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Distribution of crustal magnetisation deduced from the inversion of MAGSAT data over Turkey

Mujgan Salk

Dokuz Eylul Universitesi, Muhendislik Fakultesi, Jeofizik Bolumu, Bornova, Izmir-Turkey
E-mail: msalk@izmir.eng.deu.edu.tr

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Abstract: *NASA launched the magnetic field satellite, MAGSAT, to examine specifically large- and medium scale lithospheric anomalies. The data measured by Magsat have been used to study the distribution of crustal magnetisation in an area between 25°- 45° E longitude and 35°- 45° N latitude. Magsat maps were prepared by extracting the external and main field from the measured data. The data interpretation is performed in view of a magnetisation model in which the Earth's lithosphere beneath Turkey is subdivided into blocks having dimensions of 2° in latitude and longitude. Each block is represented by a dipole as being parallel to the main core field. The model parameters are updated by an iterative scheme until a reasonable fit between the theoretical data and the model response is obtained. A method that produces an approximation to a crustal magnetisation distribution from the inversion of satellite magnetic anomaly data is described. The method consists of an equivalent source representation of the observed anomaly field. The application of the method to the Magsat data indicates that positive magnetisation values dominate eastern and western Turkey. Negative magnetisation values are observed in the Black Sea. The low amplitude magnetisation anomalies may be related to a relatively shallow Curie isotherm that reflects high rate of heat flow.*

Key Words: *Crustal Magnetisation, Magsat Data over Turkey.*

INTRODUCTION

A low-altitude magnetometer satellite (MAGSAT) orbited the Earth about eight months in 1979 for the measurement of the Earth's magnetic field about 16 times in per second (Arkani-Hamed and Strangway, 1986). The mission has stimulated new researches that examine the sources of intermediate-wavelength magnetic anomalies of the Earth. The vertical components of magnetic field were prepared covering the area between 25°-45° E and 35°-45° N by using Magsat data supplied from the British Geological Survey. Salk and Ergun(1997) carried out the quantitative interpretation of similar data for the development of global crustal model of Turkey by using a forward technique of Meyer *et al.* (1983). An inversion technique, which was described by Mayhew *et al.* (1980), was used to determine the distribution of crustal magnetisation for the vertical component magnetic anomaly data of Turkey.

The inversion of satellite magnetic anomaly data gives valuable information about the spatial variation of physical properties of the crust. The standard method is to invert the observed data by using an equivalent layer magnetisation model based on a latitude-longitude dipole source array on the Earth's surface. A series of magnetic moments estimated from the equivalent source computation vary irregularly, and are of no particular physical significance. Searching a continuous distribution of magnetisation that provides a theoretical data set close to the measured data could develop a physically meaningful model of the magnetic source distribution while all layers having a fixed thickness value. The outcome is a preliminary approximation to gross features of the magnetisation variations in the crust (Mayhew, 1979). The sources consist of many blocks having dimensions of 2° and thicknesses of 20 km. And approximate source function was developed to explain the anomaly caused by such a volume. This paper is a

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review of a practical method in searching a preliminary approximation to a crustal magnetisation distribution that explains the measured satellite data. The term ‘crust’ as used here means that a layer bounded by the Earth's surface and the Curie isotherm, and may or may not correspond to the petrologic crust in a certain area.

MAGNETIC FIELD OF THE CRUSTAL MODEL

An equally subdivided area that covers the region under investigation is constructed on the surface of the Earth. It is assumed that a dipole is located at the centre of each mesh. The magnetic moments of these dipoles are updated to obtain a satisfactory fit between observed data and model response in view of the least-squares theory (Rao *et al.*, 1985; Meyer *et al.*, 1983). In practice, the magnetic moments are normalised by the volumes (determined from the dipole spacing and an arbitrary depth of 20 km below the Earth's surface) to compute apparent magnetisation values. Each of the uniformly magnetised crustal blocks is now represented by a single dipole located at the centre of the block. A dipole has coordinates *r', f', l'* in spherical coordinate system. Its scalar magnetic moment is as follow:

$$m(r', \theta', \lambda') = M\tau , \qquad (1)$$

where *M* denotes magnetisation value. The block volume depends on co-latitude *(q')*, upper surface depth (r_2), and block thickness *(d)* and it is given by

$$\tau = (\pi/135) \sin 1^\circ \sin\theta' (3 r'^2_2 d - 3r'_2 d^2 + d^3). \qquad (2)$$

The upper surface depth is always equal to zero.

