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SPACE-TIME RELATIONS OF CENOZOIC SILICIC VOLCANISM IN THE GREAT BASIN OF THE WESTERN UNITED STATES*

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ABSTRACT. Physical stratigraphy supported by more than 250 K-Ar age determination demonstrates a definite space-time pattern of Cenozoic silicic volcanism within the Great Basin. Known vent areas of voluminous ash-flow units and the approximate source areas for sequences of related sheets whose original distribution is known provide the most important control points. These are supplemented by many dates on tuffs and lavas which lack more complete stratigraphic control.

Cenozoic volcanism began about 40 m.y. ago. Although locally abundant elsewhere, volcanic rocks 30 to 40 m.y. old are most abundant in east-central Nevada. The locus of pyroclastic volcanism, as defined by the time of most intense activity and the time of latest significant activity within a given area, then shifted progressively outward from east-central Nevada toward the margins of the Great Basin. Silicic volcanism had ceased by 25 to 30 m.y. ago in east-central Nevada and by 20 m.y. ago was restricted to the marginal areas of the Great Basin. The intensity of silicic volcanism has decreased progressively during the last 10 m.y.

East-central Nevada, where silicic volcanism first terminated, is less seismically active and possibly has a thicker crust than other parts of the Great Basin. The observed pattern of outwardly migrating volcanism may have been the result of convection within the mantle with a rising current centered on the east-central part of the Great Basin.

INTRODUCTION

This paper summarizes and interprets chronologic data bearing on the space-time distribution of Cenozoic volcanism in and near the Great Basin of the western United States (fig. 1). Nearby areas are included because pyroclastic rocks that erupted from vents within the Great Basin spread beyond its margins, and some rocks erupted from vents slightly outside the geomorphologically defined boundaries of the province appear to belong to this episode of volcanic activity.

The discussion is limited to the silicic volcanic rocks that constitute the bulk of the volcanic material of Cenozoic age in the Great Basin. These silicic volcanic rocks are predominantly pyroclastic material which forms voluminous and areally extensive sheets of ash-flow tuff (Gilbert, 1938; Mackin, 1960; Coats, 1964; Noble and others, 1964; Orkild, 1965; Sargent, Noble, and Ekren, 1965; Cook, 1965; McKee, 1968a; and others). The high-potash intermediate lavas present in many parts of the province are not included; available data (for example, Anderson and Ekren, 1968; Stewart and McKee, 1968) suggest that within any given area such rocks were usually erupted before the silicic rocks. Mafic volcanic rocks (mostly basalt flows) are much less common than the silicic rocks and have not yet been dated in many regions, but

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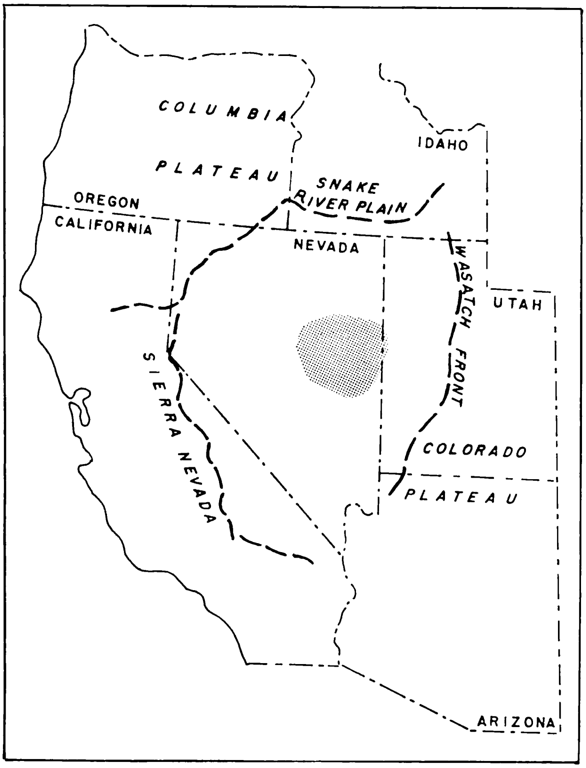

Fig. 1. Great Basin region of the Basin and Range province. Core area of silicic volcanism shaded.

where they have they usually prove to be the youngest rocks of the volcanic sequence.

