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ESTIMATED TEMPERATURE GRADIENTS BY CURIE POINT ANALYSIS IN THE IMPERIAL VALLEY

P-7038

3 June 1977

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ABSTRACT

Eureka Resource Associates proposes to map the Curie point isotherm from a carefully flown aeromagnetic survey for a geothermal study of the Imperial Valley.

The Curie point analysis can provide estimated temperature gradient information to much greater depths than conventional methods. While not an absolute determination, it provides relative depths to the Curie point (~500°C) and hence useful qualitative data as to the lateral variation in temperature gradients. It is conceivable that the technique could locate temperature anomalies not previously known.

Specific products to be delivered to each client are:

- Curie point isotherm contour map
- Estimated temperature gradient map (C°/100 m)
- Bouguer gravity map
- Residual field aeromagnetic map, second vertical derivatives of residual field map, offset profiles of aeromagnetic data and depth to basement map (from aeromagnetic and gravity data)
- Digitally enhanced Landsat images
- Tectonic interpretation of the Curie point depth surface incorporating published data, imagery and photography
- Base map showing townships, ranges and cultural features
- Composite prospect map
- Final report (2 copies)
- All maps will be to a scale of 1:125,000.

The cost of participation in the project is $31,000 to each client. By sharing in this exploration package, subscribers obtain the data at a price (approximately $1.10/sq km or $.004/acre) far less than that of an exclusive survey, and get an independent interpretation of the integrated data complex as well.

INTRODUCTION

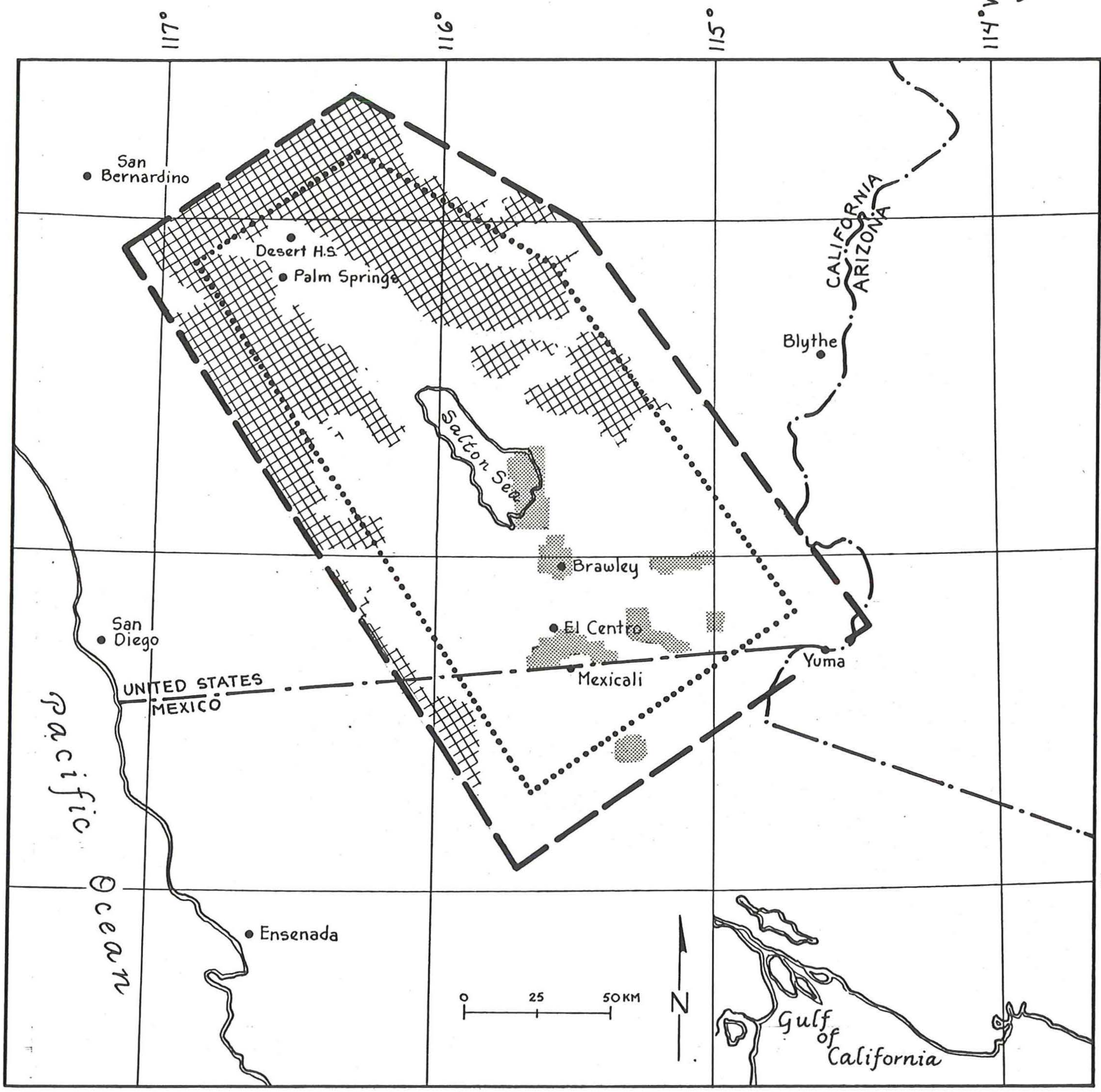
Eureka Resource Associates, Inc. proposes a geothermal study of the Imperial Valley which will include new aeromagnetic data, a Curie point analysis and temperature gradient map, gravity, Landsat imagery and tectonic interpretation. The area to be surveyed (Figure 1) is a large one, encompassing all the KGRA's in the region.

Extensive temperature gradient measurements have been taken in the Imperial Valley. A contour map published by Combs (1971, Figure 2) has been a valuable guide in planning exploration and siting geothermal drill holes. Many of the data from deeper wells have helped in local mapping of the temperature gradients of the more significant geothermal areas. However, for the majority of the region, the temperature gradient map shown in Figure 2 is based upon shallow temperature observation holes averaging approximately 90 m deep.

What is needed is a method that explores to a much greater depth (2.5 - 10 km) and relates, at depth, the tectonic and regional relationships of the geothermal anomalies.

The technique of Curie point analysis can provide temperature gradient information to much greater depths than conventional methods. While not an absolute determination, it provides relative depths to the Curie point (approximately 500°C) and hence useful qualitative data as to the lateral variation in temperature gradients. It is conceivable that the technique could locate temperature anomalies not previously known to exist in the Imperial Valley or not revealed in the shallow temperature gradient map.

The Curie point temperature is the temperature at which a ferromagnetic substance becomes paramagnetic, around 500°C ± 25°. These temperatures are



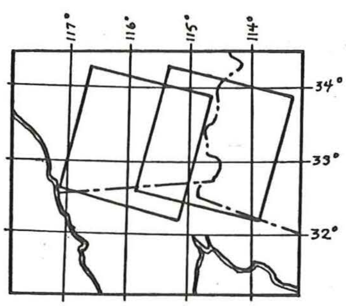
LEGEND

OUTLINE OF AEROMAGNETIC FLIGHT BLOCK

KGRA

ELEVATION ABOVE 2000'

