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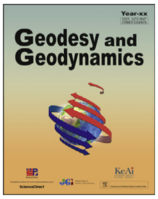

An analysis of the characteristics of crustal magnetic anomaly in China based on CHAMP satellite data

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ABSTRACT

Based on the observation data of CHAMP satellite from 2006 to 2009, a 2D crustal magnetic anomaly model in China is established to study the distribution characteristics of crustal magnetic anomaly. In this paper, the 2D anomaly model is derived from the Legendre polynomial expansion of harmonic term $N = 6 - 50$. The result shows that many elaborate structures reflected in magnetic anomaly map well correspond to the geologic structures in China and its adjacent area. The magnetic anomaly at low satellite height behaves complexly, which is mainly caused by the magnetic disturbance of shallow rocks. In contrast, the magnetic field isolines at high satellite height are relatively sparse and only magnetic anomalies of deep crust are reflected. This fact implies that the 2D model of crustal magnetic anomaly provides an important method of the space prolongation of geomagnetic field, and is of theoretical and practice importance in geologic structure analysis and geophysical prospecting.

1. Introduction

Crustal magnetic field, or lithospheric magnetic field, is an important component of geomagnetic field. Generally, the crustal magnetic field is extremely stable, which can be scaled through geological ages. However, local crustal magnetic field may possibly change rapidly during drastic geological events (volcanism, seismogenic period, etc.) [1].

Geological structure is closely related with crustal magnetic anomaly, which suggests that plate structure, thickness of sedimentary rock, volcanism and earthquake may be studied by the analysis of magnetic anomaly. Meanwhile, measurement and modeling of magnetic anomaly are important mineral prospecting methods due to the significant difference between magnetic mineral enrichment regions and their vicinities. Thus, the establishment of crustal magnetic anomaly model is of great theoretical significance and application value [2–4].

The model of crustal magnetic anomaly based on satellite data has advantages of wide coverage and high resolution. Up to now, many domestic and abroad researches have proposed different kinds of crustal anomaly models derived from satellite data [5]. Initially, spherical harmonic analysis of harmonic term $N = 13 - 29$ was applied to plot global distribution of scalar and vector geomagnetic anomalies from MAGSAT satellite data [6]. Later on, observation data of CHAMP satellite were also used to describe global geomagnetic anomaly. The MF model series, which are derived by removing all known contributions of magnetic field (e.g. the core and the magnetosphere) except for the crustal field, are the most widely used global crustal magnetic field models [7,8]. Several other models, including the GRIMM models [9], the BGS model series [10], the CHAOS model series [11], the high resolution model LCS-1 [12], have been proposed based on the observation data of MAGSAT, CHAMP, Swarm and other geomagnetic satellites.

In China, An et al. [13] used spherical cap harmonic analysis method to study magnetic anomaly in China and its adjacent area. More approaches, such as rectangular harmonic analysis and equivalent dipole-moment method, have been presented on the basis of MAGSAT satellite data [14,15]. Recently, using POGO and MAGSAT satellite, the geomagnetic anomaly in China was analyzed [2,16].

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However, previous 3D models of crustal magnetic anomaly have the features of higher minimum wavelengths (larger than 1000 km) and lower truncation levels (no more than 20th order), which makes them relatively rough and difficult to be refined. As the truncation level of 3D models is hard to be improved further, these models are only restricted to the description of large-scale crustal magnetic anomaly.

In elaborating structures of the distribution of geomagnetic anomaly, 2D polynomial model has its own advantages over 3D model in building local anomaly models. Based on this consideration, the paper establishes a 2D crustal anomaly model on the basis of CHAMP satellite observation data and Legendre polynomial expansion method, which provides analytical basis for small-scale magnetic anomaly in China and its adjacent area. On the other hand, the comparison among models in different years and at different altitudes reveals the relationship between geological structures and geophysical parameters.

2. A brief introduction to CHAMP satellite and data selection

CHAMP satellite was launched by Germany in July 2000. The satellite had a relatively low, near-circular and near-polar orbit, which enables the observation of crustal magnetic field of the whole earth. High-performance fluxgate magnetometer, starlight camera and Overhauser proton magnetometer were installed on the satellite for measuring magnetic field.

The magnetometer can measure three-component magnetic fields with linear deviation of ±10 pT and average noise level of 50 pT (RMS). In calibrated operation mode, this instrument supplied data with 150 m spatial resolution under the sampling of 50 pT (RMS). While the Overhauser magnetometer is used to measure the scalar amplitude of magnetic field at the frequency of 1 Hz. The non-directional error is lower than 0.2 nT and the resolution is 10 pT. The Overhauser magnetometer overcome omnidirectional fields, and avoided blind area problems commonly encountered by conventional devices. Therefore, the CHAMP satellite was able to obtain high-quality magnetic data.

