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Plate tectonics of the Laramide orogeny

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ABSTRACT

In terms of plate tectonics, most orogenic belts are arc, collision, or transform orogens marked by regional batholiths, overthrust nappes, and en echelon fold trains, respectively. None of these models fits the crustal buckling of the classic Laramide orogeny, marked in the central Rocky Mountains by fault-bounded, basement-cored uplifts separated by intervening sediment-filled basins. Reported patterns of current seismicity, volcanism, and deformation in the modern central Andes document two modes of subduction; one involves plate descent at an abnormally shallow angle and may simulate Laramide conditions. In the more familiar mode, a plate descending steeply into the asthenosphere beneath the continental margin generates standard arc morphology with an active volcanic chain; crustal seismicity outside the subduction zone near the trench is confined mainly to a back-arc fold-thrust belt. In the unfamiliar mode, the descending slab of lithosphere slides along under the overriding plate of lithosphere, with which contact is maintained; crustal earthquakes are widespread across the dormant arc massif, within which local block uplifts bounded by reverse faults are prominent, and magmatism is meanwhile suppressed because the asthenosphere is never penetrated by the descending slab. The largely amagmatic Laramide style of deformation can be ascribed to the dynamic effects of an overlapped plate scraping beneath the Cordillera. That inference is strongly supported by the close correlation, in both space and time, between a prominent magmatic null or gap in the western Cordillera and the classic Laramide orogeny in the eastern Cordillera.

INTRODUCTION

Plate tectonics explains orogenesis as a product of plate interactions (Dewey and Bird, 1970). Three common types of orogenic belt can be identified:

1. Arc orogens, where (a) continued consumption of oceanic lithosphere at a

(Armstrong, 1968). To some extent, however, this older regime continued into Paleocene time and thus overlapped partly in time with formation of the classic Laramide structures (Dorr and others, 1977). Continuation of thin-skinned tectonics into Paleogene time was confined to the Idaho-Wyoming segment (Armstrong and Oriel, 1965) of the thrust belt near the juncture between Sevier and Laramide trends; thrusting did not persist along the Nevada-Utah segment (Armstrong, 1968) farther south (see Fig. 1).

The segment of the Cordillera that underwent classic Laramide tectonism along its eastern side was the same segment that experienced a pronounced Paleogene lull in magmatism farther west (Armstrong, 1974). This null in igneous activity within the Sevier-Laramide segment of the Cordillera can be interpreted as a temporary gap in the continuity of the magmatic arc that was evolving within the Cordillera in response to subduction along the Pacific margin of the continent (Snyder and others, 1976). We now have firm paleontologic data (Evitt and Pierce, 1975) from the coastal belt of the Franciscan subduction complex in the Northern Coast Ranges of California to confirm that coastal subduction persisted beyond Mesozoic and through much of Paleogene time (Travers, 1972). Both north and south of the Sevier-Laramide segment of the Cordillera, thin-skinned Sevier-like deformation apparently persisted into Paleogene time while Laramide-style deformation was in progress in the intervening area (Burchfiel and Davis, 1975). Significantly, the magmatic null or gap did not extend far into Canada or Mexico (see below).

The Paleogene lull in arc magmatism in the western Cordillera was accompanied by pronounced migration of the inland limit of arc activity far into the eastern Cordillera where Laramide deformation was simultaneously in progress. Thus, significant reduction of arc activity along its accustomed trend—marked by the great Mesozoic batholiths lying well west of the Sevier belt—was accompanied by a spread of desultory arc-related magmatism into the classic Laramide region well to the east of the Sevier belt. Lipman and others (1971) first suggested that

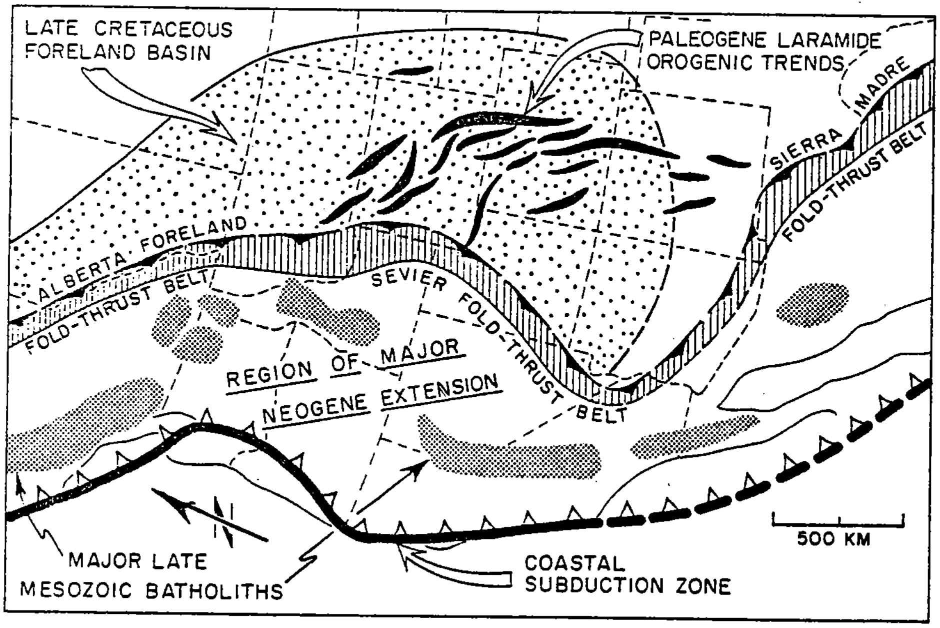

Figure 1. Sketch map of the Cordillera showing relation of Laramide orogenic trends to other major tectonic elements near the Mesozoic-Cenozoic boundary.

of basement rocks in the Laramide structures. Lowell (1974) also related Laramide deformation directly to shallow subduction, but appealed mainly to associated buoyant effects, rather than to the dynamic shear that seems to us to be the most likely linkage between the two. In either case, the Laramide problem reduces in gross outline to an analysis of the mechanical behavior of a surface slab of lithosphere subject to the influence of a subterranean slab sliding beneath it. Relative motion between the two plates was probably oriented along a northeast-trending line (Coney, 1976, 1978).

