Cenozoic Paleogeography of the Western United States

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CENOZOIC PLATE TECTONIC SETTING OF THE CORDILLERAN REGION IN THE UNITED STATES

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ABSTRACT

Plate tectonics of the Cenozoic Cordillera involved interactions of the Pacific, Farallon, and American plates. Salient events included changes in the motions of the Pacific and American plates with respect to the hotspot reference frame, variations in the angle of descent of the Farallon plate beneath the Cordillera, subdivision of the Farallon plate into separate derivative plates as the Pacific-Farallon ridge met the Farallon-American trench, and partial disruption of the American plate as lateral Pacific-American movement along the San Andreas transform succeeded Farallon subduction at the continental margin. Paleogene shallowing of Farallon plate descent began in latest Cretaceous time, continued well into the Eocene, and was associated with the classic Laramide orogeny inland, a prominent null in arc magmatism farther west, and suspected strike slip in response to oblique subduction along faults near the coast. Mid-Cenozoic steepening of Farallon plate descent through the Oligocene allowed gradual rejuvenation of arc magmatism along the whole Cordillera, and probably influenced the development of Cordilleran core complexes. Neogene evolution of the San Andreas transform triggered local deformation and volcanism related to migratory triple junctions along the coast, transferred slices of the American plate to the Pacific plate, extinguished arc magmatism along a belt parallel to the San Andreas transform, and perhaps promoted uplift and crustal extension inland because no subducted slab is present adjacent to the transform plate boundary.

INTRODUCTION

Perhaps no segment of the circum-Pacific rim has undergone a more complex tectonic evolution during the Cenozoic than the Cordilleran region of the western United States. This paper sketches the overall plate tectonic constraints, as best judged now, within which the varied facets of that evolution can be viewed in context. The main substance of the presentation is a series of paleotectonic and paleogeographic maps. Each is a coordinated synthesis of the main tectonic elements that were present and of the general facies patterns that were prevalent at selected stages in the geologic history of the region since the Late Cretaceous. The reconstructions shown are entirely personal ones and perhaps are idiosyncratic in part. Nevertheless, the insights that led me to choose the particular features to depict stem from countless discussions with geologists too numerous to name here. The maps should be taken as points of departure for further discussions, rather than as final conclusions to be accepted at face value. The accompanying brief text does little more than indicate the lines of thought that guided drafting of the maps.

PLATE CONFIGURATIONS

Figure 1 indicates the changing plate configurations that most influenced western North America during the Late Cretaceous and Cenozoic. Four key steps in a continuously unfolding story are shown like still frames from a motion picture. For each key stage in the evolution of the Cordillera from Cretaceous times to the present, solid arrows or solid lines within vector arrays shown by insets denote directions of relative plate motions, whereas dashed lines show plate motions relative to the hotspot reference frame (both sets of motions modified after Coney, 1978). Stippled regions contained subducted slabs shallower than 400 km below the surface in positions thus suitable to foster arc magmatism (see Figures 2 and 3 for profile views of the subducted slabs).

At 80 mybp (Fig. 1A), near the beginning of the Campanian, subduction of the Farallon plate was apparently underway at a Farallon-American trench that extended continuously from Mesoamerica to Alaska (Coney, 1978). This relationship is implicit from the pattern of spreading ridges reconstructed for the Cretaceous from the distribution of magnetic anomalies observed on the present Pacific seafloor (Larson and Pitman, 1972; Kanasewich and others, 1978). It is at variance with the earlier suggestion by Atwater (1970) that one end of the Kula-Farallon ridge may have swept up the North American coast during the Late Cretaceous. This latter behavior is essentially precluded by the discovery in the Bering Sea of Early Cretaceous magnetic anomalies interpreted as a record of the position of the Kula-Farallon Ridge at that time (Cooper and others, 1976). There remains some chance that unknown oceanic plates, which have since been entirely subducted beneath the American plate, were present offshore during the Cretaceous, but no evidence available now points in such a direction. The existence of a continuous Farallon-American trench along the oceanic flank of the Cordillera is compatible with the initial notion of Hamilton (1969) that the Cretaceous batholith trend, subparallel to the coast from Mexico to Alaska, represents the eroded roots of a once continuous magmatic arc, which stood parallel to the subduction zone along the continental margin.

From 80 to 40 mybp, continued subduction of the Farallon plate beneath North America was coordinate with the development of Paleogene subduction complexes, including the Coastal Belt Franciscan of California (Evitt and Pierce, 1975), and with the Laramide Orogeny farther inland in the Central Rockies (Coney, 1976). Relations farther north in regions bordering the Gulf of Alaska are still uncertain, but the last vestiges of the once extensive Kula plate were being drawn into the Aleutian arc-trench system during this period (DeLong and

