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Basin-range structure in western North America: A review

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ABSTRACT

For more than 1,500 km along the western Cordillera of North America, late Cenozoic extensional faulting has produced block-faulted basin-range structure characterized by alternating elongate mountain ranges and alluviated basins. The faulting follows older geologic patterns, particularly those of Mesozoic and early Tertiary deformation and of early and middle Tertiary igneous activity. Basin-range structure is commonly inferred to represent either (1) blocks tilted along downward-flattening (listric) faults in which the upslope part of an individual rotated block forms a mountain and the downslope part a valley or (2) alternating downdropped blocks (grabens) that form valleys and relatively upthrown blocks (horsts) that form mountains. Such structure has been produced by extension estimated to be from 10% to 35% of the original width of the province and as much as 100% in specific areas. The province is characterized by anomalous upper mantle, thin crust, high heat flow, and regional uplift.

Current theories on the origin of basin-range structure can be grouped loosely into four main categories. In the first, the structure is presumed to be related to oblique tensional fragmentation within a broad belt of right-lateral movement and distributed extension along the west side of the North American lithospheric plate. This motion was initiated by the collision of the East Pacific Rise with the North American plate, which brought together the North American and Pacific plates to form the right-lateral San Andreas transform fault system. The second theory relates extension to spreading caused by upwelling from the mantle behind an active subduction zone (back-arc spreading). The third theory relates the basin-range structure to spreading that resulted from presumed subduction of the East Pacific Rise beneath part of North America. The fourth theory relates the basin-range structure to plate motion caused by deep-mantle convection in the form of narrow mantle plumes. The combination of anomalous upper mantle, thin crust, high heat flow, regional uplift, and extension with a previous history of high heat generation can best be related to back-arc spreading. The spreading may have been accelerated by slackening of confining pressure after the destruction of the subduction system along western North America and may have been accompanied by right-lateral shear because of the development of the transform western margin of North America.

INTRODUCTION

Basin-range structure consists of block-faulted mountain ranges and intervening alluviated valleys. It is one of the most distinctive geologic features of western North America and is more extensively developed there than in any other part of the world. Knowledge of its origin is critical in understanding the structural development of western North America, as well as of other regions where similar structures occur.

In this report, I will outline the geologic setting and characteristics of basin-range structure and current theories of origin. The subject involves many facets of geology that I can only summarize here. A review of the historical development of ideas concerning basin-range structure has been given by Nolan (1943) and Roberts (1968).

DISTRIBUTION OF BASIN-RANGE STRUCTURE

High-angle extension faulting extends throughout much of the western Cordillera of North America from Canada to northern Mexico (Fig. 1-1). Basin-range structure consisting of alternating mountains and valleys is best developed in the Basin and Range physiographic province (Fig. 1-2) that extends from southern Oregon and Idaho through most of Nevada and parts of California, Utah, Arizona, and New Mexico to northern Mexico—a total distance of more than 1,500 km. In the United States, the province is about 500 to 800 km across in the Great Basin region of Nevada and western Utah. The elevations of the valleys in the Great Basin are generally 1,300 to 1,600 m; mountain crests are commonly 2,000 to 3,000 m and locally about 3,600 m. Elevations of valleys and mountains are commonly 500 to 1,000 m lower in most of southeastern California, southern Arizona, and southwestern New Mexico. In the United States, basin-range structure extends around much of the Colorado Plateau province, a tectonically stable region underlain by relatively undeformed Paleozoic, Mesozoic, and Cenozoic sedimentary rocks, with a general surface elevation of 1,200 to 1,800 m. Extensional faulting along the east margin of the Colorado Plateau and southward to near the international boundary forms the Rio Grande rift valley (Chapin and Seager, 1975). In Mexico, basin-range structure extends southward along either side of the Sierra Madre Occidental, a high plateau (1,800 to 3,000 m) of relatively undeformed Cenozoic volcanic rocks. Elevations west of the Sierra Madre Occidental range from sea level along the coast to 1,000 to 2,000 m in some of the higher mountains inland. East of the Sierra Madre Occidental, elevations are generally higher; they range from about 1,000 to 1,500 m in valleys to 2,000 to 3,000 m in mountain ranges. Basin-range structure also occurs in Mexico along the east side of Baja California, north of lat 28°N. Some extensional faulting and possible basin-range structure also occur in the southern part of the Sierra Madre Occidental and in the so-called Central Mesa (really a physiographic basin) to the west.

GEOLOGIC SETTING

Western North America has had a complex history traceable into Precambrian time. The relation, if any, of older structures to the development of late Cenozoic basin-range structure is of critical importance. For example, is the distribution of basin-range structure largely determined by structures developed in Precambrian, Paleozoic, or Mesozoic time, or is the

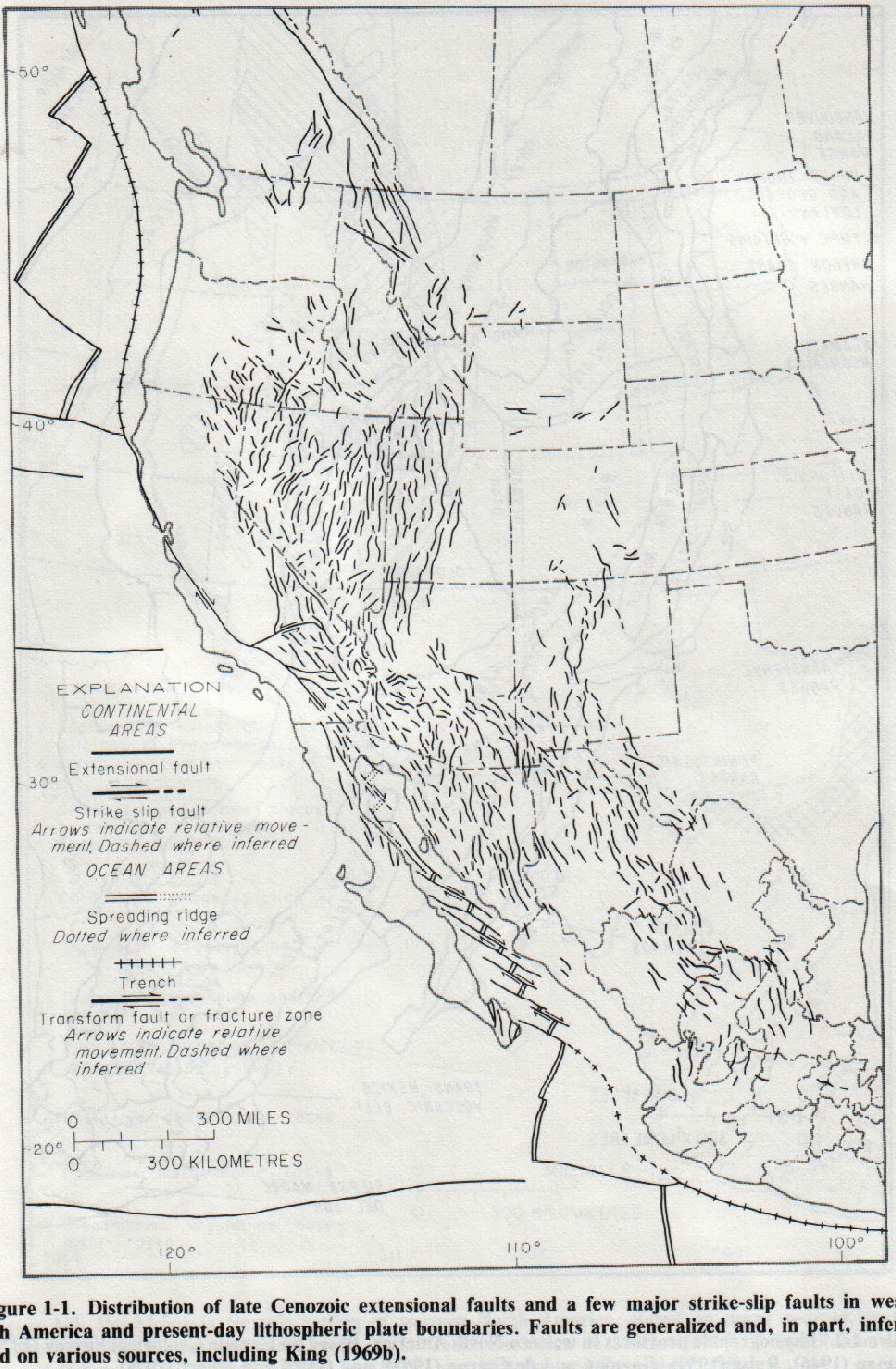


Figure 1-1. Distribution of late Cenozoic extensional faults and a few major strike-slip faults in western North America and present-day lithospheric plate boundaries. Faults are generalized and, in part, inferred. Based on various sources, including King (1969b).

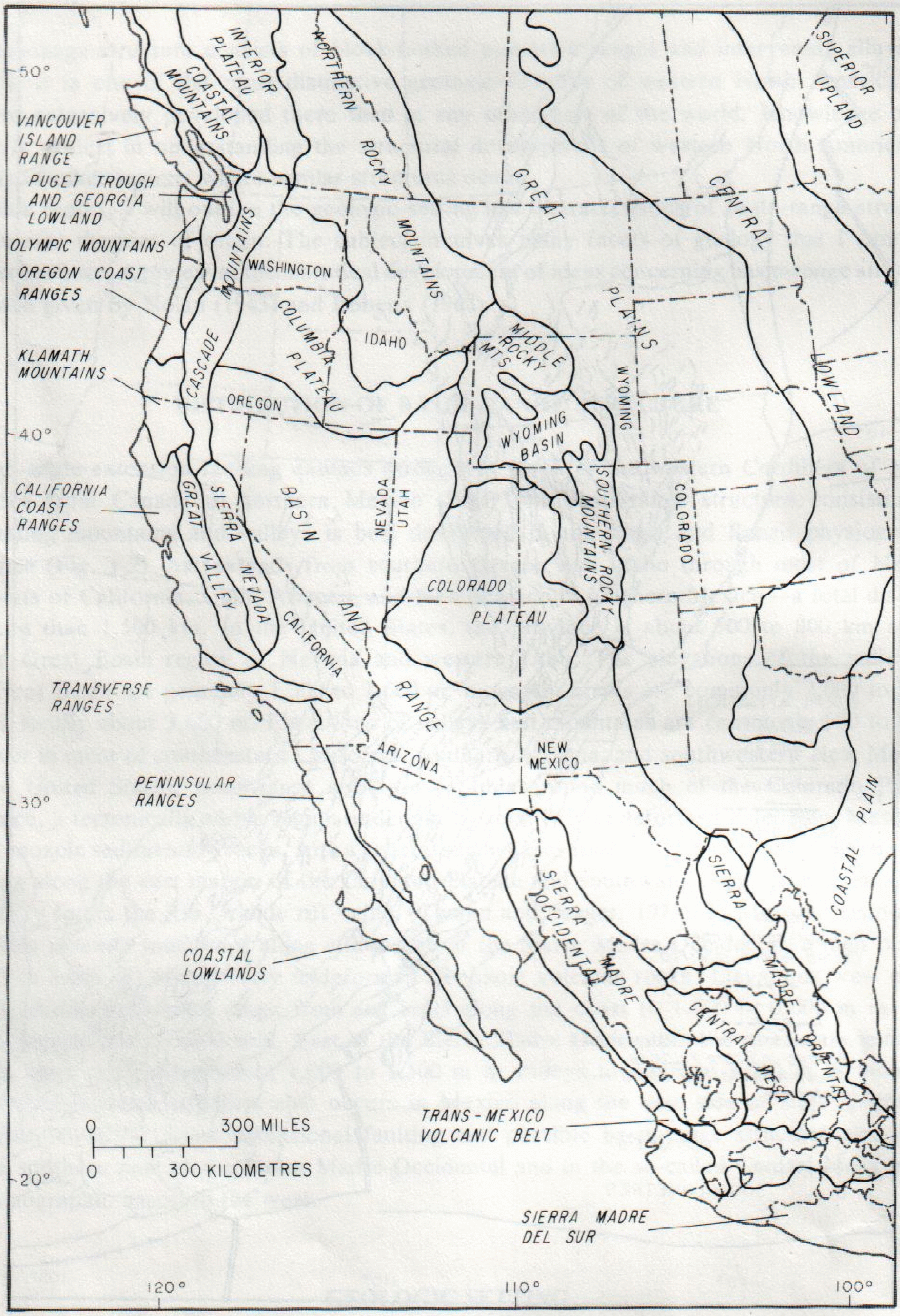


Figure 1-2. Physiographic provinces in western North America. Based on Canada Geological Survey (1970a), Fenneman (1946), Raisz (1959), Guzman and de Cserna (1963), and Gastil and others (1975).

