

Lithospheric magnetic variations on the Tibetan Plateau based on a 3D surface spline model, compared with strong earthquake occurrences

PengTao Zhang^{1,3}, Jun Yang^{1,2}, LiLi Feng^{3*}, Xia Li³, YuHong Zhao³, and YingFeng Ji^{1,2*}

¹State Key Laboratory of Tibetan Plateau Earth System, Environment and Resources (TPESER), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China;

²University of Chinese Academy of Sciences, Beijing 100049, China;

³Qinghai Earthquake Agency, Xining 810001, China

Key Points:

- The resolution of lithospheric magnetic field models over the Tibetan Plateau is greatly improved by incorporating data from more than 200 ground-based portable stations.
- Moderate to strong earthquakes ($M \geq 5$) occur predominantly in regions where the vertical component (Z) of the lithospheric magnetic field is negative, particularly within the range of -50 to 0 nT.
- The lithospheric magnetic field is a key indicator for revealing deep thermodynamic conditions and identifying seismic hazard zones.

Citation: Zhang, P. T., Yang, J., Feng, L. L., Li, X., Zhao, Y. H., and Ji, Y. F. (2026). Lithospheric magnetic variations on the Tibetan Plateau based on a 3D surface spline model, compared with strong earthquake occurrences. *Earth Planet. Phys.*, 10(1), 30–43. <http://doi.org/10.26464/epp2026007>

Abstract: The National Geophysical Data Center (NGDC) of the United States has collected aeromagnetic data for input into a series of geomagnetic models to improve model resolution; however, in the Tibetan Plateau region, ground-based observations remain insufficient to clearly reflect the characteristics of the region's lithospheric magnetism. In this study, we evaluate the lithospheric magnetism of the Tibetan Plateau by using a 3D surface spline model based on observations from >200 newly constructed repeat stations (portable stations) to determine the spatial distribution of plateau geomagnetism, as well as its correlation with the tectonic features of the region. We analyze the relationships between $M \geq 5$ earthquakes and lithospheric magnetic field variations on the Tibetan Plateau and identify regions susceptible to strong earthquakes. We compare the geomagnetic results with those from an enhanced magnetic model (EMM2015) developed by the NGDC and provide insights into improving lithospheric magnetic field calculations in the Tibetan Plateau region. Further research reveals that these magnetic anomalies exhibit distinct differences from the magnetic–seismic correlation mechanisms observed in other tectonic settings; here, they are governed primarily by the combined effects of compressional magnetism, thermal magnetism, and deep thermal stress. This study provides new evidence of geomagnetic anomalies on the Tibetan Plateau, interprets them physically, and demonstrates their potential for identifying seismic hazard zones on the Plateau.

Keywords: Tibetan Plateau; magnetic variation; seismicity; surface spline model; enhanced magnetic model

1. Introduction

The magnetic field is composed of a lithospheric magnetic field and an external magnetic field. Lithospheric magnetism is generated primarily by magnetic minerals (e.g., FeO, Fe₂O₃, and TiO₂) in the crust below the Curie point temperature (approximately 200–700 °C) (e.g., Purucker and Whaler, 2015). Owing to the magnetic properties of rocks and their evolutionary differences, the lithospheric magnetic field may provide information about

the composition of the crust and surface topography and has been widely used in related studies (e.g., Hsu et al., 1996; Abramova et al., 2020; Erbek, 2021). For example, a study in the Sichuan–Yunnan region proposed that the landmass boundary corresponds well with the lithospheric magnetic field, which is usually manifested as a zero-value line or a low-value region (Feng LL et al., 2017), and a similar phenomenon has been confirmed in other fracture tectonic settings (e.g., Su SP et al., 2017; Erbek, 2021; Liang X et al., 2024). The piezomagnetic effect serves as a vital mechanism for understanding the relationship between stress and magnetic fields. Laboratory studies have indicated that rock magnetization under uniaxial stress is inversely related to stress: magnetization is enhanced by stress release and decreased by stress accumulation (Hao GQ et al., 1982; Yang T et al., 2020).

First author: P. T. Zhang, 451334165@qq.com

Correspondence to: L. L. Feng, ynufl@sina.com

Y. F. Ji, yingfengji@itpcas.ac.cn

Received 11 JUL 2025; Accepted 11 SEP 2025.

First Published online 17 OCT 2025.

©2025 by Earth and Planetary Physics.

Multiple earthquakes in Tibetan Plateau fault zones (e.g., the Lenglongling Fault) and other fault zones exhibit similar magnetic response characteristics (e.g., Feng XX and Li X, 2016; Zhang HY et al., 2022; Wang CJ et al., 2024). In addition to the piezomagnetic effect, the magnetocaloric effect may play an important role. The thermal transition from ferromagnetism to paramagnetism is represented by the Curie isotherm (Langel and Hinze, 1998; Rajaram et al., 2009). Variations in the Curie isotherm reflect changes in deep thermal structure, and its burial depth is closely correlated with the values of the surface geothermal gradient (Maule et al., 2005).

Most findings indicate that the horizontal and vertical vectors of the lithospheric magnetic field differ significantly near fracture zones (e.g., Yang XH et al., 2020; Yang L et al., 2024; Gao GM et al., 2025). The lithospheric magnetic results for different landform types also differ significantly. For instance, according to aeromagnetic data (Ou JM et al., 2013; Lei Y et al., 2018; Gao GM et al., 2018; Jiang Y et al., 2021), the Tibetan Plateau overthrust corresponds to a magnetically negative anomaly, whereas the Sichuan Basin corresponds to a positive anomaly. The variability in the lithospheric magnetic field in North China is associated with significant magnetic anomalies in the Yanshan block, in contrast to the balanced distribution in the North China block (e.g., Su SP et al., 2017).

Von Frese et al. (2008) combined satellite magnetic anomalies with gravity field data and reported that transverse magnetic anomalies (TMAs) in the U.S. are correlated with crustal thickness variations and that the eastern part of the U.S. TMAs is influenced by Precambrian Rift Mg–Fe rocks, whereas the western part exhibits a weakened anomaly due to Rio Grande Rift heat flow. In summary, the lithospheric magnetic field provides key geophysical evidence for understanding crustal tectonic evolution and fracture systems through its anomalous distribution.

Earthquakes usually occur in tectonic zones characterized by changes in lithospheric magnetic anomalies (e.g., Feng LL, 2019; Song CK and Chen B, 2024). Wen LM et al. (2017) reported that geomagnetic anomalies are generated mainly by shallow-source magnetic bodies superimposed on a weak magnetic basement, and that the magnetic anomalies in regions where strong earthquakes occur are usually negative. That is, the epicenters of strong earthquakes are located mainly in weak negative anomaly zones of ΔZ (the vertical component) of the lithospheric magnetic field and near the zero-value line, while strong earthquakes seldom occur in large-scale positive or negative anomaly zones (e.g., Wang QH et al., 2017). However, the types and distributions of magnetic minerals within the crust vary across regions, leading to heterogeneity in the lithospheric magnetic field and in the characteristics of strong earthquakes. Zu Q et al. (2021) investigated the distributions of magnetic minerals within the crust in Taiwan and their relationships with the locations of earthquakes. They suggested that the types and distributions of magnetic minerals in the crust differ across regions, which affects the occurrence of strong earthquakes, and further proposed that when the subsurface temperature is less than approximately 450 °C, areas with low levels of magnetization (where rocks tend to be brittle) are most

prone to earthquakes.

In addition, the observational methods and data processing techniques used in different studies affect the results. For example, station measurements capture detailed magnetic anomalies but are susceptible to shallow disturbances, whereas satellite data (e.g., CHAMP and Swarm) provide global coverage and uniform accuracy, suppressing shallow noise and reflecting deep tectonic features (e.g., crustal magnetism) but with lower resolution (especially for short-wavelength anomalies) (Du JS and Chen C, 2015; Lei Y et al., 2018). Notably, drastic localized changes in the lithosphere, such as volcanic eruptions or earthquakes, can cause rapid changes in the regional lithospheric magnetic field. Therefore, geomagnetists study seismomagnetic relationships by monitoring changes in the regional magnetic field and selecting reasonable models that can aid in understanding the physical processes in the crust that correlate with earthquake events (Yang T et al., 2011; Zhang L et al., 2018).

The Tibetan Plateau is one of the most seismically active areas in China and has experienced multiple strong $M > 7$ earthquakes over the past 10 years, but the unique geographic and climatic conditions of the Tibetan Plateau make it very difficult to conduct field surveys. In recent decades, geomagnetic data have been obtained via satellites, continuously operating observatories, and portable observation stations. Kang GF et al. (2012) reported that the positive and negative magnetic anomalies within the Tibetan Plateau are generally weak and that the boundaries of the anomalies are highly consistent with tectonic boundaries. Feng Y et al. (2023) combined ground, airborne, and CHAMP satellite data to construct a three-dimensional (3D) surface spline model and a regional spherical harmonic analysis (RSHA) model of the Tibetan Plateau; they reported that the Plateau's distribution of magnetic anomalies is consistent with its topography. To reflect lithospheric magnetic variations on the Tibetan Plateau in a more detailed way, Jiang Y et al. (2021) constructed a CLAS model and similarly reported that the distribution of its magnetic anomalies is consistent with the topographic relief of the Plateau. They also reported that the distribution of magnetic anomaly boundaries coincides with the major fracture zones (e.g., the Arjin fracture). Gu CL et al. (2010) focused on the Wenchuan earthquake and reported that the total intensity of the lithospheric magnetic field within 100 km of the epicenter was significantly strengthened by negative anomalies and that the magnetic declinations and inclinations were consistent with the directions of the fault zones. The zero-value lines of magnetic declination and inclination also compare well with the direction of the rupture zone. The National Geophysical Data Center (NGDC) of the United States added aeromagnetic data to a series of geomagnetic models to improve the resolution (<https://www.ngdc.noaa.gov/geomag/EMM/index.html>), but in the Tibetan Plateau region, ground-based observation data were missing; thus, the NDGG models do not reflect the characteristics of lithospheric magnetism in the whole region. For these reasons, few previous studies have focused on detailed relationships between strong earthquakes and lithospheric magnetic field anomalies on the Tibetan Plateau (e.g., Luo Y, 2013).

In this study, we use magnetic vector field data collected since 2008 from 209 repeat stations deployed by the China Earthquake

Administration (CEA) on the Tibetan Plateau, together with the China Geomagnetic Reference Field (CGRF), to construct a geomagnetic model for the Tibetan Plateau region. We investigate the relationship between lithospheric magnetic anomalies and tectonics, and we analyze the spatial distribution of the lithospheric magnetic field in the region to refine its characteristics around $M > 5$ earthquake epicenters and examine the corresponding relationship with the occurrence of strong earthquakes.

2. Data and Methods

2.1 Data Acquisition

Since 2008, the China Earthquake Administration has carried out ground-based magnetic field vector measurement surveys nationwide every year. Between 2008 and 2018, 1371 repeat stations, which are portable observation stations that conduct periodic, repetitive observations at the same location, were established to measure the magnetic vector field. They essentially cover the Chinese mainland except for some uninhabited areas, and 209 of these stations are located on the Tibetan Plateau. The geomagnetic model used in this study, which is based on these data, was established in combination with the China Geomagnetic Reference Field, a geomagnetic model for the Chinese region (e.g., [Chen B et al., 2016](#)). The distribution of repeat geomagnetic stations on the Tibetan Plateau and in the surrounding areas is shown in [Figure 1](#). In addition, there are seven geomagnetic reference observatories (permanent observatories) on the Tibetan Plateau and in neighboring regions, located in Lhasa, Lanzhou, Golmud, Jiayuguan, Kashi, Chengdu, and Kunming; continuous observational data from these geomagnetic reference observatories are used to process the repeat station observations.