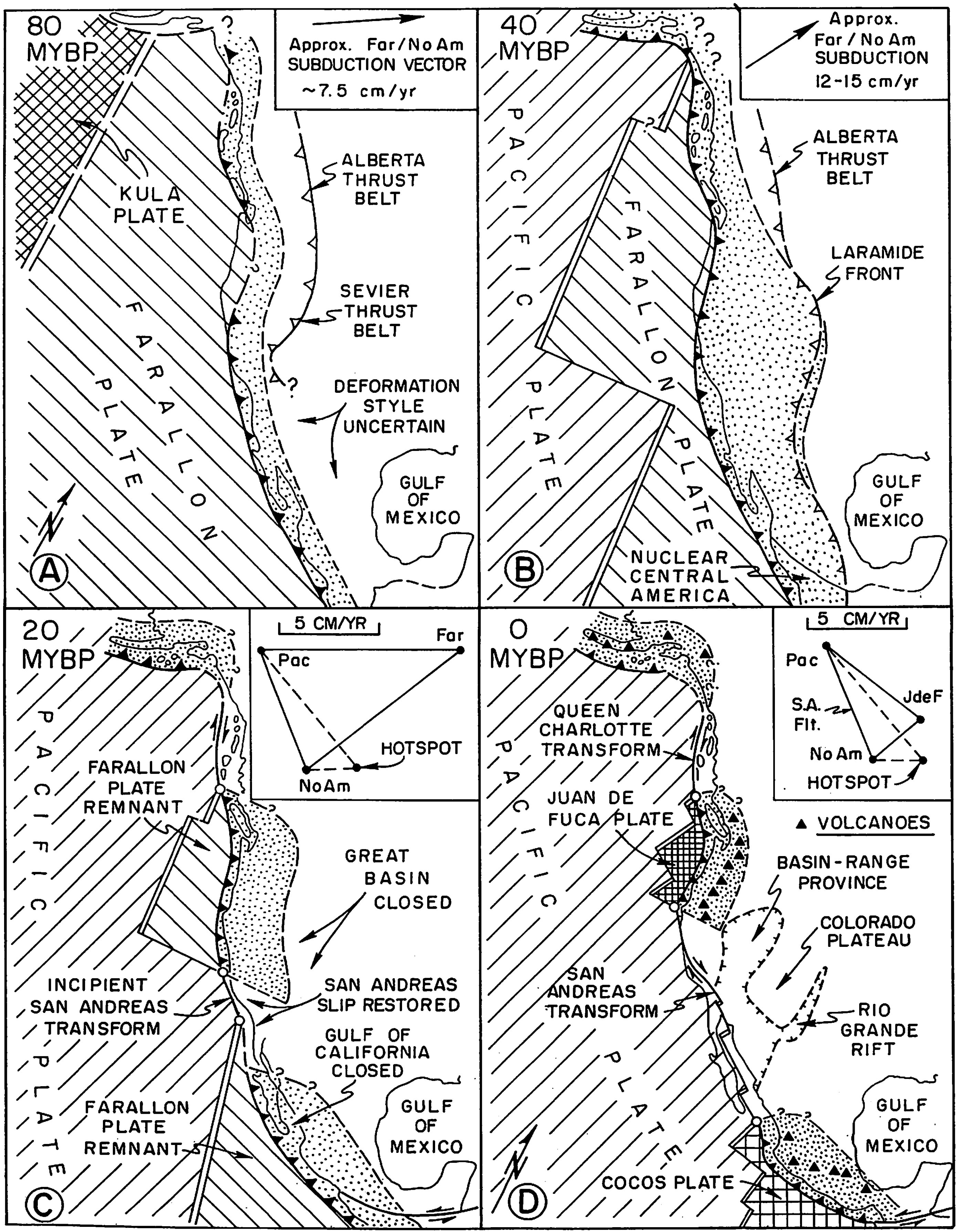

Figure 1. Inferred plate configurations and plate motions (insets). See text for discussion.

others, 1978). The Kula-Pacific ridge probably ceased spreading during the Paleocene before its arrival at the Aleutian trench (Byrne, 1978). If so, the area of the Pacific plate was abruptly augmented at that time by the bodily addition of any portion of the Kula plate that still remained at the surface. Accordingly, the boundary of the Farallon plate that lay off insular British Columbia at 40 mybp was presumably a northern segment of the Pacific-Farallon ridge, rather than the Kula-Farallon ridge. North of Vancouver Island, arc-related magmatism that continued sporadically during the time span from 80 to 40 mybp ended near the close of that period in coastal British Columbia and the southeastern Alaska panhandle (Dickinson, 1972, 1976). This behavior is compatible with establishment of the Queen Charlotte transform by Pacific-American plate interaction as early as 40 mybp (Fig. 1B).

From 40 to 20 mybp, continued subduction of the Farallon plate along the coast from Vancouver Island southward gradually drew the Pacific-Farallon ridge against the Farallon-American trench. The first contact occurred off southern California late in the Oligocene (Atwater and Molnar, 1973). Allowing for subsequent opening of the Gulf of California, the initial contact was between the segment of the Pacific-Farallon ridge adjacent to the Mendocino fracture zone, then an active transform, and the continental margin in the vicinity of the present Transverse Ranges (Blake and others, 1978). As the Pacific and American plates thus came into contact, the San Andreas transform was initiated by Pacific-American plate interaction (Atwater, 1970). When this Pacific-American transform began to function, the Farallon plate was subdivided by about 20 mybp into separate derivative plates (Fig. 1C). Although the early histories of these two plates were probably complex (Menard, 1978), their lineal descendants are the modern Juan de Fuca and Cocos plates whose subduction continues even now off the Pacific Northwest and Mesoamerica, respectively.

From 20 mybp to the present (Fig. 1D), the San Andreas transform boundary between the Pacific and American plates gradually lengthened as the Mendocino and Rivera triple junctions migrated up and down the coast, respectively (Dickinson and Snyder, 1979a). Progressive lateral shifts in the position of the transform transferred successive crustal slices of the North American continent to the Pacific plate (Garfunkel, 1973). Displacements of these crustal slices relative to the interior of the continent have caused major fault offsets in coastal California, the opening of the Gulf of California as Baja California pulled obliquely away from the Mexican mainland, and complex deformation within the offshore California Continental Borderland where many key tectonic relations are still unclear. Farther inland, arc magmatism has been extinguished along a gradually lengthening segment of the continental margin as the nature of the plate interaction along the edge of the continental block was converted sequentially from subduction to lateral transform slip (Snyder and others, 1976). Neogene extensional deformation within the Basin and Range Province in general occupies, but is not confined entirely to, the region adjacent to the San Andreas transform where no subducted slab of oceanic lithosphere is present between the two migrating triple junctions (Dickinson and Snyder, 1979b). Along the trend of the transform system itself, local sedimentary basins and volcanic fields related to Neogene passage of the migratory triple junctions lie now within a belt of active wrench tectonism associated with continuing transform deformation along the edges of the adjoining Pacific and American plates (Dickinson and Snyder, 1979a).

PLATE MOTIONS

Two lines of evidence using offshore data allow the motions of the plates whose interactions controlled West Coast tectonics to be estimated independently from any onshore geologic data (Coney, 1978). First, patterns of magnetic anomalies generated by oceanic spreading ridges allow the mutual relative motions among the Pacific, Kula, and Farallon plates to be gauged directly. Second, the motions of the Pacific and American plates with respect to the semi-fixed hotspot reference frame can be inferred from the orientations and age progressions of oceanic hotspot tracks composed of seamounts and volcanic islands. Uncertainties about the timing of some hotspot tracks in both the Atlantic and Pacific still remain, but the general picture seems clear now. Motions of the Pacific and American plates with respect to hotspots in the Pacific and Atlantic, respectively, can thus be interpreted as approximations of the motions of those two plates with respect to underlying asthenosphere. This approach involves the assumption that hotspots in the asthenosphere move slowly, if at all, in comparison to the rapid motions of lithosphere plates (Morgan, 1972). By considering hotspot data in conjunction with the data on relative motions from magnetic anomalies in the Pacific, the motions through time of all the plates involved in interactions affecting the Cordilleran region can be reconstructed for the past 150 my or so (see Fig. 1). Relative motions between each pair of adjoining plates and the motion of each plate with respect to the hotspot reference frame in the asthenosphere both can be obtained in this fashion (Coney, 1978). The results are most reliable for the past 75 my, for which the motion of the Pacific plate is now well controlled by recent data for the Emperor-Hawaii hotspot track (Dickinson, 1979).

Prior to 80 mybp, subduction of the Farallon plate beneath the American plate was approximately normal to the Cordilleran margin at a rate somewhat less than 10 cm/yr. This behavior is standard when compared to relations for modern arc-trench systems. From 80 to 40 mybp, however, subduction of the Farallon plate was abnormally rapid, nearly 15 cm/yr, and the vector of convergence with the American plate was oriented obliquely to the Cordilleran margin, with a prominent component of dextral slip present. From 40 to 20 mybp, the convergence vector fell again to normal values, and the obliquity of subduction was reduced somewhat. From 20 mybp to the present, dextral motion between the Pacific and American plates has displayed a variable rate but a rather consistent orientation reflected by the general trend of the San Andreas transform system. Beginning about 5 to 7.5 mybp, subduction of the Juan de Fuca plate, derived from the once larger Farallon plate, has slowed to an anomalously low rate of less than 5 cm/yr in a direction markedly oblique, again in the dextral sense, to the Cordilleran margin.

