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TECTONIC AND MAGMATIC DEVELOPMENT OF THE GREAT BASIN OF WESTERN UNITED STATES DURING LATE CENOZOIC TIME

EDWIN H. McKEE

U.S. Geological Survey, 345 Middlefield Road, Menlo Park, Calif. 94025

and

DONALD C. NOBLE

Mackay School of Mines, University of Nevada-Reno, Reno, Nev. 89557

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In the latter part of the Cenozoic, about 18 Ma, the first basin and range faulting developed in the central part of the Great Basin of western United States. This extensional tectonic system formed as a result of drag on the North American plate as the Pacific plate moved obliquely northwestward along the San Andreas fault. Basin and range faulting migrated rapidly to the eastern and western margins of the Great Basin and, although still the prevailing fault activity throughout the Great Basin, is presently most active in these regions. The north edge of the Great Basin at the Snake River Plain and west across southeast Oregon marks the northern limit of basin and range extensional faults. Northwest-trending faults along this north boundary and north of it are at right angles to the basin and range normal-fault system and have a large strike-slip component. This northern boundary of the Great Basin is the tectonic zone along which the east-west-extending Basin and Range province has been moving for the past 18 Ma. In the axis of the Great Basin a narrow north-trending zone of basalt intruded the crust at the same time that basin and range faults developed in the region, about 18 Ma ago. The belt of basalt widens northward as it approaches the north edge of the Great Basin and becomes diffuse and widespread in southeast Oregon and southwest Idaho, reaching enormous dimensions in the Columbia Plateau farther north. The basalt, which replaced andesitic igneous activity of the middle Cenozoic, was produced by widespread partial melting in the upper mantle when the tectonic regime changed from a convergent- and subduction-related system, to the extensional basin and range system. The locus of magma generation migrated to the eastern and western margins of the Great Basin simultaneously, and as it migrated, it produced a series of eruptive centers along the north boundary of the Great Basin.

KEY WORDS: Faulting, Great Basin (U.S.A.), magma, tectonics.

INTRODUCTION

By 1970, adequate radiometric age and petrochemical data from Cenozoic igneous rocks in western United States were available to define patterns in age and rock distribution (Armstrong *et al.*, 1969; McKee *et al.*, 1970). These patterns were used with the then-new plate-tectonic model of Atwater (1970) by Lipman *et al.* (1972) and by Christiansen and Lipman (1972) as the basis for a coherent picture of the Cenozoic evolution of western North America. A number of later papers have refined but not fundamentally changed these original concepts.

In essence, the tectonic development of western North America during the latter half of the Cenozoic is a two-chapter story. The older igneous rocks, from about 40 to 18 Ma ago, are largely silicic to intermediate calc-alkalic types apparently resulting from the subduction of the Pacific (Farallon) plate. Rocks less than 18 Ma in the Great Basin and the Columbia Intermontane region to the north are basaltic or bimodal basalt-rhyolite in character. They are probably derived from the upper mantle and in the Great Basin are associated with extensional tectonics that produced the normal faults characteristic of the region today. This second chapter, from 18 Ma to the present, is the topic of this paper.

INTER-REGIONAL COMPARISON

Because the Basin and Range and the Columbia Intermontane regions have strikingly different physiography and a number of geologic differences, they are usually separated in discussions of their development. There are, however, significant similarities and throughgoing features in the two regions that can be used to relate them to a mutual late Cenozoic magmatic and tectonic history.

The transition from the Great Basin to the Columbia Intermontane region is abrupt at the Snake River Plain westward across southeastern Oregon, at about latitude 43°N. Basalts of middle Miocene and younger age, however, overlap the boundary and seem to be related to a souce and tectonic system common to both provinces. The volume of basalt is greatest to the north, in the Columbia Plateau, and becomes progressively less southward, dying out completely in the central part of the Great Basin. North-trending extensional faults best developed in the southern part of the Great Basin die out northward and are almost completely absent north of the southeastern Oregon–Snake River Plain line. North-trending features such as dike swarms are, however, found north of this line, extending into the Columbia Plateau. Many of the major differences between the two regions in effect represent local expressions of a single process—a broad extension due to movement of the Pacific plate northward along the San Andreas fault.

