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CENOZOIC STRUCTURE AND TECTONICS OF THE NORTHERN BASIN AND RANGE PROVINCE, CALIFORNIA, NEVADA, AND UTAH

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ABSTRACT

During the early Cenozoic, the northern Basin and Range province was largely an upland from which detritus was shed eastward into basins in the western part of the Colorado Plateaus province. Within this upland area, broad sedimentary basins locally formed that may in part have been created by extensional faulting.

During the middle and part of the late Cenozoic, the major tectonic features in the northern Basin and Range province were related to widespread volcanic activity that began in the northern part of the province about 43 m.y. ago and spread southward along an arcuate east-west-trending front and ended about 6 m.y. ago in southern Nevada and Utah. East-west-trending volcano-tectonic and graben structures, igneous and mineral belts, and structural lineaments are related to this southward sweep of igneous activity.

During part of the middle and throughout the late Cenozoic, local and regional extension and local strike-slip faulting dominated the tectonics of the northern Basin and Range province. Low-angle extensional faults that juxtapose younger over older rocks developed primarily from 20 to 10 m.y. ago. They occur within a diffuse 200- to 300-km-wide zone extending north-northeastward in eastern Nevada and westernmost Utah, and within a 100-km-wide northwest-trending zone along the Walker Lane, astride the California-Nevada state line. Block faulting that has created the characteristic physiography of the present-day northern Basin and Range province is controlled by north-south or north-northeast-trending normal faults that have broken the province into blocks, generally about 30 km across. Such block faulting is commonly superimposed across areas of low-angle faulting and, in addition, extends into areas previously unaffected by extension. Block faulting has occurred primarily during the past 10 m.y.

INTRODUCTION

The northern Basin and Range province in Nevada, western Utah, and parts of adjacent states is a high desert area of largely interior drainage characterized by north or north-northeast-trending mountains and valleys. The elevations of the valleys are generally 1,300 to 1,600 m; mountain crests are commonly 2,000 to 3,000 m and locally about 3,600 m. The entire Basin and Range province (fig. 1) 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 2,500 km.

This article summarizes information on the character and development of Cenozoic structures in the northern Basin and Range province and emphasizes the regional distribution of structures. Concepts of the Cenozoic history have developed greatly in the past 15 years as a result of plate tectonic theories and studies of metamorphic core complexes and low angle detachment faults. Ideas continue to evolve rapidly with many different viewpoints (Stewart, 1978; Zoback and others, 1981; Eaton, 1982).

EARLY CENOZOIC STRUCTURES

The Paleocene to middle Eocene history of the northern Basin and Range region is obscure because rocks of this age are sparse. During most of this time, the region was probably an upland from which debris was shed mainly eastward into basins in the western part of the Colorado Plateau province (Hintze, 1973). Within the broad upland area, large sedimentary basins locally formed. Strata in some of these basins are as thick as 1,000 m and consist of alluvial fans deposits adjacent to mountains fronts and lake deposits in the central parts of basins (Fouch, 1979). Igneous activity was slight or may not have occurred at all. Only a few uncertainly dated Paleocene to middle Eocene igneous rocks are known from the region (Carlson and others, 1975).

Evidence of tectonic activity in the early Cenozoic is seen in the Sheep Pass Formation of east-central Nevada, which represents fluvial and lacustrine deposition in a broad internal drainage system. The Sheep Pass Formation rests unconformably on faulted and broadly folded Paleozoic strata (Kellogg, 1964; Moores and others, 1968), presumably deformed in the middle and late Mesozoic, and contains boulder

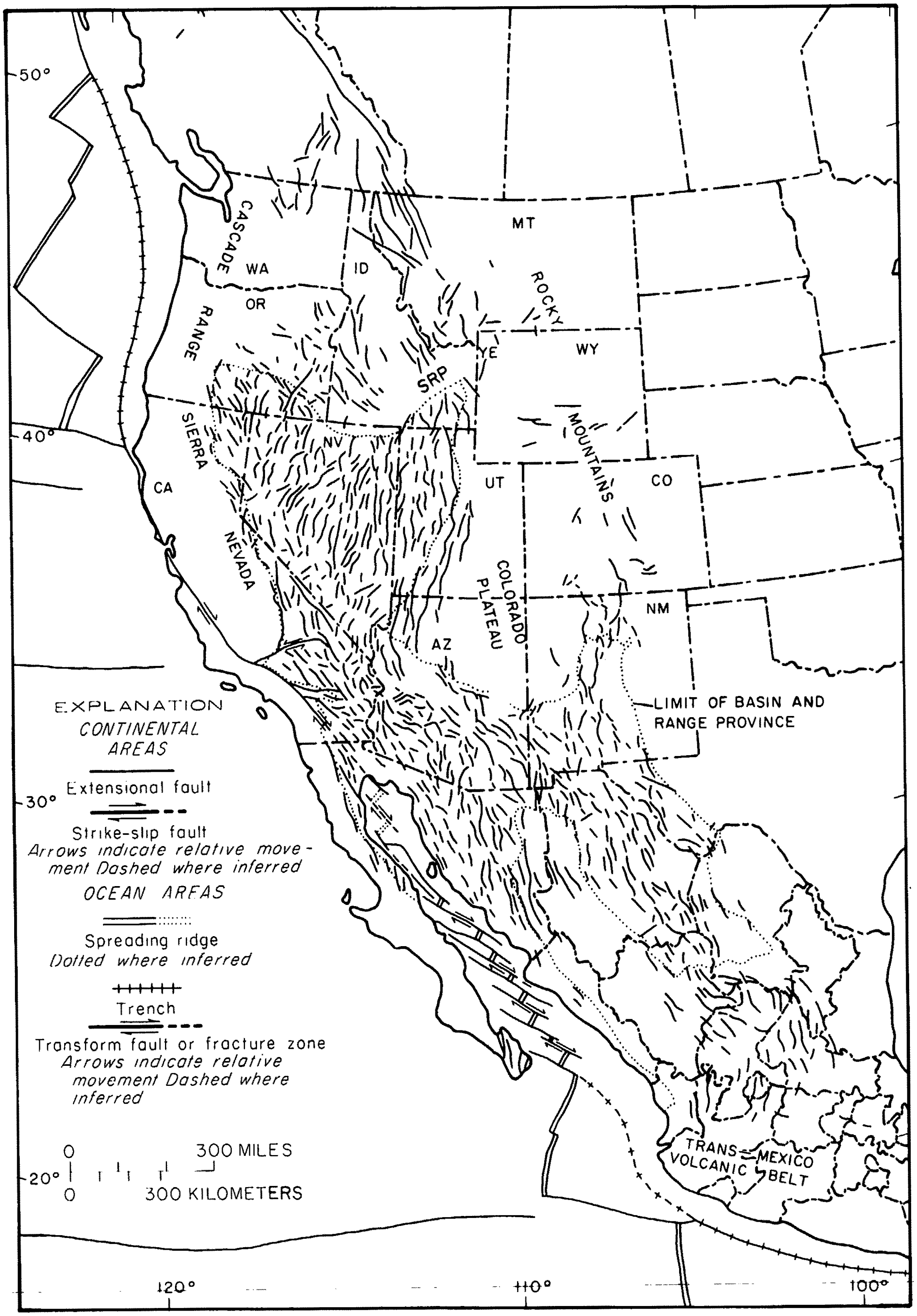

Figure 1. Distribution of late Cenozoic extensional faults, major strike-slip faults, and physiographic provinces in western North America and present-day lithospheric plate boundaries. From Stewart (1978). States: WA, Washington; OR, Oregon; CA, California; CO, Colorado; ID, Idaho; MT, Montana; WY, Wyoming; NV, Nevada; UT, Utah; AZ, Arizona; NM, New Mexico. Localities SRP, Snake River Plain: YE, Yellowstone.

conglomerate (Kellogg, 1964). Although much of this pre-Sheep Pass structure may be related to Mesozoic deformation, some may be related to deformation during deposition of the Sheep Pass Formation, as small faults cut conglomerate in the lower part of the Sheep Pass but do not affect overlying limestone and mudstone (Kellogg, 1964). Large slide blocks of Paleozoic rocks in the Sheep Pass (Newman, 1979) indicate considerable relief in the areas adjacent to the depositional basin. Newman (1979) suggests that the basin in which the Sheep Pass was deposited resulted from normal faulting.