Throughout the period from 150 mybp to the present, the American plate has moved generally westward with respect to the hotspot reference frame

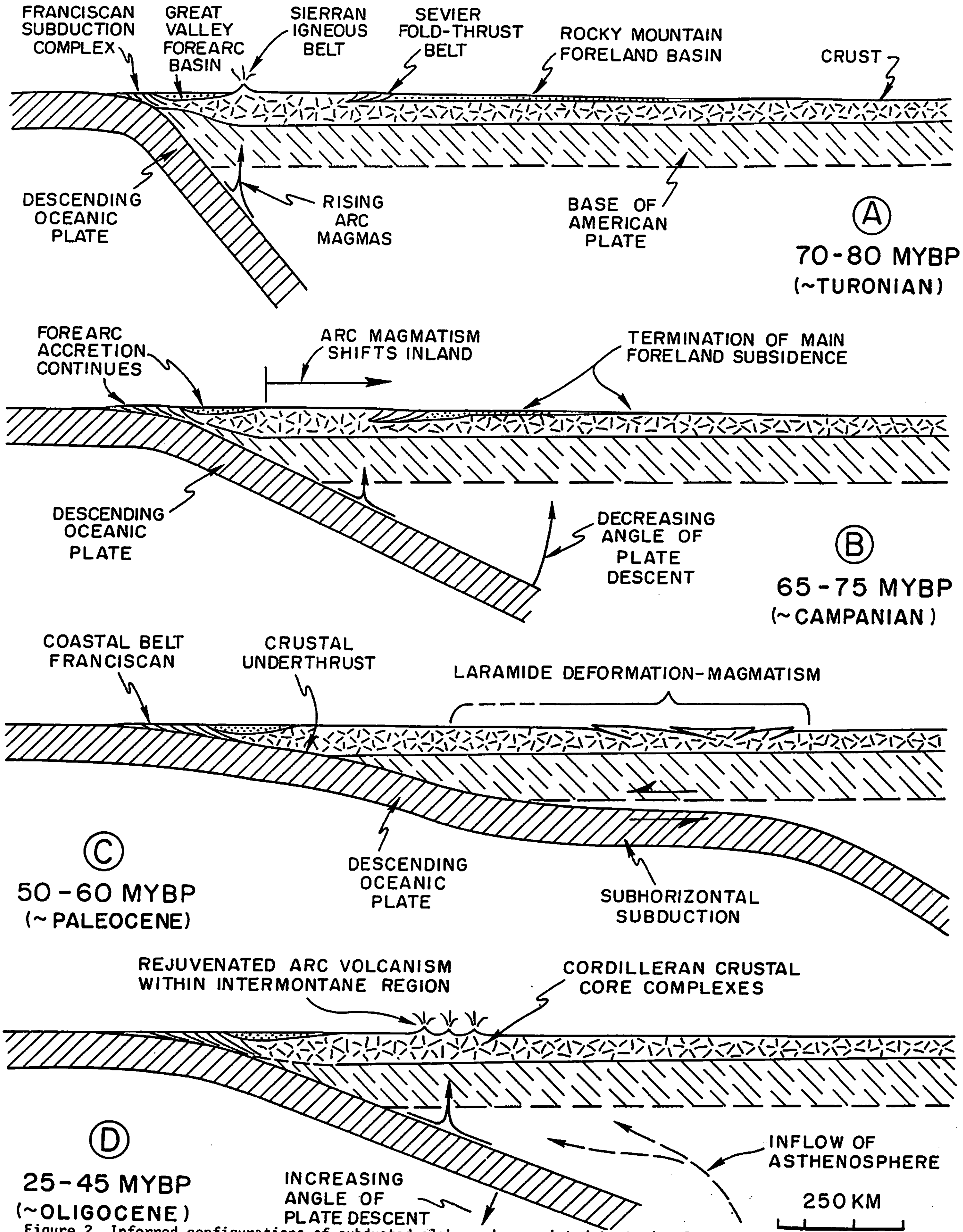

Figure 2. Inferred configurations of subducted slabs and associated tectonic elements at key stages in the evolution of the Cordillera from Cretaceous times to Oligocene. See Figure 1 for plan view and plate motions.

(Coney, 1978). Prior to 80 mybp, this motion was evidently northwestward at rates in excess of 5 cm/yr, and from 80 to 40 mybp the motion was nearly due west at about 5 cm/yr. Throughout the duration of the Sevier and Laramide orogenies in the eastern Cordillera, there was thus a persistent tendency for the continental block to encroach steadily upon the line of flexure in the Farallon plate where it bent to descend beneath the subduction zone along the Cordilleran margin. This behavior served to suppress the development of a marginal spreading sea, such as the Sea of Japan, behind the magmatic arc located in the western Cordillera (Dickinson, 1979). The westward motion of the continental interior further promoted the complexly evolving Sevier and Laramide tectogenesis as the continental block pressed continually against the rear flank of the arc-trench system (Coney, 1971, 1972, 1973).

During the past 40 my, the net motion of the continental interior with respect to underlying asthenosphere has been slightly south of west at about 2.5 cm/yr, substantially less than previously (Coney, 1978). For the motion of structural blocks within the Cordillera, the effects of Neogene extensional breakup within the Basin and Range Province would modify that rate somewhat. Nevertheless, the change from a fast to a slow rate of motion appears coordinate with the termination of orogeny in the eastern Cordillera.

SUBDUCTION MODES

The various changes in plate motions can be correlated successfully with inferred changes in the geometry of subduction beneath the Cordillera (Coney and Reynolds, 1977; Cross and Pilger, 1978; Keith, 1978; Lipman, 1979). As shown by Figures 2 and 3, the key factor to be considered for regional relations is the configuration and dip of the subducted slab at depth well beneath the Cordillera. The position of the slab in the mantle below the heart of the Cordillera controls the distribution of arc magmatism and the nature of continental tectonism beyond the arc trend (Dickinson and Snyder, 1978).

The local structural geometry of the descending slab close to the subduction zone is controlled mainly by the progress of tectonic accretion at or near the trench (Karig and others, 1976). Surficial materials are detached by decollement from the downgoing plate and added to the edge of the overriding plate. These materials form an accretionary prism that depresses the descending slab to quite shallow dips beneath the accretionary mass, which adopts a wedge shape in profile. The accretionary processes are affected by convergence rate in relation to sediment supply but act only in the general vicinity of the subduction zone. The local dip of the descending slab beneath the accretionary prism can thus be treated independently from the overall dip of the slab at depth beneath the arc.

This latter and more fundamental aspect of slab dip depends generally upon the relation between the negative buoyancy of the descending slab and the plate convergence rate normal to the trench (Luyendyk, 1970). The dip angle in a sense reflects the vector resultant of a vertical sinking rate for the slab and its lateral motion rate. Shallow slab dips correlate with high convergence rates, and vice versa. This simple dependence of slab dip on convergence rate presumably requires suitable modification to allow for the differing physical properties of oceanic lithosphere having different ages at the time of subduction. Old lithosphere is colder and denser than young lithosphere, and therefore tends to sink more readily (Molnar and Atwater, 1978).

In the Late Cretaceous prior to 80 mybp (Fig. 2A), the convergence rate (Fig. 1A) at the Farallon-American trench was similar to standard values for modern arc-trench systems. As inferred from the potassium gradient in granitic rocks of the Cretaceous batholiths (Dickinson, 1970, fig. 6; Keith, 1978, fig. 3), the dip of the subducted slab beneath the Cordillera was about 50 degrees, a rather normal value for modern arc-trench systems. Arc magmatism was concentrated within a belt that lay 150 to 200 km distant from the trench. The depth from the surface to the subducted slab of lithosphere beneath the arc was typically from 125 to 175 km. At such depths, the slab had penetrated beneath the continental lithosphere, and was thus able to generate arc magmas (Barazangi and Isacks, 1976). Westward drift of the continental lithosphere over the asthenosphere continually pressed the edge of the overriding plate against the line of flexure in the descending plate (Burchfiel and Davis, 1976). The resulting contraction inland behind the arc trend was associated with thrusting in the Sevier belt.

