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Estimation of Curie point temperature and geothermal structure of island arcs of Japan

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Abstract

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Curie depth analysis from aeromagnetic data was performed in a nationwide project to assess the geothermal resources of Japan. Creation of a Curie depth map of Japan was completed in 1984, and it agrees well with thermal structures such as the high-temperature gradient regions of volcanic chains, low-temperature regions of the forearc basins and the intermediate-temperature regions of the backarc basins.

Measured temperature-gradient (∇T) data were gathered in order to estimate the Curie temperature from the ∇T and the Curie depths. When ∇T is assumed to be constant with respect to depth, a remarkable difference is found in the estimated Curie temperature (T_c^e) of the backarc and forearc side of the basins. In the backarc side an average T_c^e of 450°C is reasonable for both the Curie depth estimated from aeromagnetic data (average depth of about 10 km in the backarc side) and the temperature gradients (average gradient of 4.5°C/100 m).

The average T_c^e on the forearc side was found to be low, at about 300°C. The difference in the Curie temperatures between the two areas may be due to a regional difference in rock type (e.g., granite as opposed to basalt).

In the case of the Northeast Japan arc, as suggested by some authors, the isotherms may suddenly fall between the volcanic front and the trench. Based on model studies, we recognized that a Curie depth map obtained by the algorithm we developed should include an averaging effect. This suggests that the inferred Curie depth curve across the line marking the sudden fall in the Curie isotherm should gradually increase towards the trench. Therefore, the low Curie temperature that we estimated may indicate an apparent shallow Curie depth caused by the averaging effect against an area bearing deep Curie depths.

Hence, the reasons for the inconsistency of the estimated Curie temperature between the forearc side and backarc side may be as follows: (1) the averaging effect of the Curie depth estimate, which makes the Curie depth apparently shallower in the forearc side and (2) the lower Curie temperature of basaltic rocks which are assumed to be distributed along the east side of the aseismic front.

Introduction

A nationwide project to assess the geothermal resources of Japan has been initiated by the New Energy Development Organization (NEDO) with the cooperation of the Geological Survey of Japan (GSJ). A part of the project was the creation of a Curie (point) depth map of Japan from aeromagnetic data, which was collected by EG&G Geometrics Inc. The project was completed in 1984.

The methods of analysis used in the project and the procedure used in making the Curie depth map have been described by Okubo et al. (1985a). The Curie depth map of Japan compared with heat flow and the onshore measured temperature gradients has been discussed by Okubo et al. (1985b).

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Here we will explain several other significant aspects: the outline of the Curie depths of Japan, comparison of temperature gradients measured onshore and offshore with the Curie depths, estimation of the Curie temperature, and the comparison of geothermal structure across the Northeast Japan arc with the result of the Curie depth estimate for the model.

Curie point depth estimates of Japan

The method of Curie depth estimation is based on depth estimation using the broad, long-wavelength magnetic anomalies inferred to be associated with magnetization contrasts at the Curie transition depth, which can range from a few kilometers to tens of kilometers below the surface. Here we use "Curie depth" to describe the depth to the inferred Curie point transition of magnetic minerals.

The mathematical model on which our analysis is based is a collection of random samples from a uniform distribution of rectangular prisms, each prism having a constant magnetization. The model was introduced by Spector and Grant (1970), and has proven very successful in estimating average depths to tops of magnetized bodies. We emphasize that the rectangular prism is only a convenient geometry from which the develop the necessary theory, not a required geologic model.

Our principal result from Spector and Grant's analysis is that the expectation value of the spectrum for the model is the same as that of a single body with the average parameters for the collection. We then develop the equations expressing the theoretical spectrum for the single body. Using the equations, we can determine some average parameters such as the depth to the base of the body (inferred Curie depth) by comparison of the spectrum for the observed anomaly with that of the theoretical one. Based on three-dimensional magnetic model studies, we concluded that an algorithm is useful to the estimates of Curie depth (Okubo et al., 1985a).

The algorithm requires an extensive two-dimensional data set to calculate the spectrum. Hence, an inferred Curie depth should be an average depth within an extensive square area.

Figure 1 shows the contour map of the inferred Curie depths of the Japanese Islands. The shallow (less than 8 km below sea level) Curie depth regions, which should correspond to high-temperature gradient regions, lie within the Quaternary volcanic provinces and geothermal areas from Hokkaido to Kyushu. The deep (more than 15 km) Curie depth regions lie over the pre-Neogene structural belts and the forearc side of the basin. The intermediate Curie depth regions are located in the backarc basins. The average Curie depth of the onshore area is approximately 10 km below sea level, and the average of the offshore area in the Pacific Ocean is approximately 15 km.

