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Curie point depth based on spectrum analysis of the magnetic anomaly data in East and Southeast Asia

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Abstract

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. A method to estimate the depth extent of magnetic sources (Curie point depth analysis) was applied to the magnetic anomalies of East and Southeast Asia. Although the geologic and physiographic complexities of this area constrain the method, certain correlations between the Curie point depths and heat flow data are apparent and the Curie point depths are consistent with the tectonic settings. Shallow basal depths of magnetic sources that extend in back-arc regions correspond to high heat flow values. The correspondence of deep basal depths with low heat flow values along the trench axis suggests that they are both related to the subducting plate. We also estimate the Curie point depths from heat flow data using a one-dimensional heat conductive transport model. Good agreement between the Curie point depths derived from heat flow data and magnetic data suggests that the Curie point depth analysis is useful to estimate the regional thermal structure.

Keywords: magnetic anomaly; Curie point; spectral analysis; heat flow; East and Southeast Asia

1. Introduction

Considerable attention has been given to the spatial variation in the temperature to know the thermal structure of the earth. To determine temperature variations, the primary observable quantity is the heat flow. There are many observations of heat flow from bore holes on land and probes in deep-sea sediments (e.g., Pollack et al., 1993). Since the obtained heat flow values may reflect local thermal anomalies and their measurements are distributed geographically unevenly, it is often insufficient to define regional thermal structures. On the other hand, determination of the Curie point depth based on spectrum analysis of magnetic anomaly data (e.g., Spector and Grant, 1970; Bhattacharyya and Leu, 1975a) can be used to estimate regional thermal structures. This is a method for a reconnaissance survey. The method allows the determination of the depth at which the magnetite passes from a ferromagnetic state to paramagnetic state under the effect of increasing temperature. The obtained basal depth of a magnetic source is assumed to be the Curie point depth. The Curie point temperature is still controversial. It may depend upon composition and there are some problems on accuracy and resolution of the results. However, the Curie point depths should reflect the broad average temperature and they have

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been used to estimate the thermal structure in various regions (e.g., Bhattacharyya and Leu, 1975b).

This paper presents the method and results of the Curie point analysis in East and Southeast Asia. This area of extremely complex and active tectonics is still poorly sampled in heat flow data (e.g., Uyeda, 1980; Geological Survey of Japan (GSJ) and Coordinating Committee for Coastal and Offshore Geoscience Programmes in East and Southeast Asia (CCOP) — GSJ and CCOP, 1997). The correlation between the obtained Curie point and the heat flow data indicates that the Curie point depth is a useful indicator of the thermal structure in these regions.

2. Determination of the Curie point depth

The method to estimate the depth extent of magnetic sources can be classified into two categories: those that examine the shape of isolated magnetic anomalies (e.g., Bhattacharyya and Leu, 1975a) and those that examine statistical properties of patterns of magnetic anomalies (e.g., Spector and Grant, 1970). Both methods provide the relationship between spectrum of magnetic anomalies and the depth of a magnetic source by transforming the spatial data into frequency domain. Shuey et al. (1977) showed that the latter method is more appropriate for regional compilations of magnetic anomalies. The method used here is similar to the method of Spector and Grant (1970). The top bound and the centroid of a magnetic source, Z_t and Z_0, respectively, are calculated from the power spectrum of magnetic anomalies, and are used to estimate the basal depth of a magnetic source Z_b.

