Geophysical model of the Midcontinent Geophysical Anomaly in northeastern Kansas

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Abstract

A geophysical model of the Midcontinent Geophysical Anomaly (MGA) in northeastern Kansas was derived to fit gravity and magnetic data using an initial model suggested from COCORP seismic sections, along with available drill data. An asymmetric basin filled with interbedded basaltic and clastic rocks in the shallow crust, interpreted by Serpa et al. (1984), appears to be mainly responsible for the primary positive magnetic anomaly of the MGA. The favorable magnetization of 60° inclination and 320° declination indicates that the remanent magnetization is an important factor. Reprocessing part of COCORP seismic data reveals a possible mafic intrusion in the shallow crust beneath a secondary magnetic high. Its favorable net magnetization of 30° inclination and 80° declination suggests it occurred in a different ambient earth's magnetic field than that in which the basaltic rift basin was formed. In addition, the nonmagnetic source of high density at midcrustal levels extending to deep crust and the nonmagnetic Rice Formation basins of low density at shallow crust on both sides of the MGA were proposed to fit the gravity anomaly. The final derived model infers the mafic intrusion in the shallow crust beneath the secondary magnetic high to be of younger age than the Rice Formation.

Introduction

The Midcontinent Geophysical Anomaly (MGA) is a zone of pronounced positive gravity anomalies averaging 60 km (36 mi) wide, with flanking gravity lows and associated magnetic highs, which extends from Lake Superior over 1,000 km (600 mi) south to Kansas (King and Zietz, 1971). Based on the aeromagnatic data, its extension continues to at least the Kansas–Oklahoma border (Yarger, 1983). It is generally inferred to be related to a continental rift, which formed in late Precambrian time (Chase and Gilmer, 1973; Ocola and Meyer, 1973). Exposures of Keweenawan mafic igneous and sedimentary rocks in the Lake Superior region provide a locality for both geological and geophysical investigations (Halls, 1966, 1978; White, 1966). This area serves as a model for interpretation of gravity and magnetic anomalies further south where the Precambrian crust is covered entirely by Phanerozoic sediments.

The purpose of this study was to investigate the geophysical model responsible for the MGA in northeastern Kansas using information from the area, including gravity data (Yarger et al., 1980), aeromagnetic data (Yarger et al., 1981), and COCORP (Consortium for Continental Reflection Profiling) seismic data (Serpa et al., 1984). Drilling to the basement in this area also provides generalized geologic information on the uppermost Precambrian crust (Bickford et al., 1979).

The initial model suggested from the COCORP seismic sections was tested against the observed gravity and magnetic data through modeling. Reprocessing part of the COCORP seismic data was done along the 10-km (6-mi)-long east-west profile on the east side of the MGA. Seismic sections of improved quality in this area were needed in order to interpret the secondary magnetic-anomaly high which trends along the southeastern flank of the MGA. Finally, the derived model was improved by requiring correspondence with the gravity and magnetic data. The simultaneous use of gravity, magnetic, and seismic data, along with drill-hole information, should yield a reliable geologic and tectonic model of this ancient continental rift.

Geological and geophysical background

In Kansas, the distribution of Precambrian basement rocks within the uppermost crust is inferred primarily from shallow basement well samples and geophysical data. The older basement terrane in northern Kansas, except in the area of the MGA, is inferred to be dominated by mesozonal granite (Bickford et al., 1979; Bickford et al., 1981) containing isolated intrusions of younger epizonal granite (Steeples and Bickford, 1981; Yarger, 1983). The younger basement terrane in southern Kansas is characterized by epizonal granite and silicic volcanic rocks (Bickford et al., 1981). Within the area of the MGA, mafic igneous and arkosic sedimentary rocks were encountered in basement wells

(Bickford et al., 1979). These rocks are generally inferred to be related to the exposed Keweenawan mafic igneous and associated sedimentary rocks in the Lake Superior region. In a preliminary result of a study of thin sections from basement well samples, Bickford et al. (1979) reported mafic rocks of mostly olivine-bearing gabbroic rocks. Seven of the 12 wells that encountered mafic rocks lie along the southeastern flank of the MGA (Bickford, personal communication, 1984). Precambrian arkosic rocks and siltstones comprise the Rice Formation (Scott, 1966). They could have been formed from immature sediments derived from the faulted edges of the rift basin and then deposited within it. Sedimentary rock is usually considered to be of relatively low density and nonmagnetic compared to mafic rock (Telford et al., 1976, p. 25–26 and 121). Therefore, the presence of Rice Formation basins surrounding the mafic igneous rift basin can be inferred from the flanking lows of the gravity anomaly. Also, analysis of aeromagnetic data in Kansas has shown a magnetic quiet zone which may be associated with the Rice Formation surrounding the magnetic high of the MGA (Yarger, 1983).

Analysis of teleseismic (Hahn, 1980) and microearthquake waves in eastern Kansas (Lui, 1980; Miller, 1983) suggested the presence of a high-velocity crustal body beneath the MGA related to the mafic igneous body. Miller (1983) also suggested the existence of a low-velocity crustal body on the northwest flank of the MGA which may be related to the arkosic sedimentary Rice Formation.

Deep seismic-reflection data from COCORP across the MGA in northeastern Kansas revealed a thick layered wedge of moderately west-dipping strong reflections overlain by a zone of weak reflections beneath the base of Paleozoic strata (fig. 1). This was interpreted to be an asymmetric basin filled with the middle Keweenawan unit of interbedded basalt and clastic rocks grading upward into the upper Keweenawan unit of upper Precambrian sedimentary rocks (Serpa et al., 1984). The rift basin is bounded by east-dipping faults, interpreted by Serpa et al. (1984) to be the result of block rotation during crustal extension. Its dimensions are approximately 40 km (24 mi) wide (east-west) and about 8 km (5 mi) deep, with its center at the gravity maxima.

Based on preliminary COCORP results in northeastern Kansas by Brown et al. (1983), the generalized picture of the continental crust beneath the Paleozoic strata is that of a shallow crustal zone relatively free of reflections, a midcrustal zone with numerous reflections and diffractions, and a transition zone of rapid decrease in reflections at the expected arrival time of the Moho-discontinuity. A seismic-refraction study in northwestern Kansas combined with the regional gravity gradient (Steeples, 1976) indicated a gently west-dipping Moho at about 34–38 km (20–23 mi) deep in north-central Kansas.

Gravity and aeromagnetic data

Bouguer gravity data in northeastern Kansas compiled by Yarger et al. (1980) are shown in fig. 2. The east-west gravity profiles across the MGA (fig. 3) show the anomaly amplitude of about 80 mgal. The relative total intensity of the magnetic field in northeastern Kansas (Yarger et al., 1981) is shown in fig. 4. Details of data acquisition and data reduction, along with regional interpretation of aeromagnetic data, were described by Yarger (1983). The east-west magnetic profiles across the MGA (fig. 5) show the anomaly amplitude of about 600 gammas.

