Distribution of igneous rocks in China revealed by aeromagnetic data

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Abstract

After several decades of aeromagnetic surveys, the measured data now cover nearly the entire Chinese continent and part of the China Sea. These data were first applied in this research and could provide important insights into the distribution of igneous rocks beneath the earth’s surface. Because different types of igneous rocks have a magnetic difference and produce distinct aeromagnetic anomalies on aeromagnetic AT image with reduction to the pole or other data calculating maps. By analyzing more than 240 thousand magnetic susceptibility data points and aeromagnetic anomalies of known igneous rocks in the Chinese continent, it was determined that mafic-ultramafic rocks commonly have a high magnetic susceptibility and cause linear and strong positive aeromagnetic anomalies. Intermediate-felsic rocks have a stable and low magnetic susceptibility and show a flat gradient variation and regular shape. Volcanic rocks have large variability in regard to magnetic susceptibility and romance; therefore, the aeromagnetic anomalies are always random or show variation within a planar area and decrease rapidly when an upward continuation is applied. Following the aeromagnetic data and calculating the maps of the vertical first order derivative and the tilt derivative, and combining this information with known outcrops of igneous rocks, we renewed the boundaries of 82 known mafic-ultramafic rocks, 228 known intermediate-felsic rocks and 131 known volcanic rocks. In addition, we newly mapped concealed igneous rocks of 203 mafic-ultramafic rocks, 2322 intermediate-felsic rocks and 494 volcanic rocks. The igneous rocks can be identified as nine ultra-mafic belts, 10 mafic belts (or regions), 27 intermediate-felsic belts and eight volcanic blocks. The results indicate that the mafic-ultramafic rocks are mainly distributed in Tibet, Erenhot of Inner Mongolia and northern Qilian and the smaller zones in the western Kunlun, Tianshan, western Junggar, eastern Tibet, Maqin in Gansu and the Ailao Mountain (Mtn.) areas. The mafic rocks are mostly outcropped in northern Tibet, southwestern Sanjiang, Kangdian in Sichuan, Baise and Rongjiang in Guangxi, Yinchang in Guizhou, Dabashan Mtn., Eastern and western China such as the circumference of Songliao Basin, Erlian Basin, the southern Yellow Sea - Subei Basin, Bohai Bay Basin, eastern Zhejiang, the circumference of Hainan Island, southern Sichuan - northern Yunnan, central Tibet, the Bachu area in Tarim Basin, Junggar Basin and Turpan-Hami Basin.

1. Introduction

Igneous rocks are “probes” for a better understanding of the deep Earth (Mo, 2011). The identification of igneous rocks is crucial to developing a mean for studying tectonic evolution. Certain igneous rocks are discernible by traditional methods based on observations of the ground surface, whereas others escape detection because they are covered by overburden or are exposed only in highly inaccessible areas. The traditional method for identifying igneous rocks is geological mapping to determine where lithological units are outcropped. However, using this method, it is hard to accurately define the boundary of the igneous rocks if only considering the outcrops observed by field mapping. Therefore, methods are needed to detect igneous rocks not identifiable by traditional means are based largely on geophysical approaches.

Magnetic anomalies are usually related to the underlying basement (igneous and/or metamorphic) rocks or by igneous bodies within sedimentary layers such as intrusive plugs, dykes, sills, lava flows and volcanic rocks (Gunn, 1997). Such anomalies are
produced by magnetic minerals contained in the rocks. With the increase of mafic minerals, the magnetic intensities of igneous rocks commonly become stronger (Liu et al., 2014; Zhang et al., 2004). Therefore, aeromagnetic data can be an effective tool to map the unknown igneous bodies, especially those emplaced and concealed within overburden and sedimentary rocks (Abdelsalam et al., 2016; Anderson et al., 2016; Anudu et al., 2014; Behrendt, 2013; Chernicoff et al., 2012; Døssing et al., 2013; Ferris et al., 1998; Finn and Morgan, 2002; Ferraccioli et al., 2002; Galindo-Zaldívar et al., 2013; González-Castillo et al., 2014, 2015; Mietha et al., 2014). These igneous rocks may serve as potential sources for a variety of minerals and heat which may be utilized as guidance for the exploration of polymetallic deposits and geothermal resources (Cui et al., 2012; Lehmann et al., 2015; Shi et al., 2009; Wang et al., 2007, 2012; Yan et al., 2009). Furthermore, volcanic rocks discernible by aeromagnetic data may be traps for oil and gas such as the Tarim Basin, Songliao Basin, Junggar Basin, Huanghua depression and Jiyang depression in China (Chen et al., 2005; Li and Gao, 2010; Liu et al., 2014; Wu et al., 2010; Yan et al., 2014; Yang et al., 2006).

Chinese geologists have compiled a series of geological and mineral resource maps since the 1970s. Together with more than 300 geologists, Ma (2002) published a geological atlas of China supported by the Chinese Geological Survey and Chinese Academy of Geological Sciences. This atlas includes Chinese intrusive and volcanic rocks on the scale of 1:12,000,000. Deng et al. (2016) reported a tectonic map of intrusive rocks in China on the scale of 1:2,500,000. These research achievements of igneous rocks are mostly based on geological survey data but are rare from geophysical perspective. In this study, we report on the newly compiled aeromagnetic data in China (Xiong et al., 2013). The study area is the entire Chinese continent and part of the China Sea. An advanced processing of the magnetic data using first order vertical derivatives and tilt derivatives are effective in detecting and enhancing magnetic anomalies associated with the edges of geological bodies and therefore useful in mapping or delineating igneous rock bodies. Together, with collected susceptibility measurements and the distribution of known igneous rock, we use these data to extrapolate outcropping volcanic rock bodies and other igneous intrusion’s boundaries and discontinuities into covered areas to constrain the overall size of the mapped igneous rocks. This contribution is an attempt to provide a new and significant insight on the distribution of igneous rocks in China by analyzing and interpreting the latest compiled aeromagnetic data. This

Fig. 1. Aeromagnetic ΔT image with reduction to the pole of China on the scale of 1: 5,000,000 (Xiong et al., 2013). A combination color contour and shaded relief map of reduced-to-pole magnetic anomaly data from the detailed compilation area over the Chinese continent and part of the China Sea. The contour interval is 10 nT from –100 to 100 nT, 20 nT for –200 to –100 and 100 to 200 nT, 50 nT for –400 to –200 and 200 to 400 nT, 100 nT for –1000 to –400 and 400 to 1000 nT, and 500 nT for more than 1000 nT and less than –1000 nT.
study will also provide more detailed geophysical evidence for the study of mineral, geothermal, petroleum and gas resources and tectonic evolution in the regions where igneous rocks exist.

