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An Attempt to Define Curie Point Depths in Greece from Aeromagnetic and Heat Flow Data

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Abstract—The objective of this study is to understand the nature and extent of the regional geothermal system at depth beneath the area of Greece by constructing the Curie isotherms.

Spectral analysis of aeromagnetic data in conjunction with heat flow information revealed an almost inverse linear relation between heat flow and Curie depths and was used to construct the Curie isotherms from the existing heat flow data.

The results showed that Curie depths in the area range from about 20 km in western Greece, up to 1 km beneath the Hellenic volcanic arc. These results are consistent with the existing geothermal and geotectonic regime in the area.

Key words: Curie point, aeromagnetic, heat flow.

1. Introduction

The assessment of the variations of the Curie isotherm of an area can provide valuable information about the regional temperature distribution at depth and the concentration of subsurface geothermal energy.

One of the important parameters that determine the relative depth of the Curie isotherm with respect to sea level is the local thermal gradient (i.e., heat flow and thermal conductivity structure).

Measurements have shown that a region with significant geothermal energy is characterized by an anomalously high temperature gradient and heat flow. It is therefore to be expected that geothermically active areas will be associated with shallow Curie point depths.

The idea of using aeromagnetic data to estimate Curie point depths is not new and it has been applied to various parts of the world, either by analyzing isolated magnetic anomalies due to discrete sources (e.g., BHATTACHARYYA and MORLEY, 1965; BYERLY and STOLT, 1977) or employing the frequency domain approach (e.g., BHATTACHARYYA and LEU, 1975; CONNARD *et al.*, 1983; OKUBO *et al.*, 1985; TSELENTIS *et al.*, 1987).

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In a recent paper, NEGI *et al.* (1987), exploited the possibility of using the Curie depths inferred from MAGSAT data as first-order estimates of the thickness of the lithosphere and heat flow variations in a geothermically unexploited area.

The recent availability of aeromagnetic and heat flow data in Greece triggered our interest in determining the nature of Curie depths beneath a geodynamically mobile and geotectonically diversified region like the Aegean.

2. *Data Analysis*

The aeromagnetic data used in the present analysis come from the five areas outlined in Figure 1. Areas [D], [E], [B] and [A] were covered aeromagnetically by Hunting Ltd. and ABEM Ltd., respectively. The flight height was 300 m and the spacing between the flight lines (NE–SW) was 0.8 km. Area [C] was covered aeromagnetically by CGG at a flight height of 800 m and a flight spacing of 1 km.

The basic data used in the present analysis were provided by the Institute of Geology and Mineral Exploration of Greece as total magnetic field anomaly variations on contour maps of scale 1:50,000. Nine such maps have been used to cover each area.

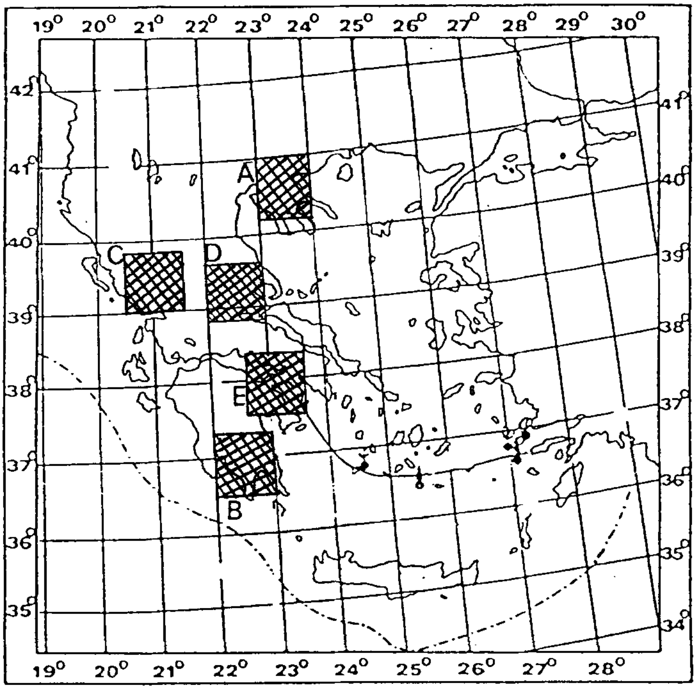

Figure 1
Areas where Curie point depths were assessed from aeromagnetic data.

The contour data were digitized and reduced to a regular grid using an interpolation program resulting in a data set of 64 × 64 points (i.e., 64 × 64 km) for each of the areas.

The dimensions of the square grids used were based on a minimum ratio of 12:1 of block size to prism dimensions (magnetic sources) as demonstrated by OKUBO *et al.* (1985). Thus, assuming a minimum anomaly of approximately 5 km, this meant a minimum block size of about 60 km.

One of the most crucial parts of the investigation is the recognition and removal of the regional field due to large-scale geological features extending considerably beyond the borders of each region and due to gross terrain features. Additionally, there may be other components arising from magnetic core fields not adequately modeled by the IGRF used. It is obvious that these long-period components might seriously affect the centroid depth estimates.