This paper relies largely upon the many potassium-argon dates now available, most of them obtained from biotite and sanidine phenocryst separates, but some from whole-rock samples.

AGE AND DISTRIBUTION OF SILICIC VOLCANIC ROCKS

Previous Work

E. F. Cook (1965) was the first to recognize a systematic temporal pattern in the distribution of Cenozoic volcanism. His stratigraphic studies revealed that the volcanic section becomes progressively younger when traced from east-central Nevada south and southeastward into southeastern Nevada and southwestern Utah. All subsequent stratigraphic studies and isotopic age data (for example, Noble, 1968; Noble and others, 1967; R. L. Armstrong, E. B. Ekren, and D. C. Noble, unpub. data) have substantiated Cook's general stratigraphic framework and conclusions.

In south-central Nevada, detailed stratigraphic and isotopic work by the U.S. Geological Survey has revealed a similar pattern. In this region the Tertiary section ranges in age from 15 to more than 25 m.y. (Ekren and others, 1968; E. B. Ekren and others, unpub. data). To the south, younger rock units appear at the top of the section and older units pinch out so that in southern Nevada almost all the silicic volcanic rocks are younger than 15 m.y. (Noble and others, 1964; Orkild, 1965; Noble and others, 1967; Kistler, 1968; R. F. Marvin and others, unpub. data).

Schilling (1965) recognized a similar tendency in Cenozoic volcanic rocks to become younger toward the southwestern and western margins of Nevada. This age change has been substantiated by recent mapping and isotopic dating by various workers (for example, Robinson, McKee, and Moiola, 1968).

In northern Nevada, southeastern Oregon, and southern Idaho stratigraphic work, in conjunction with paleontologic and some isotopic data, has demonstrated the presence of large volumes of silicic pyroclastics and lavas of Miocene and Pliocene age (for example, Mapel and Hail, 1959; Willden, 1961, 1963, 1964; Malde and Powers, 1962; Carr and Trimble, 1963; Axelrod, 1964; Coats, 1964; Walker and Repenning, 1965, 1966; Noble and others, 1968). Older rocks also are present, at least locally, in northern Nevada (Coats, 1964; Axelrod, 1966). The available data are compatible with, but do not prove, a systematic northward shift in both the locus of the most intense volcanism and the cessation of silicic volcanism.

Potassium-Argon Ages

Method of presentation.—Available isotopic data, grouped into 5 m.y. intervals, are shown in figures 2 through 5. These maps summarize over 250 individual age determinations, including 80 unpublished determinations by Armstrong, 41 determinations by McKee, and approximately 30 determinations from other U.S. Geological Survey sources. Although the accuracy of the individual dates are such as to make intervals of less than 5 m.y. statistically valid, the limited number of dates in certain intervals, together with wide variations in the precision of their geologic control, do not warrant the use of a shorter time span. In addition to a breakdown by age, the data are classified to indicate their relative importance.

Distribution pattern.—Silicic volcanic rocks older than 30 m.y. (fig. 2) are concentrated in east-central Nevada, but some are present in northern Nevada, along the Wasatch front in Utah (fig. 1), and locally in the Sierra Nevada (fig. 1). Ages between 20 and 30 m.y. (fig. 3) are most prevalent immediately outside the east-central Nevada core area.[1] Ages younger than 20 m.y. are restricted to the outer part of the Great Basin area, and those younger than 10 m.y. to the margins (figs. 3 and

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[1] Many of the 20- to 30-m.y. ages in the central Sierra Nevada are geographically displaced; most of the dated tuffs, which belong to the Miocene Valley Springs Formation or its equivalents, very probably had their sources in the western part of the Great Basin (Slemmons, 1966; Durrell, 1966).