2. Aeromagnetic anomalies of known igneous rocks

The aeromagnetic survey covered nearly the entire Chinese continent and part of the China Sea until 2011. The transformation of magnetic data using reduction to the pole with various dips at any latitude, upward continuation and magnetic derivation has been previously conducted and was published in 2013. Based on the aeromagnetic ΔT image with reduction to the pole of China (Fig. 1) and other edge enhanced maps and combined with geological data, we studied the magnetic susceptibility and aeromagnetic anomalies of known igneous rocks.

To map igneous rocks using aeromagnetic data, we first analyzed more than 240 thousand magnetic susceptibility data points that have been measured during the last several decades in China. We classified these data on the basis of lithology and then divided them into three types: mafic-ultramafic rocks, intermediate-felsic and volcanic rocks (Table 1). The result shows the distinct magnetic properties of various types of igneous rocks. The mafic-ultramafic rocks commonly show a high magnetic susceptibility ranging from 1800 to 8871 × 10⁻⁵ SI with an average of 5063 × 10⁻⁵ SI. The statistically average values show that ultramafic rocks (such as pyroxenite and peridotite) have the highest magnetic susceptibility, whereas mafic rocks such as diabase and gabbro show lower magnetic susceptibility. Intermediate-felsic rocks are usually lower than mafic-ultramafic rocks, but the magnetic susceptibility is stable in these rocks. The susceptibility values of this type ranges from 25 to 4210 × 10⁻⁵ SI with an average of 1521 × 10⁻⁵ SI. Volcanic rocks show a wide range of magnetic susceptibility and remanence; in particular, the magnetic intensity along a deep fault zone are caused by mafic-ultramafic rocks. The occurrence and similar magnetic properties may be different despite the same type of intrusions, because of the formation of different geological settings. Meanwhile, the amplitude of the magnetic anomalies is also related to the buried depth and the volume of the intrusive rocks.

2.1. Aeromagnetic anomalies of intrusive rocks

Aeromagnetic anomalies caused by intrusive rocks usually feature an isometric, ellipse or belt shape. From felsic to ultramafic, the magnetic susceptibility of igneous rocks increases gradually with the presence of mafic minerals (Table 1). The magnetic feature may be different despite the same type of intrusions, because of the formation of different geological settings. Meanwhile, the amplitude of the magnetic anomalies is also related to the buried depth and the volume of the intrusive rocks.

(1) Mafic-ultramafic rocks

Mafic-ultramafic rocks are ophiolites as fragments of ancient oceanic crust or intrusions. The practical measured magnetic susceptibility for these rocks is commonly n × 1000 SI and the highest is more than 10,000 SI. For example, the magnetic susceptibility of peridotite ranges from 1784 to 13,898 SI with an average of 7784 SI, whereas the value of gabbro is 0–11,841 SI with an average of 3536 SI. The occurrence and similar magnetic properties make it difficult to identify from the aeromagnetic data whether the rock is mafic or ultramafic. Therefore, the anomalies present an aeromagnetic anomaly zone or linear anomaly belt with high intensity along a deep fault zone are caused by mafic-ultramafic rocks in this study. The magnetic intensity of these rocks is usually strong and presents as a locally rising high aeromagnetic anomaly

### Table 1: Statistics of the magnetic susceptibility and remanence of different lithologies in China.

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Lithology</th>
<th>Number</th>
<th>Magnetic susceptibility (K × 10⁻⁵ SI) Mean</th>
<th>Remanence (Jr × 10⁻³ A/m) Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mafic-ultramafic rock</td>
<td>Ultramafic rock</td>
<td>1957</td>
<td>0–16,800 5709</td>
<td>0–89,000 839</td>
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<tr>
<td>Peridotite</td>
<td>863</td>
<td>1784–13,898 7784</td>
<td>710–156,000 8462</td>
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<tr>
<td>Pyroxenite</td>
<td>82</td>
<td>199–10,624 8871</td>
<td>126–9881 1509</td>
<td></td>
</tr>
<tr>
<td>Gabbro</td>
<td>4465</td>
<td>0–11,841 3536</td>
<td>0–41,600 947</td>
<td></td>
</tr>
<tr>
<td>Diabase</td>
<td>6562</td>
<td>0–10,300 2678</td>
<td>13–23,200 1735</td>
<td></td>
</tr>
<tr>
<td>Gabbrostone</td>
<td>725</td>
<td>360–8400 1800</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Intermediate-felsic rock</td>
<td>Diorite</td>
<td>19,949</td>
<td>0–9500 1760 1521</td>
<td>0–2182 564</td>
</tr>
<tr>
<td>Syenite</td>
<td>767</td>
<td>915–7300 4210</td>
<td>540–13,600 3960</td>
<td></td>
</tr>
<tr>
<td>Ivenite</td>
<td>2298</td>
<td>118–7070 2622</td>
<td>218–17,500 1500</td>
<td></td>
</tr>
<tr>
<td>Granite</td>
<td>37,923</td>
<td>0–10,920 856</td>
<td>54–2000 393</td>
<td></td>
</tr>
<tr>
<td>Adammellite</td>
<td>3344</td>
<td>30–2887 1257</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Granite porphyrite</td>
<td>2220</td>
<td>11–2262 350</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Granodiorite</td>
<td>23,973</td>
<td>0–8960 2004</td>
<td>0–5340 1916</td>
<td></td>
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<tr>
<td>Moyite</td>
<td>3085</td>
<td>5–4020 613</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Plagiogranite</td>
<td>761</td>
<td>0–40 25</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Volcanic rock</td>
<td>Mafic volcanic rock</td>
<td>4452</td>
<td>105–8830 1865 1318</td>
<td>– 500</td>
</tr>
<tr>
<td>Basalt</td>
<td>38,790</td>
<td>0–14,146 2570</td>
<td>0–93,900 1286</td>
<td></td>
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<tr>
<td>Trachybasalt</td>
<td>885</td>
<td>980–2600 1549</td>
<td>–</td>
<td></td>
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<tr>
<td>Spiliti</td>
<td>1341</td>
<td>–</td>
<td>1260</td>
<td></td>
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<tr>
<td>Andesite</td>
<td>30,315</td>
<td>0–16,336 1883</td>
<td>0–31,600 2723</td>
<td></td>
</tr>
<tr>
<td>Trachyte</td>
<td>5735</td>
<td>0–2910 605</td>
<td>0–3140 260</td>
<td></td>
</tr>
<tr>
<td>Keratophyre</td>
<td>725</td>
<td>–</td>
<td>766</td>
<td></td>
</tr>
<tr>
<td>Felsic volcanic rock</td>
<td>4268</td>
<td>0–670 266</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Rhyolite</td>
<td>16,315</td>
<td>0–11,000 1316</td>
<td>2900–17,000 10,000</td>
<td></td>
</tr>
<tr>
<td>Pyroclastic rock</td>
<td>16,590</td>
<td>0–3960 988</td>
<td>0–21,300 500</td>
<td></td>
</tr>
<tr>
<td>Tuff</td>
<td>20,366</td>
<td>0–11,450 1438</td>
<td>27–14,920 –</td>
<td></td>
</tr>
</tbody>
</table>
up to $n \times 10$ to $n \times 1000 \text{nT}$, which is an obvious feature with respect to the intermediate-felsic rocks in the aeromagnetic map.

