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Research paper

Characteristics of the crystalline basement beneath the Ordos Basin: Constraint from aeromagnetic data

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ABSTRACT

Aeromagnetic anomaly zonation of the Ordos Basin and adjacent areas was obtained by processing high-precision and large-scale aeromagnetic anomalies with an approach of reduction to the pole upward continuation. Comparative study on aeromagnetic and seismic tomography suggests that aeromagnetic anomalies in this area are influenced by both the magnetic property of the rock and the burial depth of the Precambrian crystalline basement. Basement depth might be the fundamental control factor for aeromagnetic anomalies because the positive and negative anomalies on the reduction to the pole-upward-continuation anomaly maps roughly coincide with the uplifts and depressions of the crystalline basement in the basin. The results, together with the latest understanding of basement faults, SHRIMP U-Pb zircon dating of metamorphic rock and granite, drilling data, detrital zircon ages, and gravity data interpretation, suggest that the Ordos block is not an entirety of Archean.

1. Introduction

Chinese geoscientists have been studying the North China Craton (NCC) for approximate 50 years (Ji et al., 2008). In the last decade, a series of noteworthy achievements has been achieved (Zhao et al., 1998; Zhai et al., 2000; Kusky et al., 2001, 2007; Zhai and Liu, 2001; Zhao et al., 2001a,b; Wilde et al., 2002, 2004, 2005, 2008; Kusky and Li, 2003; Zhai and Liu, 2003; Zhai et al., 2003; Faure et al., 2004, 2007; Guo et al., 2005, 2012; Kröner et al., 2005a,b, 2006; Wilde and Zhao, 2005; Zhai et al., 2005; Zhao et al., 2005; Santosh et al., 2006, 2007a,b, 2008, 2009a,b, 2010, 2012; Kusky and Santosh, 2009; Santosh, 2010; Santosh and Kusky, 2010; Kusky, 2011a,b; Peng et al., 2011, 2012; Wan et al., 2011, 2012; Zhai and Santosh, 2011; Lü et al., 2012; Du et al., 2013; Li et al., 2013a,b; Ren et al., 2013; Yang et al., 2013; Zhao and Zhai, 2013; Zheng et al., 2013). Among them, the research on the NCC destruction has been a particular point of emphasis (Xu, 2001; Zhang et al., 2002, 2012a,b; Yang et al., 2008; Xu et al., 2009; Zhu and Zheng, 2009; Wang et al., 2010; Lan et al., 2011; Lin et al., 2011; Pei et al., 2011; Tian and Zhao, 2011; Xiong et al., 2011; Zhang et al., 2011; Zhu et al., 2011; Huang et al., 2012; Li et al., 2012a,b,c; Wang et al., 2012; Zhang, 2012a,b; Zhang et al., 2012a,b,c; Zheng et al., 2012; Zhou et al., 2012a,b; Zhu et al., 2012a,b; Li, 2013; Ling et al., 2013; Shen et al., 2013; Xia et al., 2013)—it is regarded as the best example of craton destruction by the international academic community (Carlson et al., 2005). Widespread agreement has been achieved that large-scale lithospheric mantle thinning and transformation beneath the eastern NCC occurred mainly in the Mesozoic. Nevertheless, compared with the eastern NCC, which has thinner lithospheric mantle (only 60–100 km), about 200 km-thick craton-style lithosphere remains beneath the Ordos Basin, except for the Yinchuan-Hetao and Fen-Wei thin-lithosphere rift-depressions, which are less than 100 km thick, that formed in the Cenozoic (Chen et al., 2006, 2008, 2009a,b; Chen, 2009; Zhu et al., 2011, 2012b; Cheng et al., 2013). This means that the Ordos block did not experience lithospheric thinning like what had happened in the Eastern Block of the NCC. Therefore, lithospheric features of the Ordos block, especially characteristics of its deep basement, hold the attention of those geologists who are engaged in the study of the NCC. However, so far, little is known about its basement features. Much of the current knowledge was hypothetical, based on indirect geophysical data and outcrops around the Ordos Basin (Ma et al., 1979; Zhang, 1982, 1989; Guan et al., 1987; Hu et al., 1990; Zhang et al., 1991; Wang and Zhang,