LARAMIDE EVENTS

The model proposed for Laramide tectonism can be tested by examining in detail the space-time patterns of magmatism and diastrophism for the Sevier-Laramide and adjoining segments of the Cordillera. We here present a preliminary assessment of the pertinent relationships using refinements of data we have presented elsewhere (Dickinson, 1976; Snyder and others, 1976). Inferred trends and migrations of arc magmatism at various times (Figs. 3 through 5) are based primarily on about 2,500 radiometric dates for Cenozoic igneous rocks in the Western United States (Noblett and others, 1977). On Figures 3 through 5, stippled areas are the magmatic loci (Snyder and others, 1976) to which most available radiometric data are confined. Some loci are separated by relatively amagmatic regions such as southernmost Nevada, the Colorado Plateau, and central Wyoming. Other loci are separated by young lava fields that mask the possible continuity of older igneous suites in the Pacific Northwest.

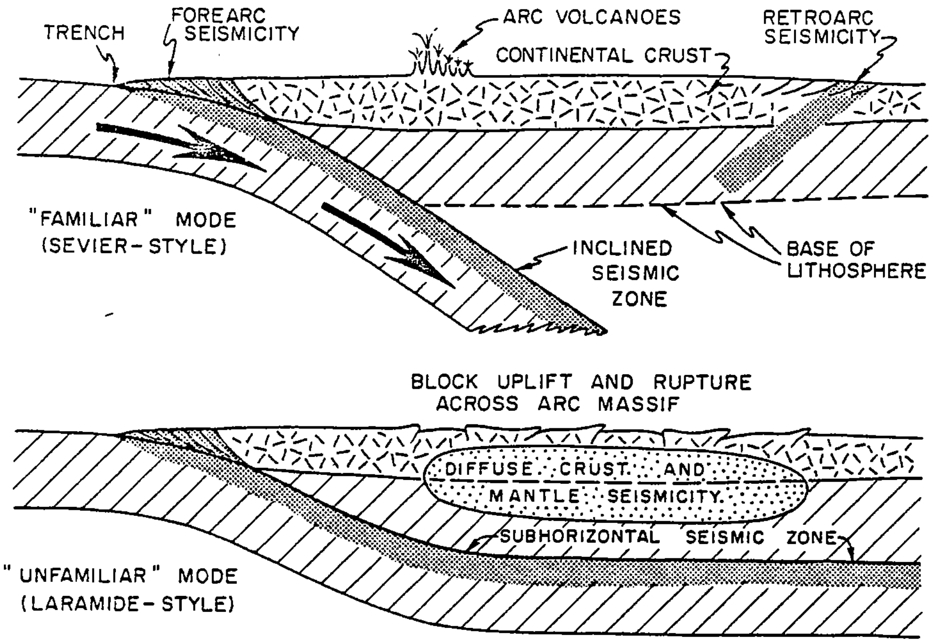

Figure 2. Diagram of two types of arc orogens displaying two modes of subduction, steep (top) and shallow (bottom) plate descent. Modified after Barazangi and Isacks (1976) and Megard and Philip (1976).

Paleogene Magmatic Null

Figure 3 indicates the general eastward expansion of diffuse arc magmatism that continued at a low level of activity when the intense Late Cretaceous magmatism along the Sierran arc trend sputtered out in latest Cretaceous time. The pattern of activity is not well controlled for this time span, because most of the dated rocks are plutonic and many of their radiometric dates may reflect uplift and cooling rather than actual emplacement. Nevertheless, the trend of arc migration is clearly inland. We infer, therefore, that the angle of plate descent beneath the Cordillera changed from steep to shallow between 80 and 70 m.y. B.P.

The Paleogene magmatic null began to develop at about 70 m.y. B.P., probably near the Idaho-Nevada-Oregon common corner along the northern edge of the Nevada locus. Within 5 to 10 m.y., arc magmatism had been snuffed out within the Nevada locus and over much of the Pacific Northwest as well. Figure 4 depicts the changing shape and size of the magmatic gap in the western Cordillera as the null evolved through Paleogene time. On the diagram, the magmatic gap that existed at various times is marked by the series of regions that lie west of the successive hachured magmatic fronts. The latter are drawn schematically to connect the westernmost occurrences of arc igneous activity within the various magmatic loci.

In detail, the magmatic null was thus diachronous. North of the Nevada locus, the magmatic gap expanded from 70 to 60 m.y. B.P. (across the Cretaceous-Tertiary boundary), whereupon it began to contract and had essentially disappeared by 45 m.y. B.P. To the south, however, the magmatic gap continued to expand until about 40 m.y. B.P. before beginning to close. Presumably, the subducted slab (which controlled the position of the magmatic front) was to some extent flexing or breaking, and thus whipping about, in its subterranean position. The Colorado locus can be regarded as a sort of pivot point between the northern and southern regions of contrasting slab behavior. Intermittent Laramide volcanism was, therefore, apparently continuous within the Colorado locus throughout the period from 70 to 50 m.y. B.P. (Tweto, 1975).

