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PLATE TECTONICS AND THE CONTINENTAL MARGIN OF CALIFORNIA

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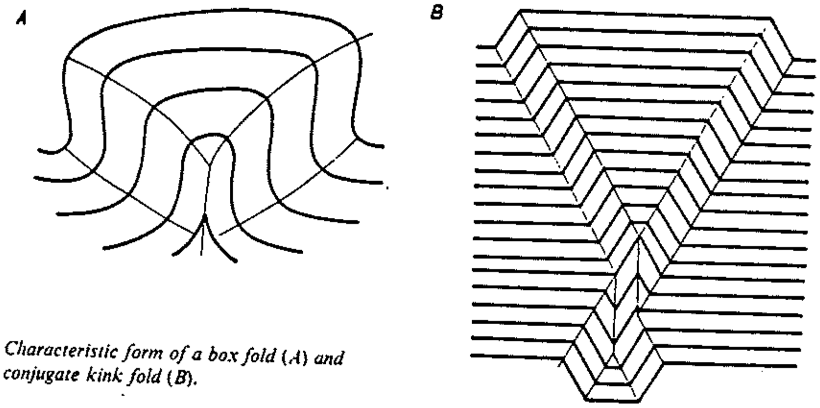
	Formation	Strike	Dip	D
0	Claremont	N50W	88W	
1	Orinda	N75W	85E	
2	Orinda	N60W	75E	
3	Orinda	N70W	83E	
4	Orinda	N80W	70E	
5	Orinda	N80W	70E	
6	Rhyolite	N60W	80E	
7	Rhyolite	N70W	70E	
8	Rhyolite	N54W	68E	
9	Rhyolite	N68W	68E	
10	Siesta Valley	N60W	60E	
11	Siesta Valley	N70W	53W	
12	Siesta Valley	N80W	62W	
13	Siesta Valley	N63W	53W	
14	Siesta Valley	N75W	38W	
15	Siesta Valley	N44W	45W	Near E. Peak F.
16	Bald Peak	N74W	15E	Flow Banding
17	Grizzly Peak	N68W	45W	Limestone
18	Grizzly Peak	N80W	54W	Flow Banding
19	Grizzly Peak	N15W	30W	Limestone n. EP F.
20	Grizzly Peak	N70W	25W	Flow banding
21	Grizzly Peak	N61W	15W	Congl. ss
22	Grizzly Peak	N85W	27W	Rhyolite
23	Grizzly Peak	N68W	6W	Rhyolite
24	Grizzly Peak	N15W	25W	Rhyolite
25	Grizzly Peak	N85E	5S	Rhyolite
26	Grizzly Peak	N31W	15W	Rhyolite
27	Grizzly Peak	N54W	21W	Rhyolite
28	Grizzly Peak	N64W	5S	Rhyolite
29	Rhyolite	N10W	2W	Rhyolite
30	Rhyolite	N65E	20S	Rhyolite



Characteristic form of a box fold (A) and conjugate kink fold (B).

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ABSTRACT

The California continental margin has undergone four main stages of tectonic evolution: (1) a rifted Atlantic-type margin evolved through the late Precambrian and early Paleozoic, (2) a complex Japanese-type margin with offshore island arcs developed in the late Paleozoic and early Mesozoic, (3) an active Andean-type margin, with a trench along the edge of the continent, existed in the late Mesozoic and early Cenozoic, and (4) the present Californian-type margin, dominated by strike slip on the San Andreas transform fault system. The miogeoclinal Precambrian to Devonian succession of the eastern Cordillera was deposited along a passive continental margin following late Precambrian rifting that pursued a jagged course. Prominent marginal offsets in central Idaho and southern California delimited the Nevada segment of the rifted margin where Paleozoic sedimentary facies were most fully developed. Interactions of offshore island arcs with the continental margin led to the thrust emplacement of allochthonous oceanic facies by partial subduction and crustal collision during the Devono-Carboniferous Antler Orogeny and the Permo-Triassic Sonoma Orogeny. Extensive island arc terranes were thus accreted to the continental margin by mid-Triassic time. By the beginning of Jurassic time, subduction had begun beneath the expanded continental margin along the Sierra Nevada Foothills. Further accretion of intraoceanic Jurassic island arc terranes along the Foothills suture belt induced subduction to shift into the Coast Ranges by the end of Jurassic time. The Cretaceous arc-trench system included the Franciscan subduction zone in the Coast Ranges, the Great Valley forearc basin, the Sierra Nevada batholith representing the roots of the magmatic arc, and the backarc Sevier fold-thrust belt. An episode of plate descent at a shallow angle below the Cordillera during the Paleogene led to the Laramide Orogeny inland while subduction continued in the Franciscan terrane. Neogene evolution of the San Andreas transform system offset coastal slices of the continental block in complex patterns, and led to termination of arc volcanism inland where slab descent did not occur adjacent to the transform. Pervasive effects of plate tectonics on the geologic history of the continental margin include changes in sedimentation owing to shifts in paleolatitude and changes in base level owing to eustatic fluctuations in the volume of ocean water or ocean basins.

Ceno
Meso Andean
Paleo Jap
PreCamb rift

subduction migrated oceanward

?

INTRODUCTION

The architecture of the earth's surface harbors only two main components, continental blocks and oceanic basins, although gradational features intermediate between the two exist. Consequently, the topic of continental margins deals with the interfaces between oceanic and continental regions. Continental margins can have only four basic tectonic configurations (Fig. 1-1):

really, only four?

1. Atlantic-type margins, the passive margins, are formed by rifting along a divergent plate juncture whose later evolution develops a midoceanic rise or spreading ridge

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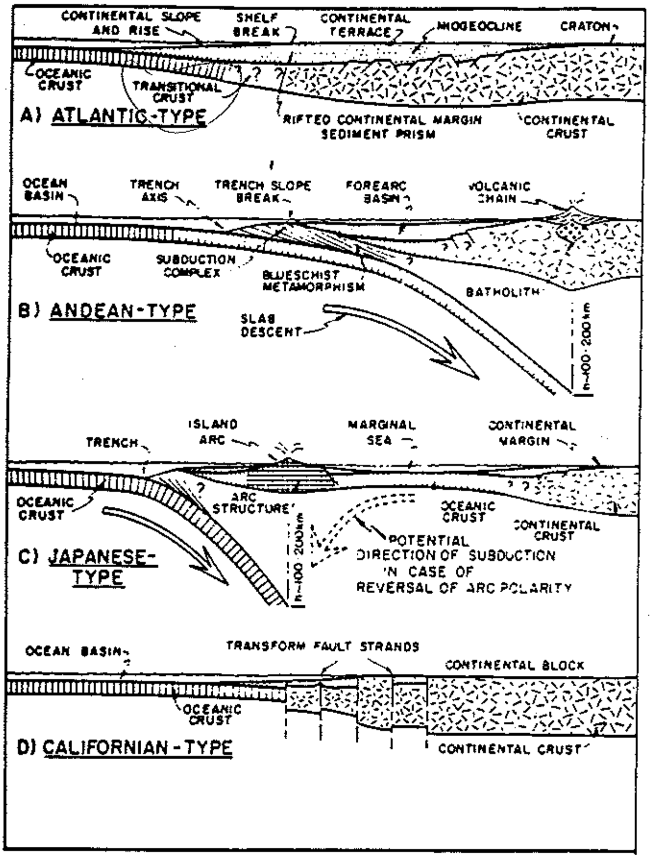

Fig. 1-1. Tectonic configurations of continental margins (after Dickinson, 1976). See text for discussion.

within the adjacent ocean basin; the ocean typically widens with time, although the passive margin may persist until the ocean begins to narrow by subduction elsewhere.

2. Andean-type margins, the classic active margins, form where subduction of oceanic lithosphere occurs at a trench along or near the edge of a continental block; the resulting arc volcanoes stand on the edge of the intact continental block, which extends unbroken across the backarc region.

3. Japanese-type margins are the most complex morphologically, because subduction occurs beneath offshore island arcs that are separated from the main continental block by small ocean basins of the marginal seas; in the classic case, marginal seas are formed by backarc spreading, but may also be older ocean floor merely trapped between arc and continent by seaward stepping of the subduction zone.

?

4. Californian-type margins are marked by relative lateral displacement of ocean

[redacted]

basin and continental block along a transform fault zone whose main fault strands are located within or near the continent-ocean interface (a belt of finite width).

The California continental margin has experienced all four of these kinds of tectonic regime during the course of recorded geologic history (Fig. 1-2):

1. Following rifting in late Precambrian time, an Atlantic-type margin persisted through the early Paleozoic until near the Devonian-Carboniferous time boundary; during this time span, the classic Cordilleran miogeocline evolved in an eastern belt of the Cordillera extending into the Mojave block of southeastern California.
2. From Late Devonian-to-Late Triassic times, a Japanese-type margin with offshore island arcs was either persistent or recurrent; during this time span, much of the eugeosynclinal terrane in the western Cordillera, including most of the Sierra Nevada block, was accreted to the continent during the Antler and Sonoma orogenies.

Sierra Nevada Block. — is this the batholith? it can't be, the age of the batholith 120-80 Ma

where are these now

3. From near the Triassic-Jurassic time boundary until the onset of the Neogene at the Oligocene-Miocene time boundary, an Andean-type margin was continuous as part of the circum-Pacific subduction system; effects included the Nevadan, Sevier, and Laramide orogenies, and accreted terranes include those of the Sierra Nevada Foothills, much of the Klamath block, and most of the Coast Ranges.