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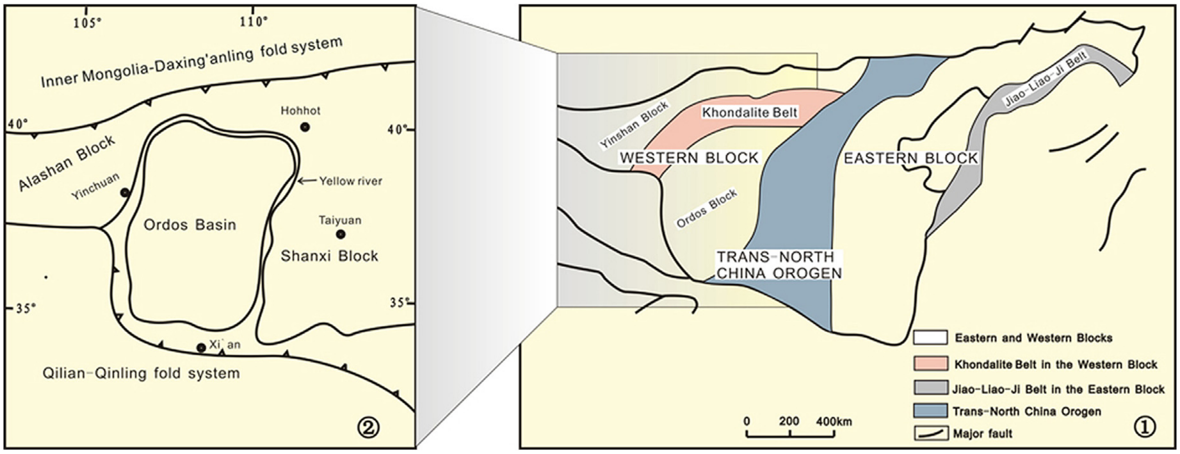

Figure 1. Regional tectonic position of the Ordos Basin (① after Zhao et al., 2005; ② after Xue et al., 2011).

1992; Bai et al., 1996; Jia et al., 1997; Deng et al., 1999, 2005; Ding, 2000; Jiang et al., 2000; Bai et al., 2007; Wang et al., 2007; Li and Gao, 2010).

Magnetic variations can reveal the distributions of various rock types, ages, and fold structures of mountain belts. Most of the significant tectonic phenomena in the Ordos Basin can be clearly demonstrated in regional aeromagnetic anomaly maps (Wu et al., 2003); similar basin basement features elsewhere also have been studied by aeromagnetic anomalies (Johnson and Swain, 1995; Ram et al., 2007; Bahadur et al., 2008). The aeromagnetic anomalies range from −514 to +904 nT and reveal different zones with distinct anomaly amplitudes. On the basis of aeromagnetic anomalies, the Ordos Basin can be divided into several parts. Along with recent progress made by regional geological surveys, drilling, isotope chronology, and seismic tomographic imaging information, we make an integrated interpretation to direct future research on the Ordos Basin basement.

2. Geological background and rock magnetism characteristics

The Ordos Basin, a major source of hydrocarbons, is located in the western NCC (Fig. 1). It occupies an area of approximately 320,000 km^2 and is bordered by 35° and 40°30′ N and 106°20′ and 110°30′ E (ECPGC, 1987). The Ordos Basin is a cratonic basin with stable subsidence and multicycle sedimentation (Yang, 2002). It is characterized by simple structures, gentle changes in the crust thickness, and geologic units inclined to the west within the basin (Yang et al., 2005). It also exhibits features of holistic rigidity and internal heterogeneity (Jia and Zhang, 2005). The Ordos Basin developed rectangular fault blocks in the Paleozoic era and was cut by an adjacent, faulted depression system in the Cenozoic era (Zhang, 1989). Consequently, its tectonic framework appears as a stable block surrounded by active tectonic belts. It is bounded to the north by the Hercynian orogenic belt in the Inner Mongolia–Daxing'anling area (Xue et al., 2011), and to the south by the Indosinian orogenic belt in the Qilian–Qinling area (Xue et al., 2011). It is separated from the Shanxi block in the east and the Alashan block in the west (Fig. 1).