We attempted to remove these components, and after trying various schemes such as fitting of quadratic surfaces and terrain modelling we finally employed a simple high-pass, frequency-domain filter.

Prior to the frequency transformation of the data set and in order to avoid signal perturbations and to compress the Gibbs effect, the data were tapered in the following way (TSELENTIS *et al.*, 1988).

We assume that the residual field vanishes at the points located a distance of four units of data spacing (4 km) from the boundary of each region. Inclusion of these points results in 66 × 66 nonequispaced data points. Next, bicubic spline surfaces were fitted to the data employing the finite element technique of INOUE (1986), in such a way that the residual field and the continuity of the first and second derivatives are maintained at each one of the data points. These surfaces were used to generate the final 64 × 64 point data set (Figure 2).

To enhance the broad features, due to deep structures, various low pass zero phase filters were designed and applied to the data. Those filters which resulted in the elimination of the small wavelength anomalies with the least visible sign of distortion were selected.

Figures 3a, b are an example of the unfiltered and filtered data set of area [E]. The corresponding wavelengths encountered are depicted in subfigures. Note the attenuation of short wavelengths in Figure 3b.

3. *Curie Point Depth Estimation*

Following SPECTOR and GRANT (1970) and OKUBO *et al.* (1985), we define $H(r, \partial) = F(r, \partial)/r$, where $F(r, \partial)$ is the amplitude spectrum of each data set, r is the magnitude of the frequency vector $(= [u^2 + v^2]^{1/2})$ and u, v the corresponding x, y spatial frequencies in radians/km.

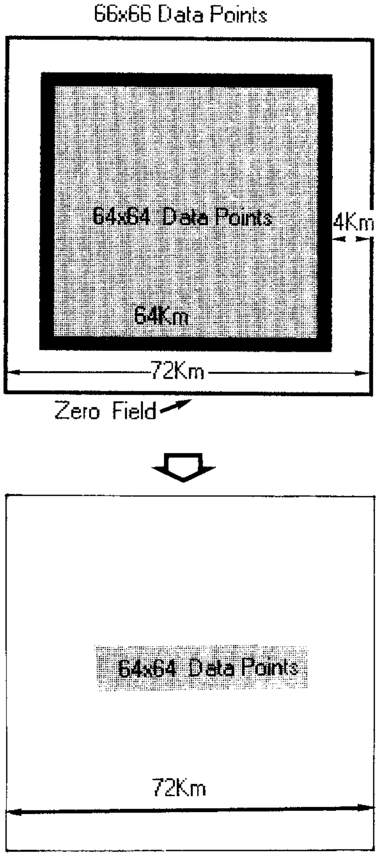

Figure 2
Creation of the 64 × 64 points data set in each region by fitting bicubic spline surfaces.

It can be shown (OKUBO *et al.*, 1985) that the average amplitude of H over an angle in the frequency plane can be written as

$$H(r) = (1/2\pi) \int_{-\pi}^{+\pi} |H(r, \vartheta)|^2 \, d\vartheta = A \exp(-2\pi r z_o) \tag{1}$$

where z_o is the depth to the centroid of the magnetic body. Similarly, the depth to the top (z_t) can be estimated from an equation of the form

$$K(r) = B \exp(-2\pi r z_t) \tag{2}$$

where

$$\bar{K}(r) = \int_{-\pi}^{+\pi} |F(r, \vartheta)|^2 \, d\vartheta/(2\pi). \tag{3}$$