The three component of the block dipole moment are then calculated in the same manner as the components of the main field:

$$m_{r'} = -m \sin I,$$

$$m_{\theta'} = -m \cos I \cos D \qquad (3)$$

and

$$m_{\lambda'} = m \cos I \sin D,$$

where *I* and *D* are the inclination and declination, respectively.

The contribution of any crustal dipole having magnetic moment *m(r', q', l')* to the potential at a point *P(r,q, l)* is given by

$$V(r,\theta,\lambda) = (\mu_o/4\pi) \frac{mL\cos(m,L)}{L^3}, \qquad (4)$$

where *L* is the vector distance between the positions of *m* and *P*. m_0 denotes magnetic permeability of vacuum. The direction cosines can be expressed in terms of the known coordinates of *m* and *P*. Then, the potential can be expressed as

$$V = (\mu_o / 4\pi) [m_{r'} (ra - r') - m_\theta' rb + m_\lambda' rc] / L^3. \qquad (5)$$

The magnetic induction *B* at *P* is

$$B \equiv (B_r, B_\theta, B_\lambda) = - \mathrm{grad}V \qquad (6)$$

$$= (- \partial V/\partial r , - \partial V/r\partial\theta , - \partial V/r\sin\theta\, \partial\lambda)$$

$$\partial V/\partial r = \mu_o/4\pi \{ m_{r'} [a(1/L^3 + 3r\frac{r'a - r}{L^5}) - 3r' \frac{r'a - r}{L^5}]$$

$$+ m_\theta' [-b(1/L^3 + 3r \frac{r'a - r}{L^5})] + m_\lambda' [c(1/L^3$$

$$+ 3r \frac{r'a - r}{L^5})]\} \qquad (7)$$

$$\partial V/r\partial\theta = \mu_o/4\pi \{ m_{r'} [(1/L^3 + 3r' \frac{ra - r}{L^5})(-\sin\theta \cos\theta'$$

$$+\cos\theta \sin\theta' \cos(\lambda - \lambda'))]$$

$$+m_\theta' [-1/L^3 (-\sin\theta \cos\theta' - \cos\theta \sin\theta' \cos(\lambda - \lambda'))$$

$$-3b\frac{rr'}{L^5} (-\sin\theta \cos\theta' + \cos\theta \sin\theta' \cos(\lambda - \lambda'))]$$

$$+m_{\lambda'} [1/L^3 \cos\theta' \sin(\lambda - \lambda') \qquad (8)$$

$$+3c\frac{rr'}{L^5} (-\sin\theta \cos\theta' + \cos\theta \sin\theta' \cos(\lambda - \lambda'))]\}$$

$$\partial V/ r\sin\theta\, \partial\lambda = \mu_o/4\pi \{ m_{r'} [-(1/L^3 + 3r' \frac{ra - r}{L^5}) \sin\theta'$$

$$\sin(\lambda - \lambda')] + m_\theta' [-\frac{1}{L^3} \cos\theta' \sin(\lambda - \lambda')$$

$$+3b\frac{rr'}{L^5} \sin\theta' \sin(\lambda - \lambda')] \qquad (9)$$

$$+m_{\lambda'} [1/L^3 \cos(\lambda - \lambda') - 3c \frac{rr'}{L^5} \sin\theta' \sin(\lambda - \lambda')]\}$$