Comparison of the aeromagnetic map (fig. 4) with the Bouguer gravity map (fig. 2) reveals correlations. The axes of both gravity and magnetic anomaly highs of the MGA lie along the same northeasterly trend of about 30° north. Across the east-west COCORP seismic line, peak of the magnetic high is at VP (vibration points) 1650–1750, while

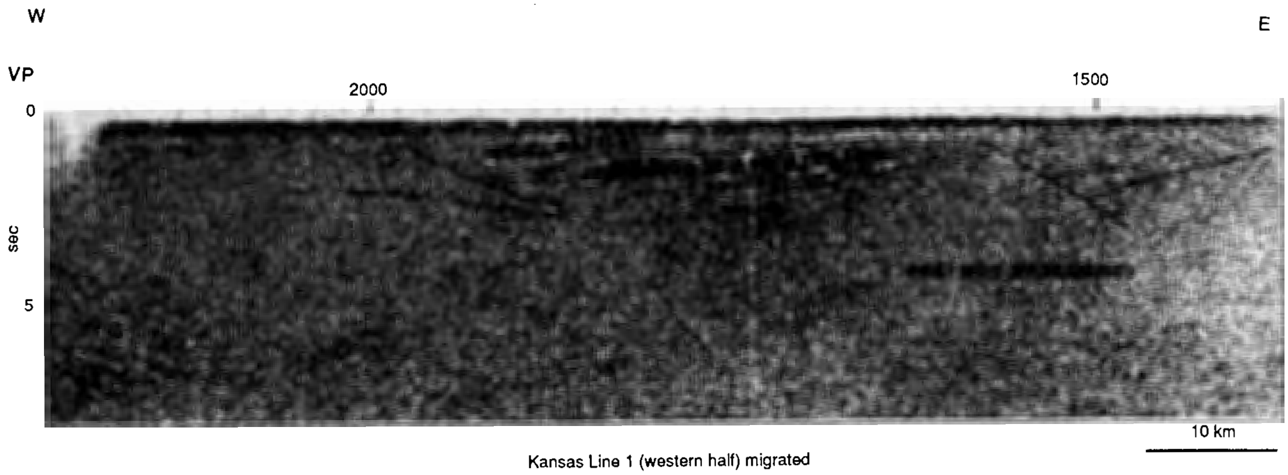

FIGURE 1—COCORP SEISMIC SECTION (MIGRATED) ACROSS THE MGA BETWEEN VP (VIBRATION POINT) 1360 AND 2334 (from Serpa et al., 1984).

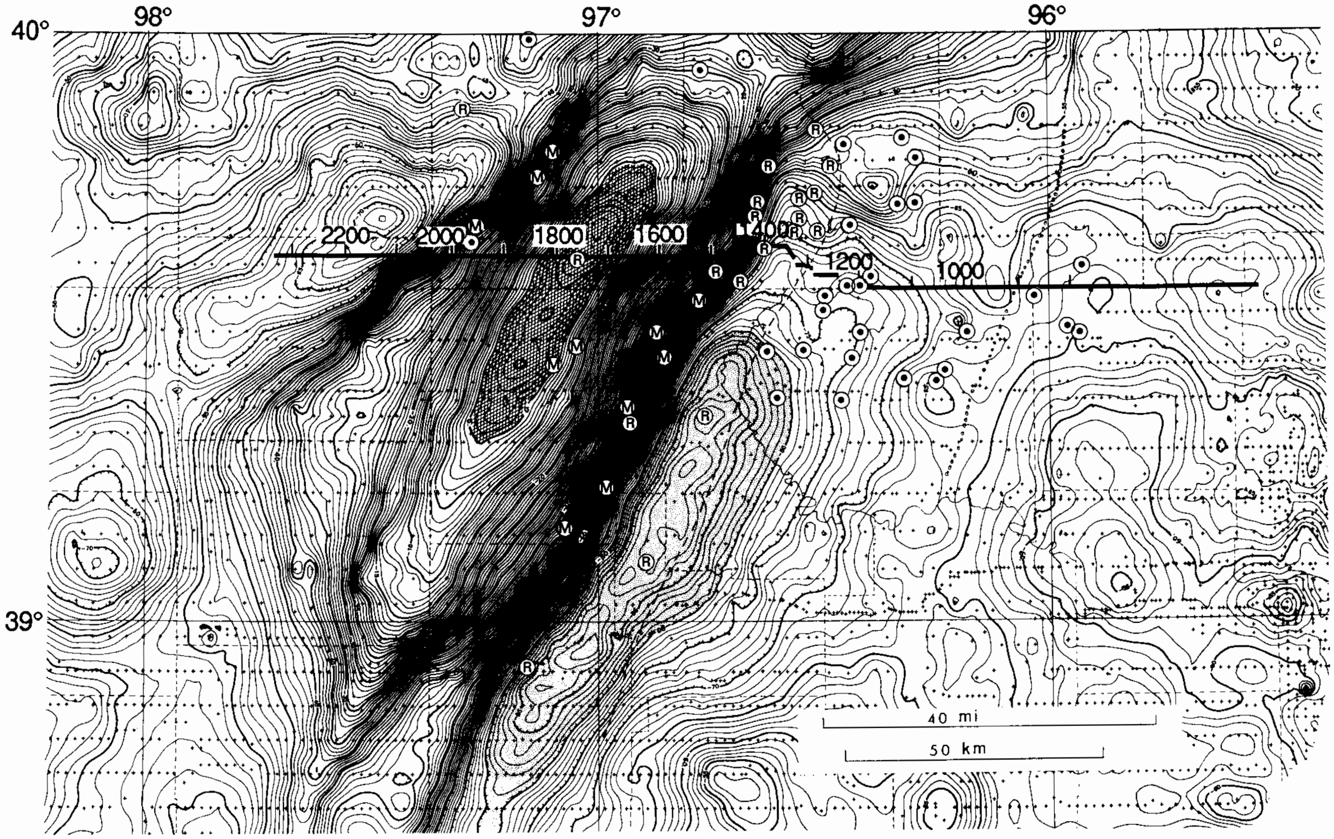

FIGURE 2—BOUGUER GRAVITY MAP OF NORTHEASTERN KANSAS USING CONTOUR INTERVAL OF 1 MGAL (Yarger et al., 1980), with an east-west COCORP seismic line (Serpa et al., 1984). Drill data (Bickford et al., 1979; Bickford, personal communication, 1984) in the MGA area: M = mafic rocks, R = Rice Formation, dot = granites, dash curve = inferred boundary between Rice Formation and granites, and dotted curve = Humboldt fault zone.

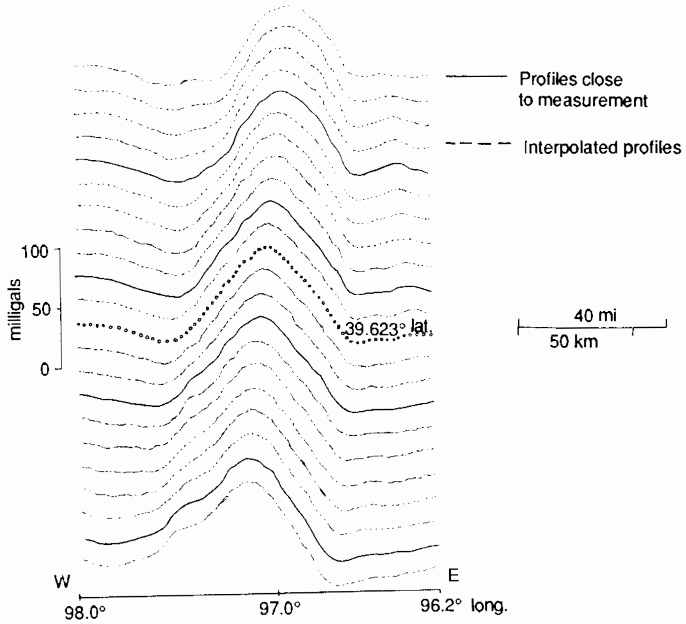

FIGURE 3—EAST-WEST GRAVITY PROFILES ACROSS THE MGA BETWEEN 96.2° W AND 98.0° W LONGITUDE. North-south spacing between adjacent profiles is 1.6 km (1 mi). Dark curves = profiles closed to measurement stations; dash curves = interpolated profiles; dotted curve = profile closed to COCORP east-west seismic line (39.623° N latitude).

the gravity high is at VP 1700–1800. The magnetic anomaly of the MGA has a shorter wavelength than the gravity anomaly. A secondary magnetic high is found at VP 1450–1470, parallel to the primary high along the southeastern side of the MGA. Its northeasterly trend coincides with the boundary between the gravity high and the southeastern gravity low. On the northwestern side of the MGA, the trend of magnetic low (at about VP 2000-2100) coincides with the boundary between the gravity high and the northwestern gravity low. This trend is approximately 45° east of north.