Assuming that the layer extends infinitely far in all horizontal directions, depth to top bound of a magnetic source is small compared with the horizontal scale of a magnetic source, and that magnetization $M(x, y)$ is a random function of x and y, Blakely (1995) introduced the power–density spectra of the total-field anomaly $\Phi_{\Delta T}$:

$$\Phi_{\Delta T}\left(k_x, k_y\right) = \Phi_M\left(k_x, k_y\right) \times F\left(k_x, k_y\right)$$

$$F\left(k_x, k_y\right) = 4\pi^2 C_m^2 \left|\Theta_m\right|^2 \left|\Theta_f\right|^2 e^{-2|k|Z_t}\left(1 - e^{-|k|(Z_b - Z_t)}\right)^2 \tag{1}$$

where Φ_M is power–density spectra of the magnetization, C_m is a proportionality constant, and Θ_m and Θ_f are factors for magnetization direction and geomagnetic field direction, respectively. This equation can be simplified by noting that all terms, except $|\Theta_m|^2$ and $|\Theta_f|^2$, are radially symmetric. Moreover, the radial averages of Θ_m and Θ_f are constant. If $M(x, y)$ is completely random and uncorrelated, $\Phi_M(k_x, k_y)$ is a constant. Hence, the radial average of $\Phi_{\Delta T}$ is:

$$\Phi_{\Delta T}(|k|) = A e^{-2|k|Z_t}\left(1 - e^{-|k|(Z_b - Z_t)}\right)^2 \tag{2}$$

where A is a constant. For wavelengths less than about twice the thickness of the layer, Eq. 2 approximately becomes:

$$\ln\left[\Phi_{\Delta T}(|k|)^{1/2}\right] = \ln B - |k|Z_t \tag{3}$$

where B is a constant. We could estimate the top bound of a magnetic source by the slope of the power spectrum of the total-field anomaly.

On the other hand, Eq. 2 rewrites as:

$$\Phi_{\Delta T}(|k|)^{1/2} = C e^{-|k|Z_0}\left(e^{-|k|(Z_t - Z_0)} - e^{-|k|(Z_b - Z_0)}\right) \tag{4}$$

where C is a constant. At long wavelengths, Eq. 4 is:

$$\Phi_{\Delta T}(|k|)^{1/2} = C e^{-|k|Z_0}\left(e^{-|k|(-d)} - e^{-|k|(d)}\right) \sim C e^{-|k|Z_0} 2|k|d \tag{5}$$

where $2d$ is the thickness of the magnetic source. From Eq. 5

$$\ln\{[\Phi_{\Delta T}(|k|)^{1/2}]/|k|\} = \ln D - |k|Z_0 \tag{6}$$

where D is a constant. We could estimate the top bound and the centroid of the magnetic source by fitting a straight line through the high-wavenumber and low-wavenumber parts of the radially averaged spectrum of $\ln\left[\Phi_{\Delta T}(|k|)^{1/2}\right]$ and $\ln\left\{\left[\Phi_{\Delta T}(|k|)^{1/2}\right]/|k|\right\}$ from Eqs. 3 and 6, respectively. Fig. 1 shows an example of a power spectrum of magnetic anomaly data. From the slope of the power spectrum, the top bound and the centroid of a magnetic layer composed of a horizontal (equivalent) layer are estimated. The basal depth of the magnetic source is:

$$Z_b = 2Z_0 - Z_t \tag{7}$$

The obtained basal depth of the magnetic source is assumed to be the Curie point depth. The obtained Curie point depth reflects the average value of the area. Therefore the results may not delineate local