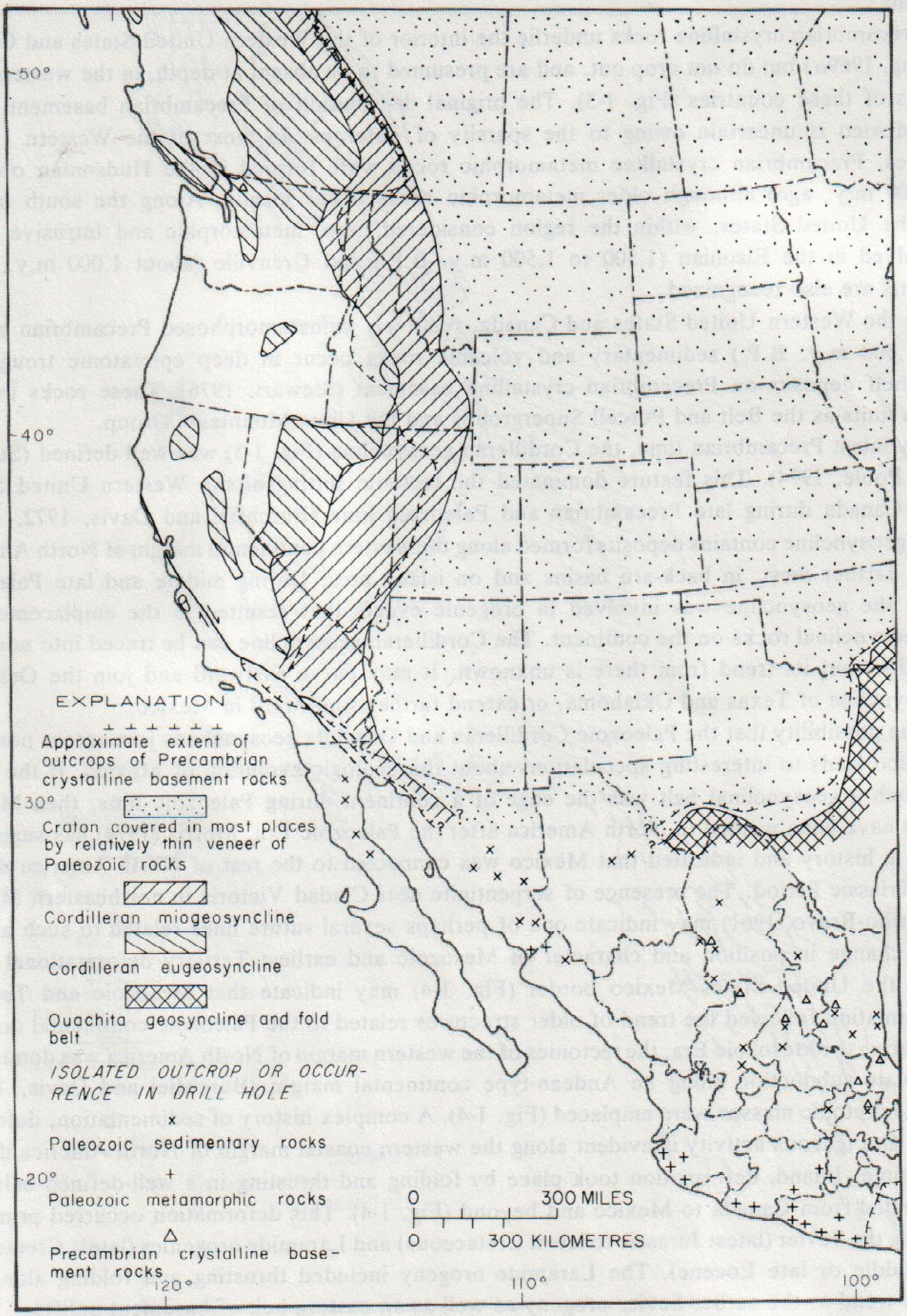


Figure 1-3. Pre-Mesozoic tectonic setting of western North America. Based on many sources, including Canada Geological Survey (1970b), Comite de la Carta Geologica de Mexico (1968), López-Ramos (1969), King and Beikman (1974), Gastil and others (1975), and Nicholas and Rozendal (1975).

distribution largely controlled by geologically short-lived and exceptional or unique Cenozoic events?

Precambrian crystalline rocks underlie the interior of the Western United States and Canada (King, 1969*a*) but do not crop out, and are presumed to be absent at depth, in the westernmost parts of these countries (Fig. 1-3). The original distribution of Precambrian basement rocks in Mexico is uncertain owing to the sparsity of outcrops. In most of the Western United States, Precambrian crystalline metamorphic rocks were formed in the Hudsonian orogeny (1,800 m.y. ago) although older metamorphic rocks occur locally. Along the south margin of the United States, within the region considered here, metamorphic and intrusive rocks involved in the Elsonian (1,300 to 1,500 m.y. B.P.) and Grenville (about 1,000 m.y. B.P.) events are also recognized.

In the Western United States and Canada, relatively unmetamorphosed Precambrian Y (800 to 1,600 m.y. B.P.) sedimentary and volcanic rocks occur in deep epicratonic troughs or as shelf deposits on Precambrian crystalline basement (Stewart, 1976). These rocks include such units as the Belt and Purcell Supergroups and the Uinta Mountains Group.

By latest Precambrian time, the Cordilleran geosyncline (Fig. 1-3) was well defined (Stewart and Poole, 1974). This feature dominated the tectonic setting of the Western United States and Canada during late Precambrian and Paleozoic time (Burchfiel and Davis, 1972, 1975). The geosyncline contains deposits formed along the western continental margin of North America and, farther west, in back-arc basins and on island arcs. During middle and late Paleozoic time the geosyncline was involved in orogenic events that resulted in the emplacement of eugeosynclinal rocks on the continent. The Cordilleran geosyncline can be traced into northern Mexico, but its trend from there is unknown. It may curve eastward and join the Ouachita geosyncline of Texas and Oklahoma, or extend farther southward in Mexico.

The possibility that the Paleozoic Cordilleran and Ouachita geosynclines join across northern Mexico leads to interesting speculations about the geologic evolution of Mexico. If the trace of such a geosynclinal belt was the edge of a continent during Paleozoic time, then Mexico must have been welded to North America after the Paleozoic Era. Morris (1974) has suggested such a history and indicated that Mexico was connected to the rest of North America during the Triassic Period. The presence of serpentinite near Ciudad Victoria in northeastern Mexico (Carrillo-Bravo, 1961) may indicate one of perhaps several suture lines related to such a join. The change in position and character of Mesozoic and earliest Tertiary deformational belts near the United States–Mexico border (Fig. 1-4) may indicate that Mesozoic and Tertiary deformation followed the trend of older structures related to the Paleozoic continental margin.

During the Mesozoic Era, the tectonics of the western margin of North America was dominated by plate subduction along an Andean-type continental margin (Burchfiel and Davis, 1975). Large plutonic masses were emplaced (Fig. 1-4). A complex history of sedimentation, deformation, and igneous activity is evident along the western coastal margin of North America during this time. Inland, deformation took place by folding and thrusting in a well-defined belt that extended from Canada to Mexico and beyond (Fig. 1-4). This deformation occurred primarily during the Sevier (latest Jurassic to latest Cretaceous) and Laramide orogenies (latest Cretaceous to middle or late Eocene). The Laramide orogeny included thrusting and folding along the same trend as the earlier Sevier orogeny as well as an eastern belt of basement uplifts.

During early and middle Cenozoic time, the tectonics of western North America was also dominated by events related to a subduction system along the margin of the continent (Lipman and others, 1972; Snyder and others, 1976). This time interval is notable for the widespread eruption of silicic volcanic rocks (Fig. 1-5) in the Great Basin region of Nevada and Utah,

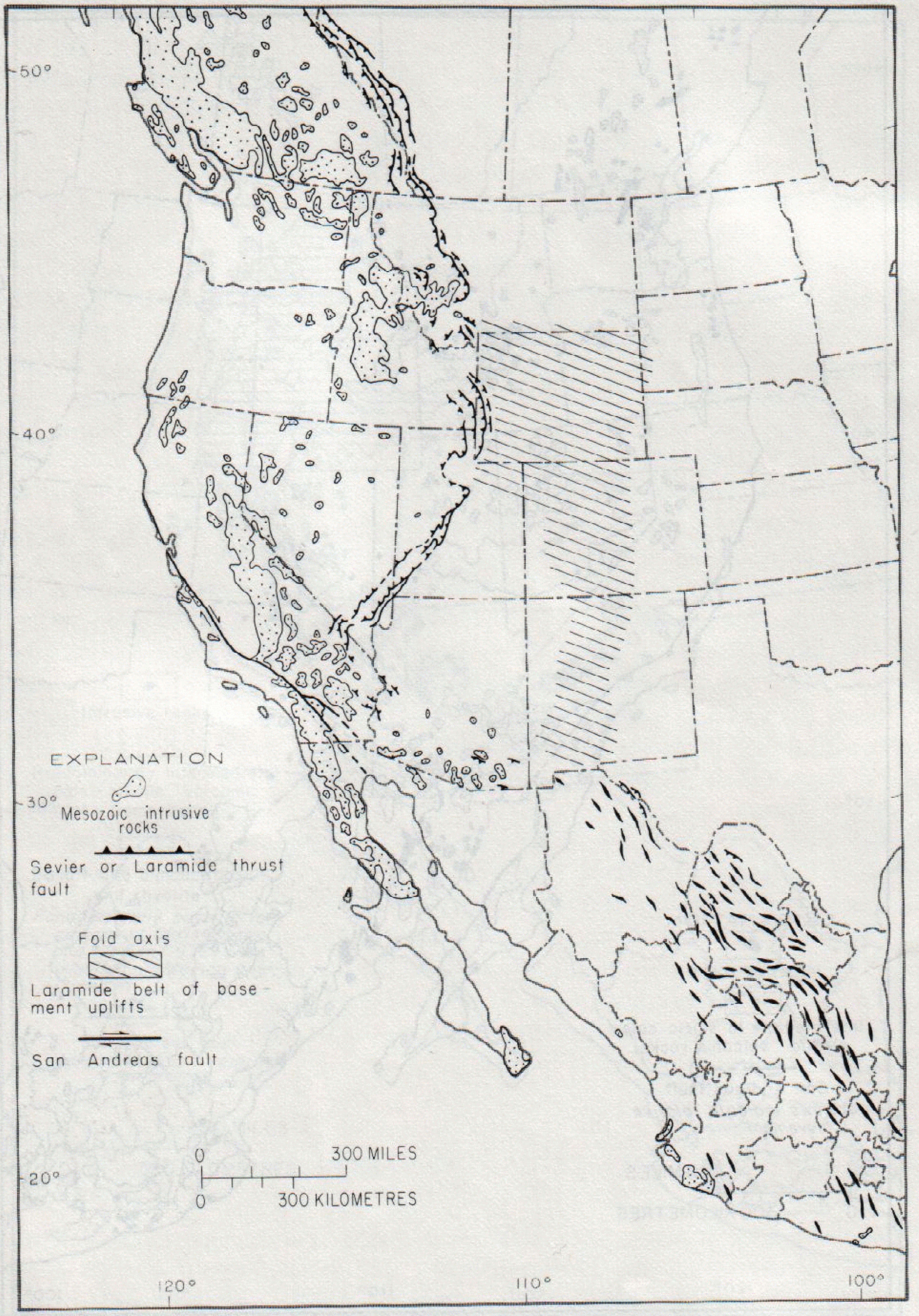


Figure 1-4. Mesozoic intrusive rocks and late Mesozoic and earliest Cenozoic deformational belts in western North America. Compiled from Canada Geological Survey (1970b), King (1969b), King and Beikman (1974), Comite de la Carta Geologica de Mexico (1968), Burchfiel and Davis (1975), and Guzman and de Cserna (1963).

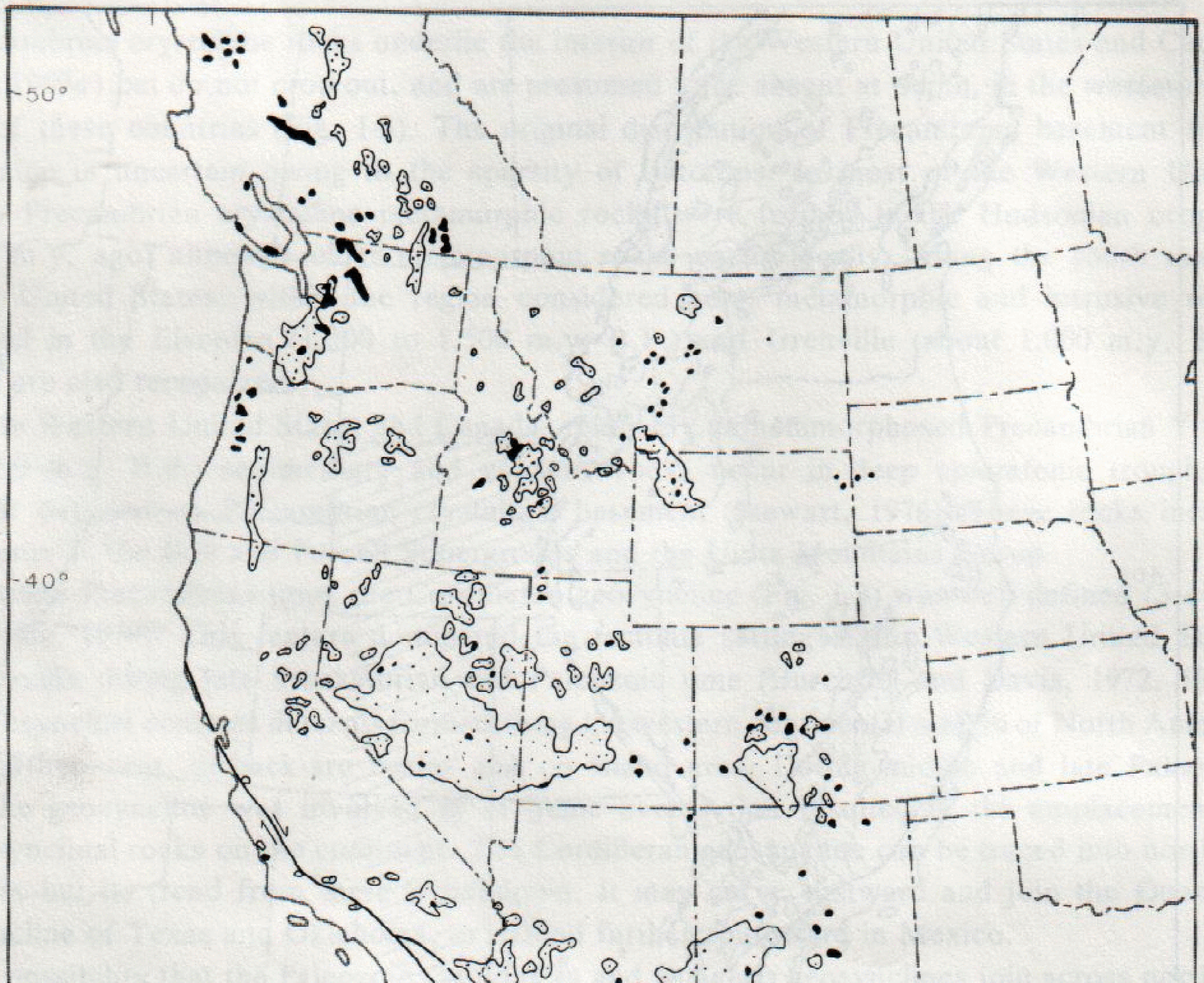


Figure 1-5. Early and middle Cenozoic (65 to 17 m.y.) igneous rocks in western North America. Compiled from Canada Geological Survey (1970b), King and Beikman (1974), Stewart and Carlson (this volume), Comite de la Carta Geologica de Mexico (1968), and Gastil and others (1975).