Obviously, the required Curie point is the depth to the bottom (z_b) of the

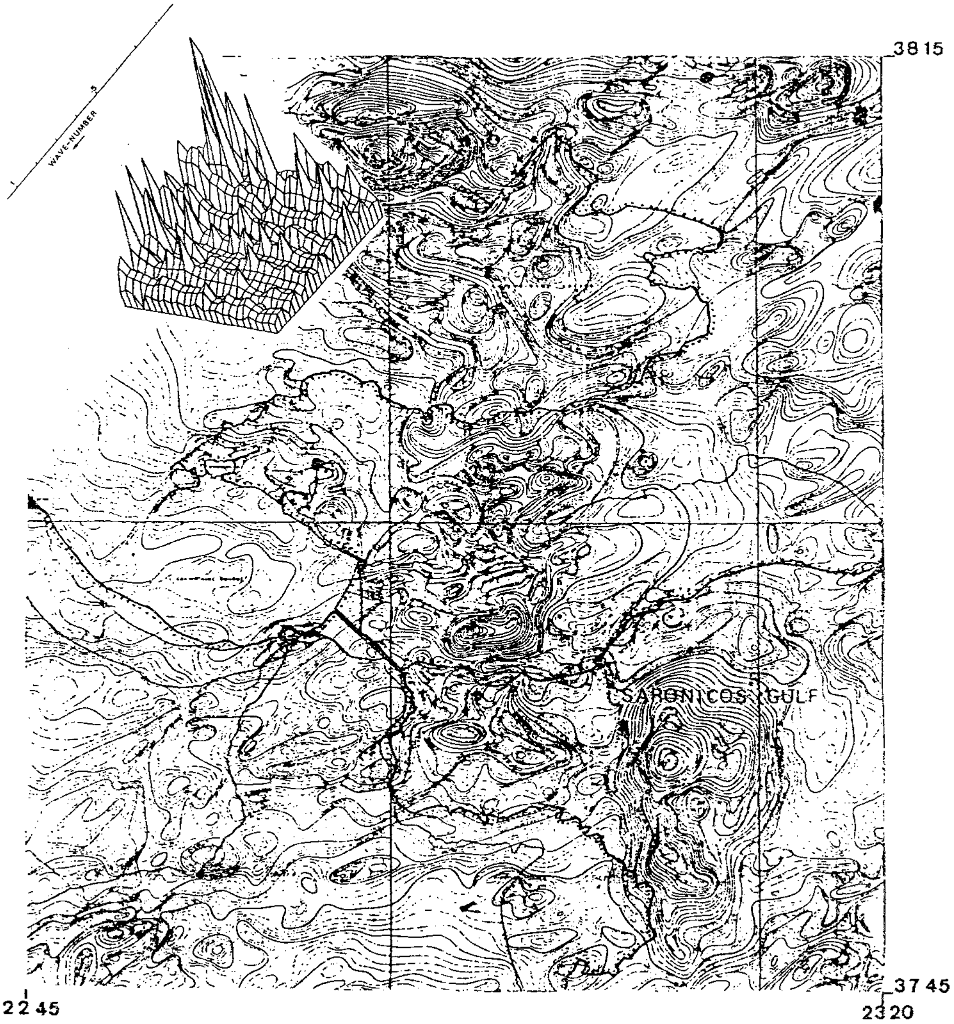

Figure 3a
Aeromagnetic map and power spectra of area [E].

corresponding magnetic body and can be easily determined from

$$z_b = z_t + 2(z_0 - z_t). \tag{4}$$

The average radial power spectra for regions [A], [D] and [E] are calculated using an algorithm by DIMITRIADIS *et al.* (1987) and are shown in Figures 4a, b, c, respectively.

The spectra are fitted by least squares to all the points within the first line segment (corresponding to deep sources) in such a way as to minimize the standard deviation of the slope.

The obtained Curie depths for each region with the corresponding errors are depicted in Table 1.

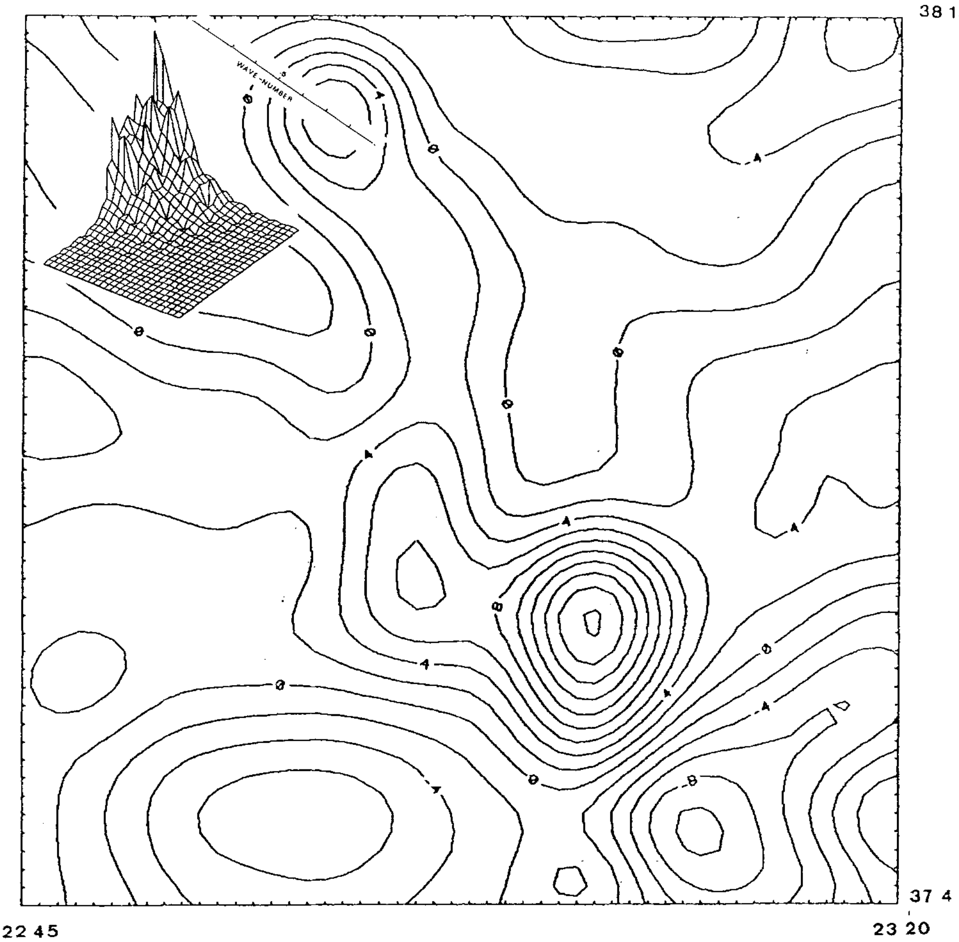

Figure 3b
Low pass filtered map and power spectra of area [E].

