DEPTH TO CURIE TEMPERATURE

Introduction

The Curie temperature or Curie point is the temperature at which a ferromagnetic mineral loses its ferromagnetic properties. At temperatures above the Curie point the thermal agitation causes the spontaneous alignment of the various domains to be destroyed/randomized so that the ferromagnetic mineral becomes paramagnetic. The term Curie point is named after the French scientist Pierre Curie who discovered that ferromagnetic substances lose their ferromagnetic properties above this critical temperature. This discovery has had great utility in providing information about the deep crust of the Earth that lies below direct human access.

The interior of the Earth is considerably hotter than the surface. Depth to the Curie temperature is the depth at which crustal rocks reach their Curie temperature. Although *paramagnetism* and *diamagnetism* contribute to the magnetism of rocks, it is the ferromagnetic minerals that are the dominant carriers of magnetism in rocks (Langel and Hinze, 1998). The dominant ferromagnetic minerals are the *iron-titanium oxide* and *iron sulfides* (*q.v.*). Generally the depth to Curie isotherm is calculated indirectly from analysis of magnetic anomalies; however in a rare case this depth was physically reached in a drilled core. The German Continental Deep Drilling Program drilled a 9.1-km deep core and its petrophysical properties showed that the most abundant ferrimagnetic mineral at this site is monoclinic pyrrhotite (see *iron sulfides*), which disappeared below about 8.6 km, and below this depth, hexagonal pyrrhotite with a Curie temperature of 260°C was the stable phase (Berckhemer *et al.*, 1997). Thus the depth to the Curie temperature of the predominant pyrrhotite was physically reached (as the drilled core reached *in situ* bottom hole temperature of around 265°C).

Utility

Magnetite with a Curie temperature of 580°C is the dominant magnetic mineral in the deep crust within the continental region (Langel and Hinze, 1998). Below the Curie isotherm depth the lithosphere is virtually nonmagnetic. From the analysis of the *crustal magnetic field* (*q.v.*), the depth below which no magnetic sources exist can be estimated. The remotely sensed magnetic (surface, airborne, satellite-borne) measurements thus indirectly provide an isothermal surface within the lower crust that in turn can be translated into geothermal gradients of the region. The nationwide geothermal resources project of Japan, initiated in the early 1980s, was perhaps the first systematic attempt to use Curie point depth estimates from the magnetic data as an integral part of a nationwide geothermal exploration program for such a large area (Okubo *et al.*, 1985). Estimates were made for temperature gradients and utilizing available heat flow data very meaningful average thermal conductivities were determined. The depth to Curie temperature can also provide an understanding of the thermal structure; e.g., in volcanic areas convective heat transfer complicates the determination of the thermal structure from heat flow measurements alone and determination of Curie point depths from magnetic data can prove to be helpful for understanding the thermal structure. From a magnetic analysis of the Tohoku arc, Japan, Okubo, and Matsunaga (1997) find that the Curie isotherm varies from 10 km in the volcanic province of the back arc to 20 km or deeper at the eastern limit of Tohoku. They find that the boundary between the seismic and aseismic zones in the overriding plate correlates with the inferred Curie isotherm, indicating that the seismicity in the overriding plate is related to temperature.

The magnetic method estimates the depth to the bottom of the magnetized layer. Due to the inherent uncertainties of these Curie temperature depths, supporting independent evidence is desirable. Possibilities include the comparison with deep seismic soundings, gravity surveys, and petrological studies. In case the estimated Curie temperature depth correlates with a velocity or density boundary, it is likely to reflect a vertical change in composition. Rajaram *et al.* (2003) applied a series of high pass filters to the aeromagnetic data of Southern India and inferred that below the exhumed crust of the Southern Granulite terrain the magnetic crust is thin (compared to the Dharwar craton) being confined to 22 km; at this depth there is a change in the seismic velocity in the seismic reflection/refraction profiles implying a compositional change being responsible for the lack of magnetic sources below 22 km. The depth extent of magnetic sources has become synonymous with the depth to the Curie temperature though in reality they may represent either a petrological or temperature boundary. Magnetization measurements and petrological studies indicate that ferromagnetic minerals are generally not present in the mantle, at least in the continental region (Langel and Hinze, 1998) implying that the Moho is a magnetic boundary.