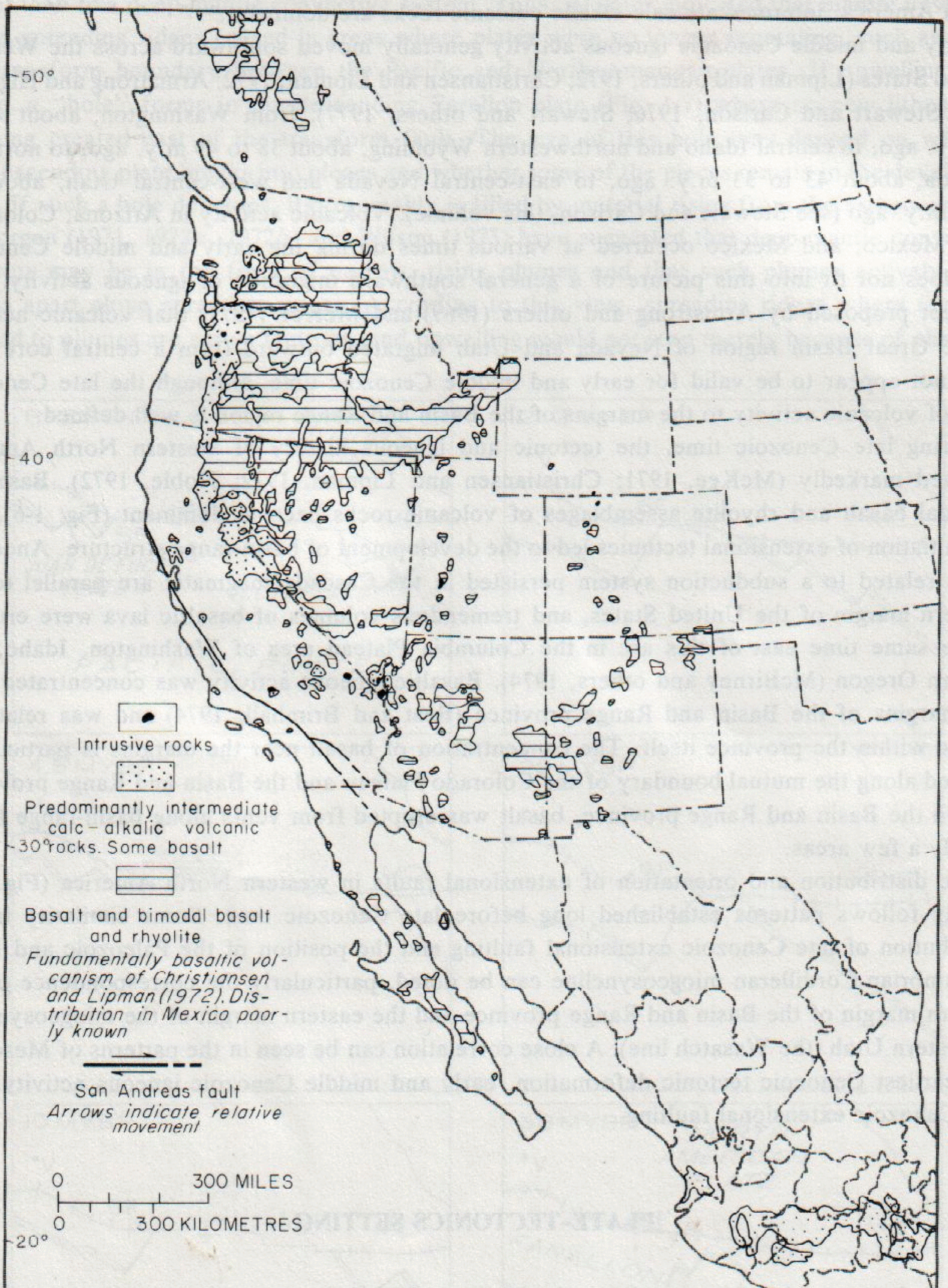


Figure 1-6. Late Cenozoic (17 m.y. to present) igneous rocks in western North America. Distribution of rocks of this age is poorly known in Mexico, and scattered basaltic rocks of this age are known, but are not shown, in Mexico east of the Gulf of California. Compiled from Canada Geological Survey (1970b), King and Beikman (1974), Stewart and Carlson (this volume), Comite de la Carta Geologica de Mexico (1968), and Gastil and others (1975).

in Colorado, southern Arizona, southwestern New Mexico, and in Mexico. Elsewhere in western North America, intermediate calc-alkalic volcanic rocks are dominant.

Early and middle Cenozoic igneous activity generally moved southward across the Western United States (Lipman and others, 1972; Christiansen and Lipman, 1972; Armstrong and Higgins, 1973; Stewart and Carlson, 1976; Stewart and others, 1977), from Washington, about 45 to 57 m.y. ago, to central Idaho and northwestern Wyoming, about 38 to 49 m.y. ago, to northern Nevada, about 43 to 33 m.y. ago, to east-central Nevada and west-central Utah, about 20 to 34 m.y. ago (see Stewart and Carlson, this volume). Volcanic activity in Arizona, Colorado, New Mexico, and Mexico occurred at various times during the early and middle Cenozoic and does not fit into this picture of a general southward migration of igneous activity. The concept proposed by Armstrong and others (1969) and McKee (1971) that volcanic activity in the Great Basin region of Nevada and Utah migrated outward from a central core area does not appear to be valid for early and middle Cenozoic time, although the late Cenozoic shift of volcanic activity to the margins of the Basin and Range region is well defined.

During late Cenozoic time, the tectonic and igneous history of western North America changed markedly (McKee, 1971; Christiansen and Lipman, 1972; Noble, 1972). Basalt or bimodal basalt and rhyolite assemblages of volcanic rocks became dominant (Fig. 1-6), and the initiation of extensional tectonics led to the development of basin-range structure. Andesitic rocks related to a subduction system persisted in the Cascade magmatic arc parallel to the western margin of the United States, and tremendous volumes of basaltic lava were erupted at the same time east of this arc in the Columbia Plateau area of Washington, Idaho, and eastern Oregon (McBirney and others, 1974). Basaltic igneous activity was concentrated near the margins of the Basin and Range province (Best and Brimhall, 1974) and was relatively sparse within the province itself. The concentration of basalt near the margins is particularly marked along the mutual boundary of the Colorado Plateau and the Basin and Range province. Within the Basin and Range province, basalt was erupted from vents along basin-range faults in only a few areas.

The distribution and orientation of extensional faults in western North America (Fig. 1-1) clearly follows patterns established long before late Cenozoic time. Some similarity in the distribution of late Cenozoic extensional faulting and the position of the Paleozoic and latest Precambrian Cordilleran miogeosyncline can be noted, particularly the correspondence of the eastern margin of the Basin and Range province and the eastern margin of the miogeosyncline in western Utah (the Wasatch line). A close correlation can be seen in the patterns of Mesozoic and earliest Cenozoic tectonic deformation, early and middle Cenozoic igneous activity, and late Cenozoic extensional faulting.

PLATE-TECTONICS SETTING

The relative motion of major lithospheric plates (Fig. 1-7) in the vicinity of western North America during middle and late Cenozoic time is well known from studies of ocean-floor magnetic anomalies (Atwater, 1970; Atwater and Molnar, 1973). During the middle Cenozoic, two major lithospheric plates, the Pacific and Farallon plates, separated by the East Pacific Rise (a spreading ridge), were present west of North America. The Farallon plate was being consumed at a subduction zone along the western margin of North America. About 29 m.y. ago, a notable change in this system occurred when the spreading ridge intersected the subduction zone; this caused a change in plate geometry and the development of a transform fault system along parts of the western margin of North America. According to Atwater's (1970) model, the spreading ridges in this system are passive features related to the pulling apart of plates rather than to a deep-mantle convective system. Thus, Atwater indicated that mantle upwelling at the spreading ridges ceased in areas where plates were no longer separating, such as along the transform boundary between the Pacific and North American plates. If upwelling does cease, a ''hole'' forms in the descending Farallon plate (Fig. 1-7) where no new lithosphere is being created east of the transform fault. The size of this hole may depend on whether the descending plate breaks into pieces and whether some of the pieces remain in the developing hole. If such a hole develops, it presumably is filled by material rising from the asthenosphere.

Morgan (1971, 1972*a*, 1972*b*) and Wilson (1973) have suggested that deep-mantle convective systems may be in the form of narrow, rising plumes and that such plumes actively drive plates apart along spreading ridges. According to this view, spreading ridges where they are related to plumes are active features, and upwelling would not stop merely because of changing

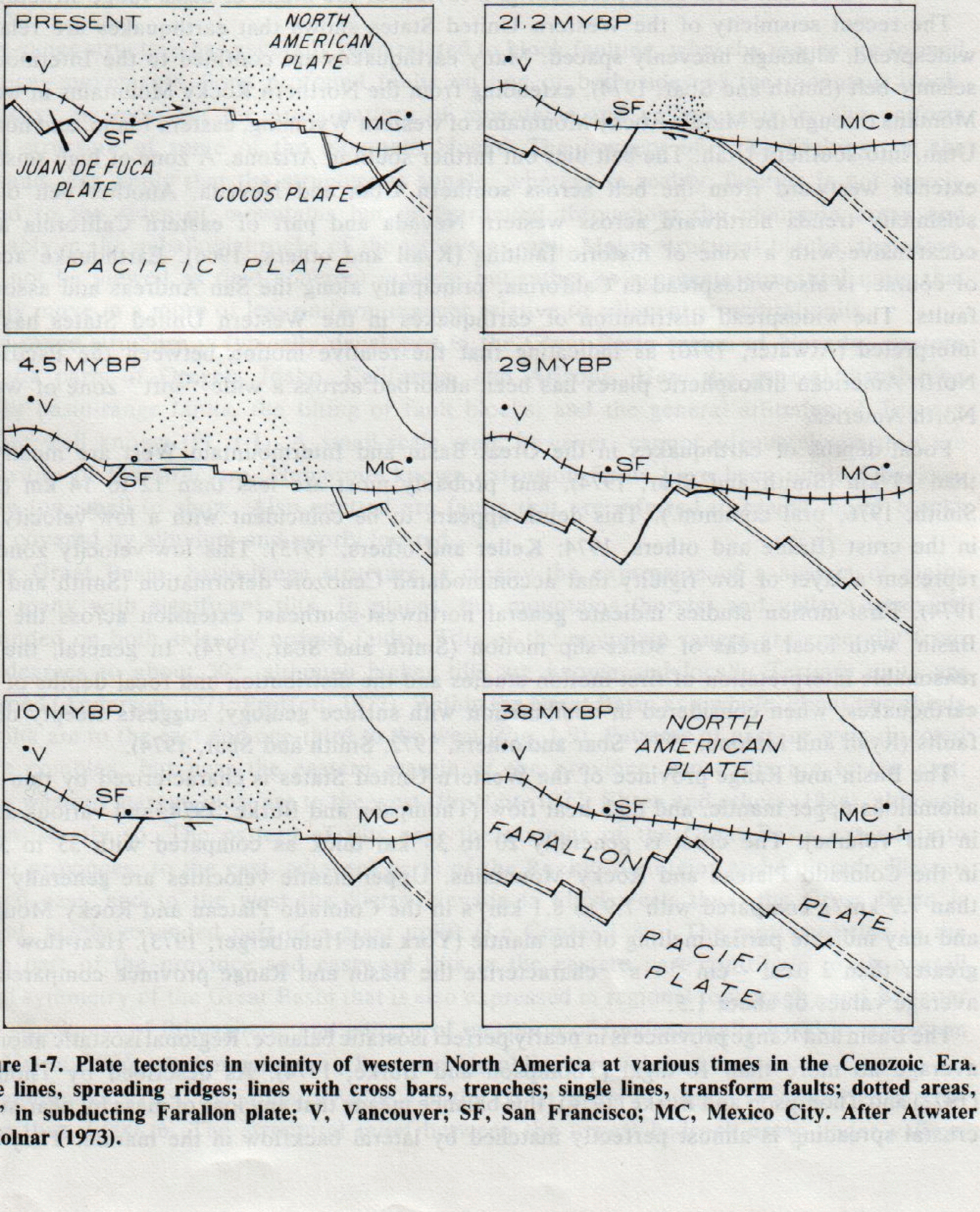


Figure 1-7. Plate tectonics in vicinity of western North America at various times in the Cenozoic Era. Double lines, spreading ridges; lines with cross bars, trenches; single lines, transform faults; dotted areas, ''hole'' in subducting Farallon plate; V, Vancouver; SF, San Francisco; MC, Mexico City. After Atwater and Molnar (1973).

plate geometry. Plume activity could persist along what was formerly a spreading ridge, even if the ridge and plume system were overridden by a continent. Thus, if a plume existed along the East Pacific Rise and was overridden by western North America, mantle upwelling would continue and could be an important tectonic factor. Wilson (1973) has suggested, for example, that such a plume is responsible for the uplift of the Colorado Plateau.

REGIONAL GEOPHYSICS

The regional geophysics of the Basin and Range province in the United States has recently been reviewed by Thompson and Burke (1974), and discussions of various aspects of the subject are included in the present volume. I will only briefly describe here those characteristics of the province that seem most pertinent to a review of the origin of basin-range structure.

The recent seismicity of the Western United States shows that earthquakes are relatively widespread, although unevenly spaced. Many earthquakes are confined to the Intermountain seismic belt (Smith and Sbar, 1974), extending from the Northern Rocky Mountains in western Montana through the Middle Rocky Mountains of western Wyoming, eastern Idaho, and northern Utah, into southern Utah. The belt dies out farther south in Arizona. A zone of high seismicity extends westward from the belt across southern Utah and Nevada. Another belt of high seismicity trends northward across western Nevada and part of eastern California and is coextensive with a zone of historic faulting (Ryall and others, 1966). Earthquake activity, of course, is also widespread in California, principally along the San Andreas and associated faults. The widespread distribution of earthquakes in the Western United States has been interpreted (Atwater, 1970) as indicating that the relative motion between the Pacific and North American lithospheric plates has been absorbed across a wide "soft" zone of western North America.

Focal depths of earthquakes in the Great Basin and Intermountain West are mostly less than 15 km (Smith and Sbar, 1974), and probably most are less than 12 to 14 km (R. B. Smith, 1976, oral commun.). This depth appears to be coincident with a low-velocity zone in the crust (Braile and others, 1974; Keller and others, 1975). This low-velocity zone may represent a layer of low rigidity that accommodated Cenozoic deformation (Smith and Sbar, 1974). First-motion studies indicate general northwest-southeast extension across the Great Basin, with local areas of strike-slip motion (Smith and Sbar, 1974). In general, the most reasonable interpretation of first-motion studies and the distribution and focal depths of small earthquakes, when considered in combination with surface geology, suggests steeply dipping faults (Ryall and Malone, 1971; Sbar and others, 1972; Smith and Sbar, 1974).

