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# Analysis of Magnetic Anomalies Over Yellowstone National Park: Mapping of Curie Point Isothermal Surface for Geothermal Reconnaissance

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The bottom of the magnetized crust determined from the spectral analysis of residual magnetic anomalies is generally interpreted as the level of the Curie point isotherm. This paper studies the spatial variation of the Curie point isotherm level in Yellowstone National Park with the help of aeromagnetic data. A very shallow isothermal surface at a depth of only 5–6 km below sea level is associated with the central part of the Yellowstone caldera. It seems to extend along a narrow corridor toward the southwestern and eastern edges of the map. Except in a few localized spots, the isotherm deepens considerably in the areas outside the caldera. Because the caldera encloses most of the areas of hydrothermal alteration, fumaroles, and boiling springs in the park, this study indicates a strong correlation between the spatial variation of the Curie isotherm level and the concentration of subsurface geothermal energy.

## INTRODUCTION

Crustal rocks lose their magnetization at the Curie point temperature. At this temperature, ferrimagnetic rocks become paramagnetic, and their ability to generate detectable magnetic anomalies disappears. Thus the deepest level in the crust containing materials which create discernible signatures in a magnetic anomaly map is generally interpreted as the depth to the Curie point isotherm.

One of the important parameters that determines the relative depth of the isotherm with respect to sea level is the heat content in a particular region. The heat content is generally proportional to the local temperature gradient, thermal capacity, and generation of heat. A region with significant geothermal energy near the surface of the earth is characterized by an anomalously high temperature gradient and heat flow. It is therefore to be expected that regardless of the composition of the rocks, the region will be associated with a conspicuously shallow Curie point isotherm relative to the adjoining regions. For example, according to *Blackwell* [1971] the Curie isotherm lies at an average depth of approximately 22 km in the Basin and Range province, whereas it rises to 10 ± 3 km below sea level in Yellowstone National Park [*Smith et al.*, 1974]. The park is well known for its surface manifestations of geothermal energy.

The expected correlation between the spatial variation of the Curie isotherm level and the concentration of subsurface geothermal energy can be tested by means of an analysis of the magnetic anomalies over a specified region. The anomalies are analyzed for estimating the depths to the bottoms of magnetized bodies in the crust. These depths, when contoured over the entire area, should provide a picture of the spatial variation of the Curie isotherm level. This picture, in turn, should correlate to a significantly high degree with various known indices of geothermal activity in the area under consideration. We chose Yellowstone National Park for such a test not only because of its obvious geothermal manifestations but also because of the possible presence of molten magma at shallow depths, as was strongly indicated by various types of data [*Eaton et al.*, 1975].

The practical importance of a study on the above correlation lies in the possibility of establishing a useful reconnaissance method, based on aeromagnetic data, for rapid regional geothermal exploration. It is obvious that the principal objective of this study is to delineate the Curie point isotherm surface over the entire area and thus to trace the changes in the isotherm level as one moves from the central area of geothermal manifestation, the Yellowstone caldera, to adjoining areas. These changes are expected to reflect the relative variation in geothermal activity in the area. For such a study the average isotherm depth for the whole area [*Shuey et al.*, 1973; *Smith et al.*, 1974] is not of great importance.

## DATA

The Branch of Theoretical and Applied Geophysics of the U.S. Geological Survey conducted an aeromagnetic survey over the Yellowstone National Park area [*U.S. Geological Survey*, 1973]. The applied geophysics group of the University of Utah, Salt Lake City, Utah, digitized the data and removed the main geomagnetic field. The data were digitized with a spacing of 2.08 km. The digital data available to us cover an area, 131 km by 131 km, extending from 44°1'N to 45°7'N latitude and from 109°40'30"W to 111°15'W longitude. The area includes all of Yellowstone National Park. The flight elevation was 3.96 km with respect to sea level over the area from 44°1'N to 44°45'N latitude and 109°40'30"W to 110°15'W longitude. For the rest of the area the elevation was 3.66 km.