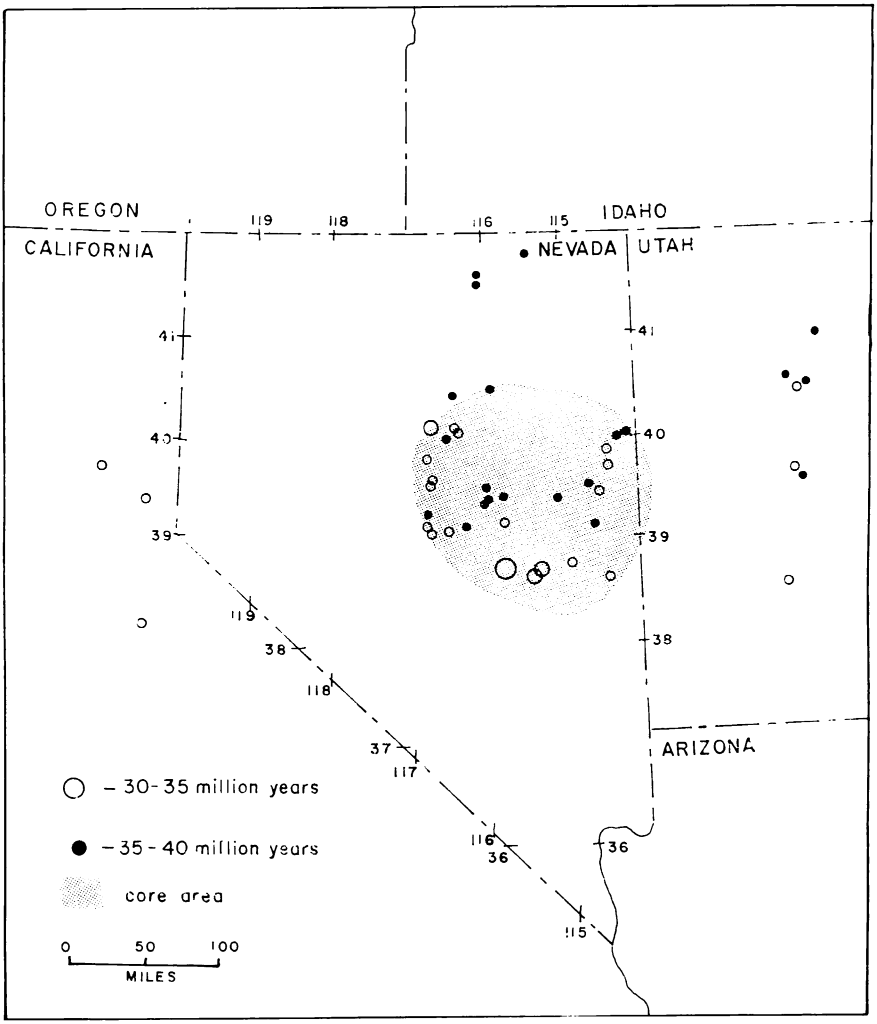

Fig. 2. Distribution of silicic volcanism in the Great Basin from 30 to 40 m.y. ago. Large symbols indicate (1) major volcanic centers of known age, or (2) the geographic centers of major ash-flow sheets or sequences of genetically related sheets for which approximate original distribution is known, but whose source is unknown. A single large symbol usually represents several, and in certain instances more than 10, isotopic dates. Medium-sized symbols show the approximate centers of major ash-flow sheets whose original distribution is partially known. Small symbols are used to represent isolated dates on ash-flow units whose areal distribution relations are uncertain, dates on lava bodies and air-fall tuffs that are not known to be genetically related to major volcanic centers, and dates on tuffaceous sedimentary rocks.

