nevadan orogeny, a postulated event which has long been in the literature [Knopf, 1929]. Schweickert et al. [1983] date the orogeny at 158-153 m.y. B.P.

The prebatholithic Sierran assemblages are "stapled" into the composite Sierran province by granitoid plutons. The post-Triassic plutons tend to fall into two principal age groups [Stern et al., 1981; Chen and Moore, 1982]. Most of the U-Pb ages are within either the 172-148 m.y. range (Jurassic) or the 120-80 m.y. range (Cretaceous). The limits of the first sequence are imprecisely known, but evidently a hiatus in plutonism lasted from about 145 to 121 m.y. B.P. The emplacement of the Cretaceous intrusives, which form one of the large batholithic belts of the world, ended rather abruptly at about 80 m.y. B.P. Many Jurassic plutons appear to lie in a vaguely defined NW-SE belt which is crossed, and partly obliterated, by the belt of Cretaceous plutons [Bateman, 1981, p. 82]. The Jurassic belt can be construed to strike about N40°W, and the Cretaceous belt about N25°W.

An unusual event, the formation of the Independence Dike Swarm [Moore and Hopson, 1961] occurred at about 148 m.y. B.P. [Chen and Moore, 1982]. The swarm occupies an area more than 24 x 350 km from the Sierra Nevada and Inyo Range to the Mojave Desert, and consists of steeply dipping N-S dikes of mafic to granodioritic composition. Probably, the swarm originated during crustal extension.

Two Cretaceous compressional events are noted in Figure 3. One was reverse faulting which provided avenues for major quartz-gold deposition in the Mother Lode belt [Schweickert, 1981b; Albers, 1981]. The time of the faulting is uncertain, but it was probably between 127 and 108 m.y. B.P. Another compressional event produced folding about N20-70W axial surfaces, with local well-spaced cleavage, observed widely in areas both to the east and to the west of the batholithic belt [Nokleberg and Kistler, 1980; Schweickert, 1981a]. The structures of this event are cut by 92-81 m.y. plutons and are believed to have formed between 100 and 90 m.y. B.P. (R. A. Schweickert, informal communication, 1983). They may reflect dextral shear as well as compression, and may have formed contemporaneously with dextral slip on the Kern Canyon fault [Schweickert, 1981a, p. 114-118].

Between the time of latest plutonism (80 m.y. B.P.) and a time of Miocene volcanism (20 m.y. B.P. or younger), the southern Sierra were deflected clockwise in an oroclinal bend [Kanter and McWilliams, 1982].

Uplift and erosion of the Sierra doubtless occurred at the time of the Nevadan orogeny and, judging from the sedimentary record of the Great Valley sequence to the west, continued during Jurassic and Cretaceous magmatism [Dickinson and Rich, 1972; Ingersoll, 1982]. However, the uplift of the Sierra then slowed, and parts of the province were covered by Eocene fluviatile gravels and Cenozoic volcanics at a time of moderate topographic relief [Bateman and Wahrhaftig, 1966].

A gap in Sierran igneous activity prevailed in most parts of the Sierra between 80 and about 33 m.y. B.P. Thereafter, volcanism was sporadic and chemically heterogeneous [Dalrymple, 1964]. Oligocene rhyolitic ignimbrites 33-20 m.y. old were followed by andesitic, latitic, and basaltic products [Slemmons, 1966]. Andesitic volcanism was widespread 13-4.5 m.y. B.P., but in the Sierra south of the latitude of Mono Lake (38°N), eruptions from 12 to 1

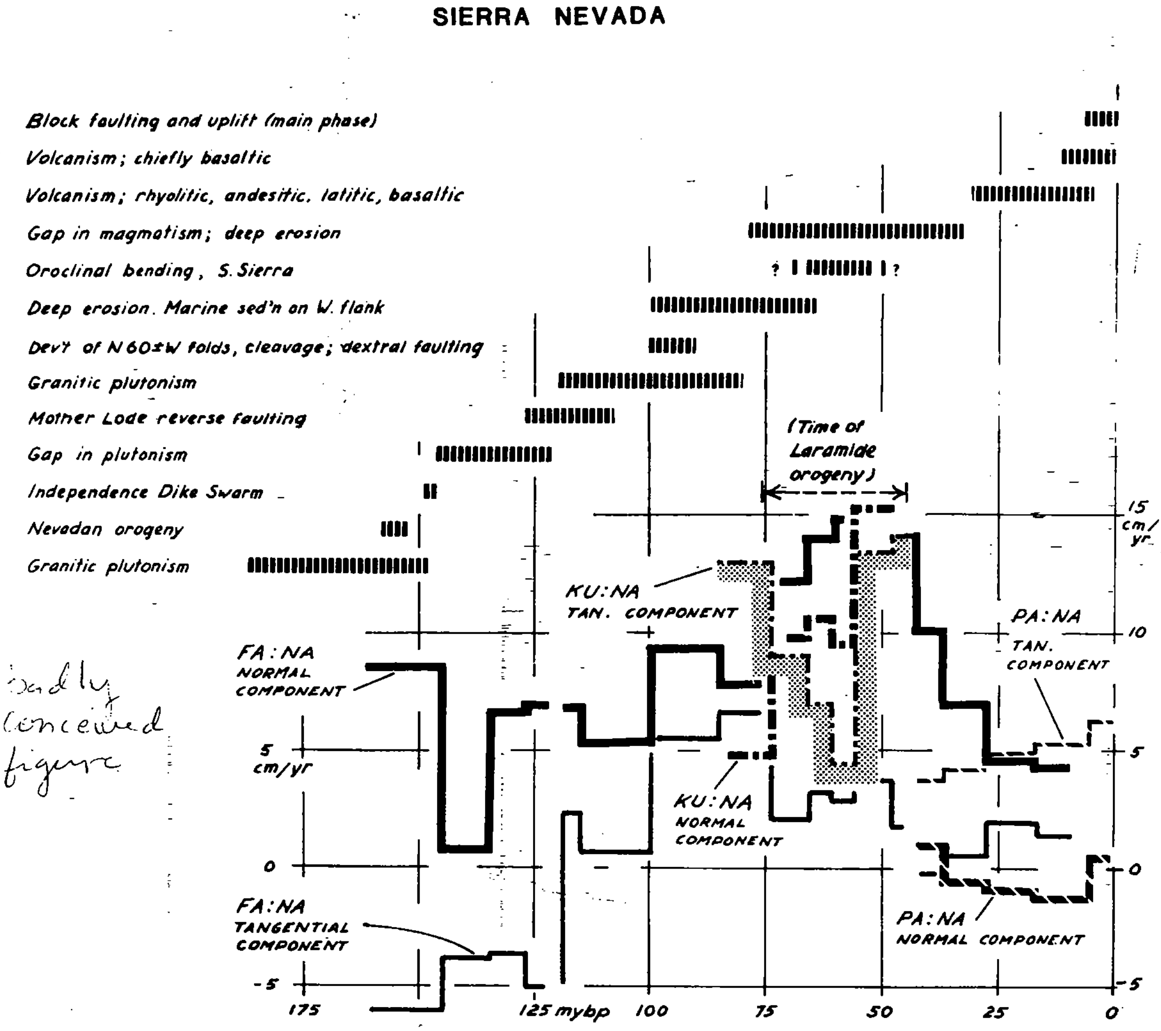


Fig. 3. Chart of events in Sierra Nevada compared with relative plate motion. Plate motions from Engebretson [1982]. See text for explanation.

badly conceived figure

m.y. B.P. were largely alkaline basalt, much of which is potassic [Moore and Dodge, 1980]. Farther north a tract of basaltic volcanic rocks dated at 2.3-1.3 m.y. [Dalrymple, 1964] extends 50 km eastward from the vicinity of Donner Pass.