The ground magnetic field observation data include the total geomagnetic field strength (F) and magnetic declination (D) and

inclination (I) collected by repeat observation stations on the Tibetan Plateau and its surrounding areas. However, the distribution density of the stations varies greatly. In the eastern part of the Plateau, the average distance between neighboring stations is approximately 70 km; in the southern part, the distance is 100 km; in the northwestern part of the Plateau is a large gap area with no monitoring. The lack of ground-based magnetic measurement data in this NW region imposes a significant limit on the reliability of our data and on the spatial resolution of the modeled lithospheric magnetic calculations presented below in this study.

To collect data measuring the three independent components of the geomagnetic field across the study area, we used two sets of GSM-19T proton progression magnetometers (PPMs) with a sensitivity of 0.15 nT at 1 Hz, a resolution of 0.01 nT, and an absolute accuracy of ± 0.15 nT; two sets of global positioning system (GPS) receivers; and a set of fluxgate longitude and latitude instruments with an accuracy of 0.2 arcmin.

Each repeat observation station consists of a primary sensor point (point A) and an auxiliary sensor point (point B); the distance between these two measurement points is not less than 20 meters. To meet the requirements for repeated measurements, the horizontal gradient in the area around each station must be less than 3 nT/m, and there must be no anthropogenic electromagnetic interference (e.g., [Wang ZD et al., 2018](#)).

To ensure the stability and reliability of the instruments, each proton feed magnetometer was calibrated before each measurement using the exchange synchronization measurement method, and the total difference in the geomagnetic field between points A and B was obtained ([Gu ZW et al., 2006](#)). When the preparations were completed, the measurement started. A nonmagnetic warp

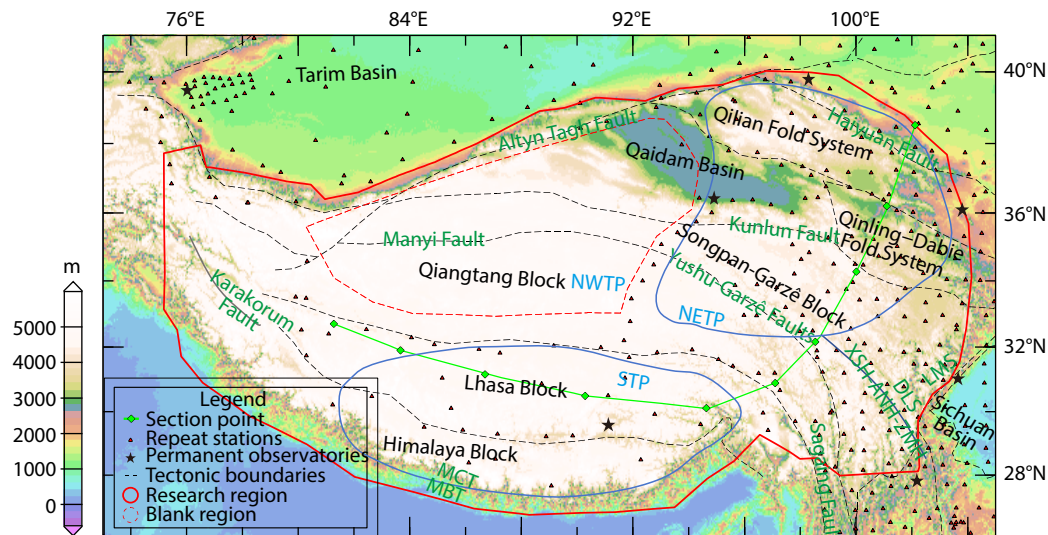


Figure 1. Distribution of ground magnetic field observations on the Tibetan Plateau. The solid red line delimits the study area of the Tibetan Plateau. The dashed black lines indicate the known suture zones. The dashed red line surrounds the depopulated zone of the northwestern Tibetan Plateau, an area with a large monitoring gap. The solid green line represents the profile consisting of ten selected points, which is used to compare the results from our model to the EMM (<https://geomag.org/models/>) in an area with good repeat station (portable station) coverage. NETP: northeastern Tibetan Plateau; STP: southern Tibetan Plateau; NWTP: northwestern Tibetan Plateau; DLS: Daliangshan Fault; LMS: Longmenshan Fault; XSH-ANH-ZMH: Xianshuihe-Anninghe-Zemuhe Fault; MBT: Main Boundary Thrust Fault; MCT: Main Central Thrust Fault.

beam was installed at point A for magnetic declination (D) and inclination (I) measurements, and a proton spinning magnetometer (PPM) was installed at point B for total geomagnetic field measurements. Six sets of vector data were observed at each station, each set containing 4 D/I pairs and 10 F measurements, and each set of measurements took 8–10 minutes.

2.2 Data Processing

To obtain the lithospheric magnetic field, geomagnetic observations must be corrected for daily variations to eliminate exogenous perturbations. The daily variation correction is usually based on the continued observation data of the geomagnetic station; the field measurement data (F , D , and I) of the geomagnetic field at the measurement points in the Tibetan Plateau region are corrected for the daily variation in fluxes to minimize as much as possible the influence of exogenous geomagnetic variations. According to the observation time, a certain magnetostatic day during the observation period is selected as the flux correction day: the 2021 measurements are corrected to relative values by reference to the data from July 4, 2021; the 2022 measurements are corrected with reference to data from July 25, 2022. The following methods of daily variation correction (Chen B et al., 2017) were used:

$$\begin{aligned} F_{\text{site_int_}T_i} &= F_{\text{site_mea_}T_i} - F_{\text{site_ext_}T_i} \\ &= F_{\text{site_mea_}T_i} - F_{\text{obs_ext_}T_i} \\ &= F_{\text{site_mea_}T_i} - (F_{\text{obs_mea_}T_i} - F_{\text{obs_int_}T_i}) \\ &= F_{\text{site_mea_}T_i} - (F_{\text{obs_mea_}T_i} - F_{\text{obs_int_}T_0}) \\ &= F_{\text{site_mea_}T_i} - (F_{\text{obs_mea_}T_i} - F_{\text{obs_mea_}T_0}), \end{aligned} \quad (1)$$

where $F_{\text{site_int_}T_i}$ is the result of the daily variation flux of a geomagnetic element observed at time T_i ; $F_{\text{site_mea_}T_i}$ is the measured value of the geomagnetic element at time T_i ; $F_{\text{site_ext_}T_i}$ is the part of the exogenous field in the measured value of the geomagnetic element at time T_i ; $F_{\text{obs_ext_}T_i}$ is the part of the exogenous field in the value of the geomagnetic element measured at time T_i at the geomagnetic station closest to the measurement position; $F_{\text{obs_mea_}T_i}$ is the value of the geomagnetic element measured at time T_i at the geomagnetic station closest to the measurement position; and $F_{\text{obs_int_}T_i}$ is the part of the exogenous field in the value of the geomagnetic element measured at time T_i at the geomagnetic station closest to the measurement position. $F_{\text{obs_int_}T_0}$ is the endogenous field part of the value of the geomagnetic element measured at 00:00–03:00 on the day in which the daily variation occurs at the station nearest to the measurement location; $F_{\text{obs_mea_}T_0}$ is the value of the geomagnetic element measured at 00:00–03:00 local time on the day in which the daily variation in the geomagnetic element occurs at the station nearest to the measurement location.

The daily variation data are corrected to January 1, 2020, thus eliminating the endogenous field discrepancies in the observations of different years. Long-term variation correction is performed using the natural orthogonal component (NOC) model of the Chinese mainland, a modeling method that calculates the natural orthogonal component of the geomagnetic field in China from January 1, 1995, to the present, using geomagnetic data from 31 permanent observatories in China.

Before modeling, the observed data need to be processed. First, the measured data are checked for obvious errors, and the intra-group averages of the six sets of data are calculated to obtain the final values of the repeat stations. To better represent the distribution of the geomagnetic field, measurement points with large geomagnetic anomalies must be deleted (An, 1993). The selected deletion criteria are as follows:

$$\Delta X = X_{\text{ob}} - X_{\text{IGRF}} \geq 500 \text{ nT}, \quad (2)$$

$$\text{or} \quad \Delta Y = Y_{\text{ob}} - Y_{\text{IGRF}} \geq 500 \text{ nT}, \quad (3)$$

$$\text{or} \quad \Delta Z = Z_{\text{ob}} - Z_{\text{IGRF}} \geq 500 \text{ nT}, \quad (4)$$

where X_{ob} , Y_{ob} , and Z_{ob} represent the endogenous field values normalized to January 1, 2020; and X_{IGRF} , Y_{IGRF} , and Z_{IGRF} represent the theoretical values of the measurement points on January 1, 2020, which are calculated according to IGRF14. ΔX , ΔY , and ΔZ denote magnetic anomalies (or residual magnetic field values). A total of nine geomagnetic measurement points were deleted according to this criterion.

2.3 Lithospheric Magnetic Calculations and Endogenous Field Modeling

A surface spline function was used to fit the geomagnetic field. Harder and Desmarais (1972) first applied this method to interpolate discrete surface data. In this method, a continuous gradient surface is used to accurately reflect the observations at the measurement point. Compared with other interpolation methods (e.g., kriging, the equivalent-source method, the radial basis function, and the minimum-curvature algorithm), the surface spline function enables the effective simulation of regional three-dimensional models. It can elaborate the attenuation variation of small-scale magnetic fields in the radial direction, captures more detailed information on small-scale magnetic anomalies, and is more suitable for processing observation data (Feng Y et al., 2013; Tang Y and Feng Y, 2023). Moreover, compared with other interpolation methods that rely on scale parameters or specific models (e.g., the equivalent source method depends on the “scaling constant” and kriging relies on a variogram), the surface spline function does not require selection of specific scale parameters through a trial-and-error process. This advantage allows it preserve data characteristics while avoiding fitting-deviations caused by parameter mismatching, thus reducing the probability of artifact generation (Billings et al., 2002). In summary, the spline function of the surface represents not only the distribution of the geomagnetic field over the surface but also the distribution of the horizontal gradient (north–south and east–west) of the geomagnetic field over the surface. The method can achieve stability and good convergence. The formula is as follows:

$$B(x, y) = a + bx + cy + \sum F_i r_i^2 \ln(r_i^2 + \epsilon), \quad (5)$$

$$\sum F_i = \sum F_i x_i = \sum F_i y_i = 0, \quad (6)$$

where x and y are the horizontal and vertical coordinates of the point to be fitted, respectively. x_i and y_i are the horizontal and vertical coordinates of the i -th original measurement point, respectively. $B(x, y)$ is the quantity of the x and y points to be solved, a_i and F_i are the fitting coefficients, N is the number of

original data points, $r_i = \sqrt{(x - x_i)^2 + (y - y_i)^2}$ is the distance from the point to the i -th repeat station, and ϵ is the curvature factor that controls the maximum difference between the fitted surface values and the original values. The northward component X , the eastward component Y , and the vertical component Z can be computed with the internal magnetic field data of the total intensity F , magnetic inclination I , and known magnetic declination D .