Nevadan
Sevier
Laramide

4. During the Neogene, plate interactions along the coast gave rise to the San Andreas transform system that now dominates the present Californian-type margin; Neogene intraplate deformation also formed the Basin-and-Range province of the intermountain region, including easternmost California and parts of adjacent states.

accretion

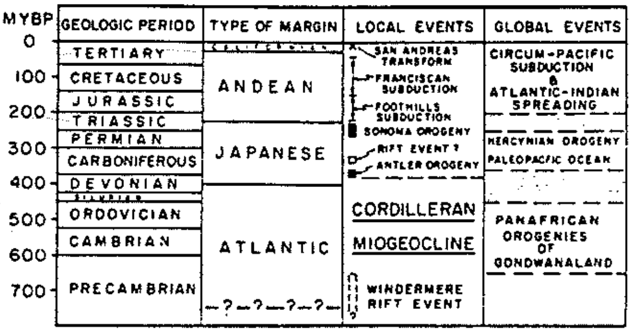

Fig. 1-2. Major phases and events of Cordilleran history shown in relation to key global trends. Time scale generalized after Lambert (1971).

These evolutionary tectonic stages in the history of the California margin can be discussed either in the order in which they happened, from ancient to modern, or in the order in which they must be reconstructed, from modern to ancient. Certain technical advantages lie in both directions. For clarity, I will follow the flow of time from ancient to modern. Bear in mind, however, that my homework was completed in the opposite fashion, from modern to ancient, before I could begin my exposition.

The reconstruction of past plate interactions depends upon the ability to interpret the significance of key petrotectonic assemblages, which are associations of rock masses diagnostic of specific plate tectonic settings (Dickinson, 1972). For the four main types of continental margins, the following petrotectonic assemblages are the critical indicators or signals in the rock record:

1. For Atlantic-type margins, an elongated wedge of shelf sediments, which rests unconformably on older basement rocks, thickens laterally toward the old ocean basin; where the adjacent ocean basin has been closed subsequently by subduction, the sediments thicken instead toward a tectonic join against a parallel belt of deformed but coeval oceanic strata.

2. For Andean-type margins, an intricately deformed belt representing a subduction complex, which formed by detachment of surficial layers from a descending plate at a trench and is composed of oceanic sediments, ocean-floor lavas, and ophiolitic scraps of oceanic crust, lies outboard and parallel to a coeval belt of metavolcanics and batholiths representing the igneous suite of a magmatic arc. Commonly, an intervening belt of relatively undeformed and unmetamorphosed sedimentary rocks was deposited within forearc basins of the arc-trench gap, while deformation and metamorphism were underway in the flanking subduction zone and magmatic arc.

3. For Japanese-type margins, metavolcanic belts representing island arcs are separated from rock masses formed along the edge of the continental block by coeval oceanic assemblages that formed within the intervening marginal sea. Once the marginal sea is closed by subduction, the oceanic assemblages are crumpled by severe deformation along the suture belt that formed by later crustal collision (disscussed later) between the exotic rock masses of the offshore island arc and the indigenous ones of the continental margin.

4. For Californian-type margins, disparate sedimentary facies and basement terranes are juxtaposed in elongate belts that have been shuffled complexly by strike slip parallel to the continental margin. Lateral displacement of sediment piles with respect to sediment sources is contemporaneous with deposition and is cumulative with time.

LATE PRECAMBRIAN AND EARLY PALEOZOIC

The initial stage in the evolution of the California continental margin was the deposition of the miogeoclinal sediment wedge along a passive continental margin of Atlantic type (Stewart, 1972). The rifting that initiated deposition was accompanied or preceded by basaltic volcanism at about 850 m.y.b.p. (Dickinson, 1977). Continental separation was probably not completed, however, until about 650 m.y.b.p. (Stewart and Suczek, 1977), or not long before the start of the Cambrian. Sedimentation was thereafter essentially continuous along the passive continental margin until the Late Devonian, when the onset of the Antler Orogeny marked the advent of a wholly different tectonic regime (Dickinson,

[redacted]

no unconformity

1977). At that time, regional thrusting carried eugeoclinal oceanic facies eastward as a deformed allochthon across the miogeoclinal strata (Stewart and Poole, 1974).

Any extrapolation of plate-tectonic concepts into the Precambrian involves some degree of inference. In the present instance, the degree is minimal and of the same order as that required for the application of plate tectonics to ideas about the Paleozoic. Moreover, there is a logic that forces the extrapolation. Facies relationships of lower Paleozoic strata in Nevada document the existence of a passive continental margin of Atlantic type (Lowell, 1960). Those strata pass conformably downward in the Death Valley region into the latest Precambrian strata (Stewart, 1970). Thus, the Cordilleran continental margin either was created by rifting of some kind during the late Precambrian or had existed since the time that crustal blocks first formed early in the Precambrian.

lower Paleozoic
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PreCambrian
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sedimentary
record

If the Cordilleran margin had long existed, then some igneous and metamorphic record of an active continental margin, or some long sedimentary record of a passive continental margin, should be present within the region. However, neither is the case. There is certainly no hint that any coherent age belt of Precambrian basement rocks lies parallel to the Cordilleran trend. Quite to the contrary, the transcontinental trends of the Precambrian age belts that sweep across the continent are sharply truncated by the trend of the Cordilleran miogeocline (see Fig. 1-3). Nor does the sedimentary record of the miogeocline extend far back into the Precambrian. Although the basal strata do lie below the lowest known Cambrian fossils, the inland flank of the sediment wedge rests with marked angular unconformity across the whole array of Precambrian age belts.

ANTLER - Devonian
360 Ma

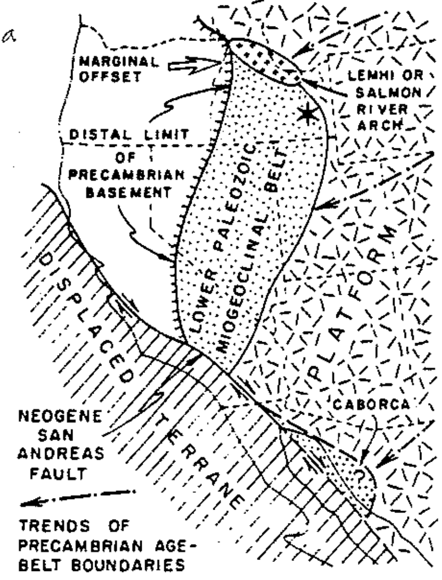

Fig. 1-3. Principal tectonic elements of Cordilleran rifted continental margin of the early Paleozoic (post-Windermere, pre-Antler). Modified after Stewart (1972), Stewart and Poole (1974, 1975), and Suczek (1977a, b). Asterisk denotes Precambrian Bannock Volcanics near Pocatello.

Precambrian Rifting

The early history of the continental margin was somewhat different in the northern and southern parts of the Cordillera. In Canada, initial rifting probably preceded Belt-Purcell deposition that began about 1450 m.y.b.p. (Gabrielse, 1972). This sedimentation apparently followed pre-Grenville continental separation of a crustal block that did not extend south of the type Belt-Purcell basin lying athwart the international boundary (Dickinson, 1977). Farther south, the earliest continental separation leading to the inception of miogeoclinal deposition was evidently a post-Grenville event (Stewart, 1972). In the north, the old Beltian margin was doubtless modified considerably by the later event, which triggered Windermere deposition, for Belt and Windermere strata are separated by a regional unconformity. The Belt and Windermere sequences are both thick wedges of clastic sediments that thicken westward.

The ultimate test of these or other ideas about continental rifting along the Cordillera will be the ability to detect the existence of the detached continental fragments elsewhere in the world. The various crustal blocks separated by suture belts within the composite modern continent of Eurasia (including Alaska) are prime prospects for correlation. Secondary prospects are those crustal blocks that were present within the supercontinent of Gondwana following the Panafrican orogenic events near the Precambrian-Paleozoic time boundary. Because of the Precambrian ages of the postulated rifts, correlation must consist of matching templates defined not by fossils but by radiometric age belts and paleomagnetic polar paths. Unfortunately, the key targets for study lie within interior Eurasia in places that are largely inaccessible politically to field geologists from elsewhere.

Dating of the rifting event associated with Windermere deposition is not yet satisfactory. Interbedded basaltic volcanics near the international boundary were erupted roughly 850 m.y.b.p. However, continued terrestrial deposition above the lavas locally suggests that final continental separation may have been much later. A key component of the Windermere succession along the whole length of the Cordillera is a unit of tillites and associated glaciomarine turbidites. These strata may ultimately provide unique constraints on the timing and paleolatitude of the rifting, although better data are needed to proceed further.

The tillite sequence probably reflects deposition either at high paleolatitudes or within and near highlands presumably formed by thermotectonic uplift along the rift belt prior to and during continental separation. Thus, if the tillites are truly correlative in a time-stratigraphic sense, either a uniformly polar position for the rift belt or simultaneous rifting may be implied. Independent paleomagnetic data potentially can resolve such a question. If the tillites are not coeval, but occur in stratigraphic association with comparable depositional phases of the Windermere rift sequence, then diachronous rifting would be suggested. Diachronous rifting would also be indicated if the tillites are coeval but associated with disparate depositional phases of the Windermere rift sequence. In the general case, of course, plate movements would be expected to generate some diachroneity of both glaciation and rifting across any region as large as the whole Cordillera.