Abnormally high convergence rates prevailed at the Farallon-American trench from 80 mybp in the latest Cretaceous until 40 mybp in the Late Eocene (Fig. 1B), but then fell to normal values again until 20 mybp in the Early Miocene (Fig. 1C). Dips on the subducted slab beneath the Cordillera can be inferred generally from the distribution of arc magmatism (Coney and Reynolds, 1977), and specifically from the potassium gradients in arc volcanic rocks (Keith, 1978). During latest Cretaceous times (Fig. 2B), slab dip was decreasing steadily from the normal values that had prevailed previously to angles of no more than 10 degrees in the Paleogene (Fig. 2C). During the Oligocene (Fig. 2D), slab dip was increasing rapidly again toward normal values.

As slab dip decreased, arc magmatism swept inland and decreased markedly in volume. This behavior can be ascribed to a change in the locus of melting beneath the arc. The place at which descending lithosphere finally penetrated into asthenosphere lying below the overriding plate shifted farther and farther inland. The period of shallowest slab dip during the Paleogene marked the time of a prominent magmatic null in the western Cordillera (Snyder and others, 1976). This null was somewhat diachronous, being slightly older in the north than in the south. The existence of such a null was first established by Damon (and others, 1964; and Bikerman, 1964; and Mauger, 1966).

As arc magmatism shifted inland, backarc tectonism also migrated eastward and changed in structural style.The thin-skinned thrusts of the Sevier orogenic belt in the present intermontane region gave way to basement-cored uplifts of the Laramide orogenic belt in the Central Rockies. The extent and timing of the Laramide Orogeny in the eastern Cordillera coordinated well with the extent and timing of the Paleogene magmatic null in the western Cordillera. Laramide deformation can thus be ascribed also to the effects of plate descent at an abnormally shallow angle (Dickinson and Snyder,

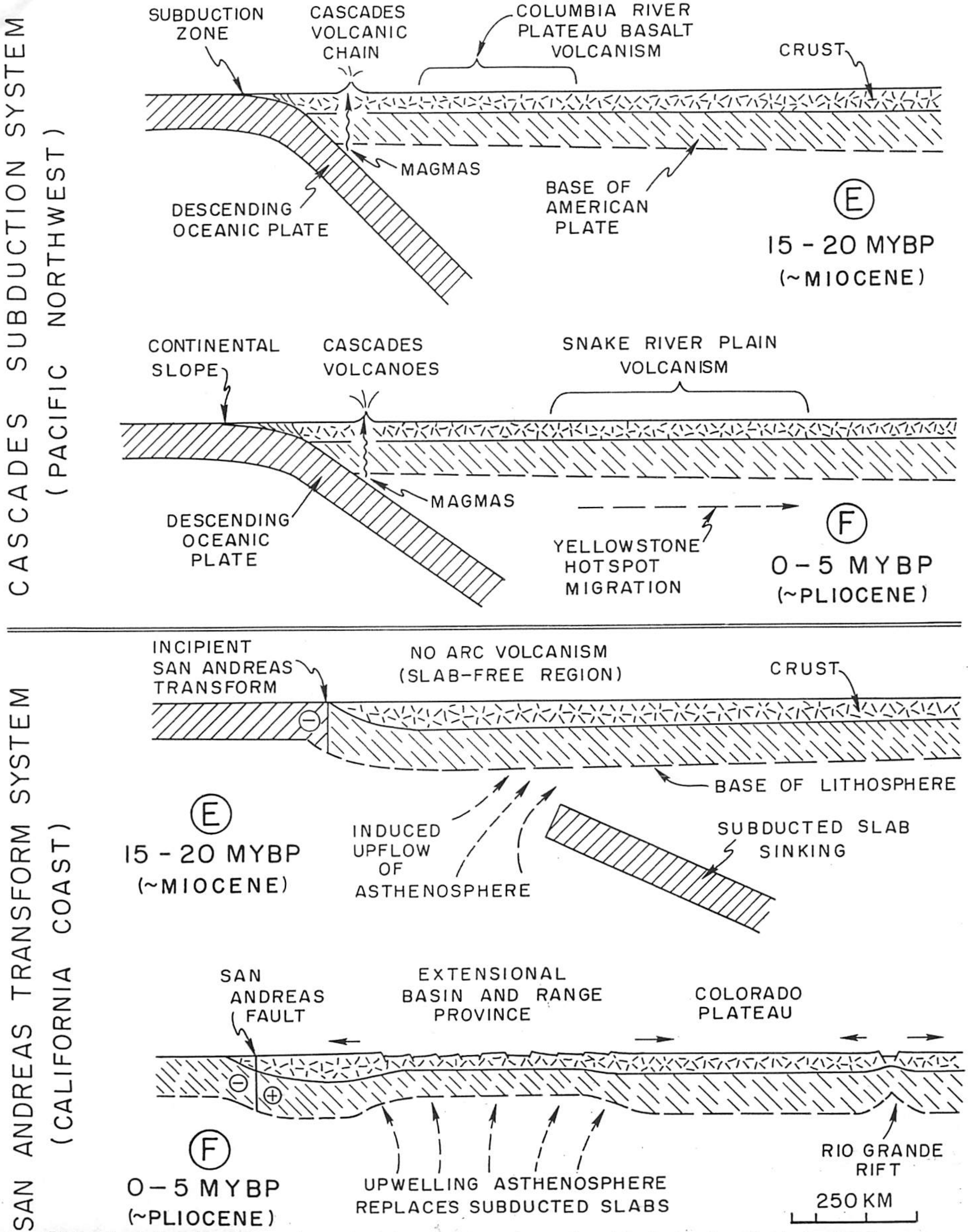

Figure 3. Inferred configurations of subducted slabs and associated tectonic elements during the Neogene evolution of the Cordillera. See Figure 1 for plan view and plate motions.

1978). In effect, the descending plate was scraping subhorizontally beneath the overriding plate, which accordingly failed by deep-seated basement shear.

During the Paleogene period of plate descent at a shallow angle, several additional effects of such an unfamiliar mode of subduction may be reflected by tectonic elements near the west coast. The so-called proto-San Andreas fault responsible for local Paleogene basin formation in California (Nilsen and Clarke, 1975) may have been merely a transcurrent tear fault in the overriding plate in response to markedly oblique convergence The unusually shallow angle of plate descent could have allowed the descending plate to bond partially with an overlying sliver of the overriding plate, and to carry such a sliver for some distance laterally up the coast. Emplacement of underthrust Paleogene schist terranes beneath granitic crustal blocks in the region surrounding the Mojave Desert may also have been facilitated by the strikingly shallow angle of plate descent.

As slab dip increased again following the time of the magmatic null and the Laramide Orogeny, arc magmatism swept back seaward and recovered its full intensity by the Miocene. The recovery was earlier in the north than in the south, such that a wave of arc magmatism moved southward across Nevada through the Oligocene (Stewart and others, 1977). This pattern of magmatism can be ascribed to the surficial effect of a migrating subterranean flexure in the descending slab, whose dip was greater to the north than to the south of the flexure. As the descending slab pulled downward away from the overriding slab, a surge of asthenosphere was presumably required to fill the wedge of space opening between the two plates. Associated thermal effects may have promoted development of the so-called Cordilleran core complexes, whose ages correlate reasonably well with the rejuvenation of arc magmatism along the Cordilleran trend (Coney, 1979). After 20 mybp (Fig. 3), the regions adjacent to the Cascades subduction system and the San Andreas transform system underwent wholly different types of evolution.

