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Patterns

East-west patterns of Cenozoic igneous rocks, aeromagnetic anomalies, and mineral deposits, Nevada and Utah

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ABSTRACT

In Nevada and western Utah, Cenozoic igneous rocks within several age increments crop out in arcuate, generally east-trending belts, each successively younger to the south. Broad aeromagnetic highs with superimposed short-wavelength anomalies are associated with some of these outcrop belts. Mineral deposits are aligned along the belts in easternmost Nevada and western Utah. The east-west patterns are the result of a southward-migrating front of igneous activity that, in Nevada and Utah, started about 43 to 34 m.y. ago near lat 40°N and ended about 17 to 6 m.y. ago near lat 37°N. During any one time interval, igneous activity was concentrated near the leading edge of the east-trending front. The volcanic front may be related to igneous activity localized along a southward-propagating transverse break or structural warp in a subducting plate.

INTRODUCTION

Regional geologic maps showing the distribution of Cenozoic igneous rocks of several age increments and aeromagnetic maps showing anomalies that appear to correlate with these igneous rocks indicate east-west patterns of igneous activity in Nevada and western Utah. In western Utah, igneous rocks occur in well-defined east-west belts that have long been recognized; in Nevada, the east-west pattern is less evident and has not previously been considered in detail.

In western Utah, the tendency of mineral deposits and Tertiary intrusive igneous rocks to be arranged in east-trending zones or belts has been discussed by Butler and others (1920, p. 100), Morris and Lovering (1961, p. 78–81), Hilpert and Roberts (1964, p. 29–31), and Tooker (1971, p. 80–81). The most prominent of these belts includes the metal deposits and intrusions in the central Wasatch and Oquirrh Mountains, along a westward projection of the Uinta arch (Uinta Mountains) of northeastern Utah, and is referred to collectively as the Oquirrh-Uinta mineral belt (Hilpert and Roberts, 1964). This belt lies along a part of the Cortez-Uinta axis, a major east-west tectonic zone in which the thickness and lithologic trends of Paleozoic rocks are disrupted (Roberts and others, 1965; Stewart and Poole, 1974). Roberts (1964, 1966) interpreted some east-west mineral belts in easternmost Nevada as continuations of the Utah belts but proposed that most mineral belts in Nevada have other orientations.

This report presents new data that support the concept that mineral deposits and Tertiary igneous rocks in western Utah are aligned along east-west belts and discusses the possibility of similar, probably related, east-west patterns of igneous rocks in Nevada.

VOLCANIC ROCKS

The distribution of the various ages of Tertiary volcanic rocks in Nevada and western Utah is complex, and concepts concerning their origin are still evolving. Armstrong and others (1969), Armstrong (1970), and McKee (1971) suggested a pattern of progressive outward shift of silicic volcanism from the center to the margins of the Great Basin of Nevada and western Utah. Christiansen and Lipman (1972, p. 266) and Lipman and others (1972) agreed with Armstrong and others (1969) on a progressive outward occurrence of volcanism during the past 16 m.y. but emphasized a general southward migration of calc-alkalic volcanism from Oregon and Washington in Eocene time and into the Great Basin of Nevada and Utah in Oligocene time. Armstrong and Higgins (1973) also noted this southward shift of older volcanic rocks and indicated that volcanism started about 55 m.y. ago in Washington and reached southern California 22 m.y. ago. Noble (1972, p. 146) pointed out that the model of outwardly shifting volcanism (Armstrong and others, 1969), although generally correct, was oversimplified. He suggested that early Miocene silicic volcanism occurred in a curving belt concave to the northeast that extended from eastern Oregon across Nevada into southwestern Utah and that middle and late Miocene intermediate volcanism occurred in a similarly shaped belt extending from Oregon through northern California and southwestern Nevada into southeasternmost Utah.

In order to study the pattern of volcanic activity in Nevada, western Utah, and adjacent areas, we have prepared four maps (Stewart and Carlson, 1976) showing the distribution and lithologic type of volcanic rocks in four different time intervals (45 to 34 m.y. B.P., 34 to 17 m.y. B.P., 17 to 6 m.y. B.P., and 6 to 0 m.y. B.P.). These maps (Fig. 1) reveal important trends of Cenozoic volcanic activity in the region.

The 43- to 34-m.y. B.P. time interval includes the oldest Tertiary volcanic rocks and, except for a few areas, the oldest Tertiary intrusive rocks within the area studied. Andesitic and some rhyolitic lava flows are widespread from this time interval in a broad band (A–B, Fig. 1A) extending from western Utah to central Nevada. Silicic ash-flow tuffs, as well as andesitic and rhyolitic flows, occur in an elliptical area adjacent to and north of this band in northeastern Nevada.

Volcanic activity apparently did not slacken between the oldest (43 to 34 m.y. B.P.) and the next youngest (34 to 17 m.y. B.P.) group of rocks. The boundary between these two groups of rocks is approximately in the middle of a transition from dominantly andesitic and rhyolitic lava in older rocks to dominantly silicic tuff in younger rocks (McKee and Silberman, 1970, Fig. 2; McKee, 1971, Fig. 2; Noble, 1972). During the 34- to 17-m.y. B.P. interval, silicic tuffs were widespread in a broad, slightly arcuate east-west band (C-D, Fig. 1B) lying south of that in older rocks and extending from southwestern Utah to eastern California. Scattered volcanism occurred north of the tuff province, but little occurred to the south.

Volcanic activity was sparse at the close of the 34- to 17-m.y. B.P. interval and at the beginning of the next younger interval (17 to 6 m.y. B.P.) (McKee and others, 1971); 17 m.y. B.P. was approximately at the middle of this time of slackened activity. In addition, the character of volcanism changed at this time from largely silicic and