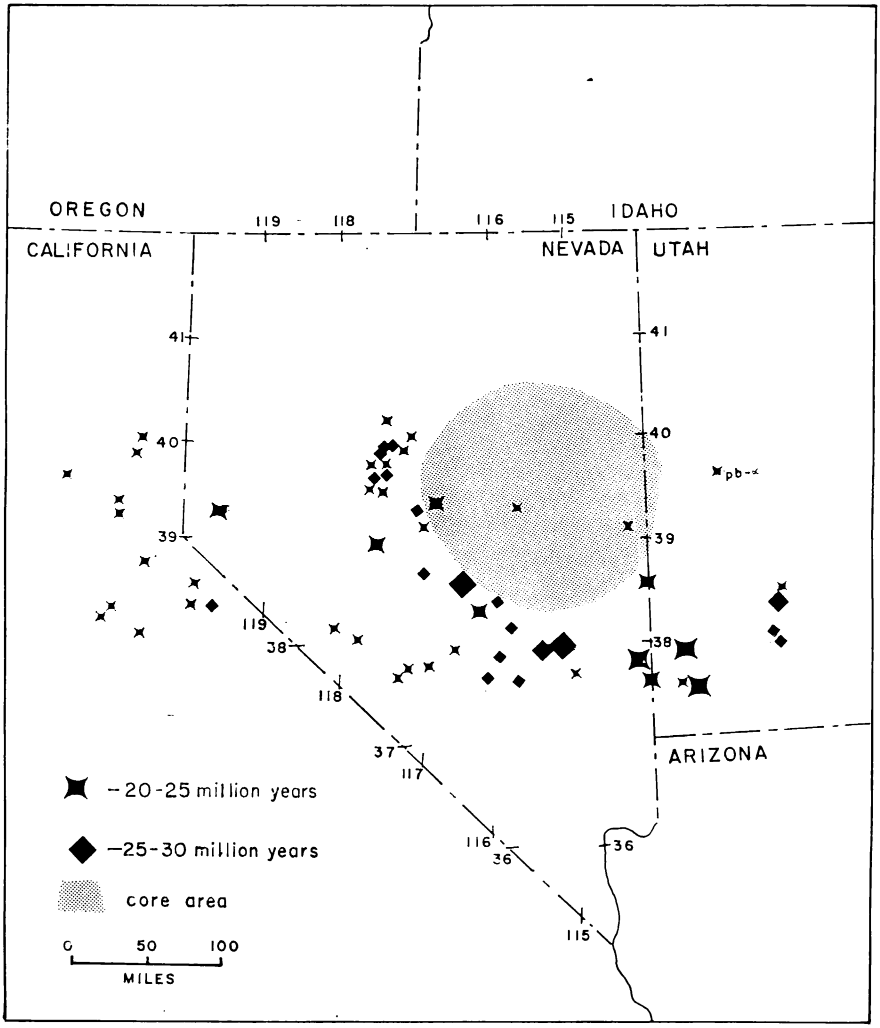

Fig. 3. Distribution of silicic volcanism in the Great Basin from 20 to 30 m.y. ago. Large symbols indicate (1) major volcanic centers of known age, or (2) the geographic centers of major ash-flow sheets or sequences of genetically related sheets for which approximate original distribution is known but whose source is unknown. A single large symbol usually represents several, and in certain instances more than 10, isotopic dates. Medium-sized symbols show the approximate centers of major ash-flow sheets whose original distribution is partially known. Small symbols are used to represent isolated dates on ash-flow units whose areal distribution relations are uncertain, dates on lava bodies and air-fall tuffs that are not known to be genetically related to major volcanic centers, and dates on tuffaceous sedimentary rocks.

