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Curie Temperature Isotherm Analysis and Tectonic Implications of Aeromagnetic Data From Nevada

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Estimates of the depth to the Curie temperature isotherm in Nevada are in accordance with other regional geologic and geophysical information and together can be explained in the context of present-day tectonism. A method to estimate the depth extent of magnetic sources from the statistical properties of magnetic anomalies was applied to a statewide compilation of aeromagnetic data from Nevada. Basal depths of magnetic sources show no apparent correlation with the so-called magnetic quiet zone, which trends northerly through the eastern part of the state, or with basin-and-range topography. However, certain correlations with published heat flow measurements are apparent and suggest that undulations in basal depth of magnetic sources are related in part to undulations in the Curie temperature isotherm. For example, an area of shallow basal depth (< 10 km) near Battle Mountain corresponds to an area of exceptionally high conductive heat flow and indicates a shallow depth to the Curie temperature isotherm in this region. A narrow zone of shallow basal depth extends south from the Battle Mountain area along the 118°W meridian to at least latitude 38°N, which also is a zone of historic surface offsets and high-magnitude earthquakes. The correspondence along the 118° meridian of shallow basal depth, high heat flow, high lower crustal seismic velocities, attenuated *P* and *S* wave arrivals, historic faulting, and large earthquakes suggests that they each are related to an active north trending spreading zone in this part of the Basin and Range province.

INTRODUCTION

During the last few decades, magnetic data acquired by aircraft have proven useful for extrapolating the location of magnetic rocks from outcrops to covered areas, for defining the shape of subsurface lithotectonic features, and for interpolating subsurface geologic information between more widely spaced geophysical measurements such as seismic reflection and refraction profiles. In this paper we examine a new compilation of magnetic data from the state of Nevada and relate it to other regional geologic, topographic, and geophysical information. In particular, the spectral properties of the magnetic field are used to infer depths to the Curie temperature isotherm in Nevada and to draw conclusions about the tectonic setting of the area.

Certain oxides and sulfides of iron, such as magnetite and pyrrhotite, possess a spontaneous magnetization at room temperature that is manifested in rocks as remanent magnetization and ferrimagnetic susceptibility. Above the Curie temperature (approximately 580°C for magnetite at atmospheric pressure), spontaneous magnetization vanishes, and these minerals exhibit paramagnetic susceptibility. Because paramagnetism is a small effect compared to spontaneous magnetization, rocks are essentially nonmagnetic at temperatures greater than the Curie temperature of the most important magnetic mineral of the rock. It should be possible therefore to estimate the depth and configuration of the Curie temperature isotherm from subtle characteristics of magnetic anomalies if magnetic lithologies exist at these depths.

Estimates of the depth to the Curie temperature should be treated with caution for both mathematical and geologic reasons. First, these estimates are inverse calculations and encompass all of the nonuniqueness and mathematical instabilities inherent in such methods. These calculations are especially difficult because estimates of Curie temperature depth attempt to define the nature of deep crustal sources that produce generally low-amplitude and long-wavelength magnetic anomalies compared to shallower sources. Second, techniques to estimate depth to the Curie temperature actually estimate the basal depth of magnetic sources. A surface that describes basal depths, however, may not be an isothermal surface because rock magnetic properties, and the Curie temperature, in particular, may vary from place to place due to lithologic or mineralogic changes.

With these caveats in mind, a Fourier domain technique was applied to the compilation of aeromagnetic data from Nevada in order to estimate the basal depth of magnetic sources in this region. The method uses the statistical properties of groups of magnetic anomalies within overlapping rectangular cells. The regional scope of the magnetic compilation allowed the state to be divided into numerous cells and permited an investigation of lateral variation of basal depth throughout the state. The estimates of basal depth show interesting comparisons with heat flow measurements, earthquake activity, recent faulting, and seismic data that are interpreted in terms of extensional tectonics of the Basin and Range geologic province.

GEOLOGICAL AND GEOPHYSICAL SETTING

The state of Nevada lies within the Basin and Range geologic province (Figure 1), which is characterized by approximately east-west extension, widespread volcanism, regionally elevated topography, thin crust, low upper mantle velocity, and high heat flow. As summarized by *Zoback et al.* [1981], modern topography and extensional tectonism of the Basin and Range reflect only a late stage episode in a more complicated history related to interaction between the Pacific, Farallon, and North American plates. An episode of continental rifting during the late Precambrian left a passive continental margin and a westward thickening wedge of shelf deposits along western North America [*Stewart*, 1972]. As inferred

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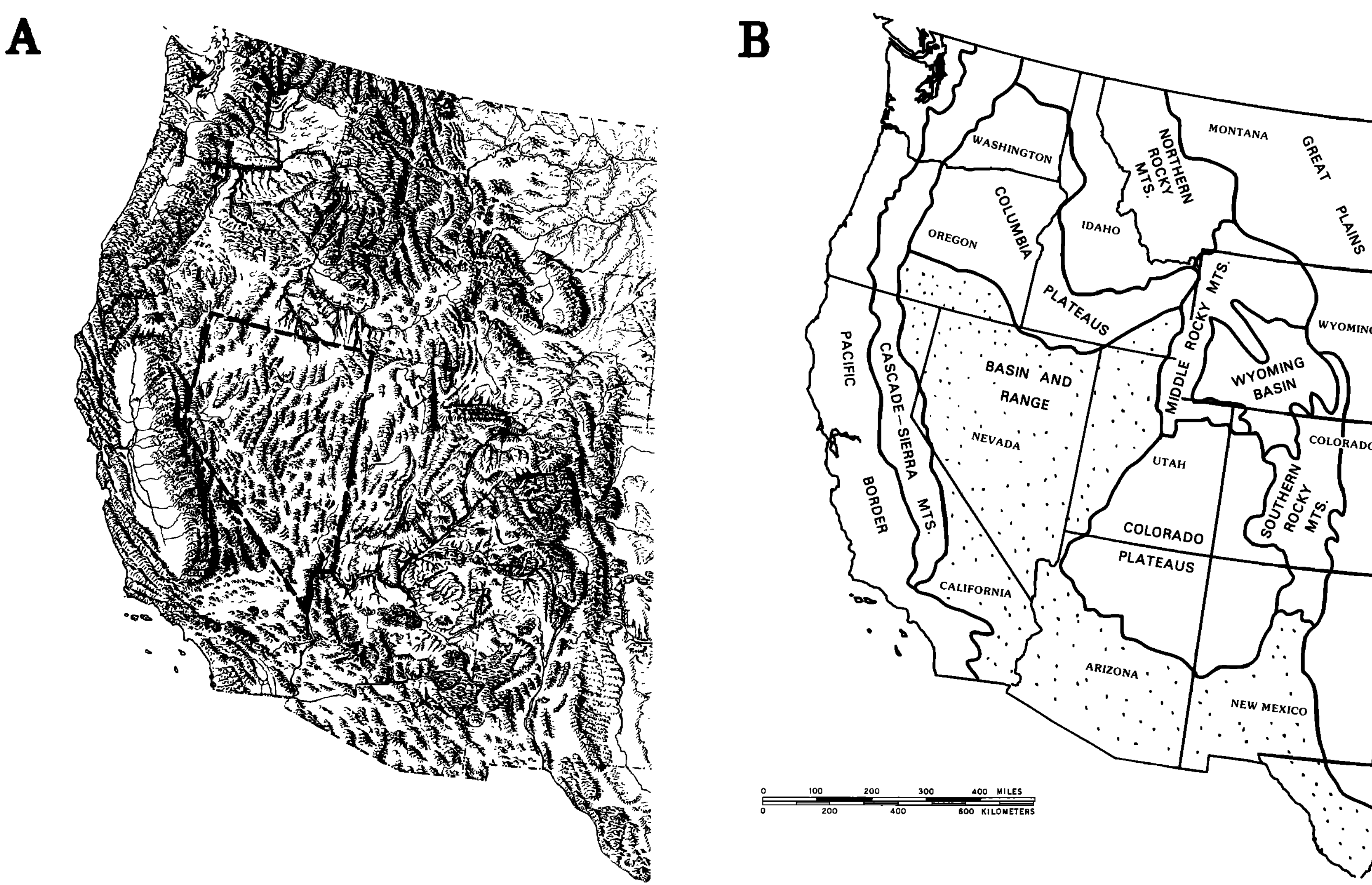


Fig. 1. (*a*) Physiographic map of the western United States. (*b*) Physiographic divisions of the western United States. Both maps from *U.S. Geological Survey* [1968].