Figure 5 depicts the manner in which arc volcanism was rekindled within the Nevada locus by the progressive southward sweep of the magmatic front (compare Armstrong and Higgins, 1973, Fig. 2; Stewart and others, 1977, Fig. 2). An analogous shift of arc magmatism carried arc activity back across the Arizona locus as well. We infer that the angle of plate descent beneath the Cordillera changed gradually from shallow to steep between 40 to 45 and 20 to 25 m.y. B.P. (compare Coney and Reynolds, 1977). The arc front thus swept forward as the dip of the subducted slab increased. Presumably, each successive position of the magmatic front was a register of some critical depth contour on the subducted slab. The due-east trend of the arc front as it swept down across the Nevada locus can thus be interpreted as the record of a flexure in the subducted slab. The flexure, which evidently propagated southward with time, lay between a steeply dipping slab to the north and a gently dipping slab to the south. The occurrence of successive age belts of mid-Cenozoic igneous rocks along due-east trends in the Great Basin has been interpreted in identical fashion by P. W. Lipman (in Stewart and others, 1977). The presence of a subducted slab thus having transient due-east strikes locally may well be the correct explanation for the indication of a nominally flat-dipping slab inferred earlier by Lipman and others (1971) from geochemical arguments based on the potassium content of arc-related Cenozoic igneous rocks.

By the beginning of Neogene time, the magmatic null and gap were past, and a continuous arc trend again extended parallel to the continental margin in the

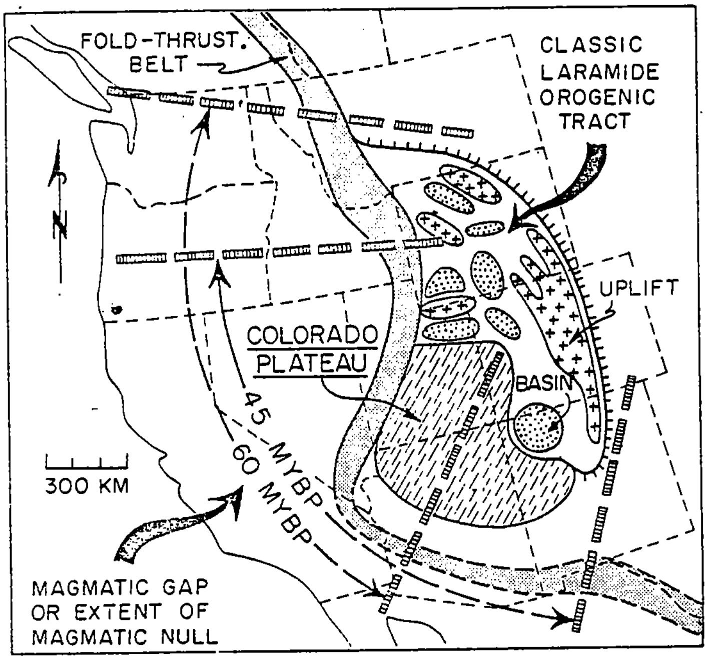

Figure 6. Diagrammatic map showing spatial relationship between Paleogene magmatic gap (after Figs. 4, 5) and area of classic Laramide orogeny.

faulting in the northern Cascades (Misch, 1966) could also have been a local effect of the Laramide tectonism. Important deformation may have occurred in the Great Basin during early Cenozoic time and could conceivably record Laramide events that are largely masked now throughout the Basin and Range province by younger volcanic cover and much more widespread late Cenozoic faulting.

CONCLUSIONS

Our chain of logic thus runs as follows:

1. The Laramide orogeny had unusual attributes that distinguish it from standard models for arc, collision, and transform orogens.
2. The classic Laramide orogeny in an eastern segment of the Cordillera occupied a time span coincident with the development of a magmatic null and cessation of thrusting in a paired western segment of the Cordillera.
3. Recent work in the central Andes shows that both cessation of volcanism and block deformation across the width of the arc massif are related to subhorizontal subduction of consumed oceanic plate beneath the continental plate.
4. Therefore, we ascribe classic Laramide deformation to the mechanical effects on the overriding plate of the overlapped underlying plate; that is, a regime in which the subducted plate scrapes horizontally beneath the surficial plate.

In his discussion of Rocky Mountain tectonics, Grose (1972) concluded that the Laramide orogeny was caused by "primary horizontal or gently inclined compressive stress . . . [that] . . . acted in the lower crust and/or mantle generally from west to east" in association with plate consumption far away along the coast. In effect, our inferences here suggest a specific plate-tectonics context for such postulated stresses.

The greatest weakness in our argument is the lack of evidence for wholesale disruption of the sub-Andean foreland basin, as occurred in Wyoming and Colorado

D. S. Storm, and G. Yuan in W. R. Dickinson's class on sedimentary basins). Suggestions from P. C. Coney and W. B. Hamilton improved the text.