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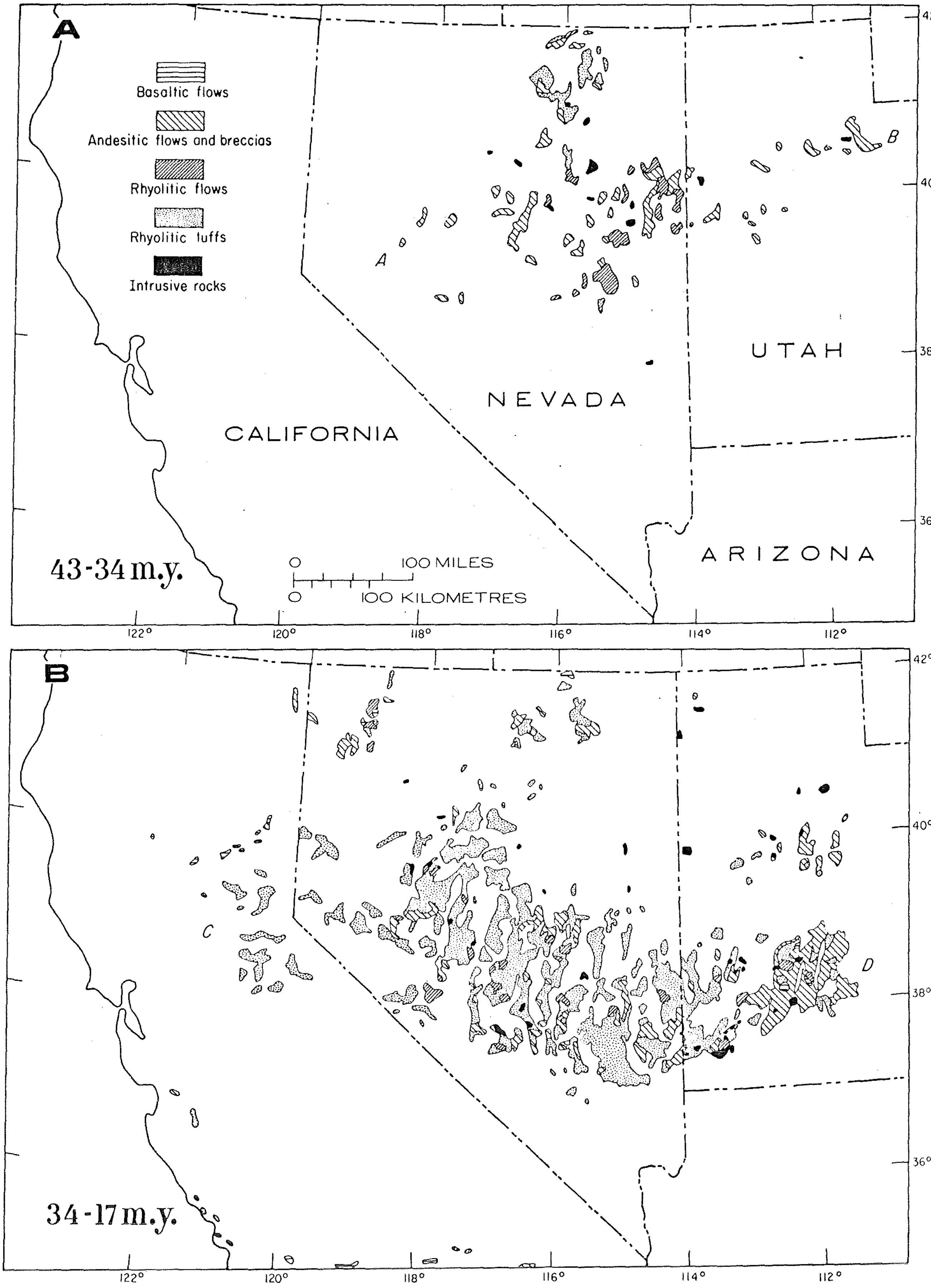
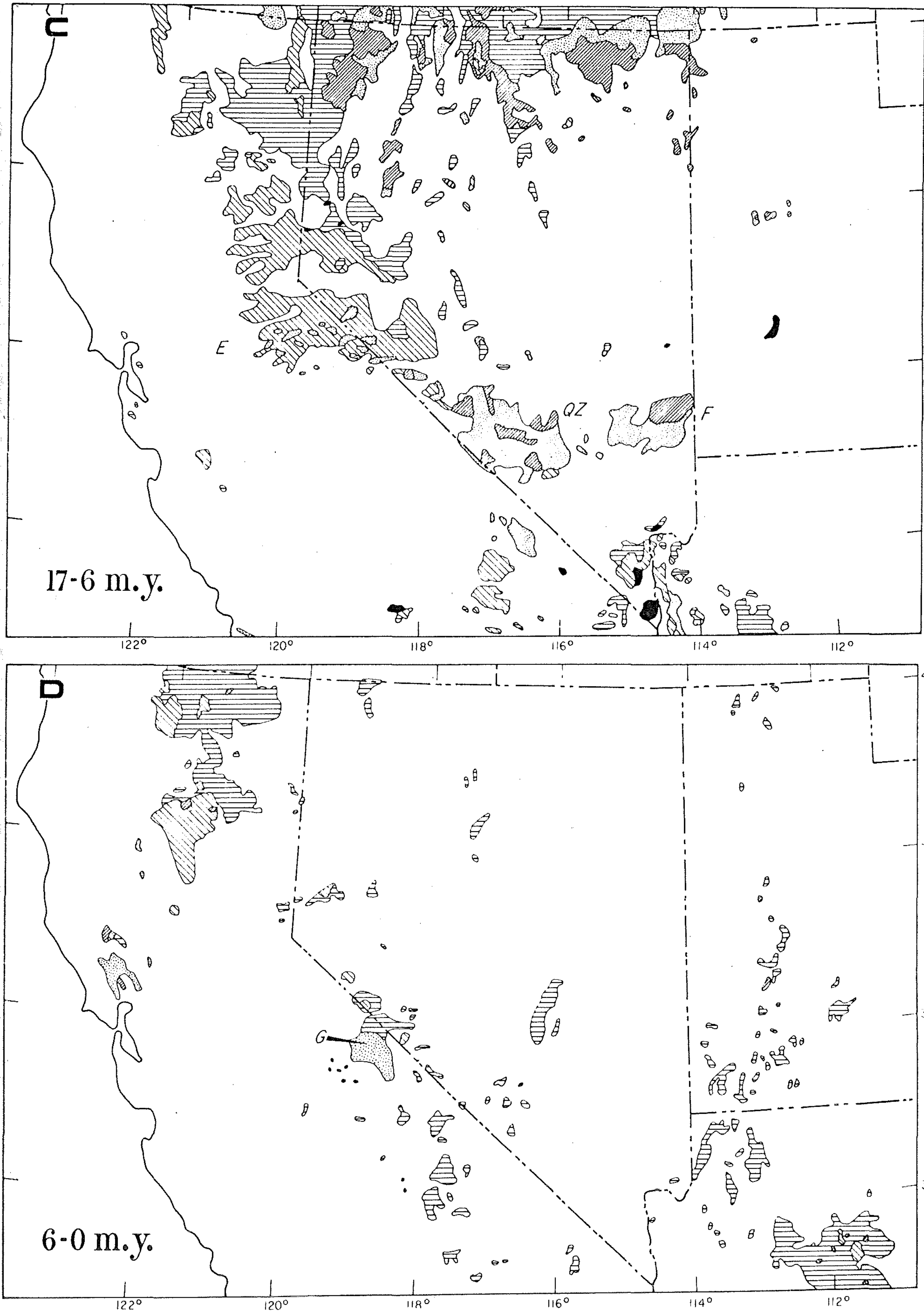


Figure 1. Generalized maps showing distribution of Cenozoic igneous rocks in Nevada, Utah, and parts of adjacent states. Letters refer to local mentioned in text. A, rocks ranging in age from 43 to 34 m.y.; B, rocks ranging in age from 34 to 17 m.y.; C, rocks ranging in age from 17 to 6 m.y.