Paleozoic Miogeocline

Between southeastern California and southeastern Idaho, the strike of the Cordilleran miogeocline is generally continuous across Nevada and Utah in a belt now 250 to 500 km wide (Stewart and Poole, 1974). The aggregate thickness of pre-Antler strata increases regularly from perhaps 1000 m at a hinge line on the southeast to about 10,000 m near the Paleozoic orogenic front on the northwest. The shape and dimensions of the sediment wedge are similar to those present beneath the continental terraces or shelves that border the Atlantic Ocean today. Moreover, the rate of sedimentation of shelf deposits within the Cordilleran miogeocline declined logarithmically through time in a manner compatible with the inferred thermotectonic subsidence of a rifted continental margin (Stewart and Suczek, 1977). A basal clastic phase of latest Precambrian to mid-Cambrian sandstones with associated shales and conglomerates attains local thicknesses of as much as perhaps 7500 m, whereas overlying mid-Cambrian to mid-Devonian carbonates and shales nowhere exceed 5000 m in thickness. Some of the initial clastics were probably shed from relict highlands associated with the rift belt that delineated the Cordilleran edge of the continent, but most were dispersed westward from the stable craton of the continental interior. Carbonate sediment was generated along the miogeoclinal trend itself, within a belt of organogenic productivity in the carbonate factory at shelf depth in marine waters (Matti and McKee, 1977).

The overthrust Roberts Mountains allochthon of the Antler orogen contains complexly deformed lower Paleozoic turbidites, argillites, cherts, and greenstones. These strata are interpreted as the deposits of the continental rise and ocean basin that lay adjacent to the rifted Cordilleran margin during early Paleozoic time; transitional facies probably represent continental slope deposits (Stewart and Poole, 1974).

Marginal Offsets

The failure of the Cordilleran miogeoclinal assemblage to continue along strike into central Idaho or into the modern Pacific Ocean off California requires explanation. Several authors have suggested that the miogeoclinal trend was truncated by a rifting event that carried away its southwestern extension during late Paleozoic or early Mesozoic time (e.g., Hamilton, 1969; Burchfiel and Davis, 1972). However, this type of explanation cannot apply to its truncation on the northeast against a Precambrian projection of the continental interior. Perhaps neither termination of the Nevada segment of the miogeocline reflects a postdepositional rifting event.

In plan view, most modern Atlantic-type continental margins display a jagged shape that reflects a compound origin as short rift segments linked by marginal offsets. The latter are oriented parallel rather than perpendicular to the spreading direction, and hence undergo transform faulting during continental separation and hinge faulting during later thermotectonic subsidence. Severe gashing or even rupture of the continental block may occur at the marginal reentrants where paired rift segments and marginal offsets meet. Moreover, the sedimentary history of rifted-margin segments and marginal-offset segments

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of the same continental margin may be distinctly different. Consequently, the regional distribution of miogeoclinal sedimentary units can be strongly affected by the locations of marginal offsets inherited from earlier rifting events.

affected by the locations of marginal offsets inherited from earlier rifting events.

Thus, the tectonic discontinuities that terminate the Nevada segment of the miogeocline in central Idaho and southern California are interpreted here as the record of marginal offsets of Precambrian age (see Fig. 1-3). Their trends together define the direction of rift movements during the continental separation that initiated the miogeocline. On the northeast, the trend of the offset is given generally by the elongation of the Lemhi or Salmon River Arch. The same orientation is suggested also by a line connecting major centers of Windermere volcanism in southeastern Idaho near Pocatello and along the international boundary between northeastern Washington and southeastern British Columbia. These volcanics may mark the position of eruptions akin to those that occur along marginal fracture ridges or within marginal reentrants. On the southwest, the trend of the offset is given generally by a line joining the western side of the Mojave block, where the miogeoclinal belt is last seen in California, with the area where thick Paleozoic strata reappear near Caborca in Sonora. Offsets within the much younger San Andreas transform system of similar trend have clearly spoiled any chance to view straightforward relationships along the older structure. For example, the western fringe of the Mojave block has now been faulted far to the northwest as part of the Salinian block in the Coast Ranges.

LATE PALEOZOIC AND EARLY MESOZOIC

The following stage in the evolution of the California continental margin saw the development of a complex Japanese-type morphology with offshore island arcs and marginal seas that influenced the evolution of the continental margin itself. In detail, the system was probably more complex than the Japanese system of the northwest Pacific and may have more closely resembled the Melanesian system of the southwest Pacific (cf. Churkin, 1974b). In particular, the polarity of the offshore island arcs was in part or at times reversed, with the trench on the continental flank of the island arc. This configuration allowed crustal collisions (Fig. 1-4) to occur between active island arcs and the passive continental margin inherited from the previous Atlantic-type stage of evolution. The Devono-Carboniferous Antler Orogeny and the Permo-Triassic Sonoma Orogeny both probably reflect collisions of this type along the continental margin where the Cordilleran miogeocline had been deposited (Dickinson, 1977). Thus, the Japanese-type configuration of the continental margin apparently prevailed from roughly mid-Devonian to mid-Triassic times.

During both the Antler and Sonoma events, oceanic assemblages of turbidites, cherts, argillites, and greenstones were thrust as allochthons across the western flank of the Cordilleran miogeoclinal belt. The Roberts Mountains allochthon of the Antler orogen contains only lower Paleozoic strata of Cambrian through Devonian age. The Golconda allochthon of the Sonoma orogen contains only upper Paleozoic strata of Car-

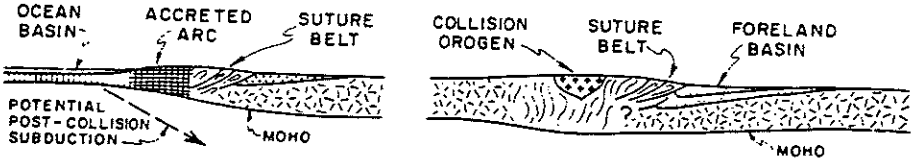


Fig. 1-4. Scenarios for crustal collision. Suture belts mark locations of former ocean basins closed by subduction. See text for discussion.

boniferous and Permian age. The internal structure of both allochthons ranges from complicated to chaotic. Recumbent isoclines, imbricated thrust sheets, schuppen zones of lenticular fault slices, sheared melange bands, and massive olistostromal layers are all present locally. Such tectonic complexity involving oceanic rocks is the mark of a subduction complex formed by the structural telescoping and tectonic stacking of successive increments of oceanic strata peeled by detachment off the top of an oceanic slab descending into the mantle at a subduction zone.

To emplace such a subduction complex upon a previously passive continental margin seemingly requires that the continental block be drawn partly beneath the subduction complex during crustal collision between the continental margin and an arc-trench system, which might be an intraoceanic island arc or might lie along an active continental margin (Fig. 1-4). Without the kind of tectonic contraction and plate descent implied by crustal collision, it is not clear how the stratified fill of the adjoining ocean basin can be either deformed or uplifted enough to cover the edge of the adjacent continental block with a complex allochthon.

The chief alternative for the emplacement of the two allochthons is the concept of backarc thrusting behind an offshore island arc. Although backarc thrusting is well known in association with continental-margin arcs, its occurrence has not been reported in connection with intraoceanic arcs. For an intraoceanic arc, behavior that included backarc thrusting would presumably be transitional to polarity reversal, whereby the main subduction zone shifts from one flank of the island arc to the other. The degree of tectonic dislocation and stratal disruption encountered in the two allochthons is clearly greater than that observed within typical backarc fold-thrust belts, such as the younger Cordilleran belt discussed later. Consequently, the crustal collisions responsible for the Antler and Sonoma events may well have stemmed from polarity reversal of offshore island arcs (cf. Moores, 1970; Speed, 1977), but not from minor backarc thrusting without polarity reversal.

Marginal Seas

With available data, the origins of the late Paleozoic marginal seas remain uncertain (Burchfiel and Davis, 1972; Silberling, 1973; Churkin, 1974a). They apparently were not simply interarc basins formed by backarc spreading, because there are no calc-alkalic igneous assemblages that could represent remnant arc terranes associated anywhere with the strata of the miogeoclinal belt that flanked the marginal seas (Dickinson, 1977). They were perhaps most likely to have been trapped marginal seas formed when initiation of subduction within a preexisting ocean basin formed intraoceanic island arcs not far from the Cordilleran continental margin. The possibility cannot yet be excluded, however, that they were residual marginal seas with only transient existence as remnants of large ocean basins. This idea holds that each wide ocean shrank in response to continued subduction beneath the flank of an exotic island arc that finally collided with the continental margin after the intervening ocean had closed completely (cf. Moores, 1970). In any event, the initial widths of the marginal seas are unknown at present.

Interpretations hinge critically upon whether the late Paleozoic island arc terranes of the present Klamath Mountains and Sierra Nevada stood close to the Cordilleran margin throughout their evolution. If so, prominent pulses of Devono-Carboniferous and Permo-Triassic volcanism along the Sierran-Klamath trend invite correlation with the Antler and Sonoma events of similar timing farther east, and make some brand of backarc thrusting both an attractive and plausible suggestion (e.g., Burchfiel and Davis, 1972). To date, however, there is no paleomagnetic confirmation of the late Paleozoic position of these terranes with respect to the Cordilleran margin. In the overthrust allochthons farther east, there is a surprising paucity of volcanic debris except in direct association with pillow lavas and pillow breccias regarded as fragments of Paleozoic ocean floor. Unless some record of volcaniclastic detritus can be discerned in turbidites of the overthrust oceanic assemblages, it seems unlikely that the strata could represent the fill of marginal seas bounded on one side by fringing island arcs of normal polarity, with subduction downward toward the continent as for modern Japan. Even the presence of island arcs of reversed polarity should be reflected by the occurrence of ash layers within the sediment sequence for all times during which the island arcs stood close to the Cordilleran margin, unless prevailing winds blew consistently or intermittently offshore. A careful census of the volcaniclastic detritus within the Roberts Mountains and Golconda allochthons thus deserves high priority. It is my impression that little if any calc-alkalic debris is present in either assemblage.