OUTLINE OF CURIE POINT & ESTIMATED TEMPERATURE GRADIENT MAP COVERAGE



LANDSAT COVERAGE

FIGURE 1

LOCATION MAP SHOWING AEROMAGNETIC AND LANDSAT COVERAGE

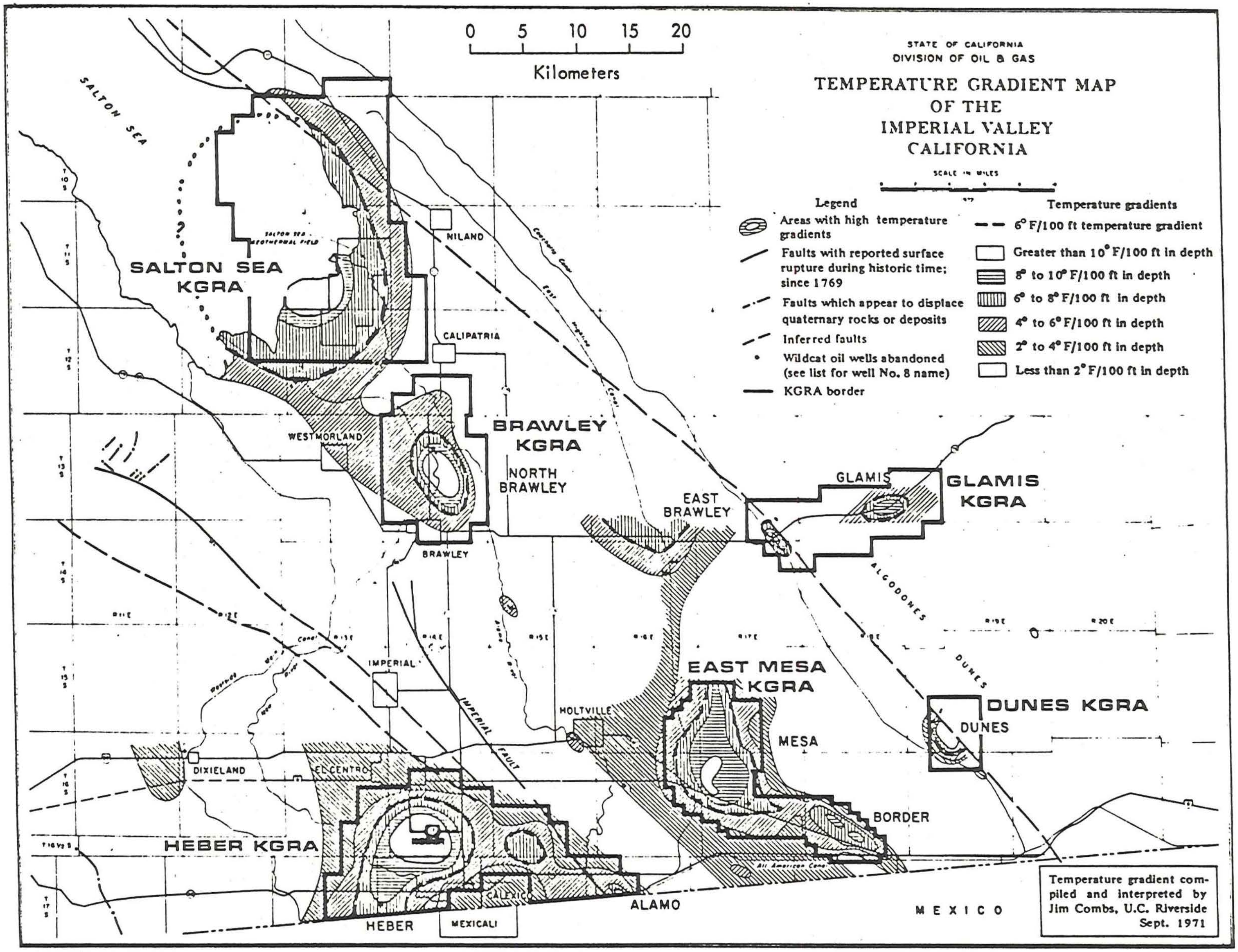


FIGURE 2

TEMPERATURE GRADIENT MAP OF THE IMPERIAL VALLEY, CALIFORNIA, SHOWING KGRAS.
(from Palmer, et al, 1975)

below the melting point of the igneous rocks believed by some to be the source of most of the heat in the Imperial Valley (Randall, 1975). Eureka has taken the Curie point isotherm concept from the research stage and developed it to a routine exploration method to use in conjunction with other geophysical and geological data.

To determine the Curie point depth and the shape of the Curie point isothermal surface, we propose a carefully planned and executed aeromagnetic survey and analysis of the data, using Eureka's proprietary computer programs based on the work of Bhattacharyya and Leu (1975, 1977). Published gravity, microearthquake and electrical resistivity data, drill hole information, and enhanced Landsat imagery, as well as the primary aeromagnetic data will be used to help establish a meaningful temperature and structural framework of the Salton Sea Trough.

The program is offered to the geothermal industry on a participation basis, and will be valuable for both those companies with existing land holdings in the region and those companies seeking a land position and needing reliable exploration data to help them evaluate potential farmouts, joint ventures or direct land acquisition.

APPROACH

Aeromagnetic Survey

Eureka has designed the aeromagnetic survey to cover a large region encompassing the Imperial Valley and surrounding area. The aeromagnetic coverage of approximately 12,640 line km (7900 line miles) will have NE-SW flight lines with a spacing of 3.2 km (2 miles), at right angles to the three major fault systems: San Andreas, San Jacinto and Elsinore, giving maximum magnitude to subtle anomalies arising from these NW-SE faults. Flight lines will vary in length from 93 km (58 mi) in the north to 144 km (90 mi) in the south and extend far enough beyond the anticipated shallow Curie point depths of the Salton Sea Trough to indicate the significantly deeper surrounding Curie point depths. Nine tie lines about 18 km (11 mi) apart, flown at nearly right angles to the flight lines, will help in the profile analysis and in the tying and contouring of data. The survey will be semi-drape flown at approximately 450 m (1500') clearance above terrain to minimize topographic effects. For most of the area this will be equivalent to constant barometric because of the flat terrain. Magnetic and altimeter (radar and barometric) data will be recorded on analog and digital recorders.

It is anticipated that the magnetic gradient over most of the Imperial Valley will be low. Exceptions will be the areas of basement outcrop to the northeast and southwest, the south end of the Salton Sea where there are extrusive rhyolite domes, and near the Cerro Prieto Volcano (rhyodacite cone) in Mexico. To achieve maximum resolution, a 0.25 gamma sensitivity setting will be used for the proton magnetometer, four times more sensitive than is commonly used, and values will be recorded every 1.2 seconds. Because of the necessity for maintaining tight altitude and flight azimuth tolerances, the survey will be flown in the early morning hours to avoid the turbulence caused by thermal conditions.

A 0.25 gamma base station magnetometer with analog recorder will be set up in the flight area to monitor diurnal variations. The airborne survey data will be corrected for diurnal changes to ensure that the geomagnetic variations are due solely to spatial variations within the crust.

We have been informed by the military authorities that permission to fly over their gunnery ranges must be requested and scheduled in advance. The same arrangements will be required for those flight lines in Mexico. Hence some logistical effort is anticipated to deal with these problems.

Curie Point Depths

The Curie point is the temperature at which rocks lose their ability to retain magnetism, that is, the temperature at which a material changes from ferromagnetic to paramagnetic behavior. Most rocks contain some ferromagnetic mineral, and the amount of ferromagnetic mineral contained in a rock ordinarily determines the magnetic properties of the rock. The most common ferromagnetic mineral is magnetite, which at elevated temperatures, say above 500°C, is the only stable ferromagnetic mineral (Erskine, 1976). The Curie point of pure magnetite is 578°C, but the major portion of the magnetic susceptibility is lost rather abruptly at a temperature of 500°C ± 25°C (Nagata, 1961). It is the latter temperature that we recognize to be the effective Curie point of the earth's crust, as determined from aeromagnetic data.

We base our calculations of the Curie point depth on the assumption that the crust becomes non-magnetic at the depth where the temperature reaches 500°C. Above that depth the crust retains its magnetism. Hence the Curie point depth is calculated by estimating the thickness of the magnetic crust. We estimate that thickness by (1) calculating the centroid location of the sum of the bodies causing anomalies in a block of data; (2) calculating the average depth to the top of the same bodies; and (3) assuming that the magnetic crust is symmetrical about its centroid. A description of the method, essentially that of Bhattacharyya and Leu (1975 and 1977), described in greater detail by Erskine (1976), is included in the Appendix.

A contour map indicating the estimated depth to the Curie point isotherm in kilometers will be furnished on a transparent overlay (scale 1:125,000) to digitally enhanced Landsat images. Because of mathematical operator sizes, approximately 18 km (11 mi) will be lost from around the edge of the aeromagnetic coverage shown in Figure 1.

Temperature Gradient Map

An estimated temperature gradient map will be constructed from the Curie point depth map, based upon the assumption of a Curie temperature of 500°C and a mean surface temperature at sea level. The resultant temperature gradient map (C°/100 m) will give a gradient averaged over a much greater temperature and depth range than the present temperature gradient contour map compiled from shallow, 90-m drill holes.

Landsat Imagery

Eureka has developed a unique tectonic mapping style based on the enhancement of selected Landsat imagery, which has proved useful in defining regional and detailed structural features. The approximately five years of suitable satellite coverage is examined to select 'ideal' scenes combining near zero cloud cover and low sun angles. These are usually September and October scenes--periods of low vegetation vigor. Bands 4, 5 and 7 (0.5 to 1.1 microns on the electromagnetic spectrum) are digitally enhanced to produce a false color composite print at scales of 1:250,000 and/or 1:125,000 for prospect definition. It is important to use specific scales and seasons to develop the optimum conceptual picture of both the regional tectonic framework and the local structure affecting the distribution of geothermal anomalies.

For this project portions of two enhanced color composite images, scale 1:125,000 (Figure 1) will be used in our interpretation and furnished to each participant. These frames will be digitally processed by (1) a LaPlacian (second derivative) edge enhancer, (2) geometric rectification to fit polyconic map projections (maximizes scale accuracy in all directions) and (3) a new gray level adjustment (contrast enhancement). The results will be scenes with much greater detail and resolution of geologic, linear and curvilinear features than the standard EROS optical enlargements to the same scale.

Skylab photography and, where available coverage permits, high altitude IR color and color photography (scale ~ 1:130,000) will be used to reveal more local detail in areas of special interest.

INTERPRETATION

The Curie point isotherm map, temperature gradient map, Landsat imagery and published data will be combined with the following aeromagnetic maps in an interpretation of individual anomalies which seem to be promising geothermal targets:

1. Residual field map
2. Filtered residual field map
3. Second vertical derivative of residual map
4. Offset profiles along flight lines
5. Depth to basement contour map

The Curie point isotherm will also be interpreted in a plate tectonic setting, emphasizing a regional framework of Southern California and the Gulf of Mexico. Reference will be made to previous plate tectonic investigations: Atwater, 1970;

Elders and Biehler, 1975; Elders et al., 1972; and Larson, 1972.