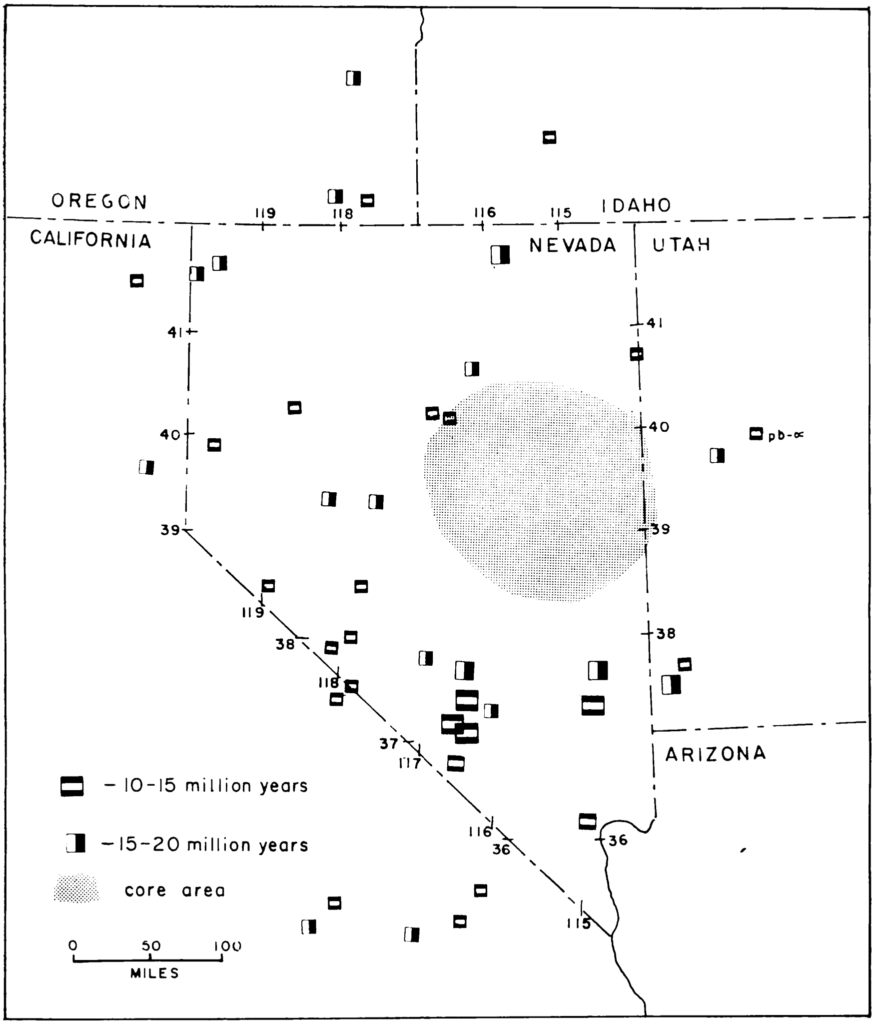

Fig. 4. Distribution of silicic volcanism in the Great Basin from 10 to 20 m.y. ago. Large symbols indicate (1) major volcanic centers of known age, or (2) the geographic centers of major ash-flow sheets or sequences of genetically related sheets for which approximate original distribution is known but whose source is unknown. A single large symbol usually represents several, and in certain instances more than 10, isotopic dates. Medium-sized symbols show the approximate centers of major ash-flow sheets whose original distribution is partially known. Small symbols are used to represent isolated dates on ash-flow units whose areal distribution relations are uncertain, dates on lava bodies and air-fall tuffs that are not known to be genetically related to major volcanic centers, and dates on tuffaceous sedimentary rocks.

