INTERPRETATION OF MAGNETIC ANOMALIES OVER SOUTHERN IDAHO USING GENERALIZED MULTIBODY MODELS

by

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ABSTRACT

Data from several aeromagnetic surveys over southern Idaho, flown at different times, elevations, and line spacings, have been integrated into a consistent digital data set at a fixed elevation of 3.8 km above sea level. The integrated magnetic field then was continued upward to the levels of 7.6 km and 11.4 km above sea level. The dominant feature in the magnetic maps of southern Idaho is a zone of high intensity over the Snake River Plain. Over the western part of the plain, the magnetic anomaly pattern is relatively simple, with a high along the south edge and a low along the north edge of the plain. The eastern part of the plain is characterized by a complex anomaly pattern having numerous highs and lows. The Idaho batholith lies in an area of low-amplitude anomalies. Large magnetic anomalies are produced by Tertiary intrusive and extrusive rocks east and west of the Idaho batholith. Anomalies in some areas southeast of the Snake River Plain are apparently associated with the Precambrian basement.

A method using generalized multibody models has been applied to the inversion of magnetic anomalies over the horizontal surface at a height of 7.6 km above sea level. A three-layer model is selected for the analysis. The direction of magnetization is constrained to lie within ±15 degrees of the normal or reversed direction of the present geomagnetic field vector. The results of analysis provide generally satisfactory interpretation of the magnetic anomalies. Reasonable estimates have been obtained for the depth to the top and the thickness of an upper layer of magnetic material consisting mainly of basalt and silicic volcanic rocks. This material is often overlain by nonmagnetic rocks. The thickness of both magnetic and nonmagnetic near-surface materials ranges from a few hundred meters to a few kilometers. The magnetized bodies in the middle layer are responsible for the generation of a majority of the larger observed anomalies. Major intrusive bodies, at least 6 km thick, are detected in the magnetic data over many areas, particularly in the eastern Snake River Plain and in the areas to the north. At Craters of the Moon and the northeastern end of the plain, elongate highly magnetized zones underlie major volcanic rifts. The Idaho batholith seems to consist of uniform, weakly magnetized rocks from the surface to a depth greater than 6 km. The bottom of the magnetic crust ranges in depth from 7 to 26 km below sea level, agreeing well with depths to the top of the highly conductive crust interpreted from magnetotelluric soundings in eastern Idaho.

INTRODUCTION

A method using a generalized multibody model for the inversion of magnetic anomalies has been described by Bhattacharyya, (1980). The method has been used for the inversion of the magnetic anomalies in southern Idaho. This paper summarizes the results of this first large scale application of the method.

The regional surface geology of southern Idaho is moderately well known. However, only a few deep holes have been drilled and detailed geophysical surveys cover only a small part of the area. Thus, major uncertainties exist relative to the subsurface geology. The cause of some of the regional magnetic anomalies is apparent but many of the anomalies cannot be correlated with known geologic features. The results of inversion of the anomalies are compared with the geology as known from surface mapping and drilling and inferred from other geophysical data. This process leads to an extension of the knowledge of the subsurface geology.

TREATMENT AND ANALYSIS OF MAGNETIC DATA

Magnetic data

Aeromagnetic surveys were made in southern Idaho with flight lines over most of the area at an elevation of 3.8 km above sea level and from 1.6 to 9.3 km apart. Published maps of the magnetic data at the scale of 1:500,000 and 1:250,000, contoured with an interval of 20 gammas, are available. The magnetic data were digitized from the contour maps with a grid spacing of 1.9 km. The digitization interval is one-half of the flight elevation, and very little information on the regional anomalies is lost in the digital representation of the maps.

A cubic surface in both x and y were fitted to the data by the principles of least squares in order to determine the 'regional'. East-west and north-south regional gradients of -1.5 and 0.71 gammas for a distance of 1.9 km respectively were subtracted from the digitized magnetic data to obtain the residual field values. The residual magnetic map is shown in Figure 1. To check for the presence of terrain-induced anomalies, a topographic map was prepared using available digital data. No evidence of even moderate correlation between the residual magnetic map and the topographic map was apparent, indicating the absence of any appreciable anomaly induced by terrain magnetization.

Figure 1.--NEAR HERE

Many small wavelength features in the residual map (Figure 1) are not suitable for regional interpretation. For this reason, the digital magnetic data were continued upward by recursion filters (Bhattacharyya, 1976) to two levels; 7.6 km above sea level (Figure 2) and 11.4 km above sea level (Figure 3). The maps of upward-continued field values, particularly the map in Figure 3, are useful in qualitative regional interpretation. For quantitative analysis, however, the map at 7.6 km above sea level is used exclusively.

Figures 2 and 3.--NEAR HERE

Procedure for analysis of data

The analysis of magnetic data (Figure 2) was carried out by a new method for three-dimensional modeling of magnetic data, as described in the companion paper (Bhattacharyya, 1980). We assume a magnetic rock mass, hereafter called a unit, surrounding the area that is located vertically below the area containing the data of an observed anomaly. The height of the observational surface from the magnetic sources primarily determines the critical dimension of the smallest inhomogeneity in magnetization that can be resolved from the data. This critical dimension is approximately 1.5 h, where h is the height of the observational surface above the magnetic sources. A block with square horizontal cross-section having sides approximately equal to this critical dimension is viewed from the observational surface as homogeneously magnetized. The unit is divided into a number of these blocks horizontally and vertically. Though each block is homogeneously magnetized, there may be change in magnetization from one block to the other.

The total field generated by the distribution of blocks representing the rock mass is then compared with the field observed at all the observation points in the area of the observed anomaly. The mean-square error, which is the sum of squares of the differences between observed and calculated field values for all the observation points, then can be determined. An iterative approach is used to adjust the strike of the rock mass and the vertical extents of individual blocks for minimizing the mean-square error. Most of the magnetic anomalies in southern Idaho appear to be produced by induced magnetization or by remanent magnetization in Cenozoic volcanic rocks magnetized approximately in the normal or reverse direction of the present geomagnetic field. The magnetization vector was, therefore, constrained within ± 15 degrees of the normal or reversed direction of the present geomagnetic field vector. The distribution of magnetization obtained at the end of the iterative process delineates the magnetized source in the region under study.

Model

The selection of a model representing the magnetized source is extremely important to the interpretation of magnetic data. Based on resistivity, magnetotelluric, seismic refraction, and geologic data, the three-layer model shown in Figure 4 was chosen. Initially it is assumed

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Figure 4.--NEAR HERE

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that the regions separating the layers are not magnetized. Figure 4 shows the different layers and blocks into which the magnetized rock mass is divided. Each of the two top layers consists of nine rectangular blocks. The third layer is not subdivided into blocks because it is expected to be at such a great depth that inhomogeneity in magnetization of blocks of relatively small horizontal dimension cannot be resolved from the observed data. In the discussion on results of analysis of magnetic anomalies, the term 'block' denotes the smallest element of the magnetic model. 'Unit' is used to denote the set of nine blocks each in the upper and middle layers and the single large block in the lower layer.