Measured temperature gradients

The temperature gradient data for estimating the Curie (point) temperature were gathered. Most of the onshore data are temperature measurements taken from Uyeda et al. (1958), Horai (1959), Uyeda (1960, 1961), Horai (1963a, b, c), Uyeda et al. (1963a,b), Uyeda and Horai (1964), Kono and Kobayashi (1971) and Honda et al. (1979). Most of the offshore data were collected from drillholes reaching depths of 3000–4000 m. The locations of the temperature measurements are shown in Figure 1. The relationship between the inverse temperature gradients and the Curie depths at the locations of the temperature measurement are shown in Fig. 2. Note that the circles denote the data in the backarc side (the area to the northwest of the dashed line in Fig. 1) and dots denote the data in the forearc side (the area to the southeast of the dashed line in Fig. 1). The average temperature gradient of the backarc side is about 4.5°C/100 m, and the average of the forearc side is about 2.2°C/100 m.

The estimated Curie temperature (T_c^e) is hereafter defined with the following equation:

$$T_c^e = \nabla T \times D_c + C$$

where D_c is the Curie depth, below sea level, inferred from aeromagnetic data collected at the same location as the temperature measurement, and C is the temperature at sea level. In this definition, temperature gradients are assumed to

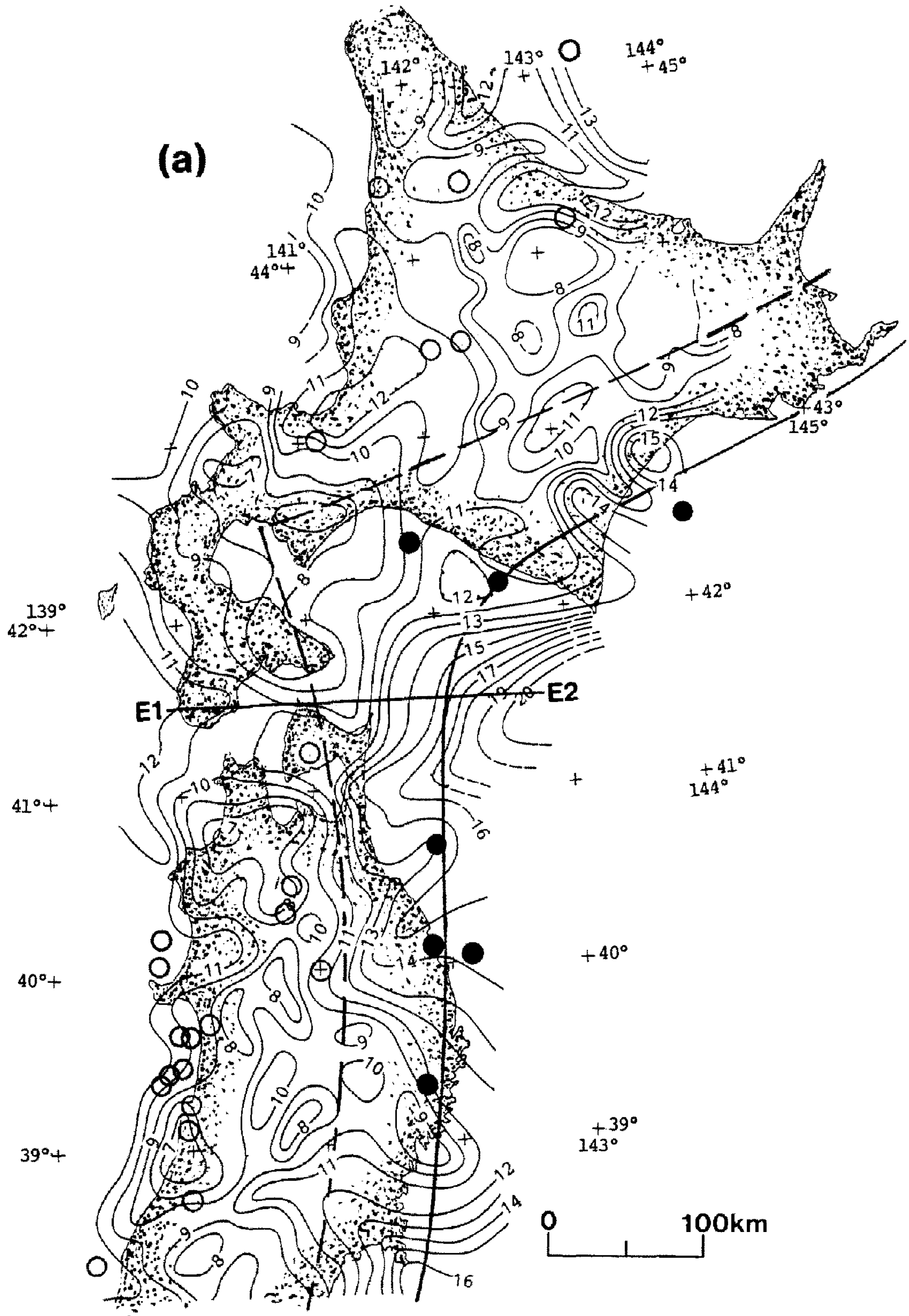


Fig. 1. Curie depth contour map of Japan, indicating the locations of temperature measurements. Dots denote the locations of temperature measurements defined as the forearc type, and circles designate the backarc type. Dashed curves denote the boundary between the forearc type and backarc type, these curves roughly corresponding to the volcanic fronts. Continuous curves indicate the aseismic front (Yoshii, 1975). Curie depth contour interval is 1 km, the contours denoting inferred Curie depths (km) below sea level. Significance of line E1–E2 is explained in text and Fig. 8. a. North Japan. b. Central Japan. c. South Japan.

be constant with respect to depth. This gradient can actually vary even in the conduction-dominant zone because thermal conductivities of rocks can vary. Unfortunately thermal conductivity data at depth are absent; hence we are forced into fixing the thermal conductivity with respect to depth. This is the same type of assumption as that of a constant temperature gradient. Moreover, regional average values of thermal conductivity cannot be defined because of the absence of data. This means that it is better to compare temperature gradients, instead of heat flows, in order to

