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ABSTRACT

An equivalent layer magnetization model obtained from inversion of long wavelength satellite magnetic anomaly data indicates a very magnetic source region centered in south central Kentucky. The magnetization maximum nearly coincides with a gravity high elongated north-south and extending into Tennessee. Previous refraction profiles suggest that the source of the gravity anomaly is a large mass of rock occupying much of the crustal thickness. The outline of the source delineated by gravity contours is also discernible in aeromagnetic anomaly patterns. Taken together, the geophysical data suggest a large, localized mass of intracrustal rock which is both dense and very magnetic. A simple magnetization/density model is given which accounts for the gravity and long wavelength aeromagnetic anomalies due to the body. We interpret it as a mafic plutonic complex, and several lines of evidence are consistent with a rift association. The body is, however, clearly related to the inferred position of the Grenville Front. It is bounded on the north by the fault zones of the 38th Parallel Lineament. The inferred mean magnetization (4 A/m) of the body is large, but not inconsistent with values reported by others for deep crustal bodies associated with long wavelength magnetic anomalies. Such magnetization levels can be achieved with magnetic mineralogies produced by normal oxidation and metamorphic processes and enhanced by viscous build-up, especially in mafic rocks of alkaline character.

INTRODUCTION

A long wavelength magnetic anomaly map of the United States based on satellite total field measurements [1] shows a prominent high centered in Tennessee. An equivalent layer magnetization model derived by inversion of the anomaly data reveals a magnetic source region centered in Kentucky (Figure 1). The model is a representation of large-scale magnetization variation within a layer of arbitrary (40 km) thickness (the top of which is at the Earth's surface) which would give rise to a magnetic anomaly field best-fitting that observed.

The information in such a model represents lateral variation, to some resolution limit, in the mean vertical integral of magnetization from the Earth's surface to the (maximum) Curie isotherm. Compelling arguments can be made that significant magnetization is generally absent from the mantle [2] so that magnetization variations such as those of Figure 1 in general arise from lateral variation in mean magnetization within the crust and/or Curie isotherm undulations where they occur within the crust in areas of high heat flow. However, because the high altitude of the data limits the resolution of magnetization models to very long wavelengths, it is possible that the magnetic source region referred to in Figure 1, which appears to be spread out over a very large area, could represent a very poorly resolved, much more local source having an exceptionally large magnetic moment. An example is the anomaly due to the Kursk magnetite ore deposit of the Soviet Union, which is clearly seen in the map of Regan et al [3]. Why the crust in and around Kentucky might have anomalous magnetization relative to surrounding areas is not at all evident from regional geologic maps. However, geophysical data, described next, indicates a large mass of unusually magnetic (and dense) rock centered beneath Kentucky (we refer to it as the "Kentucky body"). The Kentucky body contributes substantially to, but probably cannot fully account for, the magnetic anomaly measured at the satellite.

OTHER GEOPHYSICAL ANOMALIES

Regional gravity maps such as [4] show a prominent high in central Kentucky, elongated nearly north-south and extending into Tennessee. The anomaly is roughly 200 km long, 70 km wide, and has a relief of up to 70 mgal. Its maximum nearly coincides with the magnetization maximum of Figure 1, suggesting a common source. As discussed later, the anomaly probably sits on the Grenville Front. Figure 2, excerpted from the regional Bouguer gravity map published by the Tennessee Valley Authority [5], shows the anomaly in some detail.

Two refraction profiles [6] have their end points near the gravity maximum; these are shown in Figure 2 in fence diagram form. The east-west line shows a dramatic apparent thickening of the lower crustal layer passing through the gravity gradient into the anomaly. The north-south line shows a similar step in the intra-crustal refractor, which again occurs at the gravity gradient coming off the south end of the main part of the anomaly. A published [7] travel-time graph for this refraction line clearly shows a large, abrupt offset of the refractor; the authors commented on the unusual clarity of arrivals from it. While giving a simple image of complex crustal structure, the refraction results do suggest that the source of the gravity high is strong relief in a surface of positive density contrast.

The gravity high has a characteristic magnetic anomaly pattern associated with it. Figure 3 shows selected contours from the aeromagnetic map published by the TVA [5]; the -30 mgal contour from Figure 2 is also shown to indicate the position of the body. In the vicinity of the body a high-frequency, high amplitude anomaly pattern is present, and is separated by a prominent linear low from more subdued anomalies to the west. The same kind of relationships characterize the Grenville Front in Ohio [8] as defined by boreholes to basement (pre-Grenville volcanics to the west, their presumed metamorphic equivalents bearing Grenville ages to the east of the Front [9]. Further, an elongate gravity anomaly occurs along the Front in Ohio having the same relationship to the high frequency magnetic anomaly pattern as the gravity anomaly associated with the Kentucky body. By analogy with the situation in Ohio we draw the position of the Grenville Front in Kentucky on the basis of the geophysical anomalies and the few boreholes to basement near it. Keller et al [10] drew it similarly, mainly on the basis of the basement sample descriptions published by them.

Of importance to this study is a large-amplitude, long wavelength magnetic anomaly which can be picked out of the high-frequency pattern; it is nearly coincident with the large gravity anomaly, and in the next section we model it as arising from magnetization associated with the Kentucky body as a whole.

Some other important anomalies are seen in Figure 3. The northeast-trending gradient in the lower right corner of the map is a bit of the "New York-Alabama Lineament" of King and Zietz [11]. To the west of the body is a cluster of prominent magnetic anomalies having the appearance of being associated with a volcanic complex, but no borehole information is available to confirm this. Subdued gravity anomalies are associated with it (Figure 2). A magnetic lineament runs southeast through the complex, appears to cut off the Kentucky body at its south end, and ends at the magnetic gradient. Although the western anomaly complex is different in character from the anomalies associated with the Kentucky body, the connecting lineament suggests some genetic relationship.