Details of analysis

Sixty anomalies selected for analysis are distributed throughout the map. An area of (22.8 km x 22.8 km) contains the points of observation for each anomaly. This area is assumed to be enclosed by a rock mass with a horizontal coverage of (34.2 km x 34.2 km). The horizontal dimensions of the rectangular blocks in the top and middle layers are equal to 11.4 km. The initial values assumed for different parameters are:

$$h_{t1} = 0,\ h_{b1} = 0.95 \text{ km},\ h_{t2} = 1.90 \text{ km},\ h_{b2} = 7.60 \text{ km},$$
$$h_{t3} = 9.5 \text{ km, and } h_{b3} = 15.2 \text{ km},$$

where h_{t1}, h_{t2}, and h_{t3} are the depths to the top and h_{b1}, h_{b2}, and h_{b3} are depths to the bottom of the three sets of blocks from the ground surface.

At the end of the iteration procedure we obtain numerical values for the following quantities: (1) strike of the rock mass, (2) depths to the top and bottom of the blocks, and (3) magnetization vectors associated with the blocks. Figure 5 is a plan view of the blocks drawn according to the computed strike direction for the 60 anomalies analyzed from the data over southern Idaho. An example of the results of computation is given in Figure 6.

Figures 5 and 6.--NEAR HERE

Figure 6A contains the values obtained for the blocks in the top layer. The blank blocks mean little or no magnetization. The three numbers in each block, starting from the top, represent, respectively, the magnetization in units of 10^{-6} cgs emu, depth to the top from the ground surface, and thickness, both in kilometers.

Figure 6B presents the values of parameters associated with the blocks in the middle layer. The three numbers in each block correspond, respectively, to the magnetization in units of 10^{-6} cgs emu and depths to the top and bottom of the block, in kilometers, with respect to sea level. A negative depth means that the corresponding surface is above sea level.

The computed values for the variables in the third layer are useful to estimate the bottom of the magnetized crust, often interpreted as the Curie-point isothermal surface. Because of the great depth of this layer below the observational surface, less detailed information is obtained in the modeling. For this reason, the lower layer is discussed in a separate section.

REGIONAL GEOLOGY AND MAGNETIC ANOMALIES

The geology of southern Idaho is varied and complex and this is reflected in the regional magnetic field. In the Albion Mountains (Figure 7) near the southern border of the state, Precambrian

Figure 7.--NEAR HERE

metamorphic rocks are exposed in a series of gneiss-dome complexes and similar rocks are exposed east of the Idaho batholith. Precambrian metamorphosed sedimentary and volcanic rocks are exposed in a zone extending south from Pocatello. Late Precambrian, Paleozoic, and Mesozoic sedimentary rocks, which have an aggregate thickness of more than 15 km, make up most of the ranges in the eastern half of southern Idaho. The Idaho batholith occupies much of central Idaho and similar rocks are exposed in the Owyhee Mountains in southwestern Idaho and perhaps underlie other areas. The bulk of the Idaho batholith is granitic rock but more mafic phases occur as satellites or border facies on the west. East of the Idaho batholith Eocene volcanic rocks blanket large areas and bodies of Eocene granitic intrusive rocks occur within and east of the Idaho batholith.

Basalt and rhyolite of Miocene and younger age cover much of southern Idaho and in some areas are very thick. The dominant physiographic feature is the Snake River Plain, which extends arcuately across Idaho, and is characterized by low surface elevation and relief relative to the areas to the north and the south and by a complete cover of Cenozoic sedimentary and volcanic rocks. The gross structure of the plain and the compositions and ages of rocks underlying the volcanic rocks are largely unknown. Block faulting over eastern Idaho, north and south of the Snake River Plain, has produced the basin and range topography that dominates these areas.

At low levels over the volcanic rocks covering much of southern Idaho the magnetic field is complex and numerous local anomalies cannot readily be interpreted in terms of the regional geology. Even at the elevation of 3.8 km above sea level (about 2 km above the surface), where most of the data in Figure 1 were recorded, the magnetic field produced by the volcanic rocks is complex. However, when the residual magnetic field is continued to 7.6 km above sea level (Figure 2), anomalies of regional extent persist and they can be related to regional geologic features. The dominant magnetic feature is a zone of relatively high magnetic intensity over the Snake River Plain. In the west a high lies along the south and southwest edge of the plain with a magnetic low near the north edge. Over the eastern Snake River Plain the magnetic field increases in complexity and consists of highs and lows covering the entire area. North of the plain, an area of relatively low magnetic intensity coincides with the Idaho batholith and major positive anomalies are associated with Eocene intrusive and extrusive rocks. South of the plain the most prominent positive anomalies appear to relate to highs in the Precambrian basement. Both the geology and magnetic anomalies in the western part of southern Idaho differ from those in the eastern part. For convenience in discussing the results of analysis of magnetic anomalies, we shall consider these two areas separately.

WESTERN PART OF SOUTHERN IDAHO

Western Snake River Plain

The explanation for the regional magnetic anomaly over the western Snake River Plain is not apparent from surface geology. Cenozoic rhyolite and basalt are exposed throughout much of the area, but locally Cenozoic sedimentary rocks are as much as 2 km thick. Much of the volcanic rock is moderately to highly magnetic. The highest residual intensity in southern Idaho occurs in the northwest end of the Snake River Plain.

The magnetic anomaly, covered by units 5 and 7 in Figure 5, is part of a regional magnetic high which overlies an extensive area to the north beyond the map area where basalt of the Columbia River Basalt Group of Miocene age is at or near the surface. Analysis of unit 7 indicates near-surface basalt in the eastern blocks in the upper layer where basalt crops out. In the central and western blocks the model indicates basalts underlie sediments ranging in thickness from 0.8 to 1.5 km where drill holes have revealed a maximum thickness of at least 1.2 km of sediments over thick basalt flows (Newton and Corcoran, 1963; Bowen and Blackwell, 1975). The analysis indicates an appreciable thinning of the sediments in the southwestern block. Over most of the area occupied by the anomaly the tops of the blocks in the middle layer lie directly below the upper magnetic body with a total thickness of magnetic rock varying from 1.5 to 3.2 km.

In a borehole about 60 km northwest of Boise the most shallow major basalt unit lies about 0.4 km below sea level (Bowen and Blackwell, 1975). The northeastern block of unit 5 is closest to the borehole and the computed elevation to the top of the block in the middle layer is 0.5 km below sea level.

A borehole about 80 km south of Boise drilled 0.7 km of sediments before penetrating first basalt and then rhyolite (McIntyre, 1977). In the northwestern blocks of unit 10, located a few kilometers east of the borehole, the depths to the top and bottom of the upper magnetic block are computed to be 0.8 and 1.7 km, respectively. In the borehole, considerable alteration was reported, presumably resulting in a reduction in magnetization below 1.7 km. This deep borehole penetrated granitic rock at 2.4 km below sea level. The magnetized northwestern block in the middle layer of unit 10 is located at 2.3 km below sea level, extending vertically to a depth of 13.7 km.

West of Boise, a magnetic low is covered by the southeastern part of unit 5 and the northwestern part of unit 8. It is approximately coincident with one of the closed gravity highs along the axis of the Snake River Plain (Mabey, 1976). Results of analysis of units 5 and 8 indicate that in this area near-surface materials range in thickness from 0.5 to 1.6 km and are weakly magnetized. The magnetization of the middle layer is also weak. The bottom of the middle layer ranges from 8 to 12 km below sea level. If crustal material above 8 km below sea level is responsible for the gravity high, the material is practically nonmagnetic.

Numerical analysis of the magnetic high, midway between Boise and Twin Falls (units 18 and 21), and the surrounding lows to the northwest (units 15 and 18), east (unit 21), and south (unit 19) indicate that the most strongly magnetized rock is in two blocks in unit 18 located directly below the magnetic high. These blocks contain highly magnetized rock with normal polarity that extends vertically from near the surface to 7 km below sea level. It appears that a highly magnetized region 8 km thick, probably an intrusive body, is responsible for the magnetic high.