By subtracting the main magnetic field from the 3D surface spline (SP) model, the lithospheric magnetic field of the Tibetan Plateau and its surrounding areas can be obtained. The formula is as follows:

$$\Delta B = B_{SP} - B_{EMMmain} \quad (7)$$

where B denotes any component of the geomagnetic field, B_{SP} is the component after surface spline fitting, and $B_{EMMmain}$ is based on the Enhanced Magnetic Model 2015 (EMM2015) (<https://www.ncei.noaa.gov/products/enhanced>) for the main magnetic field. However, it is important to note that the absence of satellite/aerial data may affect the results. For example, the interpolation results for the northwestern Tibetan Plateau exhibit significant uncertainty. This further reduces the spatial resolution of the overall data—not only making accurate reconstruction of detailed features of regional magnetic anomalies difficult but also potentially generating nonphysical anomalous gradients at the edges of the data-blank region (approximately along the Altyn Tagh Fault, the central boundary of the Qaidam Basin, west of the Kunlun Fault, and the boundary between the Qiangtang and Lhasa blocks) (Gu ZL et al., 2025). Additionally, station observation data are constrained by the limited near-surface observation height, which prevents the complete preservation of magnetic field signals with wavelengths exceeding 150 km (Thébault et al., 2010).

2.4 Checking with a Checkerboard Test

We construct a checkerboard test using latitude and longitude ranges consistent with those of the study area, setting the grid resolution to $0.5^\circ \times 0.5^\circ$ —a spatial resolution comparable to that of the ground observation data. In the validation design, each $2^\circ \times 2^\circ$ grid cell was assigned either a positive value (50 nT) or a negative value (−50 nT), with positive and negative values alternating in adjacent regions. The set magnitude range corresponds to the actual intensity range of the lithospheric magnetic field model (Figure S1a). The final interpolated results were output at a grid resolution of $0.2^\circ \times 0.2^\circ$ (Figure S1b). The surface spline model interpolation calculations employed in this study demonstrate that the interpolated results effectively preserve the alternating positive–negative pattern of the original checkerboard data. Only in regions with abrupt gradient changes at positive–negative value boundaries does the interpolation smoothing effect create transition zones between −50 nT and 50 nT, a phenomenon consistent with the expected behavior of interpolation methods. These results demonstrate that the surface spline model established in this study objectively reflects the spatial variation trends of ground observation data without significantly affecting the resolution of the original data.

3. Results

3.1 Features of the Magnetic Field in the Lithosphere of the Tibetan Plateau

The X , Y , and Z anomalies of the lithospheric magnetic field in the Tibetan Plateau region were obtained by the abovementioned method (Figure 2). The distributions of the X , Y , and Z components have several common features, which essentially coincide with those of geological formations (Ou JM et al., 2013; Qiu YD et al., 2017). For convenience, we divide the Tibetan Plateau into three regions for in-depth analysis, namely, northeast, south, and northwest.

In the northeastern part, the components are weak and mostly negative (Figure 2). This region includes the entire Qilian fold system, the western part of the Qinling–Dabie fold system, the Qaidam Basin, the eastern part of the Songpan–Garzê block, and the Qiangtang block (Figure 1). As the edge of the Plateau, the Qilian fold belt shows a broad band of negative magnetic anomalies interspersed with areas of positive anomalies in the Z component. The northeastward thrusting of the Plateau led to stress release in the northern Lenglongling Fault and stress accumulation in the southern part, which triggered anomalies in the magnetospheric field (Liu YH et al., 2019). For the X component, the Qilian fold system and the Qaidam Basin appear to be connected by a broad negative anomaly belt that also extends in a north–south direction (Figure 2a). The Y and Z components of the Qaidam Basin are located in a positive anomaly zone (Figures 2b and 2c). The eastern part of the Songpan–Garzê block shows a large negative anomaly zone for the Z component. The eastern Qiangtang block as a whole shows weak positive or negative anomalies, and the boundary between this region and the Lhasa block clearly presents a positive–negative transition in the Z component.

In the southern part, the lithospheric magnetic field of the Lhasa block is complicated; the Z component is characterized mainly by negative anomalies in the western and eastern portions (except the central portion), and the Y component is characterized primarily by positive anomalies. The boundary between the Lhasa block and the Himalayas is most remarkable in the X component, which is coincident with the zero-value line. For the Himalayas, the Z component shows a broad negative anomaly zone, which is interpreted as deep material along the strike (Kang GF et al., 2012). The X and Y components show mainly positive anomalies.

For the northwestern Tibetan Plateau, the X and Y components exhibit mainly positive anomalies, whereas the Z component is almost entirely negative. Since there are few repeat observation stations on the northwestern Plateau, the lithospheric magnetic fields are obtained by interpolation from the observations of the surrounding stations; thus, the confidence of the results may be insufficient.

3.2 Relationships Between Lithospheric Magnetic Fields and Moderate to Strong Earthquakes

In this study, 1067 $M \geq 5$ earthquakes that have occurred on the Tibetan Plateau since 1900 were selected. Of these, 862 earthquakes were of the M_5 class (5.0–5.9), 199 earthquakes were of

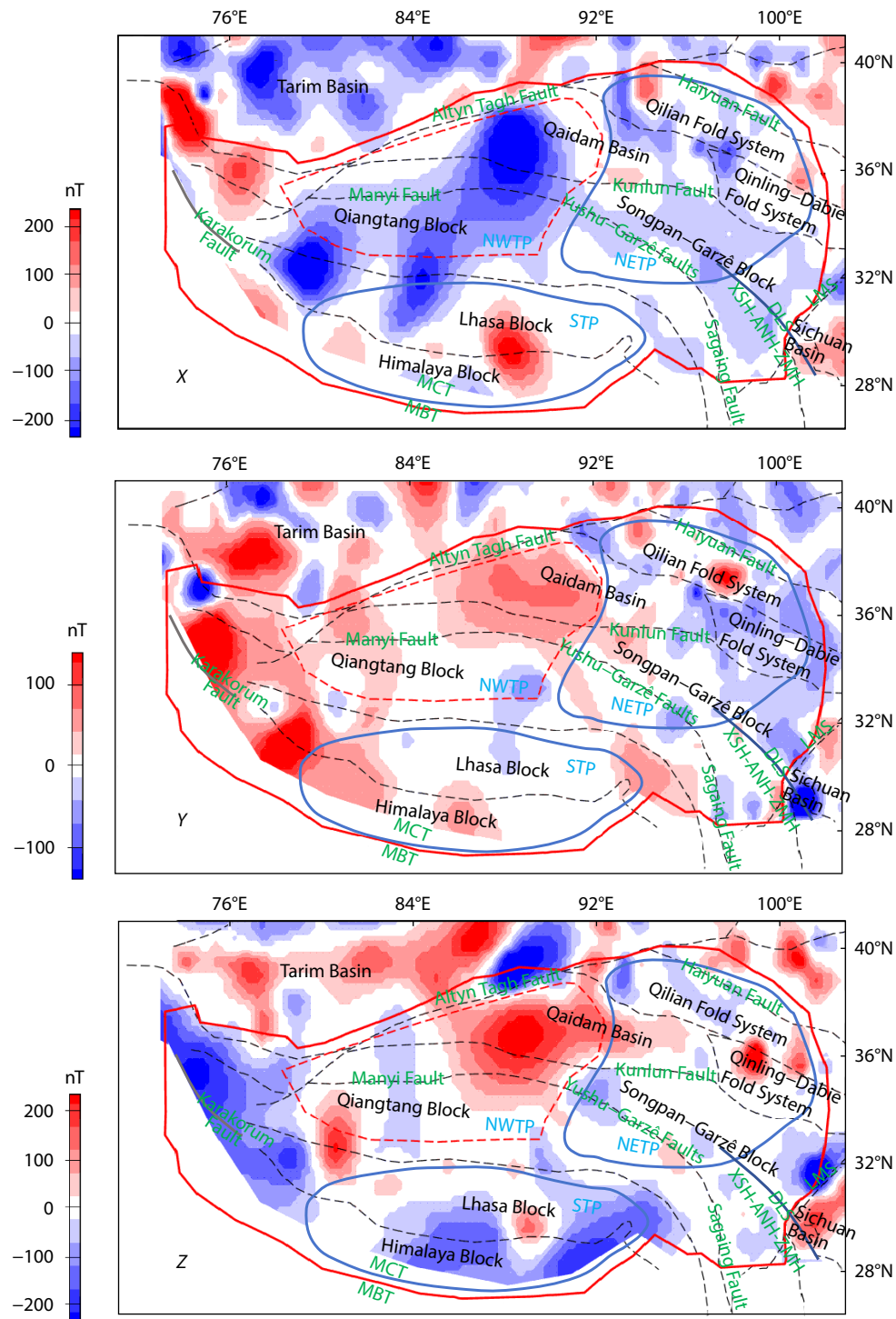


Figure 2. Spatial distribution of the lithospheric magnetic field on the Tibetan Plateau calculated in our study on the basis of magnetic vector data from repeat observation stations. The northward component (X), eastward component (Y), and vertical component (Z) of the lithospheric magnetic field are calculated using the surface spline model based on magnetic vector field data from the 209 repeat observation stations deployed by the China Earthquake Administration on the Tibetan Plateau since 2008. The dashed red line surrounds the depopulated zone of the northwestern Tibetan Plateau, which is a large monitoring gap. The solid red line indicates the study area on the Tibetan Plateau. The black dashed lines represent the major tectonic boundaries (suture zones) of the Tibetan Plateau. The color bars on the left indicate the numerical distribution values (nT) of the X, Y, and Z components. NETP: northeastern Tibetan Plateau; STP: southern Tibetan Plateau; NWTP: northwestern Tibetan Plateau; DLS: Daliangshan Fault; LMS: Longmenshan Fault; XSH-ANH-ZMH: Xianshuihe–Anninghe–Zemuhe Fault; MBT: Main Boundary Thrust Fault; MCT: Main Central Thrust Fault.

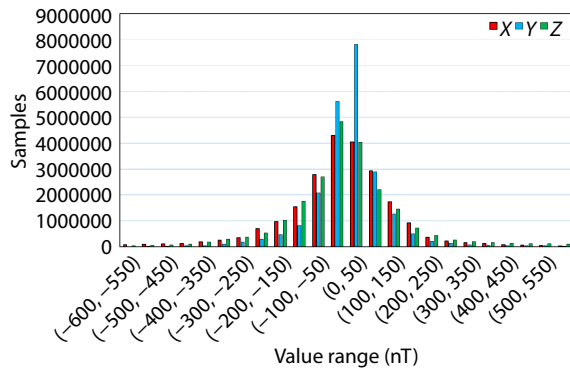


Figure 3. Statistical plot of the X , Y , and Z component intensities of the lithospheric magnetic field in the entire area of the Tibetan Plateau covered by this study; the study area was gridded using a standard $0.01^\circ \times 0.01^\circ$ mesh. Calculations of the magnetic vector field strength at each grid unit were made using a surface spline model based on data from the 209 repeat stations in the study area. Red, blue, and green histograms represent the northward component (X), eastward component (Y), and vertical component (Z), respectively, of the magnetic field.

the $M6$ class (6.0–6.9), 26 earthquakes were of the $M7$ class (7.0–7.9), and 6 were of the $M8$ class (8.0–8.9). We divided the three components of the lithospheric magnetic field within the Tibetan Plateau into $0.01^\circ \times 0.01^\circ$ grids and analyzed the X , Y , and Z values at each grid using steps of 50 nT (Figure 3). We chose steps of 50 nT because the magnitude of the lithospheric magnetic field associated with earthquakes is essentially a few tens of nT (Lei Y et al., 2018; Zhang HY, 2024). We assessed the intensity of the lithospheric magnetic field at the epicenters of the 1067 $M \geq 5$ earthquakes (Figure 4) and 231 $M \geq 6$ earthquakes (Figure 5). Note that we did not perform a statistical analysis of the $M \geq 7$ earthquakes in this study because of their small sample size ($n = 32$).