rocks ranging in age from 6 to 0 m.y. Explanation and scale shown in A. Compiled from various sources, including Jennings (1973), Stewart and Carlson (1974, 1976), P. B. King (unpub. map), and P. D. Rowley (unpub. data).

intermediate calc-alkalic rocks prior to 17 m.y. B.P. to basalt and bimodal assemblages of basalt and rhyolite subsequent to that time (McKee and others, 1970; Christiansen and Lipman, 1972). During the 17- to 6-m.y. B.P. interval, volcanic activity was widespread in northern, southern, and western Nevada and adjoining areas. The northern area is a part of an extensive region of basaltic and rhyolitic volcanism that also covers eastern Oregon and the Snake River Plain in Idaho. In southern Nevada, volcanic activity occurs at the south tip of the state and in adjacent parts of California and Arizona and also as an east-trending belt of tuff near lat 37°N (E–F, Fig. 1C). This tuff belt appears to extend to the west-northwest into eastern California. Several major volcanic centers occur in this belt of tuff, including, from west to east, the Little Walker caldera (Noble and others, 1974) in California, and, in Nevada, the Silver Peak caldera (Robinson and others, 1968), the Black Mountain caldera (Noble and Christiansen, 1974), the Timber Mountain caldera (Christiansen and others, 1977), and the Kane Springs Wash caldera (Noble, 1968). The tuff belt lies generally along or slightly south of the south margin of the tuff province in the next older group of rocks. In western Nevada and eastern California, in addition to the tuff already mentioned, andesitic lava flows and breccias are widespread and are a southward continuation of andesitic volcanism in the Cascade Range of Oregon and Washington (Peck and others, 1964; Lipman and others, 1972). Basalt is widespread in northwestern Nevada and northeastern California directly east of and, in part, within the andesitic belt.

The 6-m.y. age, the boundary between the two youngest time intervals, marks the approximate end of widespread ash-flow tuff activity in Nevada and Utah. Subsequent volcanic activity was largely confined to isolated cinder cones and lava flows, mostly along the borders of the Great Basin in eastern California, westernmost Nevada, and western Utah (Christiansen and Lipman, 1972; Best and Brimhall, 1974).

The maps (Fig. 1A through 1D) reveal complex patterns of Cenozoic volcanism. Several geologic trends seem apparent: (1) a belt of andesitic rock in westernmost Nevada and eastern California (Fig. 1C, 1D) related to calc-alkalic volcanism parallel to the Pacific margin of North America (the Cascade trend); (2) arcuate broad east-west igneous belts at a high angle to and, in part, crosscutting the Cascade trend (Fig. 1A, 1B, 1C, 2); and (3) a general restriction of volcanism to the margin of the Great Basin region in the past 17 m.y. (Figs. 1C, 1D). In addition, changes in the type of volcanism with time are evident: abundant andesitic and rhyolitic lava flows from 43 to 34 m.y. ago (Fig. 1A), dominantly silicic tuffs from 34 to 17 m.y. ago (Fig. 1B), basalt and a variety of other rock types from 17 to 6 m.y. ago (Fig. 1C), and mostly basalt from 6 m.y. ago to the present (Fig. 1D).

The east-west patterns of igneous activity are the main concern of this paper. Cenozoic igneous rocks within the first three age increments (43 to 34, 34 to 17, and 17 to 6 m.y. B.P.) crop out in arcuate, generally east-trending belts, each successively younger to the south. The belt during the 43- to 34-m.y. B.P. interval was near lat 40°N (A–B, Fig. 1A), that during the 34- to 17-m.y. B.P. interval was near lat 38°N (C–D, Fig. 1B), and that during the 17- to 6-m.y. B.P. interval was near lat 37°N (E–F, Fig. 1C). During this last interval, volcanic activity was widespread in Nevada and California, and the only activity considered here to be related to the east-west trend consists of tuff and related flow rocks that extend from eastern California across southern Nevada to the Utah border (E–F, Fig. 1C).

The pattern of distribution of igneous rocks with age (Figs. 1, 2) indicates that the igneous activity in eastern California, Nevada, and western Utah moved southward along a generally east-trending front. During any particular time interval, the igneous activity was concentrated near the leading edge of the front. In Nevada, the front may have moved steadily southward and, in places, southwestward (Arms and others, 1969, Figs. 3,4) where Utah the southward migration of ig activity appears to have taken place in distinct shifts or jumps (HI to LM, L PQ, PQ to TU, Fig. 5).

No east-west volcanic belts are r nized in rocks younger than 6 m.y. 1D). Nonetheless, the large area of tuf Bishop Tuff, Gilbert, 1938) in eastern California, near lat 37°N (G, Fig. could be related to a final phase o southward-migrating volcanic front. tuff lies more or less along the trend east-west belt (E–F, Fig. 1C) related t 17- to 6-m.y.-old volcanic rocks.

East-west patterns are also reveal the distribution of intermediate calc-al lava flows and intrusive rocks. These are also important because they appe be the source of many east-tren aeromagnetic anomalies and to be spa related to similarly trending belts of mi deposits. The intermediate calc-al rocks, mostly andesite and latite f occur in two diffuse east-trending belts 3). Rocks in the northern belt range about 32 to about 43 m.y. old and the the southern belt from about 20 to a 34 m.y. old. Calc-alkalic lavas and intr bodies also occur outside of these bel several areas, notably in northeas southernmost, and westernmost Nev The latter area, however, is part of the

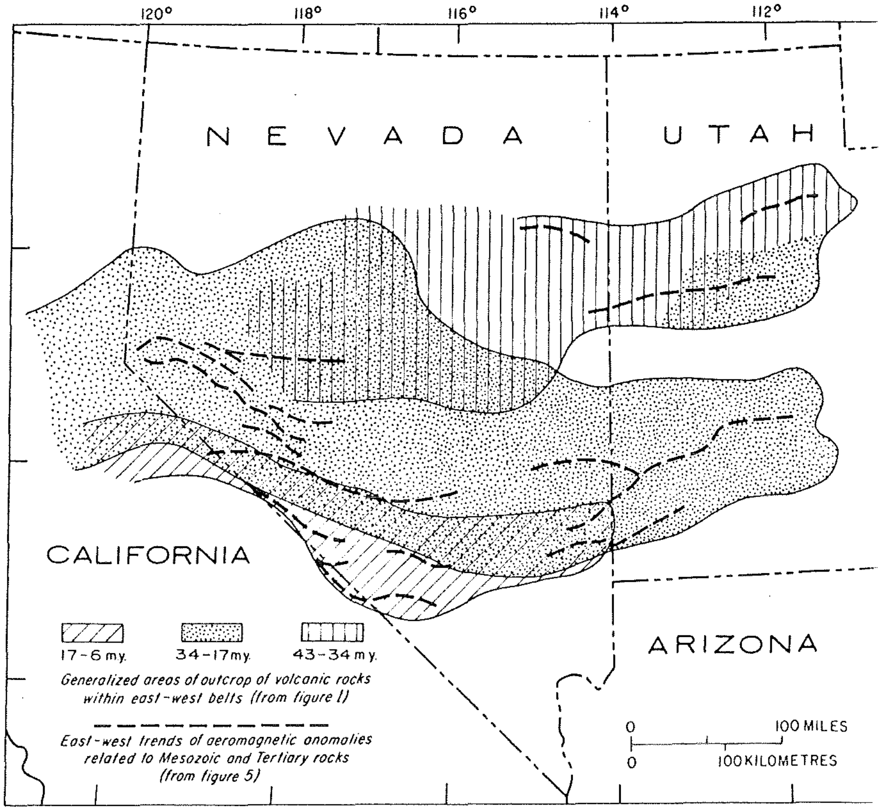


Figure 2. Generalized east-west patterns of Cenozoic igneous rocks and positive aeroma anomalies showing southward migration of igneous activity in California, Nevada, and Utah. on Figures 1 and 5.

cade belt, and most rocks there range in age from about 10 to about 16 m.y.