The crystalline basement beneath the Ordos Basin is covered by Neoarchean, Paleoproterozoic, Meso-Neoproterozoic, Paleozoic, and Meso-Cenozoic deposits, that average 4–5 km thick (Yang, 2002; Yang et al., 2005). Basement metamorphic rocks outcrop sporadically around the basin (Zhai and Liu, 2003; Xia et al., 2006a,b, 2008), and the framework of "three uplifts and two depressions" is distributed from north to south (Yang, 2002). In general, magnetism of metamorphic rocks and igneous rocks is higher, but is lower for the sedimentary cover (Wang and Zhang, 1992; Li and Gao, 2010). Thus, the distribution of crystalline basement rocks can be assessed via aeromagnetic anomalies. Positive magnetic anomalies in the Ordos Basin and adjacent areas are mainly induced by Archean–Paleoproterozoic metamorphic gneiss, leptynite, basic volcanic rocks and syn-tectonic granite (Table 1).

3. Aeromagnetic data and methods

The aeromagnetic data presented in the course of this study were collected by the China Aero Geophysical Survey and Remote Sensing Center for Land and Resources (AGRS) over the Ordos Basin and its adjacent areas from 34–41°N and 106–110°E, at a scale of 1:20,000. The aeromagnetic data on the AGRS CD comprise 88,558 sets of line data. Line-data files are in the Geosoft database format (XYZ file). Each line data set consists of individual magnetometer readings with pertinent locational information, as well as magnetic anomaly values along each line.

Processing aeromagnetic data involves the sequential processes of editing, correcting for diurnal effects, removing the Earth's background magnetic field, leveling of all data to a common base, and, finally, applying a gridding routine. To improve the interpretation of the aeromagnetic data, two magnetic-data-enhancement procedures were employed in the study area: frequency-domain reduction to the pole and upward continuation.

Reduction to the pole is a filter used in low-magnetic latitudes to change an anomaly to its equivalent at the north magnetic pole. This process removes the skewness of the anomalies to make the

Table 1
Magnetic magnetism of rocks in Ordos Basin (after Li and Gao, 2010).

Geological age	Rocks	Magnetic magnetism ($\times 10^{-5}$ SI)
Archean–lower Proterozoic	Gneiss and leptynite, basic volcanic rocks, granite	1800–5000
	Migmatite and marble	20
Middle–upper Proterozoic	Low grade metamorphic rock	1–9
Paleozoic	Carbonate rock and continental clastic rock	<20
Mesozoic	Coarse clastic rocks such as conglomerates and coarse sandstones	1–9
	Mudstone, siltstone	10–30
Cenozoic	Aeolian sands	50

anomalies overlie the sources. In the study area, it must be accompanied by variable inclination reduction to the pole because the study area has a wide latitude span. Upward continuation separates a regional magnetic anomaly, resulting from deep sources, from the observed magnetic signal (Zeng et al., 2007), and it tends to accentuate anomalies caused by deep sources at the expense of anomalies caused by shallow sources.

The software used was OASIS MONTAJ (Geosoft 1999), which is a PC-based earth science data processing and analysis program compatible with Windows 95 and NTTM platforms. This software has the advantage of processing and reducing data by applying specific algorithms and techniques; it also is capable of creating high-quality maps and images.

4. Aeromagnetic anomaly features and geological interpretation

Spatial distribution features of regional aeromagnetic anomalies are aggregate effects of different sedimentary formations and crystalline basements (Ma et al., 1979). In the Ordos Basin, aeromagnetic anomalies can be induced by oblique magnetization of the geomagnetic field, rock masses in shallow strata, and the overlying sedimentary cover. Therefore, aeromagnetic data need to be processed by upward continuation to different heights to ensure that regional anomalies can reflect basement features concentratedly.