(2) Intermediate-felsic rocks

The rocks mainly include diorite (quartz diorite and diorite porphyry) and granitoids (granodiorite, granite, granite porphyry, biotite granite and monzonitic granite), and they are spread in a wide area with a different lithology and are characterized by broad magnetic variations. From the susceptibility data, the magnetic of the intermediate-felsic rocks is obviously weaker than that in the mafic-ultramafic rocks. The magnetic susceptibility values mainly range from $n \times 10$ $\text{SI}$ to $n \times 1000 \text{SI}$ and rarely achieve 10,000 $\text{SI}$. Moreover, the values of intermediate rocks (average for diorite = 1760 $\text{SI}$, syenite = 4210 $\text{SI}$ and iernite = 2622 $\text{SI}$) are higher than those of felsic rocks (average for granite = 856 $\text{SI}$ and plagiogranite = 25 $\text{SI}$). Due to the different formation time and geological background, the same type of rocks with the same lithology may present distinct magnetic susceptibilities. Analyzed the aeromagnetic anomaly caused by known rocks, the magnetic intensity generally decreases from diorite to granodiorite to granite. Both diorite and granodiorite can produce significant magnetic anomalies but are unclear when the rock volume is smaller. Most of the granites can be identified in the aeromagnetic map and feature broad magnetic variation and some of them may be non-magnetic (such as those in Songpan, South Hunan) and show a negative anomaly on the aeromagnetic map. However, there is usually a circular anomaly around these non-magnetic granitic massifs due to the enrichment of magnetic minerals by thermal metamorphism in the host rock. This feature can be used to delineate the intermediate-felsic rocks with weak or non-magnetic anomalies (Zhu, 2013). Magnetic anomalies caused by intermediate and felsic rocks have a similar aeromagnetic feature, and the anomaly ranges from $n \times 10$ to $n \times 100 \text{nT}$ with a flat gradient and regular shape, either as an ellipse region or a linear belt in the Aeromagnetic $\Delta T$ and the vertical first order derivative with reduction to the pole.

To map the intrusive rocks, it is necessary to remove the anomalies caused by volcanic, metamorphic and other magnetic rocks and combine them with geological and geophysical data. The boundary of the intrusive rocks can be determined in one of the following ways:

(i) take the gradient zone as the boundary of the rocks on the aeromagnetic $\Delta T$ image with reduction to the pole;
(ii) or take the zero zone as the boundary of the rocks on the map of the vertical first order derivative with reduction to the pole when the aeromagnetic anomaly is smaller or unclear;
(iii) or take the inner circle of the magnetic gradient zone as the boundary of the rocks when the rocks are non-magnetic or feature a negative magnetic anomaly;
(iv) finally, compare the boundary delineation above the map of the tilt derivative with reduction to the pole to take a suitable correction, because a high aeromagnetic anomalous zone usually represents the boundary of the magnetic body on this map.

2.2. Aeromagnetic anomalies of volcanic rocks

Because of the quick consolidation when erupted to the earth's surface, volcanic rocks, such as basalt, andesite, tuff, volcanic breccia, lava, rhyolite and trachyte, are magnetically heterogeneous with a higher magnetic remanence (Table 1). The susceptibility of volcanic rocks is changed over a wide range; the results may exhibit large differences when the measuring point moves a small distance in the field survey. The average susceptibility values of volcanic rocks are lower than mafic-ultramafic rocks but similar with the values of intermediate-felsic rocks. However, the remanences in volcanic rocks show opposite characteristics that are closer to the mafic-ultramafic rocks. The susceptibility data slightly decreases from mafic to felsic volcanic rocks that similar with the magnetic feature of intrusive rocks, such as the average values of basalt, andesite and rhyolite are 2570, 1883 and 1316 $\text{SI}$, respectively.

The anomalies caused by these rocks are featured by a jumping variation along the survey profile with a strong amplitude and higher gradient, and by a ring, semi-ring or irregular belt with a planar sprawling variation on the aeromagnetic $\Delta T$ image with reduction to the pole. Therefore, these anomalies were referred to as the anomaly of volcanic rocks due to the difficulty in distinguishing them in detail from aeromagnetic data. The basalts have strong magnetic anomaly with a broad range of variation from $n \times 10$ to $n \times 1000 \text{nT}$, whereas andesite is lower than basalt and ranges from $n \times 10$ to $n \times 100 \text{nT}$. These anomalies sharply changed in the aeromagnetic maps and decrease rapidly when an upward continuation is applied.

According to the time of geological formation in Chinese continent, the aeromagnetic anomalies for the volcanic rocks (in southern China) formed in the Precambrian show as a linear zone with positive and negative amplitudes alternatively displayed along the tectonic strikes, and this is very different from the anomaly caused by the latest volcanic rocks with a sprawling presence. This indicates that the magnetism of old volcanic rocks became similar to the magnetic sedimentary and metamorphic strata after folding. The aeromagnetic anomalies for the volcanic rocks formed at a later time, and they are featured by sharply changed and irregular planar anomalies with alternative positive and negative anomalies, and this phenomenon is probably related to the heterogeneity and reversed magnetization of the volcanic rocks. Usually this phenomenon occurs when planar lavas or huge volcanic rocks cover the surface, e.g., the Permian basalt in the southern Sichuan and Paleogene volcanic rocks in the Qiangtang Basin (northern Tibet) produce such aeromagnetic anomalies. After confirmation with the known effusive rocks, the ages of the volcanic rocks were determined to be younger when they are distributed as a planar coverage, and most of the rocks are formed in late Paleozoic, Mesozoic and Cenozoic. Therefore, it can be inferred that the sharply changed and irregular anomalies with a planar shape were mostly caused by volcanic rocks at a younger age.