Two high intensity magnetic anomalies lie along the southwestern edge of the Snake River Plain. One of them is partly covered by unit 17. Most of the upper blocks in this unit are of moderate magnetic intensity and extend to the ground surface. The thickness of these blocks varies from 0.5 to 1.2 km. The rocks in the block at the southeast corner, which lies partly off the plain, seem to be nonmagnetic. In the middle layer the two blocks directly below the center of the anomaly are highly magnetized with normal polarity. They extend vertically from 0.3 km to 6 km below sea level. The magnetized rock mass seems to thicken to the northwest and thin to the northeast.

The other magnetic high is in the area of unit 10. The upper-layer blocks in the south, except the southwestern block, are close to the surface. Toward the north the magnetized region, which ranges in thickness from 0.5 to 0.9 km, is buried under a nonmagnetic layer of thickness increasing to 0.8 km. The middle layer magnetized blocks are at an average depth of 4.9 km below sea level with the bottom from 5.7 km to 8.7 km. The magnetization of rocks in unit 14, which lies between the two magnetic highs in the area of units 10 and 17, is relatively low.

A large magnetic high lies along the southern edge of the Snake River Plain near Twin Falls. Unit 31 covers a part of the anomaly near its peak. In the upper layer, only the blocks in the center and southern rows are appreciably magnetized. Here, rocks about 1 km thick are overlain by nonmagnetic material decreasing in thickness from 2.6 km in the southeastern block to 1.2 km in other blocks. Magnetized blocks in the middle layer appear to be continuous with the blocks in the upper layer. The average magnetization of rocks in the center, northwestern, and southwestern blocks is 0.02 cgs emu. The bottom ranges from 6 km to 11.5 km below sea level. The inversion of the anomaly suggests that a great thickness of strongly magnetized rock lies along this edge of the Snake River Plain.

Idaho batholith

That the rocks of the Idaho batholith are not strongly magnetized is indicated by the lack of correlation of magnetic anomalies with topography and by the low intensity of the residual field (Figure 2). We shall consider here a few anomalous features over the batholith.

Units 12 and 13 are in low-intensity areas of the residual magnetic field over the Idaho batholith. Analysis of these features indicates very little magnetization of the blocks in the upper layer. A middle layer ranging in depth from 6 to 10 km below sea level and up to 5 km thick is indicated. The considerable relief to the top of the magnetized body seems to be mainly responsible for the low-intensity features of the residual field. In general, the upper part of the Idaho batholith has a low and relatively uniform magnetization.

The largest anomaly north of the western Snake River Plain is centered over the Sawtooth batholith, an Eocene intrusive near the eastern edge of the Idaho batholith in an area of very great surface relief. The magnetic anomaly covers an area considerably greater than the mapped area of the Sawtooth batholith indicating a greater subsurface extent of the batholith. Unit 23 and the northwestern blocks of unit 25 are located on the anomaly. Here, the magnetized rocks in the upper blocks are 0.5 to 1 km thick and at the surface or as much as 1 km below the surface. The rocks in the upper magnetic layer of units 23 and 25 are rather weakly magnetized. Blocks in the middle layer are magnetized more strongly than those in the upper layer. The central block in the middle layer of unit 23 is located directly below the peak of the large positive anomaly. It extends vertically from 2.2 to 4.7 km below sea level. To the east the magnetized rock mass in the western blocks of unit 25 thickens considerably extending from 1.4 to 6.0 km. To the southeast (northern part of unit 24), the magnetized rocks of the middle layer appear to extend from 5.5 to 7.8 km below sea level. The Sawtooth batholith is thus magnetized in a complex manner and the bottom of the highly magnetized zone has an appreciable relief ranging from 4.7 to 7.8 km below sea level.

Owyhee Mountains and adjoining areas

The Owyhee Mountains contain a core of Mesozoic granitic rocks. Tertiary volcanic rocks surround the mountains and overlie large areas within the range. The outcrop pattern within the mountains is complex and several rock types with differing magnetic properties are commonly exposed within an area of a few square kilometers.

A magnetic low extends over the Owyhee Mountains and a large area to the south, which is overlain by silicic volcanic rocks. Over the main anomaly (unit 4) the rocks are apparently not strongly magnetized and the computed upper layer is at the surface and generally less than 1 km thick. To the northwest (unit 6) of the main anomaly the upper layer is overlain by nonmagnetic rocks ranging in thickness from 0.5 to 1.5 km. The same trend is observed to the southwest (unit 3). The blocks of the upper layer in these areas are weakly magnetized.

Over much of the Owyhee Mountains the magnetized blocks in the middle layer are shallow and some seem to be continuous with the upper layer. In the area of outcropping granitic rocks and areas to the northwest and southwest of the main anomaly, the computed depths to the bottom of the blocks range from 5.9 to 10.3 km below sea level. In the area of the Owyhee Mountains the application of the inversion method is compromised by the complexity of the geology and the understanding of the results obtained is limited by a lack of knowledge of the magnetic properties of the rocks involved.

A low-amplitude magnetic anomaly is located south of the Owyhee Mountains in the area of unit 2 where there is a complete cover of silicic volcanic rocks. The characteristics of the results of analysis for this unit are similar to those observed over the central part of the Owyhee Mountains and the Idaho batholith. Perhaps the batholith exposed in the Owyhee Mountains extends under this area.

Area southeast of Twin Falls

Tertiary volcanic rocks overlying Paleozoic sedimentary rocks are generally thin and locally absent in the area of the magnetic low south of Twin Falls (unit 28). In the upper layer, only the block in the center of the southern row seems to be magnetized by a moderate amount. In the middle layer, the eastern blocks are moderately magnetized. The depths to the top of these blocks are 2.3 km in the north, 3.5 km in the center, and 4.6 km in the south. The thickness increases gradually from about 1 km in the north to 2.6 km in the south.

Comments on the results of analysis

In the western Snake River Plain the magnetized blocks in the upper layer range in thickness from 0.5 to 2 km and in some areas they are overlain by nonmagnetic rocks that reach a thickness exceeding 4 km. Near-surface rocks are not generally the principal cause of the regional magnetic anomalies observed in this part of the plain. The large magnetic high along the south and southwest edge of the western Snake River Plain appears to be produced by a layer of strongly magnetized rock lying 0.5 to 6 km below sea level. This layer, which is presumed to be volcanic rock, is up to 4 km thick.

Over the Idaho batholith (units 12 and 13), thick nonmagnetic rocks extend from the surface to about 6.4 km underlain by magnetized rocks with a bottom about 11 km below sea level. A similar vertical extent is found in the blocks of the middle layer over Owyhee Mountains and areas to the southwest suggesting that the batholith may underlie these areas.

EASTERN PART OF SOUTHERN IDAHO

Area south of the plain

In the Albion Mountains, which are the highest mountains in Idaho south of the Snake River Plain, rocks dated as 2.4 billion years old are exposed in a series of gneiss domes (Armstrong, 1968). Granitic rocks of Eocene age are also exposed in the domes. Most of the rocks exposed in the Albion Mountains are not strongly magnetized and anomalies do not correlate in detail with surface geology (Mabey and Wilson, 1973). The magnetic anomaly, which is covered by the eastern two-thirds of unit 34 and the western blocks of unit 37, is apparently reflecting buried geology. The inversion produced a complex model with the primary magnetic layer 2.4 to 6.5 km below the surface and from 1.4 to 4.0 km thick.