Apparently, fault block uplift of the Sierra was minor or nil prior to 18 m.y. B.P., but became pronounced after 10 m.y. B.P. [Bateman and Wahrhaftig, 1966]. According to Huber [1981], at Deadman Pass near the head of the San Joaquin River about two thirds of the uplift of the range took place in the last 10 m.y. and about one fourth in the last 3 m.y., the present rate being estimated at 0.3 mm/yr. Concurrent dextral slip has occurred on bordering oblique slip normal faults, as demonstrated at the time of the large earthquake of 1872 in Owens Valley [Bateman and Wahrhaftig, 1966].

Sierran events vis-a-vis relative plate motions, 160-85 m.y. B.P. Figure 3 shows geological events and the estimated dates of each. Reconstructed plate motions for the Kula (KU), Farallon (FA), and Pacific (PA) plates are shown relative to a fixed North America (NA). Wide lines show the normal component of convergence relative to the continental margin/plate boundary; narrower lines show the tangential component. Positive normal and tangential components of relative motion indicate convergent and dextral interaction, respectively; negative normal and tangential components indicate divergent and sinistral interaction, respectively. The margin, which was actually probably arcuate or irregular, is assumed to have had an average azimuth of N40°W from 180 to 120 m.y. B.P., based on our perception of the trend of the Jurassic plutonic belt, and an azimuth of N25°W from 120 to 30 m.y. B.P., based on the Cretaceous plutonic belt. The plate boundary is assumed to have had an azimuth of N40°W from 30 to 0 m.y. B.P., mainly because parts of the San Andreas fault suggest this orientation. Rates in centimeters per year are indicated on the vertical scale at the side of the figure. The relative motions of the oceanic plates prior to 145 m.y. B.P. are tenuous because there is no direct evidence for the behavior of the Pacific plate before that date.

Figure 3 suggests that the normal component of convergence (8.0-8.5 cm/yr) of the Farallon plate with North America (FA:NA) can easily account for Jurassic plutonism. This convergence also could have carried island arcs and the Smartville ophiolite against North America, as postulated by Schweickert and Cowan [1975], thereby causing the Nevadan orogeny 158-153 m.y. B.P. The tangential component was large (6.0-10.0 cm/yr) and sinistral; hence any terranes which were accreted arrived from the northwest, regardless of overall trajectories.

The dramatic change from FA:NA convergence to FA:NA tangential motion or slight divergence at 145-135 m.y. B.P. would provide the relaxation implied by the Independence Dike Swarm if either the timing of the change in motion or the dike event (dated at 148 m.y. B.P.) were adjusted by about 3 m.y. In view of the uncertainties in dating rocks and plate motions, it is reasonable to suppose that the dike event may have coincided with the change in motion. The latter could have occurred at 148 m.y. B.P. but probably not earlier, as 153-148 m.y. plutons, denoting convergence, exist in the central and northern Sierra (R. A. Schweickert, informal communication, 1983). The change in relative plate motion coincides with a marked slowdown in the northwesterly movement of North America vis-a-vis hot spots. (We have not included the hot spot: North America relative motion in Figure 3).

The hiatus in Sierran plutonism about 147-121 m.y. B.P. partly coincided with, but apparently outlasted, the above-mentioned period of tangential motion (Figure 3). According to our admittedly imprecise data, convergence resumed at 135 m.y. B.P., but reliably dated plutonism did not restart until about 120 m.y. B.P., leaving an apparent delay of 15 m.y. Part (or possibly all?) of the delay may represent the time necessary for the initial descent of a new slab, sustained subduction rquired for large-scale generation, and the rise and cooling of large plutons.

For the important Cretaceous plutonism, we assume a different, N25°W, trend for the continental margin in agreement with the orientation of the Cretaceous batholithic belt. The change in assumed trend in the margin makes some appreciable differences in effective vectors of relative plate motion.

FA:NA convergence normal to the margin was greater than 5 cm/yr throughout the Cretaceous plutonic episode, and was particularly rapid (about 9 cm/yr) during the interval 100-85 m.y. B.P. when the most voluminous Sierran intrusives were emplaced. This appears to be a convincing cause and effect. FA:NA convergence, with a component of 5-7 cm/yr normal to the assumed margin, evidently caused the reverse faulting (between 127 and 108 m.y. B.P.) that localized the auriferous quartz veins of the Mother Lode (R. A. Schweickert, informal communication, 1983). Later (circa 100-90 m.y. B.P.), when convergence became more oblique, with a strong dextral component, probably the mid-Cretaceous Sierran folds and cleavage (both of which trend N20-70W) were formed, and perhaps the Kern Canyon fault underwent dextral slip (R. A. Schweickert, informal communication, 1983).

Sierran magmatic gap, 80-33 m.y. B.P., and synchronous events. The cessation of magmatism in the Sierra for an extended period probably signals a change in plate interaction. The Kula plate (KU, Figure 4) is believed to have come into existence about 85 m.y. B.P. [Woods and Davies, 1982], so conceivably the change could reflect this new presence. However, KU may or may not have contacted the California margin; if not, FA:NA interaction continued. Two (among

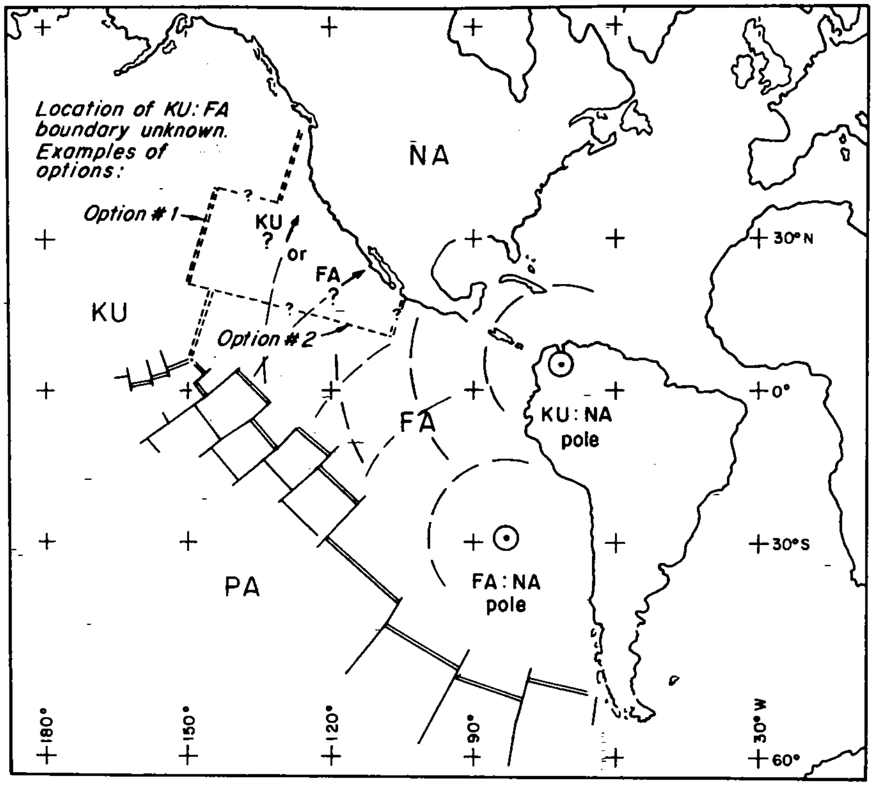
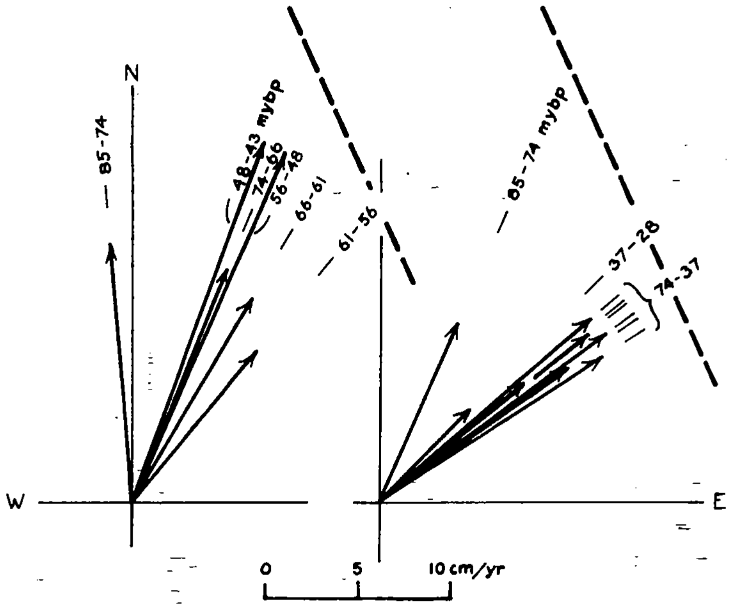