Although the two provinces are linked by some features, significant differences that developed at the same time suggest that whereas the entire region was reacting to the same tectonic system, it was not reacting in the same way; that is, the north and the south regions were uncoupled along an east-west belt running across central and eastern Oregon and from the Snake River Plain in southern Idaho to Yellowstone.

Physiography

The northern part of the Basin and Range province, the Great Basin, is separated from the southern part of the province along an east-west zone north of Las Vegas, Nev. The two parts of the province have strongly differing topographic grain (Figure 1): the northern part (Great Basin) is characterized by north-northeast-trending, long, linear, well-defined ranges, whereas the southern part, including southern Arizona and southern New Mexico, contains less linear southeast-trending mountains. Alluvial fans in the southern area are more mature, merging to form thick valley fill that has nearly buried many of the ranges. In the Great Basin the alluvial fans are mostly young and have not coalesced, and the ranges are therefore long topographic units. The general alignment of ranges, and the more advanced stage of topographic development, suggests that the southern part of the province is older than the northern part.

Sedimentary Rocks

Cenozoic sedimentary rocks in the Great Basin are found mostly on the edges of the present valleys, although in many places they are high in the block-faulted ranges. In most places these rocks are being actively eroded. Facies changes from coarse

FIGURE 1 Physiographic map of the western part of the United States. The Great Basin (northern part of the Basin and Range province) is characterised by NNE trending ranges.

conglomerates to siltstones are abrupt, and the general distribution of these lacustrine strata indicates that they accumulated in basins much like those in the Great Basin today. The age of almost all of these sedimentary rocks is late Miocene or younger (Figure 2), indicating that the basins of the ancestral Basin and Range province came into existence after early miocene time. Continued development of basin and range topography is documented by the numerous faults or faultline scarps in the province, and subsequent basin fill is recorded by the thick alluvial deposits in the valleys. The physiographic form and general type of sedimentation characteristic of the province is a distinct geologic phenomenon that started abruptly and has been

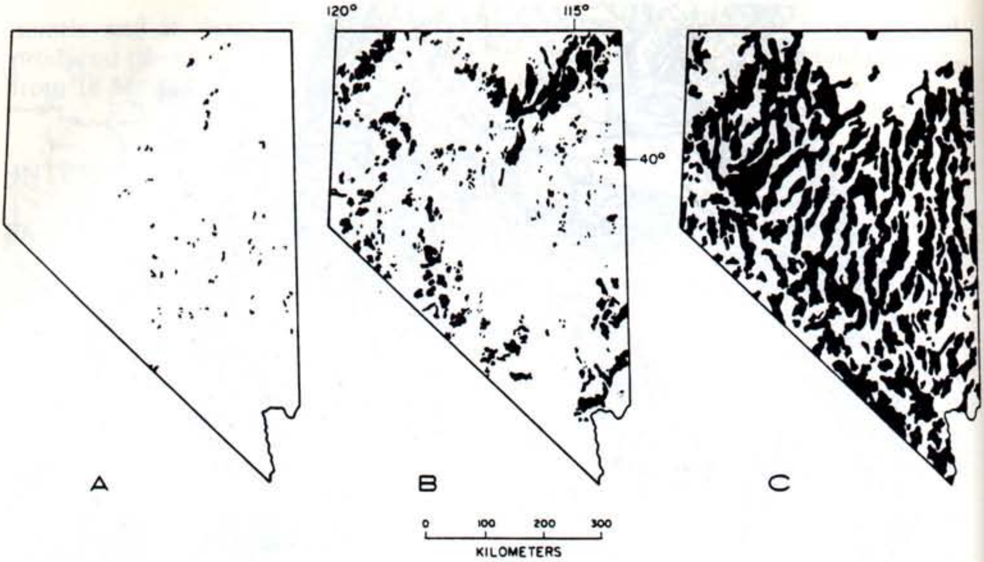

FIGURE 2 Sedimentary rocks of late Cenozoic age in Nevada. (a) are outcrops 45 to 18 Ma; (b) are 17 to 1 Ma and (c) is alluvium in the present valleys. Note the great increase between (a) and (b).

active only since the early Miocene. The oldest basis sedimentary rocks of the initial horsts and grabens of the Great Basin have been dated at about 17–18 Ma (McKee and Noble, 1974).