Even though plate convergence beneath the Cascades system is anomalously slow, the potassium gradient across the volcanic chain (Dickinson, 1970, fig. 4) suggests a moderately shallow angle of plate descent at about 30 degrees. The comparatively young age of the oceanic lithosphere in the Juan de Fuca plate, and its consequent buoyancy, may account for the observed relationships. No handy explanation is yet available, however, for the eruption of immense Neogene basalt fields in the backarc area of the Pacific Northwest. The Snake River Plain lavas may be related to a Yellowstone hotspot, which may in turn lie at the apex of a propagating lava-filled cleft in the continental block, but the Columbia River Plateau lavas remain as enigmatic as they were before the advent of plate tectonics.

In the region adjacent to the San Andreas transform, arc magmatism has been extinguished because no subducted slab is present beneath a roughly triangular region whose coastal side is delimited by the transform (Dickinson and Snyder, 1979b). The region lacking a subducted slab beneath it at depth has gradually expanded throughout the Neogene as the triple junctions at the ends of the transform have gradually moved apart. The dimensions and shape of this slab-free region as it grew through time can be estimated roughly from inferred subduction rates for the Juan de Fuca and Cocos plates at trenches along the coast. The slab-free region is created as the trailing sides of subducted slabs move back under the American plate. The present extent of the Basin and Range Province of extensional tectonism is surprisingly similar to the inferred extent of the slab-free region (Proffett, 1977). Perhaps the upwelling of asthenosphere to replace descending lithosphere that has sunk at an angle through the slab-free region has contributed to the tendency for extensional deformation. Oblique regional shear in a dextral sense caused by partial coupling of the American plate to the Pacific plate along the San Andreas transform was probably an additional significant factor in the evolution of the Basin and Range Province (Zoback and Thompson, 1978; Christiansen and McKee, 1978).

MAP SEQUENCE

Figures 4 to 10 are paleotectonic and paleogeographic sketch maps for successive stages in the evolution of the Cordilleran region from Late Cretaceous times to the present. The locations and configurations of the features shown are taken from various sources. The distributions of igneous provinces are modified after compilations by Lipman and others (1971, 1972), Christiansen and Lipman (1972), Snyder and others (1976), Stewart and others (1977), Coney and Reynolds (1977), Cross and Pilger (1978), Keith (1978), and Lipman (1979). Patterns from these and previous sources dealing with the topic converge toward common conclusions. Sedimentary and structural relations in the eastern Cordillera are adapted from contributions in Mallory (1972). Data extracted from Cook and Bally (1975) were incorporated wherever pertinent throughout the Cordillera. Paleogeographic relations near the coast are taken mainly from compilations by Snavely and Wagner (1963), Nilsen and Clarke (1975), and contributors in Nilsen (1977).

The magnificent synthesis of King (1969) was used as a base map. A major decision had to be made regarding the restoration of Neogene tectonic displacements along the San Andreas transform system and within the Basin and Range Province. Data are still inadequate to allow such restorations to be made with full confidence. Nevertheless, displacements have been too large in the aggregate to ignore completely without grossly distorting the shapes of some pre-Neogene tectonic patterns when the latter are plotted on an unrestored base map (e.g., Hamilton and Myers, 1966). Accordingly, the following geographic adjustments have been made on the series of maps:

(1) On all maps except Figure 4 for the present, the Gulf of California is shown closed by the amount of opening that has occurred since 5 mybp.

(2) Along the San Andreas fault in coastal California, 240 km of post-Miocene dextral slip are restored for Figure 5, an additional 65 km of intra-Miocene(?) dextral slip are restored for Figures 6-9, and a nominal 100 km of proto-San Andreas dextral slip, thought to have occurred during the latest Cretaceous and earliest Tertiary episode of shallow subduction, are restored for Figure 10.

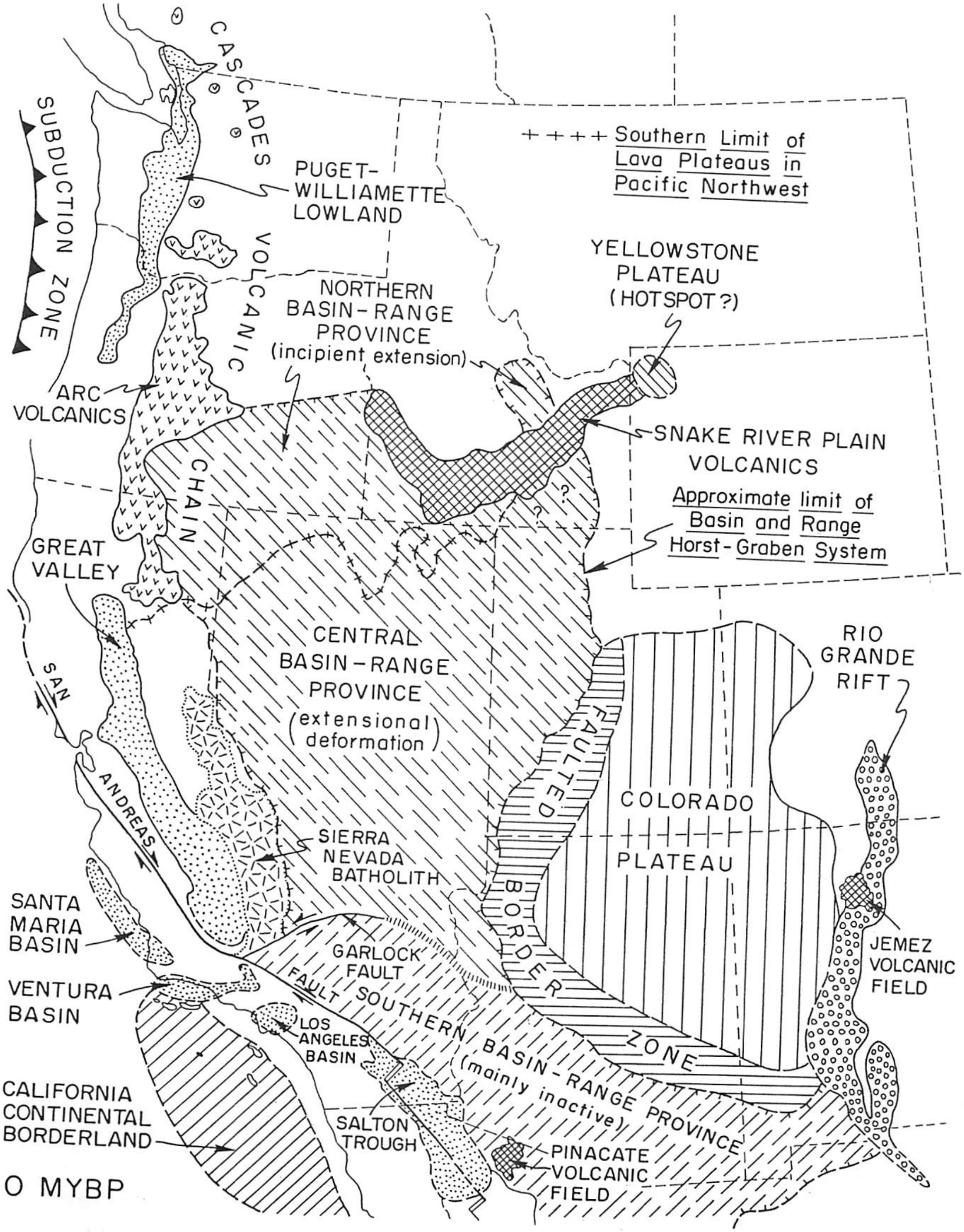

Figure 4. Paleotectonic and paleogeographic sketch map of the Cordilleran region in the Quaternary (0 mybp).