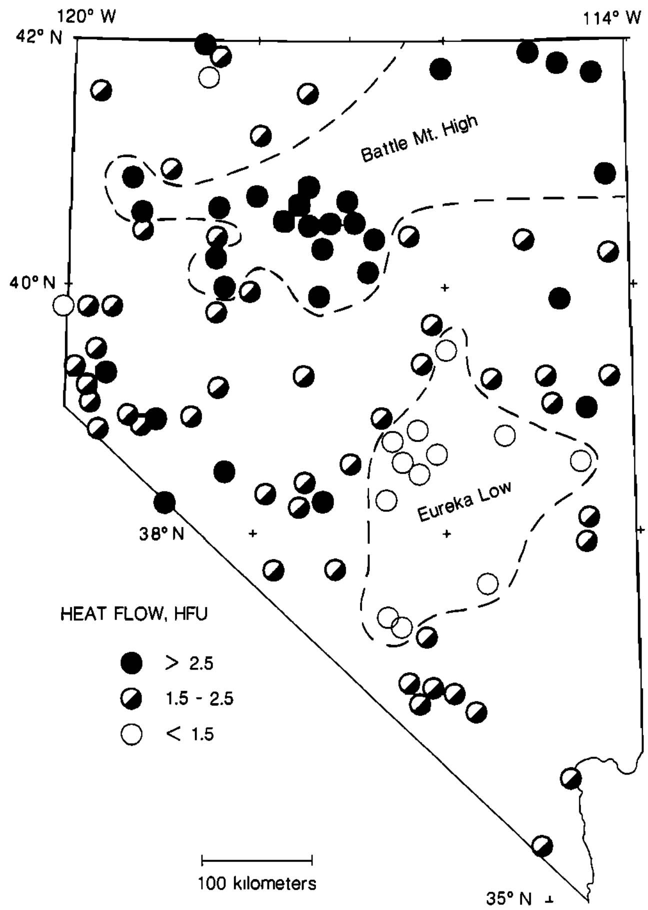


Fig. 2. Heat flow measurements from the state of Nevada [from *Lachenbruch and Sass*, 1978].

from isotopic studies [*Kistler*, 1974; *Farmer and DePaolo*, 1983], the western margin of the Precambrian continent is believed to lie in central Nevada. During late Paleozoic and Mesozoic time, several arc-related compressional orogenies moved arc-derived sedimentary sequences hundreds of kilometers eastward over coeval miogeosynclinal deposits. The Antler orogeny, for example, produced the Roberts Mountain thrust in central Nevada and was the dominant compressional event during the Paleozoic [*Stewart*, 1980]. From the Late Cretaceous into the early Tertiary, the western United States was under compression due to low-angle subduction of the Farallon plate [*Coney*, 1976; *Dickinson and Synder*, 1978] approximately perpendicular to the northwest trending subduction zone [*Evernden and Kistler*, 1970]. The Laramide deformation, largely nonmagmatic, occurred during this time and extended 1200–1500 km inland. Between 40 and 20 Ma, convergence-related extensional stress and a broad magmatic arc developed east of the trench [*Lipman et al.*, 1972; *McKee*, 1971], perhaps due to a transition from low-angle to high-angle subduction of the Farallon plate [*Eaton*, 1979], and by 20 Ma, the northern Basin and Range was a well-developed back arc environment with widespread calc-alkaline magmatism and least principal stress oriented WSW-ENE [*Christiansen and McKee*, 1978; *Zoback and Thompson*, 1978]. About 30 Ma, the spreading center between the Pacific and Farallon plates reached the trench and thereby initiated the San Andreas transform boundary [*Atwater*, 1970]. Dextral shear along the growing San Andreas fault caused the least principle stress direction in the northern Basin and Range to rotate 45° clockwise to its modern direction of WNW-ESE [*Zoback and Thompson*, 1978], but this rotation probably did not occur until 10 Ma, perhaps in response to an acceleration in relative motion between the North American and Pacific plates [*Atwater and Molnar*, 1973].

Heat flow measurements from the western United States are shown in Figure 2 [*Lachenbruch and Sass*, 1978]. Nearly all heat flow measurements from Nevada exceed the continental average (≈ 1.5 HFU) and indicate near-melting temperatures in the lower crust and upper mantle [e.g., *Roy et al.*, 1972]. Certain regions, notably the so-called "Battle Mountain high," have extraordinarily high values in excess of 2.5 HFU. *Lachenbruch and Sass* [1978] proposed that the generally high heat flow in the Basin and Range is related to lithospheric extension rather than to anomalous conductive transfer of heat from the asthenosphere. Lithospheric extension is accommodated in their model by addition of basalt to the lithosphere, either by intrusion of dikes or by basaltic underplating. Their model predicts that regions of anomalously high heat flow may also be regions of rapid extension and consequent intrusion or underplating. The Battle Mountain heat flow anomaly, for example, may indicate that this region is undergoing rapid extension and basaltic intrusion in the lower crust [*Sass et al.*, 1971; *Lachenbruch and Sass*, 1978]. The "Eureka low" (Figure 2) is a region of unusually low heat flow (compared to the Basin and Range average) that may be due to near-surface hydrologic effects [*Sass et al.*, 1971].

Earthquakes within the Basin and Range are manifestations of pervasive crustal stress caused by oblique relative motion between the Pacific and North American plates [*Atwater*, 1970; *Zoback and Zoback*, 1980*b*]. Epicenters are shallow (<20 km) and generally confined to diffuse seismic zones [*Eddington et al.*, 1988L. The most notable zone within the Basin and Range province is the Intermountain seismic belt, a 150-km-wide zone of shallow earthquakes that trends north-south through central Utah, eastern Idaho, and western Montana [*Smith and Sbar*, 1974; *Eddington et al.*, 1988]. The southern end of the Intermountain seismic zone bends west through Nevada at about latitude 37°N. A second zone of earthquakes in Nevada trends north-south along longitude 118°W and includes the locations of the Dixie Valley (mangitude 7.1) and Fairview Park (magnitude 6.8) earthquakes of 1954 [*Thompson*, 1985].

The significance of the 118° meridian seismic zone is illustrated in Figure 3 [*Ryall et al.*, 1966], which shows the location of historic offsets and epicenters for earthquakes of greater than about magnitude 7 in the western United States. Within the entire Basin and Range province, nearly all of these offsets and epicenters are located along the 118° meridian seismic zone; they extend from Dixie Valley at the north to at least the California boarder and possibly to latitude 36°N. *Thompson and Burke* [1974] pointed out that the northern terminus of the 118° meridian seismic zone is within the Battle Mountain heat flow anomaly and proposed that seismic activity, recent faulting, and high heat flow are all related to present-day extension along this zone.

REGIONAL MAGNETIC FEATURES

Aeromagnetic data from Nevada were compiled recently by *Hildenbrand and Kucks* [1988] and are shown in Plate 1. The

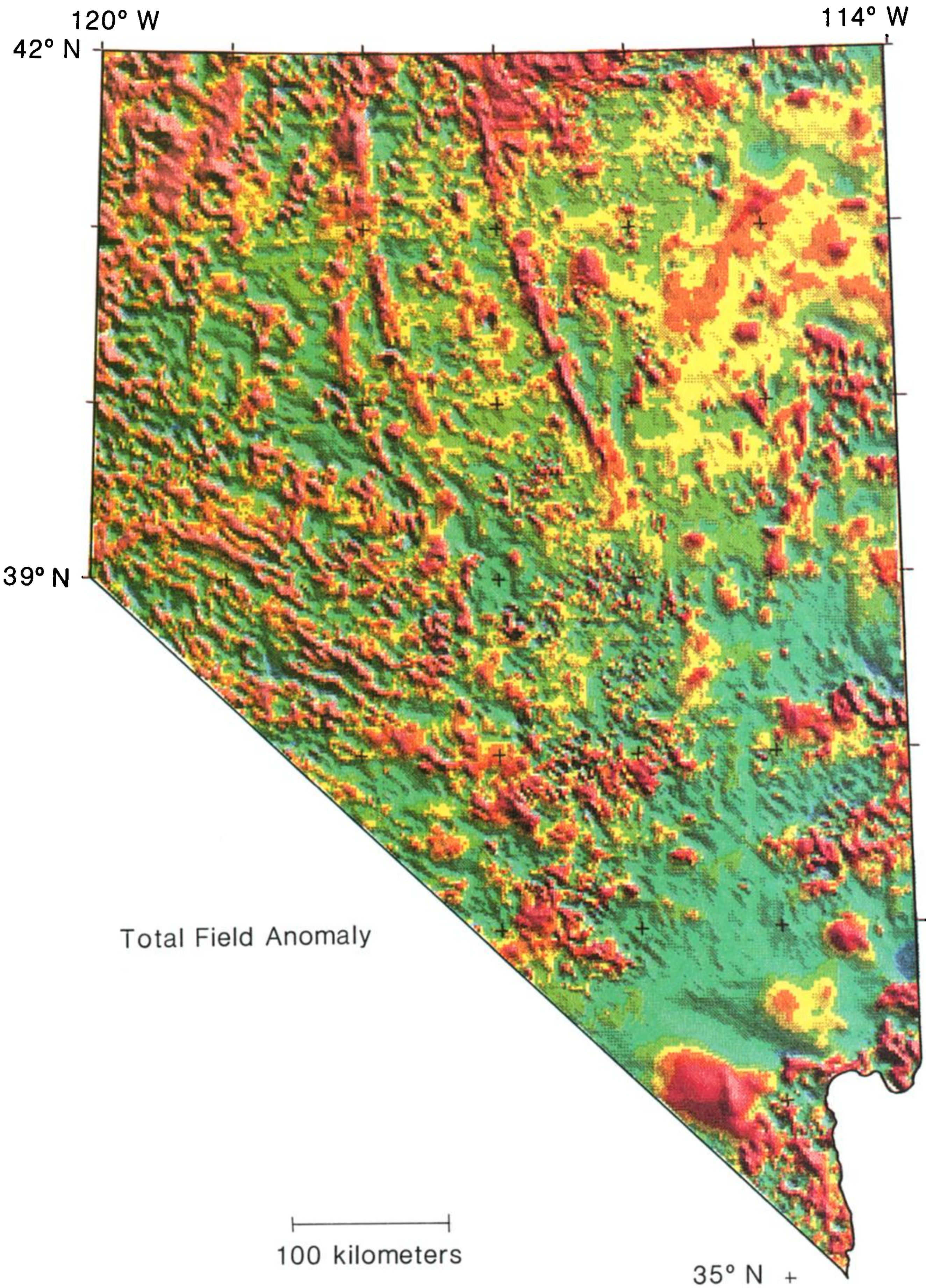


Plate 1. Color shaded-relief map showing total field anomalies from Nevada analytically continued to 305 m above terrain. Modified from the compilation by *Kucks and Hildenbrand* [1987]. Color-contour intervals variable; illumination from the northeast. Note: Grid spacing of this figure is 2 km; grid spacing of original compilation and for all computations described in text is 1 km.