AEROMAGNETIC DATA

Anomalies on a regional aeromagnetic map of Nevada and Utah provide strong support for the concept of east-west volcanic patterns. As a first step in analyzing the complex pattern of magnetic anomalies in Nevada and Utah (Fig. 4), we have tried to identify the source of each of the areas of high magnetic intensity (Fig. 5) by direct comparison of the aeromagnetic map with geologic maps, by extrapolation from outcrops into the subsurface, or by study of the general character of the anomaly (compare Case and Joesting, 1972, p. 10). The magnetic source rocks are divisible into five principal categories: (1) Precambrian metamorphic rocks, (2) Mesozoic gabbroic rocks, (3) Mesozoic granitic rocks, (4) Tertiary calc-alkalic volcanic and intrusive rocks, and (5) Tertiary basalt and related rocks. Singular indentification of the magnetic source is not always possible, but the source of half of the anomalies is positively identified, the source of another quarter is identified with less certainty, and the source of the remainder (indicated with a question mark) is only tentatively identified.

An east-west pattern of aeromagnetic anomalies related to calc-alkalic volcanic rocks is clear in western Utah and eastermost Nevada (Figs. 4, 5; Mabey and others, 1964). These anomalies occur in four east-west or east-northeast zones (H–I, L–M, P–Q, T–U), two within the northern belt of calc-alkalic rocks and two within the southern belt. Calc-alkalic rocks, spatially associated with the anomalies in the northernmost zone (zone H–I), average about 35 m.y. in age; those in zone L–M, about 33 m.y.; those in zone P–Q, about 26 m.y.; and those in zone T–U, about 20 m.y. This indicates a progressive southward shift in volcanism. The magnetic zones consist of high-amplitude and short-wavelength positive anomalies superimposed on broad positive anomalies. The high-intensity anomalies have steep gradients that indicate relatively near-surface igneous rocks, whereas the gradients on the broad-wavelength anomalies suggest deeper blocks of relatively high magnetization. The eastern limit of the anomaly belts corresponds generally to the eastern limit of surface outcrops of calc-alkalic rocks, and both limits are near the boundary between the Basin and Range and Colorado Plateau provinces.

The zones of positive anomalies in western Utah and easternmost Nevada are sepa-

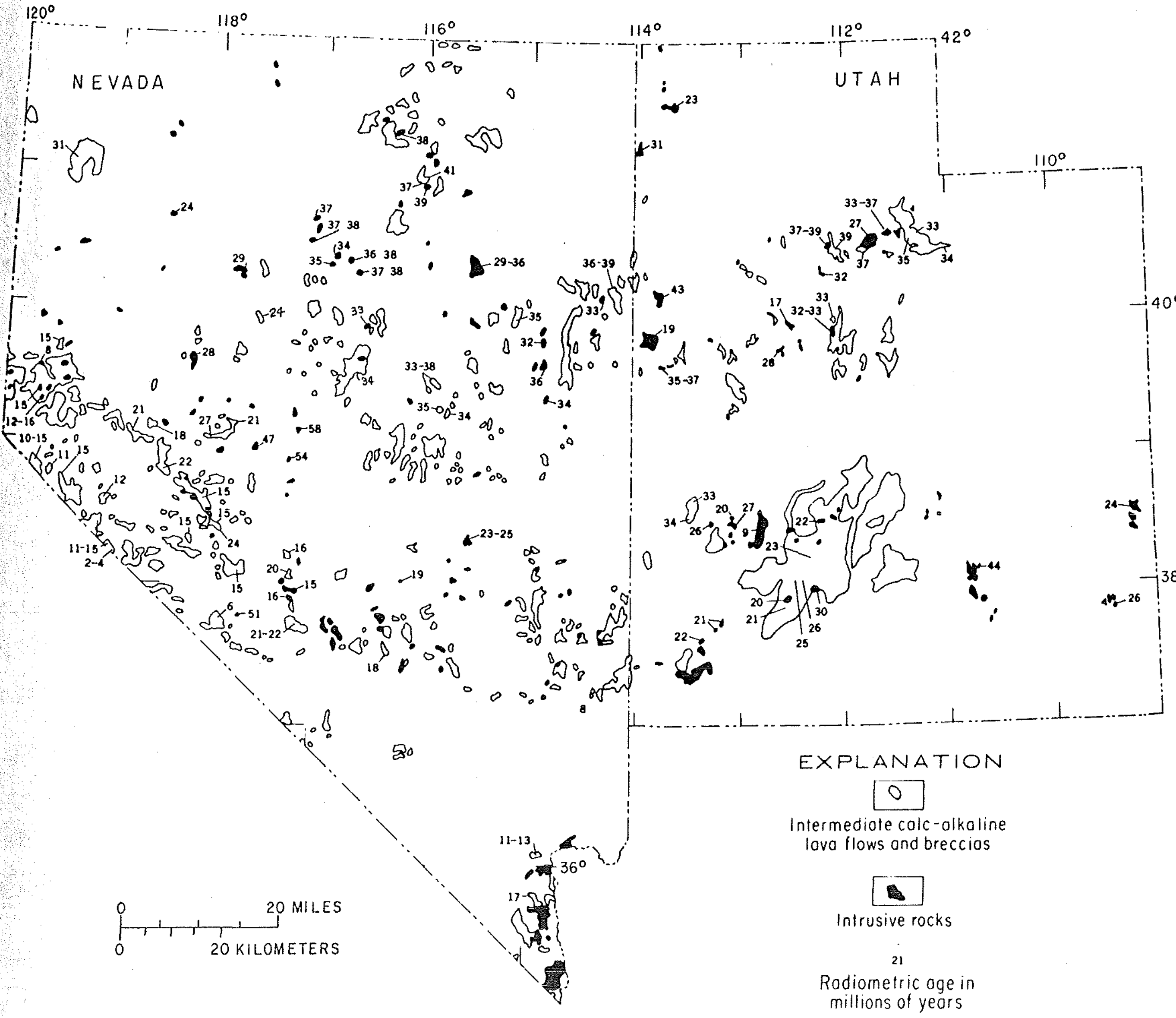


Figure 3. Distribution of Cenozoic intermediate calc-alkalic lava flows and breccias and intrusive rocks in Nevada and Utah. Compiled from Stewart and Carlson (1974), P. B. King (unpub. map), and P. D. Rowley (unpub. data). Radiometric ages from various sources, including McKee and others (1971), Silberman and McKee (1972), Marvin and others (1973), McKee and Marvin (1974), Moore (1973), Crittenden and others (1973), Lemmon and others (1973), Armstrong (1970), and Whelan (1970).