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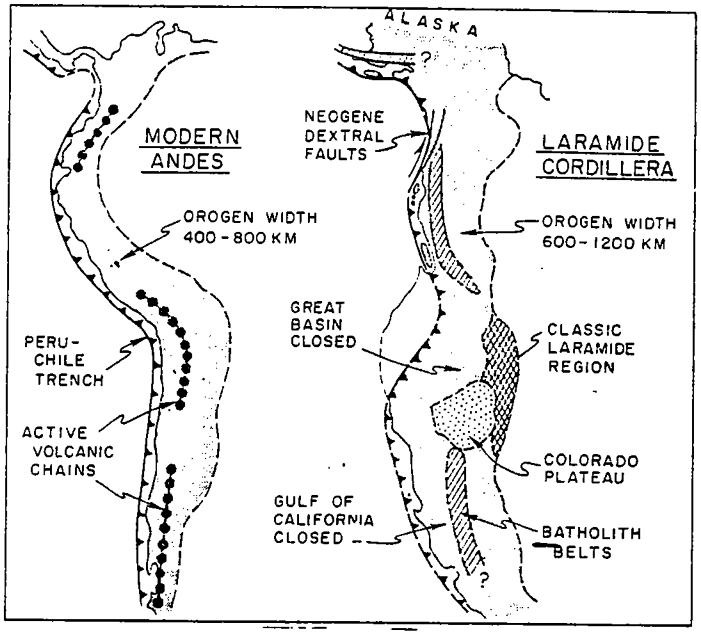

Figure 7. Diagrammatic maps at same scale comparing widths of Cordilleran orogen during Laramide time in North America and modern Andean orogen of South America. About 250 km of Neogene extension in Great Basin has been restored (see Hamilton and Myers, 1966).

for the Rocky Mountain Cretaceous foreland basin during the Paleogene Laramide orogeny. We are content, however, that our correlation of two general styles of deformation with two modes of subduction, shallow and steep, is valid. Furthermore, Figure 7 shows that the total inferred width of the Cordilleran orogen, as reconstructed for Laramide time by reversal of Neogene tectonic events, is comparable to the full width of the modern Andean system from trench to foreland. No matter how the reconstruction is accomplished for the San Andreas fault and the Basin and Range province, the widest parts of the Laramide-age Cordillera are somewhat wider than the widest parts of the Andean orogen today, but narrower segments of the Laramide-age Cordillera are not as wide as some segments of the Andean orogen. Moreover, the single Andean example simply cannot be taken as definitive of the maximum widths conceivable for all past continental-margin arc-trench systems. Our view of the Laramide orogen as a special variation of arc orogen thus remains tenable when overall dimensions are considered. Note also on Figure 7 that the characteristic lengths of alternating active arc segments and dormant magmatic gaps appear comparable for the Laramide Cordillera and the Quaternary Andes.

We close with the thought that the next step in the resolution of the classic Laramide problem must be an analysis of the mechanical behavior of a plate of lithosphere given the general sorts of boundary conditions inferred here.

ACKNOWLEDGMENTS

This work was supported by the Earth Sciences Section of the National Science Foundation with NSF Grants DES72-01728 and EAR76-22636. Our interest in the Laramide problem stems in part from discussions with P. J. Coney and L. T. Grose, and our thinking was aided at a critical stage by a set of term papers at Stanford University dealing with the sedimentary evolution of Laramide basins in Wyoming (by J. T. Bateson, D. C. Dawson, D. I. Fletcher, C. K. Keller,

western Cordillera. This Neogene arc was the one later disrupted by evolution of the San Andreas transform (Dickinson and Snyder, 1978).

Laramide Orogenic Timing

Figure 6 illustrates the close spatial relationship between the Paleogene magmatic gap and the Laramide orogenic tract. Low-angle thrusting within the thin-skinned fold-thrust belt continued throughout Laramide time to the north and to the south in Canada and Mexico, but essentially ceased west of the main Laramide tract (Burchfiel and Davis, 1975). Wrench-style deformation suggestive of relative east-to-west translation of basement is present along the northern edge of the Laramide tract (Sales, 1968). This behavior can be interpreted as a tectonic transition between (1) continuing thin-skinned deformation to the north where crustal contraction was concentrated at the fold-thrust belt in Canada and northern Montana and (2) the Laramide region of thick-skinned buckling farther south where crustal contraction was distributed over a much wider orogenic transect in Wyoming and southern Montana.

Still farther south, a Paleogene lowland lying in the region of the present Colorado Plateau was a residual topographic trough trapped between vestigial Mesozoic highlands of the Sevier orogenic belt on the west and nascent Laramide highlands on the east (Hunt, 1956). The reduced vigor of Laramide deformation in the plateau region, as compared to its effects in the Rockies, remains enigmatic to us (see Coney, 1976); perhaps the presence of Paleozoic structures inherited from the Ancestral Rockies somehow enhanced response to Laramide deformation (Coney, 1978).

Strict contemporaneity between the development of the Paleogene magmatic null and the course of the Laramide deformation is difficult to demonstrate, but roughly coeval timing is evident. Laramide structures formed generally between 70 and 45 m.y. B.P. (Coney, 1972, Fig. 2), with the most intense deformation within the core of the Laramide tract in Wyoming and Colorado coming between 65 and 50 m.y. B.P. (Berg, 1962). The Paleogene magmatic gap was largest in the midst of the indicated Laramide time span, from 60 to 55 m.y. B.P., but was prominent throughout the whole period from 70 to 45 m.y. B.P. (see Figs. 4, 5). Neither the Laramide deformation nor the magmatic null predated about 75 m.y. B.P. anywhere. The Laramide deformation had definitely ended and the magmatic gap was everywhere rapidly contracting by 40 m.y. B.P. In California, activity on the proto–San Andreas fault, whose origin may have been related somehow to the same plate interactions, was restricted to some part of the period 70 to 55 m.y. B.P. (Dickinson and others, 1978).

From the genetic relationship that we infer here between the Laramide orogeny and the Paleogene magmatic null, we would expect comparable phases of Laramide deformation to be younger in the southern Rockies than in the northern Rockies. There are hints that such may be the case. For example, the post-Laramide Challis volcanic rocks of Idaho and Absaroka volcanic rocks of Wyoming were erupted in middle to late Eocene time (Prostka and others, 1977), whereas deformation may have continued through all or part of that period in Colorado where the post-Laramide volcanic rocks are of latest Eocene or earliest Oligocene age (Tweto, 1975).