The Basin and Range province of the Western United States is characterized by thin crust, anomalous upper mantle, and high heat flow (Thompson and Burke, 1974; and various articles in this volume). The crust is generally 20 to 35 km thick as compared with 35 to 50 km in the Colorado Plateau and Rocky Mountains. Upper-mantle velocities are generally lower than 7.9 km/s compared with 7.9 to 8.1 km/s in the Colorado Plateau and Rocky Mountains and may indicate partial melting of the mantle (York and Helmberger, 1973). Heat-flow values greater than 2 μcal $\cdot$ cm^{-2} $\cdot$ s^{-1} characterize the Basin and Range province compared with average values of about 1.5.

The Basin and Range province is in nearly perfect isostatic balance. Regional isostatic anomalies average no more than 10 mgal (Thompson and Burke, 1974). As described by Thompson (1972) and Thompson and Burke (1974), this balance means that any loss of mass by near-surface crustal spreading is almost perfectly matched by lateral backflow in the mantle. They noted that if a 10-km-thick plate were merely attenuated by 10%, an isostatic anomaly of about 100 mgal would result. Because no such anomalies exist, flow of mantle material into the area at depth is required.

CHARACTER OF BASIN-RANGE STRUCTURE

Basin-range structure consists of a highly complex system of normal faults along which movement has resulted in the relative uplift of linear segments of the crust to form mountains and the relative sinking of adjacent segments to form valleys (Fig. 1-8). The mountains are usually about 15 to 20 km across and are separated by alluviated valleys of comparable width. In detail, the patterns of mountains and valleys are highly complex (Pl. 1-1, in pocket) and the ranges, although they are generally elongate, are locally equidimensional or elliptical in plan view.

Basin-range structure has generally been related to block faulting, whereby ranges are formed by vertical movements along profound faults on one or both sides of the mountain block. This theory accounts for the gross pattern of mountains and valleys, and for the uniform internal structure of some of the mountain blocks. The concept of block faulting, on the other hand, can imply that the structure is simple, whereas in reality, faulting is not merely confined to the sides of mountains but is distributed throughout the mountain areas and presumably in the suballuvial rocks of the valleys as well. Major structural blocks, therefore, should not be viewed as rigid coherent masses, but rather as aggregate structural units that generally move in a more or less uniform manner relative to adjacent structural units.

Basin-range structure is typically developed in the Great Basin region of Nevada, western Utah, and parts of Oregon, Idaho, California, and Arizona. Here the general distribution of major basin-range faults, the tilting of fault blocks, and the general attitudes of Tertiary rocks are well known (Pl. 1-1). A small-scale map, however, cannot adequately portray the complexities of the structure. Numerous known extension faults have been omitted because they are too small to show. Also omitted are faults that are inferred to bound major blocks but are covered by alluvium and poorly located.

In the Great Basin, basin-range structure is clearly the expression of a system of major blocks, many with significant tilts. In places, the mountains (horsts) and valleys (grabens) are bounded on both sides by normal faults. Tilts of the mountain ranges are generally from a few degrees to about 30°, although higher tilts are known and locally Tertiary units are overturned (Anderson, 1971; Proffett, 1972). Within the Great Basin as a whole, about two-thirds of the tilts are to the east and one-third to the west (Fig. 1-9). Patterns of east- or west-directed tilts are complex, but near the eastern margin of the province, most tilts are to the east; near the western margin, most are to the west (Proffett, 1972; Ekren and others, 1974), although less consistently so. The pattern of tilts near the margins of the Great Basin extends into adjacent provinces; to the east, adjacent parts of the Rocky Mountains and Colorado Plateau are tilted east, and to the west the Sierra Nevada is tilted west; thus, the Great Basin is a central, highly extended part of a giant uplift (Le Conte, 1889). The westward tilts in the western part of the province and eastward tilts in the eastern part contribute to an overall bilateral symmetry of the Great Basin that is also expressed in regional topography and Bouguer gravity, thickness of lithosphere, and pattern of inception of fundamentally basaltic volcanism (G. P. Eaton, 1976, written commun.; Best and Hamblin, this volume).

The amount of valley fill in major valleys in the Great Basin is from a few hundred metres to more than 3,000 m. The structural relief between the lowest bedrock areas under valleys

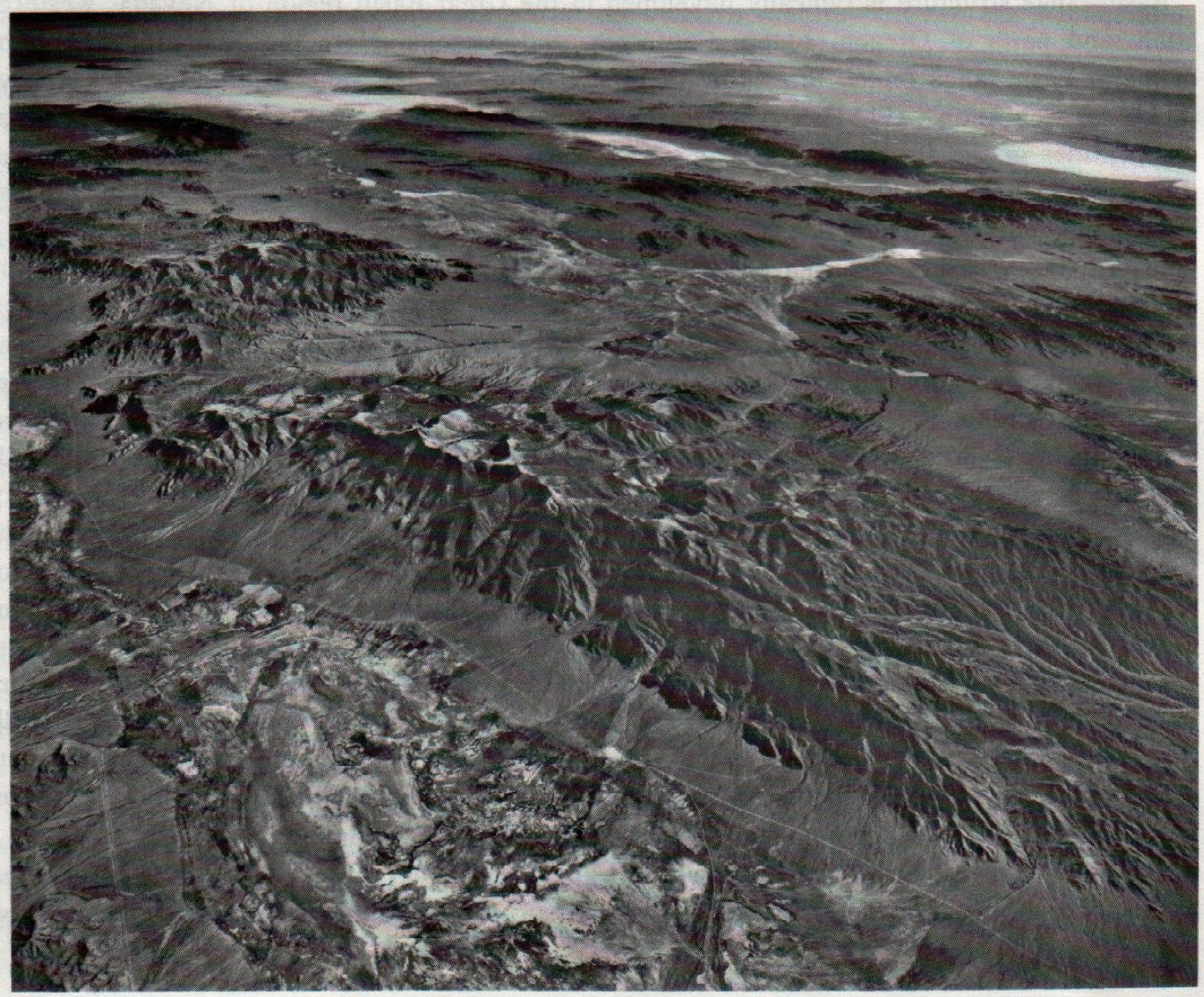


Figure 1-8 (facing page). Aerial photographs showing basin-range structure in central Great Basin. Upper photograph, low-altitude oblique photograph in central Nevada looking northwest across the Toquima Range at the Toiyabe Range in the background. Fault-bounded eastern margin of Toquima Range is well defined. Photograph by the author. Lower photograph, high-altitude oblique aerial photograph looking northeast at Snake Range in easternmost Nevada. Western Utah in background. Block-like character of range and fault-bounded western margin are clearly visible. U.S. Geological Survey–U.S. Air Force photograph.

to the highest adjacent mountains is generally from 2,000 to 5,000 m. Structural relief along the eastern escarpment of the Sierra Nevada in California and the western escarpment of the Wasatch Mountains in Utah is locally about 6,000 m (Christiansen, 1966).

Strike-slip faults are locally an important part of the tectonic framework of the Great Basin. The most conspicuous group of these faults occurs in a northwest-trending belt (the Walker lane) of right-lateral displacement and disrupted structure in the western part of the Great Basin (Albers, 1967). Total right-lateral displacement along this belt is probably 130 to 190 km and occurs in part as fault slip and in part as a more pervasive large-scale drag (Stewart

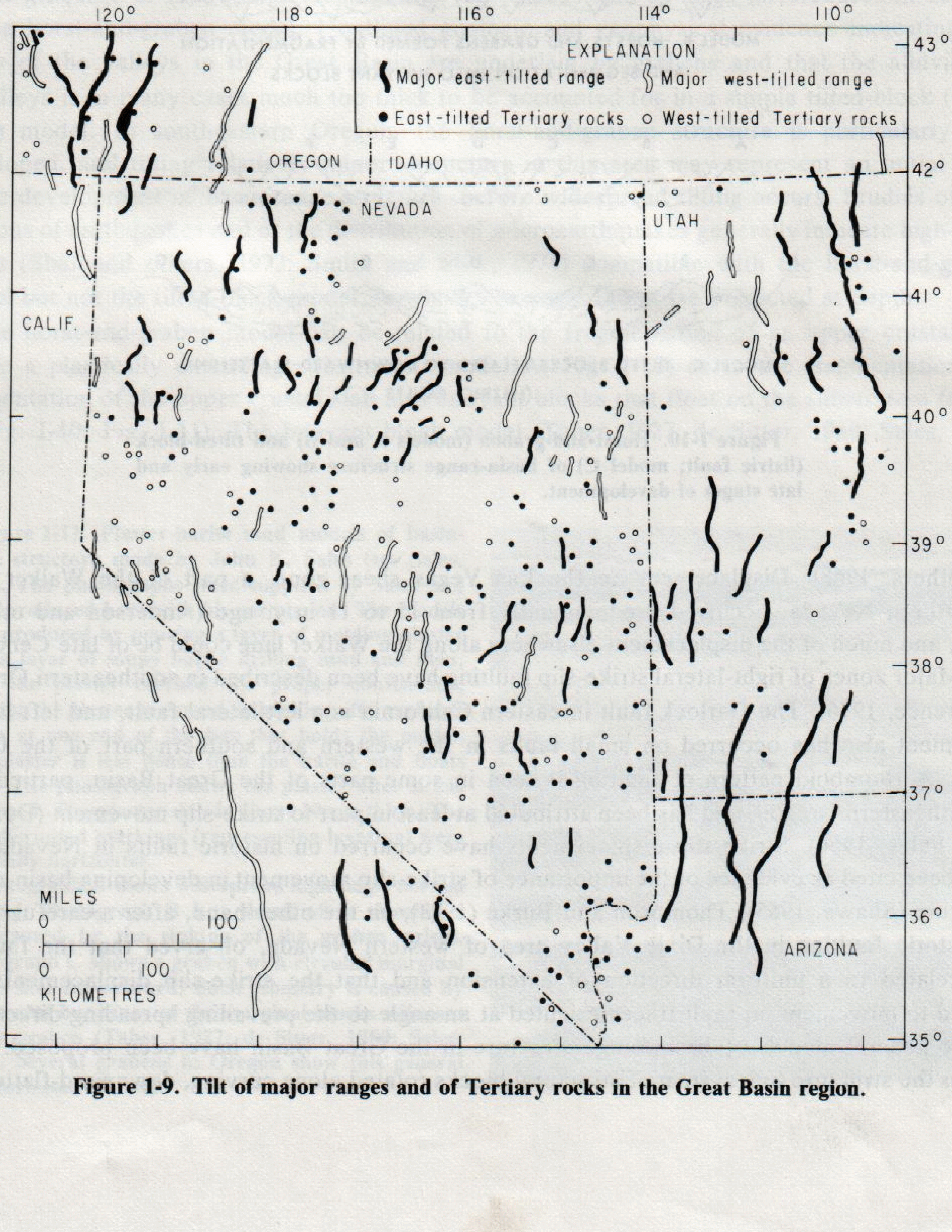
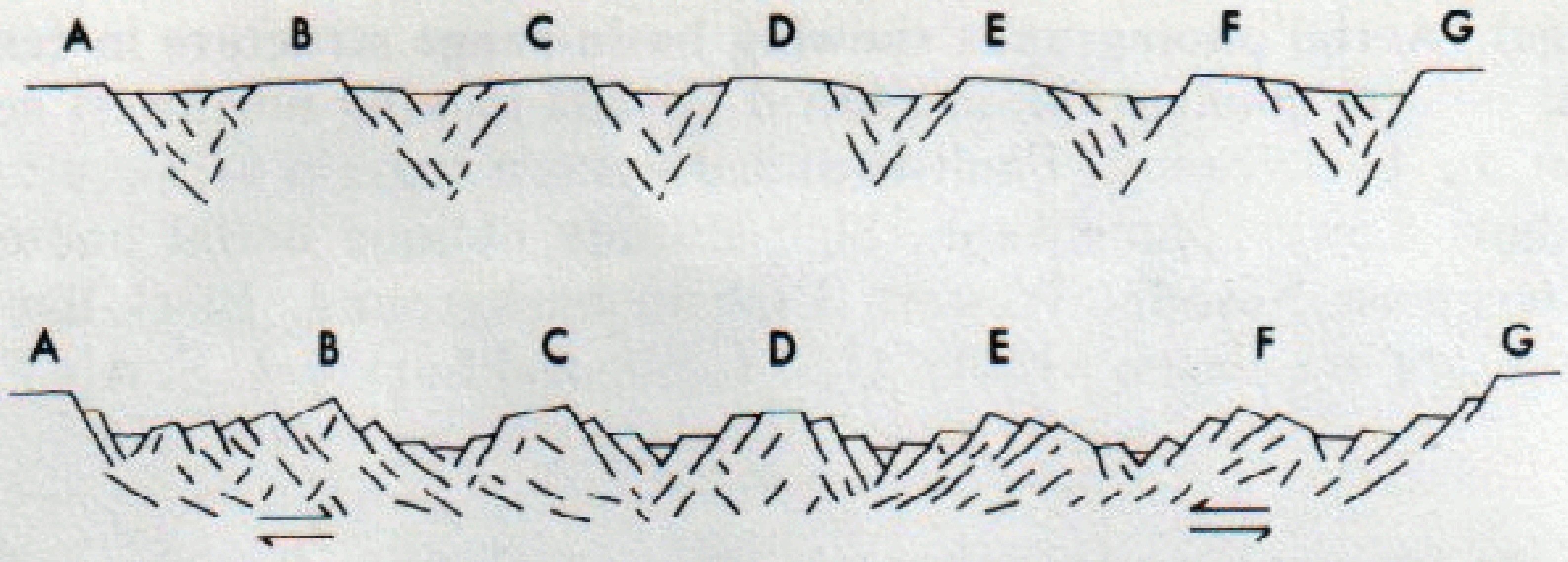
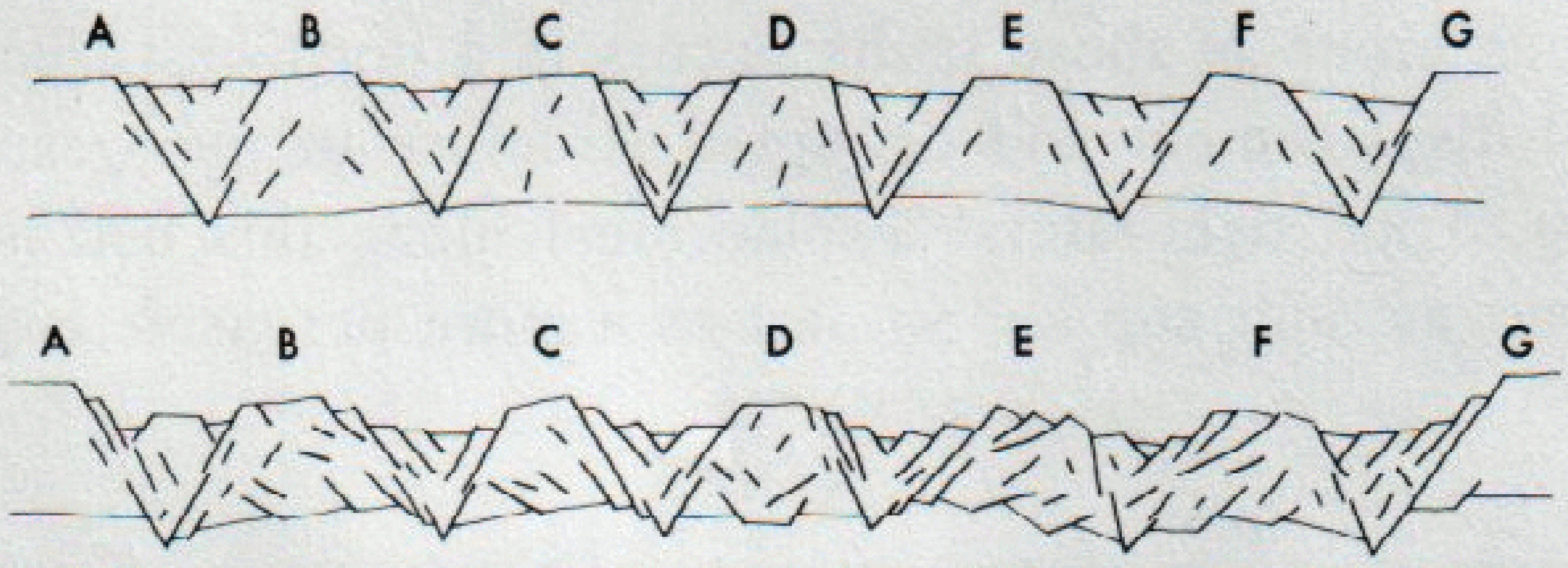