On the basis of aeromagnetic anomaly patterns, the Ordos Basin can be divided into five parts: the Yimeng region (YMR), the

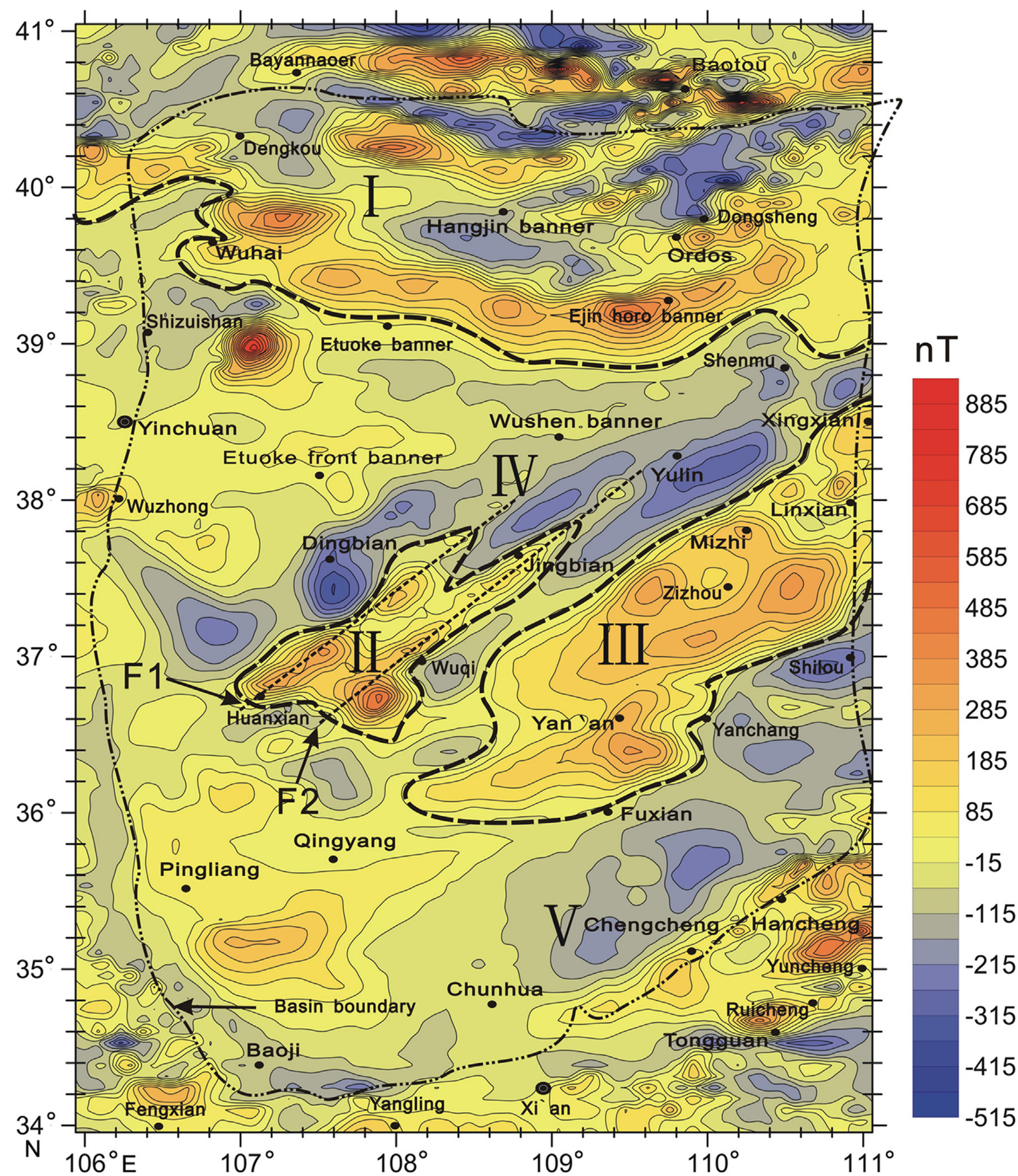

Figure 2. Map of aeromagnetic anomalies of the Ordos Basin and adjacent regions. I: Yimeng region (YMR), II: Jingbian–Huanxian region (JHR), III: Linxian–Mizhi–Yan'an region (LMYR), IV: Shenmu–Yulin–Dingbian region (SYDR), V: Shilou–Chunhua–Baoji region (SCBR); F1: Wangjiachuan-Daotu basement fault, F2: Huanxian-Datong basement fault.