Fig. 4. Major plates circa 74 m.y. B.P., showing uncertainty of location of Kula-Farallon boundary. Ruled area could have been occupied by part of Kula plate (KU) or by part of Farallon plate (FA); interaction at margin of North America (NA) would have been determined accordingly, as suggested by arrows. Dashed arcs indicate motion of KA and FA (with respect to NA) around respective poles of rotation.

several possible) options are shown schematically in Figures 4 and 5. The choice between alternatives depends on the geologic record on land, as all seafloor vestiges of the location and configuration of the KU-FA boundary have been lost by subduction.

The character and location of the Laramide orogeny (circa 75-45 m.y. B.P.) suggest that a slab was subducting at a very low angle, enabling it to reach far inland without causing plutonism in the Sierra [Dickinson and Snyder, 1978; Coney, 1978]. The calculated motions of either KU or FA with respect to NA would be appropriate, as there is a striking correlation between the timing of the orogeny and high convergence rates for both oceanic plates. The deduced components normal to the margin are 12.2-14.8 cm/yr for FA:NA and 9.5-15.3 for KU:NA during the Laramide period (Figure 3). The beginning and end of the orogeny coincided with the beginning and end of these high rates. Some persons have favored FA as the agent which caused the orogeny because FA was generated near the trench during part of the period and thus would have been young, hot, and buoyant when subducted (effects of subduction of young lithosphere have been considered by Sacks [1983]). However, Engebretson et. al. [this issue] find that the time of youthfulness and inferred elevated temperature of FA do not correlate closely with most of the orogenic period. Other possible causative factors for the orogeny could have been independent of the identity of the subducting plate. For example, a change in the "absolute" motion of NA (as determined with respect to hot spots) may have been important [Coney, 1972; Engebretson et al., this issue].

The megatransport of the Salinian block northwestward along the coast [Page, 1982] was in progress during the Cretaceous-Paleogene hiatus in Sierran



a) KU:NA

b) FA:NA

Fig. 5. Comparison between a) Kula plate motion vs. North America and b) Farallon plate motion vs. North America, in the vicinity of San Francisco (lat. 37.5°N, long. 237.5°E, present-day coordinates), for the period 85-28 m.y. B.P.. Numbers opposite vector arrows indicate time intervals for vectors. Scale applies to length of arrows. Heavy dashed line shows presumed trend of North America margin, N 25°W. A hiatus in Sierran magmatic activity, the occurrence of the Laramide orogeny, and coastwise migration of the Salinian block transpired more or less simultaneously during a large part of the time interval encompassed here - probably as a consequence of plate interactions shown either in a) or in b).

magmatism and during the Laramide orogeny. The megatransport should be symptomatic of the type of plate interaction that prevailed along the margin. The Salinian block, which is discussed more fully in a later part of this paper, started to move after 80 m.y. B.P. Probably its passage along the proto-San Andreas fault deflected the southernmost Sierra Nevada clockwise [Kanter and McWilliams, 1982] some time between 80 and 50 m.y. B.P. During this interval, the dextral tangential component of the KU:NA motion was particularly pronounced (shaded band in Figure 3), whereas FA:NA motion was more nearly orthogonal with respect to the assumed N25°W trend of the margin (Figure 5). Thus the movements along the coast suggest that KU, rather than FA, was interacting with the California margin during the Laramide orogeny and during the concurrent gap in magmatism in the Sierra. However, this is not a firm conclusion.

Later Sierran events vis-a-vis plate motions. The gap in Sierran magmatism that began near the onset of the Laramide orogeny outlasted the latter, extending to about 33 m.y. B.P. (Figure 3). Volcanism then commenced in the Sierra, indicating that a subducting slab was now descending at a steeper angle [Dickinson and Snyder, 1978]. This slab must have been FA, as KU had joined PA and had moved northward.

The Pacific plate (PA) has progressively contacted the North American margin, the initial contact probably occurring at a point on the coast of Baja California 30-28 m.y. B.P. [Atwater, 1970]. Subsequently, the plate juncture has evolved as a lengthening transform zone characterized by NW-SE dextral strike slip more or less parallel with the margin. The NW terminus of the transform is the Mendocino triple junction (MTJ), which has migrated northwesterly throughout the last half of the Cenozoic. In the wake of the migrating MTJ, transform motion has supplanted subduction, and the passage of the MTJ has been marked (inland) by the progressive extinguishing of arc-type magmatism [Dickinson and Snyder, 1979b]. Basaltic Sierran volcanism since about 12 m.y. B.P., and block faulting of the range, both reflect a cessation of the long-lasting plate convergence, and they coincide with much of the Basin-and-Range high-angle normal faulting regime. Although relaxation of transverse (compressive) stresses dictated the type of faulting, the immediate cause of uplift of the Sierra is probably expansion of what was (during most of the foregoing history) the upper mantle portion of the continental lithosphere, as suggested by Crough and Thompson [1977]. A window must have developed in the subducting slab during the transition from a convergent to a transform regime [Dickinson and Snyder, 1979a], and within the window the hot mantle below the site of the formerly subducting slab would have come into contact with the once-protected continental lithosphere.

COAST RANGES NORTHEAST OF THE SAN ANDREAS FAULT

The Coast Ranges province is crossed obliquely by the San Andreas fault (SAF). In this section, we discuss that part of the province which lies northeast of the fault. In a later section, we deal with the Salinian block on the opposite side of the SAF.

The Coast Ranges northeast of the SAF comprise a number of tectonostratigraphic terranes, some of which have traveled long distances in the late Mesozoic and in the Cenozoic. Therefore relative plate motions deduced for west-central California will not strictly apply, especially in the earlier part of our chronology. If we knew exactly where each terrane was at particular times, we could present plate motions for more relevant locations, but at present such information does not exist. Consequently, this initial analysis is very crude.

<u>Highlights of geology, paleomagnetism, and inferred events.</u> Franciscan rocks [Bailey, et al., 1964] constitute the basement of the Coast Ranges northeast of the SAF (Figure 6). These rocks, which are bounded by the Coast Range thrust (CRT) on the northeast and the SAF on the southwest, have been divided into three large belts [e.g., Blake and Jones, 1981] and an additional smaller fourth belt, not shown in Figure 6 [McLaughlin et al., 1982]. These (and their postulated subdivisions) are considered to be successively accreted terranes; they are generally younger toward the west. The easternmost, the Yolla Bolly belt, includes coherent tectonite schist that was metamorphosed in the blueschist facies probably about 120-115 m.y. B.P. [Lanphere et al., 1978]. It also includes coherent graywacke units with interbedded minor chert, and mudstone matrix olistostromes. The Yolla Bolly belt is locally thrust westward over the Central belt.