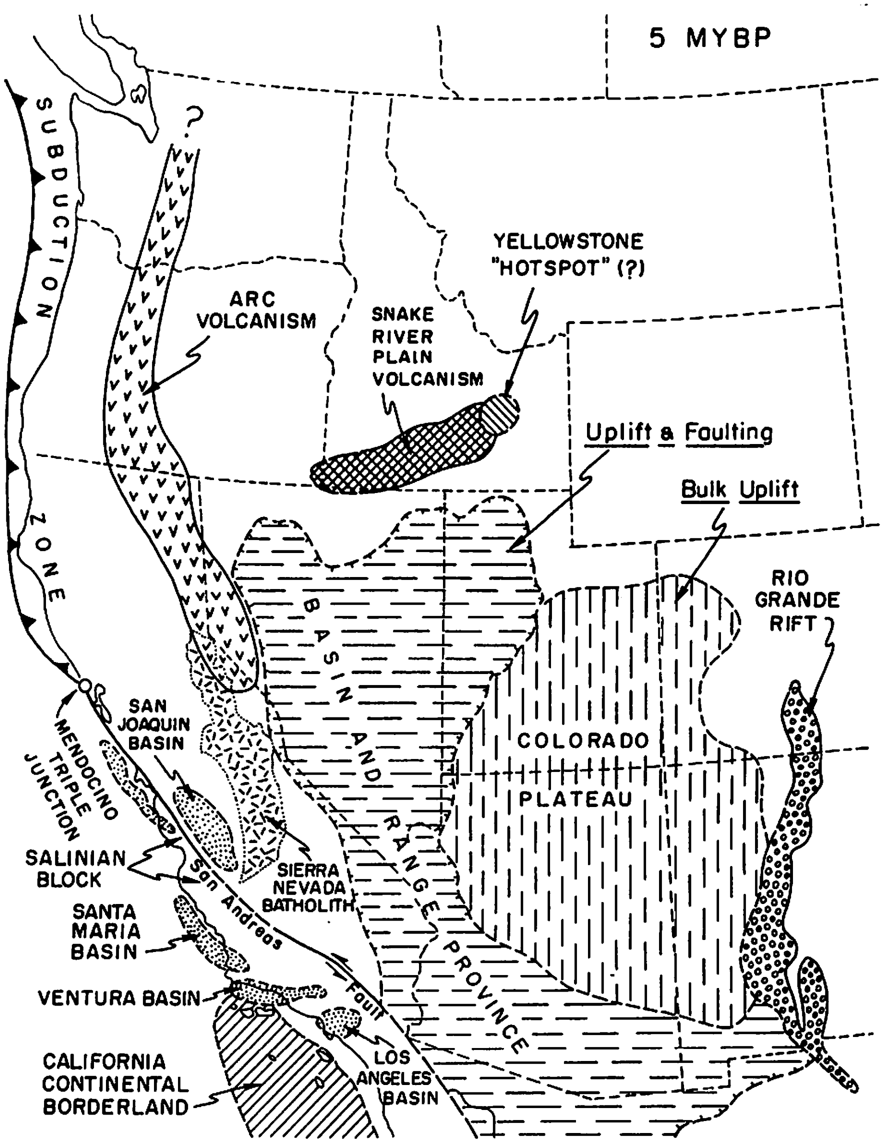

Figure 5. Paleotectonic and paleogeographic sketch map of the Cordilleran region 5 mybp at the Miocene/Pliocene boundary.

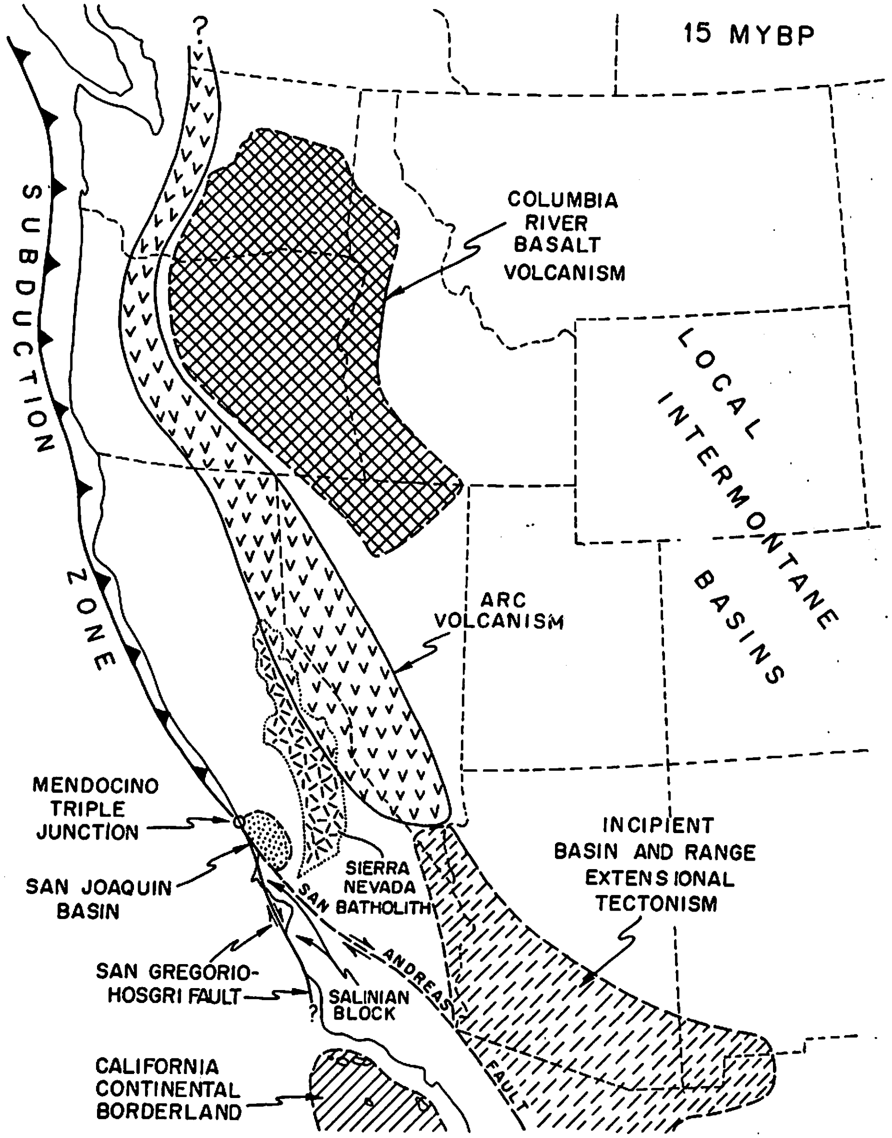

Figure 6. Paleotectonic and paleogeographic sketch map of the Cordilleran region 15 mybp in the Miocene.