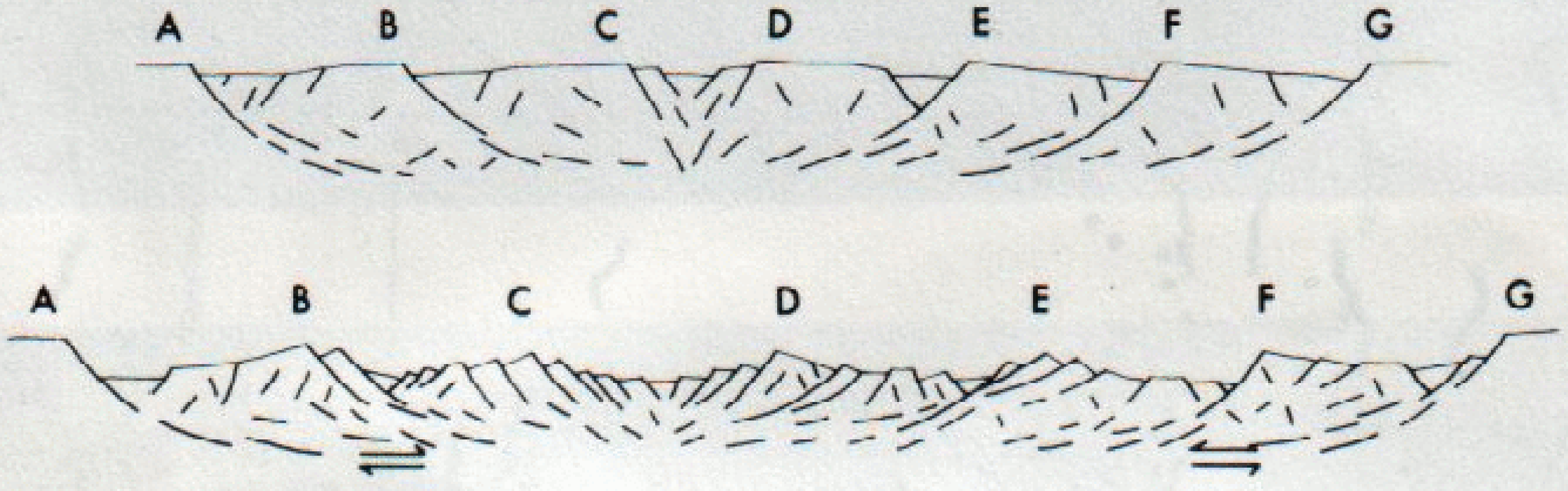
Figure 1-9. Tilt of major ranges and of Tertiary rocks in the Great Basin region.



MODEL A. HORSTS AND GRABENS FORMED BY FRAGMENTATION ABOVE PLASTICALLY EXTENDING SUBSTRATUM



MODEL B. HORSTS AND GRABENS FORMED BY FRAGMENTATION AND SEGMENTATION INTO BUOYANT BLOCKS



MODEL C. TILTED BLOCKS RELATED TO DOWNWARD-FLATTENING (LISTRIC) FAULTS

Figure 1-10. Horst-and-graben (models A and B) and tilted-block (listric fault; model C) of basin-range structure showing early and late stages of development.

and others, 1968). Displacement on the Las Vegas shear zone, a part of the Walker lane in southern Nevada, occurred predominantly from 15 to 11 m.y. ago (Anderson and others, 1972), and much of the displacement elsewhere along the Walker lane could be of late Cenozoic age. Major zones of right-lateral strike-slip faulting have been described in southeastern Oregon (Lawrence, 1976). The Garlock fault in eastern California is a left-lateral fault, and left-lateral movement also has occurred on small faults in the western and southern part of the Great Basin. A rhomboid pattern of faulting is seen in some parts of the Great Basin, particularly in southeastern Oregon, and has been attributed at least in part to strike-slip movement (Donath, 1962; Sales, 1966). Strike-slip displacements have occurred on historic faults in Nevada and have been cited as evidence of the importance of strike-slip movement in developing basin-range structure (Shawe, 1965). Thompson and Burke (1973), on the other hand, after a careful study of historic faulting in the Dixie Valley area of western Nevada, observed that the faulting was related to a uniform direction of extension and that the strike-slip displacements are related to movement on fault traces oriented at an angle to the prevailing spreading direction.

Two general models of basin-range structure in the Great Basin have been proposed. One relates the structure to a system of structural blocks rotated along curving, downward-flattening normal faults, sometimes called listric faults (for example, Lowell and others, 1975). The uptilted part of an individual block forms a mountain, and the downtilted part a valley (Fig. 1-10, model C). The second model, the horst-and-graben model, relates the structure to a system of relatively downthrown blocks (grabens) that form valleys, and relatively upthrown blocks (horsts or tilted horsts) that form mountains (Fig. 1-10, models A and B). Evaluating the relative merits of these two models is not easy, and structure in the Basin and Range province probably involves elements of both models.

In a previous article (Stewart, 1971), I discussed the two models of basin-range structure and indicated a preference for the horst-and-graben model. In this model, basin-range structure is produced by the fragmentation of an upper crustal slab over a plastically extending substratum. Extension of the substratum causes the basal part of the slab to be pulled apart along narrow, systematically spaced zones; this, in turn, causes the downdropping of complex horizontal prisms (grabens) of the brittle upper crust. Tilting is produced either by (1) the development of asymmetric grabens in which the mountain block on one side of the graben slumps downward, (2) the rotation of large blocks along downward-flattening faults after the initial formation of the grabens, or (3) rotation of large buoyant blocks due to mass differences. In support of the horst-and-graben model, I outlined geologic and geophysical evidence indicating that many of the valleys in the Great Basin are underlain by grabens and that the alluvial fill in valleys is in many cases much too thick to be accounted for in a simple tilted-block (listric fault) model. In southeastern Oregon, the horst-and-graben structure is particularly well developed, and tilting relatively minor. Structure in this area may represent an initial stage in the development of basin-range structure, before widespread tilting occurs. Studies of first motions of earthquakes and of the distribution of microearthquakes generally indicate high-angle faults (Sbar and others, 1972; Smith and Sbar, 1974) compatible with the horst-and-graben model but not the tilted-block model, in which low-angle faults are predicted at depth.

The horst-and-graben model can be related to the fragmentation of an upper crustal slab above a plastically extending substratum (model A, Fig. 1-10) or to the fragmentation and segmentation of the upper crustal slab into buoyant blocks that float on the substratum (model B, Fig. 1-10; Fig. 1-11). The buoyant block model (Taber, 1927; de Sitter, 1959; Sales, 1976)

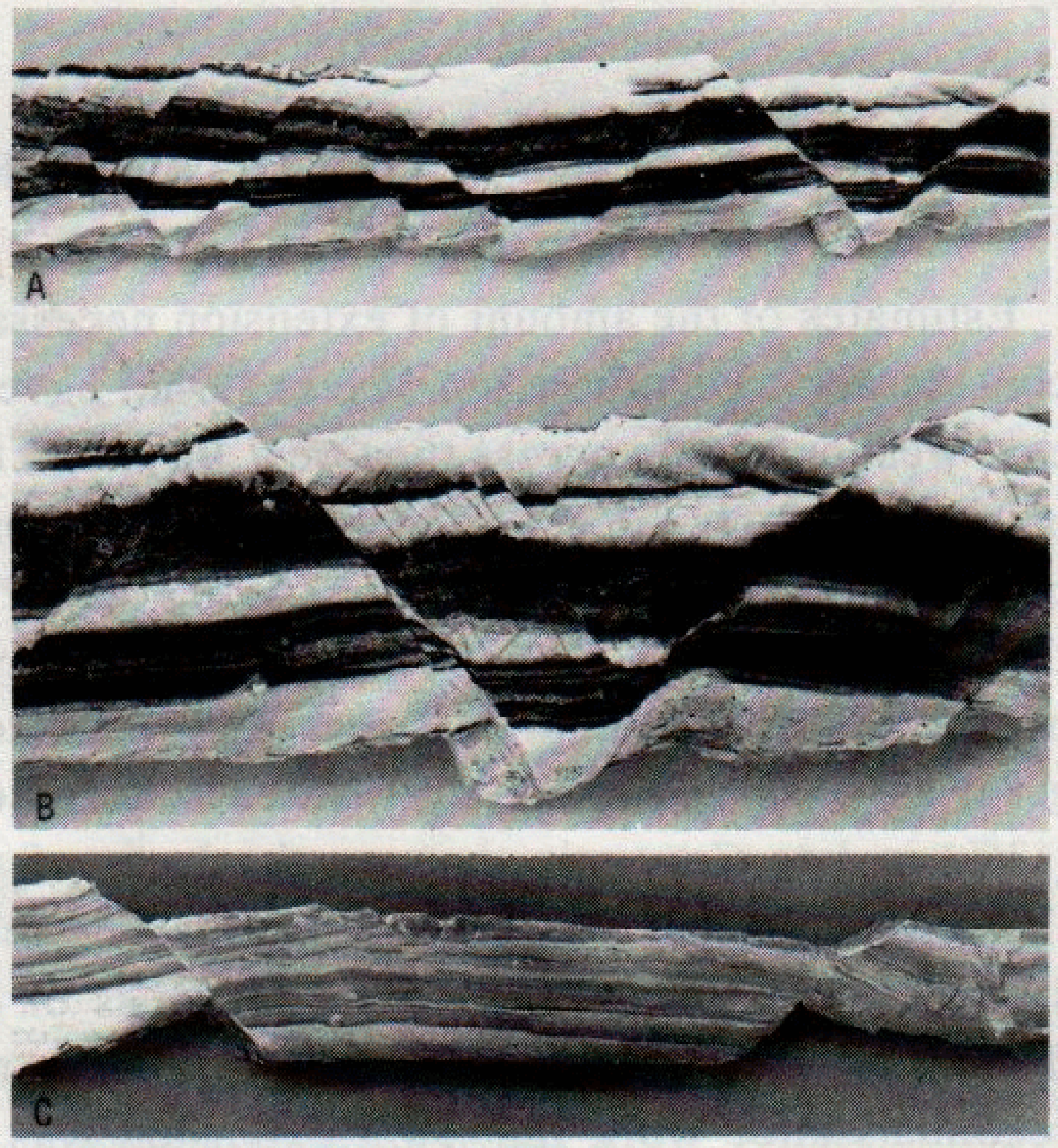


Figure 1-11. Plaster-barite mud models of basin-range structure made by John K. Sales (see Sales, 1976). The photographs were supplied by Sales and are reproduced here with his permission. The models were produced by pouring a layer of molding plaster over a layer of soupy barite drilling mud and then, after the plaster reached the proper consistency, allowing the plaster to extend by backing off a movable piston at one end of the box that holds the model. The plaster is less dense than the barite and floats on it. The photograph shows the plaster after it has hardened. The plaster slab is about 10 cm thick. The now-disrupted markings (representing layering) were originally horizontal.