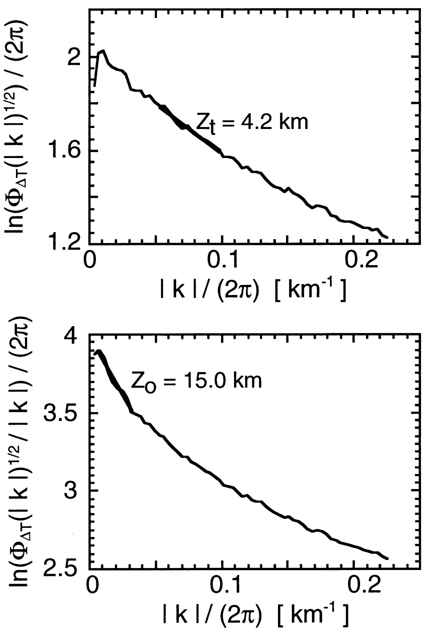


Fig. 1. Examples of spectra for the estimation of the depth to Curie point using the two-dimensional magnetic anomaly data. Here, the data cover a region of (96ºE, 7.5ºN)–(98ºE, 9.5ºN) and 4.2 km and 15.0 km are obtained as the top bound and the centroid using the gradient of spectra defined as $\ln(\Phi_{\Delta T}(|k|)^{1/2})$ and $\ln((\Phi_{\Delta T}(|k|)^{1/2})/|k|)$, where $|k|$ is the wavenumber and $\Phi_{\Delta T}(|k|)$ is the spectrum of the magnetic anomaly.

shallow or deep Curie point depth anomaly. Magnetic anomalies which are only partly included in the data may degrade the estimated spectrum, that is, there is a sensitivity to finite data length. This is one of the limitations of the spectral analysis. The advantage of the spectrum analysis of a magnetic anomaly is that estimates of the top bound and the centroid of a magnetic source can be obtained with simple assumptions of the dimension of magnetic sources and the magnetization vector.

3. Distribution of the Curie point depth of East and Southeast Asia

We estimate the Curie point depth using the magnetic anomaly map of East Asia 1 : 4,000,000 CD-ROM Version (GSJ and CCOP, 1996). The original data are on various time, scales and spacings from many countries and organizations by various methods (GSJ and CCOP, 1996). 2 km × 2 km gridded data sets were computed by a weighted average interpolation method (GSJ and CCOP, 1996).

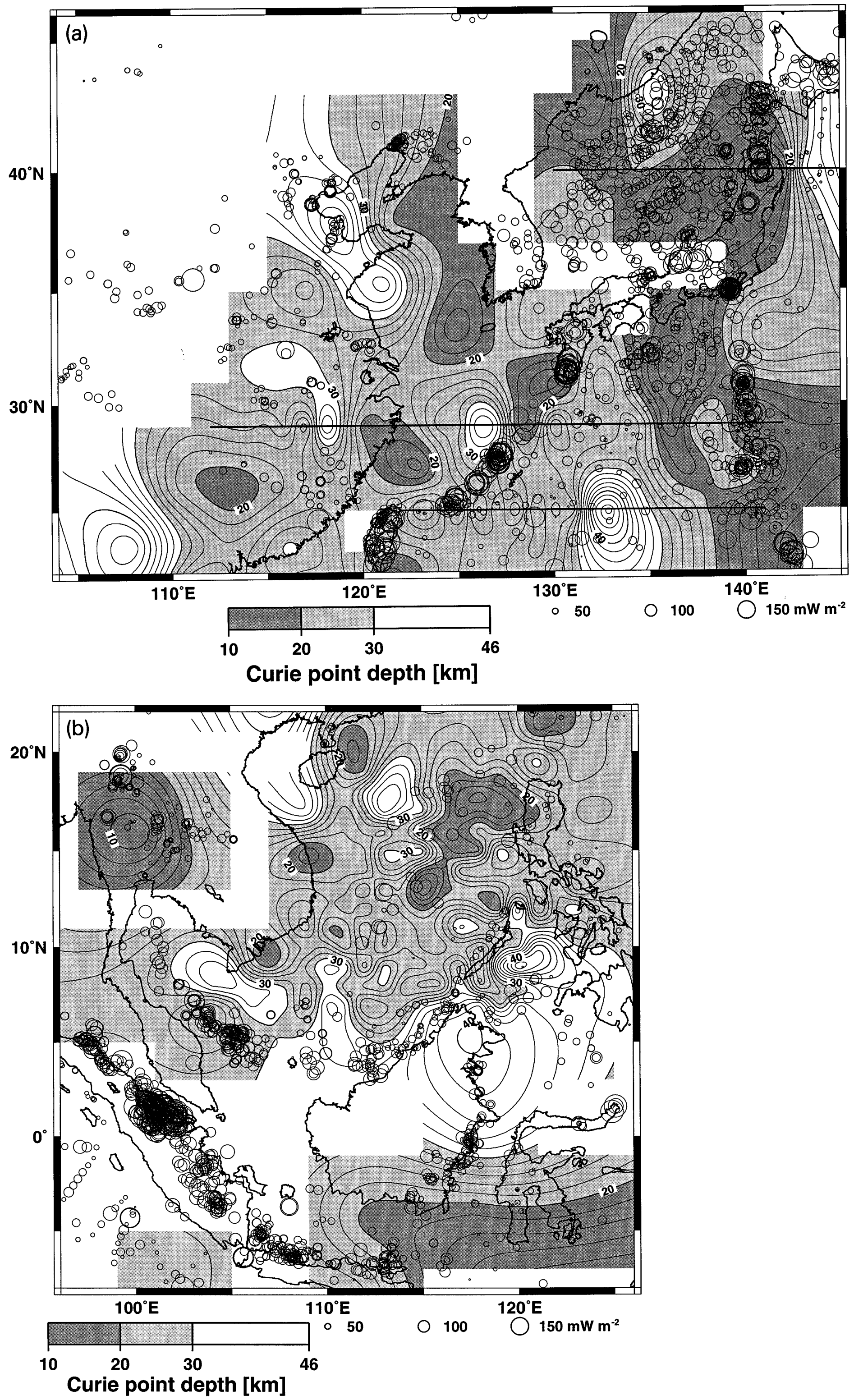
The Curie point depths are calculated using the data of squares of about 2º subregions and only at wavelengths longer than 10 km. Fig. 2 shows the contour map of the Curie point depth in South and Southeast Asia (modified after Tanaka et al., 1997). The top bound of the magnetic source is about 5 km almost all over this region. On the other hand, the centroid of the magnetic source varies from 7 to 26 km so that the basal depth of the magnetic source, the Curie point depth, ranges from 9 to 46 km (Tanaka et al., 1997).