MODEL

Figure 4 shows cross-sections of two models of the Kentucky body which account for the long wavelength aeromagnetic and gravity anomalies over it. Both are simple three-dimensional models consisting of stacks of half-kilometer-thick, four-sided prisms positioned to conform with the anomaly contours. Gravity and magnetic anomalies were computed by programs which follow [12]. Magnetization was assumed to be by induction in the Earth's main field. The magnetization value is not closely defined, but can hardly be more than 20% from that shown. Densities for the crustal layers away from the body were computed by least squares for the entire refraction section [6] to the Atlantic coast and show excellent agreement with the observed Bouguer gravity anomaly profile. Densities are relative to Talwani's standard section [13].

We thought at the start of this study that we would find that the satellite magnetic anomaly is due to the Kentucky body, since we knew that, at the satellite, a local source gives rise to an anomaly with wavelengths comparable to that observed. However, when the magnetic model of Figure 4 is computed at satellite elevations, its anomaly amplitude is found to be much too small and slightly displaced from the observed anomaly. The probable explanation is that the aeromagnetic anomaly due to the body is only one of several high amplitude, long wavelength anomalies in the area (the principal ones can be seen in Figure 3) which combine to form a single broad anomaly at the satellite. Further, this is superimposed on a broad regional high due to a generally enhanced crustal magnetization in the eastern midcontinent (Figure 1), the eastern margin of which (at least in the south) is King and Zietz's New York-Alabama lineament. This magnetic gradient is especially evident in [14], and apparently corresponds to the magnetization gradient in Figure 1 which separates the positive area of the Appalachian plateau and eastern midcontinent from more negative area to the east, the axis of which overlies the Appalachian piedmont. These inferences are supported by the work of Phillips and Hildenbrand [15], who upward continued aeromagnetic data from Kentucky and Tennessee to satellite elevation, and showed an excellent agreement with the satellite anomalies.

REGIONAL STRUCTUAL SETTING

The Kentucky body is located at the confluence of several important structural elements (Figure 5). The principal associations we summarize as follows. The body appears to be bounded on the west by the Grenville Front, and beyond that the broad linear zone of basement uplift formed by the Nashville Dome and Cincinnati Arch. The main part of the body sits adjacent to a sag in the zone of uplift. It is bounded on the north by the "38th Parallel Lineament" [16]. Just northwest of the body and north of the fault zones defining the lineament is the Jessamine Dome, the highest part of the Cincinnati Arch, and the locus of intense faulting and mineralization [17]. The south end of the body occupies the narrow wedge formed by the convergence of the Allegheny Front on the Grenville Front. The main part of the body further appears to be cut off on the south by the aeromagnetic lineament referred to previously. Some of these relationships are discussed in more detailed below.

In Ohio and Kentucky the Grenville Front is drawn on the basis of basement sample descriptions of Lidiak (in [18]), and on the basis of gravity and magnetic anomaly patterns as noted earlier. As defined this way, the Front bounds the body on its west side. The long wavelength gravity and magnetic anomalies due to the body do not, however, seem to be of the kind generally associated with the Front elsewhere. The Grenville Front in Canada has an important gravity signature which has been interpreted as an edge anomaly due to a suture zone located within the Grenville province, and separating Grenville and pre-Grenville crustal blocks [19]. But this anomaly is much broader than that due to the Kentucky body, it is relatively more asymmetrical, and in fact, it is its minimum which overlies the Front. A complex zone of positive gravity anomalies occurs in Lake Huron and the thumb of Michigan, and was used with other information [20] to draw the Grenville Front there, but again the character of these anomiies is unlike that due to the Kentucky body. Important linear magnetic anomalies occur along the Front in Canada [21,22]. These anomalies tend, however, to be significantly narrower than the long wavelength anomaly due to the Kentucky body.

Keller et al [10,23] described a chain of gravity highs trending south from Lake Michigan through northeastern Indiana and western Ohio into northeastern Kentucky to just north and east of the Kentucky body. Based on similar geophysical character of this zone with the Midcontinent rift zone, and a possible association with bimodal volcanics of Keeweenawan (1.0-1.3 b.y.) age, this zone was interpreted as an aborted rift. The zone of gravity highs lies south of a similar linear gravity high crossing the Michigan Basin which has been inferred to be an extension of the Midcontinent rift [24]. Keller has suggested that the zone of gravity anomalies is continuous with the anomaly due to the Kentucky body, and named the zone as a whole, which he extends on through to Alabama, the "East Continent Gravity High".

Like the Mid-Michigan anomaly, the zone of gravity highs crosses the Grenville Front (in Ohio) obliquely, and extends well into the Grenville Province. Unlike the Mid-Michigan anomaly, where it crosses the Front a lobe extends off the zone parallel to the Grenville Front, with the Front bounding it on the west; it resembles the gravity anomaly due to the Kentucky body in miniature.

The 38th Parallel Lineament passes between the gravity anomaly zone referred to and the Kentucky body; it is represented here by the Kentucky River Fault Zone which forms the north boundary of the Rome Trough and further east becomes "Woodward's Line", a zone of dramatic thickening to the south of Lower Cambrian sediments [25]. If the gravity anomaly zone to the north and the Kentucky body are parts of the same structure, they appear to be offset at the fault zone [16,26]. It has been claimed [10,27] that no significant offset can have occurred for over 1 b.y., but it is possible that the two segments formed offset, or were offset, in pre-Grenville time along an important fault zone which was the locus of continuing relative movement through the Paleozoic.