Basaltic Rocks

Basalts occur around the margins of the Great Basin and most voluminously in the northern part of the area (Figure 3). Almost all of the Cenozoic basalts in the Great Basin are less than about 18 Ma, and most are less than 12 Ma. With few exceptions, the oldest of these late Cenozoic basalts are in the north-central part of Nevada in a zone extending about as far south as Eureka, Nev. This region, containing basalt with a maximum age of about 18 Ma, widens northward toward the Snake River Plain. The basalt in the central part of Nevada, the southern-most area of exposures, forms a narrow north-northwest-trending belt separated by north-trending valleys. The belt, which becomes wide and diffuse toward the Nevada–Idaho or Nevada–Oregon border, crosses the Owyhee region and west end of the Snake River Plain as a zone of poorly defined north-northwest-trending lineaments or north-northwest-trending basalt dikes.

Aeromagnetic Features

One of the most prominent aeromagnetic anomalies in the Great Basin that can be related with a high degree of confidence to late Cenozoic igneous rocks is a linear high extending from north of Eureka, Nev., to the northern Nevada state line (Figure 4). This anomaly has been described in detail by Mabey (1966) and Robinson (1970) and is the southern part of the Oregon–Nevada lineament, a name used by Stewart and others (1975). Surface outcrops of basalt closely mirror the aeromagnetic belt (compare Figures 3 A and 4), and the presence of basalt at depth under alluvium in