An extensive area of low magnetic intensity lies over pre-Tertiary sedimentary rocks east of the Albion Mountains. The area is partly covered by unit 45. The upper blocks of this unit are weakly magnetized. The magnetization contrast in the middle layer is detected at a depth of 4 km in the east and 7 km in the west. The bottom of the magnetized body lies at about 9 km below sea level.

Another zone of magnetic highs extends south from Pocatello where a thick sequence of upper Precambrian rocks crop out. However, these rocks are predominantly sedimentary with minor occurrences of metavolcanic rocks. The magnetic anomaly is, therefore, expected to reflect a magnetic basement at depth. The base of the upper Precambrian sediments is not exposed in the area of the anomaly, and there is a possibility that the sediments are part of a major klippe.

Unit 52 lies in the area of the magnetic high. The blocks in the upper layer have little or no magnetization. Four northwestern blocks in the middle layer are appreciably magnetized. The center block in this layer extends vertically from 6.4 to 10.9 km below sea level. The tops of the blocks to the north and the west lie between 7.4 to 10 km. The bottoms of these blocks are located at about 11 km below sea level.

Eastern Snake River Plain

The magnetic intensity over the eastern Snake River Plain is generally high and the magnetic field, even at 7.6 km above sea level, is complex relative to that in the western plain. A combination of two sources has been suggested as the cause of the regional magnetic anomalies on the eastern plain--large intrusive masses and variations in the thickness and magnetization of the Cenozoic volcanic rock.

Three local magnetic highs occur near the southeast edge of the plain where basin and range structures intersect the plain. The anomalies are covered by units 35, 47, and 57. In all three units magnetized rock extends to from 10.4 to 12.5 km below sea level suggesting that the anomalies are produced by intrusive bodies with considerable depth extent.

The magnetic high over very young basalt flows and vents along the Craters of the Moon rift, about 100 km northwest of Pocatello, is part of a zone of high magnetic intensity extending beyond the plain in a northwesterly direction. To the northwest this zone is related to an alignment of Tertiary intrusive rocks within pre-Tertiary sedimentary rocks. The magnetic high is largely covered by unit 40. Results of analysis for the upper layer indicate the presence of magnetized rocks at the surface and 0.5 km thick in only two southeastern blocks. The remaining blocks are covered by nonmagnetic material ranging in thickness from 1 km in the north to 2.6 km in the central row and in the south. The middle layer of this unit contains highly magnetized blocks. The southwestern block and the two northern blocks in the central part of the unit are approximately coincident with the Craters of the Moon rift and extend vertically from 3.5 to 11.5 km below sea level. The two northern blocks in the western column and the northeastern block extend from 1 to 10.5 km below sea level. The two sets of blocks are highly magnetized (0.02 cgs emu). The inversion suggests that the geology underlying the Craters of the Moon is complex with evidence of a deeply buried intrusive unit below the rift. The eastern and central blocks of unit 33 are approximate linear extensions of the central and western blocks of unit 40 and suggest a possible northwesterly extension of the body underlying the Craters of the Moon rift.

About 18 km north of Idaho Falls is a magnetic high that is approximately coincident with a gravity high (Mabey, 1978). Both anomalies are probably produced by the same mass, perhaps a mafic intrusion. Unit 53 covers the area of the magnetic high. In the upper layer, the northwestern and southwestern blocks are overlain by nonmagnetic material about 0.6 km thick. The rest of the blocks extend to the surface. All the blocks are 0.5 km thick. The blocks in the center row, the northwestern block, and the center block in the southern row are highly magnetized (0.001-0.003 cgs emu). In the middle layer, two southern blocks in the central part, and the central block in the eastern part seem to touch the upper blocks and extend vertically to 11.5 km below sea level. The other blocks in this layer are weakly magnetized. These blocks may reflect the inferred intrusive body.

The east-trending zone of low intensities, covered by units 42 and 48, includes several large rhyolite domes. In unit 42 rocks in most of the blocks in the upper layer have appreciable magnetization and extend to the surface and their thickness increases from 0.5 km in the south to 1.6 km in the north. The middle layer contains strongly magnetized rocks in the two western blocks in the central row and two eastern blocks in the southern row. The center block extends from the sea level to 8.8 km. To the south the top of the block remains unchanged, but the bottom rises by about 3 to 6 km. The block to the west extends from sea level to a depth of 4.4 km. The southeastern block, continuous with the same block in the upper layer, bottoms out at 3.4 km below sea level.

In the upper layer of unit 48 all the blocks are magnetized and, on the average, are 0.8 km thick. The middle layer shows that the center block extends from 0.5 km to 3.0 km below sea level. To the south, weakly magnetized rocks extend from the ground surface to 5.3 km.

The thickness of the basalt in the area of this low zone is known from drilling and resistivity and magnetotelluric soundings to be about from 0.5 to 1 km, which is about the average computed for the upper magnetic layer. The geologic significance of the deeper layers is not clear, but no correlation with the rhyolite domes is apparent. Over most of the eastern Snake River Plain the main source of the regional magnetic anomalies appears to be rocks below 1 to 2 km from the surface. In the vicinity of the larger magnetic highs the magnetic rock extends to about 10 km below sea level.

Near the northeast end of the Snake River Plain (unit 55), a magnetic high lies partly on the plain and partly over volcanic rock north of the plain. The east-southeast trending part of the anomaly is coincident on a series of very young basalt eruptions apparently controlled by an east-southeast trending rift (LaPoint, 1977). In the middle layer the magnetization contrast between the blocks in the center row and those to the north and the south is about 0.01 cgs emu, a very high value probably reflecting the volcanic rift. The center block in the layer extends vertically from 0.9 km above sea level to 8.7 km below sea level. To the north and the east the relative magnetization of the rocks is high. The top and bottom of the center block in the eastern part are at sea level and 11.3 km, respectively. The center block in the northern row is located between sea level and 7.8 km. The remaining blocks in the middle layer are relatively weak in magnetization. Apparently an intrusive body occupying the three blocks is the main cause of the magnetic high.

Area north of the plain

The regional magnetic field is relatively subdued over predominantly sedimentary rocks located north of the eastern Snake River Plain. The only major anomaly, covered by unit 39, apparently reflects a large, buried intrusive body. In the upper layer, only a few blocks are moderately magnetized and buried under sediments ranging in thickness from 2 km in the north to 0.8 km in the south. A study of the magnetization distribution among the blocks in the middle layer indicates that the anomaly is caused by an intrusive body in the center block which extends from 1.2 km below surface to 4.5 km below sea level.

Comments on the results

The anomalies selected for analysis in the eastern part of southern Idaho are the prominent regional highs and lows in the residual magnetic field (Figure 2). The analysis suggests that most of these major anomalies on the eastern Snake River Plain do not have significant contribution from the magnetized blocks in the upper layer, which are generally near-surface basalt and silicic volcanic rocks interbedded with sediments. The thickness of these blocks ranges from 0.5 km to about 2 km in most areas. The near-surface blocks indicate a thickness greater than 3 km only in the area of unit 35 and in the area occupied by the major rhyolite domes (units 42 and 48). Many of these blocks in the Snake River Plain are overlain by materials with little or no magnetization ranging in thickness up to 2.6 km.