Plate models for the evolution of the Grenville Province in Canada have been advanced which involve the opening of a rifted ocean basin around 1200 m.y. ago (Keeweenawan or Neohelikian time), followed by subsequent closing leading to the Grenville orogenic eposides (e.g., [19]). If such a model is to be applied in the present area, the gravity high running from Lake Michigan into Ohio, if it is the expression of a Keeweenawan-age rift zone, must be interpreted as a failed arm or aulocogen running obliquely off the main rift. If the Kentucky body is part of such a structure, it can readily be interpreted as a mafic intrusive complex, an interpretation consistent with its properties (Figure 4). It is clearly associated with the Grenville Front, however, and perhaps the situation here is like that along the northern Grenville Front in Labrador where the Grenville Front Zone [28] is the site of early rifting and formation of the Seal Lake volcanics (and their Gardar counterparts in South Greenland). Further support for rifting is found in a core from a basement well in northern Tennessee over the southern part of the anomaly which contains peralkaline riebeckite syenite [10], a rock commonly formed by differentiation of mafic alkaline magmas or by alkali metasomatism of country rocks by carbonatitic-alkaline magmas; both magma types are characteristic of a rift tectonic environment.

The similarity in form of the gravity signature of the Kentucky body with that associated with other rifts inferred to be underlain by mafic intrusive complexes supports the above interpretation. The near-surface long wavelength gravity and magnetic signatures of the Midcontinent rift zone and the mid-Michigan rift are similar in form, dimensions, and amplitudes to the corresponding Kentucky anomalies. [11] modeled the former, and [24] the latter, as basalt-filled rifts. However, the gravity anomaly of the Midcontinent rift has been modeled [29,30] as a deep structure extending through much of the crust; the latter study involved extensive seismic control. Such models are quite analogous to our model for the Kentucky body. We also note the remarkable likeness between the gravity anomaly due to the Kentucky body and the Scranton Gravity High [31] both in dimensions and amplitude (Figure 7). The anomaly was interpreted [31] as the expression of a rift structure, but presumably it is related to the following Wilson cycle in which the Iapetus or Proto-Atlantic Ocean was formed during the late Precambrian and early Paleozoic [32]. Curiously, however, the Scranton structure nas no prominent associated magnetic anomaly.

SOURCE OF MAGNETIZATION

We have hypothesized that the Kentucky body is a mafic intrusive complex, possibly localized along a Precambrian rift. The mean magnetization of the body inferred from our models is about 4 A/m. This value is high compared with values measured on samples of mafic intrusive rock, and implies several volume percent equivalent magnetite. From the model of Figure 4 we cannot closely specify how the magnetization is distributed within the body except that it cannot be strongly concentrated at the top or bottom, but such a large mass of plutonic rock is undoubtedly quite heterogeneous locally, and magnetization values in parts of the complex are likely to reach substantially higher levels. We review briefly in this section the question of whether the inferred magnetization of this body is consistent with a large mafic intrusive mass, or whether a more exotic rock type or alteration history must be hypothesized.

Primary magnetic mineralogies of basic suites of igneous rocks tend to be titanomagnetites within the ulvospinel ($Fe_2 TiO_4$) - magnetite ($Fe_3 O_4$) solid solution series, characterized by both low initial saturation magnetizations and low Curie temperatures. However, the processes of 1) oxidation-exsolution, induced by slow cooling under moderate oxygen fugacity, and 2) high temperature deuteric oxidation lead in time to magnetite-rich rocks with large and stable magnetizations and high Curie temperatures; both processes are prevalent in basic intrusive suites [33]. Even in the absence of oxidation exsolution, a basic titanomagnetite would be expected to decompose via exsolution per se into a Ti-poor titanomagnetite with Curie point near 550°C.

We have been accumulating laboratory data which strongly indicates that Curie temperatures of around 560°C predominate in the deep crust. Curie points for granulite grade rocks from Precambrian terrain in Brazil, Canada, Scotland, Uganda, India and the United State are all in the vicinity of 560°C. Granulite grade rocks from the Ivrea zone have Curie points in the vicinity of 570°C, and granulite xenoliths from the Colorado Plateau have Curie points in the vicinity of 560°C. If the Curie temperature of the Kentucky body is around 560°C, then its magnetic bottom may extend well below the regional Moho of this low heat flow region, as in the lower model of Figure 4.

Metamorphic effects may also be of importance. Unless the Grenville Front represents the thrust front of a mass of metamorphic rocks transported to the vicinity of the Kentucky body from well to the east, the body has very likely been subjected to high-grade metamorphism. Metasomatic alteration associated with metamorphism may be destructive to magnetic minerals, but under certain conditions magnetization may be enhanced [33]. Decomposition of olivine, which occurs in high temperature deuteric oxidation, produces single domain grains of magnetite and hematite having large magnetic coercivities and magnetic moments [33]. Hall et al [34] examined samples of magnetite-bearing metavolcanic rocks from the Kenora province in Canada, and found that the common exsolution phenomenon in titanomagnetites was not present; rather, titanium was found to have separated out in discrete grains of ilmenite, leaving magnetite. Similar observations have been made on mafic rocks recrystallized at high temperature within the lower structural levels of the Ivrea zone.

In addition to the above mechanisms for creating more magnetic mineralogies, acquisition of viscous remanence at elevated temperatures at depth is itself an important mechanism for enhancing magnetization (e.g. [35]). These authors note that magnetizations of basement samples under larger magnetic anomalies, when held at elevated temperatures for a period of months, built up to values of 2-3 A/m.

We have discussed evidence that the Kentucky body is rift-related. It is worth considering magnetizations of rock types charcteristic of this tectonic setting. During the early doming and crustal extensional stages of continental rifting, magmatism consists largely of mantle-derived mafic undersaturated alkaline melts. With greater crustal extension and thinning, the magmas may become tholeiitic due to greater degrees of melting as well as a lower pressure more shallow depth of equilibration, and most rifts contain both alkalic and tholeiitic rocks. This analysis is supported by reported petrologies of the east African Rift, the Oslo Rift, the Rhine Graben, the Rio Grande Rift and the Monteregian Province of the Ottawa Graben.