The Central belt is characterized by melanges and large coherent sandstone bodies. Some of the latter are little metamorphosed, but others are strongly metamorphosed in the blueschist facies. The melanges consist of highly sheared argillaceous matrix and blocks of metagraywacke, basaltic greenstone, radiolarian chert, serpentinite, high grade blueschist (mostly metamorphosed 155-150 m.y. B.P.), and other rocks such as the Laytonville Limestone. Some sizeable sequences, for example the greenstone-chert-graywacke of Marine Headlands north of the Golden Gate, are considered to be individual tectonostratigraphic terranes [Blake et al., 1982]. Aside from the highest grade blocks, blueschist facies metamorphism seems to have occurred at many times from 159 to 78 m.y. B.P. [Suppe and Armstrong, 1972]. Fossils in blocks, matrix, and coherent sedimentary units of the Central belt range from late Kimmeridgian/early Tithonian at least to Turonian [Bailey, et al., 1964], hence circa 150-90 m.y. B.P. Evidently this very significant belt was not fully assembled and not fully emplaced before 90 m.y. B.P. It may have been accreted in a series of events.

The Coastal belt is separated from the Central belt by the Coastal belt fault [Jones et al., 1978], which may be a folded oblique slip thrust. A possibly equivalent fault to the north is believed to be Miocene in age [Underwood, 1982]. The Coastal belt consists largely of bedded turbiditic

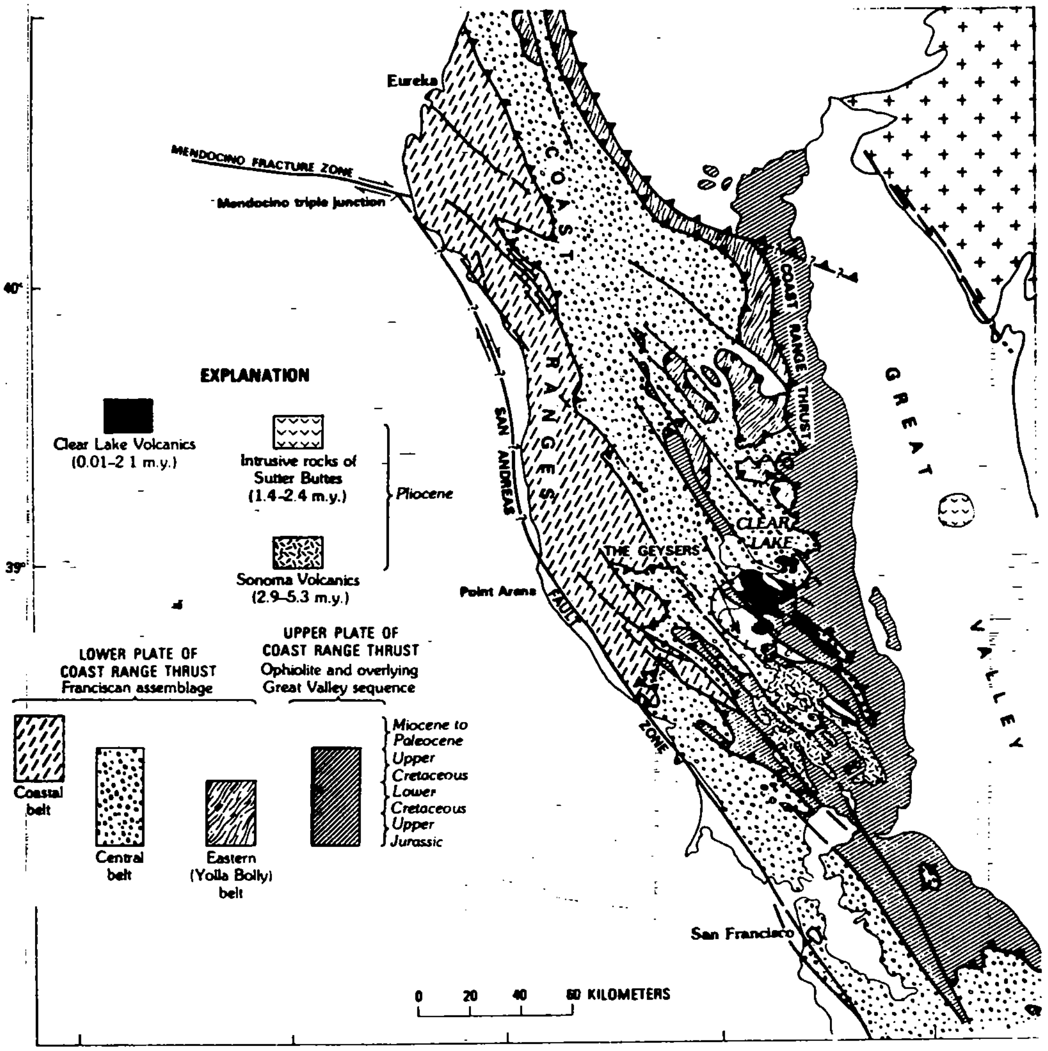


Fig. 6. Geologic map of part of Coast Ranges northeast of San Andreas fault, from Black and Jones [1974] and McLaughlin [1981], slightly modified.

sandstone and minor mudstone, mostly deformed and locally highly sheared and incipiently "melanged." The rocks are not metamorphosed above the zeolite facies. Blueschist, chert, greenstone, and serpentinite are rare and are restricted to very thin melanges or fault zones. Microfossils are chiefly Late Cretaceous and Eocene in age [Evitt and Pierce, 1975], say 95-45 m.y. B.P. as a crude estimate.

The fourth Franciscan belt, the King Range terrane (not shown in Figure 6), is on the coast just south of Cape Mendocino. It includes Tertiary turbidites, some of which are as young as middle Miocene, 15-14 m.y., according to McLaughlin et al. [1982]. These authors cite evidence for eastward obduction of the King Range terrane over a wide shear zone (melange) bounding the Coastal belt.

Paleomagnetic data from some of the rocks in the Central belt indicate large-scale movements. For example, pillow basalts near Nicosio Reservoir 45 km northwest of San Francisco seem to have moved 19° poleward (Gromme and Gluskoter [1965]; updated by G. S. Gromme, oral communication, 1980); this could mean at least 2000 km of transport. The Laytonville Limestone, which occurs as blocks in a melange 220 km northwest of San Francisco, may have been deposited about 17° from the equator [Alvarez et al., 1980]. Some of the allochthonous sequences (e.g., the Marin Headlands terrane 5-10 NW of San Francisco) include oceanic basalt and radiolarian chert overlain by terrigenous sandstone, implying an initial site far from land, transport of oceanic rocks by seafloor spreading, arrival at a convergent margin, and subsequent deposition of terrigenous sediment. Paleomagnetic results indicate circa 1500-2000 km of poleward movement of the oceanic rocks (F. Curry, oral communication, 1983). This may represent a northward component of the ocean journey toward land, or it may include poleward movement of the terrane along the coast after it made initial contact with the continent. Probably much (or all) of the Franciscan Complex has migrated significant distances from original areas of accumulation and/or convergent accretion.

To the east of the Franciscan belts, and structurally above them, is the Great Valley sequence [Bailey et al., 1964; Ingersoll, 1982]. It represents approximately the same ages as many of the rocks in the Franciscan Central belt (Tithonian, Lower Cretaceous, and Upper Cretaceous). At the base of the Great Valley sequence is Jurassic ophiolite, upon which rests an impressive pile of clastic sediment. Most of the sediment is deep marine turbidites which ostensibly were derived from Klamath and Sierran sources, and were deposited in a forearc basin alongside the Sierran arc [Dickinson, 1976; Ingersoll, 1982].