We propose a spectral analysis approach similar to that of Bhattacharyya and Leu (1975a), to estimate the depth to magnetic basement. With particular combinations of the spectra of anomalies and their first and second order moments, we can determine the locations of edges of two-dimensional structures. The depth to these edges in turn reflects the change of the basement depth along the flight lines. The profile analysis will be converted and presented as a transparent depth-to-basement overlay to the Landsat imagery.

Conventional aeromagnetic interpretation for faults, grabens, horst blocks, basement depths and topography will supplement the existing gravity data and Landsat interpretation in the third dimension.

The Curie point depth and estimated temperature gradient maps will be interpreted using the published temperature gradient maps (Combs, 1971 and Rex et al., 1971), gravity (Biehler et al., 1964) and the geological-geophysical-geochemical investigations of Rex et al., 1971.

Of particular interest will be the Salton Sea Geothermal Field. Extensive information has been published on the lithology, temperature and geochemical characteristics of the field, gathered from 24 wells ranging in depth from 159 m (590') to 2430 m (8100'). Data have been published by Palmer, 1975; Randall, 1975; Rex et al., 1972; Muffler and White, 1969; and Helgeson, 1968. Also a number of geophysical anomalies are associated with the area from electrical resistivity (Meidav et al., 1976), aeromagnetic (Griscom and Muffler, 1971), microearthquake (Hill, Mowinckel and Peake, 1975; Langenkamp and Combs, 1974; Gilpin, 1975) and gravity surveys (Biehler et al., 1964). These studies will be used to develop a structural and temperature interpretation from the Curie point depths.

A geothermal model predicated upon a near surface igneous intrusive (magma chamber) heat source will be used for evaluating those anomalous areas that seem similar. The model is based upon a 'typical' porphyry copper deposit where the heat source is also the driving force of a convection acid hot springs system, and is more fully discussed by Erskine (1976a) in a report which shows idealized aeromagnetic profiles and gravity anomalies often associated with geothermal systems.

The Curie point analysis of the well known Salton Sea geothermal field will then be compared to the sparsely documented, deeper geothermal anomalies of Brawley, Heber, East Mesa, Dunes, Glamis and the northern Salton Sea area.

A final Composite Prospect Map will summarize the data from all sources to help define the priorities of each of the targets detected in the interpretation.

A comprehensive final report will document all the supporting evidence for the selection of target locations, with emphasis on shallow Curie point anomalies, estimated temperature gradients and other supporting data.

DELIVERABLES, PRICE AND TERMS

It is anticipated that the project will be completed approximately 4-5 months after go-ahead. The final results will be presented in a seminar in Berkeley.

The following data will be delivered to each participant at the seminar. All maps will be at a scale of 1:125,000.

- Curie point isotherm contour map
- Estimated temperature gradient map
- Bouguer gravity map
- Residual field aeromagnetic map
- Second vertical derivatives of residual field map
- Offset profiles of aeromagnetic profiles
- Depth to basement map, from aeromagnetic and gravity data
- Digitally enhanced Landsat images
- Tectonic interpretation of the Curie point depth surface incorporating published data, imagery and photography
- Base map showing townships, ranges and cultural features
- Composite prospect map
- Final report (2 copies)

The price will be $31,000 for each subscriber, with a minimum of three subscribers required to undertake the project. We will start when we receive three firm orders and will require an initial payment of $15,500 (50% of price). The remainder will be due upon presentation of the final report. After July 8, 1977 the price of the program will be $35,000 to each subscriber.

Subscribers will warrant that they will not give, sell, reproduce, or disclose any information from the Imperial Valley project to non-subscribing parties, without written permission of Eureka Resource Associates, Inc.

CORPORATE EXPERIENCE

Within the last year, Eureka has completed or has underway twelve major projects, mostly in geothermal exploration. The experience of the principals and associates covers many aspects of geothermal, mineral and petroleum exploration, ranging from basic geology and geophysics to the enhancement of satellite imagery. Our experience incorporates an understanding and application of recent plate tectonic theory and interpretation to specific targets.

Eureka is the first company to apply Curie point isotherm mapping as an exploration service to the geothermal and petroleum industries. We have applied the technique to a number of projects and have developed it for use as a routine exploration tool to supplement other geophysical and geological data.

Eureka maintains its corporate headquarters in El Cerrito, California and operates 1800 square feet of research and administrative office space in Berkeley, California. Available support facilities include the libraries, computer center and technical expertise of the University of California. Several of Eureka's research associates are located nearby. The facilities of Stanford University and the U. S. Geological Survey are also convenient and available for our activities.

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APPENDIX A

DETERMINATION OF CURIE POINT DEPTHS FROM AEROMAGNETIC DATA

DETERMINATION OF CURIE POINT DEPTHS FROM AEROMAGNETIC DATA

13 December 1976

Revised 23 February 1977

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INTRODUCTION

In the exploration for geothermal resources, the horizontal variation in vertical temperature gradient is very important. Recent advances in the processing and interpretation of aeromagnetic data have provided a new method for determining this spatial information, based on the concept of loss of magnetism with increase in rock temperature past the Curie point. This paper considers the theory of magnetism relative to the Curie temperature and applies the concept to the mapping of the Curie isotherm over an area of geothermal or petroleum interest.

The Curie point of a material is the temperature at which the material loses its ability to retain magnetism after the energizing field is removed; that is, it is the temperature at which a material changes from ferromagnetic to paramagnetic behavior. All rocks generally contain some ferromagnetic mineral, and it is the amount of ferromagnetic mineral contained in a rock that ordinarily determines its magnetic properties.

This paper describes the methods used to calculate from aeromagnetic data the depth to the Curie point in the crust and discusses the meaning of the depth so calculated, in terms of temperature, temperature gradients, and a reasonable petrologic model of the crust. The primary method of calculation of the Curie point depth to be described is that used by Bhattacharyya and Leu (1975) to analyze the magnetic anomalies measured over Yellowstone National Park. The discussion of the meaning of the Curie point depth in terms of temperature and crustal models will be developed.

Applications of the determination of the Curie point surface in the crust to geothermal and petroleum exploration problems will also be briefly discussed.

MAGNETIC PROPERTIES OF MINERALS AND ROCKS

The physics of magnetism and magnetic minerals and rocks is described and documented in texts by Strangway (1970) and by Nagata (1961). For purposes of geophysical investigation, Nagata describes a rock as a scattering of ferromagnetic mineral grains throughout a matrix of paramagnetic and diamagnetic silicates. Further, "because of the presence of these ferromagnetic particles, the bulk of the rock shows the characteristics of ferromagnetism, such as the magnetic hysteresis and the Curie temperatures, although the intensity of magnetization may sometimes be not much more than that of paramagnetics," (Nagata, 1961, p. 126). There are very few ferromagnetic minerals, and they consist mainly of the more or less titaniferous iron oxides and the iron sulfide pyrrhotite. Some of the ferromagnetic minerals are very widely distributed in small quantities in most rock types. The spatial distribution of these minerals determines the pattern seen on aeromagnetic maps.

Table I is a list of the magnetic properties of selected minerals. Note that the susceptibility and saturation magnetization of magnetite are very much greater than those of any other minerals. Given the wide distribution of magnetite (with varying amounts of titania in solid solution), we recognize that the dominant control of the magnetic signal from the crust is in the mineral magnetite.

The Curie point of pure magnetite is 578°C, well below its melting point of about 1590°C. The presence of other metallic elements as substitutes for either the ferric or ferrous ion in the spinel structure of magnetite generally reduces the Curie point of the magnetite. The results of measurements have been summarized by Nagata (1961, p. 116-117) but the only geologically important substitution is in the series magnetite → ulvöspinel, where a combination of Fe^{+2} and Ti^{+4} replaces the Fe^{+3} of magnetite. Figure 1 is a

TABLE I

MAGNETIC PROPERTIES OF SELECTED MINERALS

	Susceptibility (weak magnetic field) emu/g	Neel or Curie Temperature C°	Saturation Magnetization
A. Diamagnetic minerals			
Quartz	-0.50×10^{-6}		
Calcite	-0.38×10^{-6}		
Gold	-0.14×10^{-6}		
B. Paramagnetic minerals			
Fayalite	$+100.0 \times 10^{-6}$	-147°	
Pyroxene	$78. \times 10^{-6}$	-233°	
Biotite	$60. \times 10^{-6}$		
Rhodochrosite	$100. \times 10^{-6}$	-241.5°	
Ilmenite (pure)	0.87×10^{-6}	-216°	
Rutile	0.07×10^{-6}		
C. Ferromagnetic minerals			
Magnetite (Fe_3O_4)	$100,000. \times 10^{-6}$	578°	92.0
Maghemite (γFe_2O_3)		545 to 675°C	83.5
Ilmenite-hematite solid solution		50 - 300°C	21.0 max.
Pyrrhotite (FeS_{1+x})		320°C	19.5 max.
Ulvöspinel		-153°C	
Hematite		680°C	~0.5

Compiled from Nagata, 1961 and Strangway, 1970.