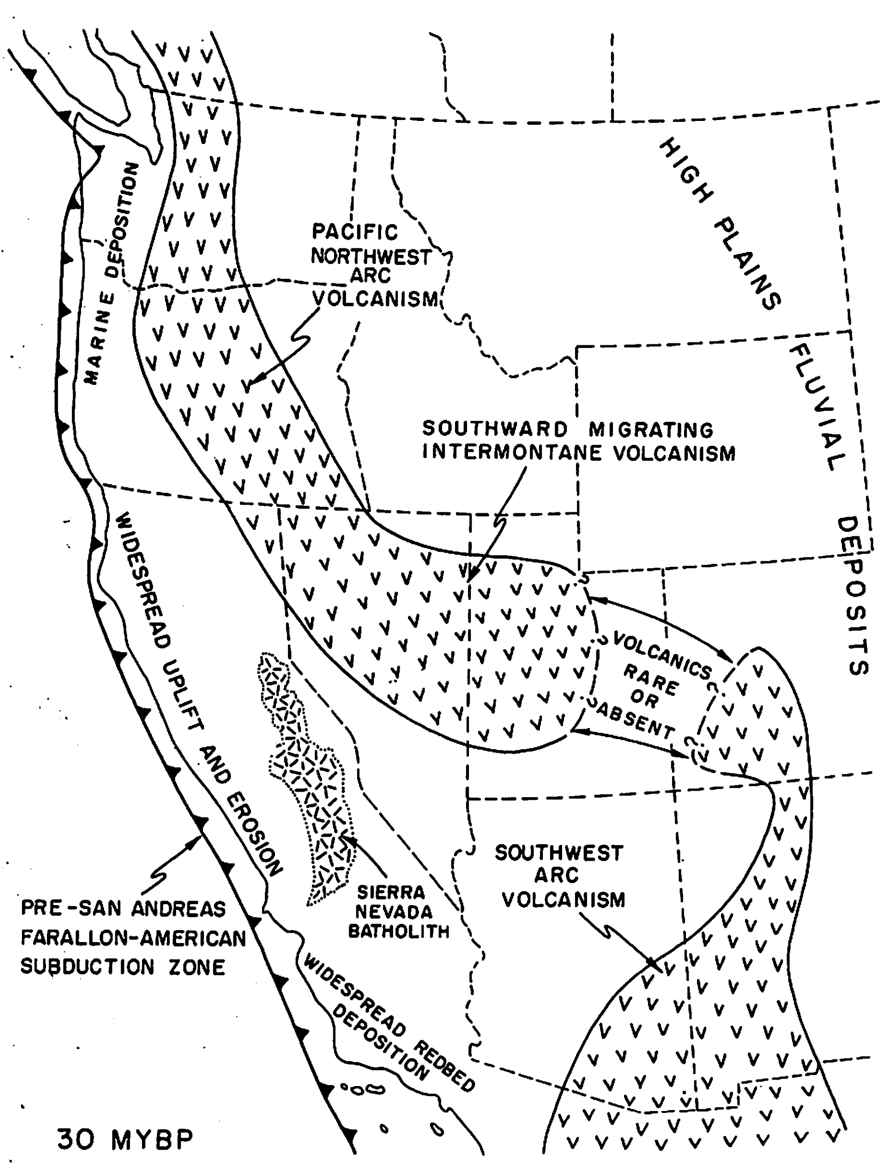

Figure 7. Paleotectonic and paleogeographic sketch map of the Cordilleran region 30 mybp in the Oligocene.

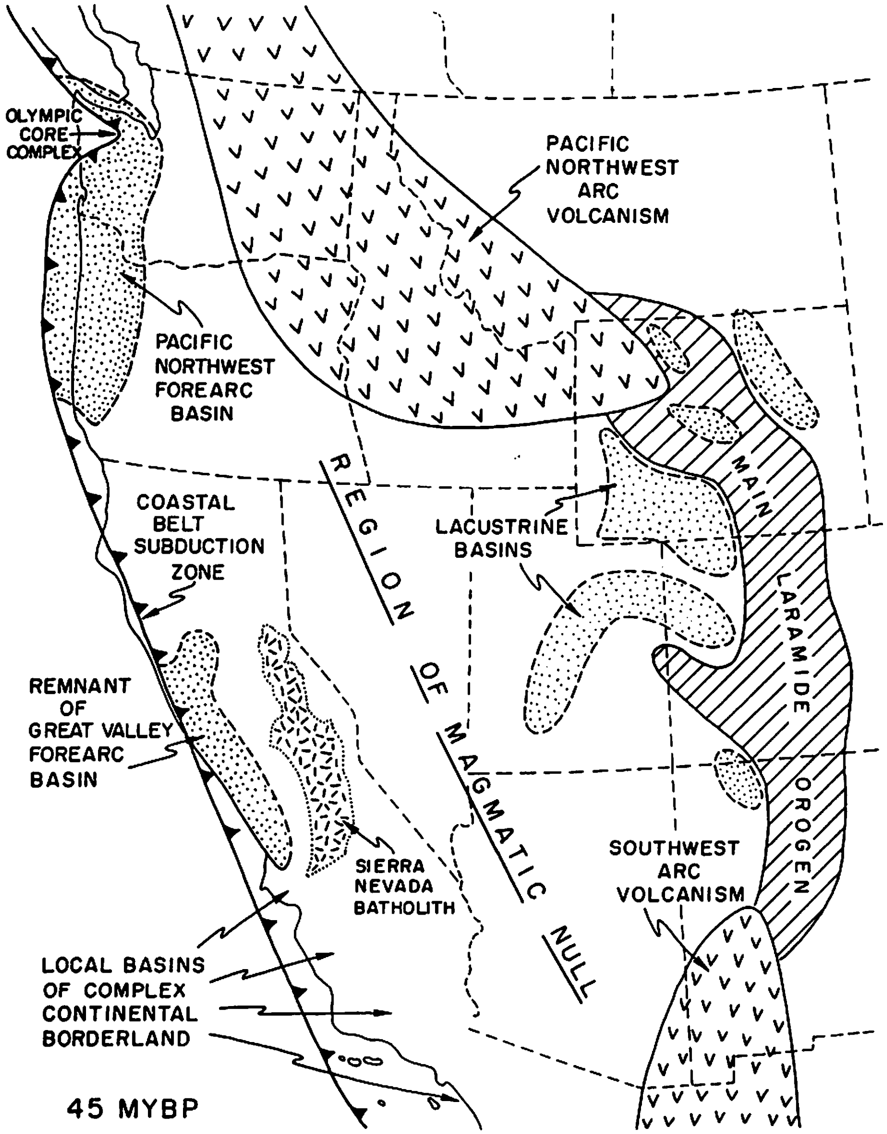

Figure 8. Paleotectonic and paleogeographic sketch map of the Cordilleran region 45 mybp in the Eocene.