The Coast Range thrust (CRT) separates the Franciscan Complex from the Great Valley sequence [Bailey et al., 1970]. Regarding the age of the fault, Blake and Jones [1981, p. 317] point out that the CRT, together with the lower part of the Great Valley sequence, is folded in the Wilbur Springs antiform, but the upper part of the Great Valley sequence is unaffected by the folding. According to E. I. Rich (oral communication, 1983), the oldest unaffected strata are Turonian, hence about 91-88.5 m.y. old [Harland et al., 1982]. Accordingly, the CRT would be older than circa 91 m.y. McLaughlin and Pessagno 1978 report early Cenomanian radiolaria from Franciscan chert below the CRT in the Geysers area, indicating a post 96 m.y. age for the fault. We tentatively conclude that early movement probably occurred on the CRT some time between 96 and 91 m.y. B.P. However, the CRT or superposed younger thrusts have affected rocks of Paleocene or younger age [Swe and Dickinson, 1970; Suppe and Foland, 1978]; therefore we suspect that much additional movement occurred in Paleocene/Eocene time. In addition, locally the CRT was reactivated or overprinted in the Neogene [Raymond, 1973]. Thus the history of the fault is long and complicated. For present purposes, we postulate reactivation between 60 and 50 m.y. and lesser reactivation during the last 20 m.y. In our view, the Franciscan Central belt was probably largely formed by the 96-91 m.y. event; together with the Yoll Bolly belt, it was pushed en masse against and beneath the Great Valley sequence.

Very likely, the Coastal belt was similarly pushed bodily against the Central belt along the Coastal belt fault, as there is no obvious gradation between the two tracts. The Coastal belt includes rocks at least as young as middle Eocene near the boundary (W. R. Evitt, informal communication, 1982), so the time of accretion was not earlier than about 45 m.y. B.P. Indirect evidence from Underwood [1982] suggests a Miocene date, hence post 25 m.y. B.P. The King Range terrane was almost certainly accreted later than about 15 m.y. B.P. (McLaughlin et al., 1982).

The Coast Ranges northeast of the SAF encompass several small to medium-sized areas of Cenozoic volcanic rocks. There is a significant, albeit imperfect, trend in age, older to younger, from the 23.5 m.y. Neenach Volcanics in the western Mojave Desert to the Quaternary volcanics of Clear Lake 140 km northwest of San Francisco. Rhyolitic, andesitic, and basaltic rocks are represented.

Cenozoic structural features in this composite terrane include strike slip faults, thrusts, and folds. The SAF has had a long history, but some lesser strike slip faults, including the Calaveras, probably originated after 4 m.y. B.P. Many of the folds are Plio-Pleistocene (circa 4.0 - 0.5 m.y.); some, but not all, are arranged en echelon as in idealized dextral wrench tectonics [e.g., Wilcox et al., 1973]. Young thrusts or reverse faults are associated with some of the folds [Aydin and Page, 1981].

Most of the province emerged above

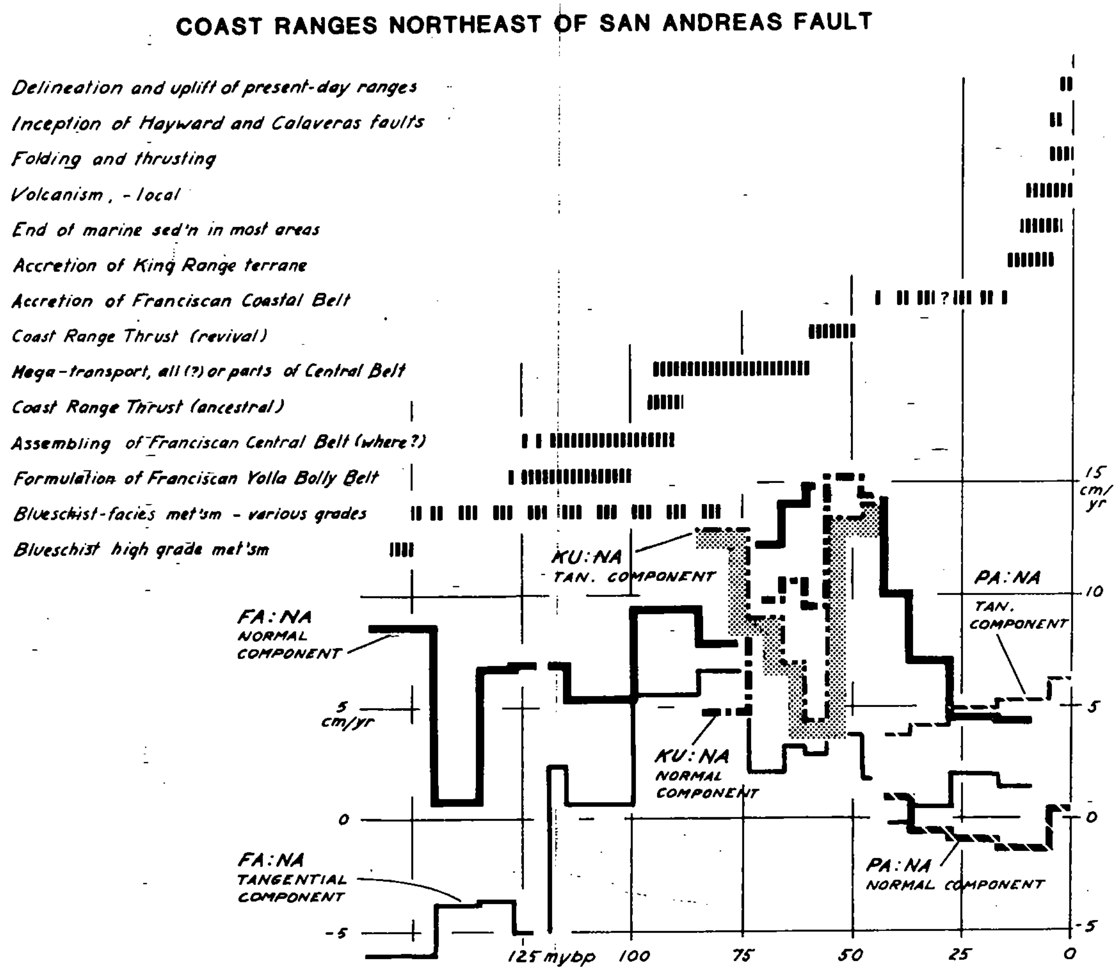


Fig. 7. Chart of events in Coast Ranges northeast of San Andreas fault, compared with relative plate motions. Plate motions from Engebretson [1982].

sea level in the Pliocene or early Pleistocene and has remained emergent ever since [Christensen, 1965]. Individual ranges such as the Diablo Range, East Bay Hills, and Temblor Range first rose in their present form within the last 1-3 m.y. [Christensen, 1965]. These ranges are virtually parallel with the contemporary transform plate boundary, rather than being arranged en echelon, so they are not clearly related to transform motion.

Plate motions responsible for Coast Range events northeast of the SAF. Figure 7 lists various events and shows reconstructed plate motions which apparently are temporally correlative.

The evolution of the Yolla Bolly and Central belts of the Franciscan probably resulted from Farallon-North America convergence, and largely occurred between 150 and 88 m.y. B.P. At least some of the components originated south of their present position and may have been assembled into accretionary complexes before moving poleward. If, as we believe, the Farallon and North American plates were in contact, the FA:NA relative motion indicates subduction that was continuous except for a 10-m.y. interval between 145 and 135 m.y. B.P. We postulate that the Yolla Bolly belt and most of the Central belt had been largely assembled when they were forced en masse against, and partway beneath, the Great Valley sequence along the newborn Coast Range thrust. Apparently, this occurred during the marked pulse of strong (9 cm/yr) FA:NA convergence 100-85 m.y. B.P. (Figure 7);

as mentioned above, on geologic grounds we suggest some time between 96 and 88 m.y. B.P. for the original CRT.