The Curie point depths in continental areas are generally deeper than those in oceanic areas. Deep Curie point depths are observed in the northwestern Pacific off northeast Japan and in the Indian Ocean off the Java arc. This is consistent with low heat flow data in these regions (Yoshii, 1979; Nagao et al., 1995). This feature may be interpreted as plate cooling (e.g., Parsons and Sclater, 1977). Shallow Curie point depths lie in the back-arc regions of Sunda, Mariana, Bonin, and Japan Trenches and consistent with high heat flow data (Yoshii, 1979; Nagao et al., 1995; Yamano, 1995). A heat flow higher than 100 mW m^{-2} occurs at the western edge of the Khorat Plateau in Thailand (Raksaskulwong and Thienprasert, 1995) and is consistent with a sudden change of the Curie point depth. Fig. 2b shows that the Curie point depth is shallow along a relict spreading axis with a northeast trending direction in the South China Basin (Taylor and Hayes, 1983). Along this axis, heat flow is high (Ru and Pigott, 1986).

Fig. 3 represents profiles of topography (National Geophysical Data Center, 1988), magnetic anomaly (GSJ and CCOP, 1996), heat flow (Pollack et al., 1993) and Curie point depth along lines shown in Fig. 2a. Heat flow data whose location is within 1º from the line are plotted. The Curie point depths are estimated from magnetic anomaly data of 2º × 2º subregions. These subregions overlap each other.

3.1. Northeast Japan

Fig. 3a shows the cross-section across Tohoku, Japan along latitude 40ºN. In this cross-section, Ishikari–Kitakami positive magnetic belt (Makino et al., 1992) is discernible around 142ºE. The part


(a)
40°N
30°N
110°E
120°E
130°E
140°E
50
100
150 mW m-2
10
20
30
46
Curie point depth [km]
(b)
20°N
10°N
0°
100°E
110°E
120°E
50
100
150 mW m-2
10
20
30
46
Curie point depth [km]

of this belt corresponds partly to the outcrops of the Kitakami granitic rocks (Makino et al., 1992). Heat flows around the Japan Trench are low, whereas those in the Japan Sea are significantly high. When more than 15 heat flow data are clustered within a distance of 1º, the mean of those heat flow values is calculated and shown by a solid circle in Fig. 3a. The boundary between the outer low-heat-flow and the inner high-heat-flow regions roughly coincides with the volcanic front. Such a distribution of heat flow is considered to be a characteristic feature of the active trench–arc–back-arc systems and is very well reflected in the profile of Curie point depths.