The principal sources for most of the anomalies in the eastern Snake River Plain are intrusive bodies of great thickness. This interpretation contrasts with an earlier interpretation (Mabey, 1978) that the anomalies were produced primarily by near-surface volcanic rock. They are often close to the surface and extend to depths ranging from about 6 to 11 km below sea level. Except in two areas, one southwest of Idaho Falls (unit 54) and the other over one of the rhyolite domes (unit 48), the bottom of the magnetized bodies in the middle layer is at a depth greater than 9 km.

Outside the Snake River Plain, the upper-layer blocks are very weakly magnetized. The thickness of this layer with inappreciable magnetization is 2.4 km in southern Albion Mountains (units 34 and 37), 4 km to the east of the Albion Mountains (unit 45), and 6.4 km near Pocatello (unit 52). North of the plain the non-magnetic layer is generally about 2 km thick.

THICKNESS OF MAGNETIC CRUST

Computed values for the depths to the bottom of the lower layer indicates, generally, the thickness of the magnetic crust. In many areas, however, the lower layer is found to have little or no magnetization. Accordingly, the bottom of the middle layer is considered to be the bottom of the magnetic crust.

The deepest level in the crust containing materials that create discernible signatures in a magnetic anomaly map is generally interpreted as the depth to the Curie-point isotherm. In some cases, the deepest level may be the depth to which magnetic contrasts extend but may not be coincident with the Curie-point isothermal surface; however, the Curie-point isotherm should not be above the computed base of the magnetized crust. Figure 8 is a contour map of the depths

Figure 8.--NEAR HERE

to the bottom of the magnetized crust. It should be noted that the density of points available to draw the contours is not very high and, in some places, paucity of data points makes the contours somewhat speculative. The reliability of computed depths is not uniformly high throughout the map and one inaccurate estimate of depth can introduce an erroneous trend appearing to be significant. However, all of the computed depths have been used to prepare the contour map. Elevations of the base of the magnetic crust range from 7.4 to 23.8 km below sea level. No correlation of the thickness of the magnetic crust with the Snake River Plain is apparent.

The area about 90 km south-southeast of Boise is underlain by extensive reservoirs of hot water; one of the largest geothermal systems in the United States (White and Williams, 1975). Figure 8 shows a large zone of shallow depths covering the eastern part of the area. The most shallow depth in the zone is 11.2 km. This zone runs arcuately to the southwest and to the east. To the southwest it contains areas with depths of about 12 km. To the east it joins a north-south-trending highs extending from the eastern border of the Idaho batholith to the southern border of the Snake River Plain. West of Idaho Falls a high trend extends west across an area of young rhyolite domes to the area of the Craters of the Moon. Along a profile crossing the plain and south of Boise, Brott et al. (1978) suggested a Curie depth of approximately 18 km; close to the computed depth as shown in Figure 8. However, the depths to the bottom of the magnetized crust in Figure 8 do not support the suggestion by Brott et al. (1978) that major crustal heat source underlies the western Snake River Plain.

Depths to the base of the magnetic crust computed over the Idaho batholith are about 14 km below sea level. The deepest point, at 16 km, is located within the Sawtooth batholith. Most of the area south and southwest of the Idaho batholith appears to have thick magnetized crust.

The most shallow magnetic crust in southern Idaho is located at the south end of the Albion Mountains where the computed base is 7.4 km below sea level. This point is slightly west of the geothermal development in the southern Raft River Valley where magnetotelluric data (Stanley et al., 1977) indicate a highly conductive layer at a depth close to the computed Curie depth. High temperature at depth appears to be the best explanation for the presence of relatively thin magnetic-resistive crust near the Albion Mountains.

To the east of the Albion Mountains the magnetic crust thickens in the area of thick sedimentary rocks. North of the eastern Snake River Plain depths are generally 10.5 to 12 km below sea level. Shallow depths also occur toward Yellowstone National Park where heat flow is very high.

Correlation with magnetotelluric soundings

Stanley et al. (1977) have calculated the depth to the highly conductive zone from magnetotelluric soundings in the eastern Snake River Plain-Yellowstone region. They found a close correspondence of the depth of 5 to 7 km for the conductive layer to the depth of 5 to 6 km for the base of the magnetic crust in Yellowstone (Bhattacharyya and Leu, 1975). A good correlation is also found between the depth to the base of the magnetic crust and the depth to the top of the highly conductive layer in the crust in the eastern Snake River Plain. Figure 9 shows the locations of the MT (magnetotelluric) stations and

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Figure 9.--NEAR HERE

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the points at which the base of the magnetic crust was computed. As indicated in Figure 9 the results from only a few MT stations are available but they provide confirmation for the thin magnetic-resistive crust southeast of the Albion Mountains, the thin zone around the Craters of the Moon, the thick areas to the east of the Craters, and the thin area to the north and toward Yellowstone. A major discrepancy may occur in the Island Park area where the MT data indicate the base of the resistive crust at 22 km below sea level, contrasted with the depth of 12 km for the nearest determinations of the base of the magnetic crust. However, there are no determinations of the base of the magnetic crust within Island Park.

Stanley et al. (1977) have examined possible explanations for the highly conductive layer at shallow depths in the crust under eastern Idaho and have concluded that it is very probably caused by elevated temperatures in the range 500^{o}-$700^{o}C$. The Curie isotherm, commonly between $500^{o}C$ and $600^{o}C$, is widely considered to determine the base of the magnetic crust. It appears, therefore, that both MT and magnetic data might be reflecting temperatures in the crust.

CONCLUDING REMARKS

Highly diverse geology of southern Idaho associated with a complex anomalous magnetic field presents a formidable challenge for the application of a generalized technique to the inversion of magnetic anomalies. The upward-continued magnetic field at 7.6 km above sea level illustrates the major regional anomalies and provides the basic data for quantitative interpretation. In many areas it has been possible with the three-layer multibody model to determine correctly the depth to the magnetized volcanic rocks, either located near the surface or buried under a considerable thickness of sediments. Not enough is known about the magnetization and thickness of the major volcanic sequences to evaluate completely the correlation between the results of the inversion and the distribution of the major magnetic units. However, data from three drill holes agree with the results of the inversion of magnetic anomalies. In two areas the results have indicated elongated bodies of highly magnetic rocks underlying major volcanic rifts.

The Tertiary igneous intrusive rocks in southern Idaho are appreciably magnetized. The results of inversion identify some of the intrusives and provide useful information on the dimensions of these masses. However, the Cretaceous igneous intrusive rocks are weakly magnetized and the results of inversion do not always reflect the distribution of these rocks, though their thickness may be determined correctly.

Two weaknesses of the method are apparent and the results may not be satisfactory in some areas. Let us consider the first weakness, which may be true for any method used for inversion of magnetic anomalies. As indicated during the discussion on the results of analysis, most of the anomalies are mainly caused by thick magnetized bodies in the middle layer. The influence of relatively thin near-surface rocks, however strongly magnetized, on the shapes of the regional anomalies is generally slight. This influence, relative to that of other buried sources, may be very small in the case of weakly magnetized near-surface rocks. With any method of inversion it is extremely difficult to detect and analyse the small effect of these rocks for estimating their location and thickness.

The second reason for unsatisfactory results of inversion of anomalies with the present method lies in the limitation of the model (Figure 4) in representing a magnetized rock mass adequately. The horizontal dimensions of a rectangular block in the upper two layers are equal to 11.4 km. At an elevation of 7.6 km above sea level, this dimension is practically identical to the critical length of the smallest inhomogeneity in magnetization resolvable from the data. However, in many areas this elementary block is too large for the volume of available magnetized material. Thus, the results of inversion provide, for the entire block, an average magnetization that is likely to deviate considerably from the true value for rock masses with the block. The computed thickness of the block is generally a good approximation of the true thickness (Bhattacharyya, 1978). For anomalies related to near-surface rocks limited in horizontal and vertical extents it is, therefore, advisable to invert magnetic data recorded at a suitable level close to the surface.