In terms of the distribution of the X component across the Plateau, the most prominent values are located in the intervals from -50 to 0 and 0 – 50 nT (Figure 3). The X component values at the epicenters of the $M \geq 5$ earthquakes are concentrated mainly in the range of -100 to 50 nT; the most concentrated interval is -50 to 0 nT, and the second-most concentrated interval is 0 – 50 nT (Figure 4). The features of the X component range at the epicenters of $M \geq 6$ earthquakes are highly similar to those of $M \geq 5$ earthquakes (Figure 5).

The most significant difference between the distribution of the X component at the epicenters of earthquakes, compared with its distribution over the whole Plateau, is in the 50 – 100 nT interval; the second-most significant differences are in intervals -50 to 0 and 0 – 50 . Note also that the number of earthquakes in intervals ≥ 50 nT is significantly smaller than that in intervals ≤ -50 nT (Figures 4 and 5). These results suggest that moderate to strong earthquakes are more likely to occur when the X component is negative, especially when its value is in the range of -50 to 0 nT.

The distribution of the Y component across the Tibetan Plateau is mainly in the range of -200 to 200 nT; values from -50 to 0 and

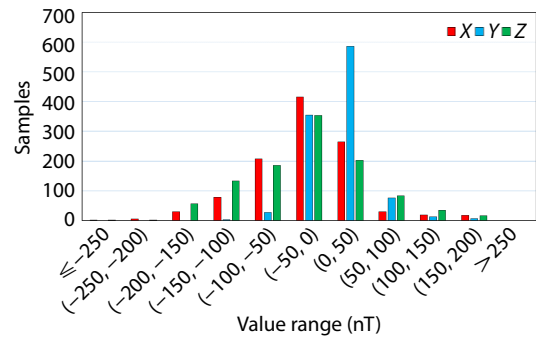


Figure 4. Statistical plot of the intensities of the X , Y , and Z components of the lithospheric magnetic field at the epicenters of $M \geq 5$ earthquakes on the Tibetan Plateau. The calculation uses a surface spline model based on magnetic vector field data from 209 repeat stations. Red, blue, and green histograms represent the numbers of northward component (X), eastward component (Y), and vertical component (Z) measurements, respectively, that fell within each intensity interval. The intensity intervals are 50 nT from -250 nT to > 250 nT.

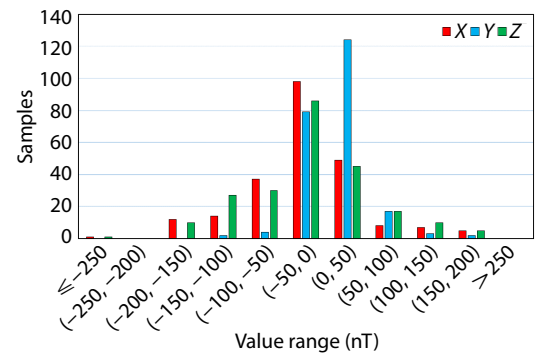


Figure 5. Statistical plot of the intensities of the X , Y , and Z components of the lithospheric magnetic field at the epicenters of $M \geq 6$ earthquakes on the Tibetan Plateau. The calculation uses a surface spline model based on magnetic vector field data from 209 repeat stations. Red, blue, and green histograms represent the numbers of northward component (X), eastward component (Y), and vertical component (Z) measurements, respectively, that fell within each intensity interval. The intensity intervals are 50 nT from -250 nT to > 250 nT.

0 – 50 nT are the most prominent (Figure 3). Y component values at the epicenters of $M \geq 5$ and $M \geq 6$ earthquakes exhibit the same characteristics (Figures 4–5).

The generation mechanisms of the Z component appear to differ from those of the horizontal (X and Y) components. The Z component is influenced primarily by deep crustal magnetic materials, particularly those closely related to the distribution of the Curie isotherm, whereas the horizontal components are influenced significantly by surface geological conditions and topography (Jiao LG et al., 2013), particularly by surface and shallow magnetic materials. The spatial distribution of the Z component typically exhibits a gradient, varying from high to low values, while the horizontal components display complex variations in both direc-

tion and intensity. Physically, Z component values primarily correlate with the vertical distribution and variations of subsurface magnetic materials, whereas horizontal component values mainly reflect the horizontal extension of and variations within these magnetic materials (Okubo et al., 2011; Jiao LG et al., 2013). The distribution of the Z component across the Tibetan Plateau is concentrated in the range of -350 to 350 nT, with -50 to 0 nT and 0 – 50 nT being the most prominent intervals (Figure 3). The strong earthquakes studied here were more likely to have occurred in areas where the Z component was negative (from -50 to 0 nT) than in areas where the Z component was positive (0 – 50 nT).

The mean values of the X , Y , and Z components at the epicenters of all earthquakes with strengths greater than $M5$ are shown in Figure 6. As above, the Tibetan Plateau is divided into a $0.01^\circ \times 0.01^\circ$ grid, and the average values of the three components of the lithospheric magnetic field are computed for each grid element by summing all the grid data to obtain the average lithospheric magnetic field values for the entire study region (histograms labeled “ALL” in Figure 6). Using the same method, we calculate the average values of the X , Y , and Z components at the epicenters for earthquakes of the $M5$ class (5 – 5.9), $M6$ class (6 – 6.9), $M7$ class (7 – 7.9), and $M8$ class (8 – 8.9). We also separately calculate the average values of the three components for earthquakes with $M \geq 5$ and $M \geq 6$. Notably, the sample sizes for $M7$ class ($n = 26$) and $M8$ class ($n = 6$) earthquakes are relatively small, which may limit the statistical significance of the results.

The calculation results show that the average values of the X and Y components in this study are consistent, with all the X component values being negative and all the Y component values being positive. However, the mean values of the Z component across the entire study region differ significantly from those at the epicenters: the former are positive, whereas the latter are negative.

Positive anomaly values of the Z component in the regional background typically originate from the lithosphere’s strong overall magnetic properties in that region. When large-scale magnetized geological bodies (e.g., lithospheric blocks with high magnetic

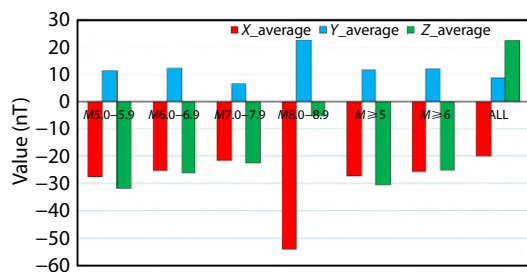


Figure 6. Mean values of the X , Y , and Z components of the lithospheric magnetic field at the epicenters of $M \geq 5$ earthquakes on the Tibetan Plateau; the study area was gridded using a standard $0.01^\circ \times 0.01^\circ$ mesh. Calculations of the magnetic vector field at each grid unit were made using a surface spline model based on data from the 209 repeat stations in the study area. Red, blue, and green histograms represent the average values of the northward component (X), eastward component (Y), and vertical component (Z), respectively, of the magnetic field.

intensity) exist in the subsurface, their induced magnetization aligns with the geomagnetic field. Consequently, a positive magnetic anomaly is formed when the Z component generated directly above this geological body aligns with the direction of the main magnetic field, thereby strengthening the total magnetic field. However, through the magnetization effect, the continuous accumulation of stress in the earthquake source region during the seismic incubation process can cause a significant reduction in rock magnetic susceptibility, leading to demagnetization (Jeleńska, 1975; Zhang et al., 2023). This transforms the region beneath the epicenter that originally exhibited a positive anomaly into one with weaker magnetism relative to the surrounding background, resulting in a negative magnetic anomaly of the Z component.

The X component values are less than -50 nT at the epicenters of earthquakes with strengths greater than $M8$. The results support that the observation that Z component values in the range from -50 to 0 nT at the epicenters of earthquakes with strengths greater than $M5$ are thought to be more indicative of strong earthquakes than X and Y components.

3.3 Potential Earthquake-prone Regions According to the Statistical Results

On the basis of the statistical results presented in Section 3.2, the stability of the Z component of the lithospheric magnetic field is indicative of the occurrence of $M \geq 6$ earthquakes. The Z component is highly sensitive to the depth of magnetic sources. Furthermore, compared with the horizontal components (X and Y components), it usually reflects the presence and geometric morphology of magnetic bodies more accurately. This characteristic provides an important foundation for linking deep geological processes with seismicity (von Frese et al., 2008; Thébault et al., 2010; Wei RQ and Yu L, 2012).

Moreover, there is a strong intrinsic correlation between regional tectonics and seismicity. Both the stress state and the rheological parameters, which are key factors governing the spatial distribution of earthquakes, are highly sensitive to temperature variations (Shi YL and Cao JL, 2008). Regional thermal conditions are directly linked to tectonic activity. The strength of tectonic processes alters thermal conduction and heat accumulation within the lithosphere, which can cause an increase or decrease in the Curie depth (Rajaram et al., 2009; Gao GM et al., 2015a, 2015b). Jiao LG et al. (2013) demonstrated that, compared with horizontal components, the Z component is more sensitive to the Curie depth, effectively reflecting thermal state variations (Qiu YD et al., 2017; Abramova et al., 2020). Similarly, according to Lei Y et al. (2018), who proposed the two equal source dipole (TESD) model, the Z component and seismicity are correlated because of variations in the Curie depth. These variations cause temperature disparities between adjacent blocks, leading to viscosity differences. Stress accumulation and seismic triggering are more likely to occur at block boundaries with significant viscosity variations. This model further indicates that areas with negative Z component anomalies frequently correspond to active tectonic zones, which are characterized by lower rock viscosities, higher geothermal gradients, and

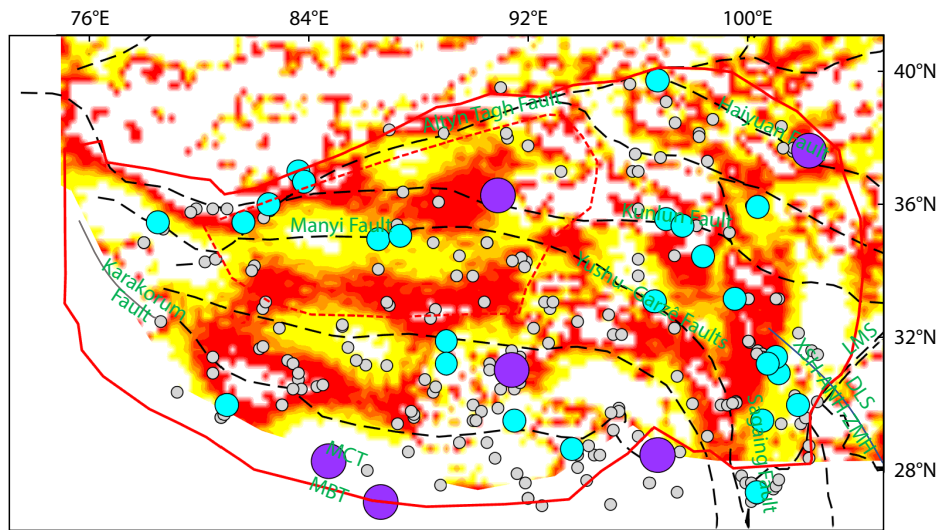


Figure 7. Earthquake-prone zones on the Tibetan Plateau according to the values of the Z component of the lithospheric magnetic field in our study, with the same region shown in Figure 2. The red area is the most earthquake-prone, and the yellow area is less earthquake-prone. The solid circles represent the $M \geq 5$ earthquakes that occurred from 1900 through 2015. The dashed red line surrounds the depopulated zone of the northwestern Tibetan Plateau, which is a large monitoring gap. Gray circles: M5 class earthquakes; green circles: M6 class earthquakes; and purple circles: M7 class earthquakes. DLS: Daliangshan Fault; LMS: Longmenshan Fault; XSH-ANH-ZMH: Xianshuihe–Anninghe–Zemuhe Fault; MBT: Main Boundary Thrust Fault; MCT: Main Central Thrust Fault.

shallower Curie depths. Because of poor tectonic stability, these areas are more susceptible to inducing seismicity.