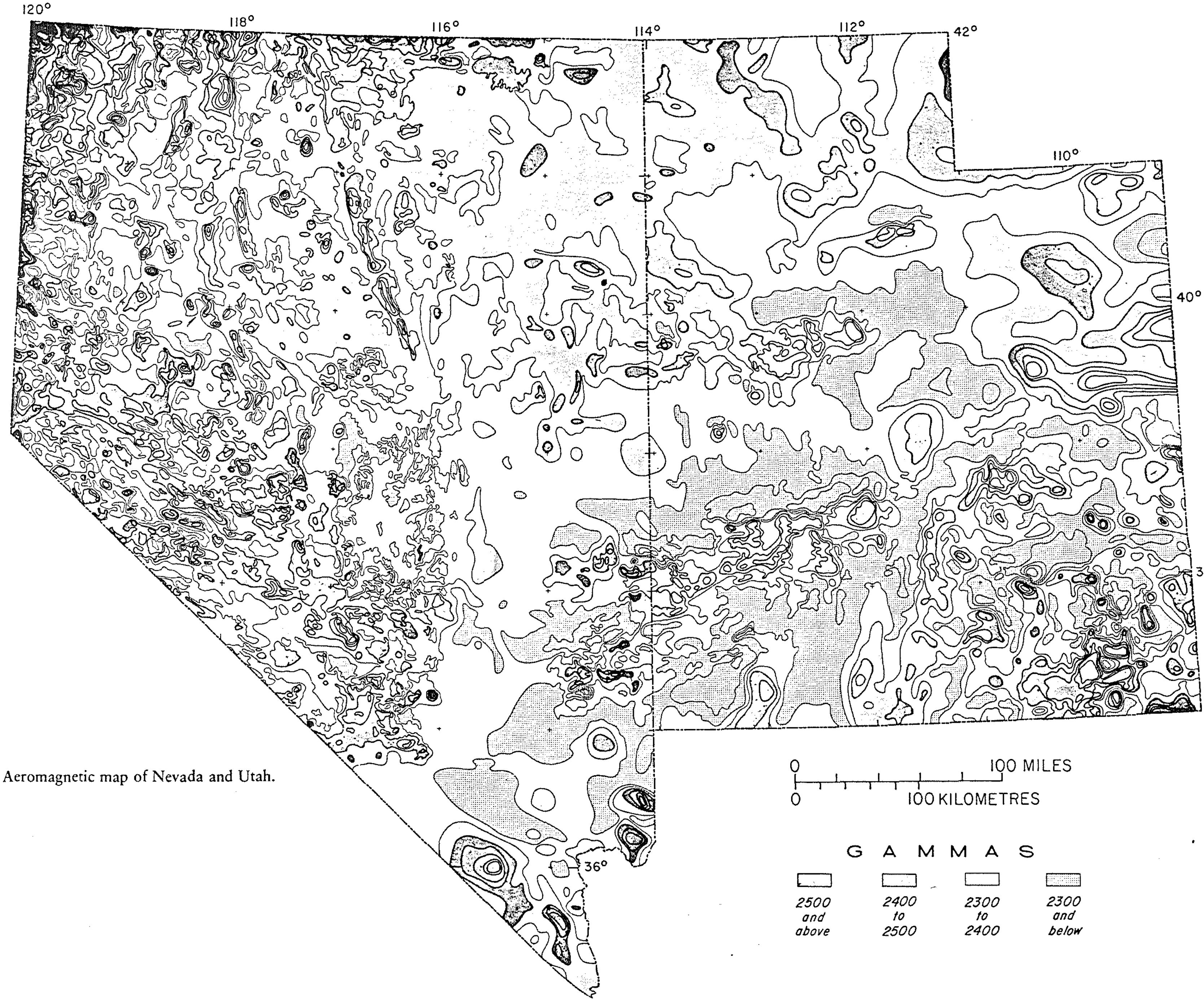


Figure 4. Aeromagnetic map of Nevada and Utah.