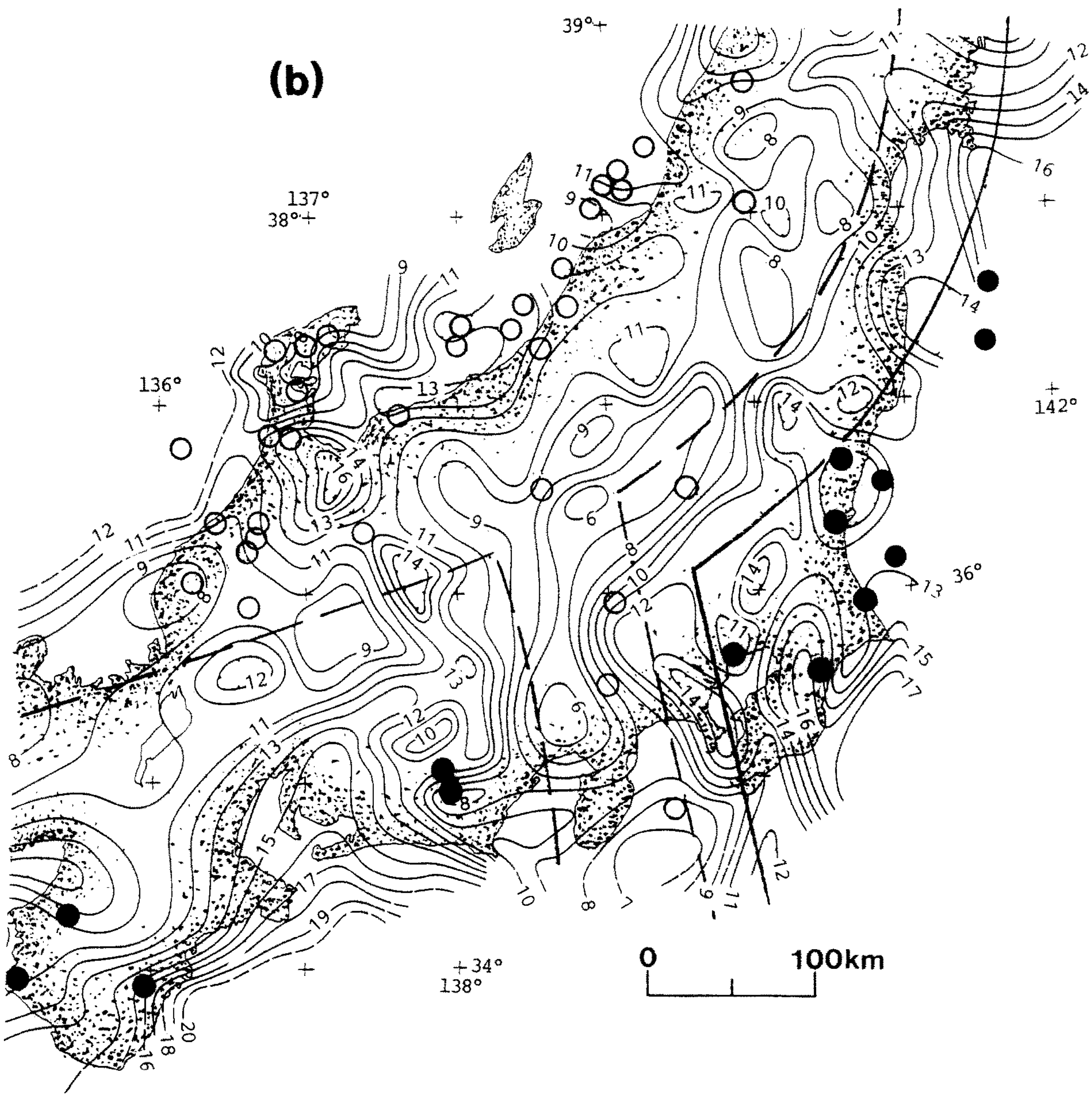
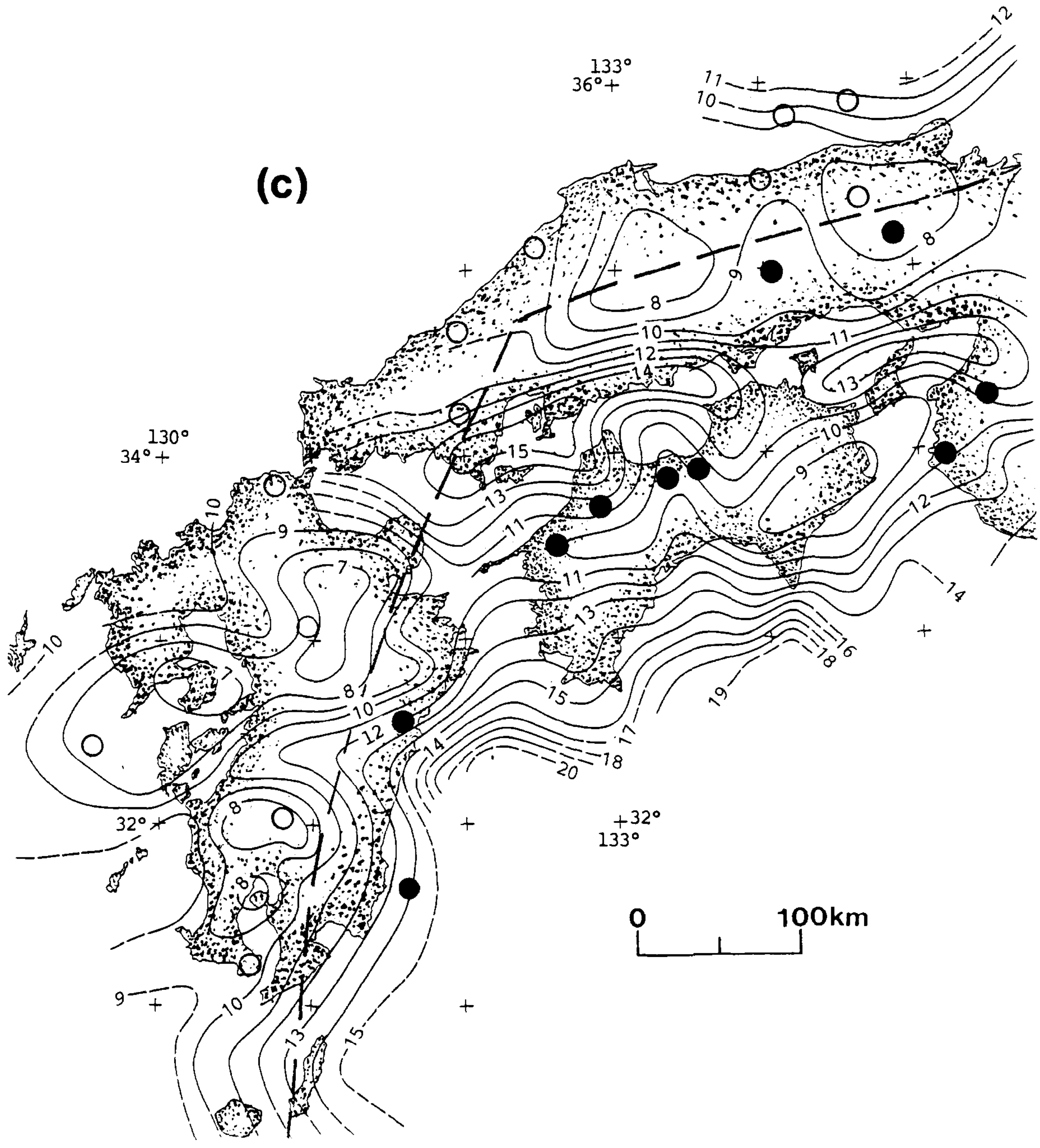


Fig. 1 (continued).

obtain information on the regional thermal condition.