Jingbian–Huanxian region (JHR), the Linxian–Mizhi–Yan'an region (LMYR), the Shenmu–Yulin–Dingbian region (SYDR), and the Shilou–Chunhua–Baoji region (SCBR). Each part has its own, distinctive features. This paper mainly concentrates on the first three of these regions.

4.1. Yimeng region (YMR)

Positive and negative anomalies occur alternately in the YMR, and show bead-shaped, linear structures trending E–W. They protrude southward slightly in their centers. In the west, gentle negative areas occur. The Wuhai–Etuoke–Yijinhuoluo positive anomalies in the southernmost part range from +5 to +485 nT, while Bayanzhuoer positive anomalies in the northernmost part range from +5 to +685 nT. The positive anomalies between the two aforementioned southernmost and northernmost areas trend E–W and ranges from +5 to +445 nT. Moreover, the negative anomalies between the positive ones also display bead-shaped, linear structures and range from −395 to −5 nT.

Comparative research was carried out among the aeromagnetic anomalies and those of upward continuation to different heights (Fig. 3). The negative anomalies were all converted to positive except in three isolated negative areas in which upward continuation was conducted to 10 and 20 km (Fig. 3A and B). However, these three isolated negative anomalies are close to zero when they are upward continued to 40 km. This illustrates that the geological bodies inducing the three isolated negative anomalies are deeply buried, while the others are shallow.

In recent years, the most widely accepted model for the tectonic evolution of the NCC was proposed by Guochun Zhao and his colleagues (Zhao et al.,1998, 1999a,b, 2000, 2001a,b, 2002, 2005, 2007, 2010a,b, 2013; Zhao, 2001, 2009). In this model, the basement of the NCC consists of three Archean micro-continental blocks (i.e., continental nuclei, including the Eastern Block, the Yinshan Block, and the Ordos Block) and three Paleoproterozoic mobile belts (Zhao and Cawood, 2012). The Western Block was formed by amalgamation of the Ordos Block in the south and the Yinshan Block in the north along the E–W-trending Khondalite Belt (Yin et al., 2009, 2011; Zhou et al., 2010; Li et al., 2011a,b; Wang et al., 2011; Zhao et al., 2012). This means that the E–W-trending positive aeromagnetic anomaly bands in the northern Ordos Basin may be influenced by the latter tectonic event.

No consensus has yet been reached concerning the distribution of continental nuclei beneath the Ordos Basin (IGAS and IGSSB, 1980; Zhang, 1982; Huang, 1984; Wang et al., 1990, 1996, 2006; Yang et al., 1990; Zhao et al., 1993; Bai et al., 1996; Wu et al., 1998; Che et al., 2012). However, most generally agree that continental nuclei exist in the northern Ordos Basin, mainly distributed in the Yimeng area. The apparent magnetism of the Taishan Group (Archean), which outcrops in western Shandong Province, is 1270×10^{-5} SI, and that of the magnetic block in the deep crust of the Sulu area is 1400×10^{-5} SI. The Sulu area block has been inferred to consist mainly of Archean metamorphic rocks (Wu et al., 2003). Comparative study of the magnetism of rocks from the Ordos Basin (Table 1) and the distribution of its basement rocks (Ding, 2000; Yang, 2002; He et al., 2003) revealed that the high positive anomalies in the north might result from the continental nuclei.

The collisional orogenic process between the NCC and the Siberian plate is recorded by the Xingmeng orogenic belt. An early Proterozoic landmass, an upper Proterozoic fold belt, a late Caledonian fold belt, and a Hercynian fold belt are developed sequentially from the Chifeng–Guyang area to the principal suture zone of Linxi–Suolun Mountain (Hu et al., 1990). Negative anomalies trending E–W roughly convert to positive when they are upward continued to 20 km. This may result from long-existing subduction or collision orogenesis from north to south, which made the later sedimentary formations coincide with the continental nucleus in an E–W direction.