On the basis of the results of the preceding analysis, we define the regions with Z component values ranging from -50 to 0 nT as the most earthquake-prone regions (red zones in Figure 7) and the regions with Z component values ranging from -100 to -50 nT or 0 – 50 nT as the second most earthquake-prone regions (yellow zones in Figure 7). The solid circles represent earthquakes with strengths greater than M5 from 1900 through 2015.

The results show that major active tectonic belts, such as the MBT and MCT, as well as extensive strike-slip fault systems, such as the Xianshuihe–Anninghe–Zemuhe Fault, are strongly associated with the previously mentioned high-risk magnetic anomaly zones. Many of these fault zones either closely overlap magnetic anomaly belts or are distributed along the boundaries of magnetic anomalies (Figures 2 and 7). These findings suggest that they serve not only as boundaries of surface tectonics but also as demarcations of deep lithospheric structure and material composition. In the tectonic context of intense northward thrusting by the Indian Plate, physical processes that take place in the deep crust, including thickening, heat activity, and strong fracturing, are profoundly reflected in the negative magnetic anomalies. These processes promote strain energy accumulation while also weakening rock magnetism.

Moreover, the southern part of the north–south seismic zone (96° – 100° E, 30° – 34° N) is considered highly prone to earthquakes, with a history of strong earthquakes, indicating tectonic instability. This area, which has an incredibly complex and active tectonic setting, is a crucial junction where the strike-slip motion of the Sichuan–Yunnan block interacts with lateral compressional stress from the eastern Himalayan syntaxis. The characteristics of the

lithospheric magnetic field make this clearly evident. This finding aligns with observations that earthquakes in this region occur frequently around transition zones or magnetic anomaly boundaries.

4. Discussion

4.1 Comparison with the EMM

Although the EMM data have been improved by satellite, oceanic, and airborne magnetometry, fewer ground-based observations are available for the Tibetan Plateau. In contrast, our model is based on data from measurements at more than 200 ground repeat stations. The EMM used for comparison with our model is EMM2015, one of several EMMs developed by the NGDC. On the basis of spherical harmonic analysis, this model is a high-order geomagnetic field model released by the National Oceanic and Atmospheric Administration (NOAA) and is applicable for geomagnetic field calculations from 2000 to 2019 (<https://geomag.org/models/>). By comparing the EMM with our model, we can validate how data selection affects modeling results and further understand the geomagnetic field on the Tibetan Plateau.

Previous results of the lithospheric magnetic field on the Tibetan Plateau obtained from the EMM (Figure S2; e.g., Luo Y, 2013) are compared with the results of this study. With a 70 km station spacing, our study primarily uses ground observation data to model the geomagnetic field over the Tibetan Plateau. This configuration effectively captures the anomalous characteristics of the shortwave components (less than 200 km) of the lithospheric magnetic field. In contrast, other models (including the EMM) primarily use satellite magnetic survey data, which can capture only the longwave components (over 400 km) of the lithospheric magnetic field. Furthermore, the ground-level lithospheric magnetic field in the

EMM for the Tibetan Plateau is based primarily on model inversion results, which exhibit significant discrepancies from actual conditions, since satellite magnetic surveys are conducted at altitudes exceeding 300 km above the surface.

Additionally, to compare the agreement between the two models, we select a profile line in the area with good repeat station coverage (Figures 1 and S2) and compare the values of the X , Y , and Z components at 10 points along this line (Figure S3). In the central portion of the profile line, the two models clearly show similar trends and are in high agreement, indicating that their results are largely consistent across most of the region.

We found that the distributions of positive and negative values of the lithospheric magnetic vectors are essentially the same, but the resolution of the EMM results is better. Nonetheless, the model calculation from ground-based observations is much improved by this study. For example, in our study, a positive magnetic anomaly of the Z component was inferred by utilizing ground vector data from the Qaidam Basin. In contrast, because of insufficient ground observations, the Curie surface burial depths of 30 km to 44 km exhibit weak negative anomalies in the same region, which are obtained by the EMM on the basis of its inversion of aeromagnetic survey data (Lei Y et al., 2024). For the eastern part of the Songpan–Garzê block, our results reveal a wide variety of weakly negative anomaly zones, whereas the EMM calculations result in weakly positive anomaly zones. Furthermore, owing to its lack of ground-based data coverage, the spatial resolution of the EMM is significantly lower on the southern Tibetan Plateau. In contrast, our study significantly improves the spatial resolution in this region and compensates for the airborne data to better identify the boundaries between regions with positive and negative values. In addition, the overall magnetic field strength calculated by the model in this study is greater than that of the EMM for all three component values. The difference in the measurement height of the data sources may be important because the EMM includes mainly satellite magnetometry and aerial data, whereas our study involves more than 200 ground measurements, and less magnetic field attenuation is observed. At satellite observation altitudes, the intensity of the lithospheric magnetic field typically constitutes less than 0.1% of the overall magnetic field strength, and its strength decreases significantly with increasing height (Maus et al., 2008; Regan and Marsh, 1982). Consequently, the lithospheric magnetic field strength calculated by our method is generally greater than that calculated by the EMM.

According to the EMM, the lithospheric magnetic field at the epicenters of medium–strong earthquakes within the Z component value range of 0–20 nT corresponds to the most earthquake-prone region, whereas the least earthquake-prone regions are those with values ranging from –40 to 0 nT (Figure S2). However, in this study, moderate to strong earthquakes ($M \geq 5$) occur predominantly in regions where the vertical component (Z) of the lithospheric magnetic field is negative, particularly within the range of –50 to 0 nT.

The present model in our study still has shortcomings, despite the promising approach of using repeated ground-based measurements to preserve magnetic anomaly signals. The accuracy and

reliability of the model cannot be assured in some areas with gaps in monitoring, which are difficult to reach and deploy stations (e.g., the northwestern Tibetan Plateau in Figure 1). However, the accuracy of lithospheric magnetic field calculations is improved, and we suggest that prediction of strong earthquakes can be significantly improved by suitable models that combine aeromagnetic data, satellite data, and ground data.

4.2 Comparison with Other Tectonic Settings

Our study reveals a statistically significant relationship between the lithospheric magnetic field and seismicity on the basis of observations from the Tibetan Plateau. Specifically, the Plateau features a large-scale weak magnetic background; borders in the Plateau's lithospheric magnetic field closely align with major tectonic block boundaries (Figure 2). Seismic epicenters show distinct clustering in regions with negative Z component values (approximately ranging from –50 to 0 nT) (Figures 3–7). The magnetic structure of the lithosphere can reflect deep weak tectonic zones and local thermodynamic conditions, which control stress accumulation and release (Yang T et al., 2020). This fundamental physical mechanism manifests in distinct forms across different dynamic environments, including subduction zones, rift zones, and cratons.

The magnetic field characteristics in other tectonic settings vary significantly. In subduction zones, magnetic anomalies are governed primarily by factors such as lithospheric age and subduction velocity and angle. For example, slow-rate subduction zones (e.g., the Puerto Rico Trench) may not have as many noticeable magnetic anomalies as rapid subduction zones (e.g., the Middle America Trench), which present large positive magnetic anomalies reflecting relatively intact subducting slabs (Counil et al., 1989; Thébaud et al., 2017). Furthermore, studies across multiple subduction zones worldwide indicate that lithospheric age is a key factor controlling the evolution of magnetic anomalies. Owing to the thermal shielding effect, younger lithosphere may exhibit more magnetic anomaly decay after subduction than older lithosphere (Choe and Dyment, 2021).

Magnetic anomalies in rift zones are controlled primarily by extensional tectonics and deep thermorheological processes, and typically exhibit banded or segmented distribution patterns. In the Trans-Atlantic Geotraverse segment of the Mid-Atlantic Ridge, near-seafloor magnetic surveys reveal that the eastern rift wall exhibits a prominent linear low-susceptibility belt and that high magnetic susceptibility zones are concentrated along the new volcanic axis, clearly offset westward from the center of the Brunhes anomaly (Tivey et al., 2003). This low magnetic anomaly is closely related to crustal extension controlled by normal faults and magnetic layer thinning rather than by hydrothermal alteration. Similar characteristics are seen in continental rift environments (e.g., the Kenyan Rift and the Mozambique Belt), where preexisting weak crustal zones (e.g., tectonically weakened areas within the Mozambique Belt) play crucial roles in controlling fault development and magnetic anomaly differentiation (Richter et al., 2021). Dominant faults at rift boundaries often form distinct magnetic gradient zones that operate as the main locations for strain concentration and tectonic activity (Counil et al., 1989;

Ramos et al., 2021).

Magnetic anomaly belts exhibit spatial correlation with seismicity; for instance, low-magnetization zones in the Trans-Atlantic Geotraverse segment correlate with microseismic activity, and similarly the high-density faults and shallow-focus earthquakes coexist in the southern Kenya Rift (Tivey et al., 2003; Muirhead et al., 2016). Consequently, utilizing magnetic boundaries to locate active faults, and identifying extensive negative magnetic anomalies to assess seismic hazard zones, appear to remain promising approaches.

Tectonic environments within cratons typically exhibit gentle magnetic anomalies. For instance, the magnetic anomaly pattern in the Tarim Basin is characterized by strong basins and weak mountains. Strong magnetic basement is associated with positive anomalies in the basin center, whereas weak or negative anomalies are present in nearby orogenic belts. These belts are associated with mantle uplift caused by high heat flow (Ou JM et al., 2013; Gao GM et al., 2017; Wang J et al., 2021; Wang J et al., 2024). In contrast, orogenic environments typically exhibit more complex and variable magnetic field characteristics. Tectonically active fold zones show predominantly negative anomalies or weak magnetic backgrounds, but magnetic fields in the Central Asian Fold Belt frequently exhibit a block-like alternating positive–negative pattern, with stable blocks corresponding to positive anomalies (e.g., Ou JM et al., 2013; Abramova and Filippov, 2019; Yuan JH et al., 2022).