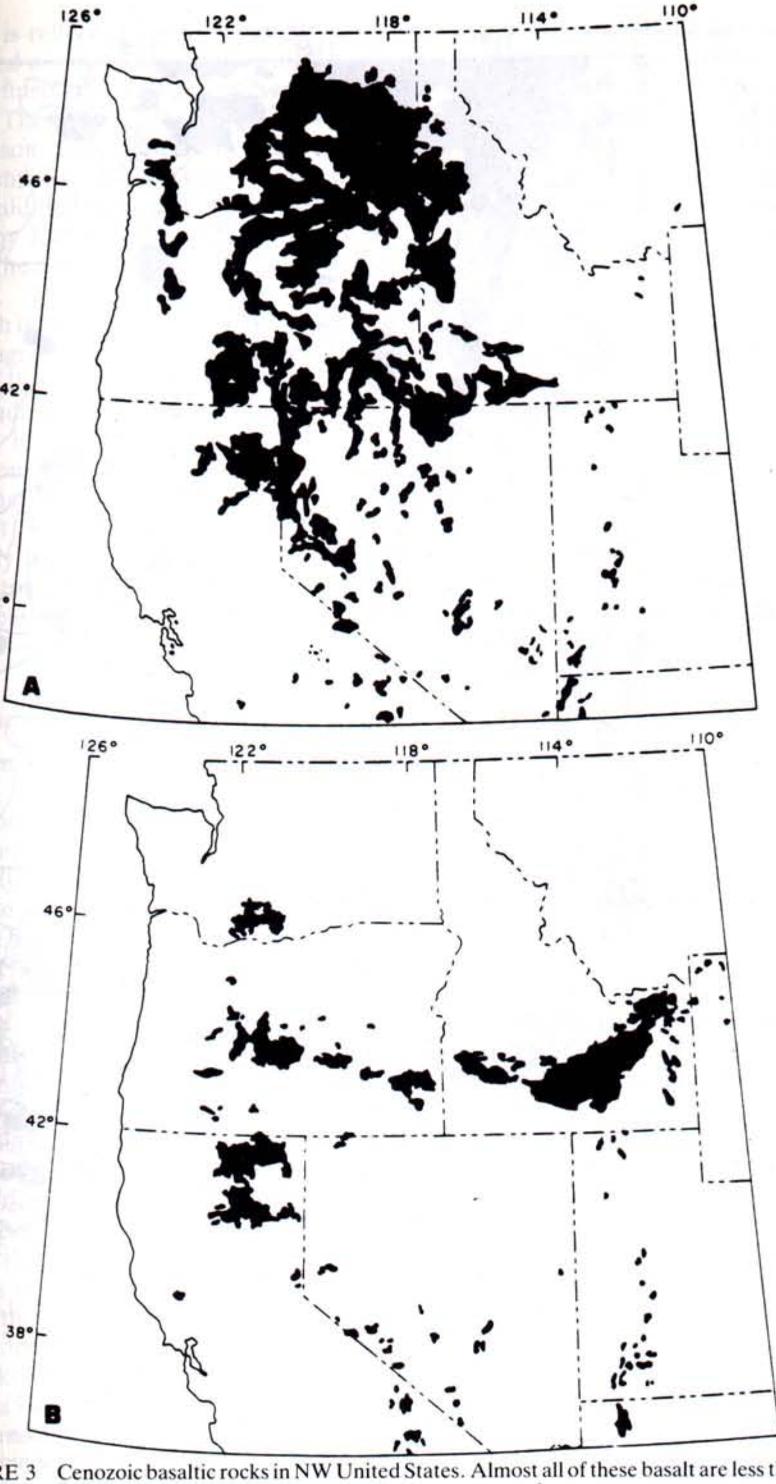

FIGURE 3 Cenozoic basaltic rocks in NW United States. Almost all of these basalt are less than 18 Ma. A: Middle Miocene (~18 Ma) to Quaternary; B: Quaternary.

FIGURE 4 Aeromagnetic map of central and eastern Nevada. Note the aeromagnetic high belt trending NNW in the north-central part of region and the continuation of this belt southward as an aeromagnetic low region.

valleys is reflected by the throughgoing pattern of the aeromagnetic anomaly. The observed anomaly amplitude and its narrow linear form most likely reflect a deep, well-defined zone of basaltic rock superimposed on the near-surface rocks (Mabey, 1966). This 200-km-long, 10-km-wide, 10–15-km-deep, sharply defined anomaly (Robinson, 1970) caused by basaltic rock suggests a basalt-filled rift. It lies in the west-central part of the Great Basin and defines, in a general way, a line of symmetry in the middle of the province. Basalts at various places along the anomaly have been dated by K-Ar at about 15–17 Ma (E. H. McKee, unpubl. data, 1984), although where the northern part of the zone widens, basalts less than 10 Ma overlie the older basalts.

South of the anomaly and along its north-northwest trend is a zone defined by low aeromagnetic intensities. This zone has been referred to as a "quiet zone" by Stewart *et al.* (1977) and is characterized by the absence of high-frequency and high-amplitude magnetic anomalies. The source of the low anomaly must reflect a major change in the magnetic properties of the basement rocks, perhaps caused by elevation under the region of the Curie isotherm. A large and deep rift in the upper crust that allows elevated heat flow could account for an elevated Curie isotherm. The rift, recorded by an aeromagnetic low in the south, turns into the aeromagnetically high belt of basalt in north-central Nevada. It becomes wider and more diffuse toward the Snake River Plain. Mabey *et al.* (1978) speculated that this rift may have been part of the rift system that marked the beginning of extensional tectonics in the Basin and Range province.

Tectonic Features

The dominant tectonic grain of the Great Basin, reflected by its unique topography, is long, narrow, linear basins and ranges of about equal width that trend north-northeast (Figure 1). These are the classic basins and ranges for which the province was named; general observation, as well as detailed geologic studies, points to the high-angle dip-slip nature of the faults that produced them. The attitude and nature of these normal faults at depth is uncertain, but geometric consideration of the surface features requires extension. If local measured extension can be applied to the entire Great Basin, a total spreading of about 100 km, or a ten percent increase in width, is indicated (Thompson and Burke, 1974).