In Fig. 2, the lines for three T_c^e values (300°, 400° and 500°C) when C is assumed to be 15°C are shown. We can easily recognize that the T_c^e of the backarc side (backarc type) is different from the T_c^e of the forearc side (forearc type). The average T_c^e ($\overline{T}_c^e$) of the backarc type is about



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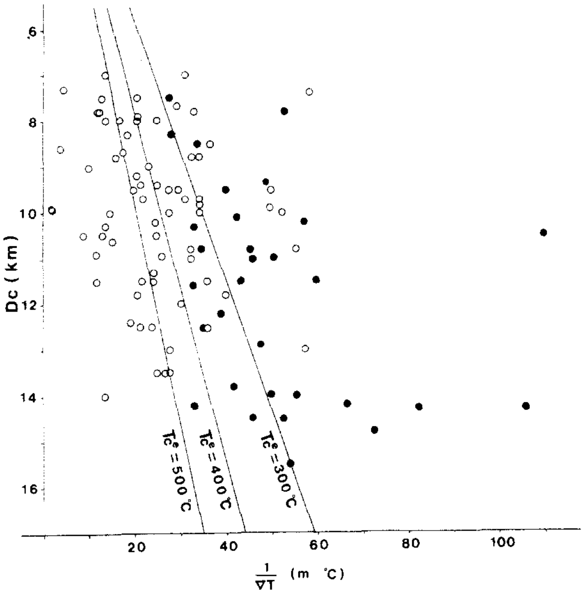

Fig. 2. Comparison of measured inverse temperature gradients ($1/\nabla T$) and Curie depths (D_c) taken from the Curie depth map. Dots denote the data in the forearc side; circles denote data from the backarc side. Lines for three Curie temperatures (T_c^e) (300°, 400° and 500°C), assuming the temperature at sea level to be 15°C, are also shown.

450°C (not taking into account the anomalously high temperature gradient data), and the $\overline{T}_c^e$ of the forearc side is about 300°C, when C is assumed to be 15°C (Table 1). In the following section, we investigate the difference in the $\overline{T}_c^e$ of the two environments.

TABLE 1

Average values of the measured temperature gradients (∇T) and the estimated Curie point temperature (T_c^e) in the backarc and forearc side of the basin. T_c^e was calculated using $T_c^e = \nabla T \times D_c + 15°$, where D_c is the inferred Curie point depth at the location of the temperature measurement.

	Backarc side	Forearc side
Average measured temperature gradient (∇T)	4.5°C/100m	2.2°C/100m
Average estimated Curie point temperature (D_c)	450°C	267°C

Estimation of the Curie temperature

The major sources of magnetic anomalies in Japan should be igneous rocks. The Curie temperature of titanomagnetite, the most common magnetic mineral in igneous rocks, is less than about 580°C. An increase in the titanium content of titanomagnetite causes a reduction in the Curie temperature (Nagata, 1961; O'Reilly and Readman, 1971). The $Fe_3O_4 - TiFe_2O_4$ (magnetite–ulvöspinel) pair represents titanomagnetite. The titanium content generally increases and the Curie temperature decreases in the more mafic igneous rocks (Buddington and Lindsley, 1964). Nagata (1961) shows that most of the natural titanomagnetites fall reasonably close to the stoichiometric magnetite–ulvöspinel pair. Byerly and Stolt (1977) claimed in their attempt to define the Curie isotherm in northern and central Arizona that the Curie temperature of most felsic plutons should lie within the range of 400°–550°C, and a Curie temperature of 500°C gives reasonable results in comparing thermal, magnetic and seismic calculations. It is doubtful that felsic plutons are the principal sources of magnetization in the Japanese island arcs. However, in the case of the backarc types it is a reasonable assumption that the major sources of magnetic anomalies are the felsic rocks. Further the measurements of temperature gradients and inferred Curie depths also suggest that the Curie temperature of felsic plutons which ranges from 400° to 550°C should give reasonable results. An average T_c^e of 450°C for the backarc type environment is thus reasonable.