where

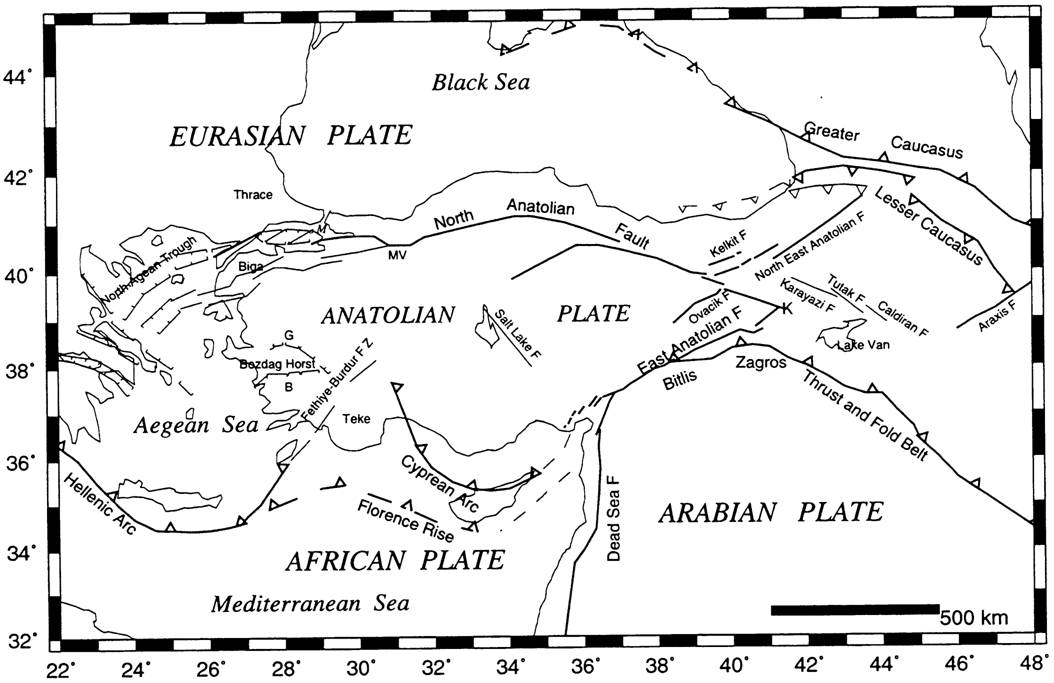

FIG. 1. Tectonic elements of the Eastern Mediterranean. M: Marmara, K: Karliova, G: Gediz, B: Buyuk Menderes (after Oral, 1994).

$$L = (r^2 + r'^2 - 2rr'a)^{1/2} \qquad (10)$$

$$a = \cos\theta \cos\theta' + \sin\theta \sin\theta' \cos(\lambda - \lambda')$$

$$b = \cos\theta \sin\theta' - \sin\theta \cos\theta' \cos(\lambda - \lambda') \qquad (11)$$

$$c = \sin\theta \sin(\lambda - \lambda').$$

The Cartesian components X, Y, Z defined as being positive towards to north, east and downwards. They are:

$$X = -B_\theta,$$

$$Y = +B_\lambda,$$

$$Z = -B_r.$$

The total field B is obtained from their root sum square:

$$B = (X^2+Y^2+Z^2)^{1/2}. \qquad (12)$$

INVERSION OF MAGNETIC DATA

The anomaly field due to a set of k dipoles is compared with the measured anomaly at the n satellite locations. The computed field at the jth point can be written as

$$G_J = \sum_{i=1}^{k} m_i F_{ij}, \qquad j=1,..,n \qquad (13)$$

where n denotes the observed data. F_{ij} represents the dipole source function given by eq. (7). m_i is the magnetic moment of the ith dipole and it is given by

$$m_i = M_i v_i,$$

where M_i denotes the magnetisation of the ith prism. v_i is the volume of a spherical prism bounded by lines of latitude and longitude surrounding the ith dipole, having equal units defined in degrees. The problem is to solve for the set of parameters M_i which minimises the squared sum of residuals between observed and computed anomaly fields over all satellite data points (Mayhew *et al.*, 1980).