Some evidence of Laramide-style deformation might also be expected in areas west of the classic Laramide tract but within the magmatic gap (see Fig. 6). The monoclines of the Colorado Plateau are a clear-cut example (Coney, 1976; Davis, this volume). Perhaps the episode of early to middle Eocene folding and high-angle

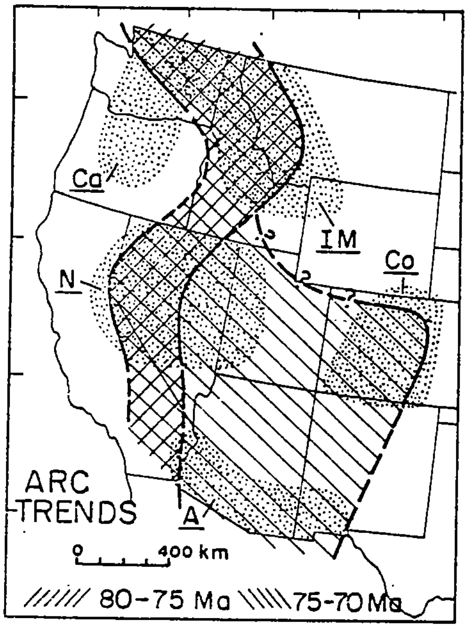

Figure 3. Areal distribution of arc-related igneous activity in the Western United States during latest Cretaceous time. Stippled magmatic loci (Snyder and others, 1976) include Ca, Cascades; IM, Idaho-Montana; N, Nevada; Co, Colorado; A, Arizona (Ma = million years before present).

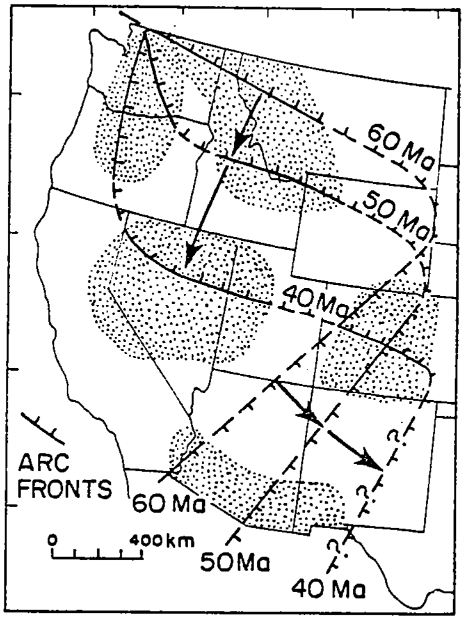

Figure 4. Diagrammatic map showing Paleogene migration of arc volcanism in the Western United States (Ma = million years before present).

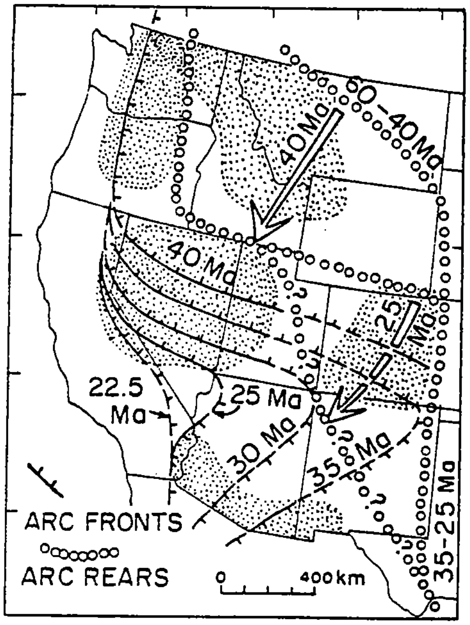

Figure 5. Diagrammatic map showing mid-Cenozoic migration of arc volcanism in the Western United States (Ma = million years before present).

the coordinated diminution and migration of arc magmatism were jointly related to a shallowing of the angle of subduction of the consumed slab descending beneath the continent from the coastal subduction zone. For the region south of the Colorado Plateau (see Fig. 1), Coney and Reynolds (1977) have shown elegantly how the spotty Laramide magmatism swept inland to Colorado, and then back again toward the coast, between Late Cretaceous and mid-Tertiary time. They have ascribed this behavior to successive shallowing and then steepening of the angle of slab descent. Under such changing regimes of subduction, the descending slab reaches melting depth in the mantle at varying distances inland from the coastal subduction zone.

We here accept this hypothesis of changing slab dip to explain the Paleogene magmatic lull. As discussed elsewhere, we are able by kinematic analysis of plate motions to exclude the chief alternative hypothesis of coastal transform activity (Dickinson and Snyder, 1978; compare Coney, 1976, 1978).

SUBDUCTION MODES

The modern Andes constitute our best modern example of a continental-margin arc-trench system analogous to the pre-Neogene Cordillera (Hamilton, 1969). Recent work in the central Andes (Barazangi and Isacks, 1976; Megard and Philip, 1976) documents two contrasting modes of subduction (see Fig. 2): (1) a familiar mode, which we regard as Sevier-like, involving slab descent into the asthenosphere at a steep angle, and (2) an unfamiliar mode, which we regard as Laramide-like, in which the descending slab of oceanic lithosphere moves into the mantle at an angle shallow enough to maintain contact with the overriding plate of continental lithosphere.