Antler Orogeny

The Antler Orogeny is the more mysterious of the two Paleozoic orogenies, for we really cannot be sure what entity collided with the Cordilleran margin then. For all we actually know, it could have been a continental-margin arc on the edge of another continent, although an intraoceanic arc is ordinarily postulated. The reason for the uncertainty is that only the overthrust subduction complex of the Roberts Mountains allochthon subsequently remained permanently attached to the Cordillera. Other elements of the Antler Orogen were evidently rifted away during Carboniferous time, for late Paleozoic ocean floor formed adjacent to the Cordilleran margin between Antler and Sonoma time, just as early Paleozoic ocean floor had formed offshore between Windermere and Antler time.

As a result of the Antler Orogeny (Fig. 1-5), an asymmetric foreland basin formed

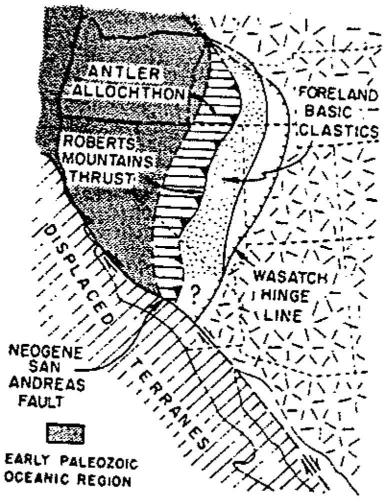


Fig. 1-5. Principal tectonic elements of Devono-Mississippian Antler Orogeny along mid-Paleozoic Cordilleran margin. Modified after Burchfiel and Davis (1972, 1975), Poole (1974), Poole and Sandburg (1977). Wasatch hinge line is the cratonal margin of the miogeoclinal belt (see Fig. 1-3).

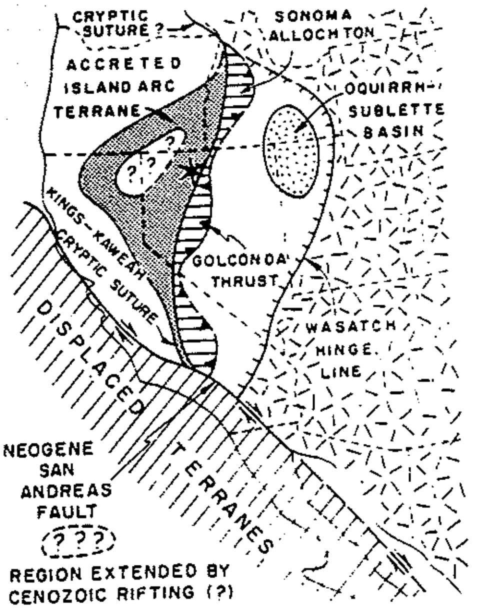
east of the Roberts Mountains allochthon where the weight of the allochthon induced a sort of isostatic moat, which subsided by flexure of the continental lithosphere. The keel of the foreland basin lay in the central part of the formerly miogeoclinal belt. Clastic wedges dumped into the foreland basin from the Antler Orogen included both subsea fans and deltaic complexes (Poole, 1974; Nilsen, 1977). In mid-Carboniferous time, when erosion had reduced the Antler Orogen to a level subject again to marine transgression, deep basins began to form in several places along the eastern flank of the Antler foreland where only fine clastics had been deposited previously. These basins included the huge Permo-Carboniferous Oquirrh-Sublette basin of Utah and Idaho, as well as poorly understood troughs in the Death Valley area where varied carbonate turbidites and associated strata of similar age are quite thick locally (Dickinson, 1977). Perhaps these post-Antler, pre-Sonoma sedimentary basins reflect subsidence following extensional deformation of the Cordilleran margin at the time that some form of rifting broke up the Antler Orogen.

Sonoma Orogeny

As a result of the Sonoma Orogeny (Fig. 1-6), extensive island arc terranes exposed now in the Klamath Mountains, northern Sierra Nevada, and northwestern Nevada were accreted to the continental margin (Speed, 1977). The time of suturing was roughly mid-Triassic (Dickinson, 1977), although the final incorporation of accreted terranes may have been slightly earlier or later from place to place along the irregular continental margin. At the same time, the Golconda allochthon was thrust partway across the eroded remnants of the Antler Orogen, but no prominent foreland basin was formed farther east. Instead, local but rapidly subsiding basins along the trend of the suture belt received thick clastic accumulations such as those in the Auld Lang Syne Group of Nevada.

The Roberts Mountains and Golconda allochthons of the Antler and Sonoma oro-

Fig. 1-6. Principal tectonic elements of Permo-Triassic Sonoma Orogeny along accretionary mid-Triassic Cordilleran margin. Modified after Silberling (1973), Burchfiel and Davis (1972, 1975), and Speed (1977). Asterisk denotes location of Auld Lang Syne sutural basin. Blank area between thrust belt and hinge line was largely submerged shelf.



gens are best preserved along the Nevada segment of the Cordilleran miogeocline within a marginal reentrant of the early Paleozoic continental margin (see Figs. 1-3, 1-5, 1-6). To the north, the allochthonous overthrust terranes narrow and eventually pinch out between accreted island arc terranes exposed along Hells Canyon of the Snake River and the projection of Precambrian basement cut by the younger Idaho batholith in central Idaho.

To the south, the overthrust belts strike into the central Sierra Nevada, and are among the tectonic elements that may have been truncated by rifting, together with the parallel miogeoclinal belt. However, the same irregular continental margin and marginal offsets inferred previously to explain the distribution of Paleozoic miogeoclinal facies can also be used to explain the distribution of allochthonous Paleozoic oceanic facies.

The key feature is an isolated remnant of the allochthons located near Garlock Station beside the Garlock fault in the Mojave desert. This Garlock or Mojave remnant of oceanic facies lies well inland from the western limit of Precambrian basement rocks in southern California. It is also much closer to the Wasatch hinge line (see Figs. 1-5 and 1-6), which marks the eastern limit of the miogeoclinal belt, than are comparable klippen farther north. The relations of the Garlock or Mojave allochthon remnant thus suggest important contrasts in the emplacement of thrust sheets along the continental margin during the Antler and Sonoma orogenies. The contrasts can be ascribed as follows to differences in the behavior of rifted-margin and marginal-offset segments of the Paleozoic continental margin during the thrusting associated with later collision events:

1. Simple extensional rifting during inception of the Nevada segment of the rifted margin caused attenuation of continental crust across a wide belt, which subsided to ac-

cumulate the well-developed band of miogeoclinal strata (see Fig. 1-3); during the later emplacement of allochthonous oceanic facies by partial subduction of the continental margin, this broadly attentuated segment was well adapted to extensive preservation of the allochthons, especially along the oceanic flank of the miogeoclinal belt far from the hinge line marking the continental limit of major subsidence.

2. In central Idaho and southern California, however, projections of the continental platform extended anomalously far to the west adjacent to marginal offsets in the initial continental margin; during later thrust emplacement of the allochthons, these relatively intact projections of the continental block could not be subducted as readily as could the attenuated Nevada segment. Consequently, the allochthons either were not emplaced as widely or were eroded more generally in central Idaho and central California than in the intervening ground; where locally present, however, as in the Garlock or Mojave locality, the allochthons extend closer to the stable craton of the continental interior.

In brief, then, marginal reentrants like the Nevada segment underwent relatively mild crustal collision owing to relative ease of partial subduction, and display widespread preservation of oceanic allochthons; by contrast, continental projections induced much stronger deformation during crustal collision, which involved more pronounced telescoping of crustal blocks and more marked uplift leading to general erosion of allochthons (e.g., Dewey and Burke, 1974).

Crucial for a correct interpretation of Sonoma orogenic events are the geologic relations of the complex fault zone termed the Kings-Kaweah suture in the southern Sierra Nevada (Schweickert and others, 1977; Saleeby, Chapter 6, this volume). Commonly viewed as a post-Sonoma transform associated with rift truncation of Paleozoic orogenic trends, the feature may instead be part of the arc-continent suture created by crustal collision during the Sonoma event.

LATE MESOZOIC AND EARLY CENOZOIC

The next stage in the tectonic evolution of California was the inception and maturation of an arc-trench system with a terrestrial volcanic chain standing along an active continental margin of Andean type (Hamilton, 1969). The earliest magmatism clearly related to this tectonic regime was latest Triassic or earliest Jurassic in age (Schweickert, 1976b, in press). The Cordilleran arc-trench system of later Mesozoic and Cenozoic age (Dickinson, 1976) was the local expression of widespread circum-Pacific subduction that began at a similar time along most parts of the Pacific rim. It is surely no accident that circum-Pacific subduction has thus been coeval with expansion of the Atlantic and Indian oceans (Dickinson, 1977). Prior to Atlantic and Indian opening, sea-floor spreading within an expanding paleo-Pacific realm was probably paired in time with the late Paleozoic closure of oceans along suture belts within and marginal to Laurasia during the final assembly of Pangaea. The pre-Jurassic floor of the paleo-Pacific has been wholly subducted beneath the circum-Pacific orogenic system, and the floor of the modern Pacific is entirely Jurassic or younger.