In conclusion, although the lithospheric magnetic field is an essential indicator of deep tectonics and seismicity, its manifestations in diverse tectonic settings need to be interpreted in conjunction with specific geodynamic processes.

4.3 Physical Mechanisms Underlying the Magnetic–Seismic Link

Our study reveals a significant relationship between the boundaries of major tectonic blocks and the distribution patterns of lithospheric magnetic fields on the Tibetan Plateau. Earthquakes in this region show a marked tendency to occur in areas where the Z component values are negative (Figures 2 and 7). Instead of coincidental spatial coupling, these statistical findings suggest an intrinsic physical connection between lithospheric magnetic field characteristics and seismic nucleation processes. As one of the world's most prototypical continental collisional orogenic belts, the lithosphere of the Tibetan Plateau has undergone intense deformation, crustal thickening, and material transport (Li TD et al., 1986; Pan GT et al., 2012; Laborde et al., 2019; Pietrolungo et al., 2024; Gao GM et al., 2025). These deep processes inevitably leave imprints on the lithospheric magnetic field and may influence earthquake occurrence through thermomechanical effects.

Earthquakes typically occur along major active fault zones and are caused by the accumulation and release of stress within the crust. Consequently, one of the main factors influencing the occurrence of earthquakes is the stress state of the subsurface medium (Zou R et al., 2018). The northward thrusting of the Indian Plate and the obstruction of the Tarim block resulted in the whole Tibetan

Plateau being within a strong compressional stress environment (Laborde et al., 2019; Li YC et al., 2024; Pietrolungo et al., 2024; Gao GM et al., 2025). The possible existence of middle–lower crustal flows further modulates the stress distribution (Clark and Royden, 2000; Li L et al., 2024). With fault zones demagnetizing during stress loading, the tectonic setting provides extensive stress conditions for the piezomagnetic effect, which may lead to the observed negative magnetic anomalies (Figure 7).

As for the magnetocaloric effect, owing to direct tectonic collision, the southern Tibetan Plateau, which includes the Lhasa and Himalayan blocks, exhibits high heat flows (often more than 80 mW/m²) and a significantly elevated Curie surface (approximately 600 °C isotherm) (Tao W and Shen ZK, 2008; Lei Y et al., 2018; Hu SB et al., 2000). This demagnetizes ferromagnetic minerals and creates widespread negative magnetic anomalies (Qiu YD et al., 2017). Alsdorf and Nelson (1999) reported an average depth of approximately 15 km for the Curie surface on the Tibetan Plateau, which is consistent with the depth of the partially molten crust. The brittle upper crust above the Curie surface (typically less than 10 to 20 km) is precisely the primary development zone for shallow earthquakes. In addition to directly causing demagnetization, thermal activity can also trigger earthquakes by promoting fluid circulation, decreasing effective stress, and weakening fault strength (Alsdorf and Nelson, 1999; Qiu YD et al., 2017; Yang T et al., 2020; Gao GM et al., 2025). Additionally, processes such as friction-induced phase transitions in iron-bearing minerals (Yang T et al., 2012) or fluid infiltration affecting the electrical and magnetic properties of fault zones (Jouniaux and Zyserman, 2016; Zeigarnik et al., 2022) may also contribute to the coupling between spatial heterogeneity in magnetic anomalies and seismicity.

Nevertheless, some moderate-to-strong earthquakes occur outside negative magnetic anomaly zones. This finding indicates that the magnetoseismic relationship is governed by a combination of factors such as crustal depth variations, magnetic susceptibility anisotropy, and multiscale tectonic responses (Lei Y et al., 2018). Rock composition, structure, temperature–pressure conditions, and deep dynamic processes all affect the characteristics of geomagnetic anomalies in various tectonic zones (Achache et al., 1987; Taylor et al., 2008; Kang GF et al., 2012). More research is needed to determine the mechanisms that connect these anomalies to seismicity. Combining compressional and thermal magnetic effects, the negative magnetic anomalies observed in the results reported here can be regarded as a comprehensive indicator of the deep thermal-stress state beneath the Tibetan Plateau, holding potential significance for seismic hazard zone delineation.

5. Conclusions

(1) According to the intensity of the lithospheric magnetic field at the epicenters of historical medium and strong earthquakes, strong earthquakes occur primarily in regions with Z component values ranging from -50 to 0 nT, and earthquakes with strengths greater than $M5$ are more likely to occur in regions with negative Z component values than in regions with positive Z component values.

(2) The lithospheric magnetic vectors obtained from more than 200 newly constructed repeat stations on the Tibetan Plateau compensate greatly for the limitations of previous EMMs that relied on airborne data.

(3) There are notable variations in the magnetoseismic coupling mechanisms across various tectonic settings (e.g., orogenic belts, subduction zones, and rift zones), demonstrating that the lithospheric magnetic field is a crucial indicator for revealing deep thermodynamic conditions and identifying seismic hazard zones.

Acknowledgments

We are grateful to the Editor and anonymous reviewers for their constructive comments and suggestions. This study was financially supported by the CAS Pioneer Hundred Talents Program and Second Tibetan Plateau Scientific Expedition Research Program (2019QZKK0708), as well as the Basic Research Program of Qinghai Province: Lithospheric Geomagnetic Field of the Qinghai–Tibet Plateau and the Relationship with Strong Earthquakes (2021–ZJ-969Q).

Author Contributions

P.Z. performed the numerical modeling and developed the study. P.Z. and J.Y. wrote the manuscript. J.Y., L.F., and Y.J. reviewed the results and improved the manuscript. X.L. and Y.Z. provided comments and collaborated on the study.

Data availability

All the data generated or analyzed during this study are included in this published article.

Conflicts of interest statement

All the authors declare that they have no conflicts of interest.

References

- Abramova, D. Y., and Filippov, S. V. (2019). Satellite regional magnetic anomalies as a reflection of the geological and geophysical properties of the lithosphere (according to champ data). *Geomagn. Aeron.*, 59(4), 479–487. <https://doi.org/10.1134/S0016793219040029>
- Abramova, L. Y., Abramova, L. M., Varentsov, I. M., and Filippov, S. V. (2020). Reflection of large tectonic structures of the eastern part of the Arctic Ocean in the lithospheric magnetic field. *Geomagn. Aeron.*, 60(5), 636–643. <https://doi.org/10.1134/S0016793220050023>
- Achache, J., Abtout, A., and Le Mouél, J. L. (1987). The downward continuation of Magsat crustal anomaly field over Southeast Asia. *J. Geophys. Res.: Solid Earth*, 92(B11), 11584–11596. <https://doi.org/10.1029/JB092iB11p11584>
- Als Dorf, D., and Nelson, D. (1999). Tibetan satellite magnetic low: Evidence for widespread melt in the Tibetan crust?. *Geology*, 27(10), 943–946. [https://doi.org/10.1130/0091-7613\(1999\)027<0943:TSMLEF>2.3.CO;2](https://doi.org/10.1130/0091-7613(1999)027<0943:TSMLEF>2.3.CO;2)
- An, Z. C. (1993). Spherical cap harmonic analysis of geomagnetic field for China. *Acta Geophys. Sin. (in Chinese)*, 36(6), 753–764.
- Billings, S. D., Beatson, R. K., and Newsam, G. N. (2002). Interpolation of geophysical data using continuous global surfaces. *Geophysics*, 67(6), 1810–1822. <https://doi.org/10.1190/1.1527081>
- Chen, B., Ni, Z., Xu, R. G., Gu, Z. W., Yuan, J. H., and Wang, L. (2016). The geomagnetic field in China and neighboring regions for the 2010.0 epoch. *Chinese J. Geophys. (in Chinese)*, 59(4), 1446–1456. <https://doi.org/10.6038/cjg20160425>
- Chen, B., Yuan, J. H., Wang, C., Xu, R. G., and Wang, Z. D. (2017). Data processing flowchart of Chinese mobile geomagnet monitoring array. *J. Seismol. Res. (in Chinese)*, 40(3), 335–339. <https://doi.org/10.3969/j.issn.1000-0666.2017.03.002>
- Choe, H., and Dymet, J. (2021). The fate of marine magnetic anomaly in subduction zones: A global appraisal. *Earth Planet. Sci. Lett.*, 561, 116787. <https://doi.org/10.1016/j.epsl.2021.116787>
- Clark, M. K., and Royden, L. H. (2000). Topographic ooze: Building the eastern margin of Tibet by lower crustal flow. *Geology*, 28(8), 703–706. [https://doi.org/10.1130/0091-7613\(2000\)28<703:tobtem>2.0.co;2](https://doi.org/10.1130/0091-7613(2000)28<703:tobtem>2.0.co;2)
- Counil, J. L., Achache, J., and Galdeano, A. (1989). Long-wavelength magnetic anomalies in the Caribbean: Plate boundaries and allochthonous continental blocks. *J. Geophys. Res.: Solid Earth*, 94(B6), 7419–7431. <https://doi.org/10.1029/JB094iB06p07419>
- Du, J. S., and Chen, C. (2015). Progress and outlook in global lithospheric magnetic field modelling by satellite magnetic measurements. *Prog. Geophys. (in Chinese)*, 30(3), 1017–1033. <https://doi.org/10.6038/pg20150305>
- Erbek, E. (2021). An investigation on the structures and the basement depth estimation in the western Anatolia, Turkey using aeromagnetic data. *Geosci. J.*, 25(6), 891–902. <https://doi.org/10.1007/s12303-021-0001-y>
- Feng, L. L., and Li, X. (2016). Research on lithospheric magnetic field feature of Lenglongling fault and its relation with Qinghai Menyuan $M_{6.4}$ earthquake in 2016. *J. Seismol. Res. (in Chinese)*, 39(S1), 117–121.
- Feng, L. L., Zhang, Z. L., Chen, B., Yuan, J. H., and Wang, C. (2017). Lithospheric magnetic field feature of Sichuan–Yunnan region and its relationship with strong earthquakes. *J. Seismol. Res. (in Chinese)*, 40(3), 352–356. <https://doi.org/10.3969/j.issn.1000-0666.2017.03.005>
- Feng, L. L. (2019). Lithospheric geomagnetic field variation in the North-South Seismic Belt from 2010 to 2016. *Acta Seismol. Sin. (in Chinese)*, 41(2), 239–248. <https://doi.org/10.11939/jass.20180059>
- Feng, Y., Sun, H., Mao, F., and Jiang, Y. (2013). Study on crustal magnetic anomaly over Mexico and its adjacent areas. *Prog. Geophys. (in Chinese)*, 28(3), 1355–1364. <https://doi.org/10.6038/pg20130329>
- Feng, Y., Nasir, A., Li, Y. J., Zhang, J. Y., Zhang, J. X., and Huang, Y. (2023). The study of the lithospheric magnetic field over Xinjiang and Tibet areas based on ground, airborne, and satellite data. *Remote Sens.*, 15(8), 2002. <https://doi.org/10.3390/rs15082002>
- Gao, G. M., Kang, G. F., Bai, C. H., and Wen, L. M. (2015a). Study on crustal magnetic anomalies and Curie surface in Southeast Tibet. *J. Asian Earth Sci.*, 97, 169–177. <https://doi.org/10.1016/j.jseae.2014.10.035>
- Gao, G. M., Kang, G. F., Li, G. Q., and Bai, C. H. (2015b). Crustal magnetic anomaly in the Ordos region and its tectonic implications. *J. Asian Earth Sci.*, 109, 63–73. <https://doi.org/10.1016/j.jseae.2015.04.033>
- Gao, G. M., Kang, G. F., Li, G. Q., Bai, C. H., and Wu, Y. Y. (2017). An analysis of crustal magnetic anomaly and Curie surface in west Himalayan syntaxis and adjacent area. *Acta Geod. Geophys.*, 52(3), 407–420. <https://doi.org/10.1007/s40328-016-0179-z>
- Gao, G. M., Shi, L., Kang, G. F., Wu, Y. Y., Bai, C. H., Wen, L. M., and Hou, J. (2018). Analysis of the lithospheric magnetic anomalies and tectonics in continental China and the adjacent regions using CHAMP satellite data. *Stud. Geophys. Geod.*, 62(3), 408–426. <https://doi.org/10.1007/s11200-016-0102-7>
- Gao, G. M., Li, Y. C., Kang, G. F., Bai, C. H., and Wen, L. M. (2025). Regional seismicity of the northeastern Tibetan plateau revealed by crustal magnetic anomalies. *Appl. Sci.*, 15(8), 4331. <https://doi.org/10.3390/app15084331>
- Gu, C. L., Zhang, Y., Xu, R. G., and Wang, L. (2010). Analysis of the variation characteristic in the lithospheric geomagnetic field before and after earthquakes. *Prog. Geophys. (in Chinese)*, 25(2), 472–477. <https://doi.org/10.3969/j.issn.1004-2903.2010.02.013>
- Gu, Z. L., Yu, S., Wang, G. N., Lai, M. J., and Wang, L. (2025). TSSS: a novel triangulated spherical spline smoothing for surface-based data. *J. Nonparametr. Stat.*, 37(3), 683–712. <https://doi.org/10.1080/10485252.2025.2449886>
- Gu, Z. W., Zhan, Z. J., Gao, J. T., Yao, T. Q., and Han, W. (2006). Application of GPS in geomagnetic survey. *Earth Planets Space*, 58(6), 723–729. <https://doi.org/10.1186/BF03351974>
- Hao, J. Q., Hastie, L. M., and Stacey, F. D. (1982). Theory of the seismomagnetic effect: a reassessment. *Phys. Earth Planet. Inter.*, 28(2), 129–140. [https://doi.org/10.1016/0031-9208\(82\)90001-1](https://doi.org/10.1016/0031-9208(82)90001-1)