Although almost no data exists for the magnetic properties of titanomagnetites in mafic alkaline rocks, rough estimates of magnetite content and thus potential magnetic susceptibility can be made from C.I.P.W. normative calculations. Chemical analyses and norms from [36] for average nephelinite and average tholeiite indicate higher total iron, oxidation index (as reflected by the ratio $FeO: Fe_2O_3$) and normative magnetite content for the average nephelinite as compared to the average tholeiite. It has been suggested [37] that oxygen fugacities (fO_2) for alkaline rocks are higher than that of the quartz-fayalitemagnetite oxygen buffer attendant during tholeiite crystallization, thus increasing the magnetite content of the associated rocks. Normative magnetite values from Nockold's calculations are 10.4% and 4.2% for the nephelinitic and tholeiitic averages respectively. The estimates are expected to be slightly high as normative magnetite, hematite and ilmenite are usually higher than modal amounts; also basalt data is used due to a scarcity of gabbro data, and basalts crystallize under higher fO_2 than gabbros. The magnetite contents do not appear to be out of line; Gold [38] estimates that the average Monteregian alkaline rock contains 5-10% modal titano-magnetite which results in aeromagnetic anomalies of up to several thousand nT amplitude (Gold, personal communication, 1981). Maximum values of magnetization for magmas containing alkaline and tholeiitic basalts, using the relationship of rock magnetite content to magnetic susceptibility [39] for the above data range from approximately 3-10 A/m equivalent induced magnetization (for the magnetic latitude of the Kentucky body).

We note that the mean magnetization of the Kentucky body is comparable with values inferred from other large-scale model studies of deep crustal magnetization. Notably, Coles [40] modeled an anomaly near Fort Nelson, British Columbia, as a body having very similar dimensions and magnetization as the Kentucky body. Coles and Haines [35] note that it is one of several anomalies which collectively produce a ridge of anomaly high measured by the Pogo satellite. Similarly, a prominent magnetic anomaly in Sweden has been modeled [41] as a large body extending through much of the crust and having magnetization 3-5 A/m. This anomaly is also seen by the Pogo satellites [42]. We also note that the Kentucky body magnetization is comparable with that inferred from long wave length aeromagnetic anomalies and ascribed to basic rocks assumed to make up the lower crust in Canada [43] and the Soviet Union [44].

Our research on lower crust xenoliths, the Ivrea Zone, and granulites from Precambrian shield areas suggests that the highly magnetic rocks which are widespread and could conceivably cause the long wavelength anomalies have a parentage which suggest large scale mafic intrusives from the upper mantle. Numerous crustal models developed as a result of xenolith studies and studies of the Ivrea zone which have appeared in the literature all have as common occurence in the lower crust a layered basic sequence of varying thickness. The gravity anomaly for the Kentucky body supports the existence of this type of lithology. A massive sequence of mafic cumulate rocks which contain titanomagnetites which have through oxidation-exsolution or exsolution decomposition produced material with' 550°C Curie points is reasonable for the Kentucky body.

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FIGURE CAPTIONS

Figure 1. Portion of equivalent layer magnetization model of Mayhew [1] for eastern United States. Model is apparent mean magnetization contrast in a 40 km thick layer obtained from inversion of Pogo satellite magnetic anomaly data. Contour interval is 0.1 A/m. Resolution is limited by the data elevation to several hundred kilometers, and magnetic source region in Kentucky and Tennessee centered on K is such more restricted than is suggested by the contours.Inset box shows area of Figures 2 and 3.

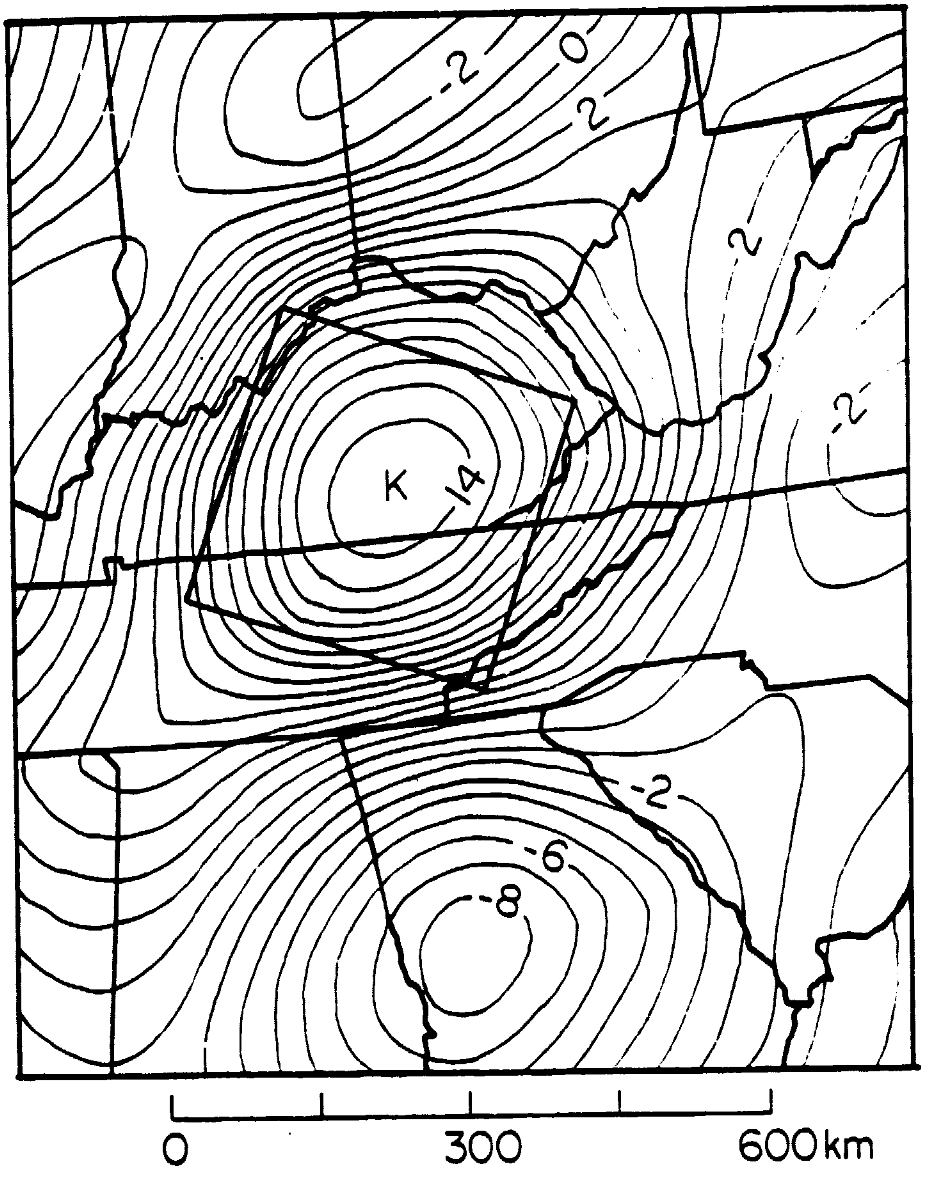
Figure 2. Bouguer gravity from [5]. Contour internal 6 mgal. Refraction profiles in fence diagram form from Warren (1968); depth scale is marked off in 10 km intervals. Inferred position of Grenville Front is heavy dashed line. Light dashed line is aeromagnetic low from Figure 3.