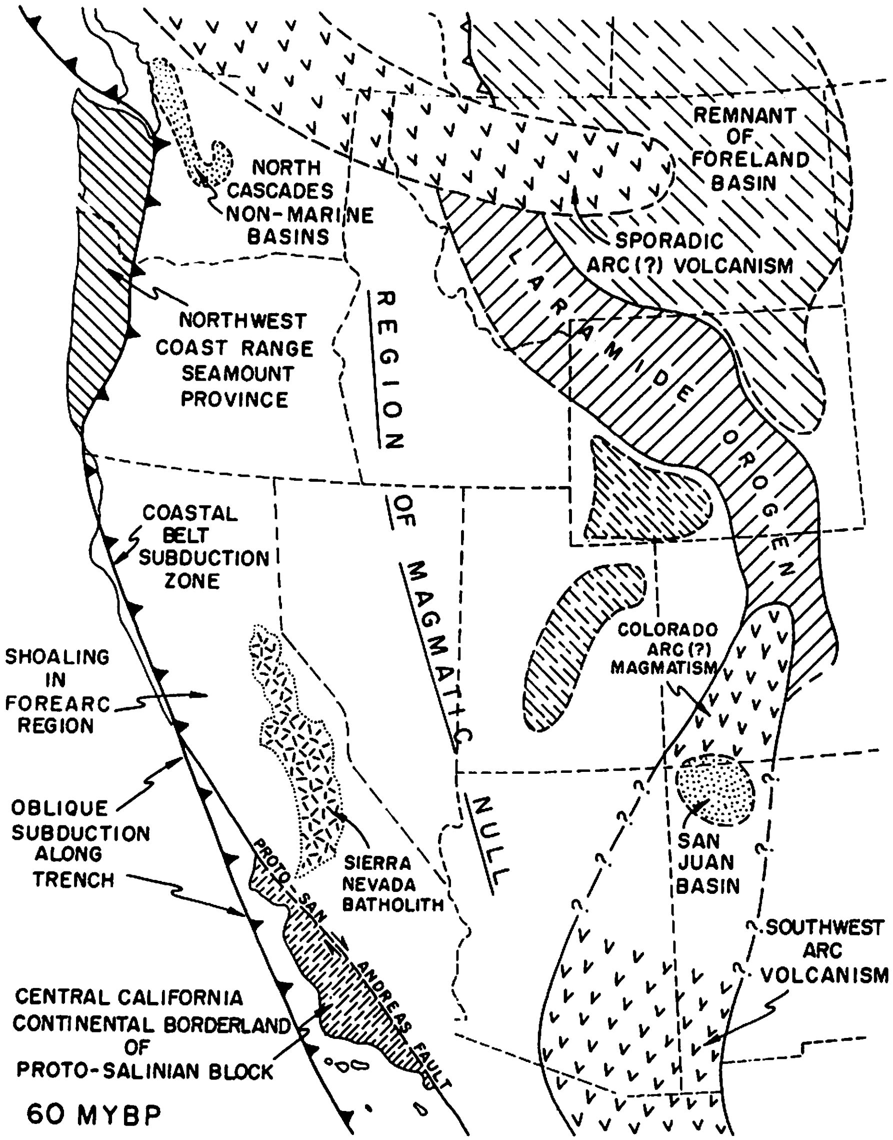

Figure 9. Paleotectonic and paleogeographic sketch map of the Cordilleran region 60 mybp in the Paleocene.

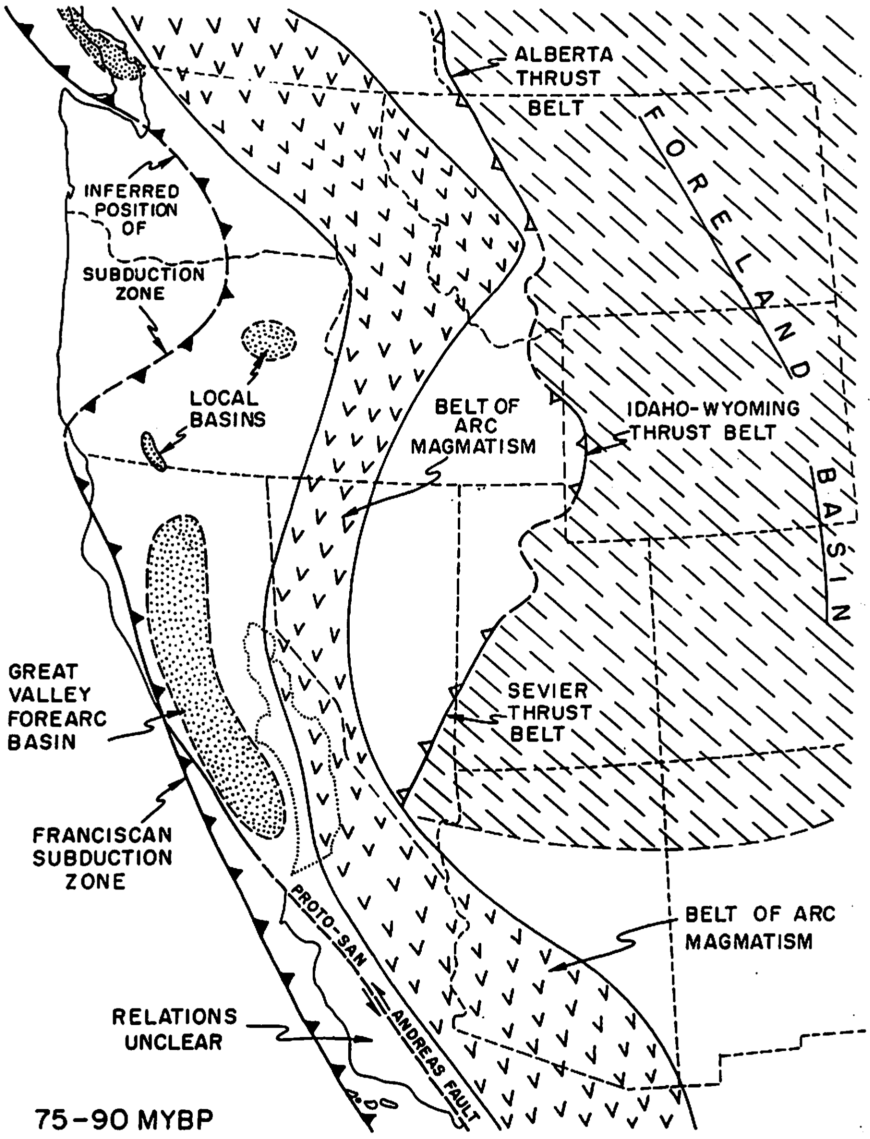

Figure 10. Paleotectonic and paleogeographic sketch map of the Cordilleran region 75 mybp in the latest Cretaceous (Campanian).

(3) Within the Coast Ranges west of the San Andreas fault, Neogene dextral slip of 115 km on the San Gregorio-Hosgri trend and a nominal 50 km of dextral slip within the Salinian block are restored for Figures 6-10 (see Graham and Dickinson, 1978).

(4) For the region from the Sierra Nevada block westward (Davis and Burchfiel, 1973), 60 km of sinistral slip are restored on the Garlock fault for all maps except Figure 4, and a coordinate amount of east-west extension has been restored by abruptly contracting the western fringe of the Basin and Range Province north of Las Vegas (Wright, 1976).

(5) For the remainder of the Basin and Range Province generally, an average overall Neogene extension of 30 per cent has been assumed relative to the original width (Proffett, 1977). Restoration of this deformation involves contracting the Basin and Range Province from 50 to 150 km from place to place, depending upon its width locally. This amount of contraction has been applied arbitrarily for Figures 6-10, but not for Figures 4-5. This procedure by convention concentrates all the main extension into the Miocene between 15 and 5 mybp.

These restorations do not properly account for complex shifts of crustal blocks within the Transverse Ranges and the California Continental Borderland where key relations are still unclear. Nor do they allow for distributive strike slip on structures akin to the Walker Lane in western Nevada. Nor are the paleomagnetic data for Paleogene strata in the Pacific Northwest fully satisfied (Simpson and Cox, 1977). The restorations made should thus be viewed as probably the minimal ones required. They are stated explicitly here to permit further geographic modifications of the map sequence to test diverse models for the geotectonic evolution of the Cordillera.

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