Enough information is not available on the depth to metamorphic basement or the magnetic properties of the basement rocks in southern Idaho to evaluate the usefulness of the results of inversion in mapping the depth to basement under thick sedimentary cover. However, the correlation between the depths to the base of the magnetic crust and the depths to the conductive layer in the crust calculated from the magnetotelluric data gives credence to the results of this analysis presented in this paper.

The application of the generalized inversion method to the diverse geology of southern Idaho indicates that the method is applicable to a wide variety of geologic terrains. Special applications scaled to specific geologic problems are likely to produce results superior to those reported in this paper.

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FIGURE CAPTIONS

Fig. 1. Residual magnetic map of southern Idaho at an elevation of 3.8 km above sea level. Contour interval is 100 gammas. Closed lows are shaded.

Fig. 2. Residual magnetic map of southern Idaho continued upward to 7.6 km above sea level. Contour interval is 50 gammas. Closed lows are shaded.

Fig. 3. Residual magnetic map of southern Idaho continued upward to 11.4 km above sea level. Contour interval is 20 gammas. Closed lows are shaded.

Fig. 4. Magnetized unit containing three layers of rectangular blocks representing the magnetized rockmass. A, upper layer; B, middle layer; C, lower layer. Regions separating layers are nonmagnetic.

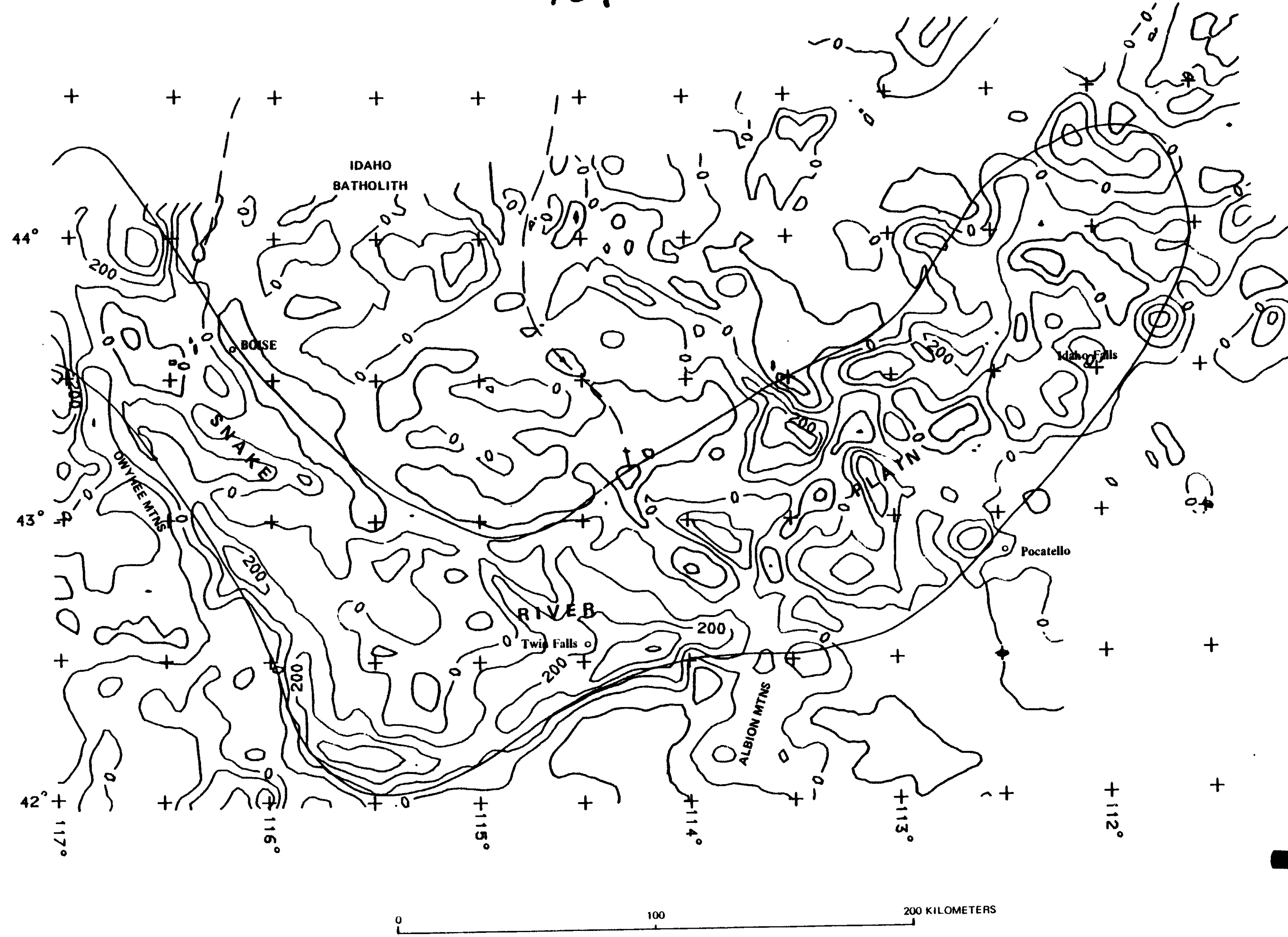
Fig. 5. A cross-section of the blocks drawn according to the computed strike directions for the 60 anomalies over southern Idaho.

Fig. 6. Results of analysis of one magnetic anomaly. A, upper layer. The three numbers in each block represent, from top: magnetization in units of 10^{-6} cgs emu, depth to the top and thickness of the block, both in kilometers. B, middle layer. Three numbers in each block represent, from top: magnetization and depths in kilometers below sea level of the top and bottom of the block. Negative number indicates elevation above sea level. Blank blocks in A and B indicate little or no magnetization.

Fig. 7. Geologic map of southern Idaho generalized from the Geologic Map of the United States (1974).

Fig. 8. Contour map of the depth below sea level of the base of the magnetized crust computed at points indicated. Contour interval is 1 km.