The Cordilleran arc-trench system was probably initiated by flip or reversal of arc polarity following the culmination of arc-continent collision during the Sonoma Orogeny (see Fig. 1-4). Accretion of the eugeosynclinal arc terrane in the Sierra Nevada and adjacent areas terminated westward subduction beneath the island arc and induced eastward subduction beneath the accretionary edge of the expanded continent. Associated volcanics and plutonics that date near the Triassic-Jurassic time boundary by both paleontologic and radiometric methods form the oldest linear belt of fully indigenous igneous rocks along the Cordilleran margin (see Fig. 1-7). This magmatic suite was erupted and emplaced partly within the recently accreted eugeosynclinal terrane of upper Paleozoic island-arc and ocean-floor assemblages, but also crosses the older miogeoclinal belt to punch up through continental basement rocks of Precambrian age in the Death Valley and Mojave regions. Volcanic detritus was first shed into the Colorado Plateau area of the intermountain region within the Upper Triassic Chinle Formation, a fluvial unit that tapped volcanic sources in highlands near the modern Mogollon Rim in Arizona.

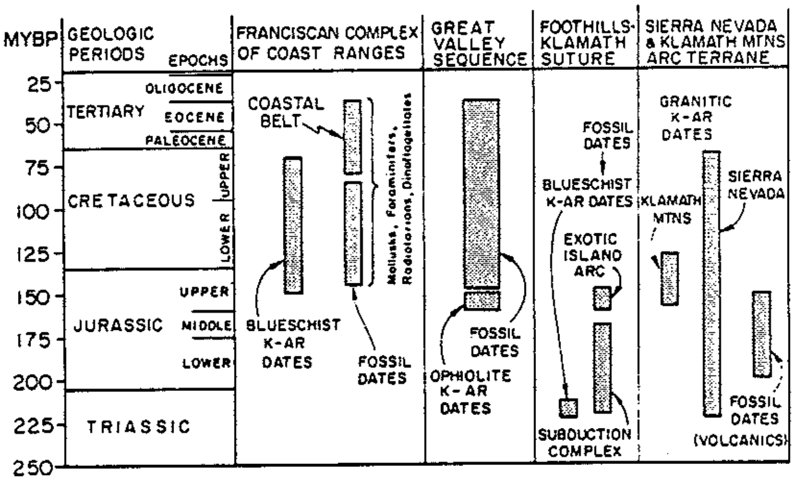


Fig. 1-7. Summary of pertinent age relationships among tectonic elements of Cordilleran arc-trench system. Key data from Armstrong and Suppe (1973), Blake and Jones (1974), Evitt and Pierce (1975), Hotz and others (1977), Irwin and others (1977), Jones and others (1976), Lanphere (1971), Lanphere and others (1978), and Suppe and Armstrong (1972).

Foothills Subduction

Prior to the Late Jurassic (Fig. 1-8), the subduction zone lay along the Sierra Nevada Foothills and within the Klamath Mountains (Schweickert and Cowan, 1975). The subduction complex is a terrane of intricately folded and faulted argillite, ribbon chert, and greenstone within which melangelike and olistostromal units are common, and pods of

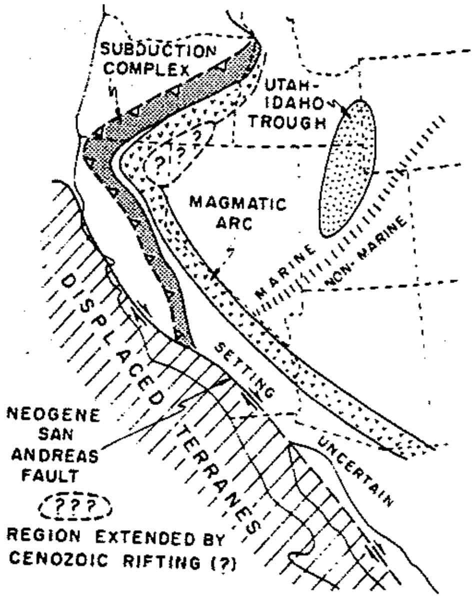


Fig. 1-8. Principal tectonic elements related to Late Triassic to Late Jurassic Foothills subduction zone and suture belt. Modified after Dickinson (1976).

serpentinite and other ophiolitic rocks are widespread. A metamorphic overprint has converted large segments of the belt to slate or phyllite, metachert, and greenschist or amphibolite, as in the Calaveras of the Sierra Nevada. Until recently, all the diagnostic fossils from these oceanic rocks were Paleozoic forms from minor limestone bodies. Dating of radiolarian cherts from the Klamaths has now shown, however, that both Triassic and Jurassic strata are also abundant (Irwin and others, 1977). Probably, the Paleozoic limestones were deposited on seamounts and other sea-floor prominences when the ocean floor was young and still at relatively shallow depth near midoceanic spreading ridges of the paleo-Pacific realm. The younger cherts and argillites were then deposited later after increments of the paleo-Pacific sea floor had subsided prior to insertion into the circum-Pacific subduction system during the Mesozoic. In general, young ocean floor stands relatively shallow and can receive calcareous sediment in favorable latitudes, but old ocean floor cannot receive calcareous sediment once it has subsided below the carbonate compensation depth.

The subduction complexes of combined Paleozoic and Mesozoic oceanic strata are caught now within the Foothills suture belt of the Sierra Nevada and along an analogous suture belt traversing the heart of the Klamath Mountains. East of the suture are the previously accreted eugeosynclinal terranes or segments of the preexisting miogeoclinal belt, and west of the suture are arc volcanics of largely Middle Jurassic age. Structural and stratigraphic relations across the suture belt are everywhere complex and not yet fully resolved. In general, however, the mid-Jurassic rocks west of the suture are less deformed and less disrupted than those of the subduction complex along the suture belt. Apparently, a Mesozoic island arc of intraoceanic origin was drawn into the Cordilleran subduction zone and accreted to the continental margin as a unit block or sliver; the crustal collisions involved apparently occurred within the Late Jurassic in California (Schweickert and Cowan, 1975). Farther north along the Cordillera, similar but even larger island-arc terranes of intraoceanic origin were added to the continental margin by analogous crustal collisions between mid-Jurassic and mid-Cretaceous time (Dickinson, 1976).

Franciscan Subduction

When the Foothills subduction zone was choked with the buoyant and exotic island arc and converted to a crustal suture belt, subduction along the expanding continental margin stepped oceanward into the Coast Ranges. Thus was generated the late Mesozoic arc-trench system (Fig. 1-9). The Franciscan assemblage was the subduction complex, the Great Valley Sequence accumulated in an elongate forearc basin within the arc-trench gap, and the Sierra Nevada batholith represents the intrusive roots of the magmatic arc (Dickinson, 1970). From Late Jurassic to Late Cretaceous, radiometric and paleontologic dates indicate that both deposition and metamorphism of the Franciscan Complex, deposition of the Great Valley Sequence, and emplacement of the Sierra Nevada plutons were coeval (Fig. 1-7). The blueschist metamorphic rocks of the Franciscan and the metamorphic wallrocks of the Sierra Nevada together form paired metamorphic belts of the classic kind linked elsewhere to processes within arc-trench systems (Miyashiro, 1967). No other geologic machine known is capable of generating simultaneously the high pressures and high temperatures required in such closely spaced subparallel belts.

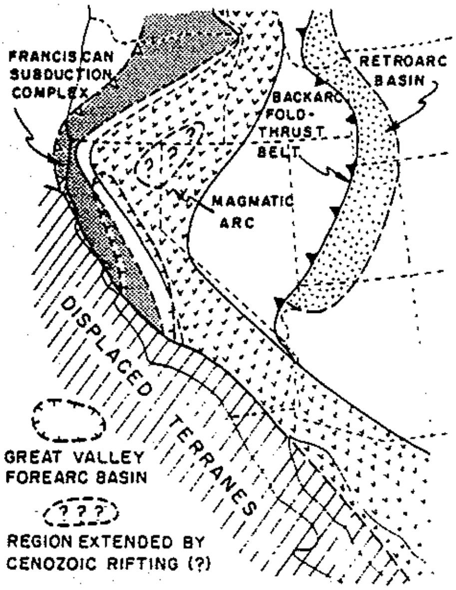
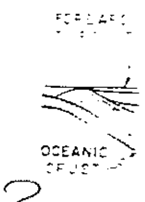


Fig. 1-9. Principal tectonic elements related to Late Jurassic to mid-Tertiary Franciscan subduction in California Coast Ranges. Modified after Dickinson (1976).

Lithologically, the Franciscan Complex is composed principally of lithic-rich and quartzofeldspathic turbidites, but also includes minor greenstone, chert, and limestone (Bailey and others, 1964). The varied facies present suggest that the Franciscan terrane is a vast collage of sea-floor pillow lavas, oceanic pelagites and hemipelagites, seamount volcanics, insular carbonate platforms, archipelagic sediment aprons, abyssal plain turbidites, trench fill turbidites, slope basin deposits, and shaly slope facies. All were presumably shuffled together somehow in the tectonic setting of the trench inner slope. The grade of blueschist metamorphism increases eastward toward the arc terrane (Ernst, 1975), reflecting successively greater depths of subduction.

In detail, several aspects of the Franciscan Complex remain enigmatic (e.g., Blake and Jones, 1974). The question of whether the characteristic lentiform structure of shear surfaces in the disrupted melanges stems from strictly tectonic slicing or from deformation of already isolated blocks floating in olistostromal matrix is still under debate. The juxtaposition of thrust slices of contrasting metamorphic grade is still difficult to reconcile with any plausible geometric scheme for internal deformation within the complex (Suppe, 1972). Perhaps difficulty in understanding stems ultimately from geologic unfamiliarity with the physical conditions that likely exist within a subduction zone. Cool rocks are carried quickly to great depths and deformed there under high strain rates. Unusual conditions of subterranean fluid pressure may develop through deferred dehydration of clays and delayed dewatering of compacting sediment. Pore pressures may thereby greatly exceed hydrostatic and approach lithostatic. Abnormally brittle strain in response to tectonic stress may then be characteristic under such conditions of low temperatures and great depths.