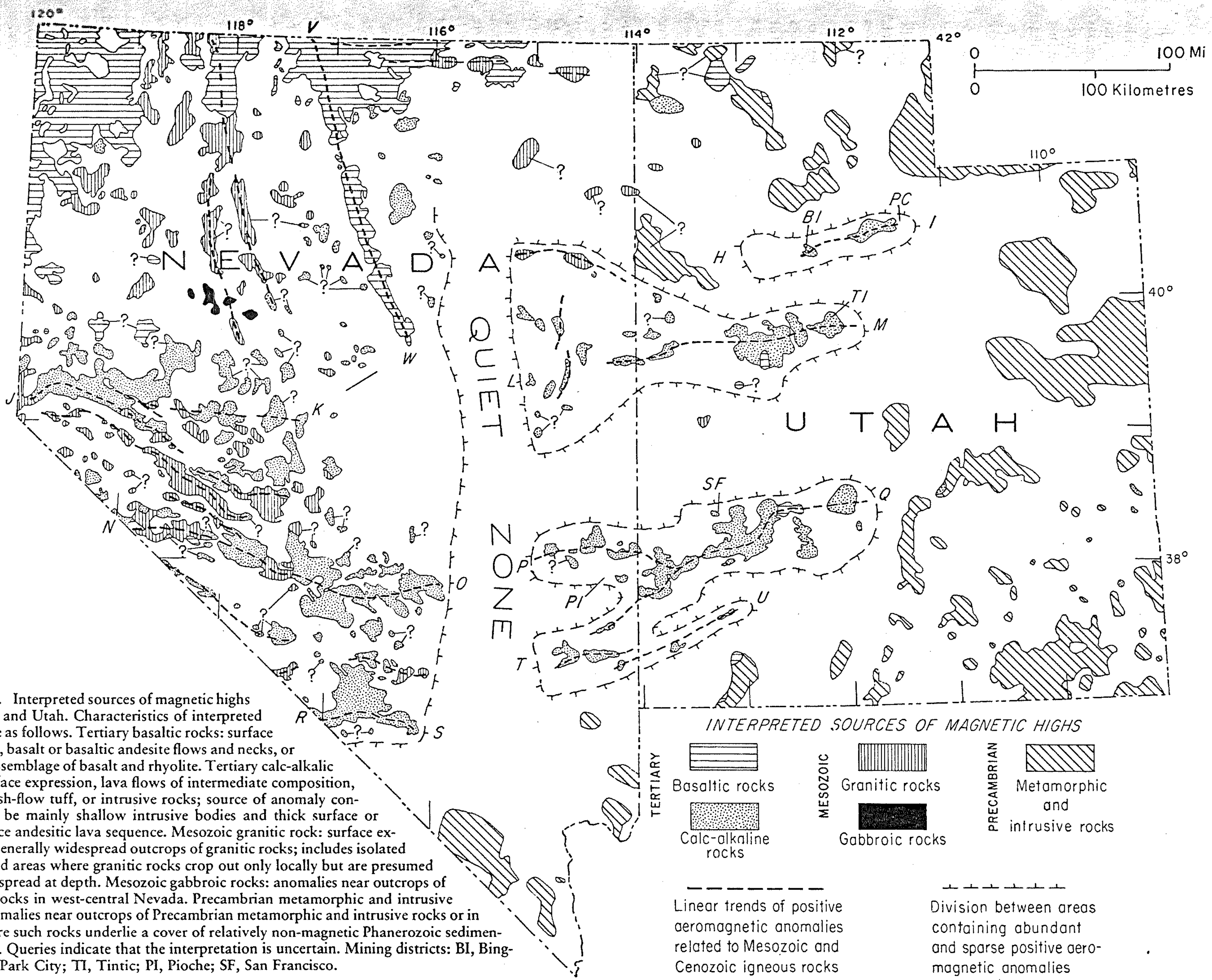


Figure 5. Interpreted sources of magnetic highs in Nevada and Utah. Characteristics of interpreted sources are as follows. Tertiary basaltic rocks: surface expression, basalt or basaltic andesite flows and necks, or bimodal assemblage of basalt and rhyolite. Tertiary calc-alkalic rocks: surface expression, lava flows of intermediate composition, siliceous ash-flow tuff, or intrusive rocks; source of anomaly considered to be mainly shallow intrusive bodies and thick surface or near-surface andesitic lava sequence. Mesozoic granitic rock: surface expression, generally widespread outcrops of granitic rocks; includes isolated plutons and areas where granitic rocks crop out only locally but are presumed to be widespread at depth. Mesozoic gabbroic rocks: anomalies near outcrops of gabbroic rocks in west-central Nevada. Precambrian metamorphic and intrusive rocks: anomalies near outcrops of Precambrian metamorphic and intrusive rocks or in areas where such rocks underlie a cover of relatively non-magnetic Phanerozoic sedimentary rocks. Queries indicate that the interpretation is uncertain. Mining districts: BI, Bingham; PC, Park City; TI, Tintic; PI, Pioche; SF, San Francisco.

rated by zones of broad-wavelength magnetic lows that contain few steep-gradient, short-wavelength anomalies. Few calc-alkalic rocks crop out in these zones of broad magnetic lows.

A north-south–oriented zone of low magnetic intensity and generally low magnetic relief extends through Nevada near long 115°W (Fig. 5). This zone appears to cut off the conspicuous east-trending aeromagnetic anomalies of western Utah and eastern Nevada. The cause of this "quiet zone" is not obvious. Its trend is parallel to and located in a thick part of the Paleozoic Cordilleran miogeosynclinal belt (Stewart and Poole, 1974, Figs. 10, 11, 12, 13), but such a spatial correlation is difficult to relate to the lack of high-intensity magnetic anomalies. In addition, it contains fairly abundant outcrops of intermediate calc-alkalic volcanic rocks (Fig. 3), which in most other areas appear to cause high-intensity positive aeromagnetic anomalies. On the other hand, some decrease in the amount of volcanic activity in the quiet zone appears to have occurred in the past 17 m.y. For example, outcrops of tuff are sparse (QZ, Fig. 1C) where the north-south quiet zone crosses the east-west trend of the 17- to 6-m.y.-old belt of tuff (E–F, Fig. 1C) that extends across southern Nevada. In addition, no outcrops of rocks younger than 6 m.y. (Fig. 1D) occur in the area of the quiet zone.

Nonetheless, the volcanic and intrusive rocks that are widespread in the quiet zone (Figs. 1A, 1B, 3) do not produce high-relief magnetic anomalies. Perhaps few large buried intrusive bodies occur in the quiet zone, even though the surface extent of volcanic rocks is great. Such buried bodies appear to produce many of the large anomalies in Utah (Moore, 1973; Mabey and others, 1964), and their absence in the quiet zone could account for the lack of high-intensity aeromagnetic anomalies. If so, then the lack of volcanism in the quiet zone could be related in some way to crustal structure along a trend parellel to the Cordilleran geosyncline.

A more likely interpretation is that the quiet zone is related to high heat flow and the resulting shallow depth of the Curie temperature. The occurrence of igneous rocks within the zone and their relatively low aeromagnetic intensity, yet with moderate magnetic relief in a few areas, suggests the possibility that high heat has caused the destruction of the magnetization of the lower parts of igneous bodies. The quiet zone corresponds to an area where the low-velocity zone in the upper mantle is unusually thick (York and Helmberger, 1973), and such thick low-velocity layers are generally attributed to high temperature and partial melting of upwelling material in an area of crustal spreading (Scholz and others, 1971; York and Helmberger, 1973; Thompson and Burke, 1974). If so, then spreading along this north-south trend was sufficient to cause high temperature in the crust, but it did not lead to volcanic activity spatially related to the quiet zone.

G. P. Eaton (1976, oral commun.) has noted that regional topography and gravity anomalies in the Basin and Range province in the Great Basin are bilaterally symmetrical about an axial ridge lying between long 115° and 116°W and that the quiet zone lies along this axis of symmetry. This relation suggests that the quiet zone is located along a medial zone of mantle upwelling in the Basin and Range province.

Extensive magnetic anomalies related to calc-alkalic rocks occur in Nevada west of the quiet zone. Several zones of anomalies appear to be elongate east and west and to coincide with the east-west aeromagnetic trends of western Utah and easternmost Nevada; anomaly JK is approximately on line with anomaly LM, NO with PQ, and RS with TU (Fig. 5). Intermediate calc-alkalic rocks related to these east-trending aeromagnetic anomalies, however, are considerably younger in westernmost Nevada than in central and eastern Nevada and western Utah (Fig. 3). Other high-intensity anomalies in western Nevada are related to Mesozoic granitic rocks and upper Cenozoic basaltic rocks. The most conspicuous of the anomalies related to Cenozic basaltic rocks is along a north-northwest zone (V–W, Fig. 5) in northern Nevada (Stewart and others, 1975).