Fig. 9. Map of the eastern half of southern Idaho showing the depth below sea level in kilometers of the base of the magnetic crust obtained in the inversion of the magnetic data (x's) and the top of the conductive layer interpreted from magnetotelluric soundings (solid). Contour interval is 5 kilometers.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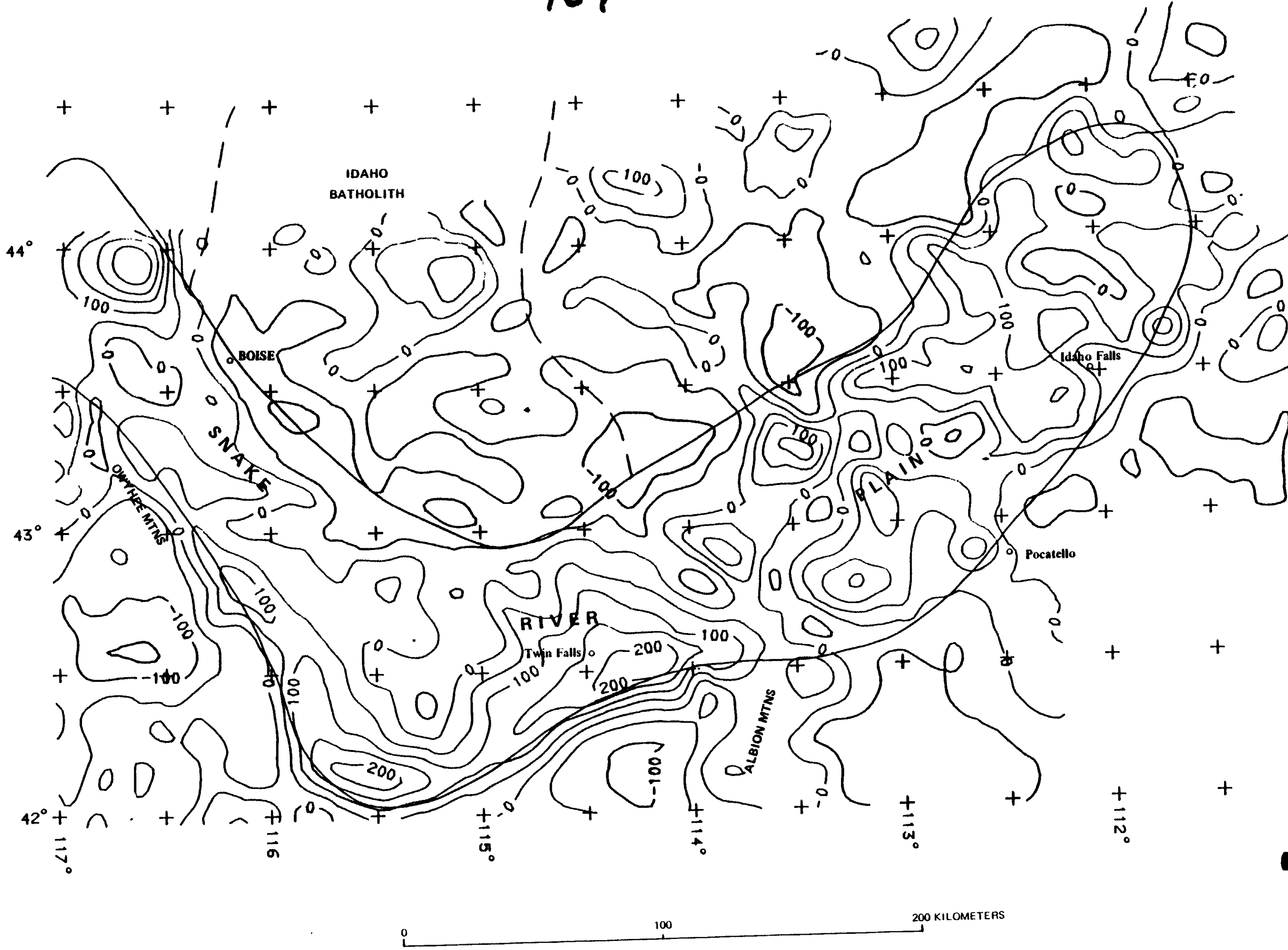
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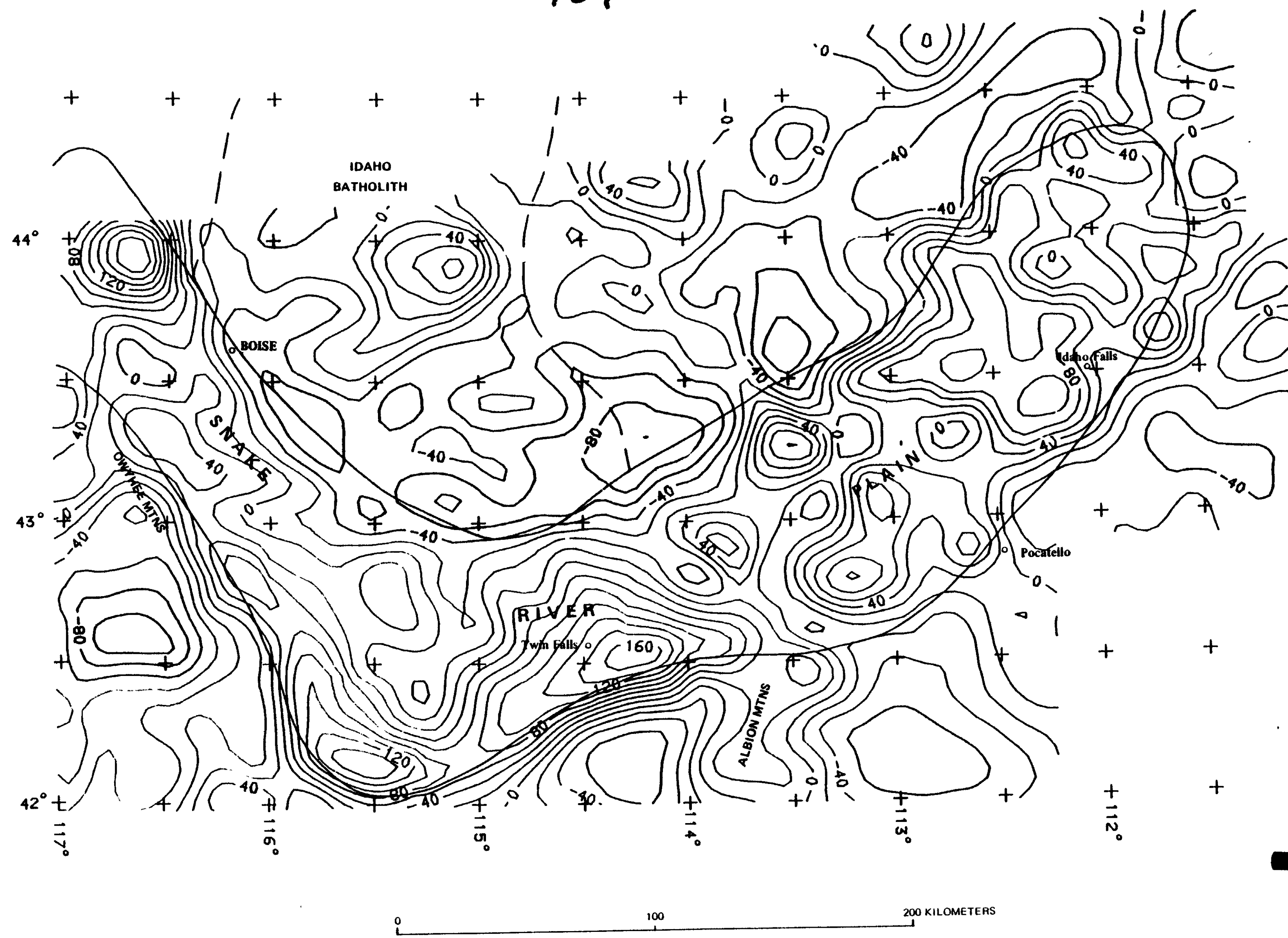

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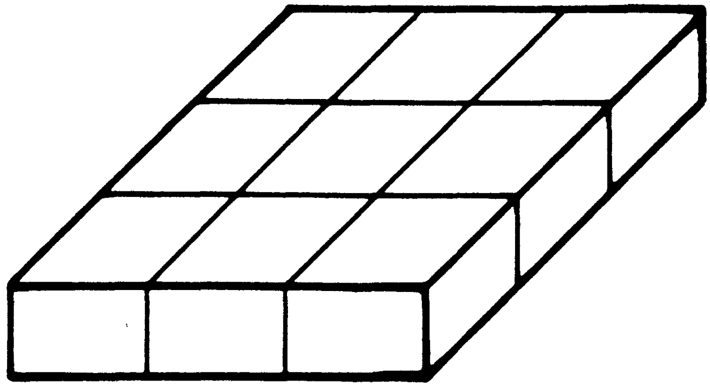