## TREATMENT OF THE DATA

*Residual.* The observed magnetic field at a point is the vectorial combination of fields produced by various sources. The most predominant of these fields is the normal geomagnetic field entirely uncorrelated to crusted geology. This field, as was mentioned before, has been removed from the observations. The remaining field contains not only the effect of bodies of finite dimensions in the crust but also the effect of large-scale geologic features extending considerably beyond the borders of the limited area of investigation. The latter effect is called 'regional' and appears in the form of a smooth surface in the data. In order to remove this effect a quadratic surface is fitted to the data by the method of least squares. The mathematical expression for the surface is given by

$$T = -69.373 + 5.737y + 1.764x + 0.208y^2 + 0.172xy - 0.017x^2 \qquad (1)$$

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where $x$ and $y$, expressed in terms of the unit distance of 2.08 km, point to the north and the east, respectively, and the origin of coordinates is taken at the center of the area. For a higher-order polynomial the coefficients of the third-degree terms are found to be relatively very small, and so they have not been considered.

This simple analysis shows that the available data contain north-south and east-west field gradients of 0.85 $\gamma$/km and 2.76 $\gamma$/km, respectively. These gradients are significant in magnitude and are not likely to be produced by bodies limited in horizontal extent in the crust of the earth. They are, however, related to the northeast-trending magnetic lineament or belt which extends from north central Nevada into Canada through Yellowstone National Park [*Eaton et al.*, 1975, Figure 7]. Since for the present study the effects of these lineaments are not desirable, the values obtained from (1) are subtracted from the available data. The remaining or residual values are assumed to be generated by magnetized bodies localized in the crust. The residual field map is shown in Figure 1.

*Filtering.* The residual map contains a large number of small-wavelength, high-intensity anomalies created by magnetized sources at the surface or at shallow depths. These anomalies distort and sometimes completely mask the effects of deep-seated bodies. The study of these deeper seated effects, which mainly generate large-wavelength anomalies, is greatly facilitated by a significant reduction of the small-wavelength components in the data. This reduction requires the use of a low-pass filter which transmits without distortion wavelengths larger than a critical or cutoff wavelength and attenuates all other wavelengths.

Let us now briefly consider the use of such a low-pass filter in relation to the objective of the study reported in this paper. The basic goal of the study is to calculate and map the depths to the bottoms of the magnetized masses in the crust of the earth. The potential field effects of these bottoms are contained in the large wavelengths of the spectrum of the total field anomalies. So low-pass filtering does not alter these effects in any appreciable way, while it removes the short-wavelength features from the total field map.

For the filtering operation, three different zero phase two-dimensional low-pass filters are designed with cutoff frequencies at (1) 0.08 cycles/km, (2) 0.10 cycles/km, and (3) 0.12 cycles/km, respectively. Thus the smallest wavelength transmitted by these filters is around 10 km. The radial responses of these filters, as shown in Figure 2, remain flat in the low-frequency region up to the cutoff frequency and then decay very sharply.

The three filters were used individually to operate upon the residual field data. A study of the resulting filtered maps indicates that the filter with cutoff frequency at 0.10 cycles/km removes the small-wavelength anomalies with the least visible sign of distortion. The corresponding map is shown in Figure 3.

## ANALYSIS OF THE FILTERED DATA

For determining the bottom depths of deep-seated magnetized bodies the filtered data have been analyzed in two ways. First, the whole area is divided into separate blocks, and the mean bottom depths of bodies causing magnetic anomalies are estimated for each block. Second, individual anomalies are carefully selected and analyzed to determine the vertical extent of causative bodies. The method remains essentially the same for analysis of the data corresponding to either a block or an anomaly. The two sets of results are then integrated to produce a map showing depths to the base of the magnetized section, or Curie point isotherm, with respect to sea level. In the following