Preliminary modeling

Earlier potential-field modeling across the MGA in northeastern Kansas by Yarger (*in*, Hahn, 1980) is shown in fig. 6. The modeling technique described by Somanas (1984) also was used in this study. It was based on calculations for the gravity and magnetic fields due to prism-shaped bodies, using formulas given by Goodacre (1973) and Bhattacharyya (1964), respectively. Arbitrary direction of net magnetization was allowed in the calculation, where net magnetization was assumed to be the resultant vector of induced and remanent magnetizations.

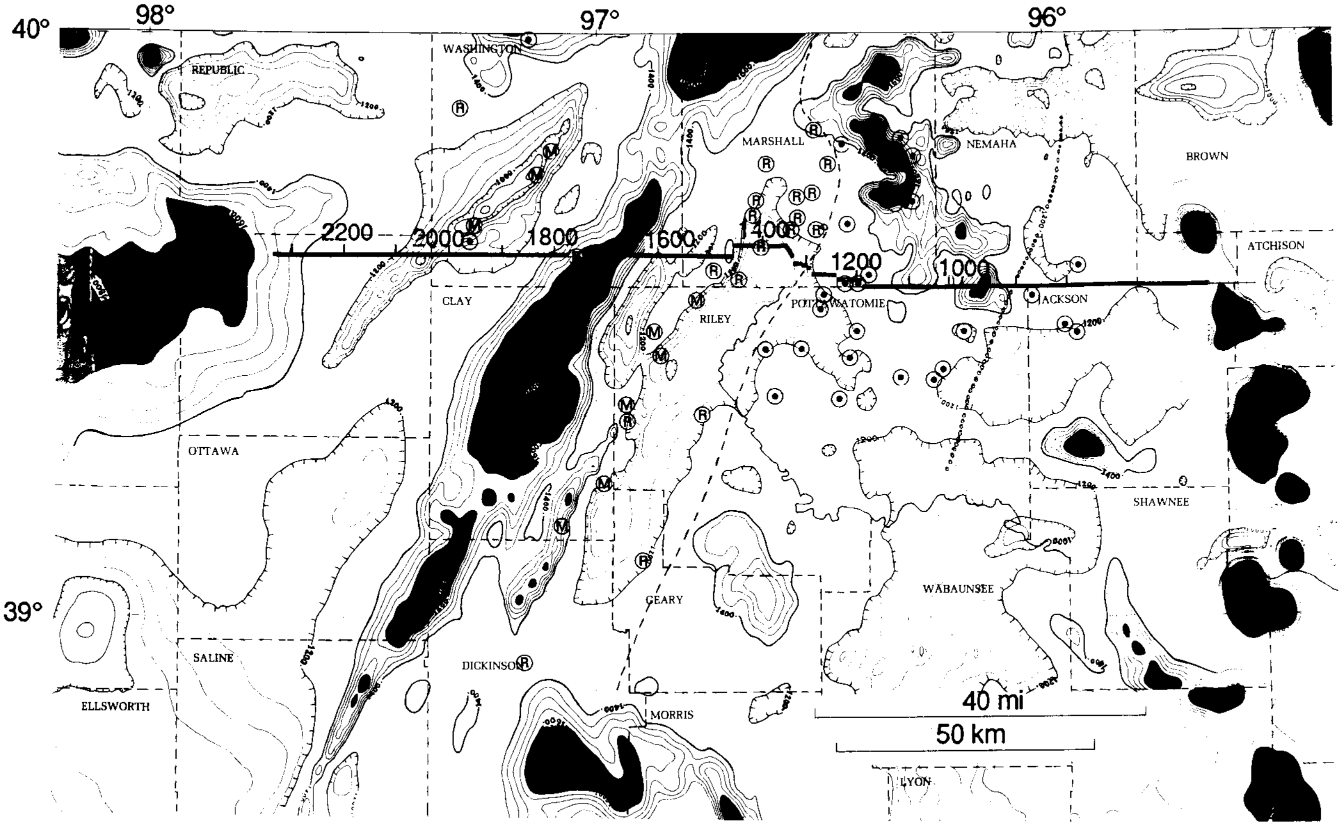

FIGURE 4 (ABOVE)—AEROMAGNETIC MAP OF NORTHEASTERN KANSAS USING CONTOUR INTERVAL OF 50 GAMMAS (Yarger et al., 1981), with an east-west COCORP seismic line (Serpa et al., 1984). Drill data (Bickford et al., 1979; Bickford, personal communication, 1984) in the MGA area. M = mafic rocks, R = Rice Formation, dot = granites, dash curve = inferred boundary between Rice Formation and granites, and dotted curve = Humboldt fault zone.

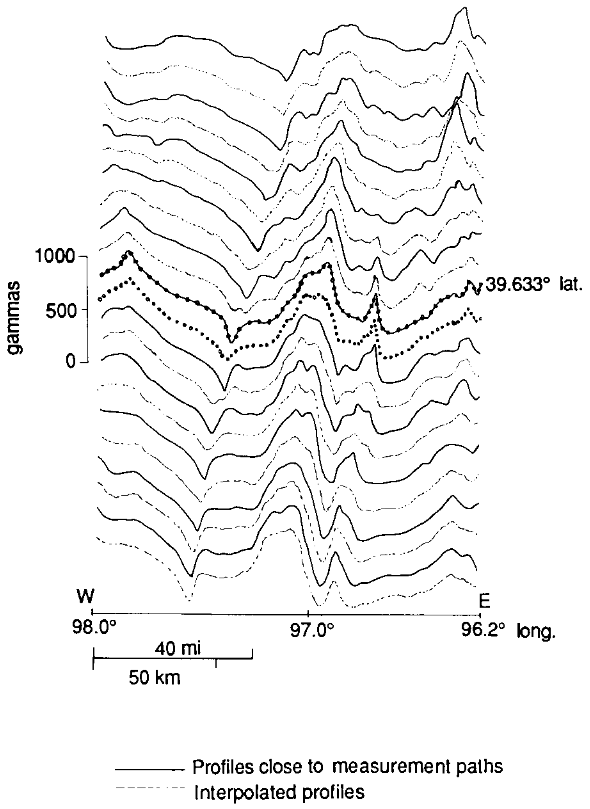

FIGURE 5 (AT RIGHT)—EAST-WEST AEROMAGNETIC PROFILES ACROSS THE MGA BETWEEN 96.2° W AND 98.0° W LONGITUDE. North-south spacing between adjacent profiles is 1.6 km (1 mi). Dark curves = profiles close to measurement paths, dash curves = interpolated profiles, dotted curves = profiles close to COCORP east-west seismic line.