- org/10.1016/0031-9201(82)90078-4
- Harder, R. L., and Desmarais, R. N. (1972). Interpolation using surface splines. *J. Aircr.*, 9(2), 189–191. <https://doi.org/10.2514/3.44330>
- Hsu, S. K., Sibuet, J. C., and Shyu, C. T. (1996). High-resolution detection of geologic boundaries from potential-field anomalies: an enhanced analytic signal technique. *Geophysics*, 61(2), 373–386. <https://doi.org/10.1190/1.1443966>
- Hu, S. B., He, L. J., and Wang, J. Y. (2000). Heat flow in the continental area of China: a new data set. *Earth Planet. Sci. Lett.*, 179(2), 407–419. [https://doi.org/10.1016/S0012-821X\(00\)00126-6](https://doi.org/10.1016/S0012-821X(00)00126-6)
- Jeleńska, M. (1975). Stress dependence of magnetization and magnetic properties of igneous rocks. *Pure Appl. Geophys.*, 113(1), 635–649. <https://doi.org/10.1007/BF01592948>
- Jiang, Y., Holme, R., Xiong, S. Q., Jiang, Y., Feng, Y., and Yang, H. (2021). Long-wavelength lithospheric magnetic field of China. *Geophys. J. Int.*, 224(3), 1780–1792. <https://doi.org/10.1093/gji/ggaa490>
- Jiao, L. G., Chen, H. R., and Gao, M. T. (2013). Magnetic constraints on the spatial distribution of seismic activity. *Earthq. Sci. (in Chinese)*, 26(2), 125–136. <https://doi.org/10.1007/s11589-013-0022-3>
- Jouniaux, L., and Zyserman, F. (2016). A review on electrokinetically induced seismo-electrics, electro-seismics, and seismo-magnetics for Earth sciences. *Solid Earth*, 7(1), 249–284. <https://doi.org/10.5194/se-7-249-2016>
- Kang, G. F., Gao, G. M., Bai, C. H., Shao, D., and Feng, L. L. (2012). Characteristics of the crustal magnetic anomaly and regional tectonics in the Qinghai-Tibet Plateau and the adjacent areas. *Sci. China Earth Sci.*, 55(6), 1028–1036. <https://doi.org/10.1007/s11430-011-4323-x>
- Laborde, A., Barrier, L., Simoes, M., Li, H., Coudroy, T., van Der Woerd, J., and Tapponnier, P. (2019). Cenozoic deformation of the Tarim Basin and surrounding ranges (Xinjiang, China): A regional overview. *Earth-Sci. Rev.*, 197, 102891. <https://doi.org/10.1016/j.earscirev.2019.102891>
- Langel, R. A., and Hinze, W. J. (1998). *The Magnetic Field of the Earth's Lithosphere: The Satellite Perspective*. Cambridge: Cambridge University Press. <https://doi.org/10.1017/CBO9780511629549>
- Lei, Y., Jiao, L. G., and Chen, H. R. (2018). Possible correlation between the vertical component of lithospheric magnetic field and continental seismicity. *Earth Planets Space*, 70, 179. <https://doi.org/10.1186/s40623-018-0949-7>
- Lei, Y., Jiao, L., Huang, Q., and Tu, J. (2024). A continental model of Curie Point Depth for China and surroundings based on Equivalent Source Method. *Journal of Geophysical Research: Solid Earth*, 129(3), e2023JB027254. <https://doi.org/10.1029/2023JB027254>
- Li, L., Wang, X., Hou, G. B., Ling, Y., and Ai, Y. S. (2024). Two thin middle-crust low-velocity zones imaged in the Chuan-Dian region of southeastern Tibetan Plateau and their tectonic implications. *Sci. China Earth Sci.*, 67(5), 1675–1686. <https://doi.org/10.1007/s11430-023-1256-0>
- Li, T. D., Xiao, X. C., Li, G. C., Gao, Y. L., and Zhou, W. Q. (1986). The crustal evolution and uplift mechanism of the Qinghai-Tibet plateau. *Tectonophysics*, 127(3–4), 279–289. [https://doi.org/10.1016/0040-1951\(86\)90065-X](https://doi.org/10.1016/0040-1951(86)90065-X)
- Li, Y. C., Liu, L. J., Li, S. Z., Peng, D. D., Cao, Z. B., and Li, X. Y. (2024). Cenozoic India-Asia collision driven by mantle dragging the cratonic root. *Nat. Commun.*, 15(1), 6674. <https://doi.org/10.1038/s41467-024-51107-0>
- Liang, X., Chu, F., Xu, R. G., Sun, H. B., Xiao, W. P., and Wang, J. (2024). The characteristics and mechanism of gravity and magnetic field changes before and after the 2014 Huoshan $M_s 4.3$ earthquake. *Seismol. Geol. (in Chinese)*, 46(5), 1151–1171. <https://doi.org/10.3969/j.issn.0253-4967.2024.05.009>
- Liu, Y. H., Zhang, Y. F., Zhang, G. H., Zheng, B. W., and Shan, X. J. (2019). Study of the D-InSAR deformation field and seismotectonics of the Menyuan $M_s 6.4$ earthquake on January 21, 2016. *Geophys. (in Chinese)*, 34(3), 896–907. <https://doi.org/10.6038/pg2019CC0195>
- Luo, Y. (2013). A huge gap of the lithospheric magnetic field model in the Qinghai-Tibet Plateau—Comment on "Characteristics of the crustal magnetic anomaly and regional tectonics in the Qinghai-Tibet Plateau and the adjacent areas". *Sci. China Earth Sci.*, 56(9), 1623–1626. <https://doi.org/10.1007/s11430-013-0682-6>
- Maule, C. F., Purucker, M. E., Olsen, N., and Mosegaard, K. (2005). Heat flux anomalies in Antarctica revealed by satellite magnetic data. *Science*, 309(5733), 464–467. <https://doi.org/10.1126/science.1106888>
- Maus, S., Yin, F., Lühr, H., Manoj, C., Rother, M., Rauberg, J., Michaelis, I., Stolle, C., and Müller, R. D. (2008). Resolution of direction of oceanic magnetic lineations by the sixth-generation lithospheric magnetic field model from CHAMP satellite magnetic measurements. *Geochem. Geophys. Geosyst.*, 9(7), Q07021. <https://doi.org/10.1029/2008GC001949>
- Muirhead, J. D., Kattenhorn, S. A., Lee, H., Mana, S., Turrin, B. D., Fischer, T. P., Kianji, G., Dindi, E., and Stamps, D. S. (2016). Evolution of upper crustal faulting assisted by magmatic volatile release during early-stage continental rift development in the East African Rift. *Geosphere*, 12(6), 1670–1700. <https://doi.org/10.1130/GES01375.1>
- Okubo, K., Takeuchi, N., Utsugi, M., Yumoto, K., and Sasai, Y. (2011). Direct magnetic signals from earthquake rupturing: Iwate-Miyagi earthquake of M 7.2, Japan. *Earth Planet. Sci. Lett.*, 305(1–2), 65–72. <https://doi.org/10.1016/j.epsl.2011.02.042>
- Ou, J. M., Du, A. M., Thébaud, E., Xu, W. Y., Tian, X. B., and Zhang, T. L. (2013). A high resolution lithospheric magnetic field model over China. *Sci. China Earth Sci.*, 56(10), 1759–1768. <https://doi.org/10.1007/s11430-013-4580-y>
- Pan, G. T., Wang, L. Q., Li, R. S., Yuan, S. H., Ji, W. H., Yin, F. G., Zhang, W. P., and Wang, B. D. (2012). Tectonic evolution of the Qinghai-Tibet plateau. *J. Asian Earth Sci.*, 53, 3–14. <https://doi.org/10.1016/j.jseas.2011.12.018>
- Pietrolungo, F., Lavecchia, G., Madarieta-Txurruka, A., Sparacino, F., Srivastava, E., Cirillo, D., de Nardis, R., Andrenacci, C., Bello, S., ... Palano, M. (2024). Comparison of crustal stress and strain fields in the Himalaya–Tibet region: Geodynamic implications. *Remote Sens.*, 16(24), 4765. <https://doi.org/10.3390/rs16244765>
- Purucker, M. E., and Whaler, K. A. (2015). Crustal magnetism. In G. Schubert (Ed.), *Treatise on Geophysics* (2nd ed, Vol. 5, pp. 185–218). Oxford: Elsevier. <https://doi.org/10.1016/B978-0-444-53802-4.00100-7>
- Qiu, Y. D., Wang, Z. T., Jiang, W. P., Zhang, B. B., Li, F. P., and Guo, F. (2017). Combining CHAMP and Swarm satellite data to invert the lithospheric magnetic field in the Tibetan Plateau. *Sensors*, 17(2), 238. <https://doi.org/10.3390/s17020238>
- Rajaram, M., Anand, S. P., Hemant, K., and Purucker, M. E. (2009). Curie isotherm map of Indian subcontinent from satellite and aeromagnetic data. *Earth Planet. Sci. Lett.*, 281(3–4), 147–158. <https://doi.org/10.1016/j.epsl.2009.02.013>
- Ramos, L. N., Aitken, A. R. A., Occhipinti, S. M., and Lindsay, M. D. (2021). Rift structures and magmatism focus VMS and gold mineralisation in the Paleoproterozoic Bryah Rift Basin, Australia. *Ore Geol. Rev.*, 135, 104192. <https://doi.org/10.1016/j.oregeorev.2021.104192>
- Regan, R. D., and Marsh, B. D. (1982). The Bangui magnetic anomaly: Its geological origin. *J. Geophys. Res.: Solid Earth*, 87(B2), 1107–1120. <https://doi.org/10.1029/JB087B02p01107>
- Richter, M. J. E. A., Brune, S., Riedl, S., Glerum, A., Neuhauf, D., and Strecker, M. R. (2021). Controls on asymmetric rift dynamics: Numerical modeling of strain localization and fault evolution in the Kenya Rift. *Tectonics*, 40(5), e2020TC006553. <https://doi.org/10.1029/2020TC006553>
- Shi, Y. L., and Cao, J. L. (2008). Lithosphere effective viscosity of continental China. *Earth Sci. Front.*, 15(3), 82–95. [https://doi.org/10.1016/S1872-5791\(08\)60064-0](https://doi.org/10.1016/S1872-5791(08)60064-0)
- Song, C. K., and Chen, B. (2024). Heterogeneity effect of elastic properties on piezomagnetic fields associated with dislocation source. *Izv., Phys. Solid Earth*, 60(2), 325–332. <https://doi.org/10.1134/S1069351324700381>
- Su, S. P., Zhao, H. Q., Li, B., Yun, M., Zhang, H. Y., and Zhang, N. L. (2017). Spatial distribution and seismic geological characteristics of the lithospheric magnetic field in the North China Region. *J. Seismol. Res. (in Chinese)*, 40(3), 345–351. <https://doi.org/10.3969/j.issn.1000-0666.2017.03.004>
- Tang, Y., and Feng, Y. (2023). Preliminary study of lithospheric magnetic field of Xinjiang based on ground, aeromagnetic data and 3D model. *Prog. Geophys. (in Chinese)*, 38(3), 1026–1034. <https://doi.org/10.6038/pg2023GG0312>