Table 1

Curie point depths as determined from aerogmagnetic (C.D. Aer.), geothermal gradient (C.D. gr), eqs. (8) and (9) and average thermal conductivity and heat flow in each region. $1\ HFU = 1 \times 10^{-6}\ cal/cm^2\ s = 41.8\ W/m^2$.

Area	C.D. Aer. km	Error km	Av. Th. Cond. $Wm^{-1}C^{-1}$	Av. H. F. HFU	C. D. gr. km	(8) km	(9) km
A	13.4	0.87	2.25	2.38	12.0	12.3	12.2
B	21.4	1.12	1.80	1.19	18.5	32.2	23.5
C	28.0	1.37	1.96	0.83	29.0	35.7	27.5
D	11.3	1.19	2.03	2.57	10.5	12.8	12.1
E	14.7	0.71	2.00	2.14	12.0	16.3	14.5

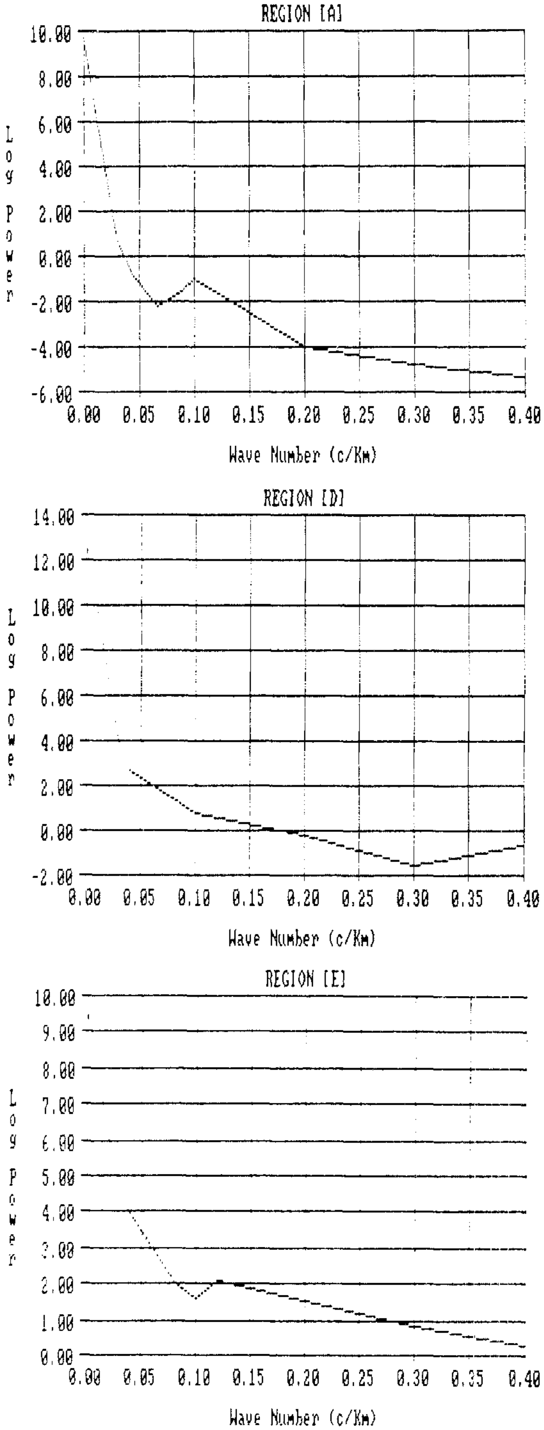

Figure 4
Radial spectra obtained from the aeromagnetic data of regions [A], [D] and [E].

4. *Temperature Depth Profiles*

In order to compare the obtained results with the temperature at depth as estimated from the existing geothermal data (heat flow), the following well-known relation (LACHENBRUNCH, 1968) is used

$$T(z) = T_o + qz/K + D^2 A_o[1 - \exp(-z/D)]/K \qquad (5)$$

where

T_o is the surface temperature
K is the thermal conductivity
A_o is the heat production
D is a scaling factor
$q = q_o - A_o Dz$
q_o is the heat flow at the surface.

For the thermal conductivity, we use the values published by FYTIKAS and KOLIOS (1978) and an average representative value obtained by considering the lithologic section and the published conductivity values of characteristic rocks found in each measuring drill hole for each one of the considered areas is tabulated in Table 1.

The geographic distribution of the heat flow values obtained in Greece from direct measurements is presented in Figure 5 and listed in Table 2. A detailed description of the heat flow data can be found in FYTIKAS and KOLIOS (1978) and is not given here. An average estimate of the heat flow for the investigated areas as determined from the above data is listed in Table 1.

Another parameter which is very important for the calculations of the thermal gradient is the distribution of heat production A_o. In a recent paper, STEGENA and MEISSNER (1985) reported the following relation between heat production and compressional wave velocity (V_p) along the European Geotraverse

$$A_o = 2.5 \times 10^6 \exp[-2.3 V_p(z)] \qquad (6)$$

despite the differences in the geological and tectonic settings, due to the lack of other reasonable A_o estimates for Greece, to adopt the above relation.