MIDDLE AND LATE CENOZOIC TECTONICS RELATED TO IGNEOUS ACTIVITY

During the middle and part of the late Cenozoic, many major tectonic and structural features in the northern Basin and Range province are related to widespread igneous activity. The pattern of igneous activity is complex (fig. 2), but one element of this pattern is a southward migration of igneous activity starting in the northern part of the province about 43 m.y. ago, spreading southward along an arcuate east-west-trending front, and ending 6 m.y. ago in southern Nevada and Utah (Snyder and others, 1976; Stewart and others, 1977; Cross and Pilger, 1978). In Utah and easternmost Nevada, middle and late Cenozoic igneous activity is confined to four distinct igneous belts (fig. 3), progressively younger to the south and each with a concentration of Cenozoic mineral deposits (Hilpert and Roberts, 1964; Stewart and others, 1977). These belts merge and become indistinct features to the west.

Many major aeromagnetic anomalies in Nevada and Utah trend east-west, east-southeast, or east-northeast (fig. 3). In Utah, these anomalies closely follow the trends of the Cenozoic igneous and mineral belts and clearly are related to magnetic Cenozoic intrusive rocks (Stewart and others, 1977; Shawe and Stewart, 1976). In Nevada, the cause of the generally easterly trending anomalies is less clear, although some appear to be related to Cenozoic and others to Mesozoic igneous rocks (Stewart and others, 1977). The anomalies in many places may mark the position of the slightly arcuate leading edge of the southward-moving front of Cenozoic igneous activity.

East-west-trending volcano-tectonic troughs locally developed in Nevada and eastern California as a consequence, or possible consequence, of middle and late Cenozoic igneous

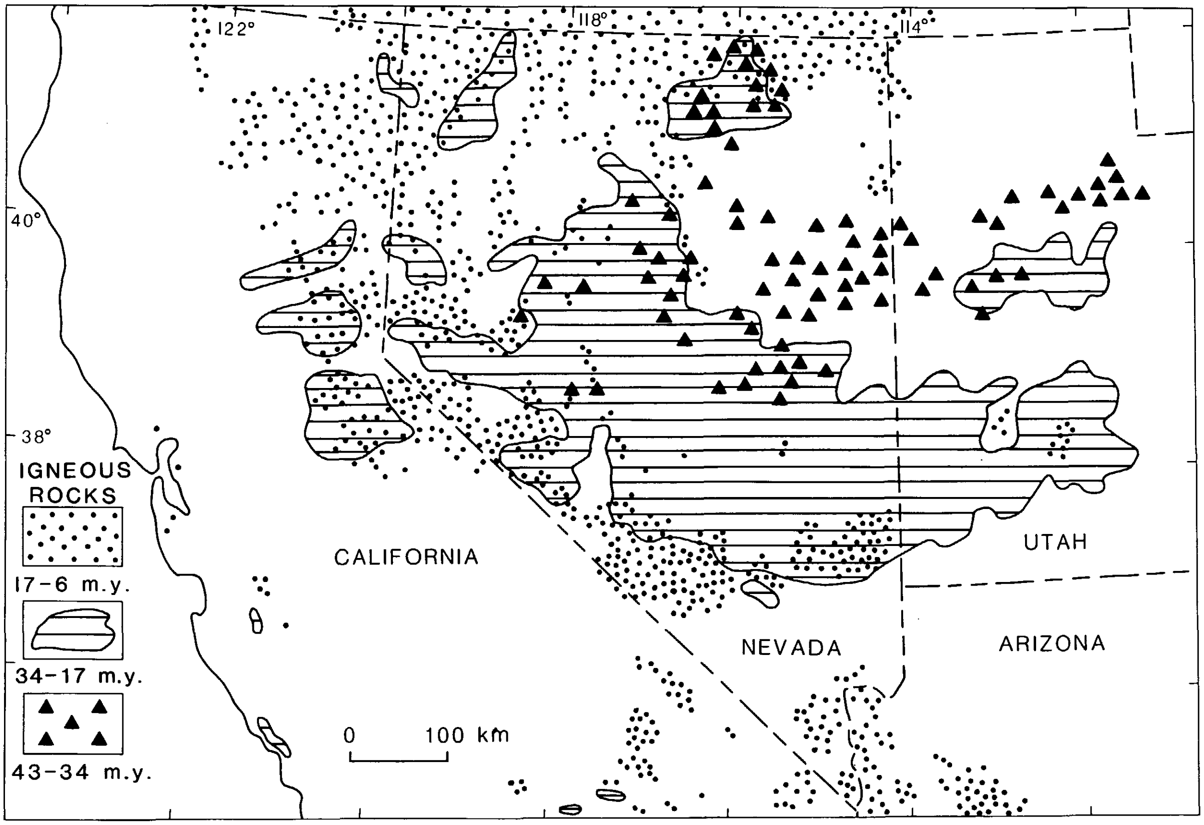

Figure 2. Distribution of 43- to 6-m.y.-old igneous rocks in Nevada, Utah, and parts of adjacent states. From Stewart and others (1977).