Photograph A shows widespread high-angle normal faulting. Photograph B is a detail of A showing a keel caused by the sinking of the graben prism. Photograph C shows a graben with elevated marginal blocks that tilt outward. Such geometry is caused by the greater buoyancy of the marginal blocks adjacent to the graben (Taber, 1927; de Sitter, 1959; Sales, 1976). Several grabens in Oregon show this general structure (see Pl. 1-1).

is particularly attractive because it allows for the rotation of large blocks on a scale that could cause entire ranges to tilt. Because of the shape of the large blocks, excess buoyancy and deficient mass is created in blocks adjacent to grabens, thus accounting for elevated margins and the tilt of mountain blocks in opposite directions away from a central graben (Fig. 1-11). Such oppositely directed tilts away from a central graben are observed at several places in southeastern Oregon (Pl. 1-1).

Advocates of the tilted-block (listric fault) model have noted that (1) major mountain blocks in the Great Basin are commonly tilted by as much as 10° to 30° or more and (2) the simplest way to explain this tilting is by rotation of large structural blocks along downward-flattening faults. This concept is supported by surface observations that some faults do decrease in dip downward (Longwell, 1945; Hamblin, 1965; Proffett, 1971, 1977) and that low-angle faults are numerous locally (Anderson, 1971; Wright and Troxel, 1973). In some areas, however, these low-angle faults may have been originally steep, and their present low dip is due to rotation of major structural blocks (Hunt and Mabey, 1966). Additional evidence for the rotation of large structural blocks above downward-flattening faults has been suggested by Moore (1960), who noted that the plan view of many fault traces are crescent-shaped in the Great Basin, indicative of spoon-shaped faults in the subsurface. Crescent-shaped traces are evident only locally on Plate 1-1, however.

The two models of basin-range structure are similar in some respects. Both probably involve the fragmentation of an upper-crustal slab over a plastically extending substratum. The thickness of this slab may be about 12 to 14 km, judged from the greatest depth of most earthquakes in the Great Basin. Both models require substantial internal readjustments along many small faults. These faults may tend to have mostly high angles; new faults may develop as older ones are rotated into low-angle attitudes (Proffett, 1972; Chamberlain, 1976). In both models, tilting of blocks has been related to (1) gravity sliding off regional highs (J. G. Moore, in Wallace, 1964), (2) lateral flow in the crust below the fragmenting slab (Proffett, 1972), or (3) mass differences that cause the rotation of individual blocks.

With present data, the character of basin-range structure at depth cannot be firmly established. A better understanding will come from integrated studies of surface geology, deep seismic profiles, first-motion studies of earthquakes, and the spatial distribution of individual earthquake swarms and aftershocks.

AMOUNT OF EXTENSION

Estimates of the amount of extension necessary to produce basin-range structure have varied considerably. Hamilton and Myers (1966) have suggested between 50 and 100 km of generally east-west extension across the Great Basin, an 8% to 18% increase in the width of the province, in late Cenozoic time on the basis of an average estimate for horizontal extension on each of 25 major range-bounding faults along lat 40°N. They and Elston (1976, 1977) have suggested that extension may have occurred in the early and middle Cenozoic Era as well, a concept not generally accepted, and that total Cenozoic extension in this case could have been as great as 100%. In 1971, I estimated total extension across the Great Basin of about 72 km (13%) in late Cenozoic time on the basis of the "graben rule" of Hansen (1965), in which the cross-sectional area of a graben can be related to the amount of lateral motion (Stewart, 1971). Also in 1971, Proffett, on the basis of detailed geologic work in the Yerington mining district in western Nevada, indicated local extension of more than 100%. He suggested from reconnaissance work that 50% extension was likely in the western and eastern parts of the

Great Basin and that less occurred in the central part. Wright and Troxel (1973) and Wright (1976) indicated 30% to 50% extension in part of the Death Valley area of eastern California, on the basis of detailed mapping. In 1974, Thompson and Burke estimated the total amount of extension across Dixie Valley to be 5 km on the basis of geophysical exploration of the valley and, using this as a typical amount of extension for major grabens, suggested about 100 km of total extension (18% increase in width) across the Great Basin. An extension of 30% to 50% (Thompson, 1972) is required if the thinness of the crust in the Basin and Range province is due entirely to lateral spreading, but as Thompson (1972) noted, this estimate may not be meaningful because of the possibility of phase conversions between crust and mantle.

Variations in estimates of extension are the result, in part, of uncertainties in interpreting basin-range structure at depth. If the structure is related to a system of downward-flattening faults, then the total extension necessary to produce the structure is probably much larger than if it is related to generally steep faults. Even extension related to steep faults, however, may lead to a large amount of spreading. This is illustrated by the Turnagain Heights translatory landslide produced by the 1964 Alaskan earthquake. During this slide, total extension was about 100%, and displacement apparently took place on generally steep faults (Hansen, 1965). The complex surface patterns of elongate ridges and valleys produced during the landslide are similar, except in scale, to those of the Basin and Range province.

The amount of extension can also be studied in relation to the thinning of an upper crustal slab and related regional uplift. These relations (shown in Figs. 1-12 and 1-13, Table 1-1) apply best to models A and C in Figure 1-10 where basin-range structure occurs above a specific level in the crust.

In Figure 1-12, the lower diagram represents in cross section a slab of the upper crust with dimensions *a* and *b*. In the upper diagram, the slab is shown with new dimensions *c* and *d* after extension and the development of basin-range structure. Some erosion of material from the uplifted blocks has taken place, and the material has been deposited in the basins. In the model, all of the material eroded is considered to be trapped in the basins, an assumption approximately true in the Great Basin where drainage is predominantly internal. Thus the total eroded area of the ranges is approximately equal in cross section to the total depositional area of the basins, not counting the relatively small increase in volume as a result of disaggregation

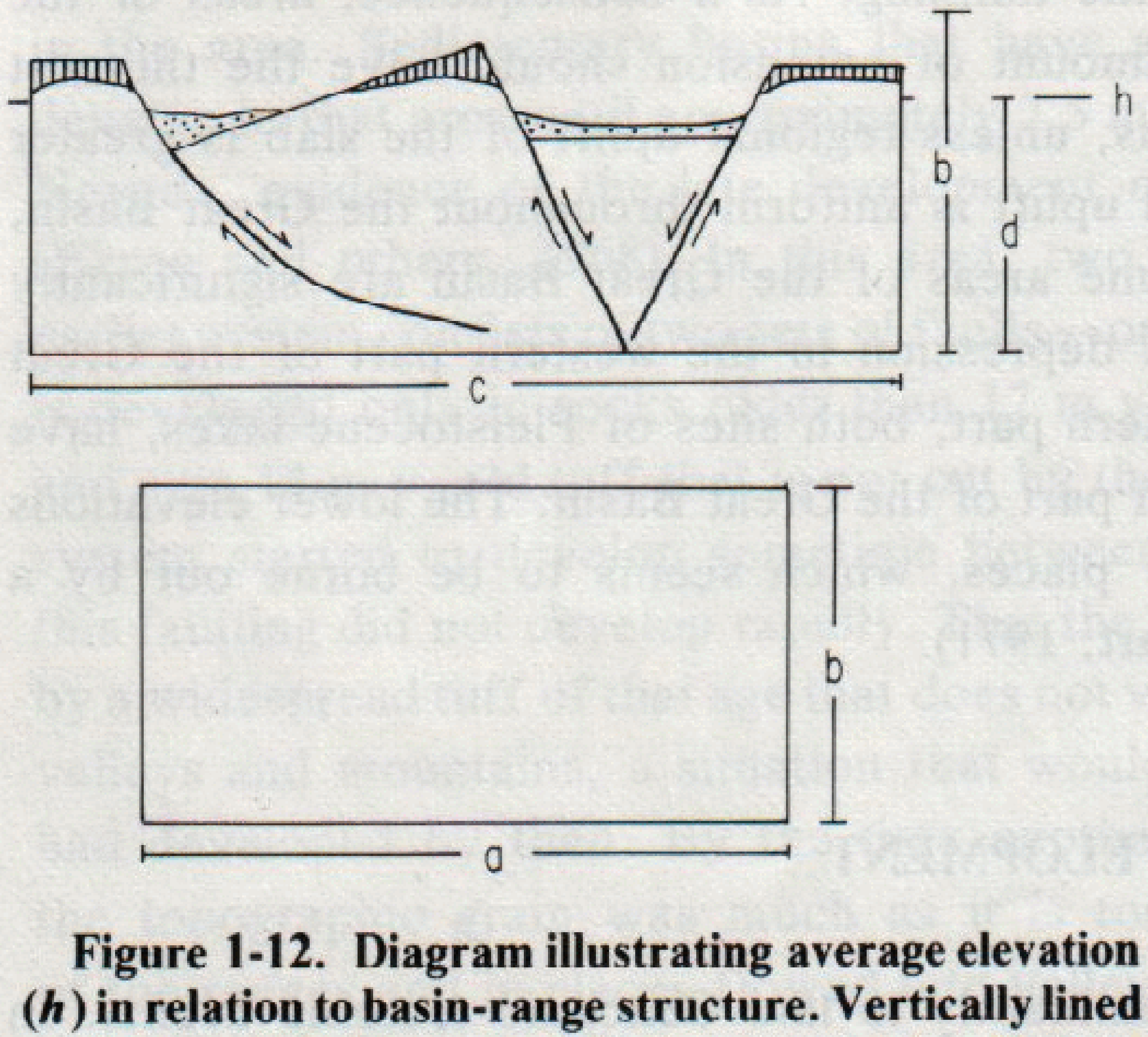


Figure 1-12. Diagram illustrating average elevation (*h*) in relation to basin-range structure. Vertically lined pattern, eroded areas; dotted pattern, depositional areas. Further explanation in text.

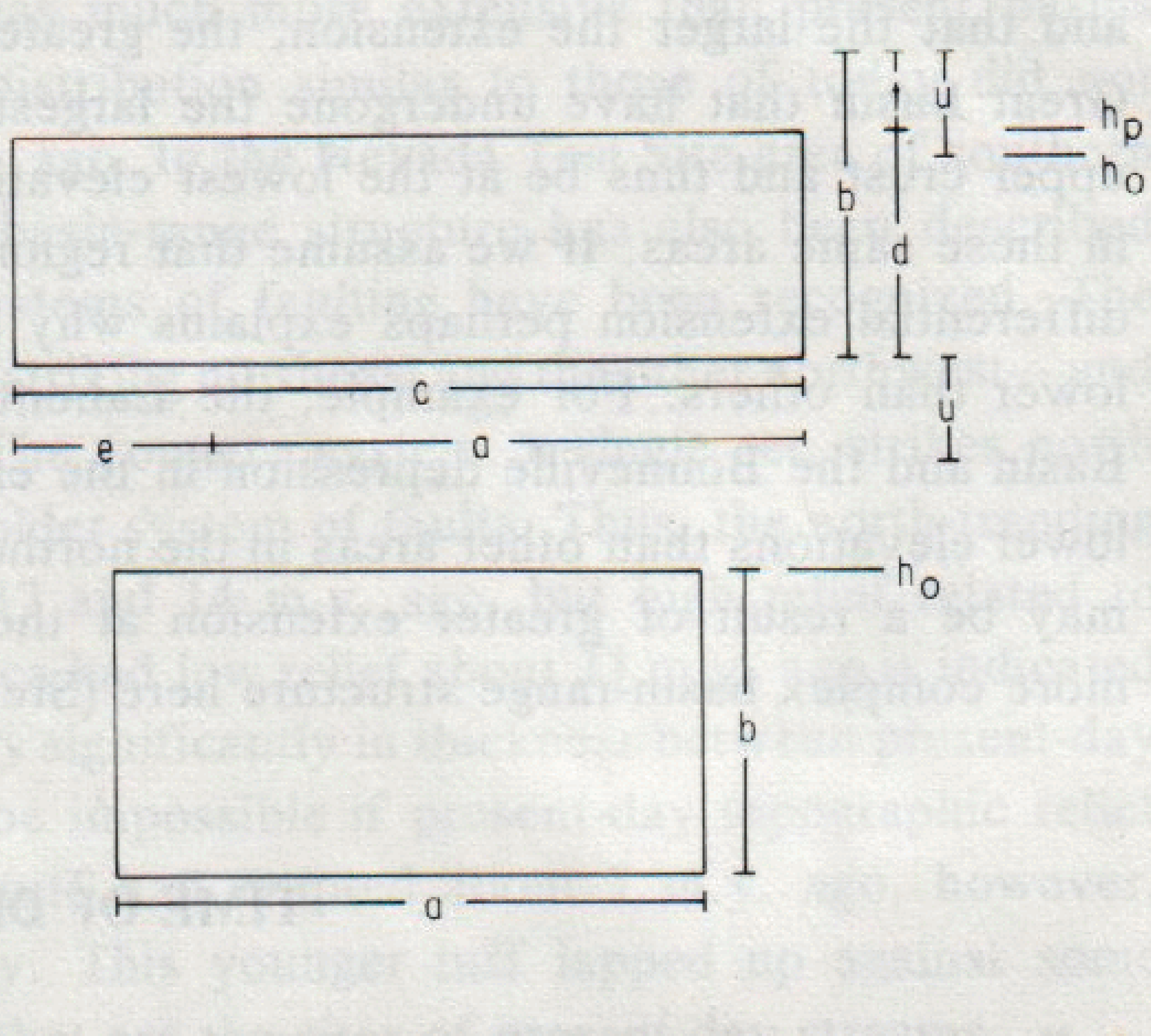


Figure 1-13. Diagram illustrating extension and uplift during development of basin-range structure. Further explanation in text.