Our study is based on magnetic measurement data acquired by CHAMP satellite from 2006 to 2009. In order to avoid S_q current and disturbances, the data of geomagnetic total field during China local time $21:00-5:00$ and $K_p < 2.0$ are chosen. Advantageously, data in range from 2 km to 2.5 km at four distinct altitudes of 319.0 km, 330.2 km, 344.0 km and 358.8 km are extracted, covering the whole China uniformly.

3. Methodology

When solving Laplace equation in spherical coordinates, Legendre polynomials are obtained via variable separation method. As an important property of Legendre polynomials, the polynomials are orthogonal in the interval [-1,1]

$$\int_{-1}^{1} P_m(x)P_n(x)dx = \frac{2}{2n+1}\delta_{mn} \tag{1}$$

where δ_{mn} denotes the Kronecker delta, $\delta_{mn} = 1$ if $m = n$ and $\delta_{mn} = 0$ otherwise.

The determination of polynomial coefficients with measurements of magnetic field is a multivariate regression problem, where regression coefficients must be recalculated after culling any variables due to the coherence of coefficients. However, the orthogonality of Legendre polynomials ensures the independence among regression coefficients, which helps transform the coefficient matrix into a diagonal matrix and greatly reduces the calculation load. Based on this property, optimal parametric solution is obtained by normalizing all coordinates of observation points to the interval $[-1, 1]$ and then solving the coefficient matrix with least-square method.

3.1. Selection of geomagnetic background field

The first 10-order model of International Geomagnetic Reference Field (IGRF) is chosen as the background field, and the anomaly value at each observation points is defined by the difference between the observation value and the IGRF referential value.

In order to effectively extract crustal magnetic field, it is necessary to remove the low-order Legendre model built on the basis of abnormal values of various geomagnetic observation points. The Legendre polynomials of harmonic term $N = 6-50$ are used to stand for the crustal magnetic anomaly.

3.2. Establishment of geomagnetic anomaly model

The general geomagnetic field T can be expanded in terms of Legendre polynomials, and the fundamental equation of geomagnetic field is as follows:

$$T_i = \sum_{n=0}^{N}\sum_{k=0}^{n} a_{nk}P_k(\Delta\varphi_i)P_{n-k}(\Delta\lambda_i) \tag{2}$$

where T_i denotes the observation data, a_{nk} are unknown parameters, and n is the truncation order of Legendre polynomials. Since the Legendre polynomials only present orthogonality in the range of $[-1, 1]$, latitude and longitude are normalized to $\Delta\varphi_i$ and $\Delta\lambda_i$ respectively.

$$\Delta\varphi_i = \frac{\left[\varphi_i - \frac{1}{2}(\varphi_{\max} + \varphi_{\min})\right]}{\left[\frac{1}{2}(\varphi_{\max} - \varphi_{\min})\right]} \tag{3.1}$$

$$\Delta\lambda_i = \frac{\left[\lambda_i - \frac{1}{2}(\lambda_{\max} + \lambda_{\min})\right]}{\left[\frac{1}{2}(\lambda_{\max} - \lambda_{\min})\right]} \tag{3.2}$$

where $\varphi_{\max}$ and $\varphi_{\min}$ represent the maximum and the minimum value of latitude. And $\lambda_{\max}$ and $\lambda_{\min}$ represent the maximum and the minimum value of longitude.

Then, a series of observation data are input as initial values of the equations and $P_k(\Delta\varphi_i)$ or $P_{n-k}(\Delta\lambda_i)$ can be calculated beforehand, so these equations reduce to a simple form:

$$T = BX \tag{4}$$

where $T = [T_1, \cdots, T_i]^{\mathrm{T}}$ is the sequence of observations, $X = [a_{00}, a_{01}, \cdots, a_{N0}]^T$ is the vector of unknowns, and B denotes the Legendre coefficient matrix which has the form:

$$B = \begin{bmatrix} P_0(\Delta\varphi_1)P_0(\Delta\lambda_1) & P_0(\Delta\varphi_1)P_1(\Delta\lambda_1) & \cdots & P_N(\Delta\varphi_1)P_0(\Delta\lambda_1) \\ \vdots & & \ddots & \vdots \\ P_0(\Delta\varphi_i)P_0(\Delta\lambda_i) & P_0(\Delta\varphi_i)P_1(\Delta\lambda_i) & \cdots & P_N(\Delta\varphi_i)P_0(\Delta\lambda_i) \end{bmatrix} \tag{5}$$

Thus, the least squares solution of equation (4) is as follows:

$$X = \left(B^{\mathrm{T}}B\right)^{-1}B^{\mathrm{T}}T \tag{6}$$

Finally, we obtain the distribution map of China crustal magnetic anomaly at different satellite altitudes.