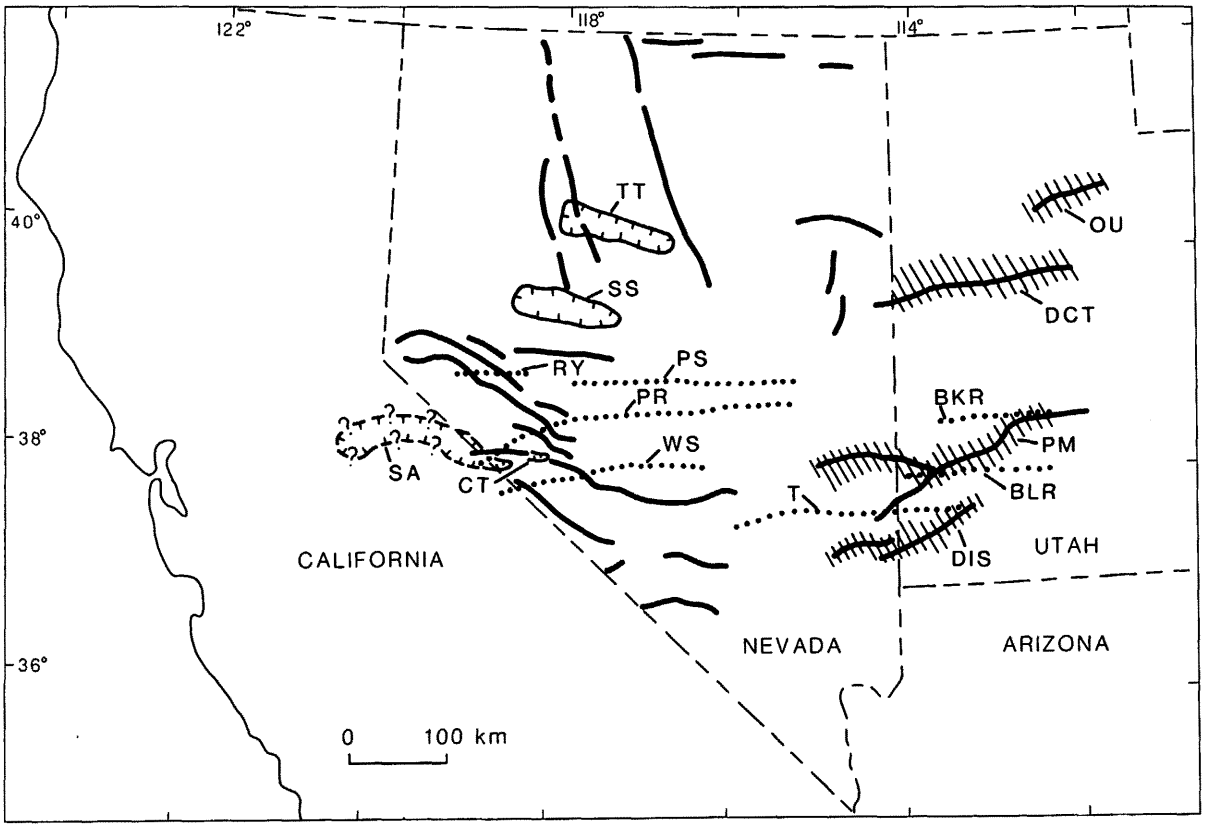

Figure 3. Distribution of positive aeromagnetic anomalies (solid lines), igneous and minerals belts (diagonal line pattern), volcano-tectonic troughs (hachured pattern), and lineaments (dotted pattern) in Nevada, Utah, and part of California. Igneous and mineral belts: OU, Oquirrh-Uinta; DCT, Deep Creek-Tintic; PM, Pioche-Marysvale; DIS, Delamar-Iron Springs. Volcano-tectonic troughs: TT, Tobin-Toiyabe; SS, Stillwater-Shoshone; CT, Candelaria; SA, Sierra Nevada-Adobe Hills. Lineaments: RY, Rawhide-Yerington; PS, Pritchard Station; PR, Pancake Range; WS, Warm Spring; BKR, Black Rock; BLR, Blue Ribbon; T, Timpiute. Based on Ekren and others (1976), Shawe and Stewart (1976), Rowley and others (1978, 1979), Speed and Cogbill (1979), and Burke and McKee (1979).

activity. In central Nevada, Burke and McKee (1979) have described two large east-west-elongate fault-bounded troughs (TT and SS, fig. 3) which were the sites of intense Oligocene and early Miocene volcanic activity (fig. 3). In western Nevada, Speed and Cogbill (1979) have described a deep east-northeast-trending fault trough (CT, fig. 3) filled with a thick accumulation of Oligocene and Miocene volcanic rocks. In eastern California and western Nevada, 9- to 11-m.y.-old ash-flow tuffs and lava are concentrated in an arcuate east-west trending belt (SA, fig. 3) (Gilbert and others, 1968, fig. 5; Noble and others, 1974; Stewart and others, 1982). The Little Walker caldera (Noble and others, 1974) lies within this belt and is the source of part of the tuff. The east-west belt may be a volcano-tectonic trough, although G. F. Brem (oral commun., 1982) has suggested that the Little Walker caldera lay at the crest of the ancestral Sierra Nevada and that the east-west pattern is in part the consequence of flows dispersed downslope both east and west from the crest. The east-west trend of these volcano-tectonic troughs suggests general north-south extension during their development.

Generally east-west-trending lineaments (fig. 3), some well defined and other highly speculative, have been described in several parts of Nevada and Utah (Crosby, 1973; Ekren and others, 1976; Rowley and others, 1978; Rowley and others, 1979). These lineaments are defined on the basis of topographic and structural features that coincide with lithologic boundaries, range and valley termini, east-west-striking high-angle faults, caldera boundaries, alinement of eruptive centers and hydrothermally altered rock, alinement of mineral deposits, and east-west-trending magnetic highs and interruptions of magnetic highs. The possible alinement of Oligocene and Miocene volcanic centers locally along these trends suggests that these lineaments may have developed in part during the middle

Cenozoic, although the extent to which these alinements follow early Cenozoic or Mesozoic structures is unclear (Ekren and others, 1976; Rowley and others, 1978). Parts of these lineaments have been interpreted to be the result of strike-slip faulting, whereas others have been interpreted as due to high-angle normal faulting.

The east-west trends of igneous activity, aeromagnetic anomalies, volcano-tectonic troughs, and lineaments are difficult to explain in terms of a subduction system, or arc, extending generally north-south along the western margin of North America. Such a subduction system might more logically be expected to produce igneous activity parallel to and inland of the subduction system and extension approximately perpendicular to it. Possibly the east-west trends are related to old structures, perhaps Precambrian in part. For example, the Oquirrh-Uinta mineral belt in Utah (fig. 3) is alined along the Cortez-Uinta axis in Utah (Hilpert and Roberts, 1964; Tooker, 1971). This axis is a major tectonic zone in which Paleozoic sedimentary trends are disrupted (Roberts and others, 1965; Stewart and Poole, 1974) and is online with a major Precambrian epicratonal trough (or aulocogen) in which the Uinta Mountain Group was deposited in the Uinta Mountains of northern Utah. Perhaps the concentration of middle Cenozoic igneous activity in the Oquirrh-Uinta mineral belt is in a zone of structural weakness first developed in the Precambrian. Other east-west trends in Nevada and Utah locally follow east-west elongate Mesozoic plutons, again suggesting that some of these features were first developed in pre-Cenozoic time.

The systematic southward migration of igneous activity during the middle and late Cenozoic argues against a purely pre-Cenozoic control for the east-west trends in Nevada and Utah. If the east-west trends are controlled by pre-Cenozoic structures, why would the Cenozoic activity be progressively younger to the south? More likely pre-Cenozoic structural zones have in places localized igneous activity, but other factors have controlled the regional pattern. Rowley and others (1978) have suggested that the east-west lineaments are related to major transcurrent faults, but here again, why the ages of the volcanic activity should decrease to the south is not known. Stewart and others (1977) following a suggestion by P. W. Lipman have hypothesized that the southward migration of igneous activity along an arcurate east-west front is related to a southward migration of an east-west warp in the subducting plate. None of these ideas seem very satisfying to explain the peculiar east-west orientation of Cenozoic igneous activity in Nevada and Utah. Nevertheless, the east-west trends are important tectonically because the development of east-west volcano-tectonic troughs during the igneous activity suggests local north-south extension in part synchronous in part with east-west extension (discussed next) during detachment faulting in metamorphic core complexes and elsewhere.