Basin and range faulting is active across the entire Great Basin. The many fault or fault-line scarps (Figure 5) in soft and easily eroded alluvium attest to the relative youth of many of the faults, as does the overall physiography. The major seismic areas, however, are along the eastern (Wasatch) and western (Sierra Nevada) edges, suggesting that these regions may be the loci of most active normal faulting and crustal extension in the area as a whole. It has been suggested by Scholz and others (1971) that this type of faulting and extension started first in the central part of the Great Basin and spread progressively toward the present margins during the latter part of the Cenozoic. Documentation of the age of initial basin and range faulting in various parts of the area is difficult because faulting has continued to the present across the region. There is abundant evidence, however, indicating that basin and range topography as a regional landform, did not exist prior to about 18 Ma ago. The sheetlike bodies of ash-flow tuffs of early Miocene age (20–25 Ma) typical of central Nevada indicate that there was little topographic relief comparable to present-day basin and range topography in that part of the area at that time, and the lack of sizable accumulations of sediments older than about 18 Ma also suggests a subdued topography, unlike that in the area today (Figure 2).

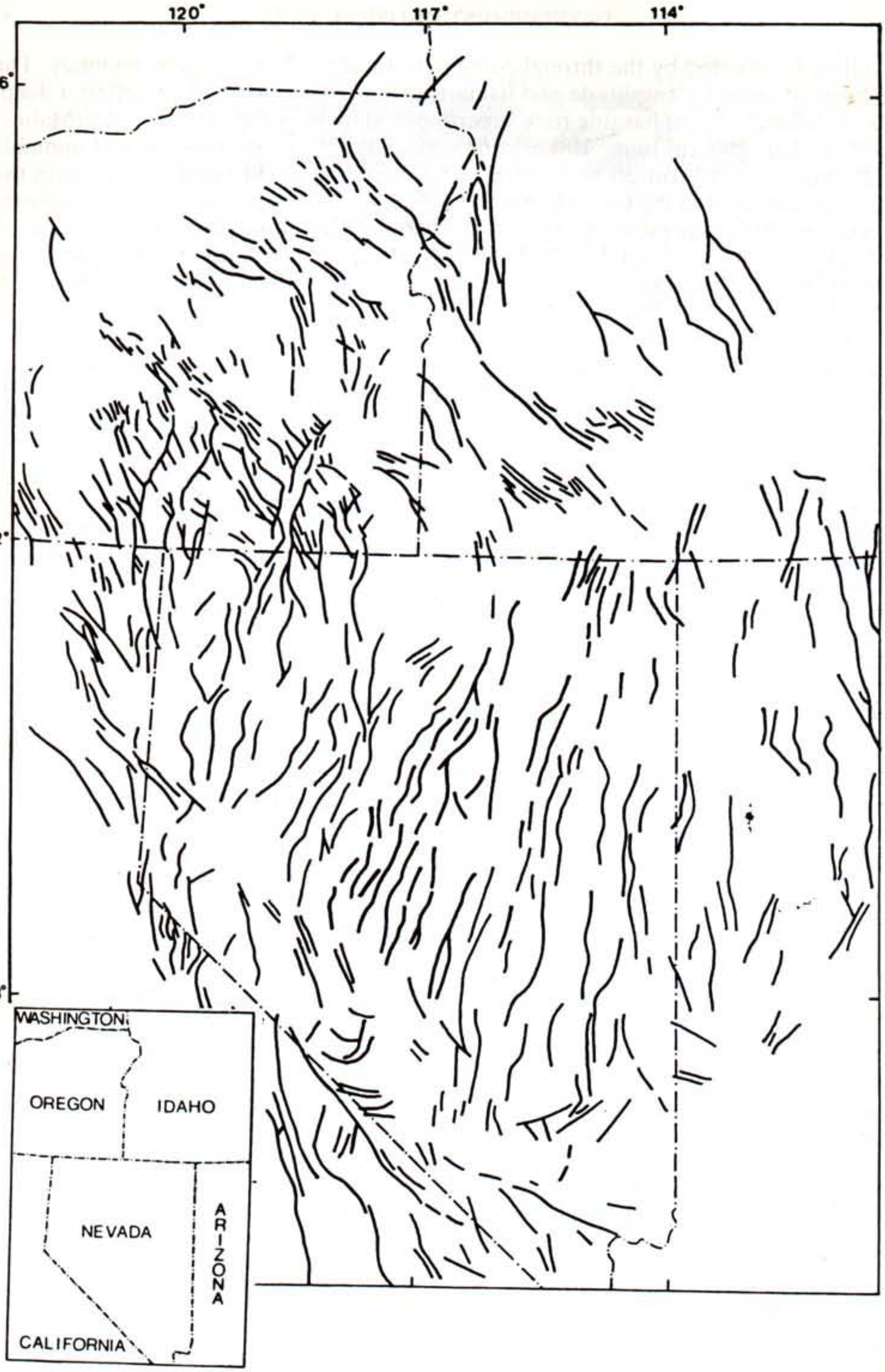

FIGURE 5 Late Cenozoic faults in the western United States. Note NNE trend of the extensional faults in the Great Basin, bounded on the north by NW trending transcurrent faults of the Brothers faults zones and on the south and west by the Walker Lane strike-slip faults.

If high-angle normal faulting in the Great Basin is comparable to rift faulting elsewhere in the world, the eruption of basaltic rocks may be related to this type of tectonism. In this case the age of basalts may indicate the age of the basin and range faulting. As noted (see also Figure 3), almost all basalt in the Great Basin is less than about 18 Ma and the oldest (16–18 Ma) of this young group of rocks froms a north-trending belt in the central part of Nevada near the axis of bilateral symmetry for the province. It is probable that basin and range faulting began in the central part of the Great Basin and spread to the margins within a short period of time and continued in all parts of the area. The most active fault zones today are the seismic belts at the Sierra Nevada and Wasatch fronts.