Figure 3. Aeromagnetic anomaly contours from [6]. Values are hundreds of nT, contour interval 400 nT. -30 mgal contour from Figure 2 is heavy solid line. Unornamented profile line is location of refraction profile; line with bar at end is location of model profile (Figure 4).

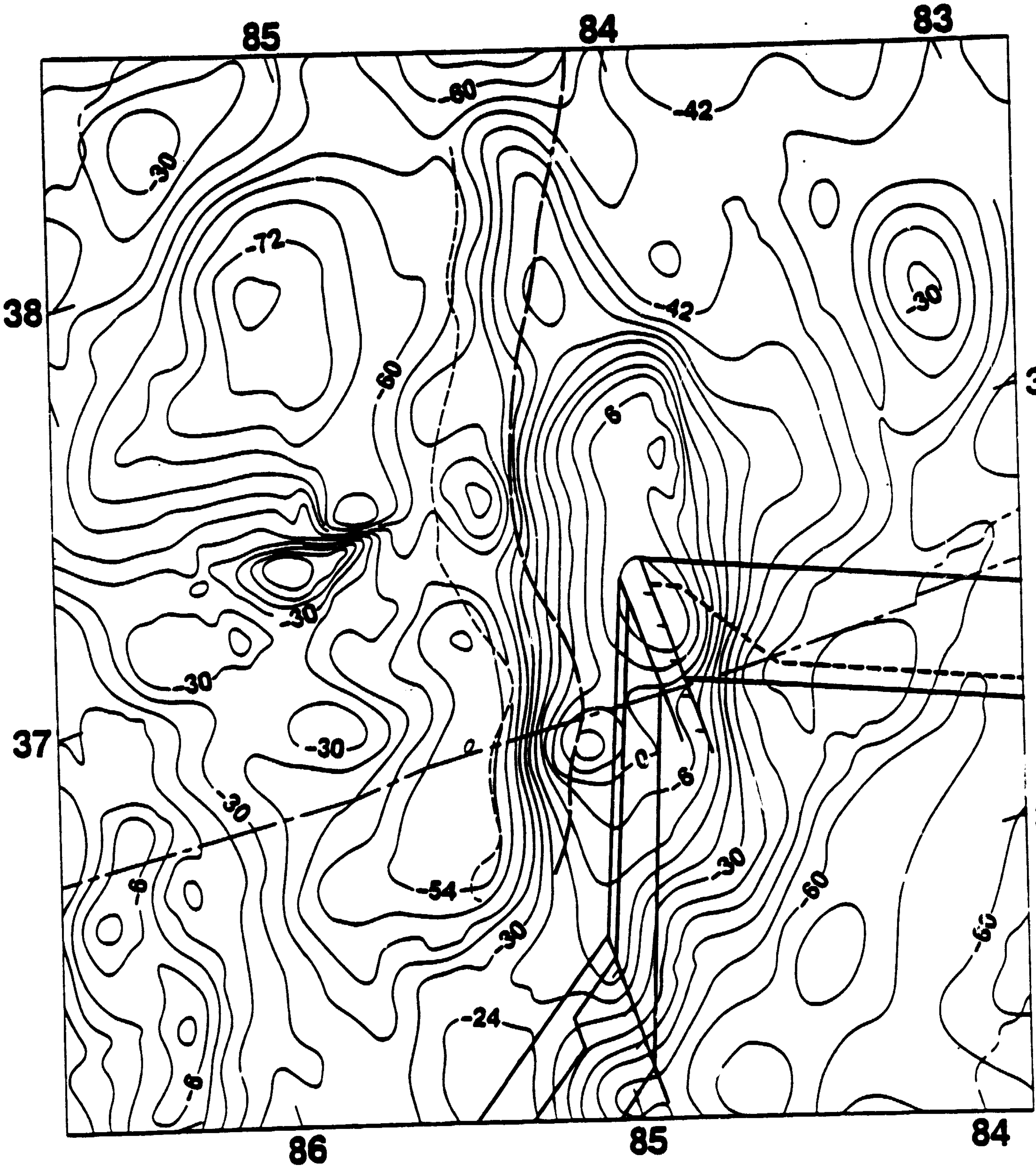
Figure 4. Alternative models for the Kentucky body. Model A extends to the local Moho; model B is in local isostatic equilibrium. Assigned magnetization and density are not significantly different, but in model B the flanking gravity lows are somewhat better accounted for. Computed anomalies shown in heavy solid lines. Thin solid lines are observed profiles along section line of Figure 3; thin broken lines are observed profiles along a parallel line 5 km to the south. Observed magnetic anomalies are relative to arbitrary datum.