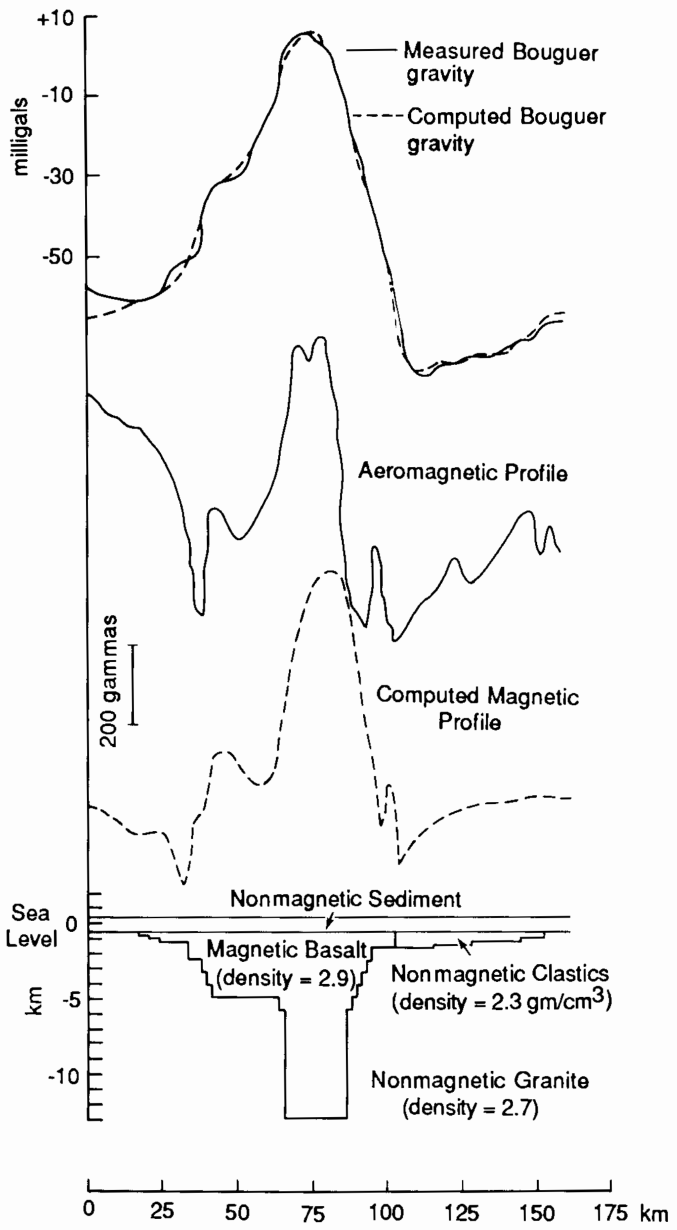

FIGURE 6—Gravity and magnetic modeling across the MGA from 96.15° W to 98.0° W longitude at 39.5° N latitude. Density is in cgs units (from Yarger; *in*, Hahn, 1980, this volume.)

Jahren (1965) reported the magnetization of Keweenawan mafic rocks near Duluth, Minnesota, to correspond to an apparent paleopole position around latitude 30°–34° N and longitude 175°–180° W. Based on this Keweenawan pole position, the earth's magnetic field in Kansas during Keweenawan time pointed west-northwest and downward, with an average inclination angle (I) of +40° (downward from the horizontal plane) and a declination angle (D) of +290° (clockwise from north in the horizontal plane). This assumes that since Keweenawan time, Kansas and Minnesota have maintained the same relative positions as parts of the North American tectonic plate and that the rifting in Kansas is the same age as that in Minnesota. The remanent magnetization of normal polarity in Kansas during the Keweenawan period would be approximately 40° inclination and 290° declination. The resultant net magnetization would be between the directions of remanent and induced magnetizations, that is, an inclination angle of 40°–68° and a declination angle of 290°– 7° east of north.

Ground surface in the area of study is regionally flat, about 400 m (1,300 ft) above sea level. The Precambrian basement surface revealed by drill data (Cole, 1976) dips slightly to the west. The Paleozoic sediments are about 1 km (.6 mi) thick, except over the Abilene anticline (about 700 m [2,300 ft)) and the Nemaha Ridge (about 200 m [660 ft]). The gravitational effect of the Paleozoic section in the MGA zone is negligible due to its small and approximately constant thickness. The strata also are considered to be nonmagnetic because of the negligible magnetite content in sedimentary rocks compared to mafic igneous rocks.

A flat magnetic regional trend of 1,250 gammas was subtracted from the observed magnetic anomaly, resulting in the residual magnetic anomaly. The linear regional gravity trend of about 65 mgal, with a gentle east-dipping gradient of 0.15 mgal/km, was added to the observed Bouguer gravity anomaly, resulting in the observed residual anomaly.

The initial model of the basaltic rift basin interpreted from the COCORP seismic section (Serpa et al., 1984; fig. 1) was tested and modified. Fig. 7 shows the east-west cross section of the model, where the long axis of the model was rotated 35° north. The datum elevation at sea level was used for gravity modeling and the flight elevation of 760 m (2,508 ft) above sea level for magnetic modeling. The computed gravity anomaly with positive density contrast of 0.22 gm/cm^3 has smaller amplitude and shorter wavelength compared with the observed data. Higher density contrast of 0.6 gm/cm^3 matches the anomaly amplitude but not the wavelength. However, the magnetic signature of the basin model fits that of the primary magnetic high of the MGA in both wavelength and amplitude. The favorable net magnetization is 60° inclination and 320° declination, which suggests that the normal polarity remnant magnetization is important in addition to that of the induced magnetization.

According to the COCORP seismic section (fig. 1), Serpa et al. (1984) interpreted the west edge of the strong reflection layers to be bounded by an east-dipping fault. In order to match the magnetic low of the MGA at VP 2040, the western boundary of the magnetic rift-basin model has been extended to about VP 2040. This suggests that the west edge of the magnetic rift basin may be terminated by another gentle east-dipping fault at VP 2040 and time 2 secs (fig. 1).

Also according to the seismic data of fig. 1, the east end of the basaltic rift basin is at about VP 1560. Therefore, the seismic data seem to preclude the possibility that the source of the secondary magnetic high (at VP 1460) is due to the thin edge effect of a large magnetic body at shallow depth as proposed in Yarger's model (*in*, Hahn, 1980) of fig. 6. In such a case the east end of the basaltic rift basin is required to extend eastward to at least VP 1460. Discussion of the possible source of the secondary magnetic high follows.