The steps for mapping the volcanic rocks should be as follows:

(i) Determine the anomalies caused by volcanic rocks on the aeromagnetic map combined with the geological background.
(ii) Consider the outer inflexion of single anomalies from the edge of the anomaly areas as the boundaries of the volcanic rocks along the survey profiles.
(iii) Take the zero value as the boundary of volcanic rocks by the vertical first order derivative with reduction to the pole.

3. Results and interpretation

From the Proterozoic to the Cenozoic, magmatic events in the Chinese continent were frequent and occurred in all of the tectonic cycles. It is generally known that a complete tectonic cycle or orogeny always includes three episodes: (1) depression of geosyncline during the pre-orogenic stage and accompanying the intrusion or eruption of mafic-ultramafic rocks; (2) crust uplift and folding in the syn-orogenic stage producing large quantities of granites; and (3) the post-orogenic stage that usually causes complicated magmatism. Therefore, magmatic action is always closely related
0.1 Yarlung Zangbo ultramafic rock belt

This ultramafic rock belt along the Yarlung Zangbo River starts at Gar and passes through Zhongba, Angren, Xigaze and Lang County from the west to the east in Tibet and extends approximately 1500 km long. The eastern region was not taken into account for this discussion due to a lack of aeromagnetic data available. There are many ophiolite rocks along this belt, such as in Luobusa, Zêtang, Dagzhuka, Bailang, Gêding, Sangsang, Saga, Zhongba, Danqiong, Hugh GuGabu, Pulan and Dongbo from east to west (Dai et al., 2011), and the belt can be divided into three segments according to the formation time: east (Qushui–Motuo), middle (Angren–Renbu) and west (Sino–Indian border to Saga). The western part may be divided into the sub-south (the Daba–Hugh GuGabu ophiolite belt) and the sub-north (the western Yarlung Zangbo/Dajiweng–Saga ophiolite belt) divisions (Pan et al., 1997). From the features of the aeromagnetic anomalies, an obvious discontinuity between the magnetic anomalies and the strike of the ophiolite belt can be established, i.e., aeromagnetic anomalies clearly show that the belt becomes two sub-belts from Renbu to the west. The northern branch passes through Dajiweng, Saga, Angren, Renbu and Qushui and Dalang from the west to the east. This anomaly belt links the sub-northern ophiolite belt of the western, middle and eastern segments linearly with positive anomalies associated with negative anomalies to the south. The amplitude of the anomalies may attain 300–700 nT, and even up to 1000 nT, which should correspond to the buried mafic-ultramafic rocks rather than the Meso-Cenozoic granitic rocks on the surface. The southern branch lays in a similar position to that of the sub-southern belt, where the ophiolite belt occurs from Daba to Hugh GuGabu (Pan et al., 1997). From the aeromagnetic map, this belt extends from Pulan and Zhada to the China-India boundary in the west and parallels the northern branch. These two branches are separated by a clear negative zone. The eastern segment of the southern branch shows a linear anomalous zone with a high amplitude of 300–900 nT, and the western one shows a string of chains with an amplitude of 100–200 nT. These two branches are different in regards to mining exploration, and the exploration of the Luobusa type chrome deposit should focus on the northern belt. However, the ores may be produced in the deep because the mafic-ultramafic rocks are mostly concealed in the west of Renbu.

(2) Pangong Tso-Nagchu ultramafic rock belt

This belt passes through Pangong Tso to Dengqen through Gerze, Nima, Bangor and Nagqu from the west to the east and is approximately 1600 km long and is composed of a series of discontinuous aeromagnetic anomalies. This belt can be subdivided into three segments: the eastern part from Dengqen to Basu has continuous anomalies with an amplitude of 100–400 nT; the middle part from Nima to Naqu has beaded-like anomalies with an amplitude of 0–400 nT and 800–1600 nT locally (e.g., Bam Tso); and the western part from Pangong Tso to Gerzesidis has beaded-like anomalies with a weak magnetism of approximately 100–400 nT and a few anomalies up to 800 nT. The anomalies obviously correspond to the exposed mafic-ultramafic rock (ophiolite), such as the ophiolites at Pangong Tso, Dongqiao, Anduo and Denggen. The anomalies quickly become smaller when an upward continuation is applied, especially when most of them vanish with an upward continuation of 5 km, implying that the mafic-ultramafic rocks are much shallower than those in Yarlung Zangbo ultramafic belts. The belt was developed in a back-arc basin of the mid-late Mesozoic in the southern margin of the Eurasian continent with a quick extension and closure, which destroyed the belt and led to incomplete ophiolite sequences (Wang et al., 1987). This may be the main reason for discontinuous and weak aeromagnetic anomalies. The ophiolites were extruded and pinched out in the south of Basu, which was considered as a result of a strong crust shortening and the horizontal displacement along the Cenozoic Gaoligong strike-slip fault. Geologists suggest that it may exist in the Luxi trench (depression) again in the western Yunnan (Zhong and Ling, 1993; Zhong et al., 1998). On the aeromagnetic map, a NS linear high anomaly zone with an amplitude of 100–800 nT probably indicates that the belt should continue to turn southward, which greatly support the geological inference.

(3) Jinsha River–Ailao Mtn. ultramafic rock belt

This belt is located in the western margin of the Yangtze block and passes through Garze, Lithang and Kangting with a NW–NNW strike. Although the ophiolites are discontinuous between the Jinsha River and Ailao Mtn., they share the same contemporary tectonic framework. The Garze-Lithang ophiolites were similar with the ophiolites along the Jinsha River and both of them were...
developed from a small rift-oceanic basin (Zhang and Zhou, 2001). The outcropped ultramafic rocks are characterized by some local rising anomalies with regular shapes and steep gradients and are narrow with amplitude of 50–100 nT. By analyzing the continuity of the anomalies, we suggest that most of the rocks are concealed, but not in great depth because the anomalies vanish when a 5 km upward continuation is applied.

(4) Western Kunlun-Altun Mtn. ultramafic rock belt

This belt is the product of the closing of the Qinling-Qilian-Kunlun Ocean in the northern margin of Qinghai-Tibet Plateau, and the age of the ophiolites along this belt are vary in different places. The ophiolites at Kudi in the western Kunlun were formed in the Neoproterozoic-early Paleozoic (Li and Zhang, 2014; Xiao et al., 2003), and the ophiolites along Honglougou-Lapeiquan and Apa-Mangya in the Altun were formed in the early Paleozoic (Zhang and Zhou, 2001). Arc anomalies along the Western Kunlun and Altun Mtn. are well correlated with the known rocks, which show positive aeromagnetic anomalies associated with negative values in the northern bank. The positive anomalies range from 100 to 900 nT.