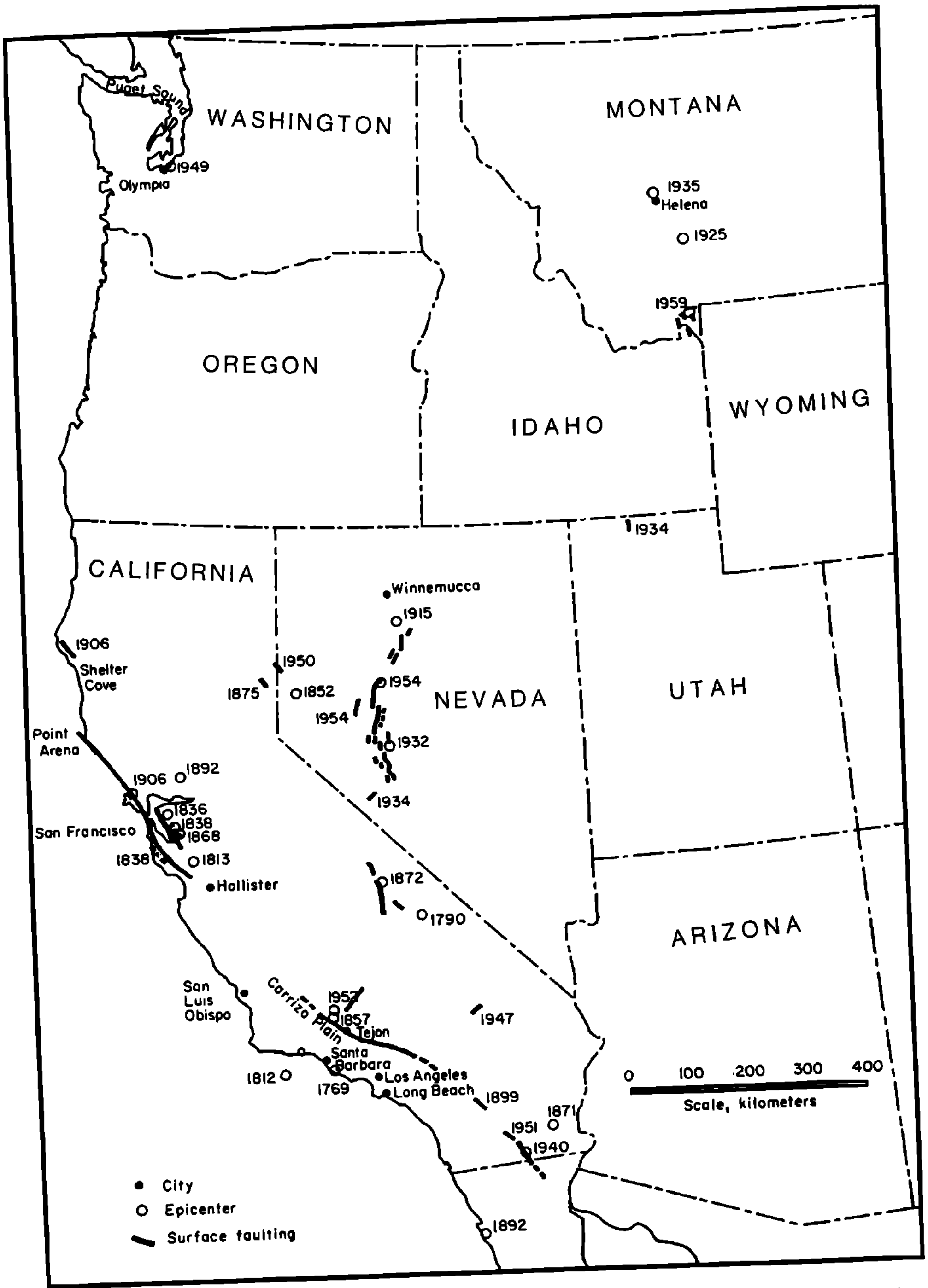


Fig. 3. Historic fault breaks and epicenters of earthquakes with magnitude greater than about seven, western United States [from *Ryall et al.*, 1966].

compilation is composed of 38 separate surveys. Technical specifications of each survey depend on its original purpose and on the type of terrain surveyed. Flight line spacings range from 400 to 4800 m, and flight elevations vary from 4600 m constant barometric altitude to 122 m above terrain. To produce the compilation shown in Plate 1, *Hildenbrand and Kucks* [1988] subtracted the appropriate International Geomagnetic Reference Field (IGRF) from each suvey, analytically continued each survey to a common horizontal surface, meshed the surveys together using newly developed techniques, interpolated the compilation to a rectangular grid with 1-km sample interval, and analytically continued the compilation to a surface 305 m above terrain [*Kucks and Hildenbrand*, 1987].

Locations of contacts between magnetic and less magnetic rocks were calculated from the aeromagnetic compilation and are shown in Figure 4. These boundaries were derived by transforming the magnetic data to pseudogravity anomalies and then calculating the magnitude of maximum horizontal gradients. *Cordell and Grauch* [1985] have shown that this two-step procedure transforms magnetic anomalies into maxima that approximately overlie edges of causative bodies. An algorithm described by *Blakely and Simpson* [1986] was then used to locate the maxima of the horizontal gradient;

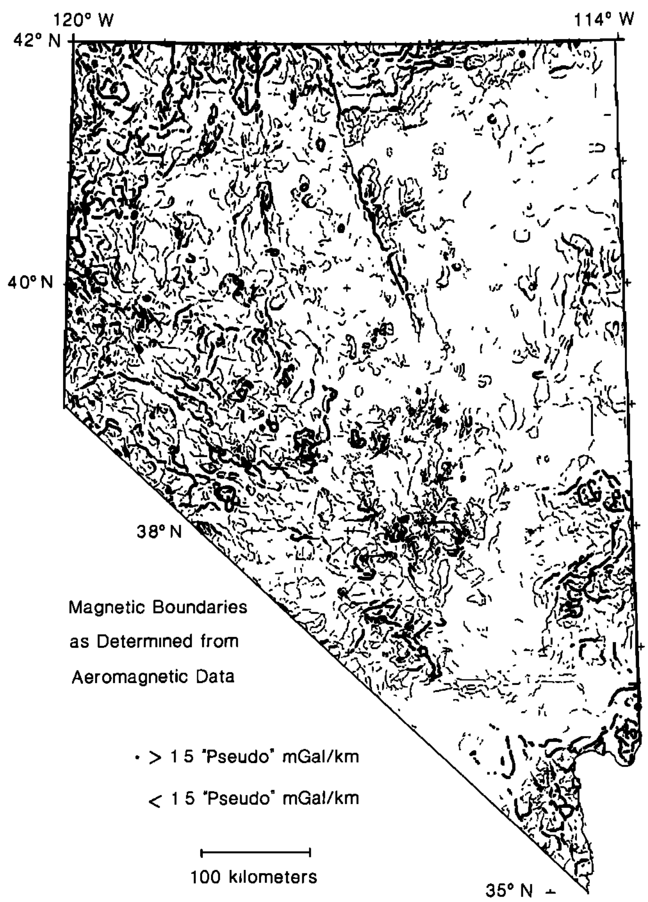


Fig. 4. Apparent magnetization contrasts calculated from the magnetic compilation using the method of *Cordell and Grauch* [1985] and *Blakely and Simpson* [1986]. Individual points indicate maxima in the horizontal gradient of pseudogravity anomalies. Chains of points are inferred magnetization contrasts.

these maxima are shown in Figure 4 and tend to lie along sinuous lines that indicate edges of inferred magnetic sources.

The details of Plate 1 and Figure 4 and their geologic and tectonic implications are well beyond the scope of this paper. Here we review only some of the more regional features of these data with reference to the location map shown in Figure 5.

Magnetic Quiet Zone

A north trending zone in the eastern part of Nevada is characterized by a general lack of short-wavelength magnetic anomalies and, consequently, is known as the magnetic "quiet zone" (Figure 5). The quiet zone is represented clearly in Figure 4 by a lack of apparent magnetization contrasts. Numerous authors have explained the absence of short-wavelength magnetic anomalies in the quiet zone by a relatively shallow Curie temperature isotherm [e.g., *Zietz et al.*, 1970; *Stewart et al.*, 1977; *Mabey et al.*, 1978; *Thompson and Burke*, 1974; *Christiansen and McKee*, 1978]. This conclusion is incorrect. A crustal section with an unusually shallow Curie temperature isotherm will be missing deep magnetic sources beneath the isotherm, whereas shallow sources will be unaffected. Deep magnetic sources generally influence the long- rather than the short-wavelength attributes of magnetic anomalies. Consequently, the lack of short-wavelength anomalies in the quiet zone cannot be explained by a simple shallowing of the Curie temperature isotherm.