Makino and Okubo (1988) estimated that the depth of the magnetic body is about 13 km near the Japan Trench axis using the one-dimensional marine magnetic anomaly data. At almost the same point, the depth of layer 3 is 10–15 km from refraction profiles of Murauchi and Ludwig (1980), the centroid of magnetic sources is 12 km from geomagnetic data with a filtering method of Oshima (1987), and the centroid of the magnetic source is 16 km obtained here. All of these studies shows almost the same depth of magnetic source.

3.2. China–Izu–Bonin Trench

Fig. 3b shows the cross-section from China to the Izu–Bonin Trench along latitude 29ºN. The magnetic anomalies of the Shikoku Basin are associated with spreading, and remarkable magnetic anomalies at the Kyushu-Palau Ridge correspond to the topographic high. The heat flow values have a trend to increase from the western end toward the eastern end of this cross-section except very high heat flow values in back-arc regions. The Curie point depths have a corresponding trend to be shallower from the western end toward the eastern end.

3.3. The northern part of the Philippine Sea Plate

The Philippine Sea Plate is surrounded by subduction zones and comprises the West Philippine Basin, the Shikoku and Parece Vela Basins and the Mariana Trough. Fig. 3c shows the cross-section across the Philippine Sea Plate along latitude 25ºN. Magnetic anomalies at the Oki-Daito Ridge and Kyushu-Palau Ridge are clearly associated with the topographic highs. The heat flow values increase and the Curie point depths decrease toward the eastern end of this cross-section. Refraction profiles of Murauchi et al. (1968) suggested that the crust beneath the Oki-Daito Ridge is thicker than the crust on either sides. This corresponds to a deep Curie point depth near 133ºE.

4. Discussion

There are some studies to investigate the Curie point depths in various regions such as the Yellowstone National Park (Bhattacharyya and Leu, 1975b), the Western United States (Shuey et al., 1977), Oregon (Connard et al., 1983), Nevada (Blakely, 1988) and the Japanese Islands (Okubo et al., 1989). Compilation of our results and previous studies shows that the Curie point depth varies greatly according to the geological context. It is shown that the Curie point depths are shallower than about 10 km at volcanic and geothermal areas, 15–25 km at island arcs and ridges, deeper than 20 km at plateaus, and deeper than 30 km at trenches (Table 1). Table 1 also shows that there are a lot of studies in regions of high heat flow and shallow Curie point depth such as geothermal areas of North America and Japan.

The basic relation for conductive heat transport is Fourier's law. In one-dimensional case under assumptions that the direction of the temperature variation is vertical and the temperature gradient $\mathrm{d}T/\mathrm{d}z$ is constant, Fourier's law takes the form (e.g., Turcotte and Schubert, 1982):

$$q = k\mathrm{d}T/\mathrm{d}z \tag{8}$$

where q is the heat flux and k is the coefficient of thermal conductivity. The Curie temperature θ_c can be defined:

$$\theta_c = (\mathrm{d}T/\mathrm{d}z)D_c \tag{9}$$

Fig. 2. Contour map of the depth to Curie point in km (after Tanaka et al., 1997) and heat flow data (Pollack et al., 1993) for (a) northeast and (b) southwest region in East and Southeast Asia. The diameter of each circle is proportional to the heat flow value. Lines in (a) show locations of Fig. 3.