In contrast, the average estimated Curie temperature on the forearc side is anomalously low. It is thought that lateral changes in the regional rock type (e.g., basalt to granite) should occur between the forearc and backarc side, and basaltic rocks should cause reductions in the Curie temperature of the forearc type. Indeed, as shown in Fig. 3, a high positive magnetic anomaly belt extends along the North Pacific Ocean coastline, and this may be caused by basaltic rocks. Ogawa and Suyama (1975) inferred on the basis of aeromagnetic and seismic data that the sources of the magnetic

Fig. 3. Total magnetic field in Northern Japan (NEDO). Arrows indicate the position of a high positive magnetic anomaly belt.

anomalies of the belt are deeply buried massive basic or ultrabasic rocks.

We now evaluate the effect of the averaging employed in the present method on the Curie depth estimates. The Curie depth in our study is the average depth within a square area. Hence, the Curie depth map contoured from the inferred Curie depths reveals a high-cut filtered effect or the averaging effect. This sometimes results in incorrect interpretations in areas where the Curie depth steeply varies, and may lead to incorrect estimates of the Curie temperature.

Geothermal structure and Curie depths across the Northeast Japan arc

A number of authors have suggested that island arc–trench systems are produced by descending mantle convection currents. From this viewpoint, Hasebe et al. (1970) estimated the temperature distribution across the Northeast Japan arc based on a model which satisfies the observations of terrestrial heat flow. Figure 4 (Fujii and Kurita, 1978) suggests that the depths of the 500 °C isotherm are shallow on shore, but suddenly attain greater depths, down to more than 50 km, between the volcanic front and the trench. It is reasonable to assume that the sudden variability in depth or the fall of the 500 °C isotherm occurs between the trench and the volcanic front.

According to the temperature measurements, the average temperature gradient in the area east of the aseismic front shown in Fig. 1 is 2.0 °C/100 m. The aseismic front is defined by Yoshii (1975) as a discontinuity in seismicity in the mantle recognized from the epicentral distribution of earthquakes at depths of 40–60 km. If we assume that the temperature gradient in the area of the aseismic front is constant at 2.0 °C/100 m with respect to the depth, the Curie temperature in the backarc is at the average, i.e., 450 °C, and that the Curie temperature has no lateral variations, then the Curie depth can be estimated as being about 22 km below sea level.

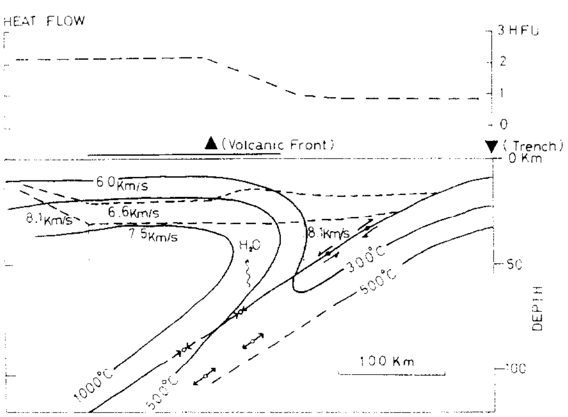

Fig. 4. Cross section of heat flow (top) and structure (bottom) beneath island arcs (Fujii and Kurita, 1978). V_p values by R.G.E.S. (1977).

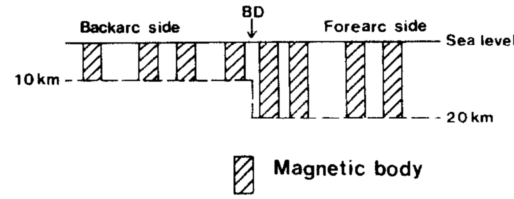

Fig. 5. Magnetic model of the Northeast Japan arc. The point *BD* marks the isotherm sudden fall line.

The average temperature gradient and the Curie temperature in the backarc (4.5 °C/100 m and 450 °C respectively), suggest that the Curie depth is about 10 km, which is consistent with the average inferred Curie depth from the aeromagnetic data in the onshore area. It is then reasonable to conclude that the average Curie depth on the backarc side is 10 km.

We then assume, in the following discussion, that the magnetic model of the Northeast Japan arc is represented by a simple model as shown in Fig. 5. In order to evaluate the averaging effect which may occur over the sudden variation in Curie depth and discuss the average effect in the Curie depth map of the Northeast Japan arc, we estimate the inferred Curie depth profile for the magnetic model shown in Fig. 5 using the same algorithm as is used in the Curie depth estimate of Japan generally.