TABLE 1-1. RELATION OF EXTENSION TO UPLIFT

Percent crustal extension $(e/a) \times 100\%$ (%)	Amount of crustal extension $e = c - a$ (km)	Thinning of slab $t = b - d$ (m)	Total uplift $u = h_p - h_o + t$ (m)		
			$h_o = 0$ m	$h_o = 700$ m	$h_o = 1{,}200$ m
5	30	639	2,539	1,839	1,339
10	58	1,296	3,196	2,496	1,996
15	83	1,937	3,837	3,137	2,637
20	107	2,610	4,510	3,810	3,310
25	128	3,250	5,150	4,450	3,950
30	148	3,910	5,810	5,110	4,610
35	166	4,553	6,453	5,753	5,253
40	183	5,206	7,106	6,406	5,906

Note: Geometric relations between variables are shown in Figures 1-12 and 1-13; description is in text.

and deposition. If these relations are approximately correct, then the average elevation h in the upper diagram (Fig. 1-12) can be used to calculate the total cross-sectional area of the upper diagram (cd). As no material has been gained or lost from the system, the cross-sectional area of the lower diagram (ab) is equal to that of the upper diagram (cd).

In Figure 1-13, the relations derived from Figure 1-12 are applied to the Great Basin along lat 40°N. Here, the average present elevation h_p is approximately 1,900 m, the width c of the Great Basin is 640 km, and the thickness d of the slab is approximately 13 km (based on average maximum focal depth of earthquakes). The average original elevation h_o of the Great Basin at lat 40°N before development of basin-range structure is poorly known, but probably was between sea level and about 1,200 m from the types of early Tertiary flora in California and Nevada (Axelrod, 1966, Fig. 4). Axelrod (1957) estimated that the average elevation of western Nevada was about 600 to 750 m in Miocene-Pliocene time, also on the basis of fossil flora. These estimates of elevations are uncertain, but nonetheless appear to indicate the extremes that should be considered. The relations between the amount of extension e, the thinning t of the slab, and the amount of uplift u, (see Fig. 1-13) are listed in Table 1-1.

Table 1-1 indicates that extension is accompanied by thinning of the upper crustal slab and that the larger the extension, the greater the thinning. As a consequence, areas of the Great Basin that have undergone the largest amount of extension should have the thinnest upper crust and thus be at the lowest elevations, unless regional uplift of the slab is greater in these same areas. If we assume that regional uplift is uniform throughout the Great Basin, differential extension perhaps explains why some areas of the Great Basin are significantly lower than others. For example, the Lahontan depression in the western part of the Great Basin and the Bonneville depression in the eastern part, both sites of Pleistocene lakes, have lower elevations than other areas in the northern part of the Great Basin. The lower elevations may be a result of greater extension at these places, which seems to be borne out by a more complex basin-range structure here (Stewart, 1971).

TIME OF DEVELOPMENT

Basin-range structure is clearly related predominantly to late Cenozoic tectonic events. In many areas of western North America, extensional faults cut widespread tuffs of early and middle Cenozoic age that formed as highly mobile ash flows, which tend to fill troughs much like water. The occurrence of individual ash-flow units at many different topographic and structural levels can only be explained by faulting.

Two types of evidence have been used to date precisely the development of basin-range structure. The first is indirect and is based on the assumption that the transition from calc-alkalic volcanic rocks in early and middle Cenozoic time to fundamentally basaltic volcanic rocks in late Cenozoic time marks the change from predominantly compressional tectonics (related to a subduction zone) to extensional tectonics (related to wrench faulting, back-arc spreading, or some other factor). The second type of evidence is direct and based on the first appearance of fault-controlled sedimentary basins and topographic forms approximately resembling those seen today.

The volcanic transition in most areas of the Great Basin was about 17 m.y. ago (McKee and others, 1970; McKee, 1971). It was much later than this, however, along the Cascade belt of calc-alkalic volcanism parallel to the western margin of North America in the westernmost Great Basin and the Sierra Nevada of California. Snyder and others (1976) have carefully documented that calc-alkalic volcanism along this belt ended perhaps as much as 20 m.y. ago at lat 35°N and progressively more recently northward to near lat 40°N, where it is still active. In southern Arizona and New Mexico, the transition may have been somewhat older than in the Great Basin. Christiansen and Lipman (1972) indicated that the transition date there was between 23 and 37 m.y. ago; Armstrong and Higgins (1973) suggested a general range of 25 to 30 m.y.; McKee and Noble (1974) suggested about 21 m.y. Several authors (Christiansen and Lipman, 1972; Proffett, 1972; Best and Hamblin, this volume) have suggested a general northward migration of the time of inception of basin-range faulting in the Western United States. Data are not complete enough to generalize about the time of transition from calc-alkalic to basaltic rocks in Mexico, although basaltic rocks in Baja California (Gastil and others, 1975) have the same spread in ages as those in most areas of the Western United States.

Direct evidence of the time of development of basin-range structure is sparse and more difficult to evaluate. In the Great Basin, large sedimentary basins, presumably formed by extensional faulting, were well defined about 11 to 13 m.y. ago (late Barstovian to Clarendonian) (Axelrod, 1957; Robinson and others, 1968; Gilbert and Reynolds, 1973). In a study in western Nevada, Gilbert and Reynolds (1973) described one such basin that was in existence from about 12.5 to 8 m.y. ago, but noted that it was much more extensive than present basins in the area. Sedimentary basins that have a distribution similar to those of today did not develop in that area until approximately 7.5 m.y. ago. In the Nevada Test Site area of southern Nevada, evidence of the late development of basin-range structure has also been described (Ekren and others, 1968). In this area, two systems of faulting have been recognized. The earlier system consists of two sets of faults—one striking northeast and the other northwest—and is developed only in rocks older than 17 m.y. The younger system, a single set, strikes north and cuts 14-m.y.-old tuff that is not cut by the older system of faults. Thus, the north-trending system started to develop sometime between 17 and 14 m.y. ago, but high relief related to this faulting did not develop rapidly. That the area had low relief about 11 m.y. ago is indicated by a widespread tuff of that age that does not vary significantly in thickness between present-day valleys and mountains, a situation that would be impossible if present-day topographic relief had developed by then. By the time another tuff had erupted about 7 m.y. ago, however, the topographic grain was much as it is today. This younger tuff lapped up against some of the ranges and in places flowed into valleys that are the sites of present-day streams.

In summary, the present basins and ranges clearly are a late Cenozoic structure. Extensional

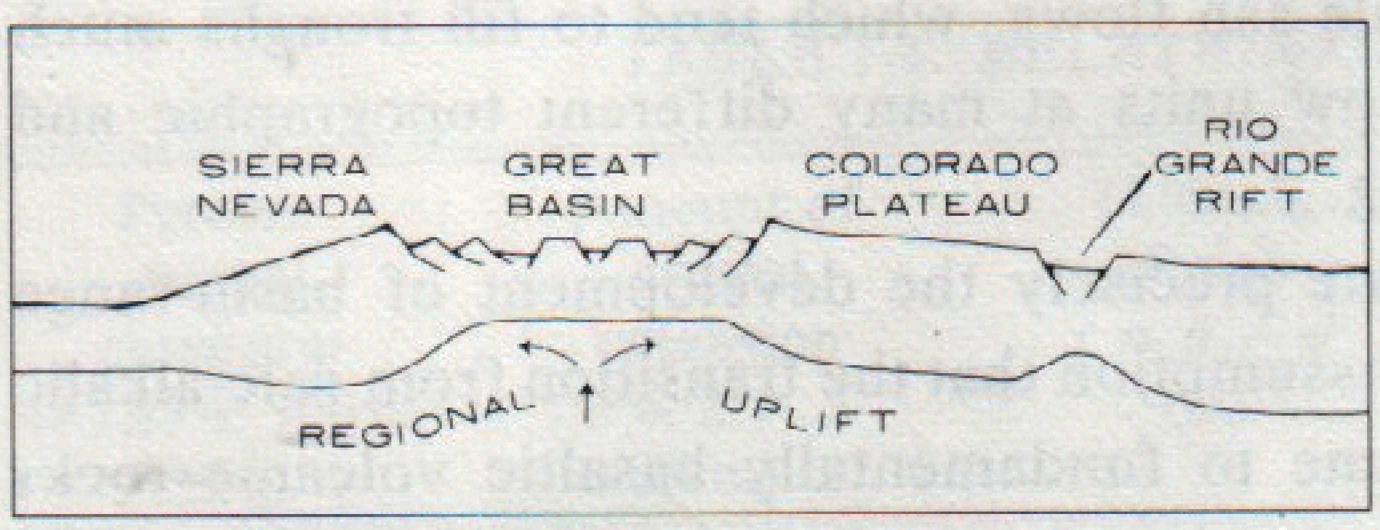


Figure 1-14. Schematic diagram illustrating regional uplift in western North America.

faulting probably started about 17 m.y. ago in much of the Great Basin, but may have started slightly earlier in southern Arizona and New Mexico. The grain of present-day topography, however, probably did not develop before 10 m.y. ago, at the earliest.

REGIONAL UPLIFT

The Basin and Range province lies within a broad region of late Cenozoic uplift (Fig. 1-14). This uplift is documented by mid-Cenozoic floras in the Cordilleran region that indicate elevations at least 1 km below those at present (see discussion and references in Proffett, 1972; Suppe and others, 1975). More precise data on uplift are available west of the Great Basin, where regional uplift of more than 1,800 m in the past 9 m.y. has been described by Christiansen (1966). The Colorado Plateau east of the Great Basin also was uplifted in late Cenozoic time, primarily between 5 and 10 m.y. ago, according to McKee and McKee (1972). Chapin and Seager (1975), however, indicated that the earliest uplift may be as old as 24 m.y. Within the Great Basin, an uplift of 2,000 to 3,000 m in late Cenozoic time seems likely (Table 1-1).

THEORIES OF ORIGIN OF BASIN-RANGE STRUCTURE

Current theories of the origin of basin-range structure can be loosely grouped into four main categories: wrench faulting, back-arc spreading, subduction of the East Pacific Rise, and mantle plumes.

Wrench Faulting

The wrench-faulting concept relates the development of basin-range structure to oblique tensional fragmentation within a broad belt of right-lateral movement along the western side of the North American lithospheric plate. This theory is based on concepts developed by Carey (1958), Wise (1963), Shawe (1965), Hamilton and Myers (1966), Sales (1966), and Slemmons (1967) and has been put in terms of plate-tectonics theory by Atwater (1970) and Christiansen and McKee (this volume). According to this view, western North America is within a broad belt of right-lateral movement related to differential motion between the North American and Pacific plates. Some of the right-lateral movement is taken up on the San Andreas fault and related zones of right-lateral shear, such as the Walker lane in the western Great Basin. The movement is also thought to produce distributed extension and tensional crustal fragmentation (including basin-range structure) along trends oriented obliquely to the trend of the San Andreas fault. This concept is illustrated in Figure 1-15, a map drawn on a Mercator projection about the pole of relative rotation between the Pacific and North American plates (Atwater, 1970). On the map, pure strike-slip motion occurs along horizontal lines, pure tension on vertical lines, and oblique tensional fragmentation on lines having other orientations. Many basin-range faults, as shown on the map, have an oblique orientation consistent with the concept of wrench faulting.

The concept of a broad zone of right-lateral displacement in the Western United States also is consistent with the concept that the broad dextral-curving pattern of Paleozoic eugeosynclinal rocks and of Mesozoic plutonic rocks in the Western United States is due to large-scale oroclinal folding (Mendocino and Idaho oroclines). The oroclinal folding from this point of view is part of the same tectonic pattern that developed basin-range structure (Hamilton and Myers, 1966).

The wrench-faulting concept is particularly attractive when accounting for major zones of strike-slip faulting in the Basin and Range province and for strike-slip first motions of earthquakes in some regions of western North America. The concept is also supported by the contemporaneous development of a transform boundary and of basin-range structure, and the similarity in latitudinal extent (Fig. 1-1) of both structures. The concept does not easily account for regional uplift that has affected the western Cordillera, nor does it entirely explain why shear stress was transmitted over such a broad zone of western North America rather than being confined to the edge of the plate, or why the Basin and Range province should extend (increase in area) instead of simply shearing without an increase in area. These and other factors of plate interactions possibly related to the development of basin-range structure are discussed by Christiansen and McKee (this volume).