The sedimentary evolution of the Great Valley Sequence conforms well to expected trends (Dickinson and Seely, 1979). Where thickest, it rests depositionally on an ophiolite sequence representing oceanic crust of Late Jurassic age. The oceanic substratum evidently represents a slice of ocean floor that was caught between the subduction zone and the arc massif. As this sliver of ocean floor lay immediately west of the Jurassic island arc that lodged in the Foothills subduction zone (see preceding discussion), it likely was generated by backarc spreading just prior to Late Jurassic crustal collision along the Foothills suture belt (Schweickert and Cowan, 1975). The steep western flank of the regional synclinorium within which the Great Valley Sequence is preserved is underthrust by the eastern part of the Franciscan subduction complex (Ernst, 1970), and imbricated thrust sheets of Great Valley strata are locally present farther west. Components of the accretionary Franciscan assemblage generally young westward on a broad scale (Berkland and others, 1972). An eastern Franciscan belt contains Upper Jurassic and earliest Cretaceous strata, a central Franciscan belt contains mostly Cretaceous strata, and a coastal Franciscan belt contains latest Cretaceous and Paleogene strata. The gentle eastern flank of the Great Valley synclinorium rests depositionally on eroded metamorphic and plutonic rocks of the Sierra Nevada arc massif, across whose eroded roots the basin margin transgressed through Cretaceous time. During the same time span, the axis of plutonism marking the magmatic front retreated eastward from the Foothills belt to the region of the present range crest (Evernden and Kistler, 1970). Thus, the arc-trench gap and the Great Valley forearc basin both widened with time in California.



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arc-massif - Sierra Nevada batholiths

Within the Great Valley proper (Fig. 1-10), Upper Jurassic strata are largely slope facies that initially prograded into an essentially starved forearc basin ponded behind an incipient subduction complex offshore. Lower Cretaceous strata are mainly turbidites deposited on a deep trough floor by longitudinal flow parallel to the structural grain defined by the basin margins, which were located at the flank of the arc massif on the east and at the position of the accretionary subduction complex on the west. Upper Cretaceous strata are principally subsea-fan turbidites that prograded into the forearc trough from sources in the arc massif. Slope and shelf facies associated with deltaic and shoreline complexes had begun to prograde into the forearc basin by latest Cretaceous time and were dominant within the Great Valley during the Paleogene.

Petrofacies within the Great Valley Sequence consistently reflect sediment derivation from igneous and subordinate metamorphic rocks of the arc massif (Dickinson and Rich, 1972). Not only are plutonic contributions present, but also volcanic debris from cover rocks that have since been almost entirely removed from the source by erosion. Lithic sandstones rich in volcanic rock fragments are dominant near the base of the sediment pile, whereas feldspathic sandstones rich in arkosic detritus derived from granite dominate near the top of the pile. Intermediate horizons contain varied mixtures of volcanic and plutonic materials whose proportions reflect the interplay between magmatism and erosion at different stages in the long evolution of the arc. Key petrologic trends in the igneous suite are faithfully recorded in the sedimentary suite. For example, potassium feldspar first becomes prominent in each at about mid-Cretaceous time. Compositionally, the Great Valley Sequence thus records the changing nature of the adjacent magmatic arc through time. The potassium content of the granitic plutons increases monotonically eastward (Bateman and Dodge, 1970), away from the subduction zone, in harmony with the transverse petrologic trends observed across modern arcs (Dickinson, 1975).

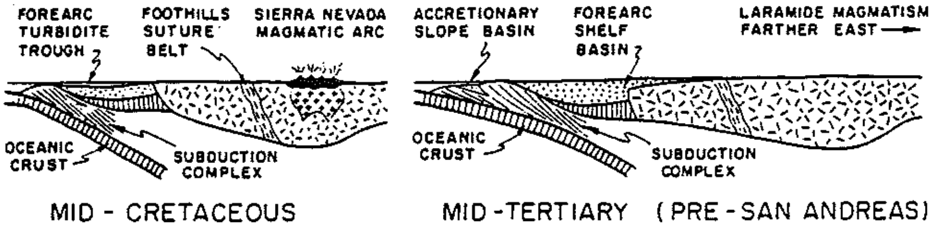

Fig. 1-10. Successive stages (schematic) in the evolution of the Mesozoic-Cenozoic forearc region in northern California. Adapted from Dickinson and Seely (1979).

Backarc Events

Behind the Mesozoic magmatic arc, a backarc fold-thrust belt was prominent along the Sevier belt in the region of the present Great Basin (Burchfiel and Davis, 1975). A prominent retroarc foreland basin occupied the area of the present Colorado Plateau and parts of the Rockies in the late Mesozoic (Fig. 1-9). By the end of Cretaceous time, however, arc magmatism had been extinguished within the Sierra Nevada, and the locus of inland

Laramide ~ ~~70 Ma~~ Paleogene 65 Ma
- no magmatism
Shallow subduction

deformation had shifted eastward from the thin-skinned Sevier belt into the classic Laramide region of the central Rocky Mountains (Armstrong, 1974). Laramide deformation involved wholesale crustal buckling of the interior foreland to form fault-bounded and basement-cored uplifts. The Laramide Orogeny in the eastern Cordillera was accompanied by a prominent Paleogene hiatus in arc magmatism covering the whole Great Basin in the western Cordillera. The presence of voluminous Paleogene clastic material in the Coastal Belt Franciscan suggests, however, that subduction continued unabated along the coast. By analogy with reported relations in the modern Andes (Fig. 1-11), the Paleogene magmatic null and the Laramide deformation can be attributed jointly to an episode of shallow subduction beneath the Cordillera (Dickinson and Snyder, 1978). Where plate descent is steep and the descending slab penetrates the asthenosphere, arc magmatism is prominent. Where plate descent is so shallow that the descending plate scrapes along beneath the overriding plate, arc magmatism is suppressed, and internal deformation is widespread across the dormant arc massif.

The Paleogene episode of shallow subduction is perhaps also recorded by the following additional geologic effects: (1) Beneath the granitic Salinian block of the central California coast, geophysical data may imply the presence of underthrust Franciscan rocks in

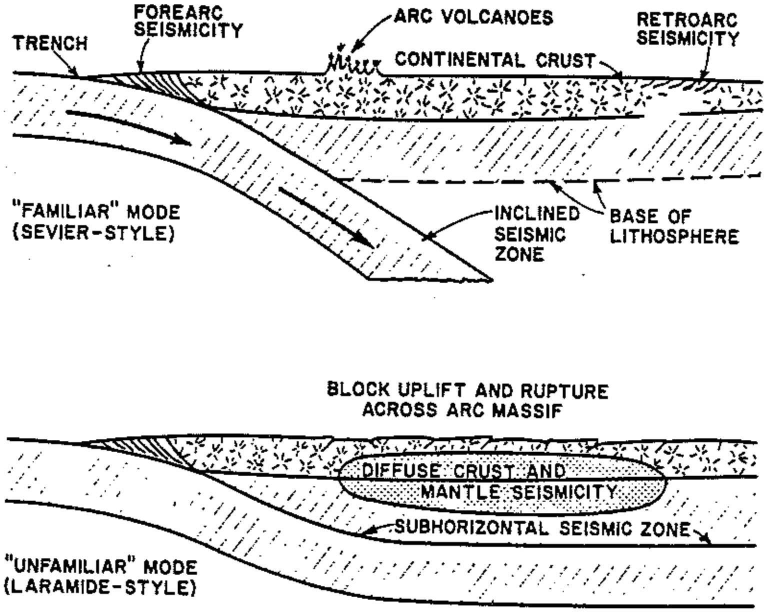

Fig. 1-11. Schematic diagrams to illustrate concept of steep (above) versus shallow (below) subduction to account for contrast between late Mesozoic Nevadan (batholithic)-Sevier (thrust-belt) style of orogeny and Paleogene Laramide Orogeny. After Dickinson and Snyder (1978).

the lower crust below a depth of about 10 km (Stewart, 1968). (2) At various places along and near the San Andreas and Garlock faults where they bound the Mojave block, exposures of Franciscan-like rock occur in the Pelona, Orocopia, and Rand schist terranes. These Franciscan-like terranes may be locally upfaulted through the granitic crust of the Mojave block from an underthrust Franciscan terrane like that present beneath the Salinian block (cf. Burchfiel and Davis, 1972, Fig. 6). The latter tract was presumably once a westward continuation of the Mojave block before offset along the San Andreas fault system. (3) The presence of blocks of Franciscan-type eclogites in Tertiary diatremes of the Colorado plateau (Helmstaedt and Doig, 1975) suggests that some of the underthrust Franciscan Complex was carried well inland without reaching depths much below the base of the overriding lithosphere. These inland occurrences of subducted Franciscan materials, erupted through the continental crust, were probably derived from parts of the subduction complex that had been entrained between the overriding and underthrust plates of the Laramide subduction system (Helmstaedt and Doig, 1975).