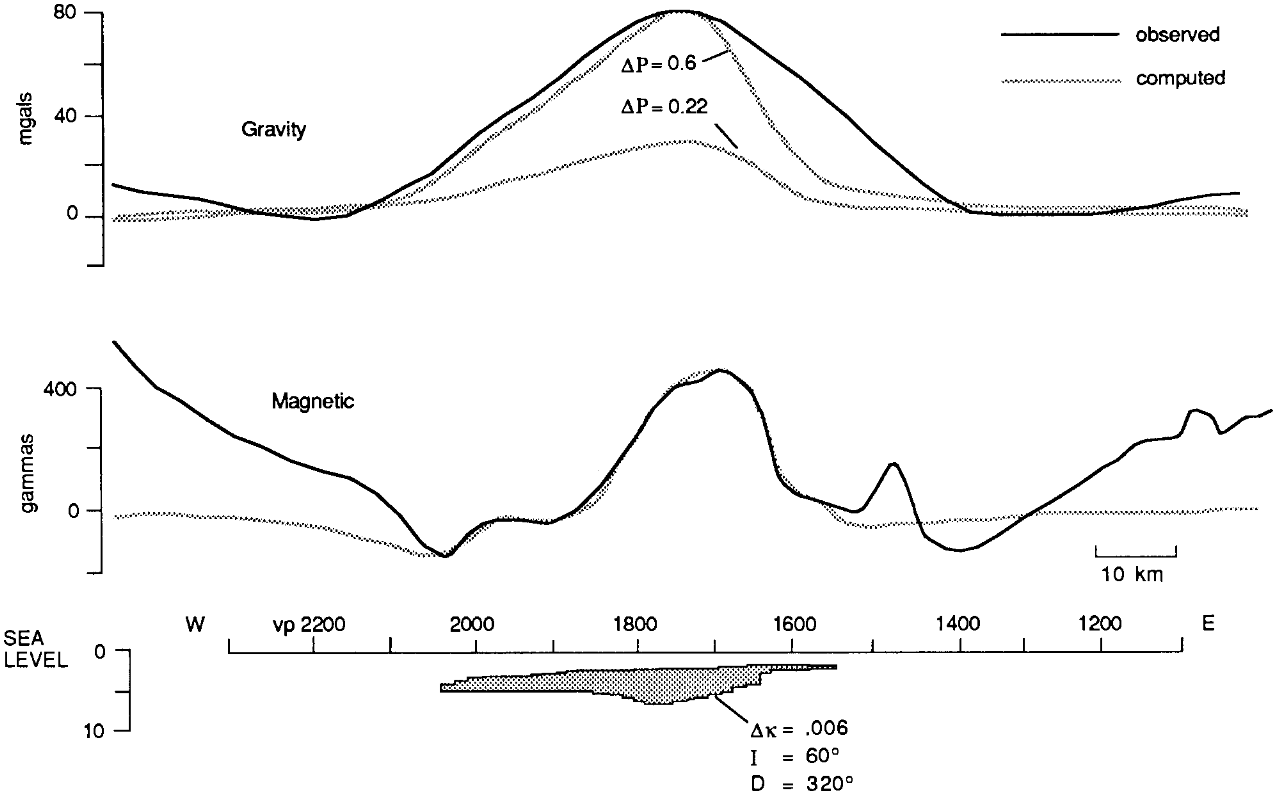

FIGURE 7—GRAVITY AND MAGNETIC MODELING OF RIFT BASIN ACROSS THE MGA ALONG THE COCORP SEISMIC LINE. Density and magnetic susceptibility contrasts are in cgs units.

Seismic reflections—reprocessing

In this study, reprocessing part of the COCORP seismic data (VP 1400–1500 of line 1) was done in order to interpret the secondary magnetic high (at VP 1460) of the MGA. The magnetic properties of rocks are not related directly to their acoustic properties. However, seismic sections of improved quality in this area could reveal clues to help interpret this secondary magnetic high. Procedures were performed to improve quality of the seismic sections. At VP 1454 the east-west seismic profile was shifted 1.6 km (1 mi) southward (fig. 8). As a result, data were recorded when the source was on the north line and receivers were on the south line. The CDP profile for such data lies midway between and parallel to both the north and the south lines as shown in fig. 8. Each CDP gather consists of spreading source-to-receiver directions, instead of in-line direction as in the usual case. Due to such field arrangement, the unwanted ground roll and other noise were not properly canceled within the geophone group, especially for the near receivers in the south line when the source was on the north line. The unmigrated seismic section across the area, shown in fig. 10, displays severe disturbance due to ground roll noise between VP 1440–1480 and times 0.6–1.8 secs. Therefore, data were reprocessed in order to carefully minimize this ground-roll problem.

COCORP seismic data between VP 1400 and VP 1500 for the upper 3 secs of two-way travel time were reprocessed at the Kansas Geological Survey, using the SPEX (Seismic Processing EXecutive, Sytech Corporation) seismic-processing system. The seismic data were sorted into CDP gathers in three separated CDP profiles: the north, the middle, and the south CDP profiles, according to fig. 8. The middle CDP profile consists of data recorded when the source was on the north line and receivers were on the south line. Samples of CDP gathers within this middle CDP profile are shown in fig. 9 for CDP 2904 (VP 1452) to CDP 2908 (VP 1454). Reprocessing, with careful muting of ground roll next to the first arrival zone, significantly improved the result. The final CDP-stacked section is shown in fig. 11. The dipping strong reflector (indicated by arrows in the figure) appears at a time of about 1.8 secs at VP 1450 and 2.0 secs at VP 1460.

There is a discontinuity of the reflector between VP 1455 and 1465 and time 1.8 and 2.0 secs. At first, it seems that the seismic character in this range is dominated by high-amplitude noise like that appearing in CDP gathers at VP 1452 to VP 1454 (fig. 9). There the noise is evident between about time 1.5 and 2.5 secs for the 12 near-traces. However, such noise is not dominant in these CDP's in the final stacked section (fig. 11; CDP number is twice VP number). Instead, a strong reflector appears at these CDP's; therefore, the discontinuity of the strong reflector at VP 1455–1465 is not due to the disturbance of high-amplitude noise.

Also note that the amount of fold for each CDP-stacked trace reduces toward both ends of the middle CDP profile as displayed at the top of fig. 11. The central part of the profile (VP 1440–1470) has a higher fold number, including both near and far source-to-receiver distances within each CDP gather. Toward both ends of the profile, each CDP gather has only far traces. To equalize the fold amount along the profile, the near traces that contain high-amplitude noise (i.e. the first 12 near-traces in each CDP gather shown in fig. 9) were omitted. The CDP gathers used in fig. 9 have been equalized both in number of fold and source-to-receiver distances so that the resulting stacked traces in the section are statistically balanced. In doing this, shallow information is lost. The result is shown in fig. 12 for 6-fold data, where only the 25th to 36th channels (total is 12 channels) for each vibration point were used. The discontinuity of reflector at time 1.8–2.0 secs between VP 1455 and VP 1465 also appears in this section.

Therefore, the discontinuity of the reflector is more likely to be due to geologic structure rather than to processing artifacts. The layered reflection of strong impedance contrast could be disconnected by mafic intrusion of a later event which, due to its high magnetite content and shallow depth, produces a magnetic high above it. Seven wells penetrating olivine-bearing gabbro, as revealed from thin-section studies (Bickford, personal communication, 1984), are located along the trend of the secondary magnetic high and could be related to this interpreted mafic intrusion.

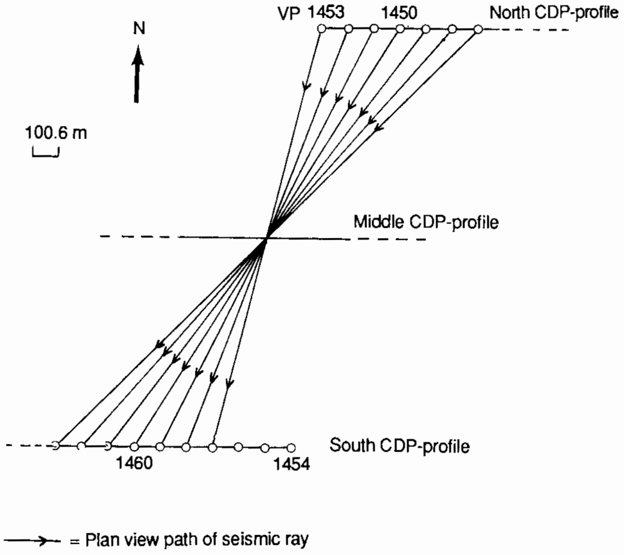

FIGURE 8—Plan view showing the north, middle, and south CDP profiles resulted from shifting of the east-west seismic line at VP (vibration point) 1454.

Remodeling

The final derived model (fig. 13) includes the interpreted mafic intrusive body at VP 1455–1465. It was modeled as a highly magnetic sheetlike shape with its long axis 35° east of north. Its favorable net magnetization of 30° inclination and 80° declination produces both the magnetic high at VP 1460 and the magnetic low on the east side of the MGA (VP 1400–1430). This magnetization differs from that of the magnetic rift basin modeled in fig. 7, which suggests that the interpreted intrusive event occurred at a different ambient earth's field, i.e. it is a different age.

The source of high density and nonmagnetism at deep crust (25–40 km [15–24 mi] below sea level) was included in order to fit the amplitude and wavelength of the gravity high. Negligible magnetic effect of deeper source was used because otherwise it would yield an undesirable longer wavelength of magnetic anomaly than that of the observed data. This suggestion, if true, implies that the loss of magnetic effect at great depth may be due to the extremely low susceptibility contrast corresponding to the unknown magnetic complexity of midcrustal levels and deep crust.

Also the sedimentary basins of low density on both sides of the MGA were included in order to fit the gravity low of the MGA. By comparing the final derived model to the COCORP seismic section of fig. 1, seismic evidence that could be correlated to the base of the sedimentary basins is found: on the east side of the COCORP profile is a west-dipping reflector beneath VP 1400 at time 1.3 secs, and on the west side of the profile, a gentle east-dipping reflector beneath VP 2100 at time 2.0 secs. These reflectors may be due to changes in acoustic properties from sedimentary rocks to granitic basement rocks.