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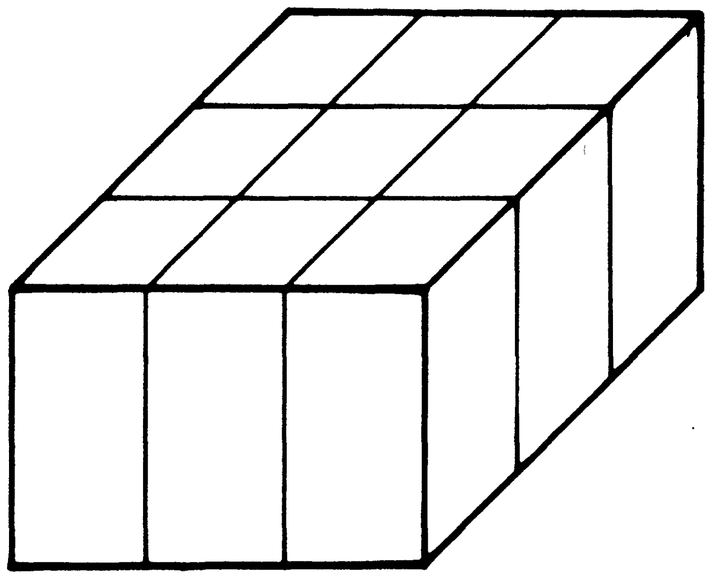

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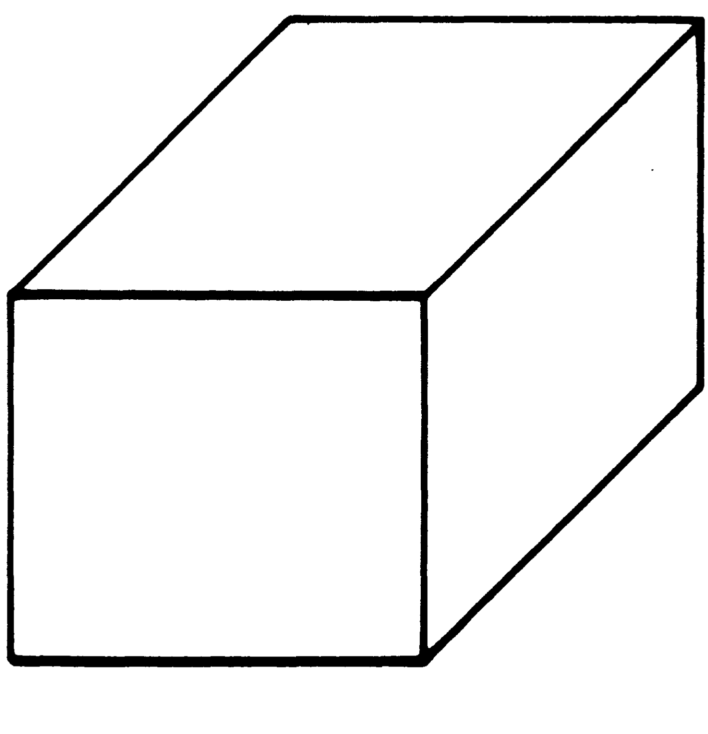

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2	956 0.0 0.9 5	8
1024 0.8 0.9 1	1297 0.0 0.5 4	515 1.1 0.5 7

A

416 1.1 7.4 3	1991 3.2 4.7 6	9
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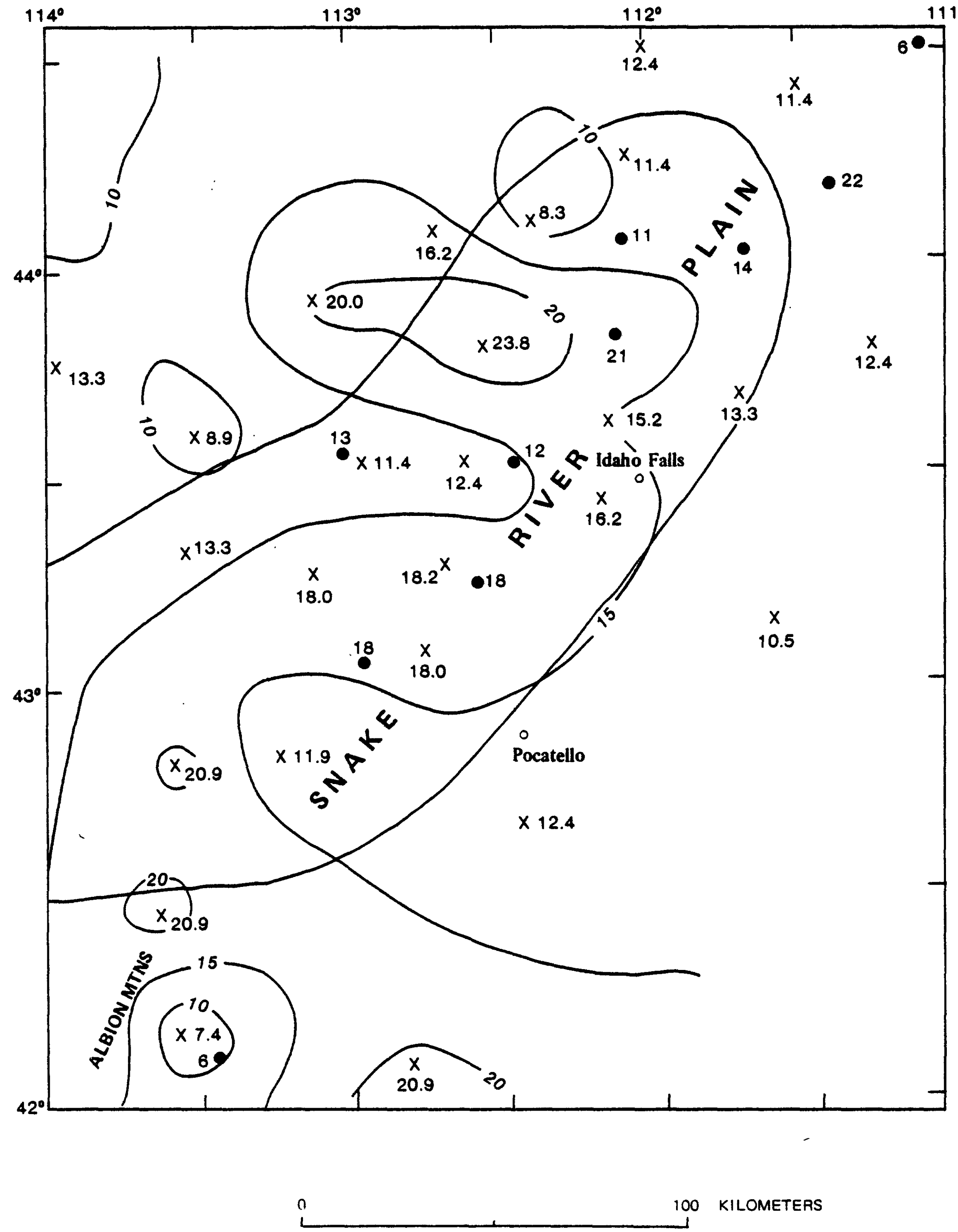

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fig 9