4.2. Jingbian–Huanxian region (JHR)

The JHR high anomaly zone consists of two parallel, banded anomaly zones trending NE (Figs. 2 and 4), and they correspond to the Wangjiachuan–Diaotu and Huanxian–Datong basement faults. SHRIMP zircon U-Pb dating of drill cores from the basement in the western and eastern Ordos Basin indicate a granite emplacement event in the Paleoproterozoic era (approximate 2035–2030 Ma) (Hu et al., 2012). The Wangjiachuan–Diaotu and Huanxian–Datong basement faults supposedly functioned as magma upwelling channels in this emplacement event (Li and Gao, 2010). The dates also suggest that the two basement faults appeared when the continental nuclei rejoined and the basement formed, prior to the Paleoproterozoic, a position that also has been supported by some workers (Wang, 1995; Zhang et al., 1999, 2007; Li and Gao, 2010). Therefore, the crystalline basement of the Ordos Basin should be divided into at least two parts. Another continental nucleus may exist, corresponding to the LMYR high anomaly region, east of the two faults (Fig. 4). Future drilling work may support or refute this hypothesis.

4.3. Linxian–Mizhi–Yan'an region (LMYR)

The positive anomalies in the LMYR range from 0 to +485 nT and trend NE along Linxian–Mizhi. High anomalies continue (Fig. 3) when reduced to the pole and upward continued to different heights. Gravity anomalies in this region reveal a graben-like shape, which has an extension to the NE (Jiang et al., 2000) and correspond to the high anomalies. The lower Proterozoic Wutai Group has been drilled to a depth of 3490 m at the LONG1 well southeast of Yulin city (Hu et al., 2012), and this unit corresponds to positive anomalies in the aeromagnetic anomaly map. It is also where a magnetic-interface uplift zone occurs on the deep basement magnetic interface map (Guan et al., 1987). While, Majiagou Formation of the Ordovician is encountered when it is drilled into 3500–4068 m depth at the negative anomaly area between Yulin and Dingbian (ECPGC, 1987). This indicates that aeromagnetic anomalies are also influenced by buried depth of the crystalline basement.

The top of the crustal magnetic layer of the seismic belt on the north border of the Ordos Basin corresponds well with the underlying Archean crystalline basement (Zhang et al., 1991). Alashan–Yinshan–Ordos high anomalies coincide with the paleo-uplifts in the northern border of the NCC, which are usually interpreted as the Archean basement uplifts (Che et al., 2012). The performance features between Linxian–Mizhi–Yan'an positive anomalies and Yimeng uplift high anomalies are basically consistent, so we infer that an Archean crystalline basement (ancient continental nucleus) likely underlies the LMYR.

The crystalline basements beneath the Ordos Basin have been reached by petroleum companies drilling in some regions. Actually, the basements mostly consist of Paleoproterozoic granites or granitic gneisses with small amounts of parametamorphic rocks. So far, rocks older than 2.3 Ga, let alone Archean in age, have not been found. The ages and compositions of these basements suggest that they may be part of a continental nucleus. It should be noted that the detrital zircon ages can provide further significant information. A 3.5 Ga detrital-zircon age was obtained from Paleozoic rocks in the southeast Ordos Basin (Chen et al., 2009a,b; Zhang et al., 2009); Archean detrital zircons are also found in metamorphic sandstones