Back-Arc Spreading

The back-arc–spreading theory relates basin-range structure to mantle upwelling and associated spreading above a subduction zone (Fig. 1-16). The concept was originally developed to explain the origin of island arcs in the western Pacific that, according to the theory, drifted out from the Asian continent by spreading (back-arc spreading) on the continent side of the arc at the same time that the arc was being underthrust by the Pacific plate (Karig, 1971, 1974; Matsuda and Uyeda, 1971). The theory relates spreading to high heat generated along a Benioff zone by friction and the upwelling of mantle material that causes spreading in the crust and, in the case of the western Pacific, leads to the development of oceanic crust in back-arc

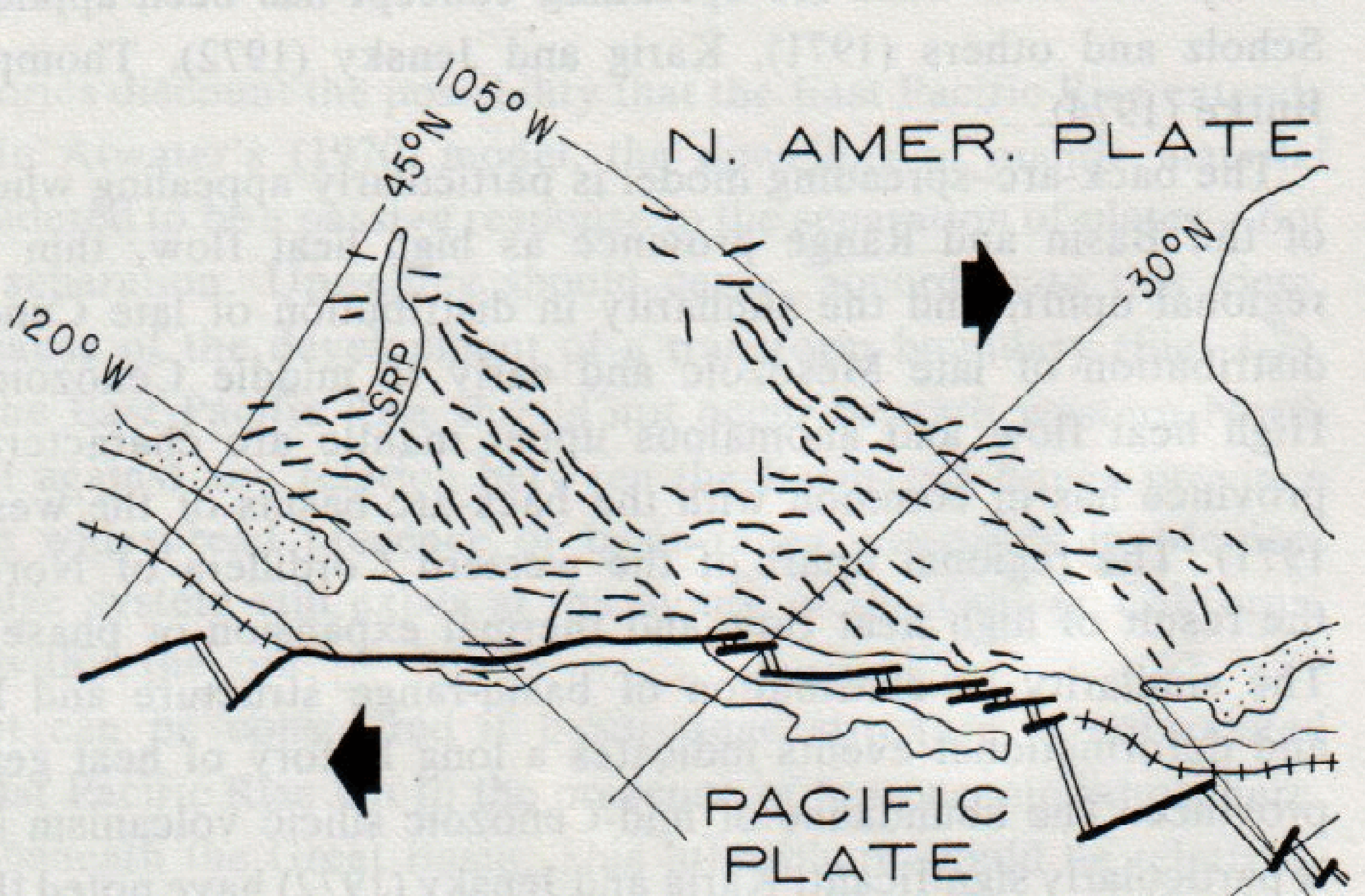


Figure 1-15. Map projected about the pole of relative rotation of Pacific and North American plates, showing relation of extensional faulting to shear in western North America. After Atwater (1970). Double lines, spreading ridges; lines with cross bars, trenches; broad lines, transform faults; narrow, short lines, extentional faults and a few strike-slip faults; dotted areas, late Cenozoic calc-alkalic volcanic rocks; SRP, Snake River Plain.

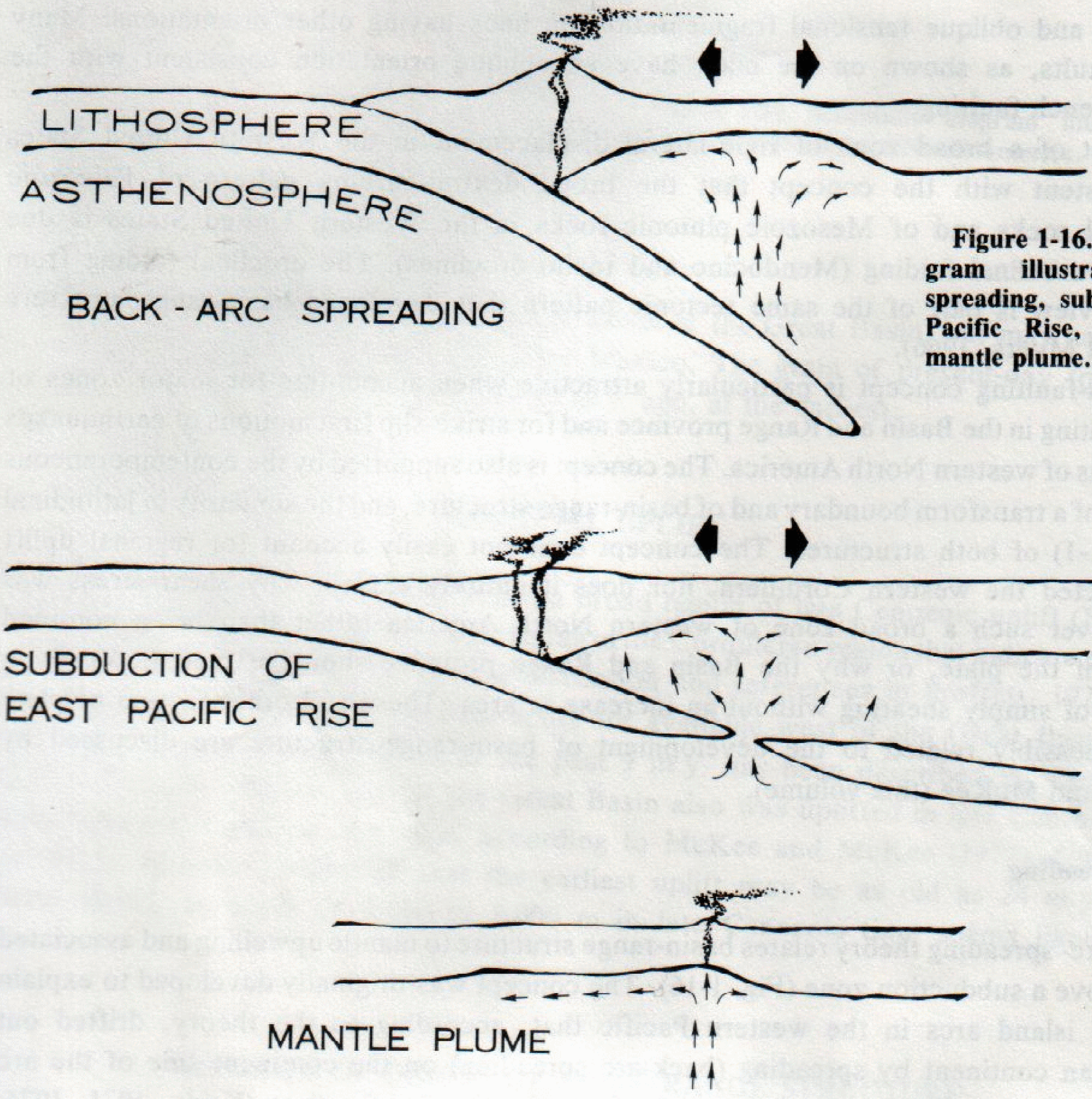


Figure 1-16. Schematic diagram illustrating back-arc spreading, subduction of East Pacific Rise, and action of mantle plume.

basins. The process is slow; calculation by Hasebe and others (1970) suggests that a subduction system would have to be active for 100 m.y. to reach the heat flow observed in the Japan arc system. The back-arc–spreading concept has been applied to western North America by Scholz and others (1971), Karig and Jensky (1972), Thompson (1972), and Thompson and Burke (1974).

The back-arc–spreading model is particularly appealing when explaining such characteristics of the Basin and Range province as high heat flow, thin crust, anomalous upper mantle, regional uplift, and the similarity in distribution of late Cenozoic extensional faulting to the distribution of late Mesozoic and early to middle Cenozoic igneous and tectonic features. High heat flow and anomalous upper mantle are characteristics that the Basin and Range province has in common with the back-arc basins of the western Pacific (Scholz and others, 1971). The regional uplift of the western Cordillera of North America can be explained as the result of high heat flow and thermal expansion or phase changes in the mantle or crust. The similarity of distribution of basin-range structure and Mesozoic and Cenozoic igneous and deformational events indicates a long history of heat generation in the Basin and Range province. The abundance of mid-Cenozoic silicic volcanism in the Basin and Range province is particularly significant. Karig and Jensky (1972) have noted the association of silicic volcanism with rifting in both marginal ocean basins and in volcano-tectonic rift zones. The broad zone of Mesozoic and Cenozoic igneous activity in the Western United States and northern Mexico is anomalous in comparison with other parts of western North and South America; this suggests that somehow the anomalously broad zone and spreading are related. Uyeda and Miyashiro (1974) also noted an association of spreading in the western Pacific with a broad zone of igneous activity.

Why did back-arc spreading, if this concept is correct, start in late Cenozoic time? Perhaps the generation of heat along a subduction system had reached some critical point where mantle upwelling and crustal spreading could start. The spreading could have been triggered by the factors, as yet unknown, that caused an episode of intense volcanic activity in much of the circum-Pacific area during middle Miocene time (McBirney and others, 1974). The voluminous basalts of the Columbia Plateau, themselves indicative of back-arc spreading, were erupted at virtually the same time as this mid-Miocene episode. Scholz and others (1971), on the other hand, have suggested that spreading was accelerated by the cessation of subduction and development of a transform boundary along the western margin of North America. They reasoned that subduction created a confining pressure on western North America and that once this pressure was relieved, the spreading rate would increase. The fact that extention is greatest in regions of North America inland from the transform boundary (Fig. 1-1) supports this concept.

Bott (1973) has outlined how oceanward spreading might occur along a stable Atlantic-type continental margin, and a similar process might take place after termination of compression. Terman (1975) has also suggested that extension is related to lack of confining pressure, although in a somewhat different context than here.

East Pacific Rise

Basin-range structure has been related to convection currents and lateral spreading on the flanks of the East Pacific Rise, which according to this theory, extends under western North America (Menard, 1960; Cook, 1969; McKee, 1971; Gough, 1974). In support of this view, Menard (1960) noted that the East Pacific Rise, if projected northward, would extend under the Great Basin area and that both the Great Basin and the East Pacific Rise are characterized by high heat flow. In addition, Menard pointed out that the ridges and troughs analogous to the basins and ranges also occur on the ocean bottoms on the flanks of the East Pacific Rise.

Present-day plate-tectonics theories discount the possibility that the East Pacific Rise extends under western North America. In Atwater's (1970) model, the upwelling of mantle material along the East Pacific Rise is considered to be a passive response to the separation of plates—not the driving mechanism of plate separation. Upwelling should cease, according to this view, once plate separation ceased because of the development of a transform boundary (Fig. 1-7). Therefore, upwelling related to the East Pacific Rise should not occur beneath western North America. An additional argument against any relation between the Basin and Range province and the East Pacific Rise is the widespread presence of basin-range structures in Mexico, in areas far east of where the ridge system still exists at the mouth of the Gulf of California and locally as spreading centers within the gulf.

A somewhat different concept can be considered if basin-range structure is not related directly to upwelling along the East Pacific Rise but to the presence of hot oceanic lithosphere, a remnant of the Farallon plate, beneath the Great Basin. This lithosphere would be relatively young and therefore hot, because the youngest parts would have been created from upwelling magma immediately prior to the collision of the ridge and trench. Its heat could help drive the spreading in the Great Basin. This concept apparently requires that part of the Farallon plate ceased its descent under North America and remained under the Great Basin. If, on the other hand, the plate did continue to descend, a hole would be left in the plate where no new lithosphere was being created inland of the transform system (Fig. 1-7). If this were true, material from the asthenosphere would presumably ascend into the hole as the plate descended, creating a convection system much like that along a ridge system. Both the "hot plate" and "hole filling" concepts are difficult to apply to Mexico, where basin-range structure lies east of areas where the ridge system still exists.

Mantle Plumes

Deep-mantle convection in the form of narrow rising plumes has been thought to play a major role in the late Cenozoic history of the Western United States (Matthews and Anderson, 1973; Wilson, 1973; Smith and Sbar, 1974; Suppe and others, 1975). According to Morgan (1971, 1972a, 1972b), such mantle plumes provide the driving mechanism for continental drift and cause plates to rift and to be driven apart from one another. The Snake River Plain–Yellowstone area in southern Idaho and northwestern Montana has been suggested (Suppe and others, 1975) as the trace of such a mantle plume. According to this theory, the plume lay under the western part of the Snake River Plain about 15 m.y. ago and has traced a path relatively eastward as the North American plate moved over it. Its present position is under the Yellowstone region of northwest Wyoming. Matthews and Anderson (1973), Smith and Sbar (1974), and Suppe and others (1975) have suggested that this plume may have caused the breakup of a large segment of the Western United States. Others (Eaton and others, 1975) related the volcanism in the Snake River Plain to a major crustal fracture that propagated northeastward, guided by structures in Precambrian rocks.

As of now, mantle plumes similar to those proposed for oceanic areas have not been proved to underlie western North America, nor is the effect of such plumes, if they exist, certain. Seemingly, several widely scattered plumes would be necessary to produce the extensional faulting observed in such a large segment of the Cordillera of western North America. As yet only one area (Yellowstone) can credibly be considered to be underlain by a plume, and even that is a matter of controversy.

CONCLUSIONS

Of the many characteristics of the Basin and Range province that should be considered in evaluating the origin of basin-range structure, the most important appear to be (1) low seismic velocity of the upper mantle, indicative of partial melting; (2) thin crust; (3) high heat flow; (4) regional uplift and extension; (5) previous history of deformation in Mesozoic and earliest Cenozoic time, and of widespread siliceous volcanism in middle Cenozoic time; and (6) position inland from a transform plate boundary.

Considered together, these characteristics generally fit well with the concept of back-arc spreading. In this system, heat generated by friction along a descending slab provides the energy for upwelling of mantle material and the resultant thinning of the crust, regional uplift, and near-surface spreading. High heat generation can be assumed because of long history of subduction along the western margin of North America that led to the widespread emplacement of plutonic rocks in the Mesozoic Era and to the eruption of voluminous volcanic rocks, particularly silicic types, in early and middle Cenozoic time. The back-arc setting is further indicated by the distribution of volcanic rocks in late Cenozoic time (Snyder and others, 1976; Stewart and Carlson, this volume) that clearly shows that an active andesitic magmatic arc existed along the western margin of the Great Basin and adjacent parts of the Sierra Nevada in California at the same time that extensional faulting was occurring farther east.

As proposed by Scholz and others (1971), back-arc spreading may have been accelerated by the slackening of confining pressure owing to the destruction of the subduction system along western North America and the development of a transform boundary. Such a concept explains why basin-range structure is mostly confined to areas inland from the transform boundary of the western margin of North America. In addition, a major component of right-lateral shear related to distributed stress from the transform system can be incorporated in the back-arc model to account for right-lateral motion along the Walker lane and other fault zones in the Western United States.

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