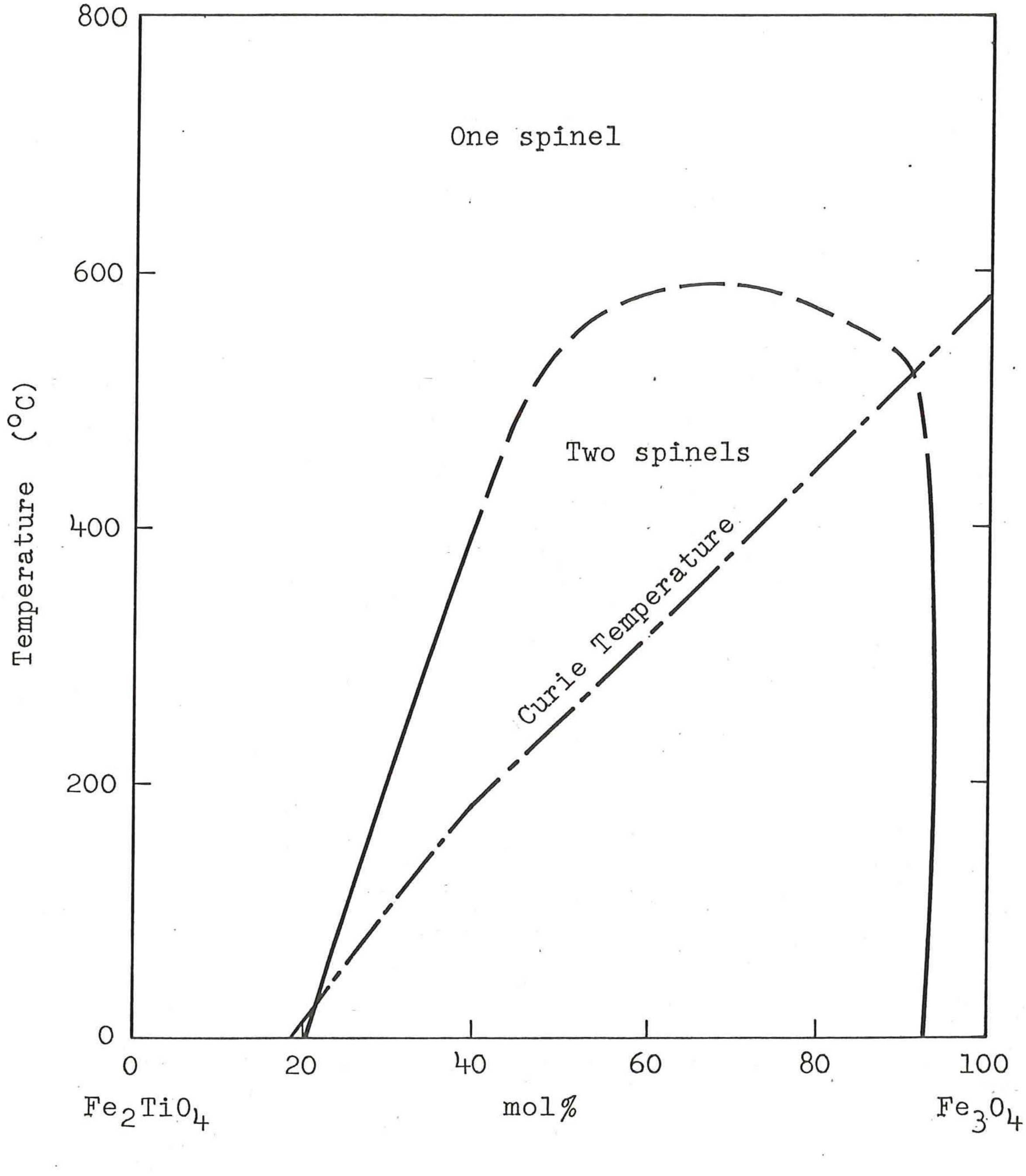


FIGURE 1

PHASE RELATIONS AND CURIE POINT

VERSUS

CHEMICAL COMPOSITION IN THE MAGNETITE-ULVÖSPINEL SERIES

(NAGATA, 1961, FIGURE 3-7 AND FIGURE 3-5) superposition of the Curie temperature versus the chemical composition in the series magnetite-ulvöspinel (Nagata, 1961, p. 82) and the subsolidus equilibrium phase diagram of the same series (Nagata, 1961, p. 84). The importance of Figure 1 may be appreciated when one realizes that the ulvöspinel end member has not been described in any mineralogy text and has only recently been recognized by x-ray microprobe analysis as a minor constituent of the magnetite of volcanic rocks. That is, since ulvöspinel exists in nature only as a minor exsolved phase from rapidly quenched melts, the magnetite end members are the dominant, in fact the only, magnetic mineral of importance in this study. The only other ferromagnetic mineral listed on Table I with a saturation magnetization approaching magnetite is maghemite. Its Curie temperature had to be estimated because maghemite inverts irreversibly to αFe_2O_3 (hematite) above temperatures of about 275°C.

At the Curie point of pure magnetite, 578°C, the equilibrium mineral assemblage in a $FeO\text{-}Fe_2O_3\text{-}TiO_2$ system is a mixture of relative pure ilmenite with relatively pure magnetite or relatively pure hematite, depending upon the fugacity of oxygen in the system as per

$$\underset{\text{Magnetite}}{2Fe_3O_4} + \underset{\text{Oxygen}}{\tfrac{1}{2}O_2} \longleftrightarrow \underset{\text{Hematite}}{3Fe_2O_3}$$

Since the magnetite has an inverse spinel structure with a unit cell dimension of 8.395Å and the ilmenite has a rhombohedral structure with a unit cell dimension of 5.538Å, the mutual solubility of the two minerals is very small. In plutonic igneous rocks the typical mineral association in this system is magnetite and ilmenite, or hematite and ilmenite. As noted by Strangway (1970, p. 32),

> "In many volcanic rocks the content of titanium is high, and the iron-titanium oxide minerals formed are a mixture of magnetite and ulvöspinel. As cooling proceeds, the ulvöspinel becomes mineralogically unstable and tends to oxidize to form ilmenite and magnetite. Since the ilmenite is rhombohedral and is structurally incompatible with the

> magnetite, an intimate intergrowth of magnetite and ilmenite forms. . . . . the effect of this is to create great magnetic stability in magnetite."

The subsolidus curve for the mixture of hematite and ilmenite (Figure 2) is very like that for the titanomagnetites (Figure 1), except that the solid solution, the one mineral phase, is much more restricted at 500 - 600°C than in the former system.

The magnetic behavior of these minerals as a function of temperature has one additional feature of particular interest here. Figures 3 and 4 are plots of magnetic susceptibility of some Japanese volcanic rocks as a function of field strength, at low field strengths. In general the susceptibility of most rocks increases as a somewhat irregular function of the exciting field strength, so for interpreting aeromagnetic data it is important to measure the susceptibility of ferromagnetic rocks at or near the very weak strength of the earth's main field (~0.6 Oersteds). Figure 5 shows the effect of measuring thermomagnetic curves at various field strengths and Figure 6 shows the measurement of the susceptibility of a ferromagetic rock at 1.35 Oersteds as a function of temperature. Note how rapidly the susceptibility drops to very low values as the Curie point is reached. Note also that susceptibility actually increases as a function of temperature until the Curie point is reached at field strengths approaching the earth's main field.

The importance of these observations will be made explicit in the following discussion of models of the magnetic crust.

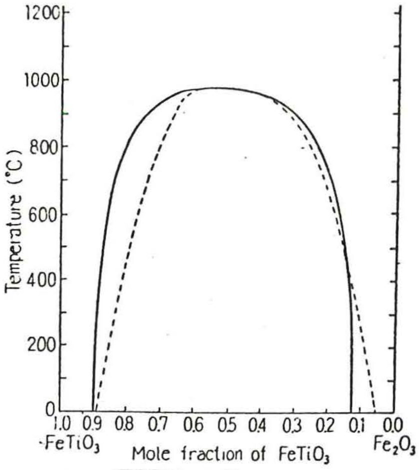


FIGURE 2

SOLVUS CURVE FOR ILMENITE-HEMATITE SOLID SOLUTION SERIES.

(Nagata, 1961, Figure 3-27)

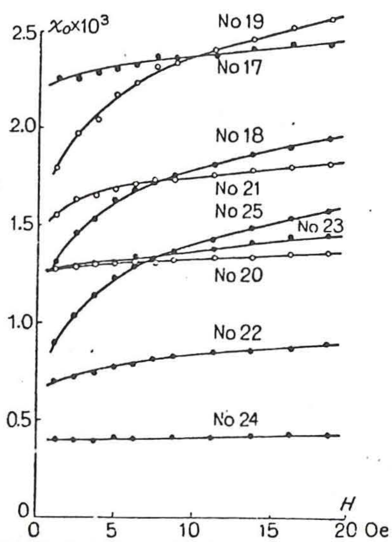


FIGURE 3

MAGNETIC SUSCEPTIBILITY OF VOLCANIC ROCKS AS DEPENDENT ON EXTERNAL MAGNETIC FIELD.