As discussed earlier, possibly the Kula plate temporarily supplanted the Farallon plate along the California-Mexico margin at about 85 m.y. B.P.; if so, it imposed strongly oblique (dextral) KU:NA convergence (Figures 5, 7). Under this influence, the western part of the Central belt of Franciscan rocks could have continued to evolve by subduction-accretion and by concurrent northwestward transport, possibly with differential movement between accreted packets. During this interval, thrusting was renewed along the Coast Range thrust circa 60 m.y. B.P. as a result of unusually strong convergence at the time of the Laramide orogeny.

The Coastal belt was most likely assembled by resumed FA:NA convergence after the Kula plate had moved farther north, soon after 45 m.y. B.P. The King Range terrane was also formed by Farallon-North America convergence and was accreted between 15 and 9 m.y. B.P. when the normal component of relative motion was 4-5 cm/yr. Accretion was completed before the terrane was bypassed on the seaward side by the prolongation of the SAF, as shown by McLaughlin et al. [1982] in their Figure 5B.

The transform regime began along the coast of southern California or Baja California 30-28 m.y. B.P. when the Pacific plate made initial contact with North America (Atwater, 1970), and the affected zone has subsequently lengthened from southern California to Cape Mendocino. In this zone, strike slip faulting, en echelon folding, and local thrust faulting occurred in response to PA:NA dextral shear. These events generally commenced after a time lag following the passage of the Mendocino triple junction, perhaps because transform motion was initially concentrated along the site of the trench as subduction ceased. In west-central California, most of the wrench-type folding took place during the last 4 m.y., coinciding with spreading in the Gulf of California and acceleration of slip on the SAF. In other words, it coincided with the partial attachment of coastal California to the Pacific plate, but it represents pervasive shear strain rather than rigid block behavior.

The timing of several episodes of Cenozoic volcanism in areas northeast of the SAF has been related by Dickinson and Snyder [1979b] to the passage of the Mendocino triple junction along the coastal margin. The Neenach Volcanics in the western Mojave Desert are 23.5 m.y. old. Toward the northwest in the Coast Ranges, the Quien Sabe Volcanics are circa 10 m.y., Berkeley Hills volcanics 11.5-6 m.y., Sonoma Volcanics 5.3-2 m.y., and Clear Lake Volcanics 2.5-0.01 m.y., roughly coinciding with the reconstructed position of the triple junction. The latter did not involve a spreading ridge, but Dickinson and Snyder [1979b] suggest that melting was induced because the path of the junction diverged slightly from the previously evolved continental margin, permitting relaxation or extension to occur. Slight PA:NA divergence does appear in Figure 7 from 37 to 5 m.y. B.P., assuming a N 40°W trend for the continental margin.

Although the transform regime now prevails, a slight convergence may have existed from 5 to 0 m.y. B.P. (Figure 7) between the Pacific plate motion (N36°W) and those parts of the San Andreas fault system which strike N40°W). If real, this convergent component may be the cause of certain Plio-Pleistocene folds and thrusts which are parallel with the SAF [A. Aydin and B. M. Page, manuscript in preparation, 1984; Page, 1981], and may even be the cause of uplift of the present ranges, which began in earnest only within the last 3 m.y. However, these speculations are tenuous.

SALINIAN BLOCK

Highlights of geology. The Salinian block (Figure 8) lies between the San Andreas fault (SAF) on the northeast and the Sur-Nacimiento fault zone on the southwest and is flanked on either side by Franciscan rocks. It extends from the Transverse Ranges in the south to the outer edge of the continental shelf northwest of San Francisco. Summaries of the geology and history of the block have been given by Ross [1978], Page [1982], and Vedder et al. [1983]. The Salinian block is composite, comprising structural slivers of granitic and metamorphic rocks partially covered by Upper Cretaceous and Cenozoic sediments. The

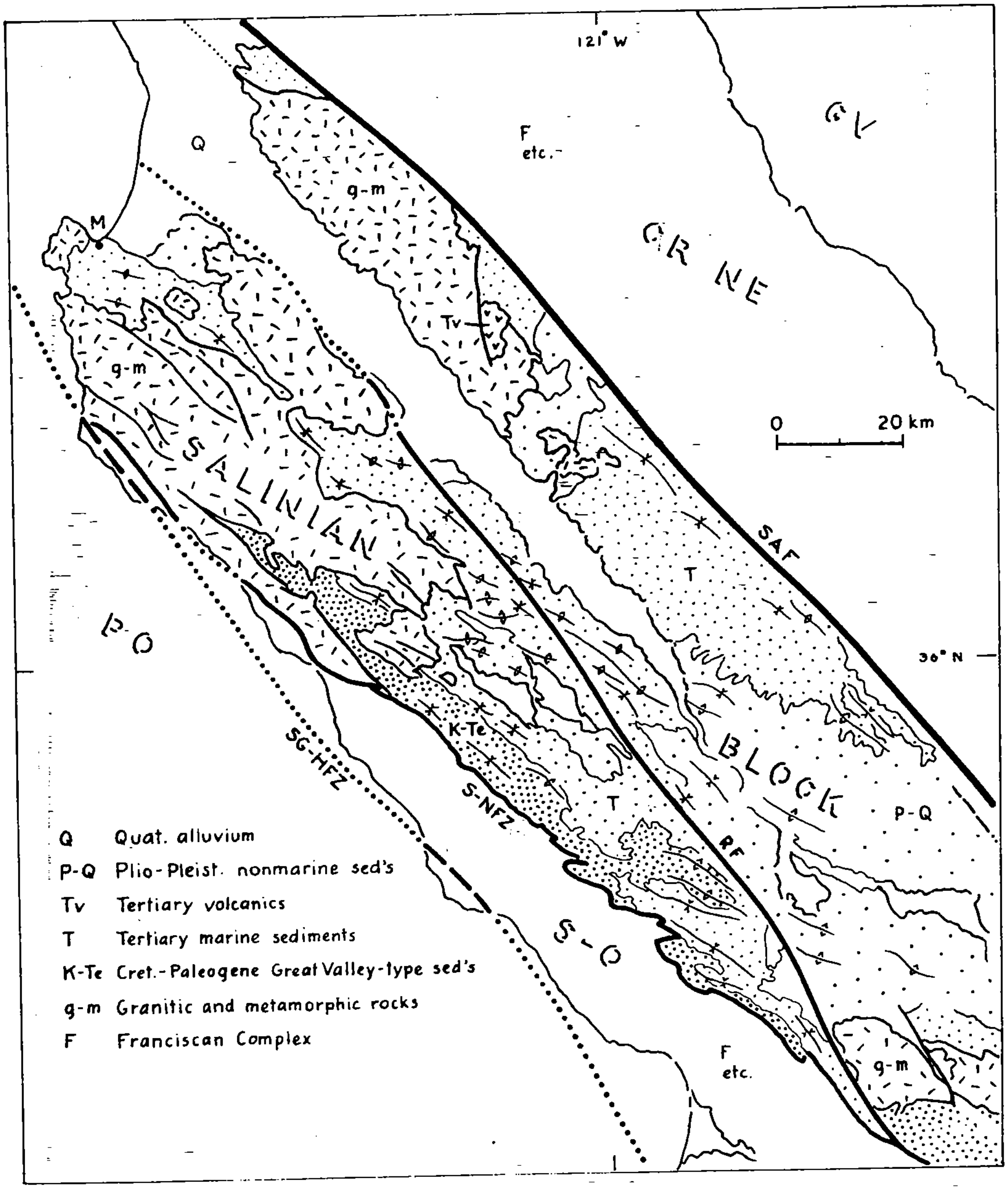


Fig. 8. Simplified geologic map of part of the the Salinian block. Abbreviations: CR-NE, Coast Ranges northeast of San Andreas fault; GV, Great Valley; PO, Pacific Ocean; S-O, Sur-Obispo belt; M, Monterey; RF, Rinconada fault; SAF, San Andreas fault; SG-HFZ, San Gregorio-Hosgri fault zone; S-NFZ, Sur-Nacimiento fault zone. (From Jennings [1977], greatly modified).