The required compressional wave velocity information for each of the investigated areas was estimated from a joint inversion of microearthquake data resulting from the operation of dense microearthquake networks in the above areas (TSELENTIS and DRAKOPOULOS 1988).

By fixing a value of 25°C for T, a value of 10 km for D and equation (6) the temperature at depth can be estimated from the following equation

$$T(z) = 25 + \frac{q_{iz}}{K_i} + \frac{2.5 \times 10^8 e^{-2.3 V_p(z)}(1 - e^{z/d})}{K_i}, \quad i = A, B, C, D, E. \qquad (7)$$

The obtained results for each one of the above regions are shown in Figure 6.

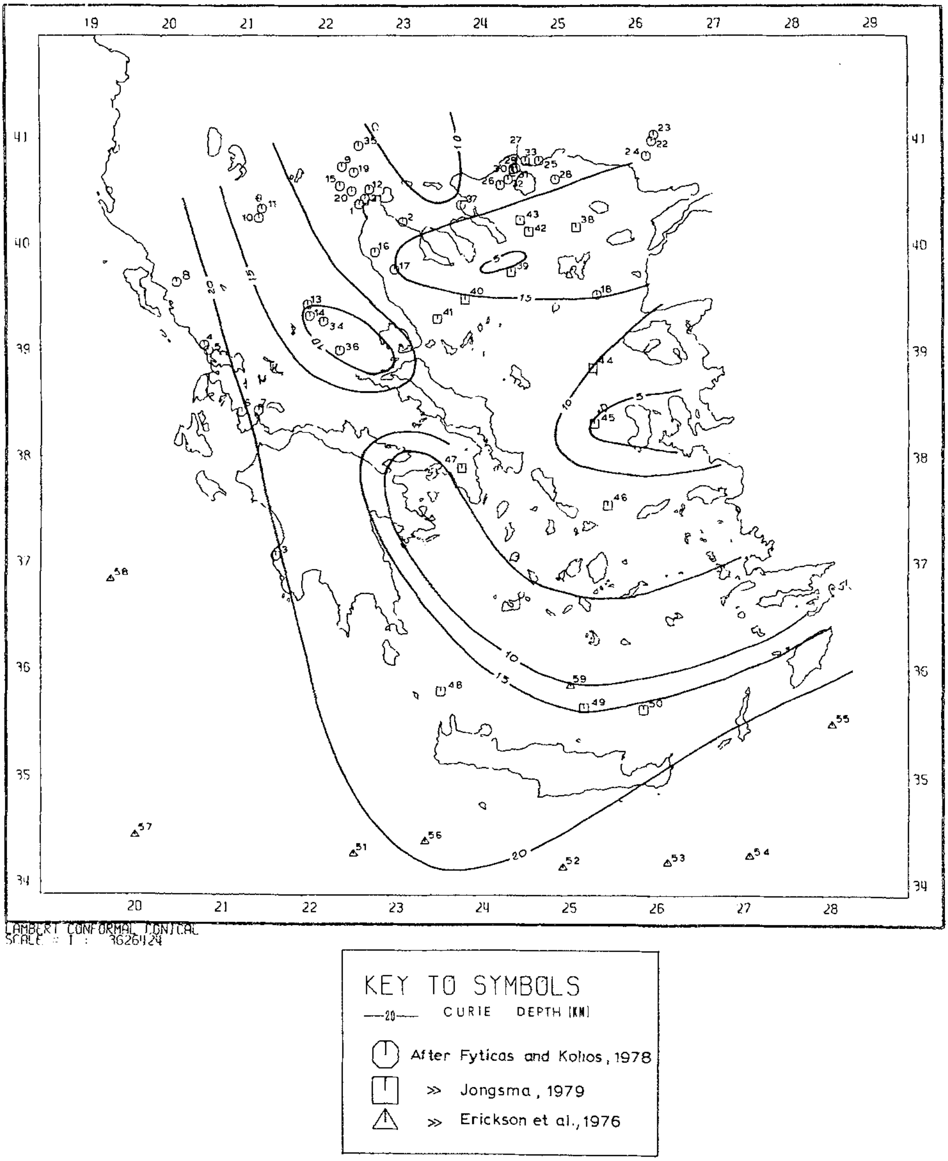

Figure 5
Location of heat flow measurements and Curie point depths contours as calculated by formula (9), Section 5.