MIDDLE AND LATE CENOZOIC EXTENSIONAL FAULTING

During part of the middle Cenzoic and throughout the late Cenozoic, local and regional extension and local strike-slip faults dominated the tectonics of the northern Basin and Range. Extensional structures vary significantly in style, age, and distribution and are here described under two categories: low-angle extensional faults and Basin-Range faults. Strike-slip faults are considered separately.

Low-angle extensional faults

A variety of low-angle extensional faults that juxtapose younger over older strata are recognized in the northern Basin and Range province. Such faults include low-angle detachment faults that probably were originally horizontal, gently dipping, or gently warped, as well as faults that were originally steep and were subsequently tilted to a low-angle position. The nomenclature of low-angle faults is not clearly established, and the term "detachment fault" has been used to describe a variety of structures, from low-angle thrust faults to widespread extensional faults that presumably were originally nearly horizontal (Davis and others, 1980), as well as widespread low-angle faults that may have evolved from tilting of originally high-angle faults into low-angle positions (Howard and others, 1982). In some places, distinguishing between these categories of low-angle faults is difficult. Current usage favors use of the term "detachment" fault for widespread fault surfaces that probably were originally horizontal, gently inclined, or gently folded. The Whipple Mountains detachment fault (Davis and others, 1980) in the Mohave Desert in southeastern California has perhaps become the type example of such a fault (Davis and others, 1980); it forms the decollement, or dislocation surface, that in this case separates a metamorphic core complex from its relatively unmetamorphosed carapace.

Low-angle extensional faults are exposed (fig. 4) within a diffuse 200- to 300-km-wide zone extending north-northeastward in eastern Nevada and westernmost Utah and within a 100-km-wide northwest-trending zone astride the California-Nevada state line. In addition, seismic reflection profiles indicate a widespread, gently west-dipping detachment surface, not shown on figure 4, in the subsurface in the Sevier Desert (Sevier Desert detachment fault) in western Utah (McDonald, 1976; Allmendinger and others, 1983; Zoback, 1983). The zone astride the state line is coextensive with the Walker Lane, a belt of disrupted topography characterized by discontinuous strike-slip faults (Gianella and Callaghan, 1934; Locke and others, 1940; Albers, 1967). The northeast-trending belt in eastern Nevada and western Utah, however, does not lie in a region of conspicuous strike-slip faulting. The zones containing low-angle extensional faults are characterized by generally high dip of middle

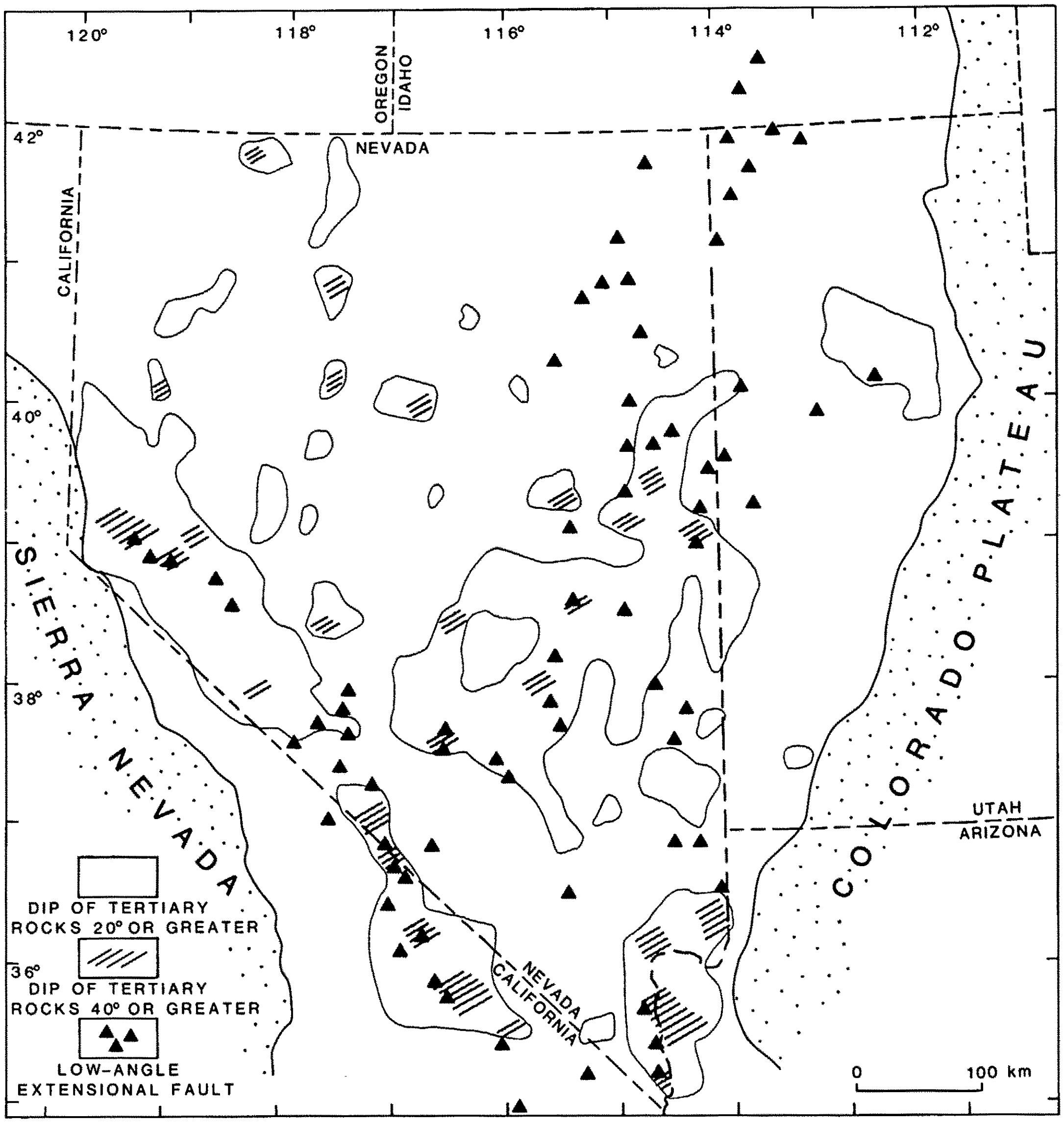

Figure 4. Distribution of low-angle faults and generalized dip of Tertiary rocks. Based in part on Hose and Danes (1973) and Stewart and Johannesen (1979).

Cenozoic rocks (fig. 4) and by the presence of metamorphic core complexes (fig. 5) and muscovite-bearing granitic rocks (Miller and Bradfish, 1980).

Many different models of low-angle extensional faults have been proposed (fig. 6). Most show a widespread low angle fault (detachment fault) with either relatively untilted or with highly tilted overlying strata (Davis and Coney, 1979; Davis and others, 1980; Wernicke, 1981; Wernicke and Burchfiel, 1982). Tilting may occur either along a system of listric faults (fig. 6) or as a consequence of a system of planar faults that bound blocks tilted domino-style (fig. 6). Study of exposed fault surfaces in the upper plate of the Whipple Mountain detachment fault (Gross and Hillemeyer, 1982) suggests that most of the faults are planar, that they join and divide in complex ways, and that they generally intersect the detachment surface at a high angle.