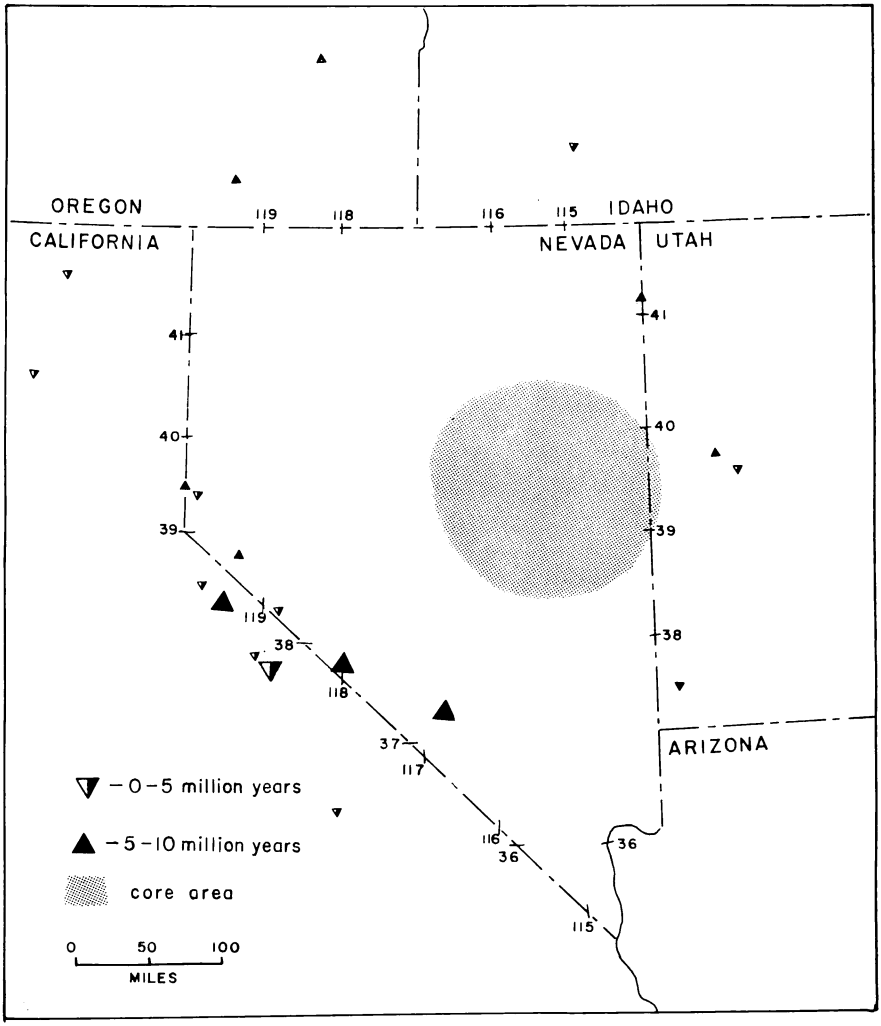

Fig. 5. Distribution of silicic volcanism in the Great Basin from 0 to 10 m.y. ago. Large symbols indicate (1) major volcanic centers of known age, or (2) the geographic centers of major ash-flow sheets or sequences of genetically related sheets for which approximate original distribution is known but whose source is unknown. A single large symbol usually represents several, and in certain instances more than 10, isotopic dates. Medium-sized symbols shows the approximate centers of major ash-flow sheets whose original distribution is partially known. Small symbols are used to represent isolated dates on ash-flow units whose areal distribution relations are uncertain, dates on laval bodies and air-fall tuffs that are not known to be genetically related to major volcanic centers, and dates on tuffaceous sedimentary rocks.

4). A striking feature of the age distribution is the almost complete absence of dates younger than 20 m.y. within the east-central Nevada core area[2] and the total absence of dates younger than 10 m.y. from almost the entire State. This distribution does not appear to represent a bias due to removal of younger units by erosion. The practice of selecting the least altered or structurally involved samples for dating would also tend to prevent a bias.

Summary of Volcanic History

Although not restricted to the east-central part of the Great Basin area, more volcanic rocks older than 30 m.y. occur here than elsewhere. Likewise, rocks of intermediate age are most abundant between the core area and the margins. Thus, even though the outer part of the Great Basin area was moderately active volcanically during middle Tertiary time, there appears to have been a definite outward shift with time of the zone of intense volcanism. More pronounced, however, was the cessation of volcanic activity that followed. Silicic volcanic activity seems to have ceased entirely within east-central Nevada 25 to 30 m.y. before the present and then moved outward systematically to the south, west, and possibly north, of the core area. Present data indicate that cessation of silicic volcanism was abrupt, areally systematic, and final.

In the eastern part of the Great Basin, the space-time distribution of volcanism was less systematic. Young rocks appear to be restricted to the marginal areas, but older volcanics are also present in abundance at and near the Wasatch front. In this area no definite outward progression of the cessation of volcanism is apparent.

Although mafic rocks are sporadically intercalated within the volcanic section, most of the mafic lavas seem to overlie the silicic volcanic rocks. In several areas in the east-central and southeastern part of the Great Basin, isotopic data (R. L. Armstrong, unpub. data) indicate that the mafic volcanism occurred within 5 m.y. of the end of silicic volcanic activity.

The volume of silicic volcanic rocks between 0 and 10 m.y. in age is distinctly smaller than that of rocks 10 to 20 or 20 to 30 m.y. old. Rocks less than 5 m.y. old are even less abundant. This change strongly suggests that the intensity of silicic volcanism has progressively decreased during the last 10 m.y.

TECTONIC SIGNIFICANCE

The overall tectonic framework of the Great Basin has a number of distinctive features. These include widespread large-scale normal faulting (for example, Nolan, 1943; Moore, 1960; Thompson, 1960; Mackin, 1960) and strike-slip faulting (Shawe, 1965; Hamilton and Myers, 1966; McKee, 1968b; and references cited therein), thin crust, low upper-mantle and crustal seismic velocities and densities, and

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[2] The 10- to 15-m.y. date at lat 40°8′ N, long 116°47′ W, is on a shard-rich bedded tuff associated with upper Pliocene vertebrate remains. The source of the volcanic material is probably at a considerable distance from the sample site.