metamorphic rocks are largely metasediments [Compton, 1966; Ross, 1978] of an unknown geographic source. Various granitoid rocks are present, but granodiorite and granite predominate [Ross, 1978]. The ^{87}Sr/^{86}Sr ratios are generally .706 or higher [Kistler and Peterman, 1978]. Uranium-lead radiometric ages range from 107 to 82 m.y. [Mattinson, 1978, 1982]. It seems most likely that the basement rocks are displaced fragments of an axial part of the Cordilleran Cretaceous plutonic arc of North America.

After deep erosion and submergence, some of the basement rocks were covered by Upper Cretaceous clastic sediments, largely turbiditic subsea fan deposits [Howell et al., 1977; Vedder et al., 1983] which are comparable to the youngest parts of the Great Valley sequence. Paleocene and Eocene turbiditic sediments are also present, but Oligocene deposits are largely nonmarine. Volcanism occurred locally near the Oligocene-Miocene time boundary (see below). Miocene sediments include organic, siliceous varieties that were deposited in deep local marine basins, some of which were arranged en echelon. Emergence, which has lasted to the present time, is marked by extensive Plio-Pleistocene nonmarine deposits partially blanketing Teritary marine formations. Although only 4-0.5 m.y. in age, the Plio-Pleistocene sediments are (in many localities) folded and faulted. As in other parts of the Coast Ranges province, the present-day individual ranges (e.g., Gabilan, Santa Lucia, and Santa Cruz ranges) rose from near sea level within the last 1-3 m.y. [Christensen, 1965]. Their long axes are subparallel with the present plate boundary.

Migration of the Salinian block. The movement history of the block has been discussed by Vedder et al. [1983] and Page [1982]. Apparently the basement rocks originated far to the south and some 150-400 km inland in the heart of a magmatic arc, and the block was somehow detached and transported coastwise, losing much of its oceanward flank at some stage. We envision transport mainly resulting from oblique convergence, as described by Beck [1983].

Recent paleomagnetic findings indicate that the block has traveled much farther than previously supposed. Salinian granitoid rocks (Cretaceous) from Ben Lomond in the Santa Cruz Mountains yield paleomagnetic inclinations tentatively suggesting substantial translation, although the results are not conclusive [Kanter et al., 1982]. Upper Cretaceous (75-71? m.y.) turbiditic sediments (Pigeon Point Formation) believed to be underlain by Salinian basement seem to have traveled poleward about 2500 km or more, according to two independent investigations [Champion et al., 1980; M. Wilson et al., manuscript in preparation, 1984]. Paleocene turbiditic flysch (65-60? m.y.) affiliated with the Salinian block give paleomagnetic indications of about 2100 km of poleward transport (D. Champion, oral communication, 1981). The credibility of these results is reinforced by paleomagnetic evidence for large-scale poleward movement of the Southern California batholith to the south [Teissere and Beck, 1973; Beck, 1980] and the Sur-Obispo belt to the west [McWilliams and Howell, 1982]. Much of the megatranslation must postdate the Pigeon Point Formation, but additional translation may have occurred before and during the deposition of that formation. Geologic relations show that the block most likely arrived in California by 55 m.y. B.P., prior to Eocene subsea fan deposition (see below).

The more recent history of Salinian migration is provided by the history of slip on the SAF (summarized by Dickinson et al. [1972]), as the SAF forms the landward boundary of the block. An Eocene subsea fan was deposited across the SAF in what is now the southwest part of the San Joaquin Valley, and was subsequently cut in two by the reawakened fault [Clarke and Nilsen, 1973]. The two parts are now separated by about 300 km. The west half rests on Salinian basement, but the east half overlies Franciscan rocks; thus the basement rocks had already been displaced by proto-San Andreas movements before the fan was built. These early movements represent part of the megatranslation of the Salinian block, discussed above. The 300-km offset of the 55-40(?) m.y. old fan is the same as the offset of the 23.5 m.y.-old Pinnacles-Neenach Volcanics [Huffman et al., 1973], so the Salinian block did not move during the Oligocene. However, motion resumed in mid-Miocene time after about 15 m.y. B.P., and accelerated markedly about 4 m.y. B.P.

Relation between Salinian events and plate motions. In Figure 9, the selected events are compared with relative plate motions. The generation of Salinian plutons 107-82 m.y. B.P. was probably the result of FA:NA convergence, as was the contemporaneous Sierran plutonism, but the suitability of the relative motion is somewhat dependent upon the original location (which is uncertain) of the Salinian intrusions. The convergence rates would

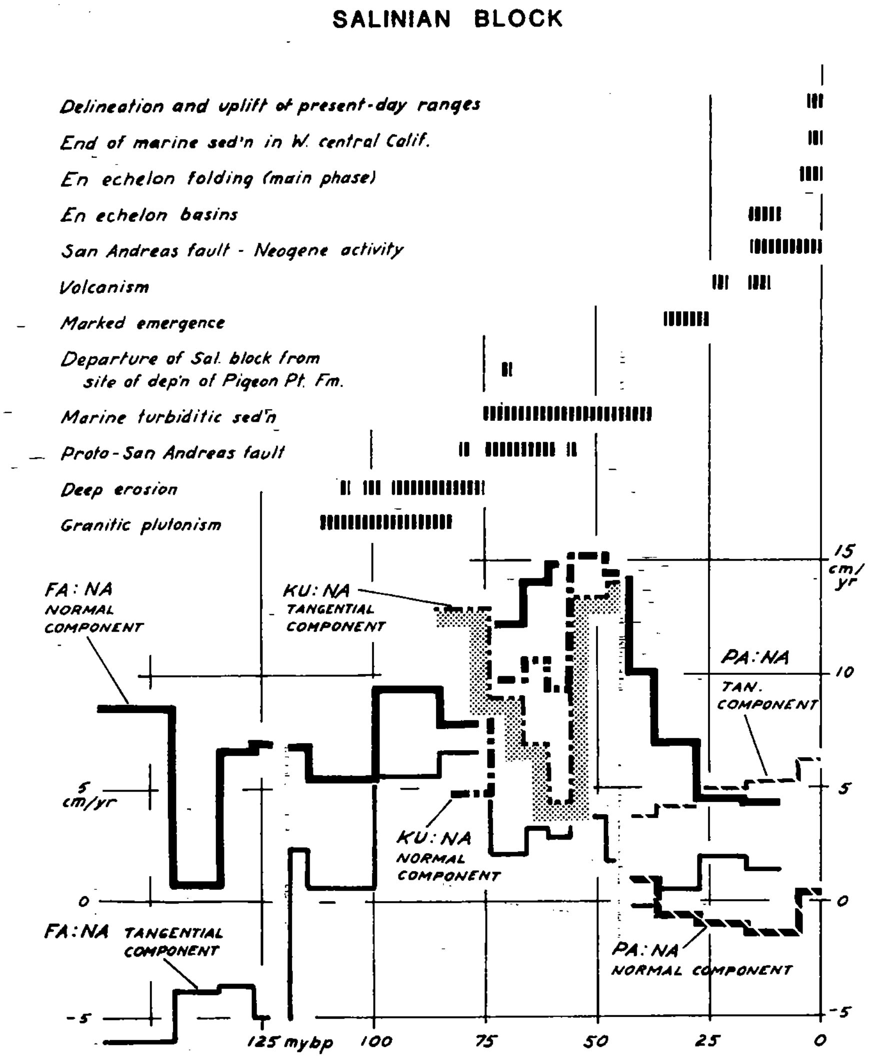


Fig. 9. Chart of events in Salinian Block, compared with relative plate motions. Plate motions from Engebretson [1982].

have been less than for the Sierra Nevada, as the scene of action would have been closer to the poles of relative motion, which were successively in the South Atlantic and in South America.