Method

Magnetic anomalies contain contributions from the ensemble of sources lying above the Curie isotherm. The depth extent of magnetic sources is often determined by spectral analysis of magnetic data. This is done by either examining the shape of isolated magnetic anomalies or by examining statistical properties of patterns of magnetic anomalies. Spector and Grant (1970) pointed out that the anomaly due to an ensemble of sources, represented by a large number of independent rectangular parallelepipeds, has a power spectrum equivalent to that of a single average source of the ensemble and the depth to the top of the body, z_t, can be estimated from the slope of the log power spectrum. A limited depth extent of the body is predicted to lead to a maximum in the power spectrum, and the wave number of this maximum $k_{\max}$ is related to the bottom of the magnetic source, z_b (depth to the Curie isotherm) thus:

$$k_{\max} = \frac{\log z_b - \log z_t}{z_b - z_t}$$

For a magnetic survey of dimension L the smallest wavenumber is the fundamental wavenumber $k = 2\pi/L$ (Blakely, 1995). Thus, $k_{\max}$ should be at least twice this to be able to resolve a peak in the spectrum and this suggests that the survey dimension must be at least

$$L \geq \frac{4\pi(z_b - z_t)}{\log z_b - \log z_t}$$

For a survey conducted 1 km above the top of magnetic sources, the survey dimension must be at least 160 km for sources extending to 50 km depth. It often turns out, however, that continental scale magnetic compilations do not have a maximum in the power spectrum indicating a flaw in the underlying assumptions. Indeed, it is very difficult to estimate the depth to the bottom of the magnetic sources, as the spectrum is dominated at all wavelengths by the contribution from the shallower parts. To avoid this complication, one calculates the centroid depth, z_0, either from isolated anomalies or by using methods based on Spector and Grant's statistical model and the inferred depth to the Curie temperature is then obtained as $z_b = 2z_0 - z_t$ (Okubo *et al.*, 1985).

The method adopted by Spector and Grant (1970) assumes that the magnetization has no spatial correlation; however there are evidences to the contrary. Pilkington and Todoeschuck (1993) from a statistical analysis of susceptibility and aeromagnetic fields indicate that the magnetization and resulting fields are correlated over large distances and can be described as a self-similar random process. Such processes have a power spectrum proportional to some power of the wavenumber, called the scaling exponent (fractal dimension), and the degree of correlation is indicated by the magnitude of this exponent. Maus *et al.* (1997) find that the limited depth extent of the crustal magnetization is discernible in the power spectra of magnetic anomaly maps of South Africa and Central Asia. From the theoretical power spectrum of a slab using fractal methods, they estimate the Curie temperature depths to lie between 15 and 20 km, with large uncertainties due to the inaccurately known scaling exponent of the crustal magnetization. They conclude that for reliable estimates of the depth to the Curie temperature, magnetic anomalies over an area of at least 1000 km × 1000 km are required.

Magnetic anomalies, long wavelength (q.v.), measured by satellites are generally inverted using an equivalent source model (see Langel and Hinze, 1998). The observed magnetic anomaly is inverted by a least squares method for an array of equal area dipole sources at the surface of the Earth. A common assumption is that the magnetization arises from induced magnetization only. The magnetization is proportional to the effective susceptibility and the thickness of the magnetized crust, which in turn is a measure of the depth to the Curie temperature. Using inverse models incorporating *a priori* ocean-continent magnetization contrasts, Purucker *et al.* (1998) generated global integrated susceptibility maps from *Magsat (q.v.)*, which can be interpreted in terms of thermal characteristics of the crust. Purucker and Ishiara (2005) have used a further refined model using *CHAMP (q.v.)* data and find for the subduction region of the 2004 great Sumatran earthquake that the subducting plate is descending so quickly that its temperature does not reach the Curie point, resulting in thickened magnetic crust due to the subducting slab.

Conclusions

Magnetic anomalies derived from *aeromagnetic surveying (q.v.)* have been used to estimate the depth and configuration of the Curie isotherm for over half a century. Estimates of depth to the Curie temperature can provide valuable insights in the assessment of geothermal energy, calculation of thermal conductivity, and geodynamic evolution. However, unknown mineralogical and statistical properties of the source magnetization have a strong effect on the accuracy of Curie isotherm depth estimates by magnetic methods. These estimates should therefore be interpreted in the context of independent geological, geophysical, and geothermal information. Estimating depth to Curie temperature on a regional scale from long wavelength anomalies requires that large areas of survey data be used for the calculations. There is still no consensus on the minimum survey area required to arrive at a reliable estimate of the Curie isotherm depth. Also, in the Fourier domain, one works with square grids of data, which can pose a problem due to the shape of the continents e.g., Indian peninsula. However, in the absence of any direct method to observe Curie depth, estimates from magnetic anomalies will continue to provide valuable information. New global magnetic anomaly maps, compiled from all available marine and aeromagnetic data and combined with *CHAMP (q.v.)* and upcoming *Swarm* satellite magnetic maps, using *spherical cap harmonics (q.v.)*, will provide a valuable basis for future global estimates of the Curie isotherm.

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Cross-references

Aeromagnetic Surveying
CHAMP
Harmonics, Spherical Cap
Iron Sulfides
Magnetic Anomalies for Geology and Resources
Magnetic Anomalies, Long Wavelength
Magnetic Anomalies, Modeling
Magnetic Susceptibility
Magsat