- Tao, W., and Shen, Z. K. (2008). Heat flow distribution in Chinese continent and its adjacent areas. *Prog. Nat. Sci.*, 18(7), 843–849. <https://doi.org/10.1016/j.pnsc.2008.01.018>
- Taylor, P. T., Kim, H. R., Kutina, J., and Johnson, G. L. (2008). Geohazard assessment from satellite magnetic data modeling—with examples from the Arctic Margin along the Canada Basin and the Korean Peninsula along 40°N (latitude) parallel. *Earth Planets Space*, 60(5), 497–503. <https://doi.org/10.1186/BF03352816>
- Thébault, E., Purucker, M., Whaler, K. A., Langlais, B., and Sabaka, T. J. (2010). The magnetic field of the Earth's lithosphere. *Space Sci. Rev.*, 155(1), 95–127. <https://doi.org/10.1007/s11214-010-9667-6>
- Thébault, E., Lesur, V., Kauristie, K., and Shore, R. (2017). Magnetic field data correction in space for modelling the lithospheric magnetic field. *Space Sci. Rev.*, 206(1), 191–223. <https://doi.org/10.1007/s11214-016-0309-5>
- Tivey, M. A., Schouten, H., and Kleinrock, M. C. (2003). A near-bottom magnetic survey of the Mid-Atlantic Ridge axis at 26°N: Implications for the tectonic evolution of the TAG segment. *J. Geophys. Res.: Solid Earth*, 108(B5), 2277. <https://doi.org/10.1029/2002JB001967>
- Von Frese, R. R. B., Kim, J. W., Hernandez, O., Kim, H. R., and Asgharzadeh, M. F. (2008). Assessing intraplate earthquake hazards from satellite geopotential field observations. *Earth Planets Space*, 60(5), 487–495. <https://doi.org/10.1186/BF03352815>
- Wang, C. J., Li, B., and Su, S. P. (2024). Analysis of seismomagnetic characteristics of Zhangjiakou-Bohai seismic belt based on annual variation of total intensity. *J. Geod. Geodyn. (in Chinese)*, 44(10), 1064–1070. <https://doi.org/10.14075/j.jgg.2023.11.102>
- Wang, J., Shen, X. H., Yang, Y. Y., Zeren, Z. M., Hulot, G., Olsen, N., Zhou, B., Magnes, W., De Santis, A., ... Yu, J. B. (2021). Initial scalar lithospheric magnetic anomaly map of China and surrounding regions derived from CSES satellite data. *Sci. China Technol. Sci.*, 64(5), 1118–1126. <https://doi.org/10.1007/s11431-020-1727-0>
- Wang, J., Yang, Y. Y., Zeren, Z., Wang, J., Wang, X., Luo, Y. X., and Shen, X. H. (2024). Preliminary geological interpretation of long-wavelength magnetic anomalies over China and surrounding regions. *Earth Planet. Phys.*, 8(3), 445–458. <https://doi.org/10.26464/epp2024025>
- Wang, Q. H., Chen, Z. Y., Zhang, Z. L., Zhao, Y. F., and Gu, J. (2017). Lithosphere magnetic anomaly analysis of related faults of the 2014 Ludian $M_{6.5}$ earthquake. *J. Seismol. Res. (in Chinese)*, 40(3), 377–381. <https://doi.org/10.3969/j.issn.1000-0666.2017.03.010>
- Wang, Z. D., Chen, B., Yuan, J. H., Yang, F. X., Jia, L., and Wang, C. (2018). Localized geomagnetic field anomalies in an underground gas storage. *Phys. Earth Planet. Inter.*, 283, 92–97. <https://doi.org/10.1016/j.pepi.2018.08.009>
- Wei, R. Q., and Yu, L. (2012). Constraints from satellite crustal magnetic field on the distribution of the epicenters for earthquakes in the continental crust of China. *Chinese J. Geophys. (in Chinese)*, 55(8), 2643–2650. <https://doi.org/10.6038/j.issn.0001-5733.2012.08.016>
- Wen, L. M., Kang, G. F., Bai, C. H., Gao, G. M., Zheng, A. R., and An, B. L. (2017). Crustal magnetic anomalies and geological structure in the Yunnan region. *Chinese J. Geophys. (in Chinese)*, 60(9), 3493–3504. <https://doi.org/10.6038/cjg20170918>
- Yang, L., Chen, S. G., Yan, W. S., Zhang, Y., Lei, G., and Yang, L. (2024). Indication of the spatio-temporal variation characteristics of lithospheric magnetic field to seismic activity in the northern north-south seismic belt and surrounding areas. *J. Geod. Geodyn. (in Chinese)*, 44(3), 304–309. <https://doi.org/10.14075/j.jgg.2023.05.148>
- Yang, T., Wang, H. Q., and Jin, H. Q. (2011). Magnetic study of fault rocks and its implications. *Prog. Geophys. (in Chinese)*, 26(3), 876–884. <https://doi.org/10.3969/j.issn.1004-2903.2011.03.012>
- Yang, T., Chen, J. Y., Wang, H. Q., and Jin, H. Q. (2012). Magnetic properties of fault rocks from the Yingxiu–Beichuan fault: constraints on temperature rise within the shallow slip zone during the 2008 Wenchuan earthquake and their implications. *J. Asian Earth Sci.*, 50, 52–60. <https://doi.org/10.1016/j.jseas.2012.01.013>
- Yang, T., Chou, Y. M., Ferré, E. C., Dekkers, M. J., Chen, J. Y., Yeh, E. C., and Tanikawa, W. (2020). Faulting processes unveiled by magnetic properties of fault rocks. *Rev. Geophys.*, 58(4), e2019RG000690. <https://doi.org/10.1029/2019RG000690>
- Yang, X. H., Wang, Y. H., and Yao, X. Y. (2020). Characteristics of lithospheric magnetic field and seismomagnetic characteristics in Yunnan area. *J. Seismol. Res. (in Chinese)*, 43(4), 745–750. <https://doi.org/10.3969/j.issn.1000-0666.2020.04.018>
- Yuan, J. H., Gu, Z. W., Xin, C. J., Song, C. K., Chen, B., Wang, Z. D., and Wang, C. (2022). Observation and study of lithospheric magnetic anomalies on profile SD in Mongolia. *Appl. Sci.*, 12(17), 8517. <https://doi.org/10.3390/app12178517>
- Zeigarnik, V. A., Bogomolov, L. M., and Novikov, V. A. (2022). Electromagnetic earthquake triggering: Field observations, laboratory experiments, and physical mechanisms—A review. *Izv., Phys. Solid Earth*, 58(1), 30–58. <https://doi.org/10.1134/S1069351322010104>
- Zhang, H. Y., Su, S. P., and Zhao, H. Q. (2022). Variation of lithospheric magnetic field anomalies before the Menyuan, Qinghai $M_{5.9}$ earthquake in 2022. *China Earthq. Eng. J. (in Chinese)*, 44(3), 735–743. <https://doi.org/10.20000/j.1000-0844.20220115001>
- Zhang, H. Y. (2024). Dynamic evolution of horizontal vector of lithospheric magnetic field before and after the 2019 Fengnan $M_{5.45}$ earthquake. *Earthq. Res. China (in Chinese)*, 40(2), 426–435. <https://doi.org/10.3969/j.issn.1001-4683.2024.02.013>
- Zhang, L., Li, H. B., Sun, Z. M., Zhou, Y. M., Cao, Y., Wang, H., Ye, X. Z., and He, X. L. (2018). Rock magnetic evidence for the seismogenic setting of large earthquakes in the Longmen Shan fault zone. *Chinese J. Geophys. (in Chinese)*, 61(5), 1715–1727. <https://doi.org/10.6038/cjg2018M0160>
- Zhang, Y., Chen, S. G., Ma, H. Y., Yang, L., Lei, G., Xiao, S. T., Yan, W. S., and Yang, L. (2023). Retrospective analysis of lithospheric magnetic field anomalies of Menyuan $M_{5.9}$ earthquake from 2019 to 2021. *South China J. Seismol. (in Chinese)*, 43(1), 46–54. <https://doi.org/10.13512/j.hndz.2023.01.06>
- Zou, R., Guo, X., Zhang, Y. S., Qin, M. Z., and Yan, W. H. (2018). Using the active source data of Qilian Mountain to study the wave velocity change before and after the Menyuan $M_{5.64}$ earthquake in 2016. *Earthq. Res. China (in Chinese)*, 34(2), 283–292. <https://doi.org/10.3969/j.issn.1001-4683.2018.02.009>
- Zu, Q., Chen, C. H., Chen, C. R., Liu, S., and Yen, H. Y. (2021). The relationship among earthquake location, magnetization, and subsurface temperature beneath the Taiwan areas. *Phys. Earth Planet. Inter.*, 320, 106800. <https://doi.org/10.1016/j.pepi.2021.106800>