Associating a temperature to the Curie point isotherm depth is a difficult task because the Curie temperatures of rocks depend on the magnetic minerals present. For example, minerals with significant magnetization have Curie temperatures which can vary from 300°C for maghemite to 680°C for hematite. On the other hand, there is evidence (MAHEW, 1982), that within most parts of the

Table 2

Thermal conductivity and heat flow data used. Data No: 1–37 are from Fytikas *and* Kolios *(1978), No: 38–50 from* Jongsma *(1974) and No: 51–59 from* Erickson *et al. (1976). Numbers correspond to those depicted in Figure 5.*

No.	Ther. Cond. $Wm^{-1}K^{-1}$	Heat Fl. HFU	No.	Ther. Cond. $Wm^{-1}K^{-1}$	Heat Fl. HFU
1	2.00	1.15	31	2.09	1.34
2	1.92	1.28	32	2.09	1.59
3	2.55	0.97	33	2.09	1.74
4	2.00	0.52	34	2.05	3.32
5	1.92	0.55	35	2.51	2.32
6	2.55	0.67	36	2.09	2.72
7	2.55	0.97	37	2.63	2.51
8	2.55	0.73	38	0.92	2.15
9	2.05	0.78	39	0.99	1.56
10	1.71	1.02	40	0.89	1.24
11	1.88	0.76	41	0.93	2.52
12	1.92	0.96	42	0.88	1.62
13	1.75	1.33	43	0.86	1.56
14	1.96	1.54	44	0.86	1.79
15	2.05	0.58	45	0.93	2.61
16	2.05	1.12	46	0.89	1.64
17	2.17	1.60	47	0.93	2.73
18	2.30	1.53	48	0.97	1.61
19	2.17	0.62	49	0.99	1.52
20	2.17	0.80	50	1.04	1.42
21	2.17	0.82	51	1.16	0.76
22	2.00	1.38	52	1.03	0.62
23	2.30	1.59	53	1.08	0.59
24	1.92	1.46	54	1.05	0.73
25	2.09	1.34	55	0.94	0.25
26	2.05	1.61	56	0.94	1.22
27	2.17	1.55	57	1.11	0.78
28	2.17	1.45	58	1.10	0.74
29	2.05	1.46	59	1.26	1.83
30	2.09	1.49			

continental crust the Curie temperature is restricted to a narrow range (about 520°C–560°C).

Since there are no studies available on the Curie temperatures of rocks from the investigated areas, the Curie temperatures can only be estimated. By using the corresponding Curie depths obtained for finite thickness magnetic bodies and calculating the thermal gradients and heat flow expected for Curie point temperatures of 550°C and 300°C, it was concluded that the actual Curie temperature is likely to be closer to 550°C than to 300°C (Tselentis and Drakopoulos, 1988).

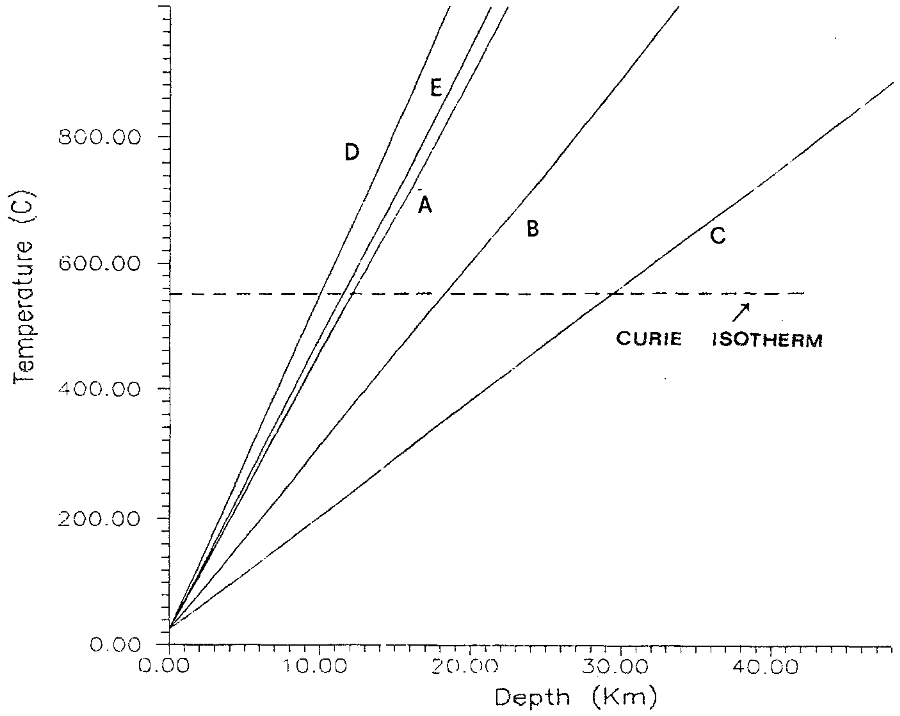

Figure 6
Temperature depth profiles of the investigated areas.

Hence, assuming an average Curie point temperature of 550°C, the Curie point depths for each one of the regions considered can be easily assessed from the intersection of the depicted curves with the 550°C isotherm. The corresponding Curie depths resulting from this analysis are shown in Table 1, and are in good agreement with the depths obtained from the analysis of the aeromagnetic data.

5. Relation Between Curie Depth and Heat Flow

To investigate any possible relation between heat flow and the obtained Curie depths, in Figure 7 we present the current results with those obtained from similar investigations in other countries and in particular a) Western United States (MAYHEW, 1982), b) India (NEGI *et al.*, 1987) and c) Japan (OKUBO *et al.*, 1985).