The magnetisation values are estimated by the standard least-squares inversion procedure for a over-determined system. Because the theoretical field arising from the source array is a linear function of the source parameters, an initial-guess for the parameters may be done by assigning arbitrary numerical values to the

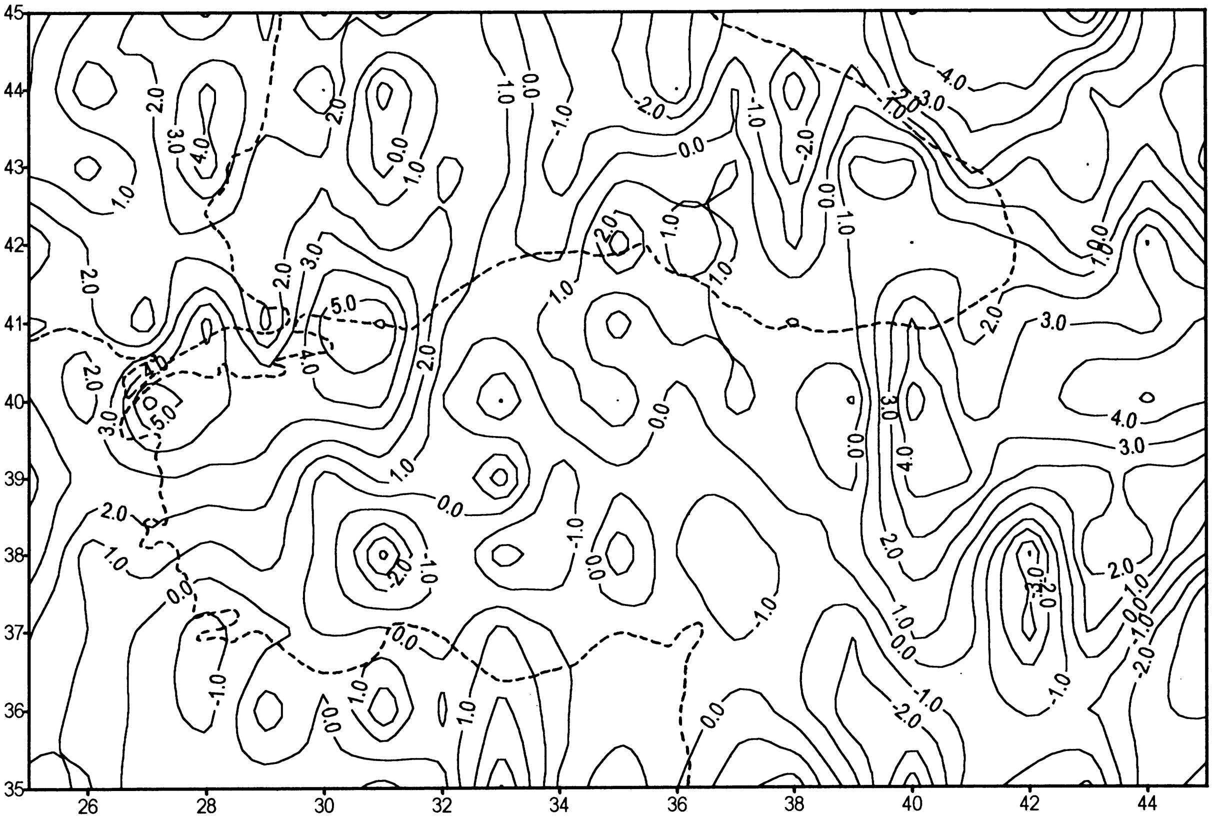

FIG. 2. Vertical component Magsat anomaly map of Turkey and surrounding regions. Contour interval: 1 nT.