The magnetic model for computing the Curie depth distribution consists of 40 prisms with horizontal sizes of 2 km by 2 km which are uniformly magnetized parallel to the geomagnetic field and randomly distributed within an area 0–255 km in the W–E direction and 0–127 km in the S–N direction. Hereafter we call the whole 255 km by 127 km rectangular area, area A. Depths to the top of all prisms are fixed at sea level. Twenty prisms are distributed randomly on the west side of area A (area B1) and depths to the bottom of these are fixed at 10 km below sea level. The remaining twenty prisms are distributed randomly on the east side of area A (area B9), and depths to the bottom of these are 20 km below sea level. Thus, the depths to the bottom suddenly drop from 10 km on the west side to 20 km on the east side across the center of area A, and this central area is defined as the isotherm fall line. Magnetic anomalies of 40 prisms were computed on 1 km by 1 km square grids by the method developed by Bhattacharyya (1964) at a constant elevation of 1.5 km above sea level over area A. The number of grid data is 256 by 128. The contour map of magnetic anomalies over area A is shown in Fig. 6.

The Curie depth was inferred using magnetic data in a 128 km by 128 km subblock and the number of subblocks for Curie depth estimation is nine. These subblocks (area B1, area B2, ..., area B9) are lined up to the east at 16 km intervals. Let each Curie depth estimated be the one at the center of each subblock (P1, P2, ..., P9).

Figure 7 shows the results of Curie depth estimates of each subblock and the average depths to

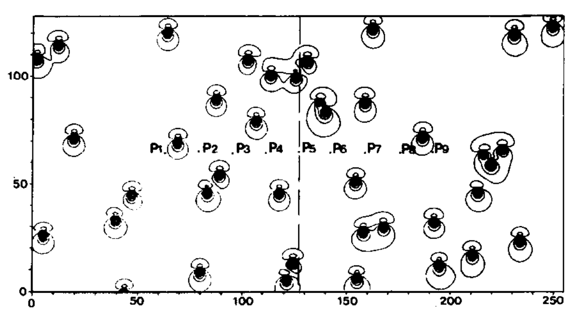

Fig. 6. Total magnetic field from 40 prisms on the surface at a constant elevation of 1.5 km above sea level, expressed as a contour map with constant contour interval. The inclination and declination of the geomagnetic field is 50° and 0°N respectively, and magnetizations of magnetic bodies are parallel to the geomagnetic field. Dashed line denotes the isotherm sudden fall line. P1–P9 are centers of the square areas at which inferred Curie depths are defined. The perimeter of the block is measured in kilometers.

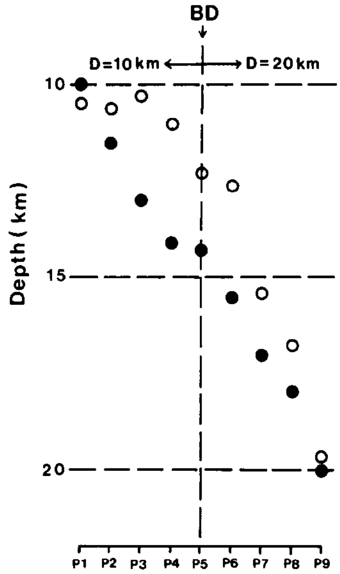

Fig. 7. Results of Curie depth estimates from the total magnetic field shown in Fig. 6. (circles) and average depth to the bottom of the prisms (dots). *BD* denotes the isotherm sudden fall line.

the bottom of the prisms (D_{cj}, $j = 1, 2, \ldots, 9$), which is defined as follows:

$$D_{cj} = \frac{1}{N_j} \sum_{i=1}^{N_j} d_{ij} \qquad j = 1,2,\ldots,9$$

where d_{ij} is the depth to the bottom of the prism in area B_j and N_j is the number of the prisms in area B_j. The inferred Curie depths at P1 and P9 are roughly consistent with the actual depths, 10 km and 20 km. This suggests that the Curie depth estimates are reasonable. The actual Curie depths at P2–P4 and P6–P8 are 10 km and 20 km respectively, and P5 coincides with the isotherm sudden fall line, although the inferred Curie depths gradually increase from 10 to 20 km toward the east. This reveals a gradual increase in the inferred Curie depths against the sudden fall of the isotherm, or the averaging effect.