Where the subducted slab dives steeply into the asthenosphere, a typical level of steady arc magmatism is stimulated at a normal distance from the trench. The usual type of standard arc orogen is thus formed in response to plate consumption. Strong crustal deformation reflected by seismicity is restricted to (1) the subduction zone near the trench, (2) the inclined seismic zone marking the upper tier of the descending slab in the mantle, (3) local subvolcanic sites near crustal magma chambers, and (4) an antithetic back-arc seismic belt along the so-called sub-Andean trend. The last-named feature is viewed here as analogous to the Sevier fold-thrust belt east of the Mesozoic arc trend, marked now by its roots in the Sierra Nevada batholith.

Where the subducted slab glides subhorizontally beneath the overriding plate of lithosphere, arc magmatism is generally suppressed. Evidently, the descending slab must actually penetrate asthenosphere to induce the magmatism. Moreover, the mantle seismic zone is truly inclined only near the trench; it forms a nearly horizontal zone slightly deeper than 100 km as it passes beneath the dormant arc massif. Crustal earthquakes are widespread across the full width of the arc massif, where reverse faults and block uplifts are common. Erosion has bitten deep into the prevolcanic terrane of the dormant arc and locally has exposed basement terranes on line with the trend of the active arc segments in which steep subduction is continuing (for example, see Audebaud and others, 1973).

Because of the existence of the Paleogene magmatic null in the Cordillera, we infer here that the shallow mode of subduction was directly responsible for the Laramide orogeny, as suggested previously by Coney (1976, 1978). We postulate that the dynamic effects of a subhorizontally subducted plate scraping along beneath the overriding continental plate were recorded by the crustal buckling and fracturing subduction zone builds an accretionary prism or subduction complex of deformed oceanic materials along one flank of the orogen and (b) magmatism induced by plate descent into the mantle constructs a volcanic chain capping a linear belt of injected batholiths along the spine of the orogen.

2. Collision orogens, where (a) continued consumption of oceanic lithosphere at a subduction zone eventually welds two once-separate continental blocks together and (b) the subduction complex of deformed oceanic materials is trapped along a linear suture belt marking the line of final ocean closure.

3. Transform orogens, where a component of contraction across an imperfect transform combines with the dominant translation to cause transpression (Harland, 1971), which gives rise to a train of en echelon wrench folds in an elongate belt parallel to the transform (Lowell, 1972; Wilcox and others, 1973).

The classic Laramide orogeny of latest Cretaceous and Paleogene age in the central Rocky Mountains—centered on Wyoming and Colorado—was unlike any of these three standard orogen types. It was marked especially by crustal buckling and associated fracturing to form giant fault-bounded, basement-cored uplifts separated by intervening basins in which sediment accumulated while deformation was in progress. There was minor magmatism similar to that common in arc orogens, but no continuous batholith belt and metavolcanic terrane or volcanic cover. There are no internal ophiolites indicative of oceanic closure, and no regionally integrated system of nappes like those common for collision orogens. Although some broad wrench deformation occurred, especially near the margins of the classic Laramide tract (Sales, 1968), no throughgoing transform structures showing major strike slip were present.

An adequate plate-tectonics model for the Laramide orogeny thus must differ from all three standard orogen models to some degree. We believe that a modified arc model is implicit in the conclusions of a number of recent workers. Our purpose here is to specify such a general qualitative model for the Laramide plate setting to serve as a basis for quantitative analysis of the plate interactions involved in the Laramide orogeny. Whereas we focus here on relative plate motions, Cross and Pilger (1978) elsewhere have speculated about absolute plate motions. Coney (1976, 1978) has discussed patterns of plate boundaries and motions throughout surrounding regions during Laramide time. Recently, Noble and McKee (1977) also discussed topics related to ours here. On the basis of the presence of eclogitic xenoliths in diatremes of the Colorado Plateau, Helmstaedt (1974) has previously proposed for Laramide orogenic movements a causative model closely similar to the one that we develop here.

LARAMIDE SETTING

The classic Laramide orogeny (Coney, 1976, 1978) occupied a particular time span and place within the Cordillera (Fig. 1), and we do not use the term here as a generic one for all deformation at the end of the Mesozoic Era. The characteristic signature of Laramide deformation in latest Cretaceous and Paleogene time was wholesale buckling and shear of the continental crust to produce asymmetric fractured uplifts and depressions oriented crudely parallel to the continental margin, but with notable local departures from that trend (Sales, 1968). In the central Rocky Mountains, the rumpling and rupture of the basement disrupted the previously integrated foreland basin with its typical wedge-shaped profile (Dickinson, 1976). The structural style contrasts markedly with older thin-skinned tectonic patterns within the fold-thrust belt of the late Mesozoic Sevier orogenic belt farther west