severe P_n wave attenuation (Pakiser and Zietz, 1965; James and Steinhart, 1966; Hill and Pakiser, 1966; Pakiser and Robinson, 1966; Woollard, 1966), continuing seismic activity (Ryall, Slemmons, and Gedney, 1966), and high heat flow (Lee and Uyeda, 1965; Roy and others, 1968). Viewed as a whole, these features emphasize the uniqueness of the Basin and Range tectonic province. Moreover, it seems likely that many of these features may be related to the Cenozoic volcanism, and indeed some of them show a pattern similar to that defined by the distribution of volcanic rocks. For example, the core area is relatively inactive seismically (Ryall, Slemmons, and Gedney, 1966; Woollard, 1958) and seems to have a slightly thicker crust (Eaton, 1963; Pakiser and Zietz, 1965; Hill and Pakiser, 1966; 1967) compared to surrounding parts of the Great Basin.

The outward shift of intense volcanic activity may have been paralleled by an outward expansion of a zone of normal faulting within the Great Basin. This faulting may be reflected by Basin and Range structures that postdate the silicic volcanic activity in most regions (Ekren and others, 1968). Such systematic volcanic migration (at a rate of approximately 1-2 cm per yr) across hundreds of miles, must reflect some primary motivating force located within the mantle. Menard (1960, 1964) has suggested that the Basin and Range region represents the extension beneath the continent of the East Pacific Rise, resulting in the uplift or distention of a zone of the crust at a rate of several centimeters per year. In the models of ocean-floor spreading (Dietz, 1961; Hess, 1962; 1965; Vine and Matthews, 1963; Vine, 1966), the distention is due to the effects of a rising column of mantle material which is part of the overall convection system in the mantle. In the Great Basin, an upwelling of mantle material that began in the core area of east-central Nevada and spread asymmetrically outward, has been suggested by K. L. Cook (1962; 1968). Magma may have resulted from direct heating of the lower crust or upper mantle by the rising hot material or from the overall rise of temperature resulting from deep-seated convective movements.

A slightly different hypothesis suggests that the convection current—or some other type of mantle disturbance—triggered the rise of diapirs of mantle material (Green and Ringwood, 1967). Magmas might have resulted (1) from the partial fusion of the diapir on release of pressure, (2) indirectly, by fusion of crustal or uppermost mantle material by the hot diapir, or (3) by a combination of the two. This mechanism would explain the common occurrence within the Great Basin of axially symmetrical volcanic centers of the collapse-caldera type, each characterized by a chemically mineralogically, and otherwise lithologically coherent sequence of tuffs and lavas distinct from those of neighboring volcanic centers (Noble and others, 1965). The generation and eruption of magmas need not be directly related to preexisting tectonic features, such as high-angle faults, that extend to deep crustal or subcrustal depths.

Armstrong proposes a third and somewhat different mechanism. He suggests that as the mantle material began to rise in the core area, the crust was progressively distended and fractured. These fractures penetrated to ever increasing depths, tapping magma sources within the lower crust and upper mantle. Release of confining pressure by the fractures would result in partial melting of hot material. Hot material at a relatively shallow depth in the crust would have been present as a direct consequence of the Mesozoic orogenies that produced the medium- and high-grade metamorphic Paleozoic rocks now exposed in the eastern Great Basin. The metamorphic rocks do not seem to have cooled below temperatures favorable for argon retention in minerals until Tertiary time (Armstrong and Hansen, 1966; Armstrong and Hills, 1967). Deeper portions of the crust must also have remained at elevated temperatures after the Mesozoic metamorphism and were thus potential magma sources. Generation and upward movement of magma would result in loss of considerable heat; the residue from partial melting would be unable to yield additional magma, so that the fractures would have to tap continually deeper sources, eventually sources within the mantle itself.

The observation that basalts are commonly erupted later than silicic volcanic rocks, in any given area, is consistent with this concept of the tapping of ever-deeper sources of magma. In this model the localization of magma types would reflect original heterogeneities of the crust and upper mantle and regional differences in thermal gradient prior to faulting. Partial melting under varying pressure-temperature conditions would result. The progressive outward shift of volcanic activity suggests that crustal fracturing began in the core area—an area that coincides with the belt of highest grade Mesozoic regional metamorphism—and moved slowly outward toward the margins of the Great Basin. Cessation of volcanic activity reflects the exhaustion of the magma sources.

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