Other models of low-angle faulting (fig. 6) indicate listric or planar faults that do not bottom downward against a detachment fault, but rather die out downward into an intact, but presumably plastically extending, substratum (Wright and Troxel, 1973; Morton and Black, 1975; Proffett, 1977). In some of these models, faults are originally steeply dipping but are rotated into low angle attitudes as the blocks are progressively tilted. In other models, high-angle faults are rotated into low-angle

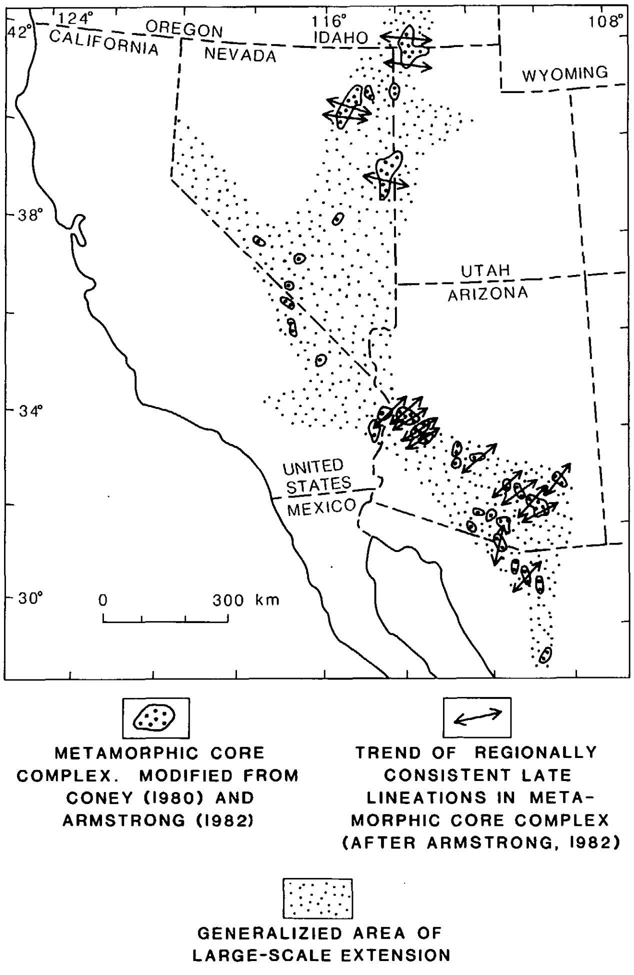

Figure 5. Distribution of metamorphic core complexes and areas of large-scale extension. In part from Coney (1980) and Armstrong (1982).

positions and are then cut by new high angle faults which are in turn rotated.

Still other models (fig. 6) show extension as thin skinned (Osmond, 1960; Wallace, 1965; Anderson, 1971) in which surface blocks moved over a substratum that was not extending or was extending at a lower rate than the surface blocks. In some examples, blocks of this type may virtually be surface landslides.

Finally, Hardyman and others (1975) and Hardyman (1978) have proposed that in a part of the Walker Lane area of west-central Nevada, detachment surfaces that separate Cenozoic volcanic rocks from underlying Mesozoic igneous and metamorphic rocks, and that also occur within Cenozoic sequences, are due to strike-slip motion that breaks the Mesozoic rocks along a few major faults, but causes diffuse strain and the development of many small-scale strike-slip and normal faults in the overlying Tertiary rocks. In this scheme, a detachment fault develops at the boundary between the lower block cut by a few major faults and the upper block of diffuse strain.

Many of the low angle extensional faults appear to be deep structures that extend, or originally extended, deep into the crust. Wernicke (1981) has proposed that low-angle extensional faults cut through the entire crust (fig. 6). Recent results from a COCORP seismic reflection profile in the Sevier Desert of western Utah shows that the subsurface Sevier Desert detachment is shallow on the east, dips on the average 12° to the west, and reaches a maximum depth of 12-15 km in westernmost Utah (Allmendinger and others, 1983; Zoback, 1983). Elsewhere steeply dipping Cenozoic and pre-Cenozoic rocks in stratigraphic sequences from 6 to 13 km thick are exposed in blocks bounded by low-angle extensional faults (Proffett, 1977; Gans, 1982; Howard and others, 1982). The steep dip of these rocks and the low-angle of the bounding faults is considered to result from rotation during extension of originally gently dipping strata and originally steeply dipping normal faults. If so, the originally steeply dipping faults must have extended to depths of 6-13 km in order to account for the thickness of rocks now exposed at the surface.

The amount of extension in areas of low-angle extensional faulting is believed to be great, from 50 to greater than 200 percent of the original width of the area. Proffett (1977) estimated 100 percent extension in the Yerington district of western Nevada, where geometry of faulting and the tilt of strata is well documented. Gans (1982) estimated more than 200 percent extension in the Egan Range in east-central Nevada. Although impossible to state in terms of percentage, I have speculated (Stewart, 1983) that the Panamint Range block in the Death Valley area has moved 80 km to the northwest along a low-angle detachment surface. Large-scale extension appears to have affected only that part of the Basin and Range province where metamorphic core complexes and low-angle detachment faults are abundant (figs. 4 and 5).

Most low-angle faulting in the northern Basin and Range province probably occurred during the middle Miocene, approximately 20 to 10 m.y. ago. The middle Miocene age of faulting corresponds to pre-basin-range extension described by Zoback and others (1981) that preceded the break-up of the region into ranges resembling the modern basins and ranges. A pre-basin-range age of most of the low-angle faults is indicated in many parts of the Basin and Range province where low-angle extentional faults are cut by, and are thus older than, high-angle basin-range faults.

A middle Miocene age for low-angle faulting is clearly indicated in the Yerington area of western Nevada, where faults that are now nearly horizontal are interpreted to have been