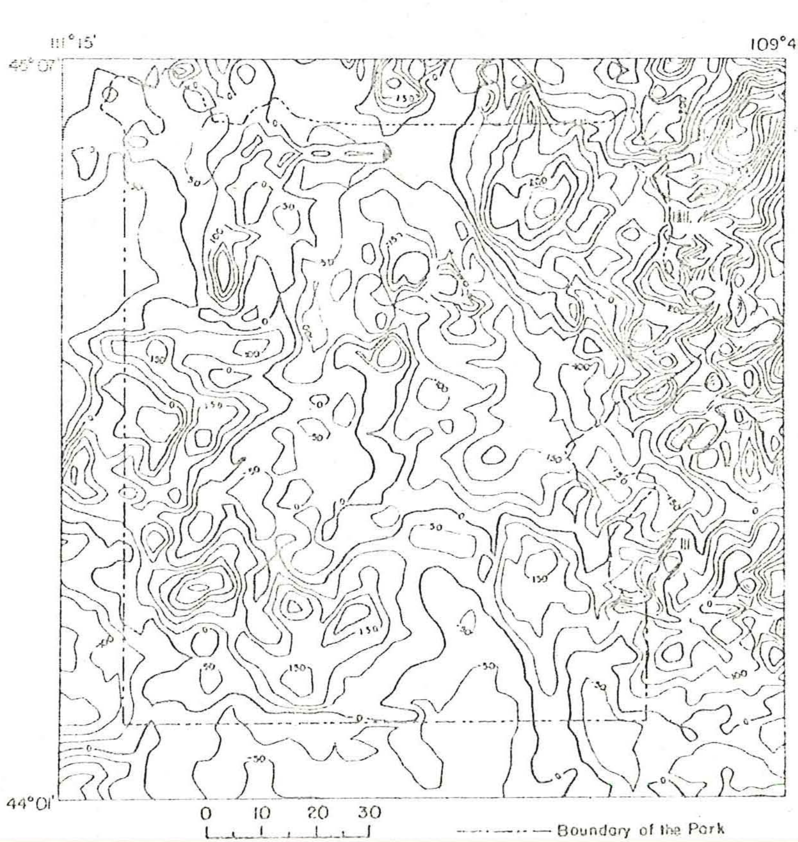

Fig. 1. Residual total field aeromagnetic map over the Yellowstone National Park. Both the international geomagnetic reference field and a least squares quadratic surface fitted to the data have been removed.

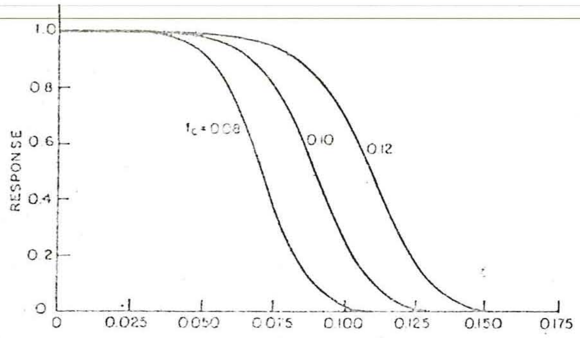

Fig. 2. Radial frequency-domain response of three zero phase, low-pass filters with different cutoff frequencies designed for and applied to the Yellowstone residual magnetic map.

paragraphs we shall first consider the analysis of the data in a block.

As noted before, the residual data cover an area, 131 km by 31 km, and contain (64 × 64) data points. Let us then consider a block of (16 × 16) data points with an areal coverage 31 km by 31 km. If the total area is now divided into overlapping blocks of this size with one half of the area of one block shared by the succeeding block, the total number of blocks available for analysis becomes 49.

The data in each block are analyzed in the frequency domain. Let us now consider one block alone. Since discontinuities in data values at the edges of the area give rise to the Gibbs phenomenon and aliasing, it is assumed that the residual field vanishes at a point which is located at a distance of 4 units of data spacing from the boundary of the block. Inclusion of these points results in (18 × 18) nonequispaced data points in the block. Bicubic splines [*Bhattacharyya*, 1969] are then fitted to the data in such a way that the residual field and the continuity of the first and second derivatives are maintained at each of the data points. These splines are used to generate (64 × 64) data points over the extended area of the block.

The two-dimensional spectrum $F_0(u, v)$ of the new set of data in the block is obtained with the help of the fast Fourier transform algorithm. $F_0(u, v)$ is therefore the discrete Fourier transform of the magnetic data. The angular frequencies $u$ and $v$ correspond to the $x$ and $y$ axes, respectively. Now, by using a method outlined in a paper by *Bhattacharyya and Leu* [1975], the spectra $F^x(u, v)$ and $F^y(u, v)$ of the first-order $x$ and $y$ moments, respectively, of the residual field are computed.

In the block under consideration there may be a few bodies producing anomalies. The mean location ($\bar{x}$, $\bar{y}$, $\bar{h}$) of the centroid of these bodies is determined with the help of the following equations in the low-frequency region:

$$\begin{aligned} \bar{x} - \frac{iu\bar{h}}{s} &= \frac{F^x(u, v)}{F_0(u, v)} - i\frac{u}{s^2} \\ \bar{y} - \frac{iv\bar{h}}{s} &= \frac{F^y(u, v)}{F_0(u, v)} - i\frac{v}{s^2} \end{aligned} \qquad (2)$$

where $s^2 = u^2 + v^2$.