Figure 6 demonstrates this point. Figure 6*a* shows a part of the Nevada aeromagnetic map. We describe the source of these anomalies by a distribution of magnetization $M(x, y)$ that varies only in the horizontal directions and extends uniformly between depths z_t and z_b ($z_t < z_b$). A simple filter transforms these anomalies into anomalies that would be caused by the same $M(x, y)$ extending to a different depth z_b'. In the Fourier domain this filter is given by

$$F(k_x, k_y) = \frac{1 - e^{-k(z_b' - z_t)}}{1 - e^{-k(z_b - z_t)}}$$

where

$$k = (k_x{}^2 + k_y{}^2)^{1/2}$$

and where k_x and k_y are wave numbers in the x and y directions, respectively, and are related to wavelengths λ_x and λ_y according to

$$k_x = 2\pi/\lambda_x$$
$$k_y = 2\pi/\lambda_y$$

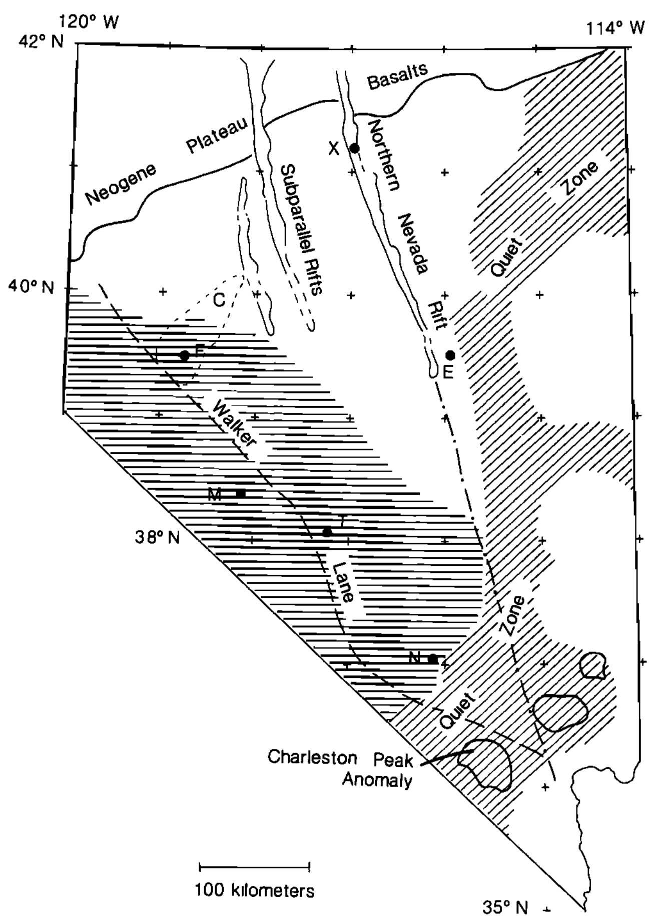


Fig. 5. Location of magnetic, geologic, and tectonic features interpreted from the magnetic compilation and other geophysical information. Dashed line indicates approximate location of the Walker Lane lineament, as described by *Albers* [1967], whereas horizontal line pattern indicates magnetic patterns related to the Walker Lane. Dashed-dotted line indicates continuation of northern Nevada rift based on isostatic residual gravity anomalies. Single letters denote place names referred to in text: T, Tonopah; N, Nevada Test Site; F, Fallon; E, Eureka; M, Mina; C, boundary of Carson Sink; X, Midas trough.

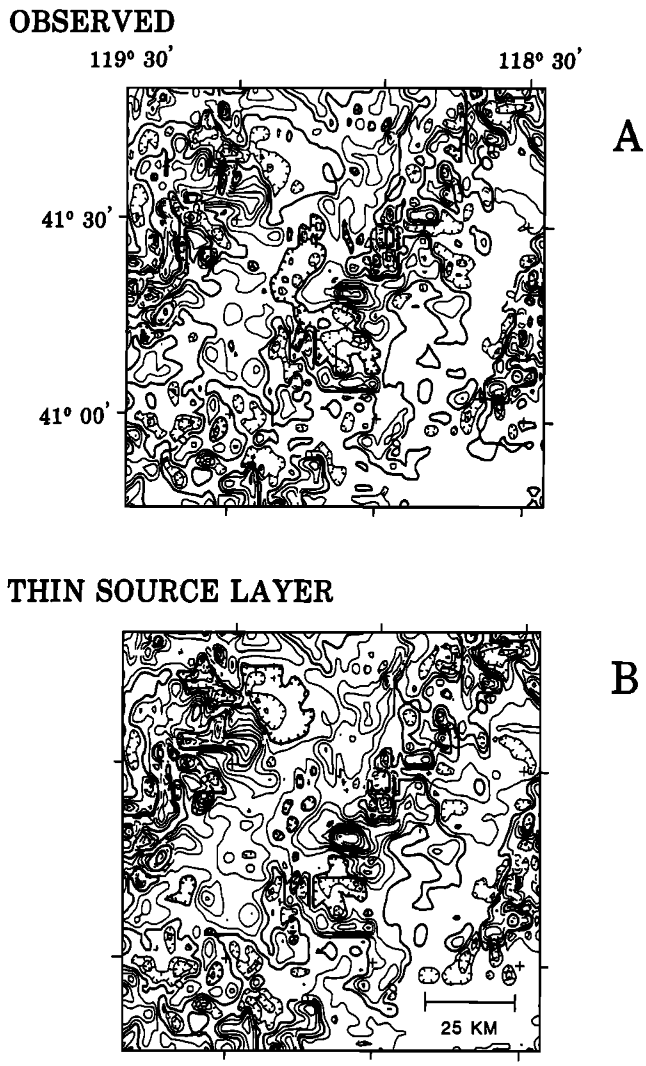


Fig. 6. The effect of a shallow Curie temperature isotherm on magnetic anomalies. (*a*) Subregion of the magnetic compilation show in Figure 3. (*b*) The magnetic anomalies of Figure 6*a* after Curie temperature isotherm rises from 25 to 5 km. Contour interval 100 nT.

This filter was applied to the anomalies shown in Figure 6*a* assuming $z_b = 25$ km and $z_b' = 5$ km, and the results are shown in Figure 6*b*. In other words, Figure 6*b* shows how the anomalies in Figure 6*a* would appear if the depth to the Curie temperature isotherm were to rise from 25 to 5 km. The similarity in short-wavelength information between Figures 6*a* and 6*b* demonstrates that a shallow Curie temperature isotherm does not dramatically affect the visual pattern of magnetic anomalies; i.e., moving the isotherm from a depth of 25 km to a depth of 5 km has not created a "quiet zone."

Although anomalies due to shallow surces are scarce in the quiet zone, anomalies due to deep sources are evident. For example, a metamorphic core complex of latest Precambrian and Paleozoic age underlies the Ruby Mountains (latitude 41°, longitude 115°) [*Stewart and Carlson*, 177; *Stewart*, 1980] and produces an anomaly with broad gradients, which suggest that these rocks have deep magnetic counterparts. *Grauch et al.* [1988] carefully studied the statewide compilation of aeromagnetic data and identified numerous anomalies related to inferred plutons and mapped granitic rocks. Many anomalies were identified within the quiet zone, but these typically have longer wavelengths and broader gradients than elsewhere in Nevada, again indicative of deep magnetic components.

Figure 7 shows the magnetic compilation (Plate 1) continued upward to 5 and 10 km higher. Upward continuation is a filtering operation that attenuates anomalies caused by shallow sources and thereby emphasizes anomalies due to deeper sources. The upward continued maps show numerous magnetic anomalies within and across the boundaries of the quiet zone. This suggests that deep magnetic sources occur within the quiet zone contrary to what would be expected if the Curie temperature were anomalously shallow in this region.

Consequently, an alternative cause must be found for the lack of short-wavelength anomalies in the Nevada quiet zone. *Stewart et al.* [1977] concluded that most aeromagnetic anomalies throughout Nevada are caused by four general rock types: Precambrian metamorphic rocks, Mesozoic granitic and gabbroic rocks, Tertiary calc-alkaline volcanic and intrusive rocks, and Tertiary basaltic rocks. A transition from dominantly andesitic and rhyolitic volcanism to dominantly basaltic volcanism occurred at about 17 Ma [*McKee et al.*, 1970; *McKee*, 1971]. *Stewart et al.* [1977] pointed out that exposures of volcanic rocks younger than 17 Ma are less abundant within the quiet zone than without, and this lack of volcanic activity since 17 Ma certainly must contribute to the lack of short-wavelength magnetic anomalies in this region. However, outcrops of calc-alkaline rocks do occur within the quiet zone but appear insufficiently magnetic in most cases to cause significant magnetic anomalies [*Stewart et al.*, 1977].

Eaton et al. [1978] proposed that intense hydrothermal alteration has diminished the magnetic properties of these rocks. Alternatively, igneous rocks within the quiet zone may be less magnetic simply because they initially crystallized with less magnetite. *Miller and Bradfish* [1980] described an inland belt of muscovite-bearing plutons located along the inferred edge of the Precambrian continent. They pointed out that these granitic plutons are similar in many respects to S-type granites, granites with probable sedimentary sources, rather than I-type granites with igneous sources [*Chappell and White*, 1974]. As discussed by *Ellwood and Wenner* [1981] and *Criss and Champion* [1984], S-type and I-type granites often can be distinguished by their opaque mineralogy and thereby classified according to the scheme of *Ishihara* [1977]: S-type granites tend to be ilmenite-bearing and I-type granites tend to be magnetite-bearing. Ilmenite-bearing granites have low magnetic susceptibilities and remanent magnetizations relative to their magnetite-bearing counterparts [*Ishihara*, 1977; *Criss and Champion*, 1984]. Although the spatial correspondence between the belt of muscovite-bearing granites and the magnetic quiet zone is far from perfect, it is possible that granitic bodies in the upper crust are relatively nonmagnetic because of their mode of crystallization. This phenomenon may contribute to the lack of short-wavelength anomalies in this region. Perhaps the magnetic properties of volcanic rocks in the quiet zone have been affected similarly, although the author is unaware of any geochemical data to support this suggestion.