parameters and then they are updated in a iterative procedure by calculating a new parameter set that gives a better fit between the measured data and model response. The parameter correction vector for the calculation of a new parameter set is given by

$$\Delta M = (A^T A)^{-1} A^T \Delta g \, , \qquad (14)$$

where *Dg* is a vector of residuals between observed and computed fields. The Jacobian matrix is defined as follow:

$$A_j = \frac{\partial F_{ij}}{\partial M_j} = v_i F_{ij} \qquad (15)$$

Once the magnetisation parameters are determined, then they are used to compute the anomaly field at any position, in particular over a surface of 400-500 km elevation for the comparison of measured satellite data with the theoretical data.

MAGSAT MAGNETIC ANOMALIES OF TURKEY

The crustal deformation in Turkey is controlled by the interaction of the African, Arabian and Eurasian plates (Fig. 1). Much of the deformation in the Eastern Mediterranean is caused by the northerly motion of the African and Arabian plates towards to the Eurasian plate. The subduction of African plate began at 40-26 Ma (Spakman *et al*,. 1988) and the later collision between the Arabia and Eurasia plates around middle Miocene, caused drastic changes in the tectonic evolution of Turkey. A number of coexisting tectonic regimes in this section of the Tethian belt are observed. They are; a continent-continent collision zone (Bitlis-Zagros, Caucuses); an extensional province (western Turkey, the northern Aegean Sea, and southern Greece); major transform faults (the North, East and Northeast Anatolian faults, the Dead Sea fault); and different stages of subduction (the Hellenic and Cyprian arcs, the Black Sea).