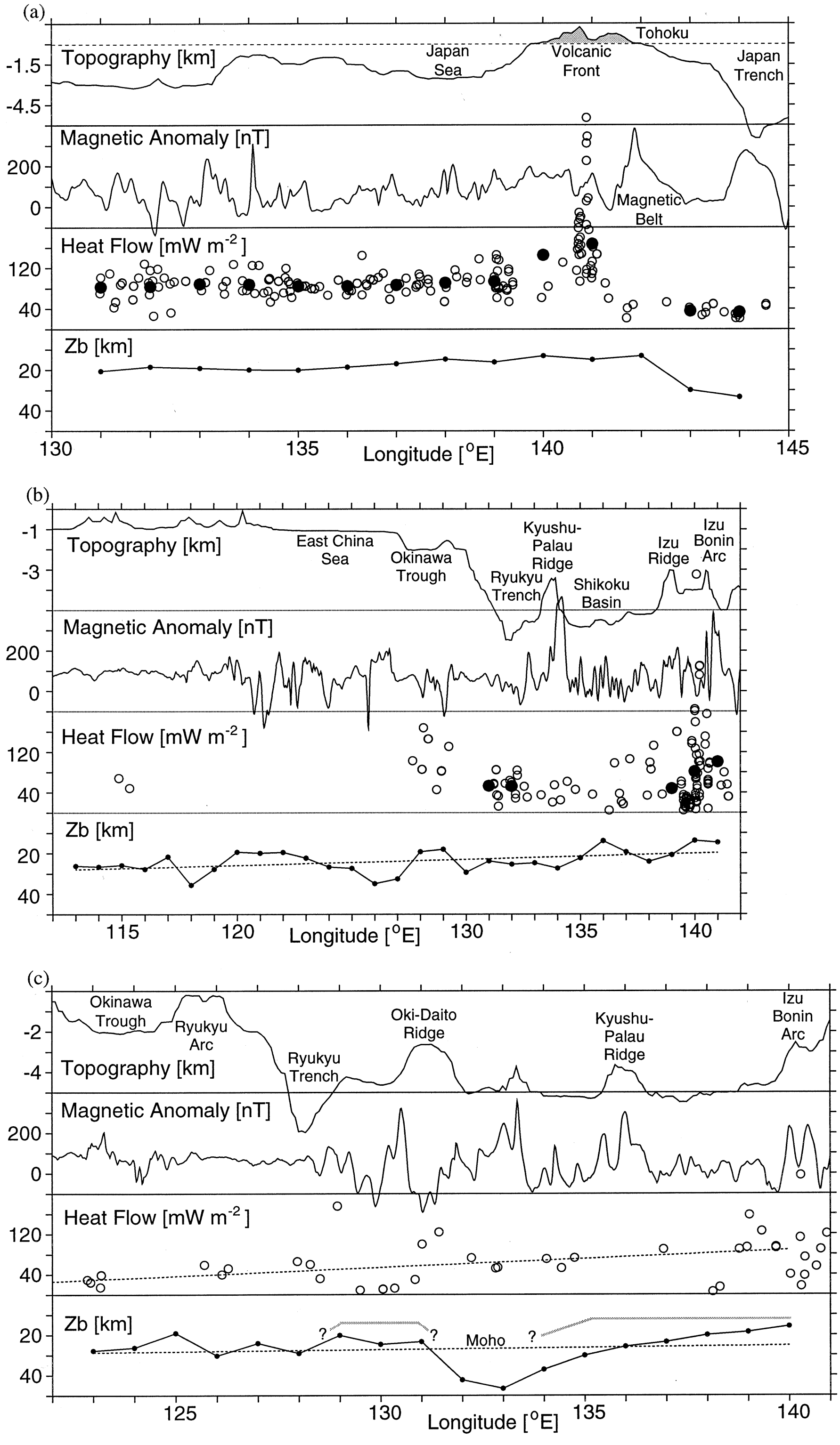

(a)
Topography [km]
-1.5
-4.5
Japan Sea
Volcanic Front
Tohoku
Japan Trench
Magnetic Anomaly [nT]
200
0
Magnetic Belt
Heat Flow [mW m-2]
120
40
Zb [km]
20
40
130
135
140
145
Longitude [°E]
(b)
-1
-3
Topography [km]
East China Sea
Okinawa Trough
Ryukyu Trench
Kyushu-Palau Ridge
Shikoku Basin
Izu Ridge
Izu Bonin Arc
Magnetic Anomaly [nT]
200
0
Heat Flow [mW m-2]
120
40
Zb [km]
20
40
115
120
125
130
135
140
Longitude [°E]
(c)
Okinawa Trough
Ryukyu Arc
-2
-4
Topography [km]
Ryukyu Trench
Oki-Daito Ridge
Kyushu-Palau Ridge
Izu Bonin Arc
Magnetic Anomaly [nT]
200
0
Heat Flow [mW m-2]
120
40
Zb [km]
20
40
?
?
Moho
?
125
130
135
140
Longitude [°E]

Table 1
A summary of Curie point depth

Region	Location	Curie point depth (km)	Reference
Volcanic area	Long Valley	4–8	Miyazaki (1991)
	Yellowstone National Park (total)	4–22	Bhattacharyya and Leu (1975b)
	Yellowstone National Park (within caldera)	5–8	Bhattacharyya and Leu (1975b)
	Yellowstone National Park	7–17	Shuey et al. (1977)
	Cascade Range	9–11	Connard et al. (1983)
	Yellowstone National Park	10	Smith et al. (1974)
Island arc	Tohoku	13–15	this study
	Indonesia	25	this study
Back-arc rift	Izu Ridge	14–15	this study
	Izu Bonin Arc	16–20	this study
	Ryukyu Arc	19	this study
	Kyusu-Palau Ridge	22–26	this study
Marginal sea	Japan Sea	12–20	Yano et al. (1982)
	South China Sea	12–36	this study
	Japan Sea	15–17	this study
	Philippine Sea	20–30	this study
Continent	northwestern Ontario	9–16	Bhattacharyya and Morley (1965)
	northern border of Basin and Range province	<10	Byerly and Stolt (1977)
	Uinta Basin	15–31	Shuey et al. (1977)