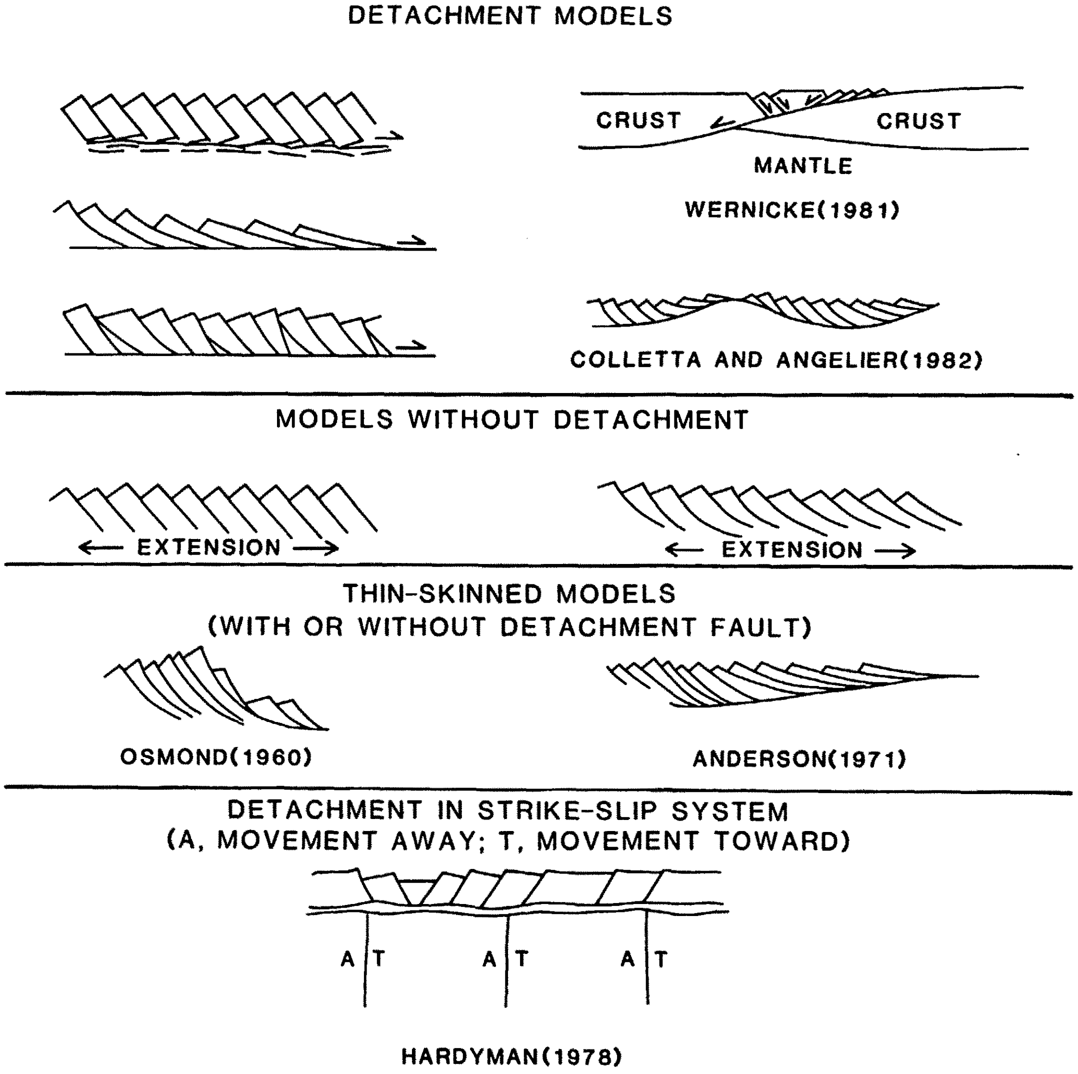

Figure 6. Models of low-angle extensional faults.

originally high-angle faults during eruption of andesitic rocks about 17 to 14 m.y. ago and to have been rotated into their present horizontal position largely before eruption of basaltic rocks 8 m.y. ago (Proffett, 1977). Directly west of the Yerington area, nearly flat faults similar to those near Yerington are cut by mafic dikes dated as 15.7 m.y. old (Hudson and Oriel, 1979), indicating that movement on some of these low-angle faults had ceased by then.

Detachment faults in metamorphic core complexes of the northern Basin and Range may also be mostly middle Miocene in age. In the Grouse Creek metamorphic core complex in northwestern Utah, a 24.9-m.y.-old stock contains foliation and late-stage lineation parallel to that in surrounding rocks, indicating that metamorphism and associated east-west extension is at least as young as this stock (Compton and others, 1977). In the Grouse Creek Range (Compton, 1983) and in the Matlin Mountains (Todd, 1983), large allochthonous sheets override 11 m.y.-old Miocene sedimentary rocks. In the Ruby Range metamorphic core complex, a low-angle fault system cuts 17-m.y.-old volcanic rocks (Snoke, 1980).

A Miocene age of low-angle faulting is also suggested by potassium-argon dating in metamorphic core complexes. In the Snake Range metamorphic complex, potassium-argon ages on mica decrease toward the Snake Range decollement or ~~detachment surface; cataclastic~~ rocks ~~near the~~ detachment are about 17 m.y. old (Lee and others, 1970). This relationship is interpreted (Lee and others, 1970) to indicate reduction in ages due to thermal stresses related to Tertiary activity along the detachment surface. In the Ruby Mountains metamorphic core complex, potassium-argon ages decrease progressively across the range and reach a minimum age of 21 m.y. in cataclastic rocks along a detachment surface (Kistler and Willden, 1969). The 21- m.y. age may be the approximate age of detachment faulting (Kistler and Willden, 1969), although Kistler and O'Neil (1975) have suggested this is a cooling age related to uplift and erosion of the range. Potassium-argon ages (E. H. McKee, written commun., 1983) of about 11 m.y. and 14 m.y., respectively, have been obtained from metamorphic minerals in the Bullfrog Hills in western Nevada and from the Trappman Hills in south-central Nevada. The metamorphic rocks in these two areas have been considered to be part of the Precambrian crystalline basement (Cornwall and Kleinhampl, 1964; Ekren and others, 1971), although they lie far from outcrops of known Precambrian basement rocks. More likely, they represent terranes metamorphosed during the Mesozoic or Cenozoic (Stewart, 1980) and are similar to the metamorphic core complexes of the Snake Range and Ruby Mountains. If so, the Miocene potassium-argon ages may indicate the time of detachment faulting or uplift related to detachement faulting. A potassium-argon age of about 17 m.y. (E. H. McKee, written commun., 1983) for metamorphic minerals on Mineral Ridge in western Nevada may also indicate a time of detachment faulting. A detachment surface on Mineral Ridge separates a core of metamorphic rocks from a relatively unmetamorphic carapace. Mineral Ridge is considered a turtleback dome by Kirsch (1971) and a metamorphic core complex by G. A. Davis and Dayton Marcout (oral commun., 1982).

Some low-angle faulting, on the other hand, may be older than middle Miocene and some is clearly younger. Gans (1982) reported that 36-m.y.-old rhyolite dikes intrude and are cut by a system of faults that rotated domino-style to low-angle attitudes. These relations suggest to Gans (1982) that initial faulting occurred during the intrusion of the rhyolite. R. E. Anderson (written commun., 1983) described features in western Utah that may indicate large-scale low-angle faulting during Oligocene time. Evidence of young detachment faulting is found in the Death Valley area, where rocks that are probably about 6 to 8 m.y. old or younger are incorporated in the Amargosa Chaos of Noble (1941) above a widespread detachment surface (Wernicke, 1981; Stewart, 1983). In the Sevier Desert, high-angle normal faults that offset Quaternary surface deposits terminate at the Sevier Desert detachment fault, implying that Quaternary movement on the detachment fault triggered movement on the high-angle faults (M. L. Zoback, oral commun., 1982).

Present data do not give a clear picture of the direction of extension during the development of low-angle faults, particularly during the Miocene, when most of these structures apparently developed. Extension directions during development of late-stage lineation in the metamorphic core complexes in northwestern Nevada and northwest Utah were nearly east-west (fig. 5). In the Grouse Creek Range, this lineation is developed in a 24.9-m.y.-old pluton, indicating that east-west extension is locally at least this young. If potassium-argon dates on cataclastic rocks in the Ruby Mountains metamorphic core complex (21 m.y.), and in the Snake Range (17 m.y.) indicate the time of detachment faulting, east-west extension may be at least as young. Zoback and others (1981), on the other hand, have outlined evidence of the preferentially oriented dike swarms and fault-slip vectors for 20 to 10 m.y. ago that indicates a uniform west southwest-east northeast extension direction, based mostly on evidence from the Arizona segment of the Basin and Range province. Zoback and Thompson (1978) indicated this same extension direction during the emplacement of a 13.8- to 16.3-m.y.-old north-northwest-trending system of dikes and lava flows in northern Nevada. Perhaps the extension direction changed from largely east-west during development of the core complexes to west southwest-east northeast at a slightly younger time, but the exact timing of these events, if they are indeed related to different times and directions of extension, is not clear. A further complexity is indicated by the southward sweep of Cenozoic igneous activity from 43 to 6 m.y. ago. This southward sweep, as described above, was accompanied by the development of east-west-trending igneous belts and east-west-trending volcano-tectonic toughs or grabens suggestive of north-south extension. This period of north-south extension overlaps in time both the east-west extension in the core complexes and the presumably younger west southwest-east northeast extension indicated by dike emplacement.