Walker Lane

A zone about 80 km wide and 480 km long straddles the southwestern border of Nevada and separates the northwest trending Sierra Nevada and the north to northeast trending topography of the Basin and Range province. The eastern boundary of the zone is a physiographic lineament called the

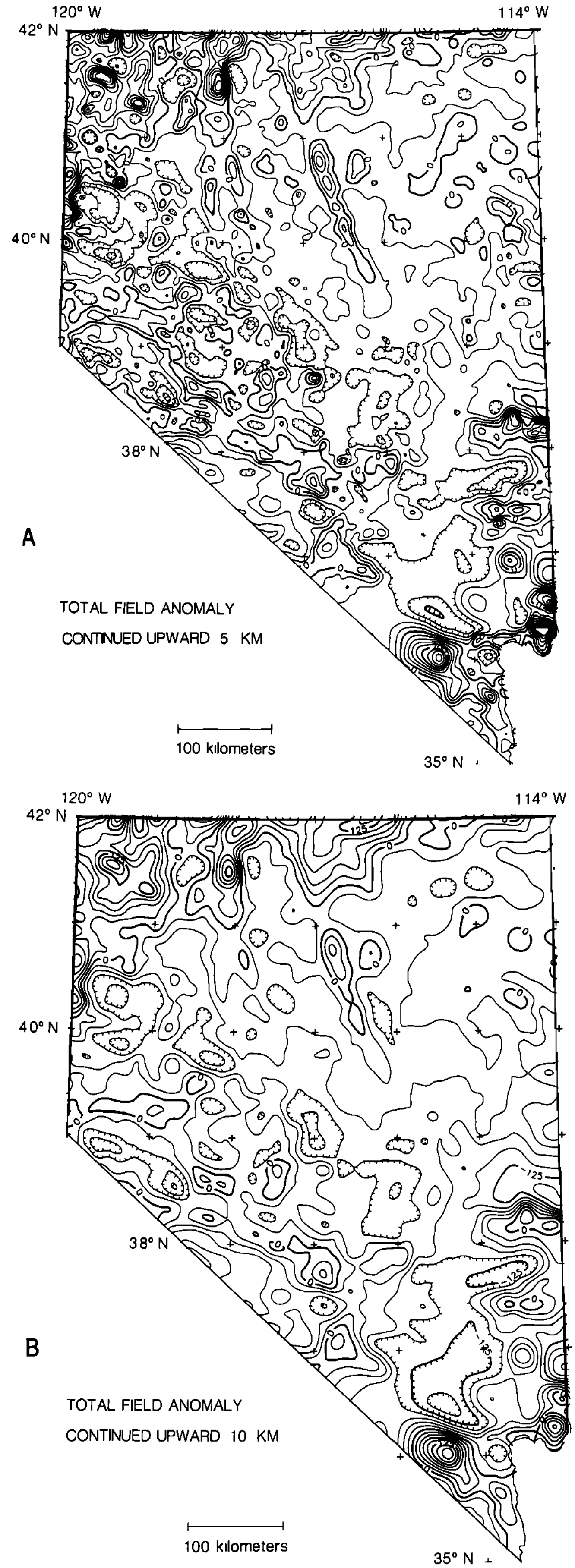


Fig. 7. Map showing magnetic compilation continued upward (*a*) 5 km and (*b*) 10 km. Contour intervals 40 and 25 nT, respectively.

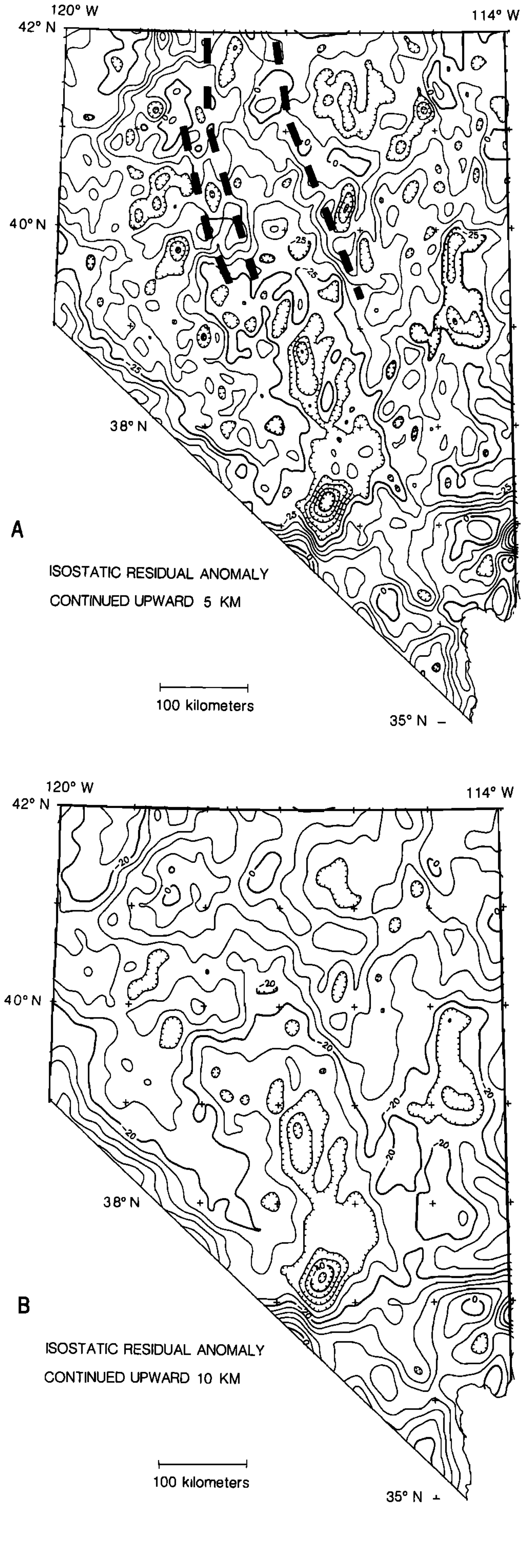
Walker Lane (Figure 5) interpreted to be a right-lateral fault analogous to the San Andreas [*Locke et al.*, 1940]. *Albers* [1967] described the entire 80-km-wide zone, which includes the Las Vegas Valley shear zone and the Death Valley–Furnace Creek fault zone, as a belt of "gigantic dextral drag" accommodated by clockwise oroflexural bending, right-lateral slippage, and total displacements of 130–190 km [*Stewart et al.*, 1968]. *Geissman et al.* [1984], however, have questioned the existence of significant oroflexural bending. They used paleomagnetic measurements from plutons and remagnetized metasedimentary rocks from near the town of Mina (Figure 5) to show that regional clockwise rotation or dextral shear has not occurred since Late Cretaceous time. *Stewart* [1988] has suggested that the Walker Lane is composed of nine regional blocks with diverse tectonic characteristics. Tectonic activity within and between the blocks probably began in the Mesozoic and was reactivated in the Cenozoic.

Magnetic anomalies in this region have arcuate, northwesterly trends generally parallel to the Walker Lane (Plate 1 and Figure 4), and certain individual anomalies are associated with outcrops of either calc-alkaline volcanic and intrusive rocks of Tertiary age or granitic rocks of Mesozoic age with trends similar to the anomaly patterns [*Stewart et al.*, 1977]. However, other individual anomalies in this region have no obvious sources exposed at the surface. Moreover, the width of the northwest trending pattern of magnetic anomalies is considerably wider than the belt described by *Albers* [1967] and *Stewart et al.* [1968], extending in some places over 150 km northeast of the Walker Lane and into topography with north to northeast trends typical of the Basin and Range province. The magnetic anomalies may indicate an underlying tectonic fabric older than modern topography and exposed geology and perhaps related to the Precambrian breakup of North America. The presence of significant anomalies with northwest trends in the upward continued data (Figure 7) suggests that some of these anomalies are caused by deep sources and supports the position of *Albers* [1967] that the tectonism of the Walker Lane is reflected throughout the crustal section.

Northern Nevada Rift

A narrow anomaly with a north-northwest trend extends 280 km through north central Nevada (Plate 1 Figure 4). The association of parts of this anomaly with basaltic and andesitic extrusive and intrusive rocks indicates that these rocks exist along the entire length of the anomaly [*Mabey*, 1966; *Robinson*, 1970; *Stewart et al.*, 1975]. Basaltic rocks in this area are dated at 15–17 Ma [*McKee and Noble*, 1986] and are considered part of a 700-km-long rift zone active in Nevada and Oregon during the middle Miocene [*Stewart et al.*, 1975]. The rift formed in response to extension during that time [*Zoback and Thompson*, 1978], and the north-northwest trend of the anomaly is one of a variety of indications that mid-Miocene extension was directed WSW-ENE. The anomaly also is reflected in upward continued data (Figure 7), which indicates that intrusive sources extend to considerable crustal depths as proposed by various investigators [*Mabey*, 1966; *Robinson*, 1970; *Zoback and Thompson*, 1978].

The magnetic expression of the northern Nevada rift ends at about latitude 39°40′N, but gravity data indicate that the rift may extend much farther south, as noted by *Mabey et al.* [1984]. Gravitational expression of the rift is especially clear in isostatic residual anomalies because long-wavelength anom-



alies caused by deep crustal and upper mantle masses that compensate topographic loads are removed thereby emphasizing anomalies due to upper crustal sources [*Simpson et al.*, 1986]. Isostatic residual anomalies were calculated from the gravity compilation of *Saltus* [1988] using the method of *Simpson et al.* [1983]. These anomalies are shown in Figures 8*a* and 8*b* continued upward 5 and 10 km, respectively, to compare with upward continued magnetic anomalies (Figure 7) and to emphasize regional attributes of the data. North of about latitude 39°40′N, a gravitational ridge corresponds to the magnetic expression of the northern Nevada rift and probably reflects high-density intrusive rocks within the rift. South of this latitude, the rift is expressed as a gradient in the gravity anomalies. This gradient continues south nearly the full length of Nevada, which indicates that the mid-Miocene rift zone may be at least 600 km long in Nevada alone, as suggested earlier by *McKee and Noble* [1986].