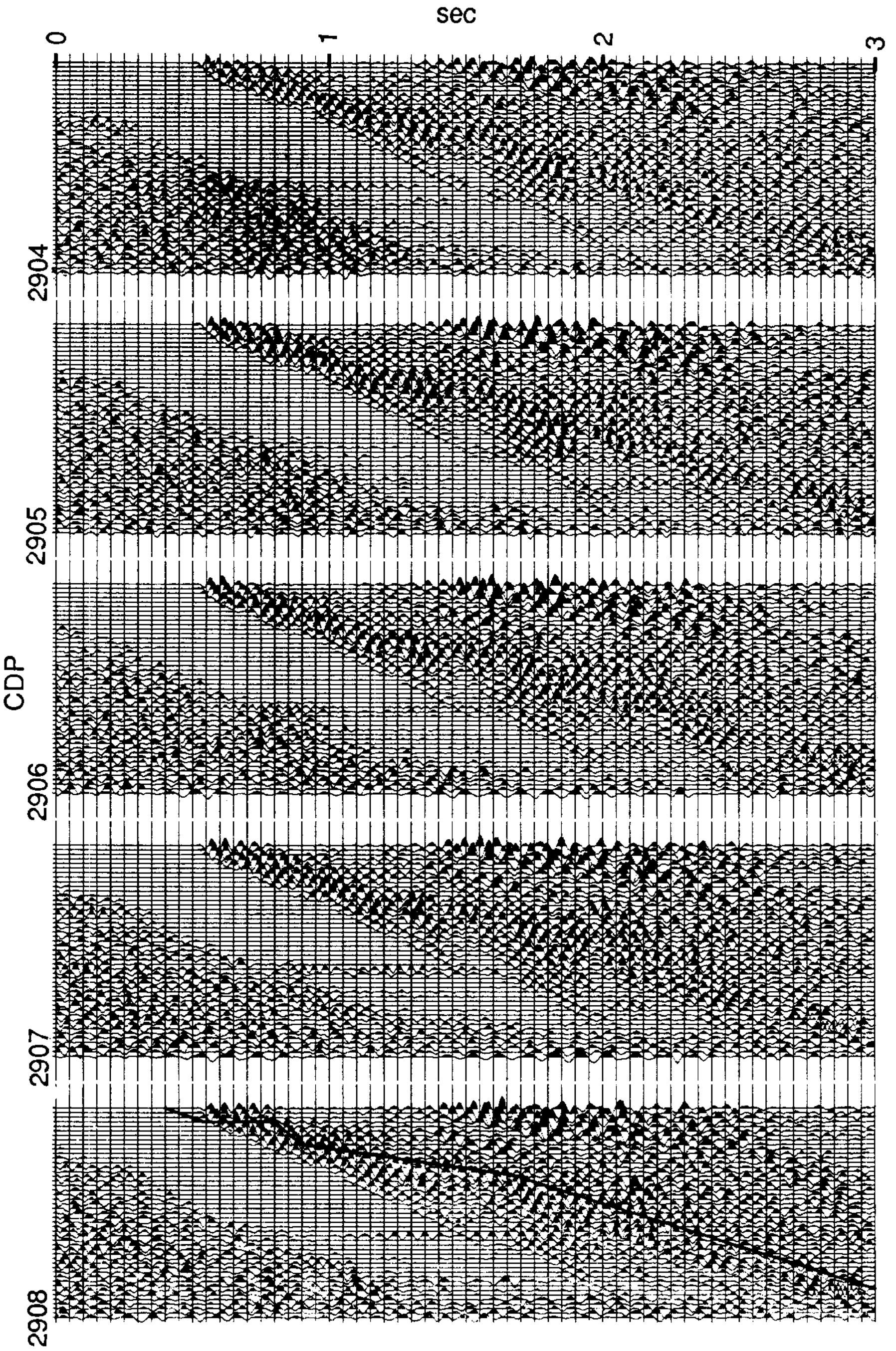

FIGURE 9—CDP gathers of CDP 2904–2908 (corresponding to VP 1452–1454) of the middle CDP profile.

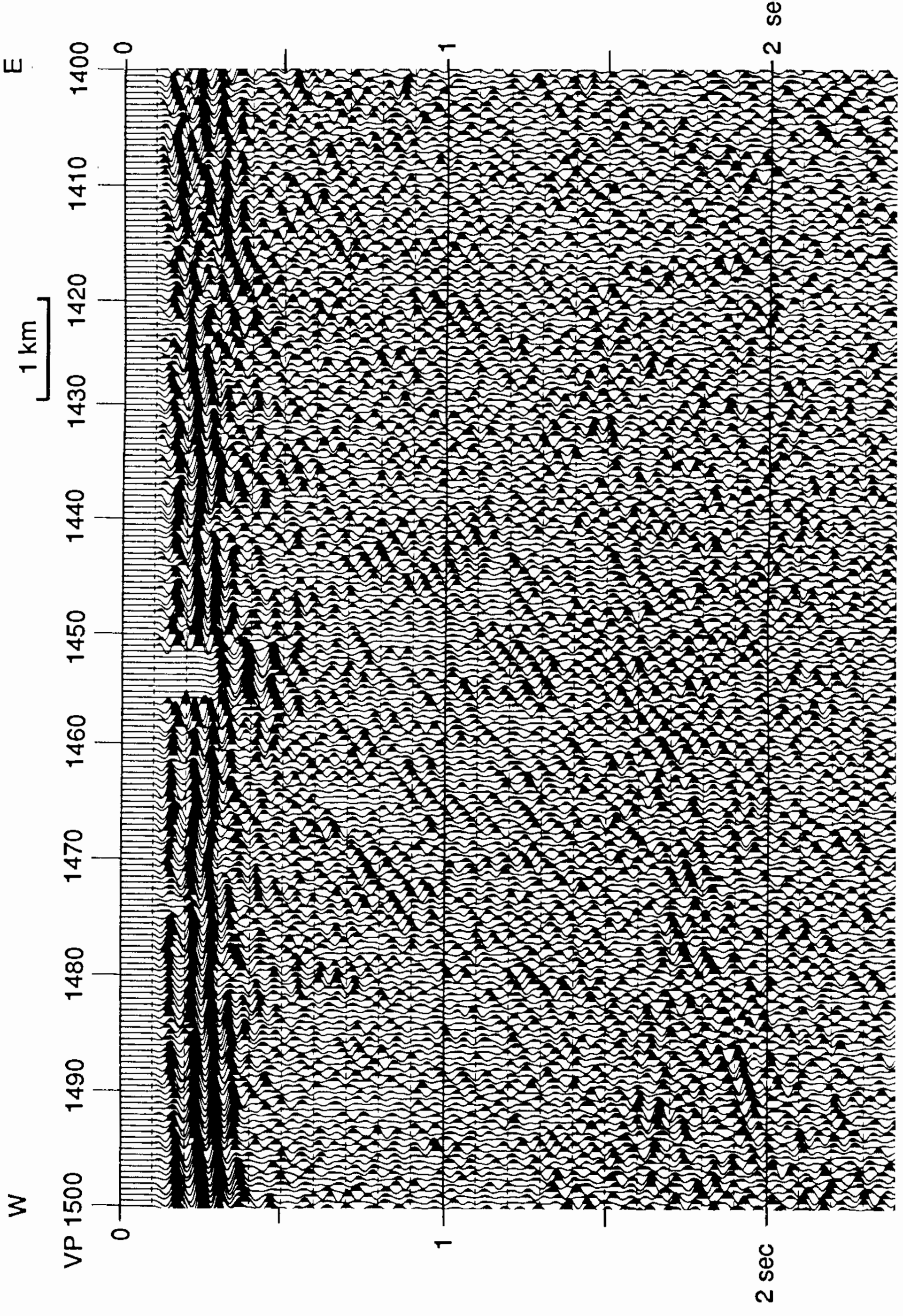

FIGURE 10—COCORP SEISMIC SECTION (UNMIGRATED) FROM VP 1400 TO VP 1500 ACROSS THE SECONDARY MAGNETIC HIGH OF THE MGA. The datum elevation is at 150 m (495 ft) above sea level (data processed at Cornell University, 1982; distributed by Seisdata Services Inc.).