In southern Nevada and southwestern Utah, other geophysical data also indicate an east-west tectonic trend spatially related to the volcanic belts described in this report. Bouguer gravity contours have a distinct east-west pattern near lat 37°N in Nevada and Utah, with lower gravity to the north (Woollard and Joesting, 1964; Diment and others, 1961; Eaton, 1975) that corresponds in part to regional changes in altitude. The east-west trend of these contours is evident (Diment and others, 1961) when anomalies caused by low-density alluvium in valleys are eliminated. The east-west pattern of gravity contours occurs along the south boundary of the volcanic belts (Fig. 2) and may reflect, in part, an abundance of low-density volcanic material in the region of the east-west belts.

An east-northeast–trending seismic zone, cutting across the grain of Basin and Range faults, extends across southwestern Utah and part of southern Nevada (Smith and Sbar, 1974). In Utah this zone follows approximately along the south boundary of the tuff province shown in Figure 1B, whereas in southern Nevada it follows approximately along the trend of the east-west belt of tuff shown in Figure 1C. As indicated by Thompson and Burke (1974), the present seismicity of the Basin and Range province is a misleading guide to the long-term pattern of faulting in the region, because late Cenozoic faulting occurs across the entire region and not just in presently active seismic zones. Nevert less, the localization of present-day ear quakes along a restricted zone that c across the grain of Basin and Range faults very likely controlled by tectonic featu predating Basin and Range faulting a possibly related to structures th influenced the east-west volcanic belts.

MINERAL DEPOSITS

Precious- and base-metal deposits Nevada and Utah consist of vein, dissen nated, and replacement ore bodies a sociated largely with Cretaceous grani rocks and Tertiary intrusive and volca rocks. Two major metallogenic provin are recognized, a western one characteri largely by precious-metal, tungsten, m cury, and antimony deposits and an easte one characterized by base-metal depos (Roberts and others, 1971, p. 17). T boundary between these two provin (Fig. 6) trends generally north or nor northeast and corresponds roughly major Paleozoic Cordilleran geosyncli trends (Roberts and others, 1971, p. 1 The orientations of the metal provin boundary and the quiet zone are simila but the metal province boundary lies gen ally 100 km west of the western bounda of the quiet zone.

East of the boundary between the tw metallogenic provinces, precious- a base-metal deposits occur predominantly two broad, east- to northeast-trendi groups. These two groups are best defin in Utah and easternmost Nevada, whe they are separated by an area (The "m Utah gap" of Jerome and Cook, 1967) th is devoid of significant deposits and that h few Tertiary igneous rocks exposed.

The northern group of precious- a base-metal deposits in easternmost Neva and western Utah includes the Oquirr Uinta and Deep Creek–Tintic mineral be (Hilpert and Roberts, 1964). Major mine deposits in both these belts in the northe group (Bingham, Park City, Tintic) are lated to middle-Tertiary intrusive rock Both belts are located along broad ea trending, aeromagnetic highs (Figs. 4, 5).

Another group of mineral deposits (Wah Wah–Tushar belt of Hilpert a Roberts, 1964) is recognized south of t "mid-Utah gap" and includes the San Fra cisco and Pioche mining districts. Th group also closely corresponds to a bro aeromagnetic high and an east-west belt Tertiary intrusive rocks.

In Nevada, the distribution and age pa tern of mineral deposits are much mo complex. Many of the mineral deposits western Nevada, and some in easte Nevada, are related to Mesozoic intrusi rocks. The Comstock, Tonopah, a Goldfield deposits, nonetheless, are of Te tiary age and are spatially related to andesi volcanic rocks. The Tonopah and Goldfie

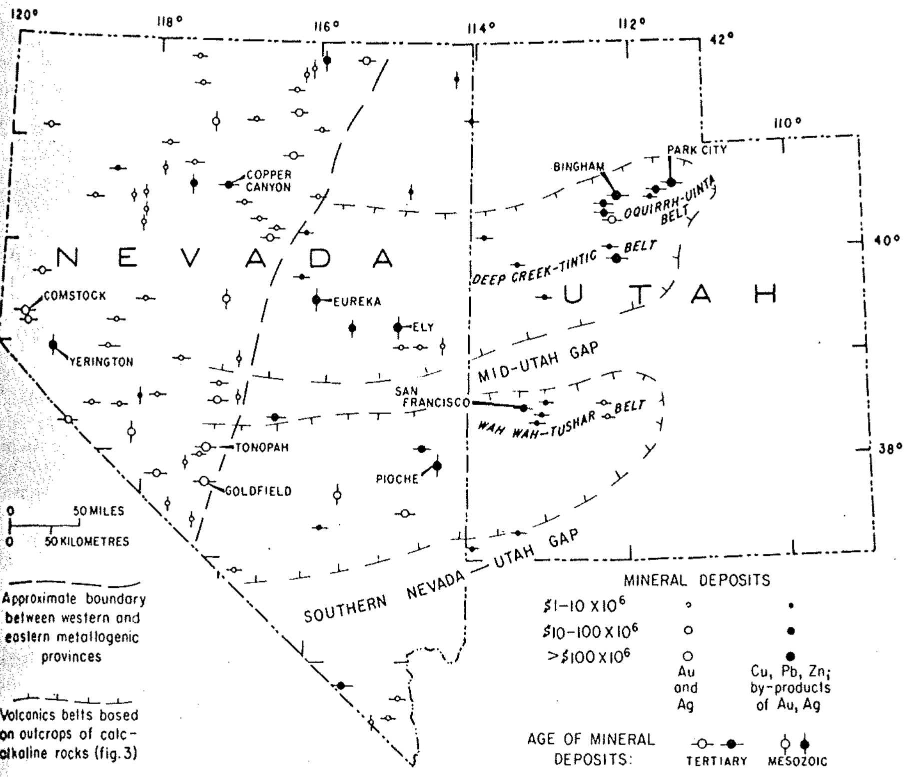


Figure 6. Distribution of precious- and base-metal deposits in Nevada and Utah with total production over $1 million. Based on Mardirosian (1974a, 1974b). Ages of mineral deposits after Silberman and McKee (1974), Silberman and others (1976), and other sources. Ages of deposits are in part interpretative.

deposits lie at the west end of the southern belt of calc-alkalic volcanic rocks. The andesitic host rocks for these mineral deposits are the same age as some andesitic rocks associated with mineral deposits in southern Utah. These relations suggest the possibility that the Goldfield and Tonopah deposits and those in the Wah Wah–Tushar belt of Utah may all be related to the same type and age of volcanism along an east-west structural trend.