	Utah High Plateaus	16–20	Shuey et al. (1977)
	China	18–45	this study
	Basin and Range province	20	Shuey et al. (1974)
	Basin and Range province	22	Blackwell (1971)
	Colorado Plateau	35	Shuey et al. (1974)
	eastern United States	37	Blackwell (1971)
Trench	Japan Trench	30–33	this study
	Palawan Trench (inactive)	30–45	this study
Total	Nevada	5–30	Blakely (1988)
	Japan	8–15	Okubo et al. (1989)
	East and Southeast Asia	9–46	this study
	Cascade Range	15	Connard et al. (1983)

where D_c is the Curie point depth, provided that there is no heat sources or heat sinks between the earth's surface and the Curie point depth, the surface temperature is 0ºC, and dT/dz is constant. From Eqs. 8 and 9:

$$D_c = k\theta_c/q \tag{10}$$

Eq. 10 states that the Curie point depth is inversely proportional to heat flow.

The Curie temperature depends on magnetic mineralogy. Although the Curie temperature of mag-

Fig. 3. (a) Cross-section of topography (National Geophysical Data Center, 1988), magnetic anomaly (GSJ and CCOP, 1996), heat flow (Pollack et al., 1993) and Curie point depth across northeastern Honshu, Japan, along latitude 40ºN. Solid circles show the mean values of heat flow data within a distance of 1º. (b) Cross-section from China to Bonin Trough along latitude 29ºN. Same conventions as in (a). Dashed line represents the linear trend of Curie point depth. (c) Cross-section across the Philippine Sea Plate along latitude 25ºN. Same conventions as in (a). Dashed lines represent the linear trends of heat flow and Curie point depth. Gray lines represent the Moho (after Murauchi et al., 1968).