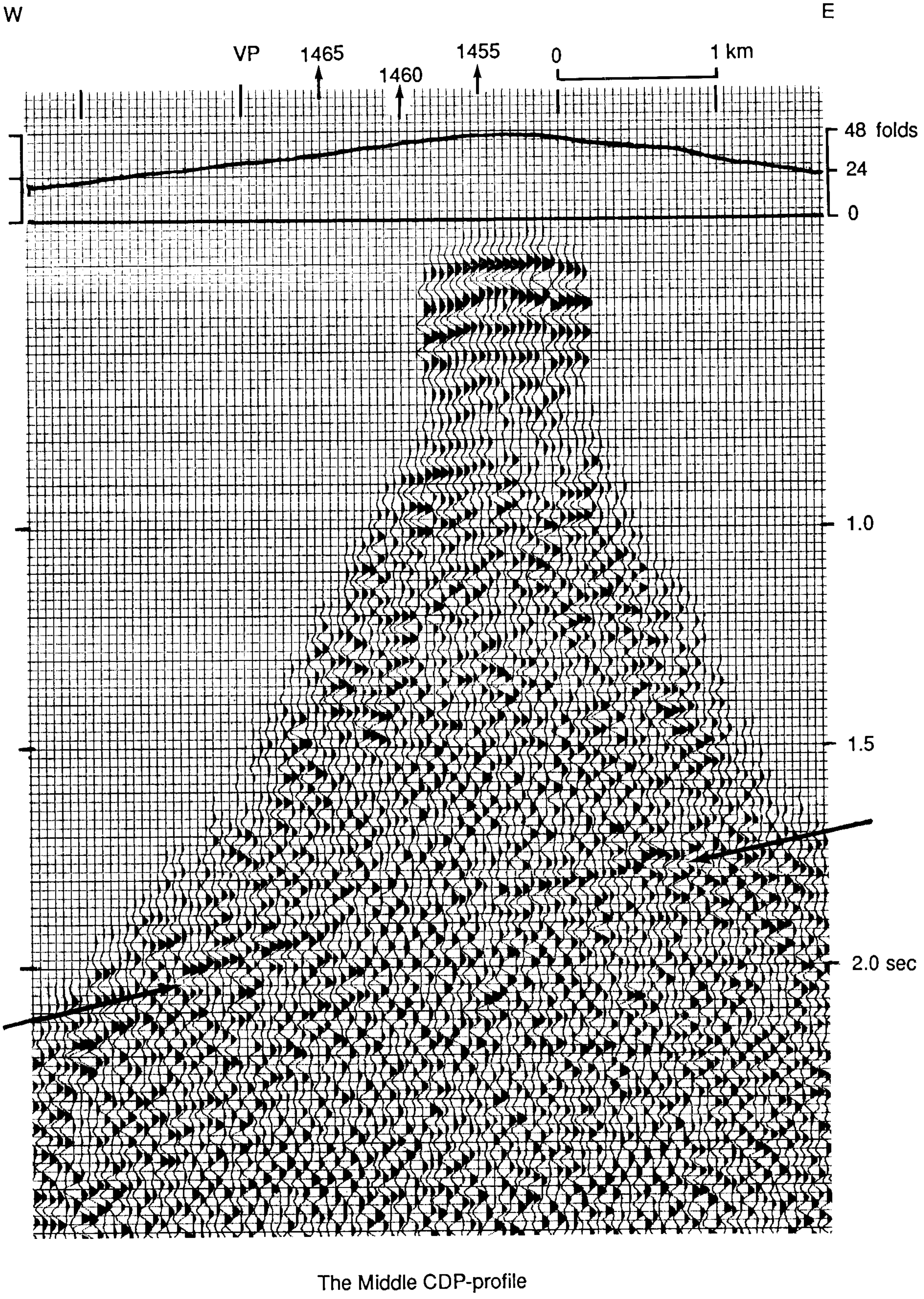

FIGURE 11—Reprocessed final seismic section of the middle CDP profile from VP 1434 to VP 1483. The datum elevation is at 397 m (1,310 ft) above sea level.

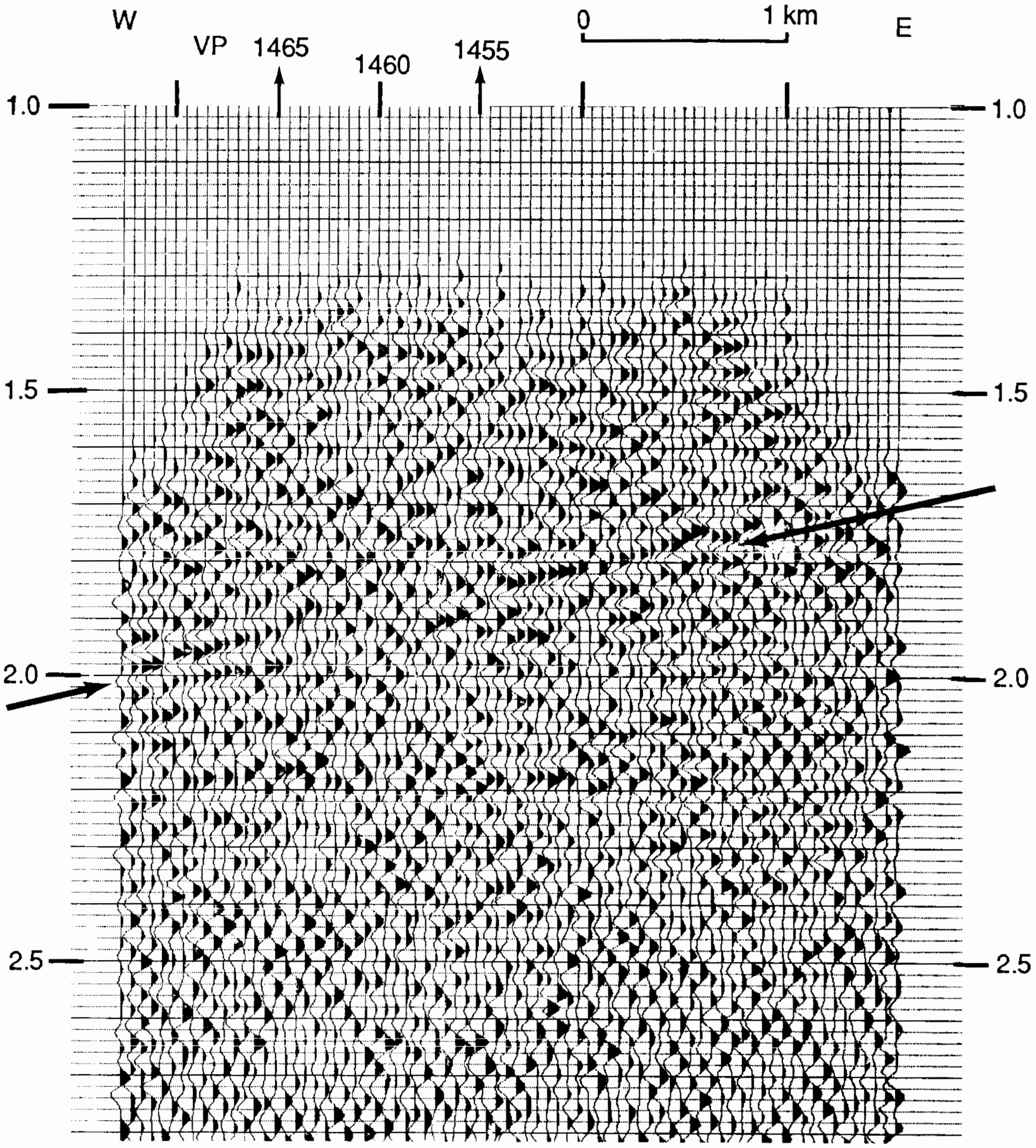

FIGURE 12—Seismic section of six-fold data using the 25th to 36th recording channels of the middle CDP profile.