Figure 5. Tectonic elements in region surrounding Kentucky body. -20 and -30 mgal gravity contours from DOD compilation shown as heavy solid lines to indicate significant highs (h). Cincinnati Arch delineated by zero level structure contour (dot-dash line) on top of Trenton [45]. Heavy long-dash line is inferred position of Grenville Front. Generalized faults of 38th Parallel Lineament principally from [46] and [27]. RCG is "Rough Creek Graben" [47]. Other symbols are as follows. WL: "Woodward's Line," ECGH: East Continent Gravity High [23], MMGH: Mid-Michigan Gravity High [24], LFZ: Lexington Fault Zone [27], JD: Jessamine Dome, PMT: Pine Mountain Thrust. Position of Kentucky body as delineated by gravity contours labled KYB. Aeromagnetic lineament referred to in text shown as short dash line. Small circles are selected basement core locations of Lidiak [18]. Solid circles are medium to high grade metamorphics. Open circles are felsic volcanics; circles with dots are basalts. Core samples of low grade metamorphics, sedimentary rocks, and plutonic rocks not shown.

Figure 6. Bouguer gravity contours from DOD gravity tape for Scranton Gravity High and that associated with Kentucky body.



-2
0
2
-2
-2
K
14
-2
-6
-8
0
300
600 km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84
83
38
37
37