TECTONIC AND MAGMATIC MODEL

Much evidence points to convergence and subduction of an oceanic plate (Farallon plate) with and beneath the North American continental plate during late Eocene, Oligocene, and early Miocene time (Atwater, 1970; McKee, 1971; Lipman *et al.*, 1972; Christiansen and Lipman, 1972; Noble, 1972). The generation of widespread calc-alkalic volcanic rocks 20 to 40 Ma in the Great Basin is probably the result of subduction of the Farallon plate beneath western North America (Figure 6). During this period virtually no basaltic rocks were erupted anywhere in this region. After about 18 Ma, basalt became a widespread eruptive rock type (particularly in the northern Great Basin) and the calc-alkalic intermediate and silicic rocks became less voluminous, or ceased to be erupted altogether in many areas. At the same time that this major change in volcanic rock type took place, a new tectonic system developed—one of north-trending rifts or basin and range faults, in which the entire Great Basin experienced profound east-west extension of perhaps as much as 50 percent (Hamilton and Myers, 1966), or more conservatively, about ten percent (Thompson and Burke, 1974). This region of extension, however, is confined to the Great Basin being bounded on the south at about latitude 37°N (southern Nevada) by a zone of east-trending structures and topographic features. This boundary is presently discernible on the basis of certain geophysical characterisics such as the termination of high heat flow and termination of the low Bouguer gravity field typical of the Great Basin (Eaton *et al.*, 1978). The northern boundary is more clearly expressed, at the location where basin and range topography and late Cenozoic structural trends abruptly end, about latitude 43°N. The eastern part of the northern boundary is the Snake River Plain; the western part is defined by the Brothers fault zone, which trends west-northwest across eastern and central Oregon (Figure 6). The Great Basin thus is a clearly defined tectonic area characterized by large northwest-southeast extension expressed as north-northeast-trending rift faults. It is bounded on the north by a large west-trending transform zone (Brothers fault zone), on the west by a number of major strike-slip faults and shear zones in the Walker Lane, and on the south by structures of uncertain nature but in general alignment with the Garlock fault. The location and orientation of these tectonic elements is shown in Figure 6.