Basin-range faulting

The term "basin-range faulting" is restricted (Zoback and others, 1981) to faulting that produced the elongate mountains and valleys that characterize the present-day Basin and Range province (fig. 1). The characteristic crest to crest spacing of the mountain blocks is generally 25 to 35 km. The mountains are usually about 10 to 20 km across and are separated by alluvial valleys of comparable width. In detail, the patterns of mountains and valleys are highly complex and the ranges, although generally elongate, are locally equidimensional or elliptical in plan view.

Basin-range structure is related to block faulting, in which ranges are formed by vertical movements along major faults on one or both sides of the mountain block. The concept of block faulting may 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 in 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.

Three general models (fig. 7) of basin-range structure have been proposed. One model relates basin-range structure to a system of horsts and grabens in which individual horsts form mountains and individual grabens form valleys. A second model relates basin-range structure to a system of buoyant blocks that float on a substratum. The third relates basin-range structure to a system of structural blocks rotated along curving, downward-flattening (listric) faults. Tilting of major blocks, a characteristic of many basin-range blocks, is most easily visualized in the buoyant block and listric fault model, although moderate tilting also can be accommodated in the horst and graben model.

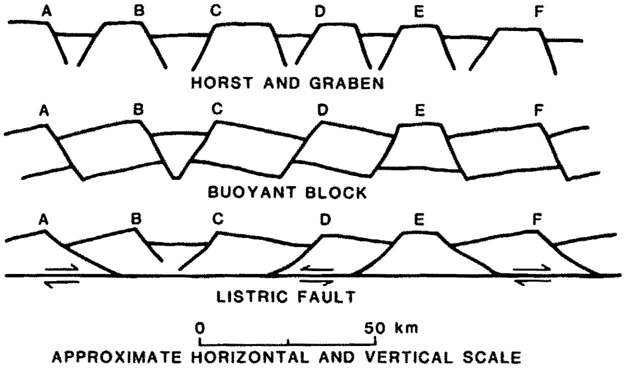

Figure 7. Models of basin-range structure. After Stewart (1979).

In a detailed review of selected subsurface data (mostly seismic reflection data) Anderson and others (1983) concluded that no single structural model explains basin-range structure but that the structure is in places due to major steep planar normal faults, in other places to moderately to deeply penetrating listric normal faults, and in still other places to sharply curving shallow listric faults that merge downward with a detachment surface.

Estimates of the amount of extension necessary to produce basin-range structure have varied widely, and at present no unanimity of opinion exists on the amount. Difficulties arise in part from uncertainties of the subsurface structure. If the major faults that bound basin-range blocks are largely planar, estimates of 10 to 20 percent are reasonable (Stewart, 1971, 1978; Thompson and Burke, 1974), whereas if the ~~faults flatten with depth, estimates of 30 to~~ perhaps several hundred percent are reasonable (Wright and Troxel, 1973; Proffett, 1977). An additional problem is the uncertainty in places as to how much extension is due to pre-basin-range low-angle faulting and how much is related to the basin-range block faulting. In places the distinction between what is here considered to be largely two distinct events (pre-basin-range and basin-range) is unclear and the two may overlap in time.

The most definitive estimate of extension related to basin-range block faulting is in north-central Nevada, where Zoback (1979) estimated about 20 percent extension. Her estimate is based on an analysis of faulting on four major fault sets where the range-bounding faults have considerable oblique (left-lateral) components of motion. The total offset along each major fault set was calculated by using gravity data to constrain the vertical offset along the faults and magnetic data to contain lateral offsets of a zone of dikes.

The grain of present-day topography, and thus the development of basin-range fault block mountains, probably develop in the northern Basin and Range province during the past 10 m.y. (Stewart, 1978; Zoback and others, 1981). A young age for present-day topography is indicated in southern Nevada (Ekren and others, 1968) where an 11-m.y.-old tuff does not vary significantly in thickness between present-day valleys and mountains, a situation that would be impossible if present-day topography 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 against some of the ranges and in places flowed in valleys that are the sites of present-day streams. In west-central Nevada, large sedimentary basins, presumably formed by extensional faulting, were well defined about 13 to 9 m.y. ago (Robinson and others, 1968; Gilbert and Reynolds, 1973). These basins were much more extensive (Gilbert and Reynolds, 1973) than present-day basins in the region, and studies of sedimentary transport directions in fluvial units in these basins indicate an integrated drainage system over large areas (fig. 8). Clearly, the present-day topography was not developed until after the close of deposition in these basins, about 9 m.y. ago. This interpretation is supported by widespread faulting of rocks younger than 9 m.y. in west-central Nevada (Stewart and others, 1982). In north-central Nevada, widespread basaltic andesite flows 17 to 14 m.y. old and an olivine basalt flow 10 m.y. old (Stewart and others, 1975; Stewart and McKee, 1977; Zoback and Thompson, 1978) are cut by major basin-range faults related to present-day ranges, whereas a 6-m.y.-old basalt (Zoback and Thompson, 1978) flowed across alluvium in what are now valleys. Here again, a young age (less than 10 m.y.) is indicated for the development of basin-range structure.

~~The general north to north-northeast~~ orientation of major basin-range normal faults (fig. 1) in the northern Basin and Range province indicates extension in an east-west or east southeast-west southwest direction. Present-day extension also has this direction, based on earthquake focal mechanisms and *in situ* stress