36
86
85
84
-60
-42
-30
-72
-42
-30
-60
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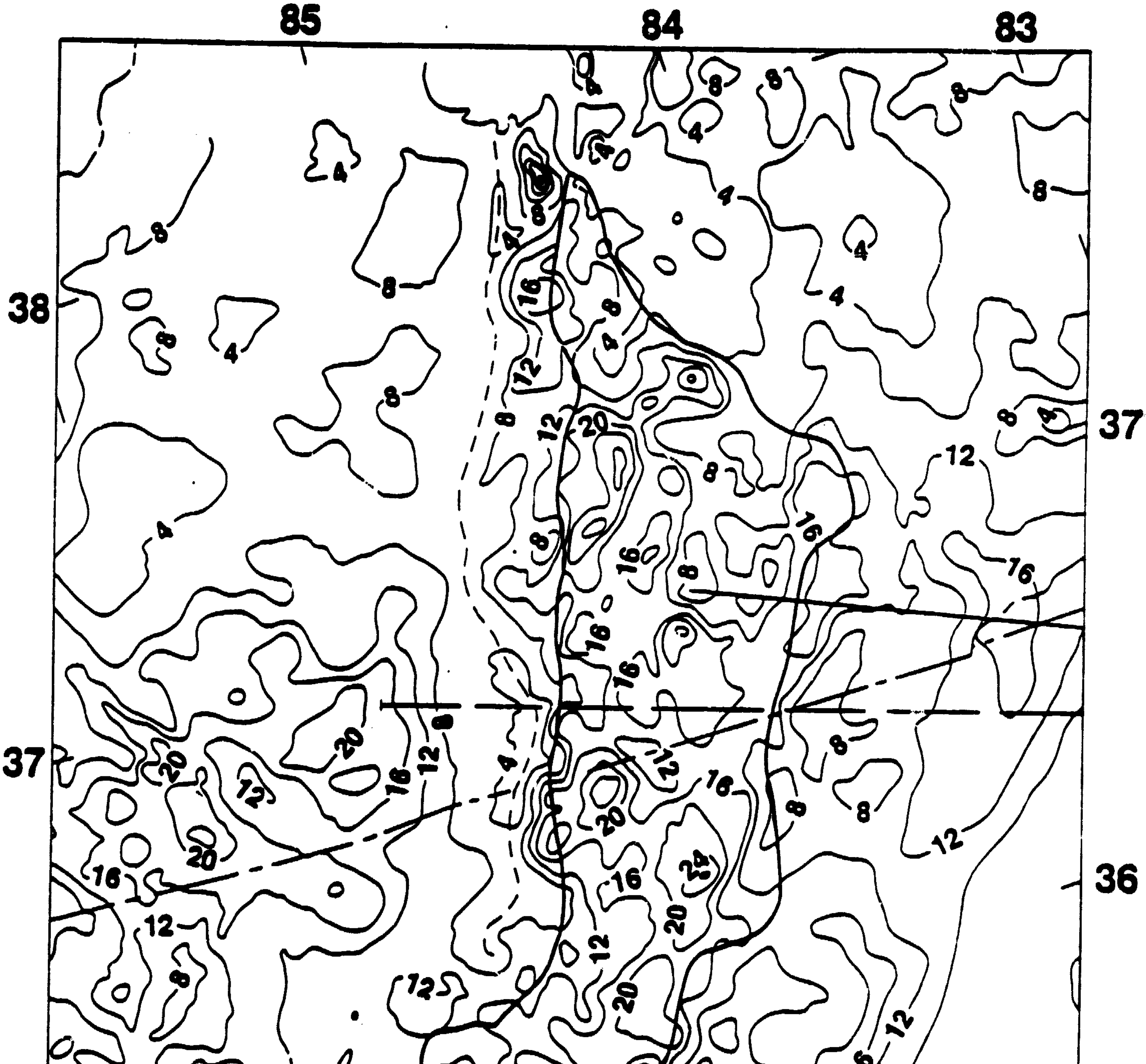
-60
-6
-24
-6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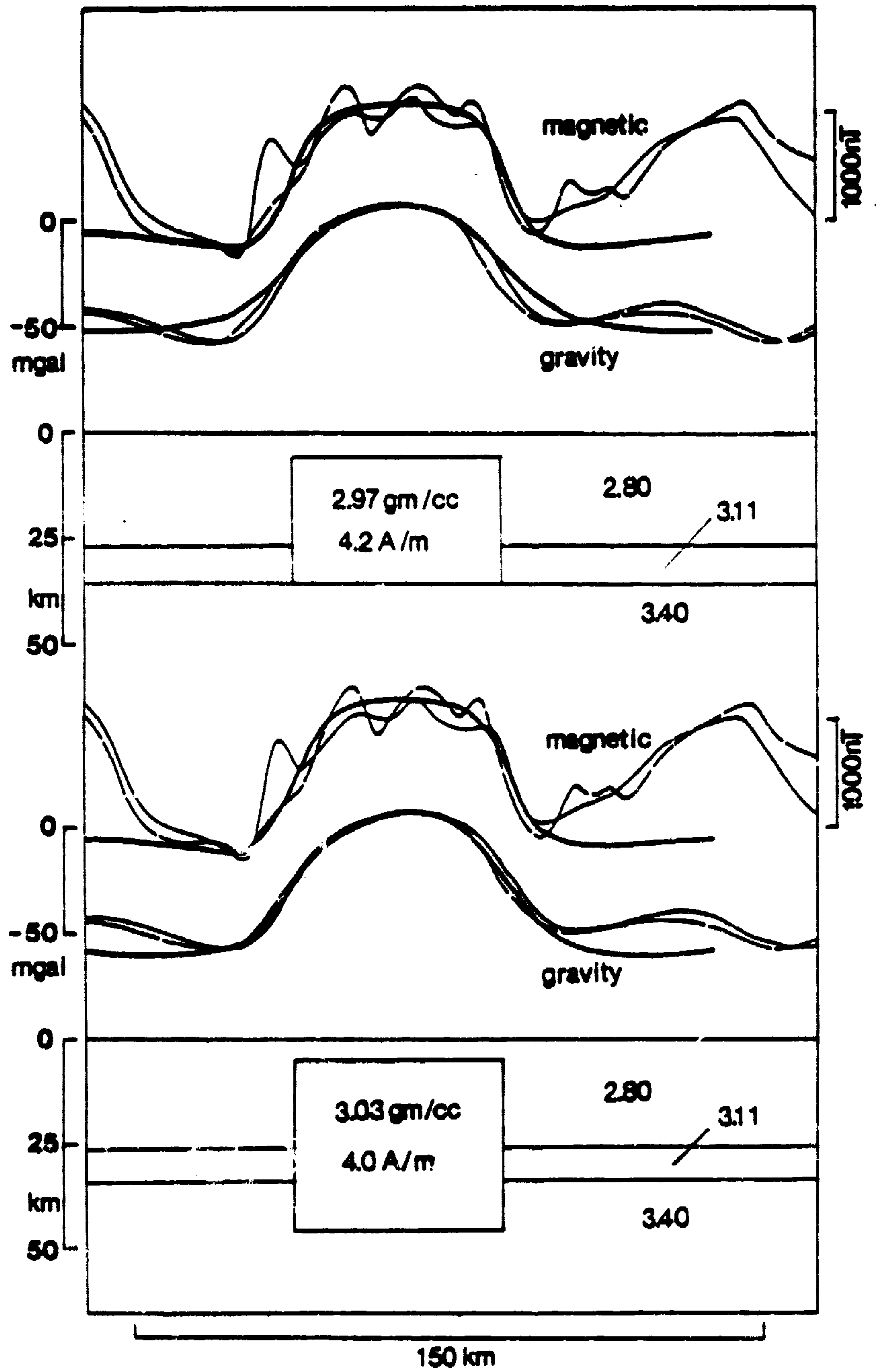
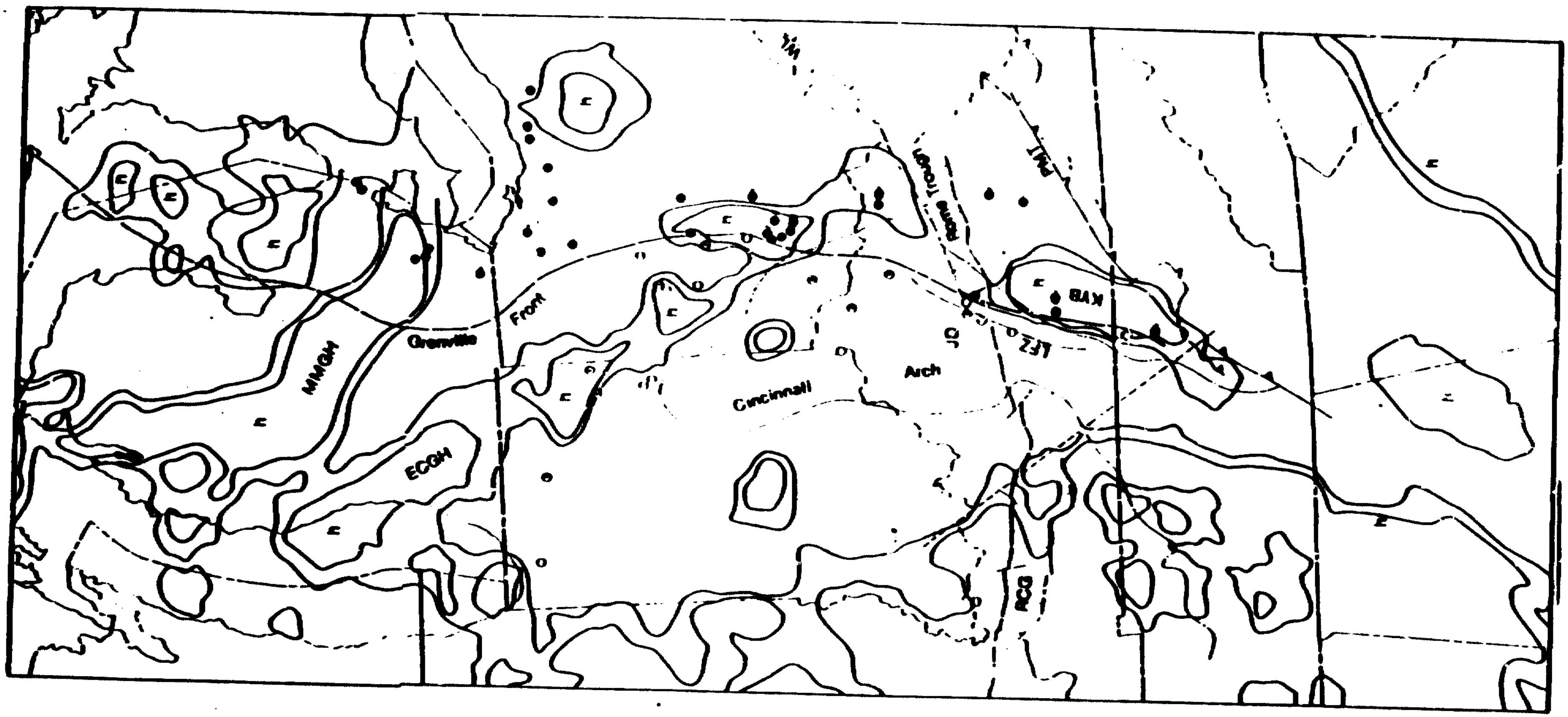
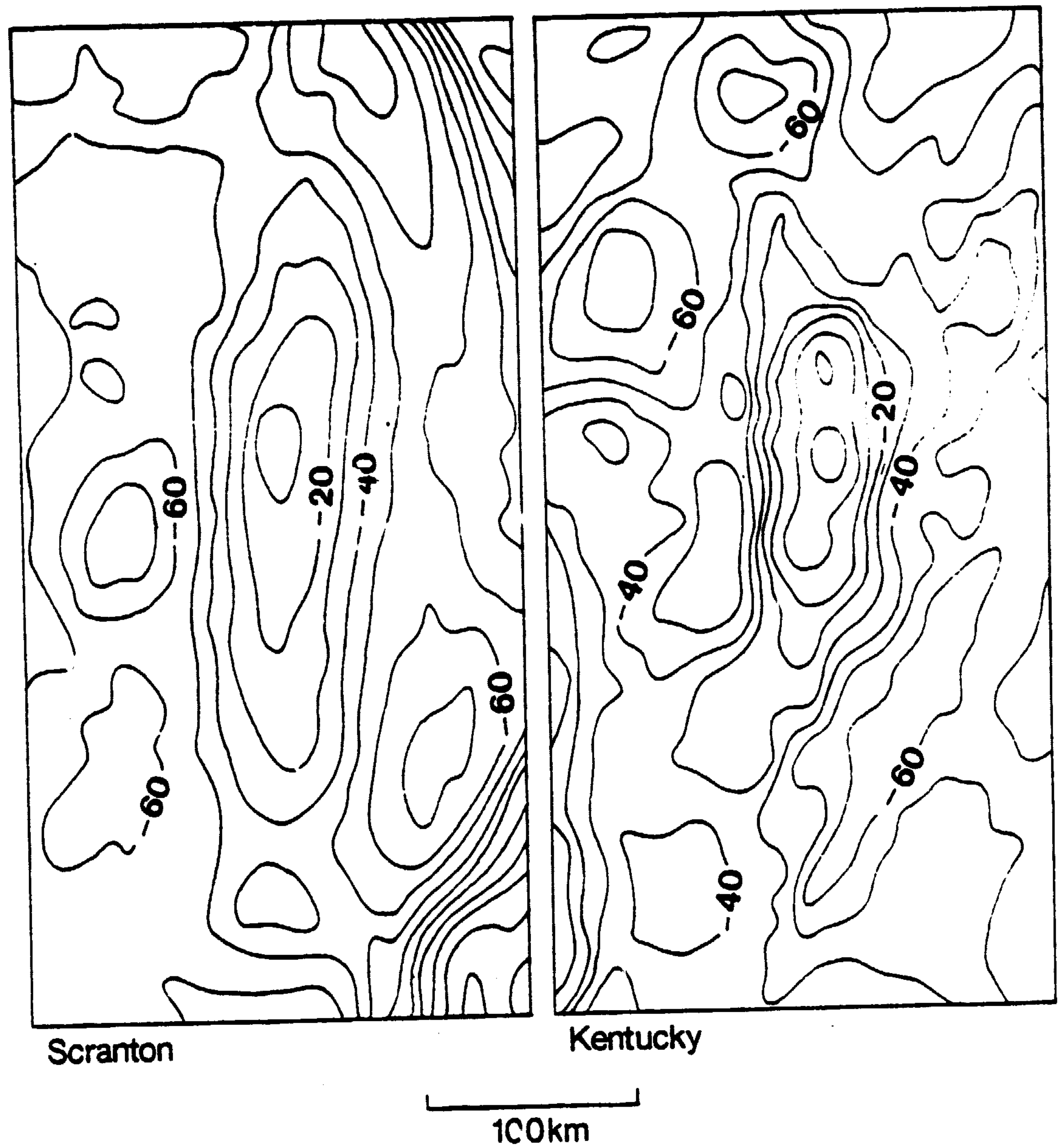
38
37
36
86
85
84



magnetic
1000nT
0
-50
mgal
gravity
0
2.97 gm/cc
4.2 A/m
2.80
3.11
25
km
3.40
50
magnetic
1000nT
0
-50
mgal
gravity
0
3.03 gm/cc
4.0 A/m
2.80
3.11
25
km
3.40
50
150 km


MMGH
ECGH
Grenville Front
Cincinnati Arch
Rome Trough
RCG
LFZ
KYB
PMT
JC


-60
-60
-20
-40
-60
-60
-60
-20
-40
-40
-60
-40
Scranton
Kentucky
100km