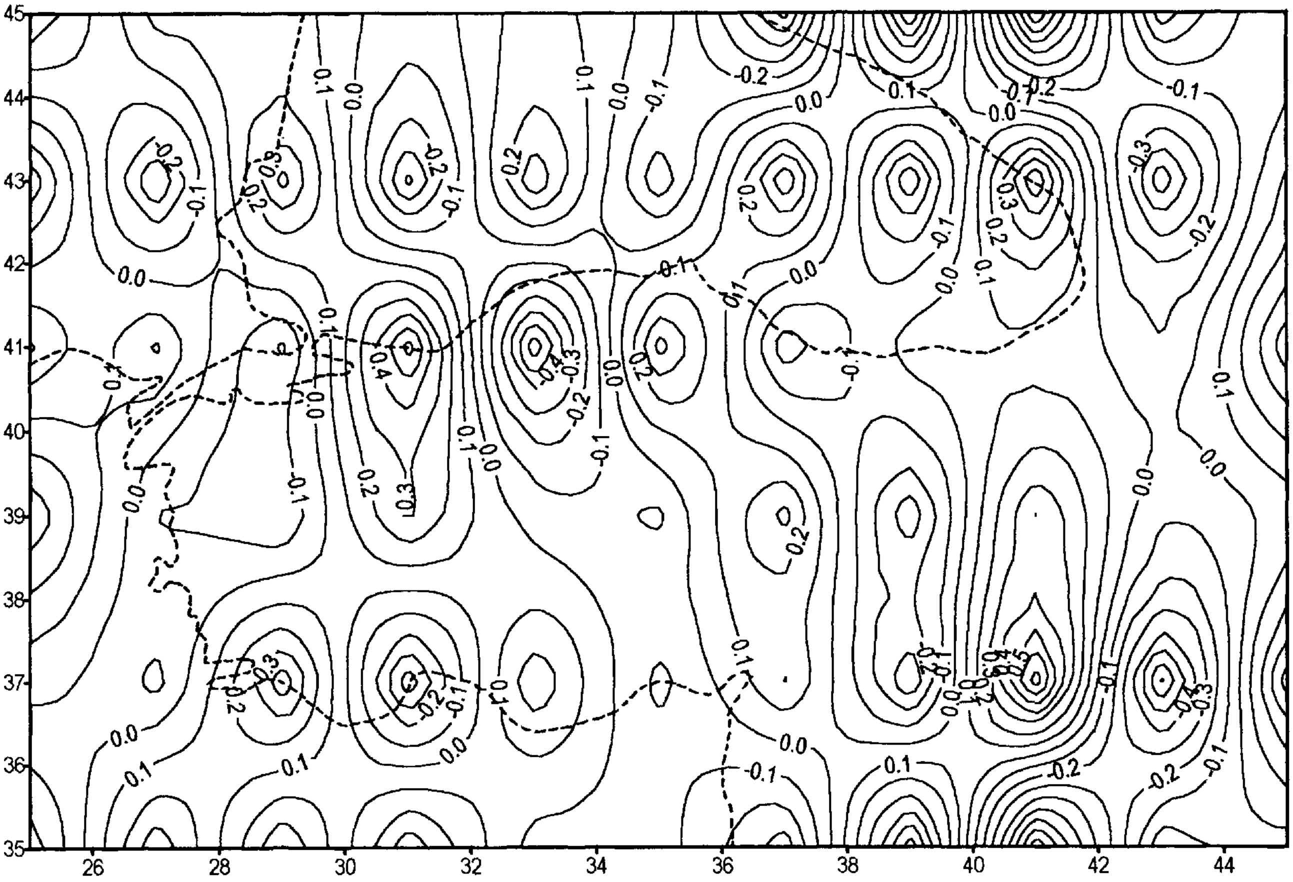

FIG. 3. Magnetisation distribution obtained from the inversion of vertical component Magsat anomaly map (crust thickness: 20 km). Contour interval: 0.1 A/m.

Satellite magnetometer observations permit the characterisation of magnetic signatures for lithospheric regions measured in hundred or even thousands of kilometres, which are less readily obtained from conventional aeromagnetic surveys. Magnetic anomalies are irregularly distributed over the region and it is difficult to recognise the dominant trends in the observed vertical magnetic anomaly map (Fig. 2). In most cases, anomalies may be correlated with basement highs, volcanic, or locally confined geological structures. Magsat magnetic anomalies are usually associated with the continental crust. Positive magnetic anomalies are observed along the Izmir-Ankara ophiolite zone, the North Aegean and massifs in western Turkey (Menderes, Gediz, Kazdag, Uludag). These anomalies can be related to intrusions of magmatic and granitic masses. Negative magnetic anomalies over the east Black Sea result from a thick pile of sedimentary rocks and also semi-oceanic crust. Positive magnetic anomalies are observed over the North Anatolian Fault Zone and along the Black Sea coast of Turkey. Those anomalies are related to granite intrusion and volcanic rocks.

The other positive anomalies that observed in eastern Turkey might be related to thick crust (with intensive magmatic and volcanic activity) as a result of collision between Anatolia and Arabia. The Taurus belt and Turkey-Syria border areas show negative anomalies. A negative anomaly in the Taurus belt might be related to the topographic relief composed of non-magnetic limestone (Salk and Ergun, 1997).

CONCLUSION

A model of regional magnetisation distribution in the crust of Turkey has been derived by the inversion of the magnetic anomaly field measured at altitudes from 350 to 550 km. Wasilewski et al. (1979) argue that the upper mantle is relatively non-magnetic, and consequently the sources of long-wavelength magnetic anomalies measured by a satellite must overly the seismic Moho. If this argument is correct, then the apparent magnetisation variations arise from gross lateral magnetisation variations within the crust, or from variations in the depth of Curie isotherm, or from the combination of both facts. In principle, the models