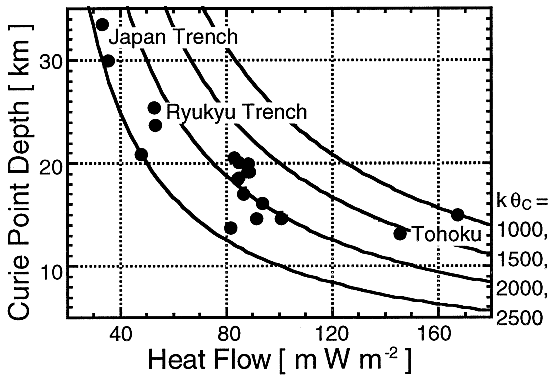


Fig. 4. The Curie point depth as a function of heat flow data, in cases of $k\theta_c$ is 1000, 1500, 2000 and 2500 W m^{-1}. Solid circles show the mean of heat flow values and Curie point depths estimated from magnetic anomaly data at selected points shown in Fig. 3.

netite (Fe_3O_4), for example, is at approximately 580ºC, an increase of Ti content of titanomagnetite ($Fe_{2-x}Ti_xO_3$) causes a reduction of the Curie temperature (Stacey and Banerjee, 1974). The Curie temperature of partially serpentinized ultramafic bodies which have metal alloys as the prime magnetic source material ranges from 620ºC to 1100ºC (Haggerty, 1978). Frost and Shive (1986) suggested that the Curie temperature of magnetite is at about 600ºC, taking into account that the Curie temperature increases with pressure. Okubo et al. (1989) suggested that the average Curie temperature is about 450ºC by comparing the Curie depth estimated from aeromagnetic data and the temperature gradients. On the other hand, thermal conductivities, k, of basalts and granites are 1.3–2.9 and 2.4–3.8 W m^{-1} K^{-1}, respectively (Turcotte and Schubert, 1982).

The predicted correlation of the Curie point depth with heat flow values given by Eq. 10 is shown in Fig. 4. We have taken $k\theta_c = 1000$, 1500, 2000 and 2500 W m^{-1}, taking into account the above values of thermal conductivity and Curie temperature. In Fig. 4 are also plotted the relationships between the estimated Curie point depth and the observed heat flow values at selected points shown in Fig. 3. Although there is considerable scatter in the observed data, it appears that reasonable agreement is obtained, taking $k\theta_c = 2000$ W m^{-1}.

Heat flow values higher than 150 mW m^{-2} are observed at volcanoes in Tohoku, Japan. These high values yield very shallow Curie point depths (about 10 km) from Eq. 10. The results of the Curie point depth analysis (about 14 km) is, on the other hand, significantly deeper than the depths obtained from Eq. 10. This suggests that our analysis cannot catch a locally shallow Curie point depth. The Curie point depth analysis with smaller subregions is however shallower than 10 km for almost the same region (Okubo et al., 1989). This suggests that the results of the Curie point depth analysis depends strongly on the size of the analyzed area. It also seems that the heat transfer mechanism of these very high heat values may not be explained by conduction only. It is probably necessary to include another heat transfer mechanism such as convection, to explain the large scatter of high heat flow data.

5. Conclusion

The Curie point depths are estimated by spectral analysis of magnetic anomaly data of East and Southeast Asia and compared with the tectonic regime and heat flow data. The Curie point depth estimates the average depth of magnetic sources and is concluded to reflect thermal structures. The Curie point depths are consistent with the observed heat flow data. High heat flow values are observed at back-arc regions where Curie point depths are shallow, whereas low heat flow values are observed at trench axes where Curie point depths are deep. The results and previous studies show that the Curie point depths are shallower than about 10 km at volcanic and geothermal areas, 15–25 km at island arcs and ridges, deeper than 20 km at plateaus, and deeper than 30 km at trenches. The Curie point depths estimated from heat flow data are very similar to the results of the Curie point depths analysis. It suggests that the pattern of the Curie point depths is useful as an index of the thermal structure.

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