LATE CENOZOIC AND PRESENT TIME

The final stage in the evolution of the California continental margin was the growth of the San Andreas transform system to create a Californian-type margin (Atwater, 1970). The Laramide deformation inland ended by about the end of the Eocene. During the Oligocene, arc magmatism was gradually revived throughout the region of the Paleogene magmatic gap in the Great Basin. By the beginning of the Miocene, a continuous volcanic arc again stood parallel to the whole Cordilleran margin south of Canada. Shortly thereafter, however, coastal subduction began to be terminated by the encounter between the Pacific-Farallon spreading ridge within the ocean and the Farallon-American trench along the Cordilleran continental margin. As increments of the Farallon plate were successively consumed beneath the continental margin, the Pacific and American plates came into contact along the progressively lengthening San Andreas transform. During the Neogene, arc magmatism was gradually interrupted over a larger and larger region where no slab has descended beneath the segment of the Cordillera that is adjacent to the transform. Arc volcanism continues in the Cascades north of the region where the coastal transform system has supplanted the subduction zone.

The San Andreas transform and the San Andreas fault are not strictly equivalent terms. The San Andreas fault is the specific zone along which most transform slip occurs today. In the past, however, other strands of the San Andreas system have served from time to time as the main slip surface of the San Andreas transform. The initial position of the transform was probably offshore close to the continental slope. In general, motion was largely offshore on one or more fault strands during the Miocene, but has been mainly onshore, and chiefly along the present San Andreas fault, during the Pliocene. The peninsula of Baja California began to separate from the mainland near the Miocene-Pliocene time boundary.

Coastal Faults

The correct restoration, for various times in the past (Fig. 1-12), of California coastal slices now lying west of the San Andreas fault can be ambiguous because of fault splays within the transform system. A key example is the Salinian block of granitic and metamorphic rocks along the central California coast. The northern end of this block seemingly has been displaced by about 570 km along the San Andreas fault from counterparts in the Tehachapi Mountains near the Transverse Ranges. However, this inference fails to allow for about 115 km of Neogene offset along the subparallel San Gregorio-Hosgri fault trend (Graham and Dickinson, 1978a, b), which branches off the San Andreas fault near the Golden Gate. Other data constrain the Neogene motion on the San Andreas fault proper in central California to about 305 km. An estimated 50 km of additional net offset can be accommodated by minor displacements along subparallel faults within the elongate Salinian block. About 100 km of the apparent basement offset cannot be explained by

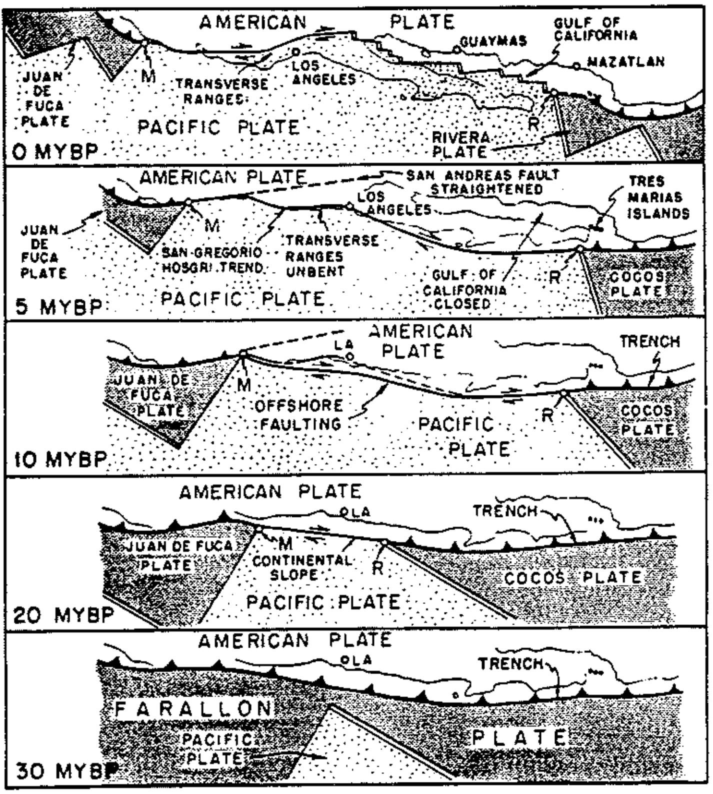

Fig. 1-12. Sequential Neogene evolution of San Andreas transform. Note migratory Mendocino (M) and Rivera (R) triple junctions. See text for discussion.

Neogene slip on any known faults. Presumably, this residual offset reflects subordinate Paleogene strike slip along a proto-San Andreas structure during oblique subduction in the Paleogene. Little is known of this tectonic regime, however, and even less can be said now about the likely magnitude and timing of aggregate lateral motions between the Salinian block and tectonic slices like the Nacimiento block lying still farther to the west. During Paleogene time, however, the Salinian block apparently was part of a fragmented continental borderland including multiple basins and positive blocks (Nilsen and Clarke, 1975).

Coastal Deformation

Neogene tectonics throughout the coastal region of California have been closely related to the San Andreas transform. Widespread structural features of characteristic morphology reflect subordinate contractional or extensional components of motion along the transform (Fig. 1-13). Contractional effects include the development of en echelon wrench folds (Wilcox and others, 1973), especially in the Coast Ranges of central California. Extensional effects include the development of pull-apart basins in southern California (Crowell, 1974a, b), especially within and east of the Peninsular Ranges onshore and within the fragmented continental borderland offshore. Transient and local episodes of basinal subsidence and local volcanism have also occurred in response to the passage of the migratory triple junctions at each end of the growing San Andreas transform (Dickinson and Snyder, 1979).

Most strands of the San Andreas fault system appear to be flexed in the region of the Transverse Ranges. Fault slices that may once have been oriented parallel to the general trend of the dextral San Andreas transform may now be twisted into crude parallelism with the sinistral faults of the Transverse Ranges. Thus, the dextral offset along the San Gregorio-Hosgri fault trend may well be shunted inland north of Point Concepcion to be partly overprinted by sinistral offset along the Santa Ynez fault. If so, the Paleogene turbidite trough of the coastal Santa Ynez Range may now be out of position with respect to the coeval turbidite trough of the inland Sierra Madre Range. Although subparallel now, perhaps the two troughs are offset segments of the same feature. Accordingly, they may once have been aligned as continuous segments of an elongate forearc basin adjacent

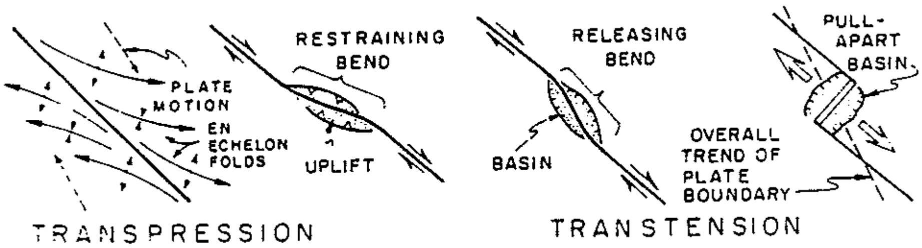

Fig. 1-13. Overall kinematics of contractional deformation from transpression and extensional deformation from transtension along transform fault trends (cf. Crowell, 1974a, b).

to part of the Franciscan subduction complex that forms a structural high in the presently intervening San Rafael Range. Such a postulated dislocation within the Transverse Ranges would have major implications for the geologic history of the Los Angeles and Ventura basins. A proper understanding of structural and stratigraphic relationships within the offshore continental borderland and in the inland Mojave block also hinges critically upon correctly gauging such aspects of the geologic history of the Transverse Ranges.

Arc Switchoff

The evolution of the coastal transform system also had major implications for the course of arc magmatism inland. Arc magmatism depends upon the presence of a subducted slab in the mantle (Lipman and others, 1971). No oceanic slab is subducted along a

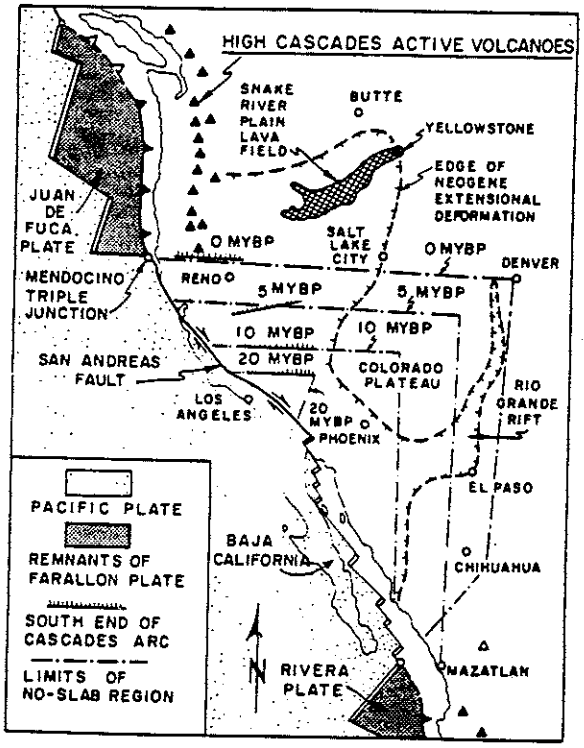

Fig. 1-14. Sketch map illustrating inferred growth of no-slab region above triangular slab-window in subducted slab of lithosphere beneath the Neogene Cordillera. Note apparent relationship to timing of northward retreat of southern termination of Cascades magmatic arc and to areal extent of Basin and Range province of widespread extensional deformation. Adapted from Dickinson and Snyder (1978).