Two nearly linear magnetic anomalies occur west of and subparallel to the northern Nevada rift (Figure 5). Their proximity and similarity to the anomaly over the northern Nevada rift indicate a genetic relationship between all three features and suggest that the mid-Miocene stress regime discussed by *Zoback and Thompson* [1978] was pervasive throughout northern Nevada. The subparallel magnetic anomalies also are associated with isostatic residual gravity anomalies (Figure 8), similar to the correspondence of gravity and magnetic anomalies over the northern Nevada rift. The subparallel anomalies do not continue as far to the south as either the gravity or magnetic expression of the northern Nevada rift, nor are they associated with exposures of basaltic rocks.

Charleston Peak Anomaly

A high-amplitude, isolated magnetic anomaly occurs in the southern part of the state centered at approximately latitude 36°00′N and longitude 115°30′W (Plate 1 and Figure 5). The boundary analysis (Figure 4) indicates that the source of this anomaly is roughly oval in shape and at least 60 km in width. A positive gravity anomaly occurs in the same general location (Figure 8). The magnetic anomaly overlies Charleston Peak, but the anomaly is not caused by this topographic edifice. Outcrops in the vicinity of Charleston Peak consist of relatively nonmagnetic sedimentary rocks of Precambrian to Mesozoic age [*Stewart and Carlson*, 1977]. Moreover, the broad gradients associated with the anomaly indicate that the top of the source is buried beneath relatively nonmagnetic surface rocks. *Blank* [1987] suggested that long-wavelength magnetic anomalies in southeastern Nevada are caused primarily by topographic relief of the magnetic basement, composed of either Precambrian or younger rocks. The Charleston Peak anomaly may be caused by a domal form upwarp of the basement and an associated Tertiary intrusion in this region (H. R. Blank, personal communication, 1987).

Two similar anomalies occur northeast of Charleston Peak (Figure 5), one of which is associated with significant gravity anomalies. *Blank* [1987] proposed that these two features also are caused by buried basement topography and suggested that the southwestern source is a decapitated core complex.

Fig. 8. (opposite) Map showing isostatic residual gravity anomalies for the state of Nevada, continued upward (*a*) 5 km and (*b*) 10 km. Dashed lines indicate location of northern Nevada rift and subparallel rifts based on aeromagnetic data (Plate 1 and Figures 4 and 7). Contour intervals 5 and 4 mGal, respectively.

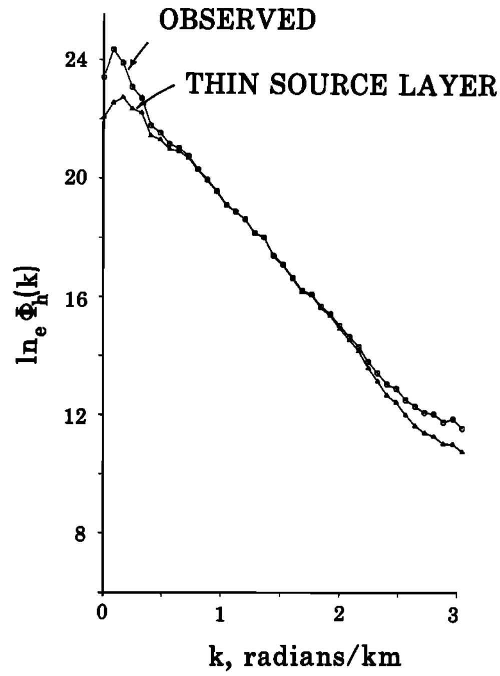


Fig. 9. One-dimensional power density spectra calculated from Figures 6*a* (observed) and 6*b* (thin source layer). Note the largest differences between the two spectra occur primarily at low wave numbers (long wavelengths).

Southern Boundary of Neogene Basalt Plateaus

An abrupt change in magnetic character occurs in the northern part of Nevada along a boundary with an east-northeast trend and regional extent (Figure 5). North of the boundary, numerous short-wavelength anomalies occur with east-northeast trends, roughly parallel to the boundary (Plate 1 and Figure 4). These probably are caused by the abundant Tertiary volcanic rocks in this region; short-wavelength anomalies with similar trends are lacking to the south (Plate 1 and Figure 4). There are several reasons to suspect, however, that the source of this boundary is more fundamental than the southern limit of volcanic topographic features. First, the boundary shows dramatically in upward continued magnetic data (Figure 7), which suggests that regional and deep-seated sources also contribute to the boundary. Second, the boundary corresponds with a physiographic depression that crosses the entire state (Figure 1; also see Figure 3 of *Zoback and Zoback* [1980*a*]) and includes the Midas trough (Figure 5) described by *Rowan and Wetlaufer* [1973]. Third, the boundary marks a small but distinctive bend in the northern Nevada rift at the Midas trough. Fourth, the boundary is on strike with high-amplitude anomalies in the southern part of the Snake River Plain.

The magnetic boundary reflects a juxtaposition of two terranes with different magnetic characters, but relative motion between the terranes, if any, must have occurred prior to the middle Miocene, the time that the northern Nevada Rift was active. The boundary crosses into the Humboldt zone, described by *Mabey et al.* [1978] on the basis of aeromagnetic, heat flow, and geologic information as a zone of crustal inhomogeneity that influenced northeastward migration of Cenozoic volcanism in the eastern Snake River Plain. *Zoback and Thompson* [1978] proposed that the Yellowstone hot spot was located at the northern Nevada rift in mid-Miocene time. Perhaps the magnetic boundary in northern Nevada is related to the existence of this hot spot during the Cenozoic.

BASAL DEPTH OF MAGNETIC SOURCES

Method

Techniques to estimate the depth to magnetic sources can be classed in two categories: those that examine the shape of isolated magnetic anomalies [e.g., *Bhattacharyya and Leu*, 1975; *Byerly and Stolt*, 1977] and those that examine statistical properties of patterns of magnetic anomalies [e.g., *Spector and Grant*, 1970; *Blakely and Hassanzadeh*, 1981; *Connard et al.*, 1983]. We concur with the conclusion of *Shuey et al.* [1977] that the latter class is more appropriate for regional compilations of magnetic anomalies. In Nevada, for example, no individual anomalies in Plate 1 are completely isolated from the effects of all other magnetic sources.

The method used here is a modification of the methods of *Smith et al.* [1974], *Boler* [1978], and *Connard et al.* [1983], which analyze the spectral information contained in subregions of the magnetic data. If magnetization $M(x, y)$ within a subregion is confined between depths z_t and z_b and has a power density spectrum given by $\Phi_M(k_z, k_y)$, then the magnetic field $h(x, y)$ has a power density spectrum given by

$$\Phi_h(k_x, k_y) = A \cdot \Phi_M(k_x, k_y)(e^{-kz_t} - e^{-kz_b})^2 \qquad (1)$$

where A is a constant that depends on the direction of magnetization and the direction of the regional field [*Blakely*, 1981]. By making certain assumptions about the statistical properties of $M(x, y)$, it is possible to calculate z_t and z_b from the observed magnetic field $h(x, y)$ using (1). The procedure involves the following steps:

1. The gridded compilation of magnetic data is divided into overlapping square subregions with dimensions W by W.
2. A two-dimensional Fourier transform is calculated for each subregion using the method of *Ricard and Blakely* [1988]. This method minimizes edge effects caused by the finite sample interval, finite horizontal dimensions, and orientation of rows and columns in gridded data.
3. Each two-dimensional Fourier transform is simplified to a one-dimensional, radial spectrum $\Phi_h(k)$ by averaging amplitude values within rings concentric about the spectral origin.
4. The shape of the one-dimensional spectra are analyzed automatically using (1) to determine an average depth to the top and bottom of magnetic sources for each subregion.

Figure 9 illustrates how the shape of Φ_h depends on z_b. It shows one-dimensional spectra calculated from the data in Figure 6*a* and 6*b* using the method described above. The differences between the two spectra are greatest at low wave numbers (long wavelengths) as expected, and these differences provide a means to distinguish and calculate an average z_b for the rectangular area using (1), as described by *Connard et al.* [1983].

Assumptions and Caveats

Estimation of depth to Curie temperature from magnetic anomalies is a risky proposition at best. The problems are both mathematical and geological. First, anomalies caused by deep magnetic sources are long in wavelength and low in amplitude relative to anomalies caused by shallower sources. This is evident in Figure 9; differences between the two spectra occur in the short wave number (long wavelength) part of the spectrum, very near the fundamental wave number ($k = 2\pi/W$) for these data, which is the smallest wave number (longest wavelength) that can be determined with conventional Fourier transform techniques. The problem is compounded because sources of long-wavelength noise are common and difficult to detect. For example, Plate 1 was compiled from 38 separate surveys. If regional fields were not removed properly from the individual surveys, wavelengths comparable to the dimensions of the surveys may be generated that are unrelated to crustal sources.

Second, all techniques to estimate basal depth of magnetic sources involve gross oversimplifications of geology. The method used here requires a high "degree of randomness" for the distribution of crustal magnetization. *Connard et al.* [1983], for example, assumed that magnetization is completely uncorrelated with itself so that its power density spectrum $\mathbf{\Phi}_M(k_x, k_y)$ is constant in (1). The degree of randomness, however, may depend on the geologic terrane. Volcanic terrane may have more variable magnetization than plutonic terrane, for example.

The completely random model of *Connard et al.* [1983] can be improved somewhat by allowing average magnetization to be constant over finite horizontal distances, and the appendix derives the power density spectrum for one possibility: The distribution of magnetization $M(x)$ consists of a series of constant levels separated by Poisson-distributed jumps. The constant value of magnetization between any two consecutive jumps also is random and described by a probability distribution. The power density spectrum of this $M(x)$ is given by

$$\mathbf{\Phi}_M(k) = \frac{\sigma^2}{\pi} \frac{\Delta}{1 + \Delta^2 k^2} \tag{2}$$

where Δ is the average horizontal distance between jumps and σ^2 is the variance of expected values of magnetization. Note that as Δ approaches zero, $\mathbf{\Phi}_M(k)$ approaches a constant, which is the limiting case used by *Connard et al.* [1983]. If Δ could be estimated for a specific geologic terrane, (2) could be used in (1) to adjust for the degree of randomness of $M(x)$. For relatively small values of Δ ($\Delta < 3$ km) and k, $\mathbf{\Phi}_M(k)$ does not greatly affect the shape of $\mathbf{\Phi}_h(k)$, and the following discussion does not incorporate the variable Δ.