(Nagata, 1961, Figure 4-3)

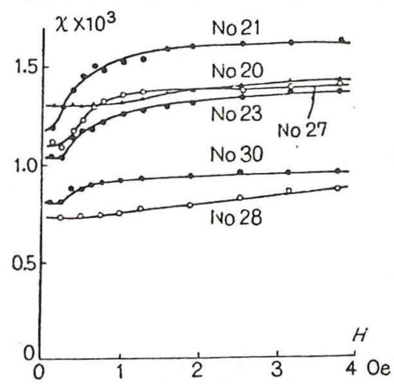


FIGURE 4

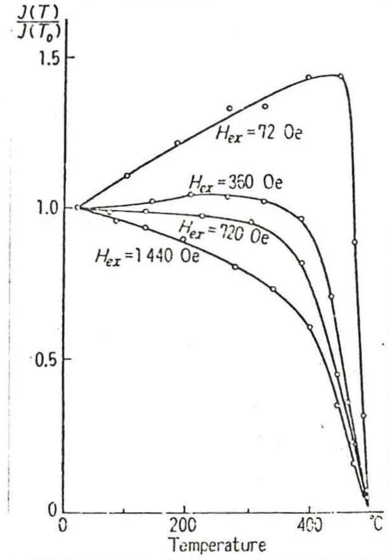
MAGNETIC SUSCEPTIBILITY OF VOLCANIC ROCKS IN WEAK MAGNETIC FIELDS.

(Nagata, 1961, Figure 4-4)

FIGURE 5

THERMOMAGNETIC CURVES IN VARIOUS MAGNETIC FIELD STRENGTHS.

(Nagata, 1961, Figure 3-19)



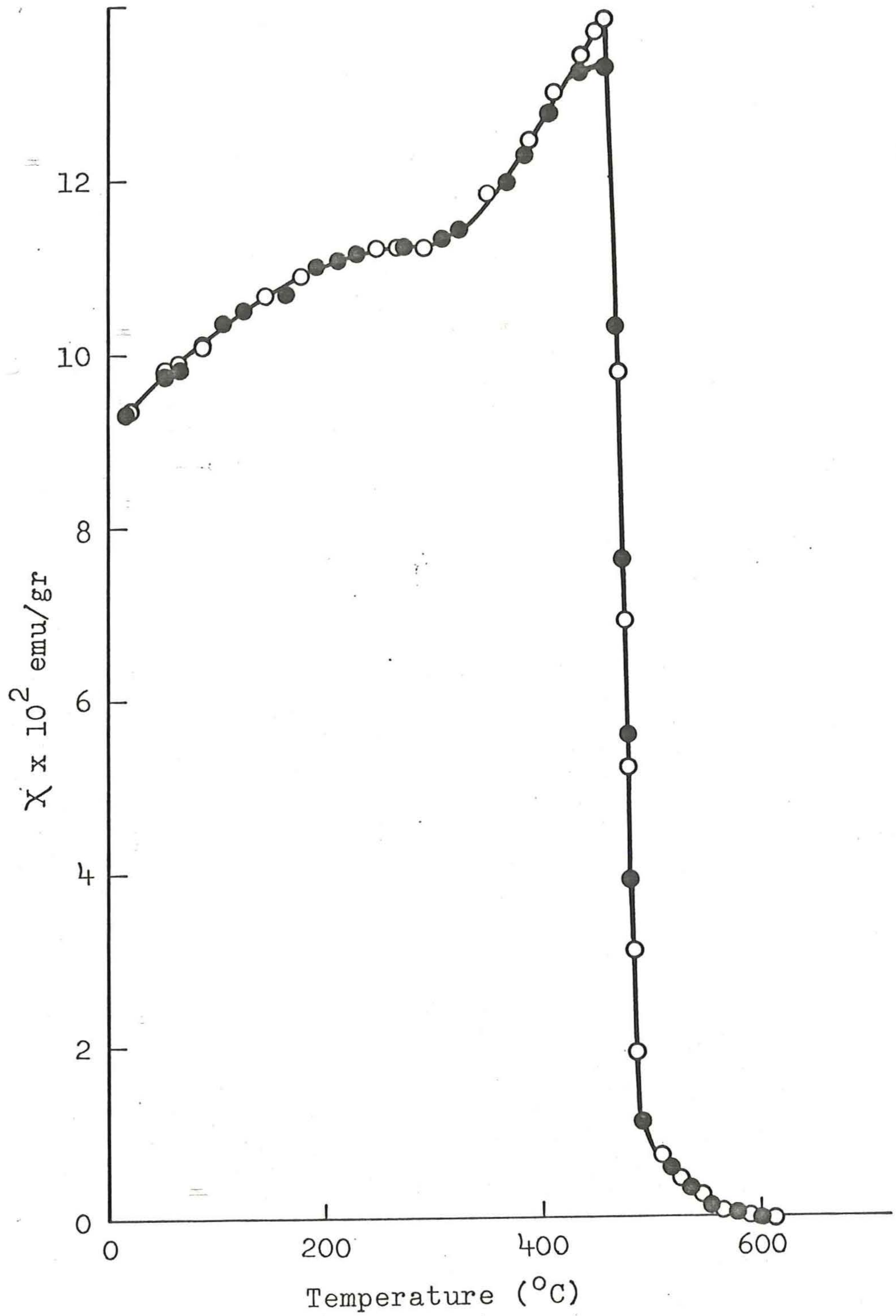


FIGURE 6

CHANGE OF MAGNETIC SUSCEPTIBILITY
WITH TEMPERATURE IN Hex = 1.35 Oe.
Sample: Haruna ferromagnetic mineral

(NAGATA, 1961, FIGURE 5-30)

MAGNETIC CRUSTAL MODELS

It is here proposed that the only mineral of magnetic significance at the base of the magnetic crust is magnetite, and that the base of the magnetic crust is determined by the Curie point (the temperature of thermal disordering) of magnetite (578°C). In defense of this proposal, we will examine briefly a thermal and petrologic model of the crust.

The temperature within the crust increases as a function of depth, as indicated on Figure 7, which is constructed from the estimates of Diment et al. (1975). The estimated thickness of the magnetic crust (compared to the petrologic crust) is indicated by the intercept of these depth temperature curves with the Curie point range, and this thickness is generally much less than the thickness of the crust estimated from seismic data. We interpret this to mean that at the Curie point depth the crust consists of average crustal material, which has an average temperature of 578°C, and which probably has been at or near that temperature for a geologically long period of time.

Figure 8 is a pressure-temperature diagram for metamorphic facies (Hietanen, 1966) from which we may deduce the metamorphic assemblage present as a function of depth in the Curie point range of crustal rocks. Using this assemblage as a guide, we can now select a magnetic crustal model. At the Curie depth in the crust, we suggest that there is a high grade metamorphic assemblage, of which the Grenville rocks of eastern Canada would be a good model. Plate I is an aeromagnetic map (scale 1/253,440) of typical high grade (muscovite-sillimanite facies) Grenville metamorphic rocks from south central Quebec, Canada. The magnetic signature of such high grade metamorphic rocks is characteristic enough in terms of high space frequencies and amplitudes to allow mapping of the Grenville metamorphic "front" on aeromagnetic maps. Note, incidentally, that the magnetic "anomalies" on this map are characteristically much longer