Californian-type transform margin. Consequently, as the transform lengthens, a triangular slab-window develops in the subducted slab, which is inclined beneath the continent; accordingly, a corresponding no-slab region of slightly foreshortened triangular shape develops within the continent (Dickinson and Snyder, 1979). Where the no-slab region exists above the slab-window, arc magmatism is interrupted. The progressive Neogene switchoff of arc magmatism in the southwestern Cordillera was in harmony with the predicted expansion of a slab-window and no-slab region in time and space (Fig. 1-14). Surprisingly, the extent of the no-slab region is also nearly, though not exactly, coincident with the Basin and Range province of extensional tectonics when the latter is taken to include the Rio Grande Rift. Upwelling of hot asthenosphere to fill the expanding slab-window in the descending slab of cool lithosphere is a potential form of mantle diapirism that may have contributed to thermal uplift and stretching of the Cordilleran lithosphere in the Basin and Range province. The late Cenozoic bulk uplift of the Colorado Plateau may stem from the same effect.

PALEOLATITUDE CHANGES AND EUSTATIC FLUCTUATIONS

The role of plate tectonics in the geologic history of the Cordilleran margin has not been restricted to the direct tectonic effects described in preceding sections. In addition, there are two indirect factors that are worldwide in impact. These are (1) changes in paleolatitude as the plates move and (2) fluctuations in mean sea level, relative to the surfaces of the continental blocks, as either the volume of the ocean basins or of the ocean waters changes through time. Both processes exert subtle influences on inland weathering, coastal morphology, and offshore sedimentation that combine to work profound control over the regional nature of the stratigraphic record. The tectonic history of the Cordillera cannot be read properly unless these other, more pervasive signals of shifting paleolatitudes and eustatic changes are filtered correctly out of the geologic data.

Paleolatitude Changes

The general effects of changing paleolatitude are easy to understand. As the plate in which the continental block rides shifted position on the surface of the earth, the Cordilleran margin may have changed both its orientation and its position with respect to paleolatitude. In general, movement across polar, temperate, and tropical zones could change the degree of weathering on land, the direction of the prevailing coastal winds, and various oceanographic parameters of temperature, currents, and tides offshore. These and related factors essentially controlled the nature of shelf sedimentation, which may thus have responded to strong secular trends unrelated to local tectonics along the Cordilleran margin itself.

Available paleomagnetic data allow the broad outlines of such secular trends in sedimentation to be inferred without ambiguity. Paleomagnetic data are ordinarily cast as polar wander paths, which can be plotted on single maps and constitute a continuous inverse record of the movement of continental blocks with respect to the poles through time. An alternate mode of representation that is more ponderous, but more graphic for our purposes here, is a series of maps on which small circles of paleolatitude are drawn separately on each continental block for different intervals or moments of time. From the latter, graphs can be constructed to show the changing paleolatitude and orientation of a given continental margin. This has been done crudely here for the Cordilleran margin near Las Vegas (Fig. 1-15). Generally, tropical paleolatitudes prevailed during much of the Paleozoic while the carbonate-rich sequence of the miogeocline was deposited. A transit of the mid-latitude desert belt of the doldrums occurred during the early Mesozoic when the great dune fields and redbed successions of the Colorado Plateau were formed. Subsequent history has unfolded within the temperate zone.

Glacial Eustatics

The global distribution of continental blocks with respect to paleolatitude can also generate eustatic changes in sea level by promoting or discouraging continental glaciation, which reduces the volume of ocean waters. The transit of the composite Gondwana supercontinent across the South Pole during the Carboniferous and Permian is seen clearly now as the trigger for widespread Permo-Carboniferous glaciation on the southern continents (Crowell and Frakes, 1970). The polar transit, as inferred from the polar wander path for the assembled fragments of Gondwana, was clearly reflected in the gradual shift of glacial maxima from western to eastern Gondwana. Surely the strikingly cyclic coastal sedimen-

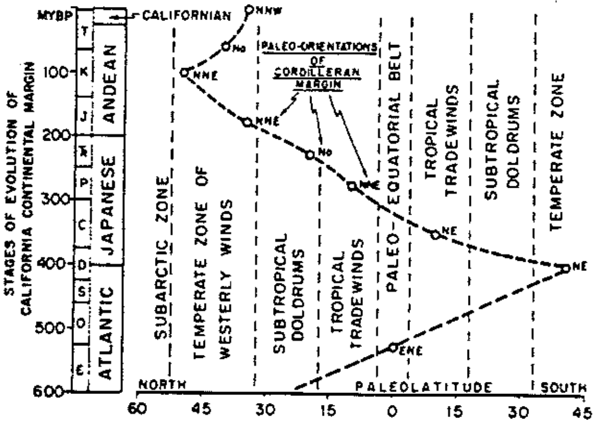

Fig. 1-15. Approximate paleolatitude trajectory of Death Valley region near Las Vegas. Climatic belts inferred from modern conditions. See text for discussion.

tation that prevailed at low latitudes among the Laurasian continental masses during the Permo-Carboniferous reflected the waxing and waning of contemporaneous glaciers in Gondwana (Wanless and Shepard, 1936). Between mid-Mississippian and mid-Permian time, there are about 60 pronounced cyclothems in the mid-continent region adjacent to the Hercynian-Appalachian foreland basin. Cyclic patterns of deposition in Permo-Carboniferous carbonates and shelf clastics of the Cordilleran miogeoclinal belt must harbor similar evidence for glacially controlled global fluctuations in sea level akin to those we know in such detail for the Pleistocene record.

Oceanic Eustatics

Eustatic changes of larger magnitude and longer wave length can be ascribed to changes in the global patterns of sea-floor spreading and subduction. To a first approximation neglecting sediment cover, the depth of the ocean floor is known now to be a simple logarithmic function of its age. The negative elevation below the rise crests, which lie typically at minus 2000 to 3000 m, is proportional to the square root of the age of the igneous substratum below the ocean floor; very roughly, depth equals $(2500 + 350t^{1/2})$ meters, where t is the age of the ocean floor in millions of years (Parsons and Sclater, 1977). Any process that operates to modify, through time, the mean age of the existing ocean floor (in the sense of length of time since its generation) can thus alter the aggregate volume of the ocean basins. As long as water volume remains constant, the freeboard of the surfaces of the continental blocks above mean sea level will also change in harmony, even magnified somewhat by isostatic feedback.

Several workers have suggested that systematic variations in the net global rate of sea-floor spreading would be reflected by changes in the volume of the ocean basins. Doubtless so, except that the implied pulsing of global heat loss would require some sort of thermal hysteresis on an improbably grand scale. Global heat production is itself geared to a rigorously continuous exponential decay governed by the laws of radioactivity. Moreover, the pace of observed eustatic draining and flooding of the continental blocks seems to occur at a tempo that cannot be explained by the thermal decay of static rise systems or the renewal of spreading in a manner much short of explosive (Berger and Winterer, 1974).

Alternately, the mean age of remaining ocean floor can be varied simply by changing the mean age of ocean floor that enters subduction zones. Given the complex global pattern of plate boundaries, this process can promote seemingly random eustatic fluctuations in arbitrarily irregular sequence. If subduction zones in aggregate consume an older and older sample of existing oceanic crust, then the average age of preserved oceanic crust becomes younger, and the volume of the ocean basins decreases. On the other hand, if subduction zones consume ocean floor closer and closer to spreading midoceanic ridges, then the average age of preserved oceanic crust becomes older, and the volume of the ocean basins increases. Continental freeboard increases or decreases accordingly.

The Phanerozoic pattern of major eustatic events is still known only roughly on a worldwide scale. The most pronounced long-term eustatic event during the Cenozoic was clearly the Oligocene drawdown (Ingle and others, 1976). All tectonically stable continental shelves bordering the Atlantic and Indian oceans underwent an episode of erosion or regression that probably was centered on a time early in the Oligocene. Prominent unconformities between Eocene and Miocene beds are widespread beneath many modern shelves, and a prominent hiatus or reduced section is characteristic elsewhere. In California, the Oligocene redbeds of the Sespe and related formations appear within many marine sections without any marked record of local deformation that might have caused uplift.

Perhaps the subduction of the east flank of the ancestral East Pacific Rise beneath the Cordilleran subduction zone allowed sufficiently older oceanic crust to persist elsewhere to cause global draining of the continental shelves. In this fashion, the generation of the San Andreas transform may have left an imprint on worldwide eustatics. This notion should be tested quantitatively, for the eustatic record on the continental blocks is one of the few potential ways in which aspects of the history of pre-Jurassic oceans can be inferred from the stratigraphic record. Unless the correct meaning of the eustatic signal can be discovered for Cenozoic events, the record of older events cannot be interpreted properly. Perhaps California geology, which has played such a key role in the evolution of plate-tectonic theory, can also provide the insight to break the eustatic code!

ACKNOWLEDGMENTS

No one can worry effectively alone about matters like those discussed here. Although none can be held responsible for the thoughts I have presented, each of the following has been generous of especially pertinent ideas in many past discussions with me: R. L. Armstrong, Tanya Atwater, B. C. Burchfiel, P. J. Coney, D. S. Cowan, J. C. Crowell, G. A. Davis, T. W. Dibblee, W. G. Ernst, S. A. Graham, W. B. Hamilton, D. G. Howell, R. V. Ingersoll, D. L. Jones, T. E. Jordan, E. M. Moores, T. H. Nilsen, B. M. Page, E. I. Rich, R. A. Schweickert, N. J. Silberling, W. S. Snyder, J. H. Stewart, and C. A. Suczek. My own research efforts in California have been sustained in recent years by the Earth Sciences Section of the National Science Foundation with NSF grants DES 72-01728 and EAR 76-22636. Thoughtful reviews by W. G. Ernst, D. W. Hyndman, and E. M. Moores significantly improved the manuscript, even though none of the three would subscribe to all the statements and interpretations included.

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