(5) Qilian Mtn. ultramafic rock belt

The ophiolites in the Qilian Mtn. are mainly located at Tiger Mtn., Dachadaban, Tadungou, Bianmagou, and Yushigou (Zhang et al., 1997) and correspond to a NW magnetic anomaly zone in northern Qilian. This anomaly zone is characterized by a set of isolated and discontinuous magnetic anomalies of approximately 50–150 nT with steep gradients and regular shapes of circles or ellipses.

(6) Eastern Kunlun Mtn. ultramafic rock belt

The eastern Kunlun Mtn. ultramafic rock belt is discontinuously located in the southern margin of eastern Kunlun, and typical ophiolites are located at Animaqing. The belt corresponds to an EW aeromagnetic anomaly zone along which there are approximately 50–100 nT isolated anomalies with steep gradients and regular shapes of circles or ellipses.

(7) Tianshan Mtn. ultramafic rock belt

This belt strikes NWW and has four ophiolite belts in the Tianshan Mtn., including the late Paleozoic ophiolite belt at Bayingou in northern Tianshan, the early Paleozoic ophiolite belt at Mishigou in the north of Central Tianshan and Changawuzi in the south of Central Tianshan, and the late Paleozoic ophiolite belt at Seyuekeyayilake in southern Tianshan (Zhang and Zhou, 2001). All of these Paleozoic ophiolites have experienced strong metamorphism so that the magnetic features looks quite different. The ophiolite belt at Bayingou is composed of gabbro (bottom) and basalt (top) with an emplacement of serpentined peridotite, and the anomalies are 0–100 nT and occur as linear zone or beaded-like zone. The Mishigou ophiolitic melange belt is composed of serpentined peridotite, gabbro, basalt, quartzite, gneiss and granite with a matrix of chlorite sericite quartz schist and albite actinolite schist. These rocks may have originated from greywacke and mafic volcanic rock (Zhang and Zhou, 2001), which led to weak flat positive anomalies of 0–100 nT above the negative background. The ophiolite at Seyuekeyayilake is composed of metamorphic peridotite, amphibolite mylonite, schistositized dolerite and pillow lava, and the rocks also display a beaded-like weak and flat positive anomaly of 0–200 nT above a negative background. The fact that the anomaly disappears after a 5 km upward continuation implies that the volume of the rocks is smaller.

(8) Junggar ultramafic rock belt

This belt is located in the west and east of the Junggar Basin. The ophiolites in the northwestern Junggar are mainly distributed in Tangbale, Mayile Mtn., Darbut and Hongguleleng, whereas the ones in northeastern Junggar spread in Kelameili, Aermantai, Keke-sentao–Josiahara and Kulty (Zhang and Zhou, 2001). The anomalies caused by these rocks display a steep gradient and isolated high anomalies with regular shapes with an amplitude range from 100 to 300 nT. The magnetic anomalies weakly match with the rarely exposed ophiolitic rocks along this belt, which indicates that most of the rocks might be buried in the depth along the Darbut Fault zone and the Kelameili Fault zone.

(9) Hegen Mtn.–Erenhot ultramafic rock belt

This belt is approximately 1000 km along the Eastern Helingol, Hegen Mtn., Northern Abag, Southern Erenhot and Bameulan and shows a NE trend. The outcropped ophiolites are scattered around the southern margin of the Siberian block and most of them were formed in the early period of the late Paleozoic. The magnetic anomalies from the rocks along both sides of the Erenhot-Western Wuqi Fault generally have a steep gradient and regular shapes (circles or ellipses) with an anomaly of 100–500 nT and a maximum up to 1000 nT.

(10) Mafic rock belt (regions)

Similar to the analysis above, we can characterize the Chinese continent by ten mafic rock belts (regions): the Memartso–Ding-gou region, the Sanjiang belt, the Minfeng–Ruqiang belt, the Xichang–Panzhuhua belt, the Napo–Baize region, the Yinjiang–Rongjiang region, the Ankang–Anlu belt, the Tancheng–Bengbu region, the Qinzhou–Hangzhou belt and the Northern Bayan Obo–Beishan belt as well as other distributed sporadically in Yuli, Alashan, Longuel and South China (Fig. 2). The anomalies from these rocks show regular ellipses or narrow zones on the magnetic field with a steep gradient and a range from 50 to 250 nT and a gradient of 10–25 nT/km on the vertical first derivative map.

3.2. Mapping of intermediate-felsic intrusive rocks

Intermediate-felsic magmatic rocks were formed in the Chinese continent since the Proterozoic with variable lithologies, and most of the granites are intrusive complexes formed by multi-periods and multi-stages. The most active of the intermediate-felsic magmatism occurred in late Paleozoic and Mesozoic-Cenozoic, and the intrusive rocks are widely distributed in orogens and rarely in cratons. The sizes of the intrusive rocks range from 1000 km² to n × 10,000 km².

Based upon the aeromagnetic data, the magnetic intermediate, intermediate-felsic and felsic intrusive rocks were inferred, and we renewed the boundaries of 228 known intermediate-felsic rocks and newly mapped 2322 concealed intermediate-felsic rocks. These rocks can be identified as 27 intermediate-felsic belts (Fig. 3 and Table 2). The distributions of these rocks are constrained spatially by deep faults.
3.3. Mapping of volcanic rocks

Volcanic events were frequent during all of the geological periods in China, and the lithologies were strictly constrained by the tectonic setting; thus, the distribution of volcanic rocks shows clear regularity. For example, the volcanism in Northwest China was intense during the Paleozoic, a large quantity of marine or marine-terrestrial volcanic rocks were produced with a main strike of NWW. During Mesozoic to Cenozoic, the center of volcanic action migrated to East China near the peri-Pacific where terrestrial volcanic rocks developed with the strike of NEE or NE. Tibet volcanism was most active in the Cretaceous and Cenozoic. Outcrops of mafic to felsic and alkali volcanic rocks were found in the Chinese continent but most of them were intermediate-felsic volcanic rocks. These rocks caused unique magnetic anomalies and were available and able to be defined by aeromagnetic data. Generally, Proterozoic or early Paleozoic volcanic rocks appear as linear anomaly zones because they suffered long-term metamorphism, whereas the Late Paleozoic and Mesozoic-Cenozoic ones present irregular anomalies within planar zones (Fig. 4).

(1) Xinjiang area

Volcanic eruptions occurred during all of the geological period from the Achaean to the Cenozoic in this area, and occurred most frequently in the Late Paleozoic. Precambrian volcanic rocks sporadically outcropped in this area experienced a different degree of metamorphism. Outcrops of volcanic rocks were linearly distributed in the Altay, Junggar, and Tianshan. Volcanic rocks are composed of spilites and keratophyres in the Altay, which caused aeromagnetic anomalies of 150–350 nT with a maximum up to 900 nT. Basalt and andesite are common in the Junggar with anomalies ranging from 100 to 350 nT even up to 400 nT. Mafic lava and calc-alkali intermediate-felsic volcanic rocks show weaker magnetic anomalies in western Tianshan with anomalies ranging from 50 to 220 nT, and a portion may reach 370 nT. The aeromagnetic data indicate that most concealed volcanic rocks strike to NW and show a close relation with the tectonic framework.