Finally, even if the technique provides an accurate z_b, there is no guarantee that z_b represents the Curie temperature isotherm. First, a variety of geologic reasons exist for truncated magnetic sources that are unrelated to crustal temperatures. A young volcanic sequence atop relatively nonmagnetic sedimentary rocks, for example, will provide a z_b at the bottom of the volcanic material even though the Curie temperature may occur at greater depth. Such boundaries may limit the depth of magnetic sources regardless of temperature distributions. Second, the Curie temperature depends on magnetic mineralogy so that a Curie temperature surface may not be an isothermal surface. Titanomagnetite ($Fe_{3-x}Ti_xO_4$), for example, is the most important iron oxide in crustal magnetic sources. It has a Curie temperature that is strongly influenced by the amount of titanium in the crystal lattice, ranging from 580°C for magnetite ($x = 0$) to 250°C for $x = 0.5$ [*Stacey and Banerjee*, 1974, p. 34]. In some geologic environments, alloys of iron with Curie temperatures in excess of 620° may be significant contributors to magnetic anomalies [*Haggerty*, 1978]. However, several recent studies [*Schlinger*, 1985; *Frost and Shive*, 1986] have investigated the magnetic properties of continental rocks with deep crustal origin and have identified low-titanium titanomagnetite as the dominant magnetic phase. Curie temperatures at these depths are estimated to be 575°C [*Schlinger*, 1985] to 600°C [*Frost and Shive*, 1986].

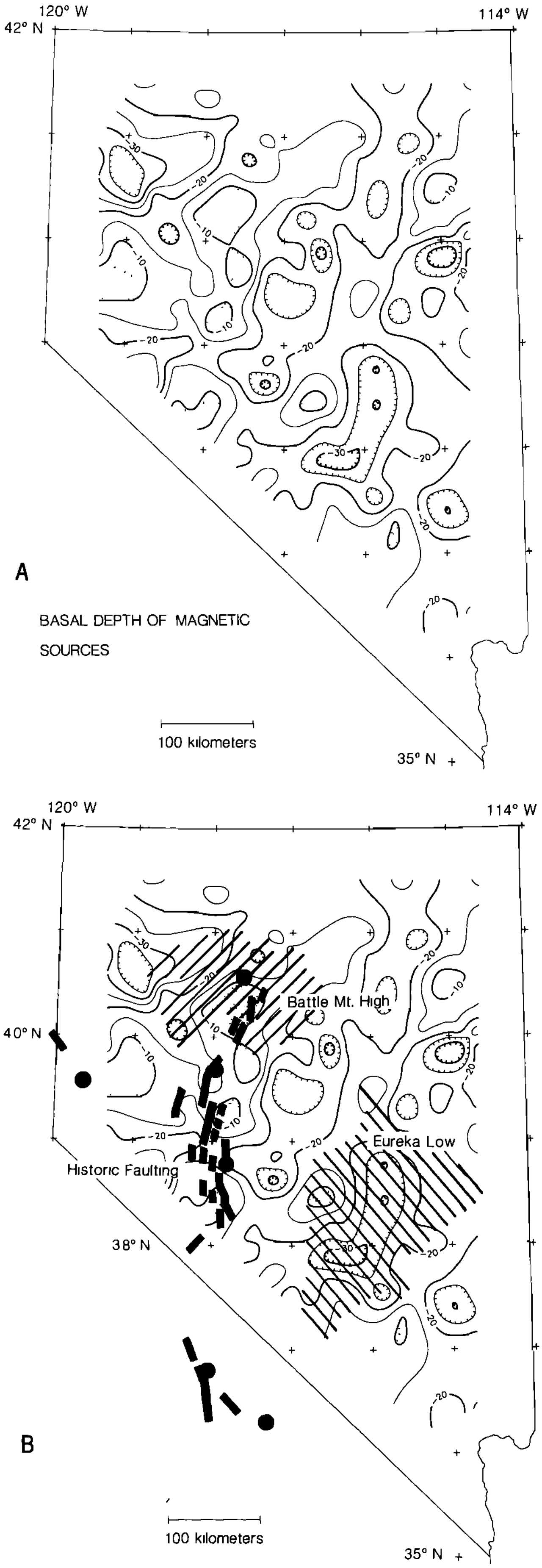
DISCUSSION

With the cautions of the previous section in mind, the Fourier domain technique was applied to the Nevada aeromagnetic data using various dimensions W for the square subregions. Basal depths of magnetic sources, estimated with $W = 120$ km, are shown in Figure 10. The surface depicted in Figure 10 undulates between depths of 30 and 5 km with wavelengths typically between 50 and 200 km. The wavelengths, however, are partially a function of the size of the subregion. Maps were also calculated using 80-km, 100-km, and 140-km subregions. Although details differ significantly between these maps, the regional features of Figure 10 (discussed subsequently) are always present. Subregions with $W < 80$ km contain insufficient data to resolve the bottom of magnetic sources.

Although the spatially continuous surface described by Figure 10 shows more variability than the discrete heat flow measurements in Figure 2, the two maps do show certain correlations that suggest that the undulations in average basal depth of magnetic sources are related in part to undulations in the Curie temperature isotherm. First, a northeast trending zone of shallow basal depth (<10 km) corresponds with exceptionally high heat flow within the Battle Mountain high and indicates a shallow depth to the Curie temperature isotherm in this region. This depth is in reasonable agreement with the depth predicted by the static lithosphere model discussed by *Lachenbruch and Sass* [1978], assuming that deep magnetic sources in this region have a Curie temperature of 580°C. Second, the basal depth of magnetic sources is predicted to be unusually deep (>25 km) in an arcuate region within the Eureka low, which suggests the presence of a depressed Curie temperature isotherm. This is an unexpected correlation if the Eureka low is caused by near-surface hydrologic phenomena as postulated by *Sass et al.* [1971]. The hydrologic effects would have to have persisted at this locality for an unreasonably long period of time in order to affect temperatures at the crustal depths implied by Figure 10.

The range of estimates found for Nevada is consistent in a general way with other estimates of Curie temperature depth from the western United States. *Byerly and Stolt* [1977] examined regional magnetic data from Arizona and found highly variable Curie temperature depths. Estimates averaged approximately 20 km for most of the state, but relatively shallow depths (≈10 km) were found within a 60-km-wide, east-west zone. *Shuey et al.* [1973] found generally shallow (≈15 km) Curie temperature depths for the eastern Basin and Range province in Utah and northern Arizona. *Shuey et al.* [1977] reported various values from smaller areas including Yellowstone National Park (7–17 km), southcentral Utah (16–20 km), and the Uinta Basin (15–31 km). *Connard et al.* [1983] used a method similar to the one described here to investigate Curie temperature depths in the Cascade Range in central Oregon. Depth estimates were found to be as shallow as 6 km, consistent with high heat flow, silicic volcanism, and geothermal manifestations of the area.

Of particular interest in Figure 10*a* is the zone of shallow



Curie temperatures that extends south from the Battle Mountain heat flow anomaly near longitude 118°W to at least latitude 38°N. This zone of shallow Curie temperatures corresponds approximately with the 118° meridian seismic zone (Figure 10*b*). *Thompson and Burke* [1974] pointed out that the Battle Mountain heat flow anomaly is on the northern projection of this active zone of historic faulting and suggested that intrusion of dikes may accompany the spreading of graben structures in this area. *Eddington et al.* [1988] suggested that buoyant uplift and ascension of magmas accompany lithospheric extension along the 118° meridian seismic zone and other seismic zones of the Cordillera. The zone of shallow Curie temperature isotherm may be caused by the same extensional phenomena along its length and may indicate active spreading in this part of Nevada.

Several recent seismic studies support this interpretation. The Consortium for Continental Reflection Profiling (COCORP) has revealed several unexpected characteristics of the deep crust in northern Nevada. An east-west transect at about latitude 40°N shows a surprisingly continuous Moho at a depth of about 33 km with only about 7 km of relief [*Klemperer et al.*, 1986; *Allmendinger et al.*, 1987]. The configuration of the Moho does not appear to be influenced by significant crustal phenomena, such as vertical crustal displacements of up to 10 km or lateral geologic transitions. Even the western margin of the Precambrian continent, inferred to be in central Nevada based on geologic and isotopic information, does not influence the configuration of the subhorizontal Moho [*Allmendinger et al.*, 1987]. Several investigators have explained the continuous Moho and other subhorizontal reflectors by accretion of basaltic material to the bottom of the crust from fractionated mantle magma below [*Klemperer et al.*, 1986; *Thompson and McCarthy*, 1986; *Catchings*, 1987; *Allmendinger et al.*, 1987], consistent with the model for anomalous heat flow of *Lachenbruch and Sass* [1978].