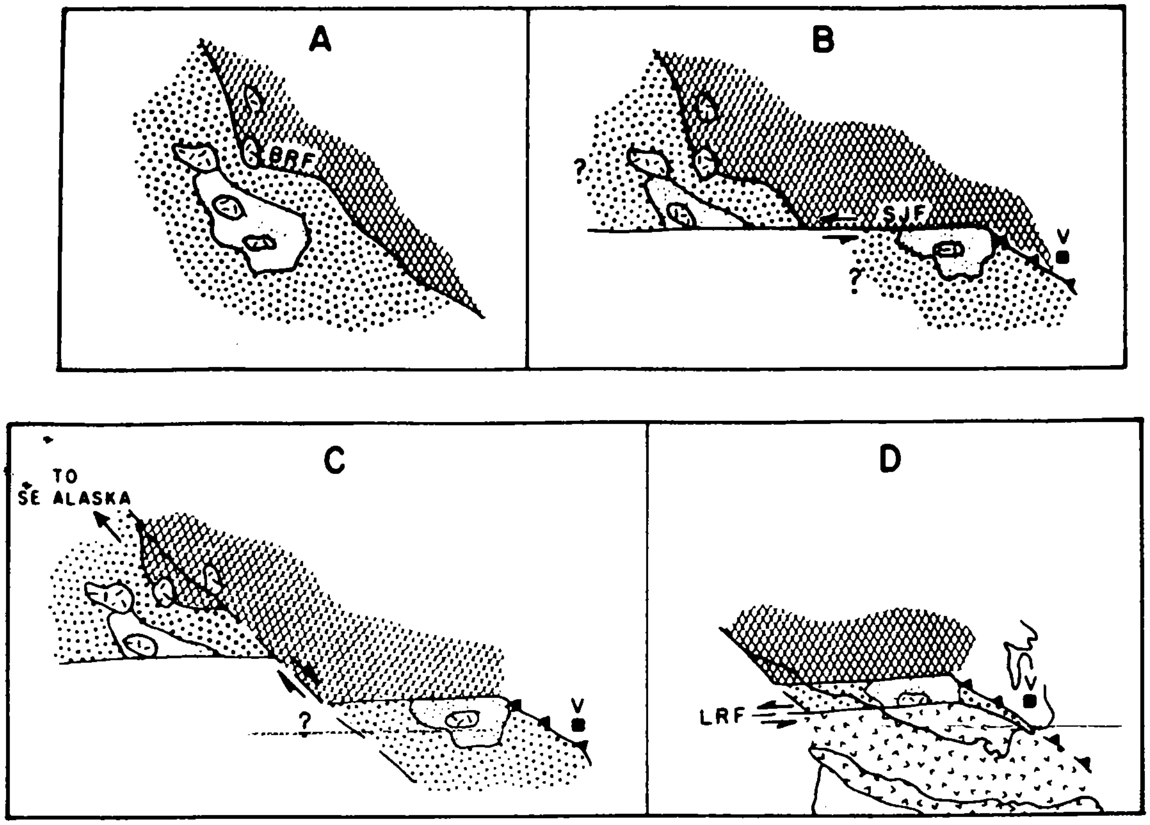

Figure 4. Diagrammatic maps showing possible early Tertiary geography and hypothesized tectonic evolution of area around what is now Juan de Fuca Strait (see Fig. 2). Most patterns are same as in Figures 2 and 3, except that short dashes represent lower Tertiary intrusive rocks. V indicates bedrock underlying Victoria, British Columbia, for reference. A: About 42 to 45 m.y. ago. Light stipple depicts synkinematically metamorphosed Jurassic-Cretaceous (?) rocks, associated with Eocene intrusive bodies, that are now exposed as Leech River complex and schistose rocks on southern Baranof Island; BRF = Border Ranges fault. B: After end of metamorphism and penetrative deformation at about 39 to 41 m.y. ago, Leech River complex and adjacent lower grade equivalents were emplaced against southern edge of Wrangellia by left-lateral slip along San Juan fault (SJF). Fault is overlain by upper Eocene–lower Oligocene Carmanah Formation. C: Truncation of margin after about 40 m.y. ago along major northwest-trending transcurrent fault carried schistose rocks on southern Baranof Island toward their final resting place in Alexander Archipelago. This allochthonous slice included what is now Chugach terrane in Figure 3 and perhaps small fragment of Wrangellia. D: Lower to middle Eocene basalts of Metchosin Volcanics and Crescent Formation were juxtaposed with Leech River complex, probably by left-lateral slip along Leech River fault (LRF) (Fairchild, 1979; Fairchild and Cowan, 1982). Emplacement postdated metamorphism of Leech River complex and predated deposition of upper Oligocene strata that unconformably overlie Leech River fault. Present-day shorelines of southern Vancouver Island and northern Olympic Peninsula are shown for reference. (FROM JOHNSON, 1984)