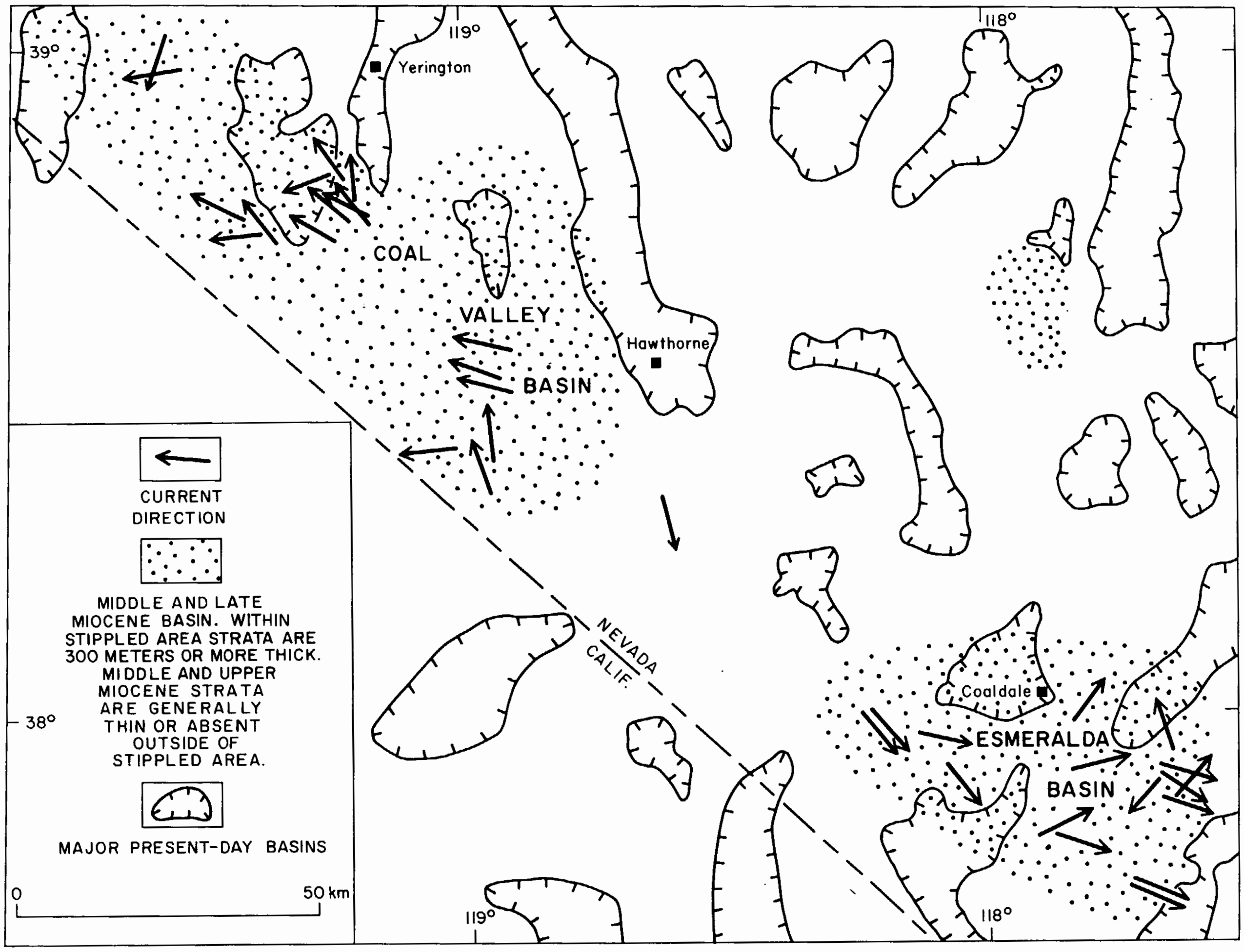

Figure 8. Distribution of middle and late Miocene sedimentary basins, paleocurrent directions in middle and upper Miocene fluvial units, and distribution of major present-day basins, eastern California and western Nevada.

measurements (Zoback and Zoback, 1980; Zoback and others, 1981).

Strike-slip faults

Major strike-slip faults, along which most movement was probably late Cenozoic in age, occur in the Walker Lane and in a diffuse east-northeast-trending zone (Garlock fault to Lake Mead fault system) in eastern California and southern Nevada. Both northwest-trending right-lateral faults and northeast-trending left-lateral faults occur. Estimates of offsets on individual faults are as great as 80 km (Smith, 1962; Stewart and others, 1968; Bohannon, 1979).

The restriction of strike slip faults to the Walker Lane and to the diffuse east-northeast zone in eastern California and southern Nevada may indicate that these zones allowed for adjustment between terranes of different tectonic character. The Walker Lane may mark the boundary between a northwest-moving Sierra Nevada block and the west-northwest-extending Basin and Range province (Wright, 1976). The east-northeast zone of strike-slip faults (Garlock fault to Lake Mead fault system) may mark a diffuse boundary between areas to the south that extended in a southwest direction and those to the north that extended in a west-northwest direction (fig. 9). Such a difference in extension direction north and south of the east-northeast zone of strike-slip faulting is compatible with evidence of extension directions during development of late-stage lineation in the metamorphic core complexes (fig. 5). In Arizona and southeastern California this extension direction is southwest-northeast, whereas in Nevada and western Utah it is east-west.

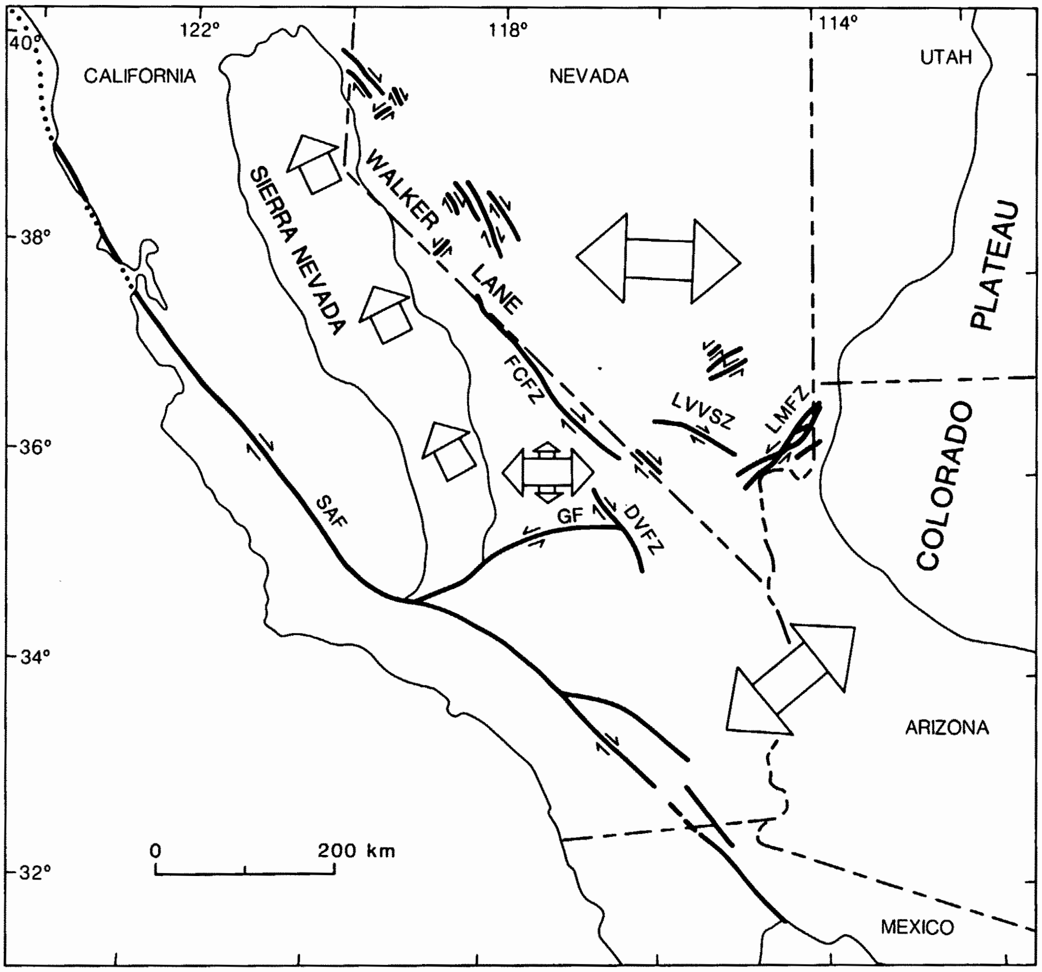

Figure 9. Strike-slip faults and an interpretation of regional extensional directions during their development. Faults: FCFZ, Furnace Creek fault zone; LVVSZ, Las Vegas Valley shear zone; LMFZ, Lake Mead fault zone; GF, Garlock fault; DVFZ, Death Valley fault zone.

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