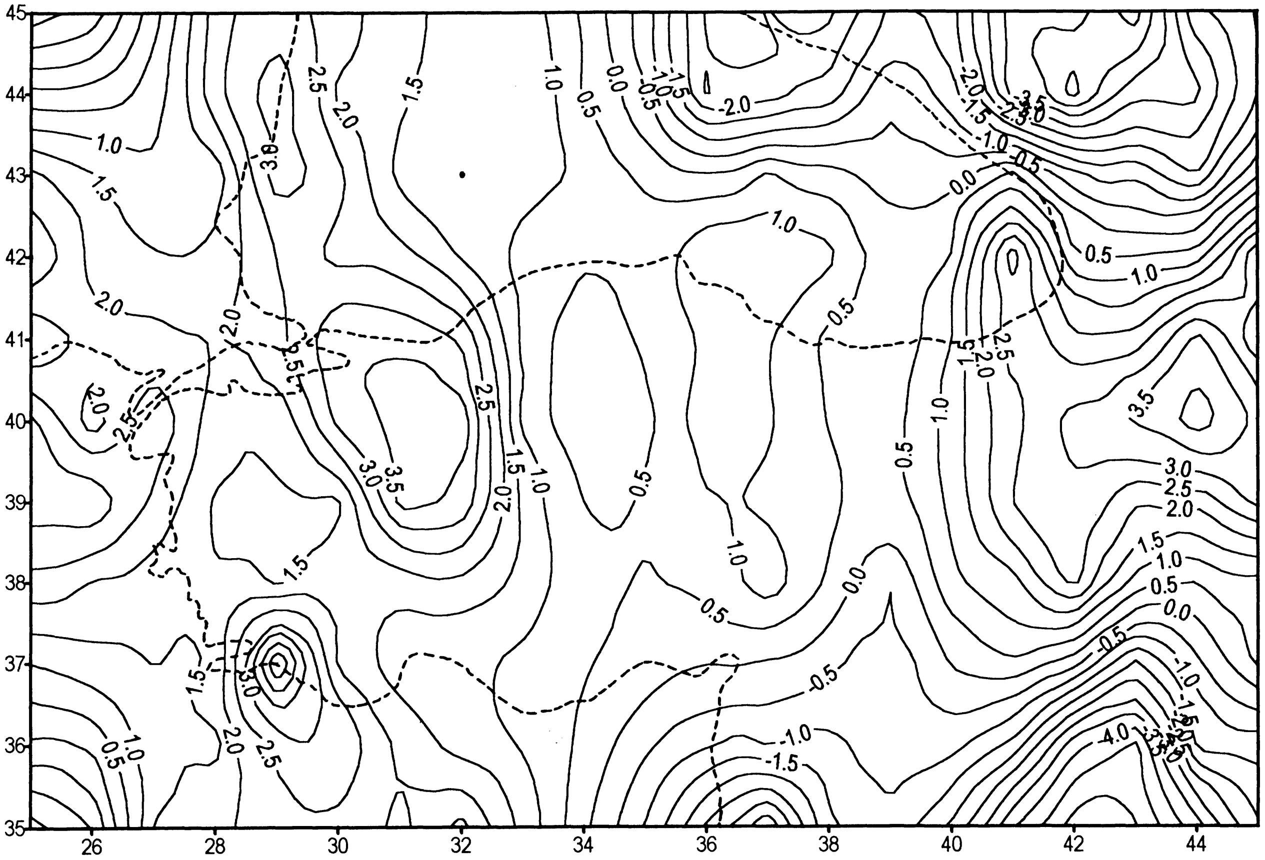

FIG. 4. Computed vertical component anomaly map associated with magnetisation distribution shown in Fig. 3 . Contour interval: 0.5 nT.

are not limited in depth by Moho or Curie isotherm whichever is the shallower for magnetite, but account for general lithospheric magnetism. Magnetisation anomalies were calculated for a crustal thickness of 20 km (Fig. 3). Figure 4 shows the vertical component anomalies computed from the calculated magnetisation model.

The magnetisation variations in the lithosphere are primarily controlled by lateral variations of the thermal thickness of the lithosphere. The low amplitude anomalies may correspond to a relatively shallow Curie isotherm that reflects high rate of heat flow. The most of the lithospheric magnetisation appears to be concentrated in the lower crust and probably in the upper mantle.

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