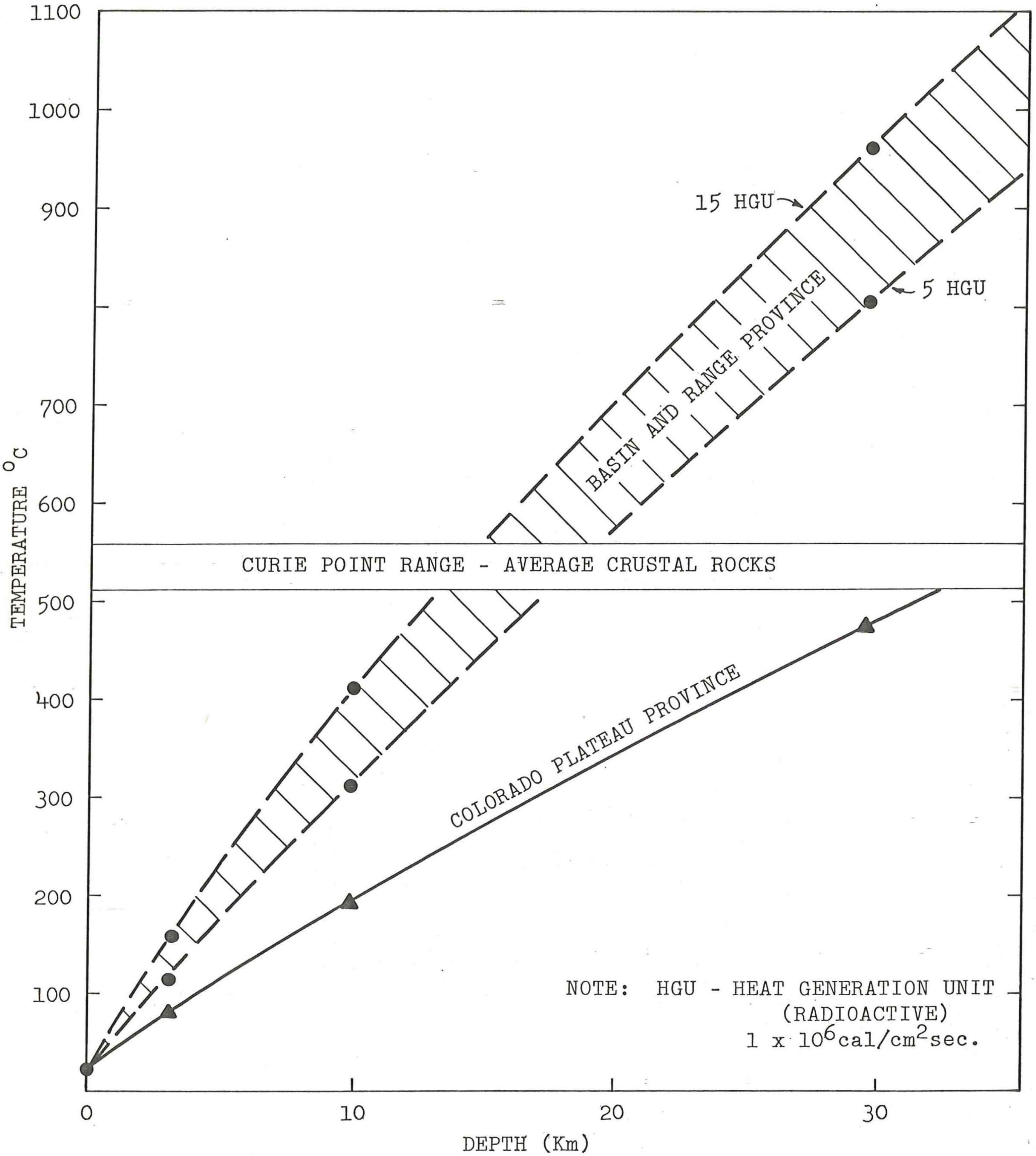


FIGURE 7

CRUSTAL DEPTH-
TEMPERATURE ESTIMATES FROM DIMENT, ET AL., 1975

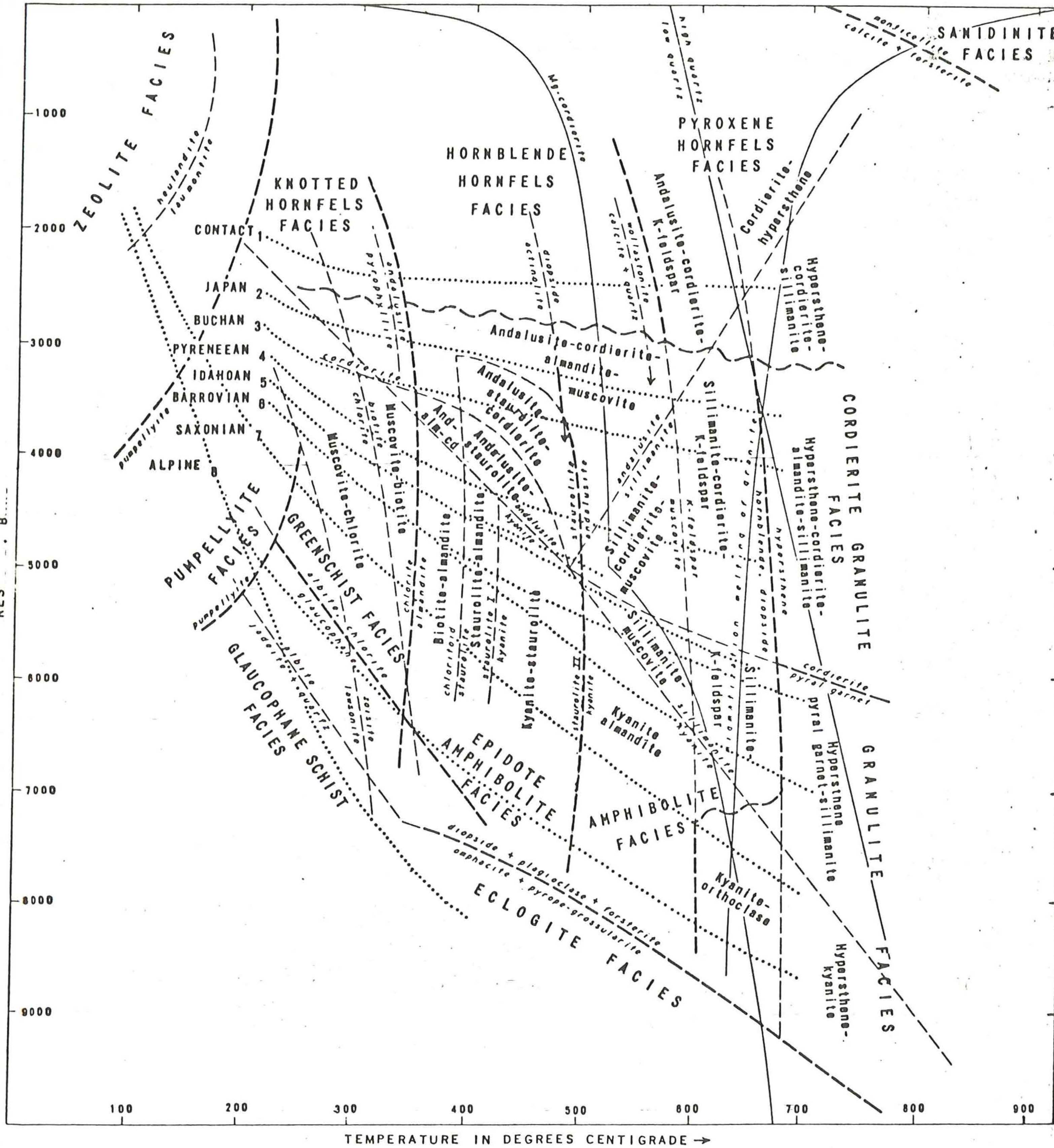


FIG. 8 —Tentative *PT* diagram showing possible stability fields of metamorphic facies and *PT* gradients in various types of metamorphism in relation to the melting curve of the granite (Tuttle and Bowen, 1958), to the curve for low-high quartz (Yoder, 1950), and to the lower stability boundary of Mg-cordierite (Schreyer and Yoder, 1964). Stability boundaries of the other index minerals are inferred from field relations. Inferred stability field of staurolite is shaded. Temperature for the triple point was chosen to satisfy field relations and the geologic thermometry for the rocks northwest of the Idaho batholith. Pressures are estimated. Wavy line shows the arbitrary limit of hornfels facies and of granulite facies. Subfacies correspond to zones in the field and are indicated by two or more diagnostic minerals (heavy print).

than they are wide; that is, that the "anomalies" are on the whole well modeled by horizontal cylinders and infinite dikes. Note also that the Grenville type metamorphic rocks are rich in magnetic signal.

We therefore suggest that at the level of the Curie point of magnetite in normal crustal rocks, active regional metamorphism to muscovite-sillimannite facies is taking place; and that in the simple metal oxide system $FeO-TiO_2-Fe_2O_3$ where reaction kinetics are not an issue, the only ferromagnetic mineral present will be magnetite. We further suggest, based upon reasonable projections from Figure 6, that the temperature indicated by the Curie point calculations described here is 500°C $\pm$ 20°C, the temperature at which the intensity of magnetization of the magnetite has fallen to about 1/10 of its maximum. Figures 9 and 10 are simplified thermal models of the crust, and on Figure 10 we have indicated diagrammatically what we think the actual and the calculated Curie point isothermal surfaces might look like.