Despite the relatively high scatter of the data, which depends mainly upon the accuracy with which the Curie depths, crustal heat generation and heat flow were

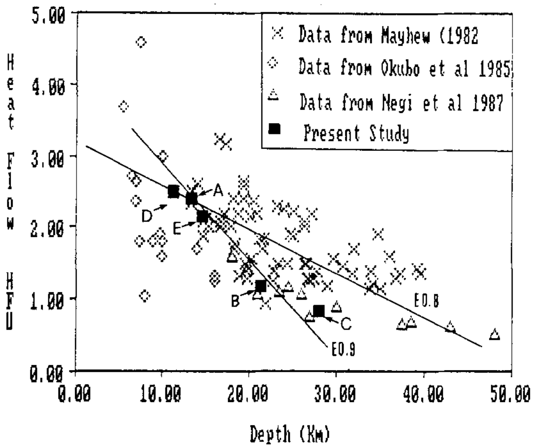

Figure 7
Curie depths versus heat flow.

determined, Figure 7 shows that the heat flow in a region decreases with increasing Curie depth.

Two gross relations between Curie depth z and surface heat flow Q are derived from the above data by linear least-squares fitting: a) all the data and b) the results of the present investigations and are shown below.

$$z = 52.5 - 16.6Q \quad \text{(all data)} \tag{8}$$

$$z = 30.5 - 9.8Q \quad \text{(present data).} \tag{9}$$

Using these equations one can estimate, within a limited accuracy, the approximate heat flow if the Curie point isotherm can be assessed from the existing aeromagnetic data.

In the following, we will use the reverse procedure by attempting to estimate Curie depths from the existing heat flow information over the area of Greece.

The predicted Curie depths for the five areas investigated by employing equations (8) and (9) are listed in Table 1 and plotted in Figure 8.

In the same figure the Curie depths are shown for comparison derived from the temperature depth profiles and the aeromagnetic data.

Since equation (8) overestimates the Curie depths by about 40% for areas [B] and [C], equation (9) is adopted as the most reliable relation between heat flow and Curie depth for the area of Greece.

By using the heat flow information listed in Table 1 and equation (9), Curie isotherms for the area of Greece were delineated and are presented in Figure 5.

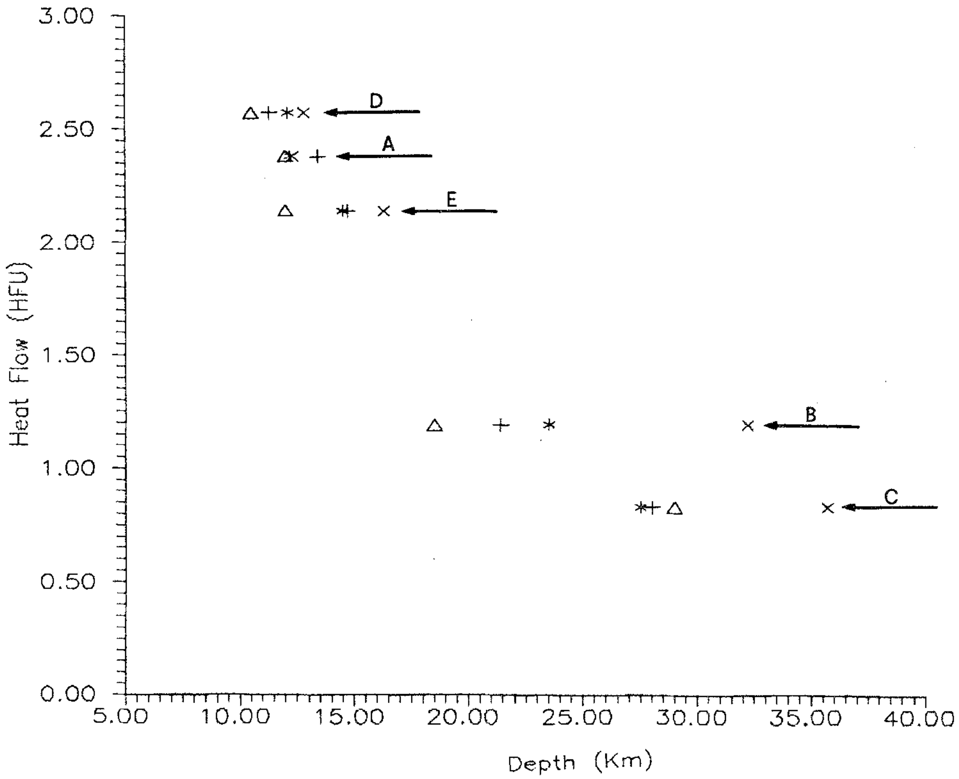

Figure 8
Comparison of Curie depths in areas [A], [B], [C], [D] and [E] as they were calculated by (×) eq. (8), (*) eq. (9), (Δ) geothermal gradient and (+) aeromagnetic data.

6. Discussion and Conclusions

The results of the present investigation reveal that the Curie depth surface varies considerably beneath Greece, reaching a value of 20 km towards western Greece and a value of about 10 km at certain regions beneath the Aegean.

The general trends of the Curie isothermal surface are consistent with the prevailing geotectonic regime in the region, which is dominated by the subduction of the African lithosphere under the Aegean lithospheric plate in a roughly SW-NE direction, at the Hellenic arc-trench system.