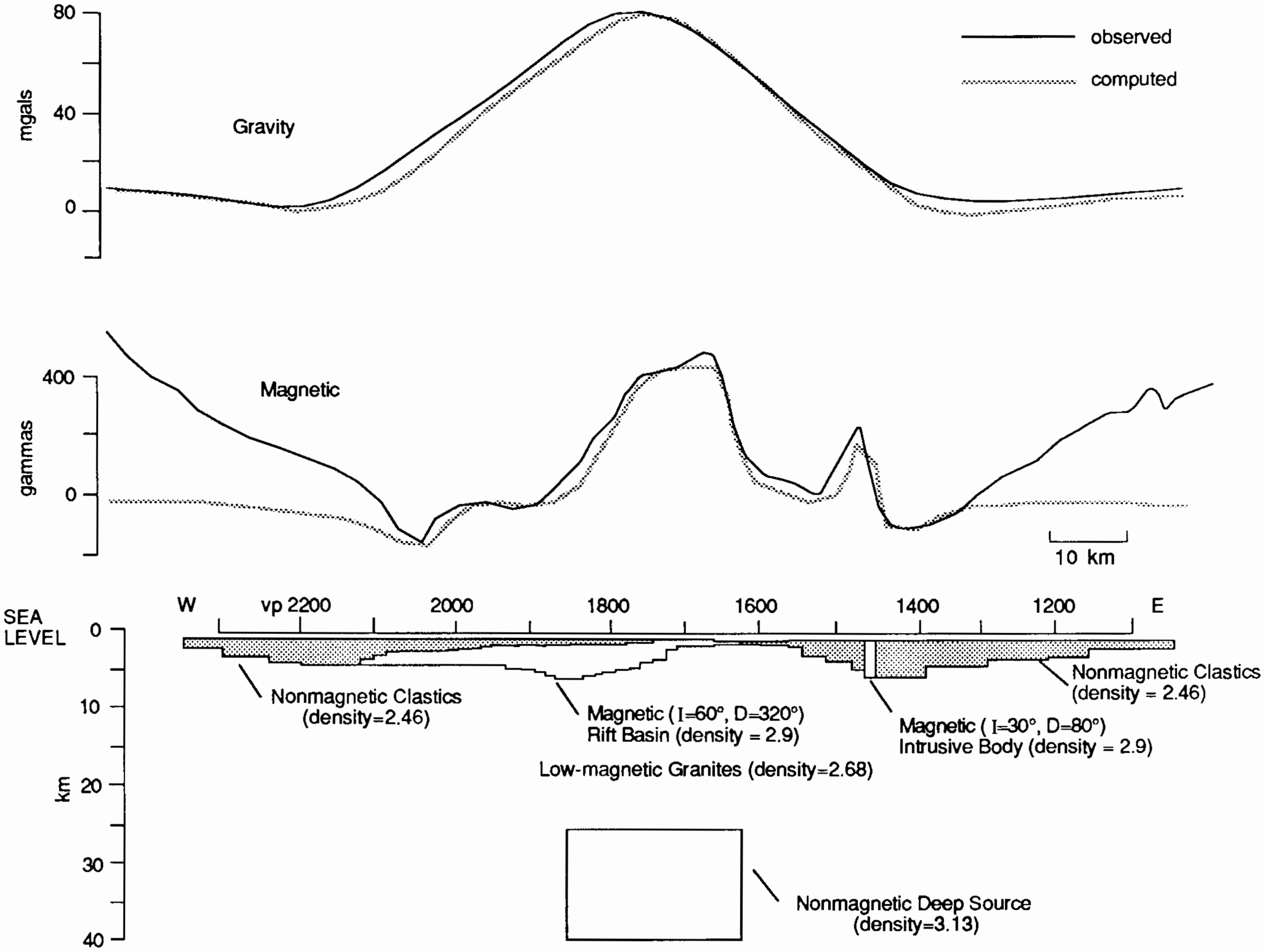

FIGURE 13—FINAL DERIVED MODEL OF THE MGA.

Conclusions

In this study, correlations of different geophysical (gravity, aeromagnetic, and seismic reflection) data along with information from drill data were used to derive a geophysical model of the MGA.

An asymmetric basin of strong seismic reflections, interpreted by Serpa et al. (1984) to be interbedded basaltic and clastic rocks, was tested and modified against the gravity and magnetic data. It was proposed to be mainly responsible for the primary positive magnetic anomaly of the MGA, possibly due to the high magnetite content of basaltic lava in the rift basin in the shallow crust. The favorable net magnetization of 60° inclination and 320° declination indicates that remanent magnetization is an important factor. Magnetic modeling also suggested the western boundary of the rift basin to be extended further to about VP 2040.

Reprocessing part of the COCORP seismic data in the area of the secondary magnetic high on the east side of the MGA and magnetic modeling revealed possible mafic intrusion in shallow crust. Seven of 12 wells, further south of the COCORP east-west line, that encountered mafic rocks of mostly olivine-bearing gabbro (Bickford et al., 1979; Bickford, personal communication, 1984) lie along the trend of the secondary magnetic high. These could be related to the interpreted mafic intrusion. Its favorable net magnetization of 30° inclination and 80° declination suggests it occurred in a different ambient earth's magnetic field than the field presented when the rift-basin basalts were emplaced.

The deeper source of high density at midcrustal to deep crustal levels was included in the final derived model primarily to fit the amplitude and wavelength of the gravity anomaly. It is assumed to have negligible magnetic effect in order not to give a longer wavelength than the observed magnetic data.

The nonmagnetic and negative density contrast on both sides of the MGA, which were correlated to Precambrian sedimentary rocks or Rice Formation, were included to fit the flanking lows of the gravity anomaly. According to the east-west COCORP seismic section processed by Serpa et al. (1984), there are reflectors that may be correlated to the base boundary of the proposed sedimentary basins. Yarger (1983) has shown the magnetic second-vertical-derivative map to have the magnetic quiet zone on both sides of the MGA related to the thick deposition of nonmagnetic sediments.

Finally, according to the final derived model (fig. 13), the crosscutting relationship of the shallow mafic intrusion at VP 1460 and the Rice Formation-filled basins infers that the intrusion was a later event, after the deposition of the Rice Formation. While this paper deals primarily with modeling of several kinds of geophysical data, the ramifications of the modeling could affect petroleum-exploration strategy in the area. It is important to note that late intrusions could provide the heat necessary to induce maturation of hydrocarbons. If the age of such intrusions is late Precambrian, then only the carbonaceous material of the Rice Formation would be affected. If, however, the intrusion is Paleozoic or Mesozoic in age, local maturation of petroleum in Paleozoic rocks could have occurred. The mechanism of local heating was hypothesized by Steeples (1982) to explain the occurrence of small oil fields along the southeastern flank of the MGA in Kansas. Brookins (1970) has shown the Riley County kimberlites to be Cretaceous in age. These kimberlites are located just a few miles from the suspected intrusion discussed in this paper. However, there is no way of knowing what type of rock would make up the intrusion hypothesized in this paper without drilling.

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