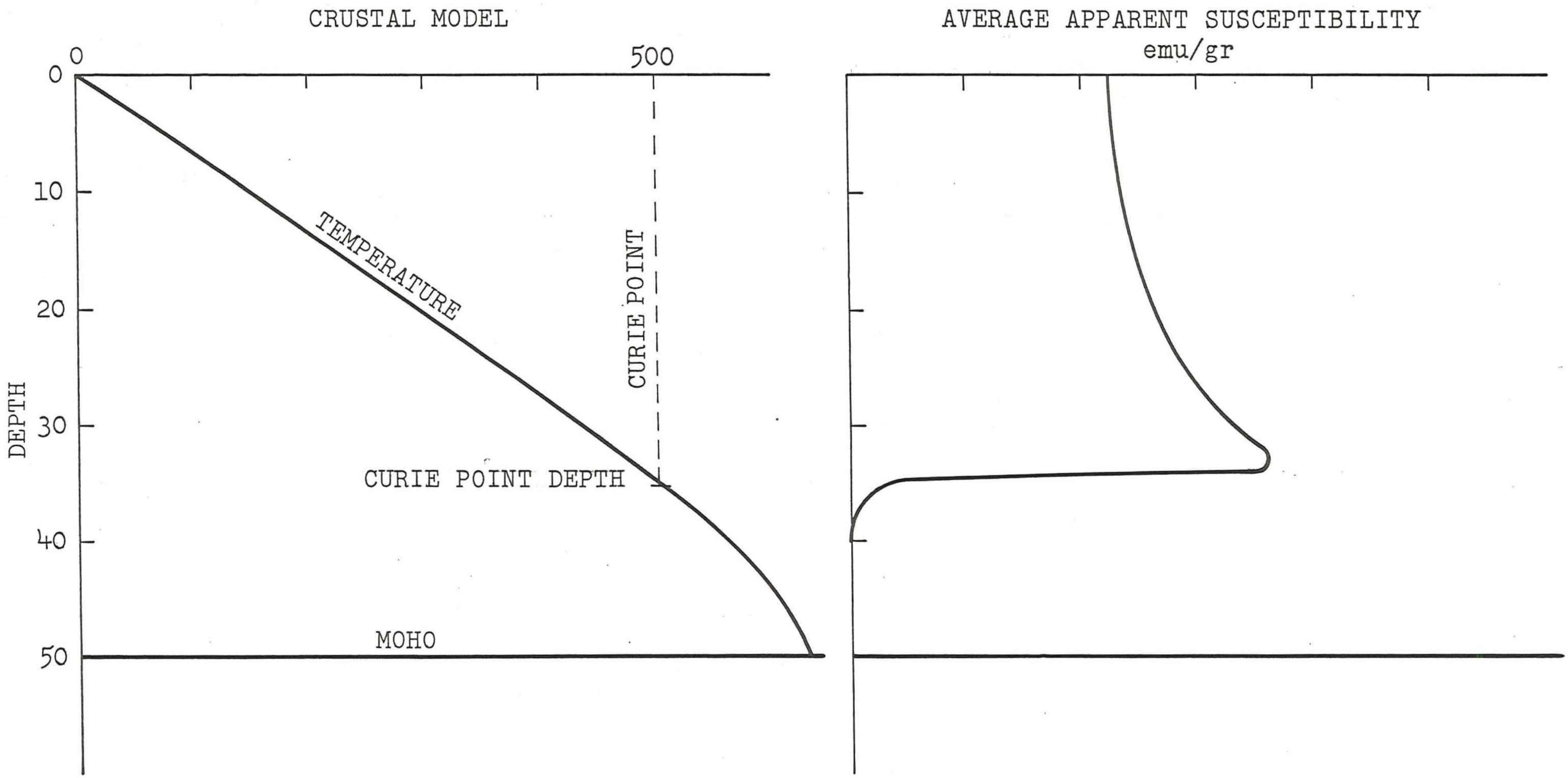


FIGURE 9
AVERAGE CRUST

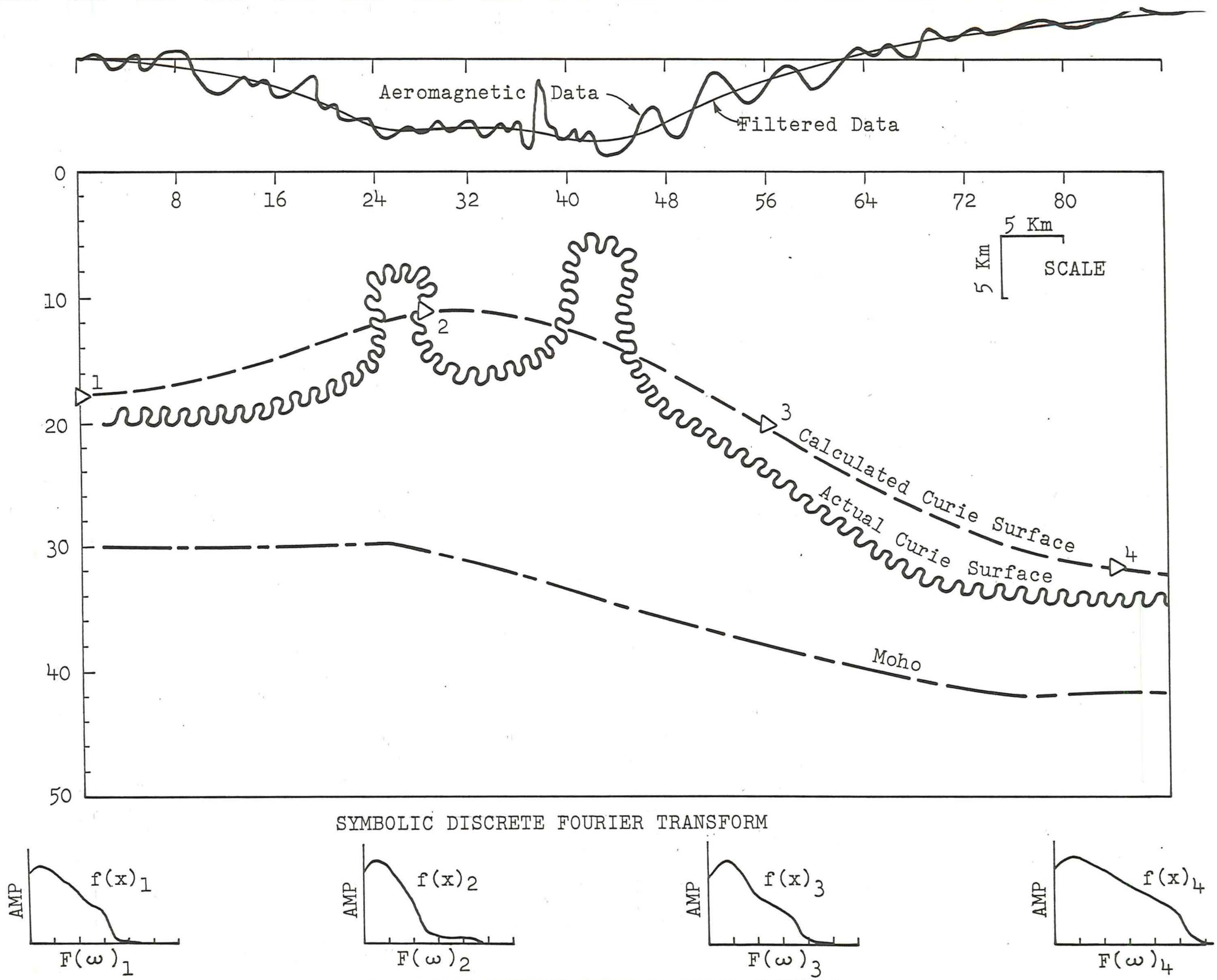


FIGURE 10 DIAGRAMMATIC CRUSTAL CROSS SECTION

DETERMINATION OF CURIE POINT DEPTHS FROM AEROMAGNETIC DATA

We estimate the depth to the Curie point in the crust by estimating the depth to the bottom of the magnetized bodies which make up the crust. In general the farther away a magnetic body (source of magnetic signal) is from the sensor, the broader is its response in space (the longer the spatial wave length of its effect). Since this effect is independent of the relative strength of magnetization of the body, it is generally used in some form or other in depth determinations from aeromagnetic data. However, the farther away a body is, the more difficult it is to estimate its distance accurately.

A summary of all the factors which must be considered in designing an aeromagnetic survey and preconditioning the resulting data prior to the actual calculation of the Curie point depth is presented in Table II. One facet of the survey design will be considered here as an example of the detail necessary in treating all these factors.

Since our primary concern in estimating the depth to the Curie point is in the quality of the low space frequency data, it is necessary to consider the sources of noise in aeromagnetic data from the point of view of space frequency content. For example, in deciding whether to drape fly the aircraft, or to fly at a constant barometric elevation, we consider that the primary noise from constant barometric flying is topographic noise. This is high frequency noise because it is near the sensor. It has very large amplitudes because the contrasts between magnetic rocks and air are large. The primary noise from drape flying is caused by the inability of the aircraft to track the relief perfectly. This noise is of very high frequency, but with good flying at relatively high altitudes, the amplitude is very small. Careful consideration of these factors shows that drape flying is desirable, with special precautions for maintaining a constant terrain clearance. In practice it is necessary that the

TABLE II

NOISE AND SIGNAL: THEIR SOURCES AND CHARACTERISTICS FOR SPACE FREQUENCY ANALYSIS

SOURCE	CHARACTERISTICS		DESIGN CONSIDERATIONS AND REMARKS
	AMPLITUDE	SPACE FREQUENCY	
A. Data noise sources			
1. Flying height			
a. very low b. intermediate c. high	large ↓ small	high but variable ↓ low	Atmospheric turbulence is a noise source at very low levels, particularly in rough terrain. ~1000 ft. seems a good compromise. The higher the data is flown, the more real signal is lost.
2. Type of flying			
a. constant barometric			Aircraft noise is minimal
(1) Topographic noise	very large	broad freq. band	When surface rocks magnetic & topography rough, this can be very difficult.
(2) Aircraft noise	very small	very high	Filtering can handle
b. constant terrain clearance			Topographic noise is minimal
(1) Topographic noise	small	high	Filterable
(2) Aircraft noise	small	very high	Filterable
3. Flight and Tie-line Spacing	small	The flight line and tie line spacing are the fundamental frequencies	The cost of the survey goes up directly as the number of flight lines increases.
4. Flight block size	If the flight block is too small, the signal amplitude will be too low at the low frequency end.		
5. Flight azimuth	small	low	Flights at right angles to basement magnetic "grain" sample basement magnetic signatures best. Other directions tend to shift the freq. to the low end of spectrum and give too large an estimate of Curie point depth.