Mineral deposits are not obviously related to the northern belt of Tertiary calc-alkalic volcanism in Nevada. The Ely, Eureka, Yerington, and other deposits within the belt are of Mesozoic age (Jerome and Cook, 1967; M. L. Silberman, 1975, oral commun.). Some, however, such as the Copper Canyon and Comstock deposits, are of Tertiary age. If all ages of deposits are considered, a vast amount of mineral wealth is included within the area of the northern calc-alkalic belt or in areas on line with it to the west. We recognize that the evaluation of mineral belts is highly subjective and that the alignment of these deposits may be coincidental (compare Noble, 1970). In addition, some of these deposits occur in the western metallogenic province and some in the eastern one. On the other hand, the possible alignment of deposits may indicate a major zone of crustal weakness that controlled the location of major east-trending intrusive and mineral-forming events in Mesozoic as well as Tertiary time. The following observations support this view: (1) The Yerington deposit is one of several deposits that occur within a well-defined east-west zone of faults and small intrusions that can be traced for nearly 45 km (Bingler, 1971, 1974, oral commun.). (2) The Ely deposit is clearly related to a narrow Cretaceous pluton that extends for about 9.5 km in an east-west direction (Jerome and Cook, 1967, Pl. 23). (3) The Oquirrh-Uinta mineral belt in Utah lies along the Cortez-Uinta axis (Roberts and others, 1965), which is a major zone of disruption of Paleozoic lithologic and thickness trends that may be related to structural weakness along the axis of a deep late Precambrian sedimentary trough (Stewart and Poole, 1974). (4) The "grain" of aeromagnetic anomalies in western Nevada is generally west-northwest or westerly. These relations suggest that the distribution of some ore deposits in Nevada and Utah may be related to deep-seated structural zones in basement rocks.

INTERPRETATIONS

The east-west volcanic patterns of igneous activity in Nevada and Utah are not easy to relate to generally accepted plate tectonic models for western North America. In the plate tectonic models, a subduction zone lay along the western margin of North America during most of middle Tertiary time (Atwater, 1970; Lipman and others, 1972). If this is so, then volcanic belts might be expected to be parallel to the Pacific margin of the continent rather than perpendicular to it.

One explanation within the framework of plate tectonic models relates the east-west patterns to a major southward-propagating transverse discontinuity in the subducting plate. Carr and others (1973; 1974) noted possible transverse discontinuities (faultlike breaks) in the subducting plate under Japan and Central America; they also noted clusters or lines of volcanoes transverse to the arc over the suggested discontinuities. The transverse belts in Nevada and adjacent states, however, are much more extensive than those in Japan or Central America.

As an alternative to the idea of a transverse discontinuity, P. W. Lipman (1975, oral commun.) has suggested that the volcanic activity might be localized along an east-west structural warp in the subducting plate, where the dip of the plate changes abruptly from steep on the north to gentle on the south. Such a relation is suggested by the general pattern of volcanism throughout western North America. A southward migration of volcanism, of which the volcanic front described in this report is a part, has been described for much of the western United States (Lipman and others, 1972; Armstrong and Higgins, 1973). The volcanism along the leading edge of the southward migrating front occurs in extensive east-west belts, whereas volcanism north of the front is restricted to a narrow zone (Cascade trend) parallel to the Pacific margin. Little volcanism occurs south of the front. Lipman suggested that the sparsity of volcanism south of the front is due to a gently dipping subducting plate, the restricted volcanism north of the front to a steeply dipping plate, and the east-west transverse belt of volcanism to localization along a warped surface between the gently and steeply dipping parts of the plate. Such a concept is supported in part by data from the Andes Mountains of South America, where intense volcanism occurs in areas where the subduction plate dips steeply and little volcanism occurs in areas where the plate dips gently (Stauder, 1973; Divisão de Geologia e Mineralogia, 1964). No east-west belts of volcanic rock comparable in size to those in Nevada and Utah occur in the Andes Mountains, however.

The cessation of major volcanic activity along east-west trends about 6 m.y. ago in southern Nevada and eastern California appears to be closely tied to late Cenozoic plate motions. As outlined by Atwater (1970) and Atwater and Molnar (1973), a subduction zone existed along the western margin of North America until about 29 m.y. ago, when the East Pacific Rise intersected North America. As a consequence of this plate geometry, a triple junction was formed, and it migrated northward. A subduction zone existed along western North America to the north of the triple junction, but none existed in the region of transform faulting to the south. About 4.5 to 10 m.y. ago, the triple junction lay directly west of southern Nevada, and the southern edge of the subducting plate probably extended inland from the triple junction and passed under southern Nevada. If the warp in the subducting plate, as proposed by Lipman, migrated southward to the point where it reached the south edge of the subducting plate, volcanic activity along the east-west trends should have ceased. The correspondence between the predicted time that subduction ceased under southern Nevada and the known time of cessation of volcanism there support this concept.

In places, crustal structures may have localized east-west volcanic activity. This possibility is suggested by the alignment of igneous rocks and mineral deposits 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), perhaps in response to a zone of structural weakness developed in Precambrian time. No other east-west mineral and volcanic belts in Nevada and Utah, however, can be related to known pre-Tertiary tectonic features. Most likely, pre-Tertiary structural zones have locally influenced the position of volcanic activity, but larger scale factors (such as a warp in the subducting plate) have controlled the regional pattern.

The east-west outcrop belts of Cenozoic igneous rocks in Nevada and Utah (Figs. 1, 2) are similar in shape, size, and orientation to the belt of upper Cenozoic volcanic rocks extending along the Snake River Plain in southern Idaho into the Yellowstone region of northwestern Wyoming. The time of inception of volcanic activity in the Snake River Plain and the Yellowstone region is progressively younger northeastward during the past 15 m.y. (Armstrong and others, 1975), suggesting to some geologists (Suppe and others, 1975) that the Snake River Plain–Yellowstone belt is the trace of a mantle plume. Others (Eaton and others, 1975) related the volcanism to a major crustal fracture that propagated northeastward guided by structures in Precambrian rocks. We know of no evidence that suggests progressively younger ages eastward along the volcanic belts in Nevada and Utah, and thus, we do not believe that the Nevada and Utah belts are traces of mantle plumes. The Nevada and Utah belts and the Snake River Plain–Yellowstone belt may be similar in that they locally follow trends of older structures, but otherwise they seem unrelated. The Nevada and Utah belts, for example, appear to have formed mainly along the leading edge of a southward-migrating front of volcanism, whereas, the Snake River Plain–Yellowstone belt is related to eastward-migrating volcanic foci.

In western Nevada and easternmost California, outcrop belts of volcanic rocks and trends of aeromagnetic anomalies are arcuate or slightly sigmoidal (Fig. 2). These patterns occur in a northwest-trending zone along the northern part of the Walker Lane, a zone of tectonic distortion characterized by oroflexural bending and right-lateral displacement (Albers, 1967; Stewart and others, 1968). The timing of right-lateral movement along the Walker Lane is imperfectly understood; some major movement may be as old as Jurassic (Albers, 1967) and some as young as late Cenozoic (Fleck, 1970; Ekren and others, 1968; Anderson and others, 1972). If the movement is primarily Mesozoic, the curving and sigmoidal patterns of volcanic rocks and aeromagnetic anomalies may be related to the eruption of Cenozoic igneous rocks along pre-existing curving structures in older rocks. If, on the other hand, the movement along the Walker Lane is primarily late Cenozoic, the curving and sigmoidal patterns may be due to right-lateral tectonic distortion of trends that were originally more nearly east-west.

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