(2) Tibet area

The volcanic rocks in Tibet were formed in the Mesozoic-Cenozoic and are mainly located in central Tibet. From the late Jurassic to the Cretaceous, a marine eruption was concentrated in the Gangdise and Nyenchen Tanglha region forming a suite of calc-alkali volcanic rocks, which are composed of andesite and trachyandesite interbedded with some basaltic andesite and rhyolite. The volcanic activities then switched from marine to terrestrial since the Cenozoic. The action center moved to Gangdise...
and even northern Tibet, which formed calc-alkali and alkaline volcanic rocks from mafic to felsic in the Paleogene and most of them are basaltic trachyandesite and trachyandesite with some trachybasalt, trachyte and phonolite. The volcanic rocks in the Tibetan area are featured by irregular variations on the aeromagnetic map from 25 to 75 nT and with some up to 100–150 nT. By analyzing the aeromagnetic anomalies, the strikes of newly mapped volcanic rocks are EW- or NWW- trending, which were strictly controlled by regional structure.

(3) The Sanjiang area in southwest China

The outcrops of volcanic rocks in this area are mainly distributed in Nujiang, Lantsang, Jinsha and Red River and their watersheds, i.e., Yanshiping, Qamdo, Weixi and Shuangjiang. Most of these rocks were mainly formed by Neopaleozoic volcanism. In the Devonian and Carboniferous, there is a suite of spilite and keratophyre volcanic clastic that was developed in Jinghong. Permian volcanism lasted a very long time and produced a large quantity of spilite and keratophyre. This process was still active during the Triassic period, and thus, intermediate-mafic volcanic rocks were found in middle-late Triassic. The responses of the rocks in this area are not distinct on the aeromagnetic map, and only a few rocks causing linear or banded anomalous zone of 25–100 nT and can be identified clearly from the background field.

(4) Kang Dian area

An eruption of mafic lavas dominated in this area during the Mesoproterozoic and the Neopaleozoic. The lithology changed from oceanic tholeiite in the southeast to continental tholeiite in northwest. Several stratigraphic units were found in the middle and upper Yangtze region, where developed volcanic rocks or the volcanic-sedimentary assemblage, for example, lava, pyroclastic rock, and the volcanic-sedimentary assemblage among the strata of Sanhuashi Group, Houhe Group, Bikou Group and Xixiang Group, and mafic to felsic lava in Fanjingshan and Shuangxiwu Group, were found. These volcanic rocks have no obvious magnetic anomalies. In the Permain, a major eruption happened in the Yunnan, Guizhou and Sichuan regions and produced a vast area of plenar basaltic magma composed of alkali basalt and tholeiite. These rocks lead to promiscuously magnetic anomalies within a vast area, which are irregular with amplitude of 100–300 nT, but the amplitude is less than 50 nT in Anshun and is probably due to the thinning of the basalt stratum in this region. The aeromagnetic data indicate that the volcanic rocks were constrained mainly by NS faults and locally by NE and NW faults.

(5) The Lower Yangtze and Southern China

Due to the tectonic activities of the peri-Pacific, the volcanism in the Lower Yangtze and Southern China were very active and
produced a vast amount of mafic, intermediate-mafic and intermediate-felsic effusive rocks in the Mesozoic and the Cenozoic. The volcanic rocks within the Lower Yangtze in the Mesozoic and the Cenozoic mainly spread along Great Khingan Mtn. and basins on both sides (Songliao Basin and Erlian Basin), including Shandong peninsula, south of Bo Hai, North of South Yellow Sea.

Table 2
Magnetic intermediate-felsic intrusive rock belts revealed by aeromagnetic data in China.