TABLE II - CONTINUED

SOURCE	CHARACTERISTICS AMPLITUDE	CHARACTERISTICS SPACE FREQUENCY	DESIGN CONSIDERATIONS AND REMARKS
B. Geologic Noise Sources			
1. Earth's main field	very large	very high	Removed by subtracting the IGRF or a "regional" field
2. Large geologic blocks that extend well beyond the area of interest horizontally	large	very high	Mostly reduced by removing a 2nd 3rd order regional fit by least squares methods
3. Small near surface magnetic geologic bodies	large	low	Reduced to manageable size by zero phase shift low pass filtering
C. Signal-magnetic bodies within the crust	medium to small	low	The mean geometry of these bodies is assumed to produce the signal necessary to map the Curie point depth
D. Computational noise sources	variable	low	These are discussed in this paper, based upon the work of Bhattacharyya and Leu (1975a)

aircraft has a good differential altimeter, that there be two pilots with dual controls (one pilot to be responsible for staying on line and the other for control of terrain clearance), and a mean terrain clearance of at least 1,000 feet.

In the following pages we will concentrate on the actual Curie point analyses after the aeromagnetic data has been flown and preconditioned according to the requirements listed in Table II.

CALCULATION OF THE CURIE POINT DEPTH

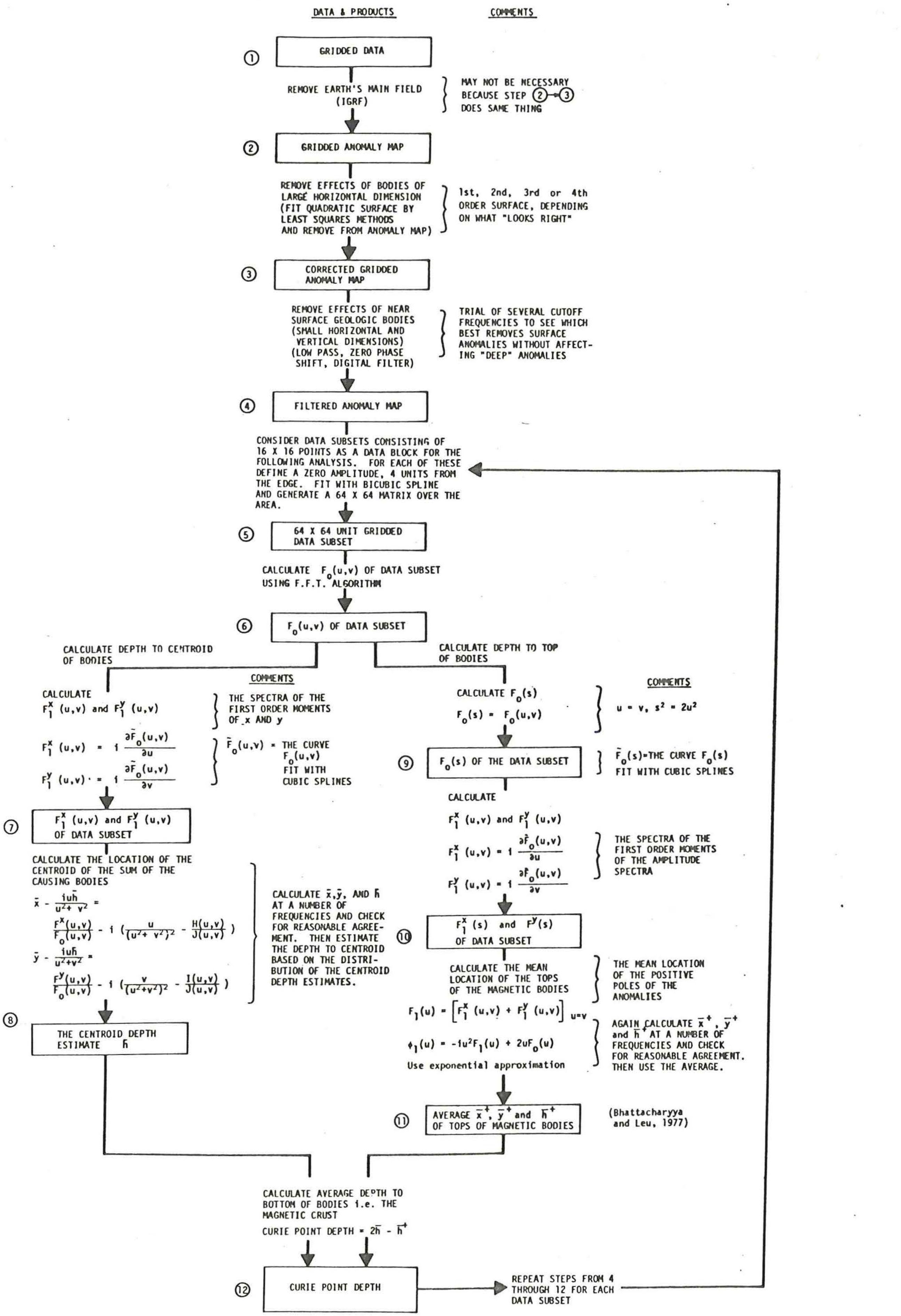
The Curie point calculation described here is based upon two papers by Bhattacharyya and Leu (1975a and 1975b). The first of these papers discusses the automatic interpretation of potential field data based upon calculation of the spectra of the moments of the anomalies and the improvement in bottom depths to be expected from such an approach when properly done. The second paper describes an application of the concepts of the first in the calculation of the depth to the Curie point from aeromagnetic data of Yellowstone. The frontispiece of this paper is a recontoured map of the Curie point isotherm for Yellowstone, calculated by Bhattacharyya and Leu (1975b), overlying an enhanced Landsat image of the Yellowstone region. The simple Landsat interpretation indicated on the overlay by dotted lines is strongly reinforced by the Curie point depth contours and suggests the value of the Curie point depth contours in guiding geothermal exploration in such an area.

Table III is a diagrammatic flow sheet of the Curie point depth calculation procedure proposed by Bhattacharyya and Leu and used on the Yellowstone data. For spectral analysis the data is divided into discrete blocks, as indicated by step 5 on Table III. In the Yellowstone analysis a square array of 16 x 16 data points, with an areal coverage of 31 kilometers by 31 kilometers was used for the basic analysis unit, with each unit overlapping surrounding units by half. They describe the procedure in the following manner.

> "Since discontinuities in data values at the edge of the area give rise to Gibbs phenomena and aliasing, it is assumed that the residual field vanishes at a point which is located at a distance of four units of data spacing from the boundary of the block. Inclusion of these points results in 18 x 18 (non equispaced) 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." (Bhattacharyya and Leu, 1975b)

TABLE III

FLOW DIAGRAM FOR CALCULATION OF THE CURIE POINT DEPTH DATA



The discrete Fourier Transform $F_o(u,v)$ is then obtained for this data block with the help of the fast Fourier Transform algorithm. By using a method outlined by Bhattacharyya and Leu (1975a), 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 will be a number of bodies causing the anomalies. The mean location of the centroid of these bodies $(\bar{x}, \bar{y}, \bar{h})$ is determined with the help of the euqations of steps 7 and 8, Table III.

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 an error in the estimate.

Next, the radial spectrum $F_o(s)$ is generated by evaluating, with the help of $F_o(u,v)$, 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 $F_o(s)$, $F^x(s)$ 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.

INTERPRETATION AND APPLICATION TO EXPLORATION PROBLEMS

The shape of the Curie point isothermal surface can indicate the location and general shape of the heat source. Although the temperature of that surface is higher than the 160 to 360°C target of geothermal exploration, and the resolution of the calculated surface is low, as indicated on Figure 10, it is the trend and anomaly pattern of the surface which is most useful rather than its absolute value.

Geothermal exploration targets are identified from this surface on the assumption that near surface heat leakage from the highs on the Curie point isothermal surface is controlled by structure. Both the detail of the aeromagnetics (the higher space frequency data) and interpretation of enhanced Landsat imagery have been used in the construction of structural models to relate the heat source mapped to near surface sources, as indicated in our very simple frontispiece interpretation.

The Curie point surface can be interpreted in a similar manner to indicate where, in an otherwise cold young Tertiary basin, source rocks have been heated enough to begin the generation and migration of petroleum. It can also be used to suggest where a basin, at relatively shallow depth, might be warm enough to have only gas and carbon remaining or even only carbon remaining (Hunt, 1975).

In theory, given a temperature and a depth, a thermal gradient map could be prepared from the Curie point depth data. However, it should be realized that, while the relative values calculated may be reliable, the error bar on absolute values is probably large.

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