The San Andreas fault, the single most important tectonic feature in the latitude of the Great Basin, separates the Pacific plate (Farallon plate) from the North American plate. The regional kinematic pattern that we see today has existed for the past 18 Ma. This pattern involves northwestward movement of the Pacific plate relative to the North American plate along the San Andreas fault. Northeastward subduction of the Pacific plate had completely ceased between latitude 37°N and 43°N by 18 Ma and

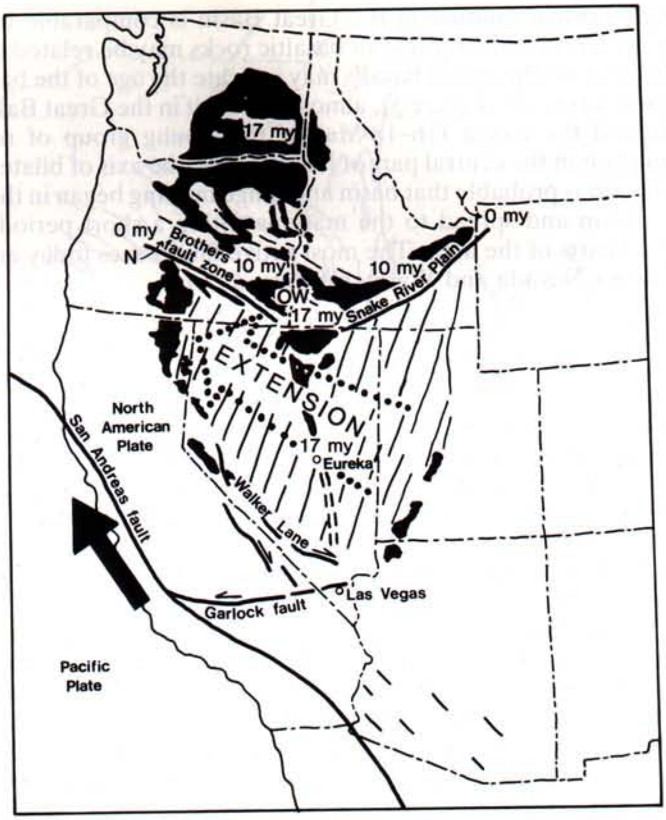

FIGURE 6 Schematic diagram of the Western United States sowing distributions and age of late Cenozoic basalt (black) and major tectonic trends (lines). N, is Newberry volcano; Y, is Yellowstone, OW is Owyhee region. Extension of the Great Basin is indicated by a dotted arrow.

was replaced by north-northwest oblique-slip movement on the San Andreas (Christiansen and Lipman, 1972; Atwater and Molnar, 1973). With cessation of subduction, the eruption of calc-alkalic volcanic rocks ended in most places. At the same time, drag by the northerly moving Pacific block along the San Andreas resulting in pulling apart or extension of the Great Basin region. Movement along the north, west, and southern part of this region was essentially strike-slip or tear faulting. The eastern boundary is defined as the easternmost extensional fault. The initial rifting occurred in the central part of the Great Basin and is now marked by the north-trending band of 15–18 Ma basalt in central Nevada. As the Pacific plate continued to move northward on the San Andreas, drag on and extension of the Great Basin followed and rifting rapidly spread from the center to the margins of the region. This progression is recorded by the symmetrical pattern of decreasing age of the inception of basaltic volcanism from the Owyhee area of southeastern Oregon eastward to Yellowstone and westward to Newberry Crater (Christiansen and McKee, 1978). South of this corridor, extension is still actively taking place in the Great Basin. As the Great Basin extended in a west-northwesterly direction it moved past the central and eastern Oregon block to the north. The boundary is the Brothers fault zone, here interpreted as a zone of transform faulting.

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