<table>
<thead>
<tr>
<th>Belt No.</th>
<th>Belt Name</th>
<th>Location</th>
<th>Aeromagnetic anomalies (nT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Great Khingan Mtn. rock belt</td>
<td>West of eastern margin fault of Great Khingan, North of Erenhot-WesternUjimqinQi fault</td>
<td>30–120, highest to 300–400</td>
</tr>
<tr>
<td>2</td>
<td>Zhangguangcai-Changbai Mtn. belt</td>
<td>East of Yilan-Yitong fault, including Sanjiang Basin, Zhangguangcai, Changbaishan and Liaodong peninsula</td>
<td>50–250, highest to 400</td>
</tr>
<tr>
<td>3</td>
<td>Lesser Khingan-Songaio belt</td>
<td>East of eastern margin fault of Great Khingan, West of Yilan-Yitong fault, North of Bayan Obo-XarMoreen fault</td>
<td>100–300, highest to 400</td>
</tr>
<tr>
<td>4</td>
<td>Beishan-North China belt</td>
<td>Beishan-YNshan-Yanshan and XiLinhok</td>
<td>75–200, highest to 300</td>
</tr>
<tr>
<td>5</td>
<td>Altai belt</td>
<td>North of Burqin fault</td>
<td>30–250</td>
</tr>
<tr>
<td>6</td>
<td>Junggar belt</td>
<td>South of Burqin fault, North of Northern Tianshan fault</td>
<td>50–230</td>
</tr>
<tr>
<td>7</td>
<td>Tianshan belt</td>
<td>South of Northern Tianshan fault, North of southern margin fault of Tianshan</td>
<td>20–300</td>
</tr>
<tr>
<td>8</td>
<td>Altun belt</td>
<td>Altun Mtn. and Minfeng, Qemo, Ruoqiang</td>
<td>25–300</td>
</tr>
<tr>
<td>9</td>
<td>West Kunlun Mtn. belt</td>
<td>South of eastern margin fault of Western Kunlun, North of Kangxiwa fault</td>
<td>50–300</td>
</tr>
<tr>
<td>10</td>
<td>East Kunlun Mtn. belt</td>
<td>Between north margin fault of Eastern Kunlun and middle Kunlun fault</td>
<td>50–250</td>
</tr>
<tr>
<td>11</td>
<td>Qilian Mtn. belt</td>
<td>Qilian Mtn., Qaidam basin, and the area between northern margin fault of Northern Qilian and northern margin fault of Eastern Kunlun</td>
<td>50–300</td>
</tr>
<tr>
<td>12</td>
<td>Hexi corridor belt</td>
<td>South of Helushan-Axayouqi fault, North of northern margin fault of Northern Qilian, West of western margin fault of Ordos</td>
<td>30–250</td>
</tr>
<tr>
<td>13</td>
<td>Qining-DabieMtn.belt</td>
<td>Qining, Dabie, Dabashan and Jianghan Basin</td>
<td>150–400 (Dabieshan), 20–50</td>
</tr>
<tr>
<td>14</td>
<td>Hoh Xil-Bayan Har belt</td>
<td>South of Middle Kunlun fault and Kangxiwa fault, North of Lazhulong–Yushu fault, West of Wudu-Kanding fault</td>
<td>20–50</td>
</tr>
<tr>
<td>15</td>
<td>Longmu Co-Shuanghu belt</td>
<td>Shuanghu, Donggou, Longmu Co</td>
<td>150–250, 50–100</td>
</tr>
<tr>
<td>16</td>
<td>Gangdise-Nyenchentanghita belt</td>
<td>Lhorong, Biru, Gongbo'gyamda, Cuode, Lhasa in Tibet</td>
<td>170–300</td>
</tr>
<tr>
<td>17</td>
<td>Qamdo-Alaoh Mtn. belt</td>
<td>Yaneshping, Qamdo, Bayu, Zhongdian, Muli, Alaio Mtn. and Simao in Sanjiang area</td>
<td>40–130, 150–200</td>
</tr>
<tr>
<td>18</td>
<td>Southeast coast belt</td>
<td>Southeast of Beihai-jiangshan-Shaxingan fault</td>
<td>100–275, 350–400</td>
</tr>
<tr>
<td>19</td>
<td>Shandong peninsula belt</td>
<td>North of Jiaxian-Xiangshui fault, West of Tancheng-Lujiang fault, including Shandong peninsula, south of Be Hai, North of South Yellow Sea</td>
<td>100–200</td>
</tr>
<tr>
<td>20</td>
<td>Taihangshan-Luliangshan belt</td>
<td>West of Shijiazhuang-Changzhi fault</td>
<td>200–400</td>
</tr>
<tr>
<td>21</td>
<td>North China plain belt</td>
<td>East of Shijiazhuang-Changzhi fault, South of Baotou-Chaoyang fault, West of Tancheng-Lujiang fault, North of Lanxian-Bengbu fault</td>
<td>100–300</td>
</tr>
<tr>
<td>22</td>
<td>Xinyang-Huqiuq belt</td>
<td>South of North China plain</td>
<td>50–300</td>
</tr>
<tr>
<td>23</td>
<td>Lower Yangtze belt</td>
<td>Jiangsu and North of Zhejiang</td>
<td>50–300</td>
</tr>
<tr>
<td>24</td>
<td>Longmenshan belt</td>
<td>East of Wudu-Kanding fault, West of Longmenshan fault, South of Luyue-Tanghe fault</td>
<td>30–100</td>
</tr>
<tr>
<td>25</td>
<td>Youjiang belt</td>
<td>Youjiang and Nanpanjiang area</td>
<td>30–100</td>
</tr>
<tr>
<td>26</td>
<td>Kangdian belt</td>
<td>East of Luqunjiang fault, West of Shizou-Mile fault, South of Weixin-Rongjiang fault, North of Jingshajiang-Honghe fault</td>
<td>50–200</td>
</tr>
<tr>
<td>27</td>
<td>Xuefengshan-Jiulingshan belt</td>
<td>Wulinshang, Xuefengshan, Jiulingshan, Luoxiaoshan and Dongtenghu basin</td>
<td>20–200</td>
</tr>
</tbody>
</table>

(6) East Kunlun-Qilian Mtn. area

Volcanic rocks in this area were formed during the period from the Proterozoic to the Cenozoic and were widely distributed in the Qilian Mtn., East Kunlun, Altun Mtn. and Hoh Xil. The eruption switched from the marine to the terrestrial since Triassic. In the Songpan-Ruoergai region, the volcanic assemblages are pillow spilite, spilitic volcanic clastolite and basalt which erupted mainly in the Silurian, whereas the Cenozoic volcanics were mostly distributed in the Hoh Xil region, and the lithologies are andesite, basaltic trachyandesite and trachyandesite with interbedded basaltic andesite and rhyolite. Aeromagnetic anomalies caused by these rocks are approximately 25–70 nT and are not easy to identify from the background because of the weaker magnetism of rocks and high flight altitude (approximately 2000 m) in the survey. In East Kunlun and the Qilian Mtn., volcanic rocks were widely erupted during the Ordovician and Silurian in a vast planar area that included andesite, interbedded basaltic andesite, dacite, rhyolite, subalkaline basalt and basaltic andesite. There are some Proterozoic and Mesozoic volcanics in this area, but the scale is smaller than the Paleozoic ones. Most of the volcanic rocks in this region are weak or even no magnetism and only some of them could produce aeromagnetic anomalies of ~100 nT.

(7) Northeast China

This region consists of Great Khingan Mtn., Songliao Basin, Sanjiang Basin, Erlian Basin, Lesser Khingan Mtn., Changbai Mtn., Yanshan Mtn. and East Liaoning. The volcanic activities continued for a long time from the Paleozoic to the Cenozoic with a dominant peak in the Mesozoic-Cenozoic. The volcanic rocks in the Mesozoic-Cenozoic mainly spread along Great Khingan Mtn. and basins on both sides (Songliao Basin and Erlian Basin) with a NNE-trending to constitute the Great Khingan-Yanshan volcanic belt, which has become an important volcanic zone in eastern China and also an important part of the Pacific-Rim volcanic belt. This belt reaches
the western margin of the Songliao Basin in the east, Erenhot in the west, the north of Great Khingan Mtn. in the north and the south banks of Yanshan Mtn. in the south. Combined with the lithologies, its aeromagnetic anomalies are different from west to east in this belt. As shown in the geological data, the west segment scatters along Genhe River-Erenhot and are composed of trachyandesite-trachyte and dacite-rhyolite with less alkali basalt, basaltic andesite and andesite. On the magnetic map, these rocks correspond to the magnetic anomalies of 25–200 nT (and some up to 250–350 nT) with irregular change in a planar area, and some rocks do not have magnetic response due to the magnetic inhomogeneity within this region. In the eastern part, the volcanism took place along the Zhalantun-Doron and produced a rock assemblage of andesite, dacite and rhyolite with less trachyandesite and trachyte. Most of these volcanic rocks caused irregularly changed magnetic anomalies in a planar area with values ranging from 100 to 500 nT and a maximum up to 600–900 nT.