These recent reflection results are somewhat contrary to earlier seismic refraction interpretations. *Eaton* [1963], for example, interpreted an east-west seismic refraction profile from Eureka to Fallon and found the crust to be 10 km thinner at the western end than at the eastern end, which requires considerably more relief on the Moho than displayed by the seismic reflection transect. *Catchings* [1987] and *Thompson et al.* [1988] reinterpreted seismic refraction data and used gravity data to reconcile the two seismic results. Their model includes a transitional layer located between lower crust and upper mantle. The bottom of the transitional layer is flat and corresponds to the "reflection Moho," whereas the depth to the top of the transitional layer varies from 24.5 km beneath Fallon to 33 km beneath Eureka and corresponds to the "refraction Moho." All of the subhorizontal reflectors seen in COCORP data occur within this transitional layer. *Catchings* [1987] and *Thompson et al.* [1988] interpreted the transitional layer as due to magmatic underplating of the lower crust; its increased

Fig. 10. (opposite) (*a*) Contour map showing depth to Curie temperature isotherm in Nevada. Calculated using 120 × 120 km subregions of the data shown in Plate 1. Depths less than 10 km shown with stipple pattern. Contours do not extend to state border because method only estimates a single depth for each 120 × 120 km subregion. (*b*) Same map as Figure 10*a*, but diagonal stipple patterns indicate locations of anomalously high (Battle Mountain high) and anomalously low (Eureka low) heat flow, and bold lines and dots show historic fault breaks and epicenters related to earthquakes greater than about magnitude 7 (Figure 3).

thickness in the Fallon area is a consequence of modern day rifting similar to structures postulated for the Mississippi embayment, East African Rift, Salton Trough, and Rio Grande Rift [*Mooney et al.*, 1983; *Catchings and Mooney*, 1988]. The proposed transitional layer is thickest in the vicinity of the shallow Curie temperature isotherm.

Independent seismic experiments conducted in 1986 by the Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) in the region between the northern Carson Sink and Dixie Valley also suggest the existence of elevated temperatures at deep-crustal depths. P_n refraction arrivals from lower crustal and upper mantle depths are strongly attenuated in this area (R. D. Catchings, personal communication, 1988), and reflection data show an exceptionally large velocity contrast at the same zone [*Jarchow et al.*, 1987]. These combined results can be explained by the presence of partial melting in this part of the lower crust (R. D. Catchings, personal communication, 1988). The location of the proposed zone of partial melting in the lower crust generally corresponds with a region of shallow Curie temperature isotherm shown in Figure 10.

Finally, P_n arrivals due to earthquakes and underground nuclear explosions were recorded along a northwest profile from Tonopah (Figure 5) to Bend, Oregon [*Priestley et al.*, 1982]. P_n delay times indicate that the crust is relative thin in a 150-km-wide region centered at the Carson Sink (Figure 1) and approximately coincident with the Battle Mountain heat flow anomaly and the 118° meridian seismic zone. Moreover, P_g and S_g arrivals along the same northwest profile are dramatically attenuated in the Carson Sink region. These phases traverse the crust at shallow to intermediate depths, and their attenuation suggests that crustal temperatures are elevated in this region (K. F. Priestley, personal communication, 1987).

CONCLUSIONS

Aeromagnetic data from Nevada illuminate various regional geologic and tectonic characteristics of the upper crust.

1. The pattern of anomalies characteristic of the Walker Lane extends up to 150 km northeast of the exposed geologic limits of the Walker Lane and into typical Basin and Range geology and topography. The magnetic pattern may indicate a tectonic fabric older than and uninfluenced by modern deformation.

2. The quiet zone is characterized by a lack of short-wavelength magnetic anomalies that cannot be explained by an anomalously shallow Curie temperature isotherm, as suggested by earlier studies. At least part of the subdued pattern of anomalies is due simply to a lack of recent volcanism in the area. The crude spatial correspondence between the magnetic quiet zone and a belt of muscovite-bearing granitic rocks suggests that granitic rocks may be less magnetic in this area simply because they crystallized with less magnetite.

3. Quantitative estimates of the depth to the Curie temperature isotherm indicate a shallow depth to the isotherm located within the Battle Mountain heat flow anomaly. The zone of shallow Curie temperature isotherm extends south along the 118° meridian seismic zone, which is characterized by historic offsets and large-magnitude earthquakes. The correspondence between shallow Curie temperatures, elevated heat flow, and seismic activity support earlier suggestions that the 118° meridian seismic zone is undergoing modern day and long-term extension.

4. Shallow depths to the Curie temperature isotherm along the 118° meridian support the conclusion, drawn from recent seismic reflection and refraction experiments in northern Nevada, that an active rift zone exists in the same area.

In solo, shallow depths to the bottom of magnetic sources are not particulary strong evidence for shallow Curie temperatures. However, the agreement between estimates of basal depth of magnetic sources, elevated heat flow, historic faulting, earthquake activity, deep crustal seismic velocity, and P and S wave attenuation strongly indicate that a north-south zone of spreading is currently active along the 118° meridian in Nevada.

APPENDIX

A stochastic model is required for magnetization $M(x)$ in order to estimate depths z_t and z_b from equation (1). Generally, $M(x)$ is considered to be completely random so that the power density spectrum $\Phi_M(k)$ in equation (1) is a constant [e.g., *Connard et al.*, 1983; *Blakely and Hassanzadeh*, 1981]. A more geologically reasonable model allows magnetization to be a randomly distributed value that remains constant over randomly distributed horizontal distances. The power density spectrum $\Phi_M(k)$ is here derived for this magnetization model.

Let $M(x)$ be a random function of x consisting of a series of constant levels separated by Poisson-distributed jumps (Figure A1). Then the number of jumps n within any distance x is predicted by the probability

$$P_p(n, x) = \frac{x^n}{\Delta n!} e^{-x/\Delta} \qquad x \geq 0 \qquad \text{(A1)}$$

where Δ is the average distance between consecutive jumps. The amplitude of $M(x)$ between any two jumps is described by the probability $P(m)$, unspecified as yet.

The power density spectrum of a random function $M(x)$ is given by the cosine transform of its autocorrelation, and the autocorrelation can be derived from the ensemble average of $M(x)$:

$$\phi(\chi) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} m_1 m_2 P(m_1) P(m_2 | m_1; \chi) \, dm_1 \, dm_2 \qquad \text{(A2)}$$

where $P(m_1)$ is the probability that $M(x) = m_1$ and $P(m_2|m_1; \chi)$ is the conditional probability that $M(x) = m_2$ a distance χ farther along x [*Lee*, 1960, p. 214].

The conditional probability $P(m_2|m_1; \chi)$ can be understood by considering two points along $M(x)$ separated by a distance χ (Figure A1). If no jumps occur between the two points, there is a 100% chance that $M(x + \chi) = M(x)$. However, if one or more jumps occur between x and $x + \chi$, the value of $M(x + \chi)$ is completely independent of the value of $M(x)$ and is given by

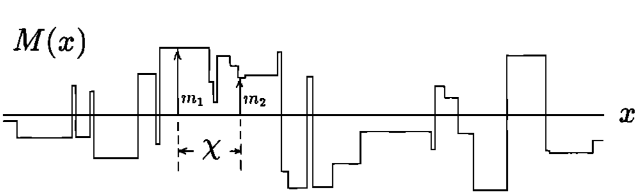


Fig. A1. Stochastic model for magnetization within a layer. Magnetization is a random but constant value between Poisson-distributed jumps. Distance χ separates two points of $M(x)$ such that $M(x) = m_1$ and $M(x + \chi) = m_2$.

probability $P(m_2)$. Equation (A1) gives the probability that n jumps will occur, mainly,

$$P_p(n, \chi) = e^{-\chi/\Delta}, \quad \text{if } n = 0$$
$$P_p(n, \chi) = 1 - e^{-\chi/\Delta} \quad \text{if } n \neq 0 \qquad \chi \geq 0$$

and the conditional probability is given by

$$P(m_2 | m_1; \chi) = \delta(m_2 - m_1)e^{-\chi/\Delta} + P(m_2)(1 - e^{-\chi/\Delta}) \qquad \chi \geq 0 \tag{A3}$$

where

$$\delta(m_2 - m_1) = 1 \quad \text{if } m_2 = m_1$$
$$\delta(m_2 - m_1) = 0 \quad \text{otherwise}$$

Substituting (A3) into (A2) yields

$$\phi(\chi) = e^{-|x|/\Delta} \int_{-\infty}^{\infty} m_1{}^2 P(m_1)\, dm_1 + (1 - e^{-|x|/\Delta})\left[\int_{-\infty}^{\infty} m_1 P(m_1)\, dm_1\right]^2 \tag{A4}$$

The mean and variance of $M(x)$ are given by

$$\bar{m} = \int_{-\infty}^{\infty} mP(m)\, dm \tag{A5}$$

$$\sigma^2 = \int_{-\infty}^{\infty} m^2 P(m)\, dm - \bar{m}^2 \tag{A6}$$

respectively [*Lee*, 1960, pp. 158–163]. Substituting (A5) and (A6) into (A4) yields

$$\phi(\chi) = \sigma^2 e^{-|x|/\Delta} + \bar{m}^2 \tag{A7}$$

the autocorrelation of $M(x)$.

The final step is to calculate the power density spectrum. The result will have a simpler form if $M(x)$ has zero mean, which can be achieved by simply subtracting a constant $\bar{m}$ from $M(x)$. (Constant magnetization is the annihilator function for horizontal layer sources. If $M(x)$ represents magnetization within a layer, therefore, any constant can be added or subtracted to $M(x)$ without affecting the magnetic anomaly.) The power density spectrum is given by

$$\Phi(k) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \phi(\chi) \cos(k\chi)\, d\chi \tag{A8}$$

Let $\bar{m} = 0$ in (A7) and substitute in (A8):

$$\Phi(k) = \frac{\sigma^2}{\pi} \frac{\Delta}{1 + \Delta^2 k^2} \tag{A9}$$

Equation (A9) is the power density spectrum of $M(x)$, a function with constant but random amplitudes offset by Poisson-distributed jumps. Note that it was not necessary to specify $P(m)$ in order to derive (A9). Hence the result is not dependent on the form of the probability distribution, and in particular, the amplitude of $M(x)$ could be described by either a Gaussian or a uniform distribution without affecting (A9).

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