The smallest Curie depths are observed along the Hellenic volcanic arc, which maps the maximum depth of the sinking African slab and also coincides with the maximum depth of the earthquake zone.

The small Curie depths (10 km) obtained beneath areas [A] and [D] are consistent with the existing hot surface manifestations and the relatively high seismic activity.

By comparing the Bouguer anomaly map of Greece, prepared by MAKRIS (1972), with the Curie depths map, we see that areas characterized by deep Curie isothermal surface are also dominated by negative gravity anomalies (i.e., the crust is comparatively thicker), and this is more evident towards western Greece.

The complex tectonic regime of the area requires substantially more data, and the present investigation has the character of a preliminary research aiming to improve our knowledge of the thermal regime of this complicated region. On the other hand, despite its qualitative character, the positive correlation obtained between Curie depths, tectonic regime and surface heat flow supports the validity of analyzing regional aeromagnetic data to map isothermal Curie point depths on a regional scale.

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REFERENCES

BHATTACHARYYA, B. K., and MORLEY, L. W. (1965), *The Delineation of Deep Crustal Magnetic Bodies from Total Field Aeromagnetic Anomalies*, J. Geomagn. Geoelect. *17*, 237–252.

BHATTACHARYYA, B. K., and LEU, L. K. (1975), *Spectral Analysis of Gravity and Magnetic Anomalies due to Two-dimensional Structures*, Geophys. *40*, 993–1013.

BYERLY, P. E., and STOLT, R. H. (1977), *An Attempt to Define the Curie Point Isotherm in Northern and Central Arizona*, Geophys. *42*, 1394–1400.

CONNARD, G., COUCH, R., and GEMPERLE, M. (1983), *Analysis of Aeromagnetic Measurements from Cascade Range in Central Oregon*, Geophys. *48*, 376–390.

DIMITRIADIS, K., TSELENTIS, G-A., and THANASSOULAS, C. (1987), *A Computer Algorithm in Basic for Radial Spectra Calculation*, Computers and Geoscience *13*, (5), 549–560.

FYTIKAS, M. D., and KOLIOS, N. P. (1978), *Preliminary heat flow map of Greece*, In *Terrestial Heat Flow in Europe* (Cermek and Ryback, eds.) 270 pp.

INOUE, H. (1986), *A Least-squares Smooth Fitting for Irregular Spaced Data: Finite Element Approach Using the Cubic* B-*spline Basis*, Geophys. *51*, 2051–2066.

MAYHEW, M. A. (1982), *Application of Satellite Magnetic Anomaly Data to Curie Isotherm Mapping*. J. Geophys. Res. *87*, 4846–4854.

MAKRIS, J. (1972), *Geophysical Investigation of the Hellenides*, University of Hamburg, 130 pp.

NEGI, J. G., AGGRAWAL, P. K., and PANDEY, O. P. (1987), *Large Variation of Curie Depth and Lithospheric Thickness Beneath the Indian Subcontinent and a Case for Magnetothermometry*, Geophys. J. Roy. Astr. Soc. *88*, 763–775.

LACHENBRUNCH, A. H. (1968), *Preliminary Geothermal Model of the Sierra Nevada*, J. Geophys. Res. *73*, 6977–6989.

OKUBO, Y., GRAF, R. J., HANSEN, R. O., OGAWA, K., and TSU, H. (1985), *Curie Point Depths of the Island of Kyushu and Surrounding Areas*, Japan. Geophys *53*, 481–494.

SPECTOR, A., and GRANT, F. S. (1970), *Statistical Models for Interpreting Aeromagnetic Data*, Geophys. *35*, 293–302.

STEGENA, L., and MEISSNER, R. (1985), *Velocity Structure and Geothermics of the Earth's Crust along the European Geotraverse*, Tectonophys. *121*, 87–96.

TSELENTIS, G-A., DRAKOPOULOS, J., and DIMITRIADIS, K. (1988), *A Spectral Approach to Moho Depths Estimation from Gravity Measurements in Epirus (NW Greece)*, J. Phys. Earth. *36*, 255–266.

TSELENTIS, G-A., THANASSOULAS, C., DIMITRIADIS, K., and ROCA, A. (1987), *Deep Basement Structure and Curie Point Depth of the Sousaki Loutraki (Central Greece) Geothermal Field as Obtained from the Analysis of Aeromagnetic Measurements.* Paper presented at the 49th Meeting of the European Association of Exploration Geophysicists, 9–12 June, Belgrade, Yugoslavia.

TSELENTIS, G-A., and DRAKOPOULOS, J. (1988), *Joint Determination of V_p/V_s from Aftershock Data in Greece.* Paper presented at the 63rd National Meeting of the Japanese Seismological Society, Tsukuba, Japan.

TSELENTIS, G-A., and DRAKOPOULOS, J. (1988), *Mapping of Curie Isothermal Surface from Aeromagnetic Measurements. Discussion and Comparison of the Existing Techniques.* Paper presented at the 50th EAEG Meeting, 6–10 June, The Hague, The Netherlands.

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