Along the Songliao Basin, Sanjiang Basin and east of Liaoning, the volcanism was weak and only developed a suite of intermediate-mafic volcanic rocks, including trachyandesite and andesite, with less basaltic trachyandesite, basalt and tholeiite. These rocks have a strong magnetism and present an irregular changed magnetic anomaly belt or zones with anomaly values of 100–300 nT and a maximum up to 500 nT.

Canceled volcanic rocks inferred by aeromagnetic data were mainly distribute within the Erlian Basin, Songliao Basin and Sanjiang Basin, which were consistent with regional NE faults except that the rocks in the Erlian Basin strike to NEE-trending, implying that volcanic activities accompanied these two sets of faults.

(8) East of North China

This area includes northern China and Shandong Peninsula, where rare outcrops of volcanic rocks were found, but the formation periods of these rocks last from the Archean to the Cenozoic. Among them, the Proterozoic and Mesozoic-Cenozoic volcanic rocks were widely distributed, whereas the Paleozoic ones were seldom. Archean and Paleoproterozoic volcanic rocks are metamorphosed during long-term tectonic movement. Mesoproterozoic volcanic rocks appear primarily in Xionger Mnt. of the Henan Province, most of which are pyroxene andesite with less dacite, rhyolite and volcanic clastolite. Some aeromagnetic anomalies caused by these rocks in this area show banded anomaly zones (50–175 nT) with regular shapes, and this may attribute to the magnetic changes of rocks after metamorphism. The Mesozoic-Cenozoic volcanic rocks appear in the Shandong Peninsula, Xuzhou and Jining-Beijing with small outcrops. The lithologies are composed of basaltic trachyandesite, trachybasalt and tholeiite with less trachybasalt, trachyte, basalt and dacite in the Mesozoic, whereas they are composed of alkali basalt, trachybasalt and tholeiite in the Cenozoic. The magnetism of these volcanic rocks varies greatly;

Fig. 4. The division of volcanic rocks by aeromagnetic data in China. ① Xinjiang area, ② Tibet area, ③ Sanjiang area in southwest China, ④ Kang Dian area, ⑤ Lower Yangtze and Southern China, ⑥ East Kunlun-Qilian Mtn. area, ⑦ Northeast China, ⑧ East of North China.
thus, the magnetic anomalies show different characteristics within different areas, for example, some anomalies are banded or zoned in a regular shape, whereas others are sharply changed in a planer area with an irregular shape. The values of the anomalies are range from 50 to 200 nT with a maximum of 500–700 nT.

4. Conclusions

According to the magnetism of igneous rocks, this study helps to characterize the distribution of igneous rocks in the Chinese continent and part of the China Sea. Usually, the geological method can hardly define the igneous rocks that were buried by sedimentary rocks or sea water, but the aeromagnetic survey could compensate for this deficiency if the igneous rocks show a magnetic difference with country rocks. However, the aeromagnetic data are unavailable when anomalies of non-magnetic igneous rocks are superimposed on the background of non-magnetic lithologies. Based upon the latest aeromagnetic data in China, we statistically analyzed more than 240 thousand magnetic susceptibility data points and summarized the characteristics of the different igneous rocks. Combined with the geological setting and outcrops of igneous rocks in China, we renewed the boundaries of 82 known mafic-ultramafic rocks, 228 known intermediate-felsic rocks and 131 known volcanic rocks, and newly mapped concealed igneous rocks of 203 mafic-ultramafic rocks, 2322 intermediate-felsic rocks and 494 volcanic rocks. These rocks could be divided into nine ultramafic rock belts, 10 mafic rock belts (regions), 27 intermediate-felsic rock belts and eight volcanic rock areas.

The ultramafic rocks are characterized by linear and high aeromagnetic anomaly belts, which occur mainly in Tibet, Erenhot, and northern Qilian, and these belts extend along deep faults or sutures, such as the Yarlung Zangbo fault zone, PangongTso-Nyima fault, Erenhot-West Ujimgin fault and northern margin fault of northern Qilian. The ultramafic rocks are also distributed in the west Kunlun Mtn., Tianshan Mtn., West Junggar, East Tibet, Maqin and Ailao Mtn. According to the aeromagnetic data, the ultramafic rock belt along Yarlung Zangbo can be divided into two sub-belts from Rinbung towards the west. The northern branch passes Dajiweng, Saga, Ngamring, Rinbung, Quxu and Nang County from west to east, and the southern one passes Daba, Xiugugabu, Purang, Zanda and the China-India borders from west to east. These two branches are separated by a clear negative zone. Furthermore, the southern branch could be subdivided into two segments. The eastern segment is linear and strong aeromagnetic anomalies, while the western segment is characterized by beaded-like anomalies. PangongTso-Nyima ultramafic rocks are not present in the south of Baxoi County, but aeromagnetic data show a NS linear anomaly belt in Mangshi in the Yunnan Province, these two belts may have the same origin.

The mafic rocks show regular ellipses or narrow zones on the magnetic field with a steep gradient. The anomaly values range from 50 to 250 nT. The rocks are mostly distributed in north Tibet, Sanjiang, Baise and Rongjiang of the Guaxi Province, Yinjiang of Guizhou Province, Daba Shan, south of Dabie Mtn., Bengbu of Anhui Province and Qiemo of Xinjiang Province. The intermediate-felsic rocks are characterized by a flat gradient and regular shape and either an ellipse region or a linear belt in the aeromagnetic AT image with reduction to the pole. They are most widely distributed in orogens and rare in cratons. Magnetic anomalies caused by volcanic rocks represent a jumping variation along the surveying profile with a strong amplitude and higher gradient, and by a ring, semi-ring or irregular belt with a planar sprawling variation on the aeromagnetic AT image with reduction to the pole. Most of them are distributed in Songliao Basin, Erlian Basin, Southern Yellow Sea-northern Jiangsu Basin, Bohai Bay Basin, eastern Zhejiang Province and surrounding Hainan Province. In the west of China, volcanic rocks are distributed in southern Sichuan – northern Yunnan, central Tibet, Marabishi County of Xinjiang Province and the north of Junggar Basin and Tuha Basin. This work provides a new distribution map of igneous rocks in China from a geophysical perspective. These findings will play an important role in concealed magmatic rocks and tectonic research. Meanwhile, the results will also provide a more detailed geophysical evidence for the study of mineral, geothermal, petroleum and gas resources in the regions where igneous rocks exist.

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References


Behrendt, J.C., 2013. The aeromagnetic method as a tool to identify Cenozoic magmatism in the Western Antarctic Rift System beneath the Western Antarctic Ice Sheet–A review; Thiel subglacial volcano as possible source of the ash layer in the WAISCORE. Tectonophysics 585, 124–136.