The above equations are valid at high geomagnetic latitudes. The frequency range in both $u$ and $v$ selected for this computation runs from the fundamental frequency to its fifth harmonic. For several frequencies in this region, $\bar{x}$, $\bar{y}$, and $\bar{h}$ are calculated, and the average of their values provides a good estimate of the location of the centroid. With careful choice of frequencies the accuracy of this estimate can be kept fairly high. However, it should be noted that the effect of shallow sources, unless removed completely from the data, will produce error in the estimate.

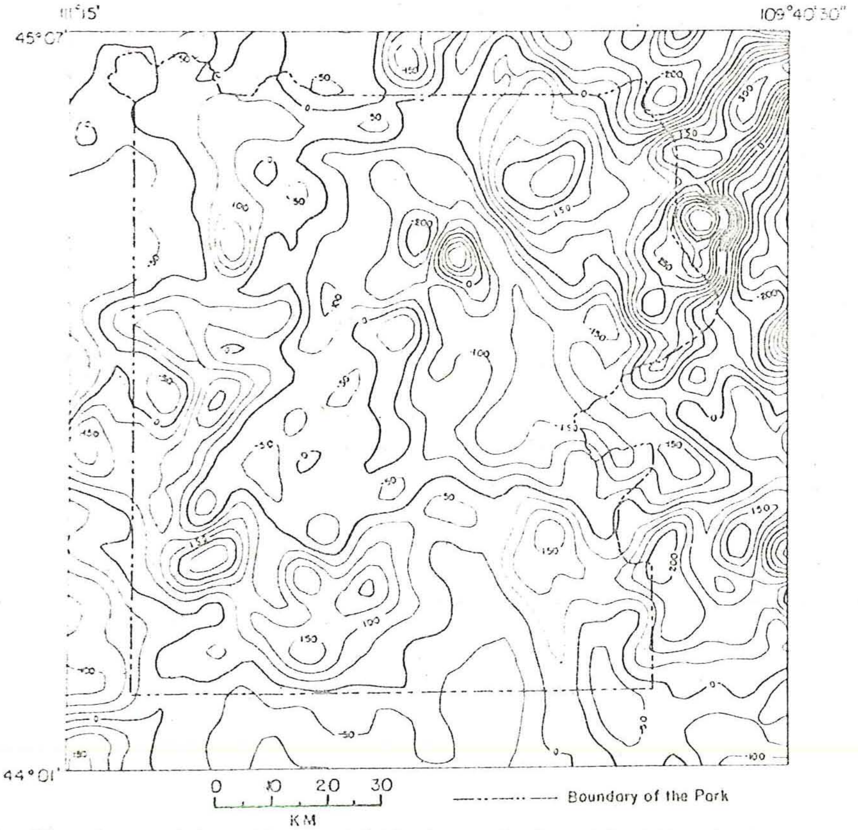

Fig. 3. Filtered map of the residual total field, after application of the 0.10-cycles/km low-pass filter.

Next, the radial spectrum $F_0(s)$ is generated by evaluating, with the help of $F_0(u, v)$, the amplitude spectrum along the line at 45° with the frequency axes. The spectra $F^x(s)$ and $F^y(s)$ of the first-order $x$ and $y$ moments of the residual field are then computed. A combination of $F_0(s)$, $F^x(s)$, and $F^y(s)$ is used to determine the mean depth to the tops of magnetized bodies for the block. Again, for the sake of accuracy the range of frequency should not exceed the tenth harmonic of the fundamental frequency.

With the average location of the centroid and the mean depth to the tops of magnetized bodies known, it is simple and straightforward to calculate the mean depth to the bottoms of these bodies. The calculated depth is interpreted as the depth to the Curie point isotherm for the block.

The spectral analysis briefly discussed in the preceding paragraphs is applied not only to the data of each of the 49 blocks but also to individual anomalies found suitable for study throughout the area. The total number of anomalies studied in this way was 35.