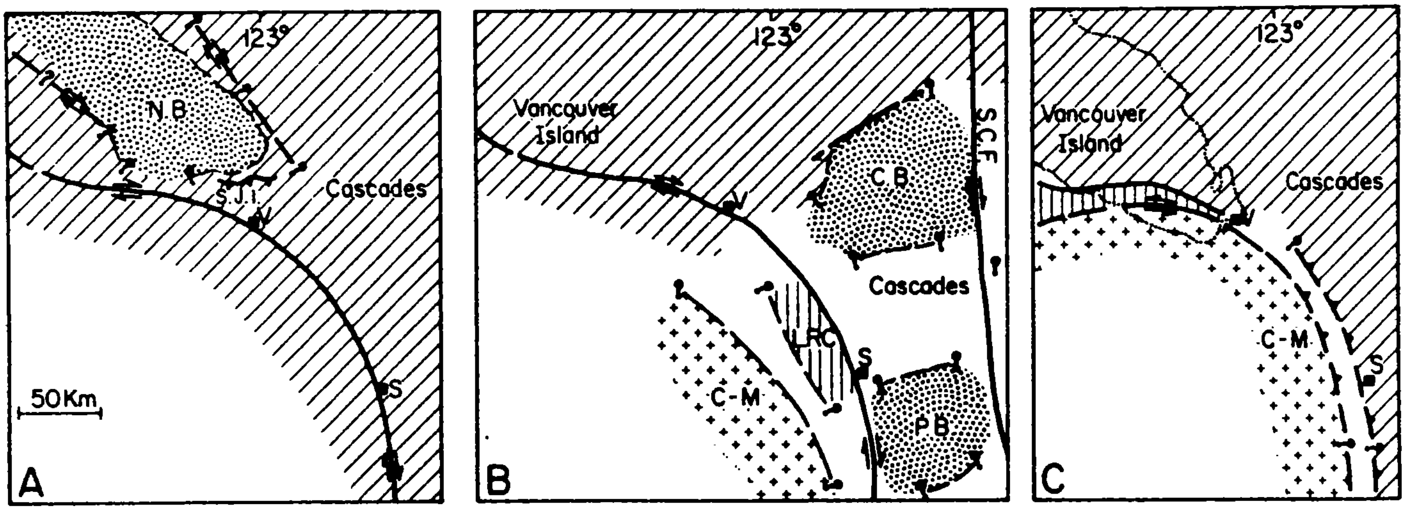

Figure 3. Schematic diagram showing postulated Late Cretaceous–early Tertiary paleogeography of western Washington and southern Vancouver Island. CB = Chuckanut Basin; C-M = Crescent-Metchosin formations; LRC = Leech River Complex; NB = Nanaimo Basin; PB = Puget Basin; S = Seattle; S.C.F. = Straight Creek fault; S.J.I. = San Juan Islands; V = Victoria. A: Late Cretaceous (Santonian-Campanian) strike-slip fault truncates pre-Tertiary basement and moves western terranes north. Splays off of main fault generate tensional setting in which Nanaimo Basin forms. Bend in fault may provide transpressive mechanism for thrusting in San Juan Islands. B: Middle Eocene. Chuckanut and Puget basins form in tensional zone between Straight Creek fault and postulated structure to west. Leech River Complex is metamorphosed in Puget Lowland and moves northwestward. Crescent-Metchosin seamount province has been accreted and is likewise moving north, outboard of the Leech River Complex. C: Latest Eocene–early Oligocene. Inferred transcurrent fault is no longer active. Margin is compressed by major left-lateral faulting on Leech River fault and thrusting in Puget Lowland (see MacLeod et al., 1977; Fairchild and Cowan, 1982; Cowan, 1982). This deformation greatly modifies original geometry of postulated fault. Dotted line shows present-day outline of Vancouver Island. (FROM COWAN, 1982)

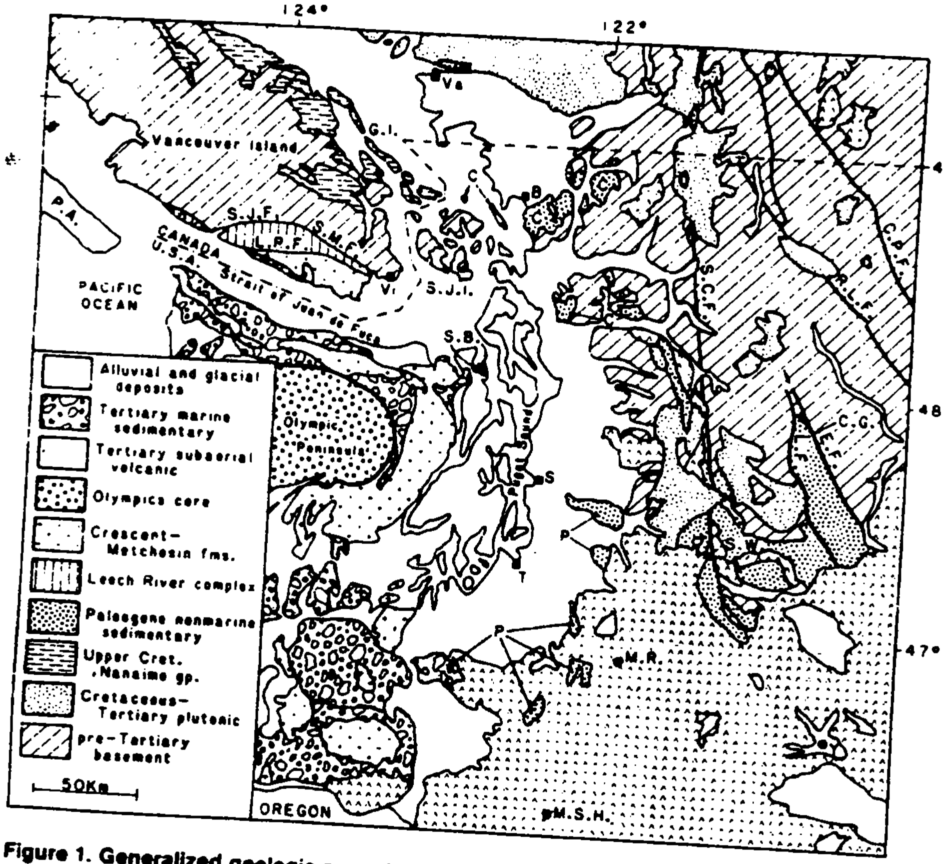

Figure 1. Generalized geologic map of northwest Washington and southwest British Columbia. B = Bellingham; C = Chuckanut Formation; C.P.F. = Chewack-Pasayten fault; C.G. = Chiwaukum graben; E.F. = Entiat fault; G.I. = Gulf Island; L.F. = Leavenworth fault; L.R.F. = Leech River fault; M.R. = Mount Rainier; M.S.H. = Mount Saint Helens; P = Puget Group; P.A. = Prometheus magnetic anomaly; R.L.F. = Ross Lake fault; S = Seattle; B = Scow Bay unit; S.C.F. = Straight Creek fault; S.J.F. = San Juan fault; S.J.I. = San Juan Islands; S.M.F. = Survey Mountain fault; S.W. = Swauk Formation; T = Tacoma; Vi = Victoria; Va = Vancouver; Y = Yakima.

(FROM JOHNSON, 1984)