We tentatively ascribe the megatranslation of the Salinian block mainly to KU:NA oblique convergence, eventually supplemented by the influence of the Farallon and Pacific plates. However, we are barely able to account for poleward movement as great as paleomagnetic data seem to require, even after stretching the geologic constraints to the limit. From 85 to about 28 m.y. B.P., the Kula and Farallon are the only known plates which might have been in contact with western North America. Of these two, the Kula alone had a large dextral coastwise component of motion (Figures 5, 9).

We will not attempt to explain the departure of Salinian basement rocks from their unknown original location, but will address the movement of the Pigeon Point Upper Cretaceous sediments. We will assume that they started a 2500 km coastal journey from a site near the Mexican margin at present-day latitude 20°N, and we will assume that the margin was oriented N25°W, which would have been more favorable than the present-day N61°W trend. Under these circumstances, Kula-North America relative motion could only propel the Pigeon Point Formation 600-700 km between 70 and 55 m.y. B.P.—a sadly insufficient amount.

A 2500 km journey could be more readily explained if the trend of the margin of Mexico were more nearly north-south than we have assumed. We know of no published observation that would accurately indicate the former trend. Obviously, the component of tangential relative plate motion is strongly dependent upon the orientation of the plate boundary vis-a-vis its position with respect to the Euler pole of rotation. During much of the period of interest, the KU:NA pole was in or near the northwest corner of South America (Figure 4). The explanation of Salinian megatransport could also be made easier by enlarging the time window to take advantage of some of the Kula plate's most favorable epochs of motion. If the Pigeon Point Formation is actually 77-80 m.y. in age instead of 70-75 m.y., and if it traveled under the influence of the Kula plate from 75 to 50 m.y. B.P., it could have moved 1500 km along a coastline trending N25°W. The balance of the journey could have been provided by the Farallon plate from 50 to 28 m.y. B.P., giving 500 km at most, and the Pacific plate from 28 to 0 m.y. B.P., contributing 400 km. (The 400 km is the sum of Neogene slip on the SAF and San Gregorio-Hosgri faults). The grand total for Salinian transport since 75 m.y. B.P. would be 2400 km. This maximum result takes advantage of 100% of the available coastwise components of motion and is therefore unrealistic, and it requires the time window to be broader than geologic evidence would indicate. We conclude that the postulated motions or apparent constraints are seriously inaccurate in one or more of the following ways: (1) The paleomagnetic results are in error; (2) the reconstructed plate motions are in error; (3) the dating of the allochthonous rocks is in error; or (4) the assumed N25°W trend for the Mexican coastline is in error.

Neogene Salinian events, like those elsewhere in the Coast Ranges, are largely the result of PA:NA transform interaction [Atwater, 1970]. Some en echelon sedimentary basins began to form in the Salinian terrane about 15 m.y. B.P. [Graham, 1978] when transform-related strain began to migrate inland from the defunct trench. The SAF revived at about the same time, and other strike slip faults became active (e.g., the San Gregorio-Hosgri and Rinconada faults). As elsewhere in the Coast Ranges, the most marked en echelon folding was temporally synchronous with spreading in the Gulf of California, commencing about 4 m.y. B.P., when the western fringe of California began to move more decisively (albeit differentially) under the influence of the Pacific plate. The part of the Salinian block which is now on land emerged above sea level 3-4 m.y. B.P., and individual ranges (e.g., Gabilan, Santa Lucia, Santa Cruz) began to rise about 1-3 m.y. B.P. In view of the orientation of the ranges parallel with the plate boundary, their rise could conceivably be related to the slight convergence which seems to have accompanied transform motion during the last 5 m.y.

CONCLUSIONS

Mixed results have been achieved from our initial attempt to relate geological events in California to computed plate motions.

The important late Mesozoic periods of plutonism in the Sierra Nevada and the postulated collisional event of the Nevadan orogeny [Schweickert and Cowan, 1975] correlate well with the reconstructed convergent motion between the Farallon and North American plates. This is not surprising in view of the generally accepted long-continued convergence along the eastern rim of the Pacific basin.

We believe that the pronounced diminution of convergence 145-135 m.y. B.P. may have been a factor in the formation of the Independence Dike Swarm, although there is a small mismatch in timing. The lack of plutonism from 134 to 121 m.y. B.P., despite the resumption of convergence, is puzzling; however, part (or all) of the interlude may represent a normal delay between the start of subduction and large-scale generation, emplacement, and cooling of plutons.

The assembling of the older parts of the Franciscan Complex is, like the Sierran plutonism, ascribed to FA:NA convergence. The latter prevailed over such a large span of latitude, it most likely played a key role even if parts or all of the complex originated far south of its present location. A strong pulse in FA:NA convergence about 100-85 m.y. B.P. seems to account for the origin of the Coast Range thrust, which apparently originated between 96 and 88 m.y. B.P., based on geologic evidence.

The most troublesome uncertainty is the question of which plate, Kula or Farallon, interacted with the margin of California in the interval 85-43 m.y. B.P., or any part thereof. The deduced properties and behavior of the Farallon plate would make it ideally suited for low-angle, rapid subduction that would explain the Laramide orogeny about 75-45 m.y. B.P. On the other hand, the FA:NA motion lacked a strong, long-continued dextral coastwise component which is required for large-scale translation of Franciscan rocks and the Salinian block during the same time interval. The KU:NA motion could largely account for both the Laramide and the migration events along the coast, but not with ease.

It is difficult to satisfy paleomagnetic requirements for 2500 km of coastwise movement of Salinian rocks even by taking unrealistically full advantage of available favorable components of KU:NA America motion and stretching the geologically constrained time window to an improbable extent. Therefore we suspect that there are substantial errors in apparent ages of rocks, paleomagnetic interpretations, the assumed coastline trend, and/or computed plate motions for the time interval in question.

Geologically dated Neogene strike slip faulting and en echelon folding correlate well with PA:NA transform motion, and the accentuation of these crustal disturbances in the last 4 m.y. coincides well with the initiation of spreading in the Gulf of California and concurrent attachment of westernmost California to the Pacific plate. Some volcanic events coincide temporally with the passage of the Mendocino triple junction.

The rise of individual Coastal ranges, commencing 1-3 m.y. B.P., as well as the development of certain folds and thrusts parallel with the plate boundary, may possibly be related to a perceived slight convergence superposed on the PA:NA transform motion within the last 5 m.y.

The tectonic history of the Coast Ranges northeast of the San Andreas fault, and that of the Salinian block, are similar for the Neogene, as are their respective correlations with plate motions. This similarity reinforces the likelihood that the two subprovinces were in mutual proximity by mid-Miocene time, if not earlier.

Acknowledgments. We are grateful to Myrl Beck Jr., Allan Cox, Richard Gordon, Lisa Kanter, George Thompson, Richard Schweickert, M. Clark Blake, and Raymond Ingersoll for encouragement and helpful ideas. Beck, Schweickert, Blake, and Ingersoll reviewed the manuscript and suggested important improvements.

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(Received November 11, 1983; accepted November 11, 1983.)