## RESULTS OF ANALYSIS

Figure 4 presents the calculated depths, rounded off to the nearest whole kilometer, to what we believe to be the Curie point isotherm with respect to sea level. The circle and triangle symbols indicate the locations of the centers of anomalies and blocks, respectively. The central part of the caldera is marked by a very shallow Curie isotherm at a depth of only 5–6 km. The closed 6-km-depth contour that is centered within the ring fracture zone of the caldera coincides very closely with the zone of observed attenuation for compressional seismic waves from local earthquakes, as shown by *Eaton et al.* [1975, Figure 5]. The isotherm outside the central part, but within the caldera rim, lies generally at a depth of 6–8 km. Around the southeastern and southern sections, just outside the rim, there are a few places with significantly shallow depths (4–6 km) of the isotherm, possibly indicative of the presence of local hot spots. Small scattered areas of surface hydrothermal alteration are seen to occur in association with them [*Eaton et al.*, 1975, Figure 3], but the relationship is not as marked as in the interior of the caldera. Further to the southeast, the isotherm seems to be deepening. In the northwestern section outside the rim, the depths of the iostherm are, in general, greater than 10 km. It is perhaps of significance that the general trend of the isotherm contours is northeast-southwest, parallel to and coextensive with the axis of the Snake River Plain with which the park has shared a common volcanic history. We are presently engaged in an examination of magnetic data for the Snake River Plain and upon its completion will have a clearer understanding of the regional depth to the base of the magnetized section outside the park.

The average elevation of the ground surface in Yellowstone National Park is about 2.5 km above sea level. Taking this elevation into account and assuming a Curie point temperature of 560°C, the temperature gradient seems to fall between 66°C/km and 72°C/km in the central part of the caldera. The remaining parts of the caldera have a gradient somewhere between 53°C/km and 66°C/km. These figures are anomalously high for heat flow in continental areas. Their continuation well to the east of the caldera, in an area underlain by Tertiary volcanic rocks, is puzzling and merits further investigation.

This study finds a strong correlation between geothermally hot regions and the thickness of the magnetized crust. A picture of the isotherm level as shown in Figure 4 suggests the presence of an extremely high degree of geothermal activity. This study therefore leads to the conclusion that appropriate analysis of aeromagnetic data can play an important role in regional reconnaissance for potential geothermal energy resources.

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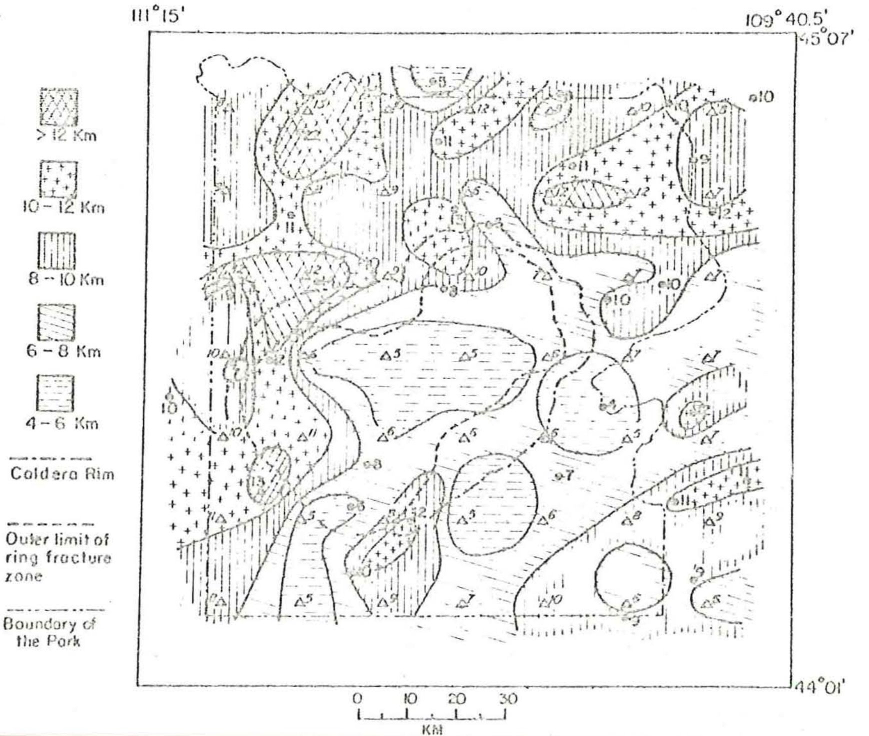

Fig. 4. Contoured map of the depths to the Curie point isotherm. Circles and triangles represent the locations of the centers of individual anomalies and grid blocks, respectively.

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