The depths to the bottom of the prisms from the Curie estimates were slightly shallower than the average depth. This effect causes the inferred Curie depth to indicate a roughly correct but nonetheless slightly deep depth in the shallow (10 km) Curie depth region and a very shallow depth in the deep (20 km) Curie depth region. This tendency can be recognized as being characteristic

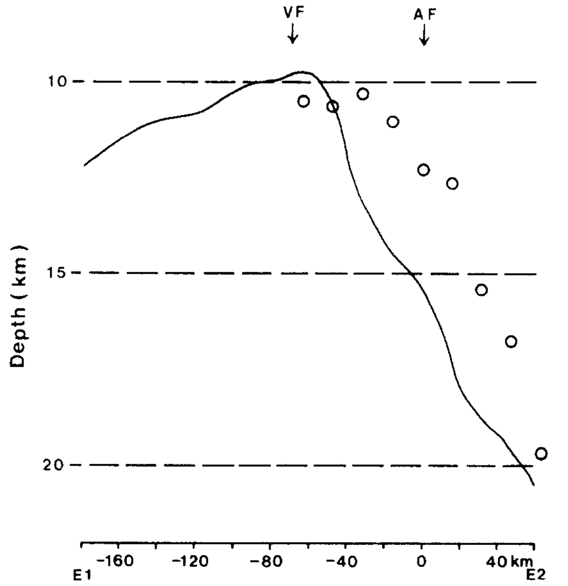

Fig. 8. Profile of Curie depths along line E1–E2 (Fig. 1) superimposed on Fig. 7 (circles) when the aseismic front (*AF*) coincides with the isotherm sudden fall line (*BD*). Open circles indicate the result of Curie estimates for the model shown in Fig. 6. *VF* denotes volcanic front.

of the potential field, where the size of an anomaly due to a causative body in the near field is larger than the anomaly in the far field. This must be generally found in the Curie depth estimate, and renders the Curie depth map more incorrect in the deeper region than in the shallower region over an area where the Curie depth varies steeply.

Figure 1 shows that the areas in which the Curie depth reaches more than 20 km are found only in the Pacific Ocean to the east of Shimokita Peninsula. To investigate this further the profile of the Curie depth data on the line E1–E2 (Fig. 1) is superimposed on Fig. 7 assuming that the aseismic front coincides with the isotherm fall line (Fig. 8).

The Curie depths on line E1–E2 gradually increase from 10 to 20 km toward the east. This rate of increase is approximately equal to that of the Curie estimates for the model, although a small lateral shift to the east of the depths in the model study can be recognized in Fig. 8.

Comparisons between the Curie depth profiles on other cross sections of the Northeast Japan arc and the inferred Curie depth curve obtained by the model study reveal a pattern similar to that of the curve of profile E1–E2; i.e., the Curie depth generally increases to the east. This suggests that if there is a Curie isotherm sudden fall line between the volcanic front and the trench, the gradual increase in the Curie depth curve across the Northeast Japan arc may be explained by the averaging effect of the Curie depth estimate. Further, the averaging effect causes the inferred Curie depth as a whole to be shallow in the forearc side of the basin and it also leads to incorrect estimates of the Curie temperature.

Conclusions

In the backarc side of the Northeast Japan arc, the average Curie temperature of about 450°C gives reasonable results in comparing the Curie depth estimates from aeromagnetic data and the temperature gradients. This Curie temperature is well within the range of the Curie temperature of titanomagnetites contained in felsic plutons. The average Curie temperature in the forearc side indicates lower values of about 300°C, i.e., there is an inconsistency in the Curie temperature in the forearc and backarc sides.

It is possible that the difference in Curie temperatures between the two areas is due to the regional difference in rock types (e.g., basalt as opposed to granite) because the Curie temperature is lower in the more mafic igneous rocks.

In the case of the Northeast Japan arc, as suggested by some authors the isotherms may suddenly fall between the volcanic front and the trench. According to a model study, the averaging effect in the Curie depth estimate from aeromagnetic data may be the cause of an apparent gradual increase in the Curie depth when it is in fact suddenly declining. When the Curie depth is estimated over a contact region between deep and shallow Curie depth areas, the averaging effect in the deep Curie depth area is larger than that in the shallow area.

The method of the Curie depth estimate produced reasonable results for three-dimensional magnetic models and many authors (e.g., Bhattacyaryya and Leu, 1975; Byerly and Stolt, 1977; Shuey et al., 1977; Smith et al., 1977; Boler, 1978; Connard et al., 1983) have shown successful results of Curie depth estimating in other regions, using a method very similar to the one we have developed. However, there may be some room for discussion as to whether the Curie depths from magnetic data agree with thermal structures, and the reliability of the method may also raise some questions.

The inconsistency in the inferred Curie temperature between the forearc side and backarc side of the basin may be explained by the following: (1) the averaging effect of the Curie depth estimate over the Curie depth fall line occurring in the vicinity of the aseismic front, which leads the inferred Curie depth as a whole to be shallower on the forearc side, and (2) the lower Curie temperature of basaltic rocks, which causes the Curie depth to be shallow on the forearc side.

Acknowledgements

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