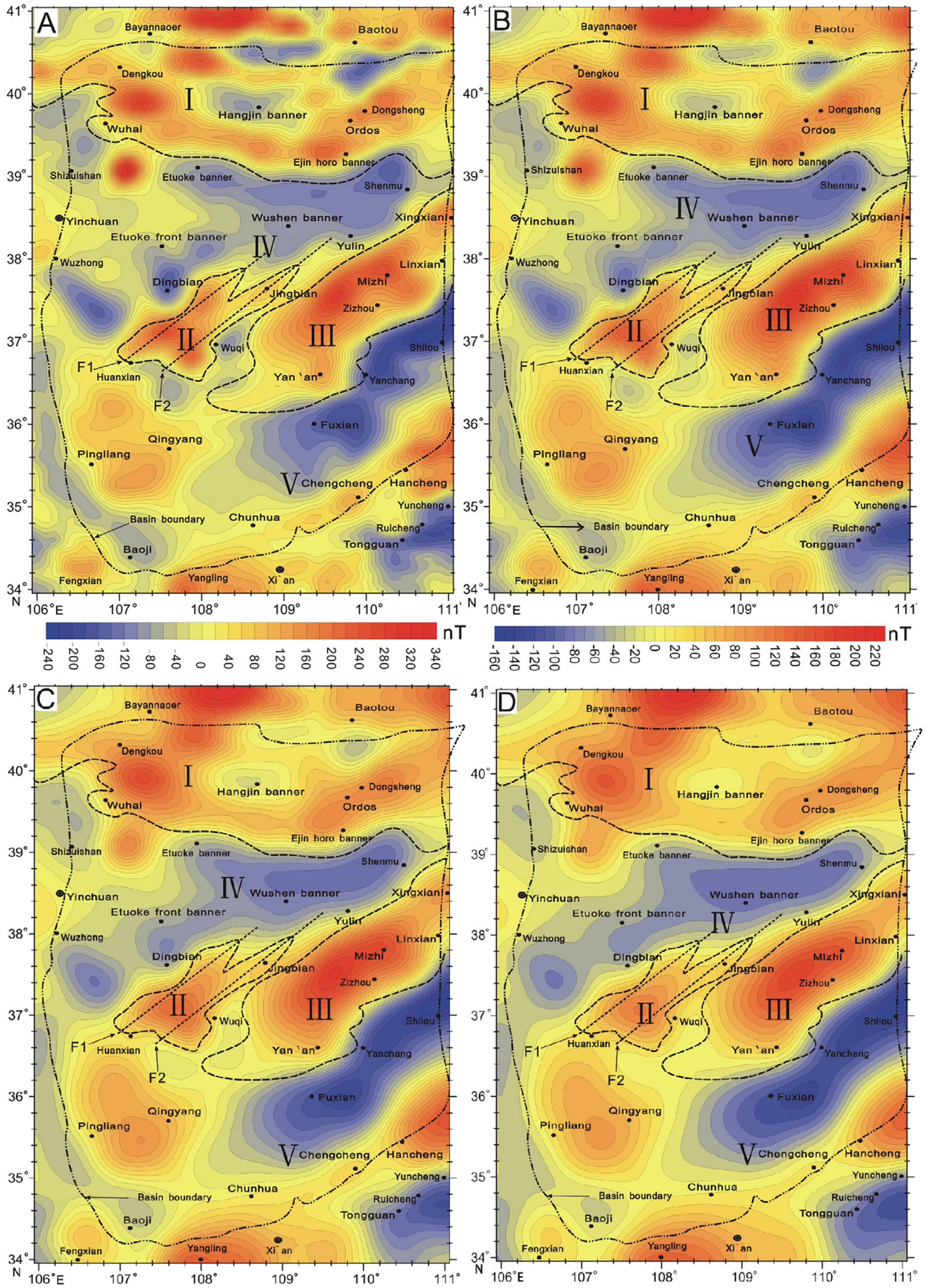

Figure 3. Contour map of aeromagnetic anomalies of the Ordos Basin and adjacent regions after reduction to the pole and upward continuation to different heights (A to 10 km; B to 20 km; C to 30 km; D to 40 km).

in the Shangdu–Huade region of Inner Mongolia (Hu et al., 2009). Additionally, a detrital-zircon U-Pb age of 3691 ± 25 Ma, was obtained from an arkose in a drill core from the Yanchang Group on the northern border of the Ordos Basin (Zhai, 2010). More recently, upward of 2000 detrital zircons were extracted from modern river sands and metasedimentary rocks in the region (Diwu et al., 2012). The U-Pb dating results show that the Ordos block has an early Precambrian basement similar to those of the eastern and central NCC. The distribution of detrital zircon ages means that an Archean continental nucleus—and likely more than one—probably lies beneath the Ordos Basin.

5. Constraint from seismic tomography

Because the number of drillings into the basement of the Ordos Basin is limited (He et al., 2003), indirect methods are the primary

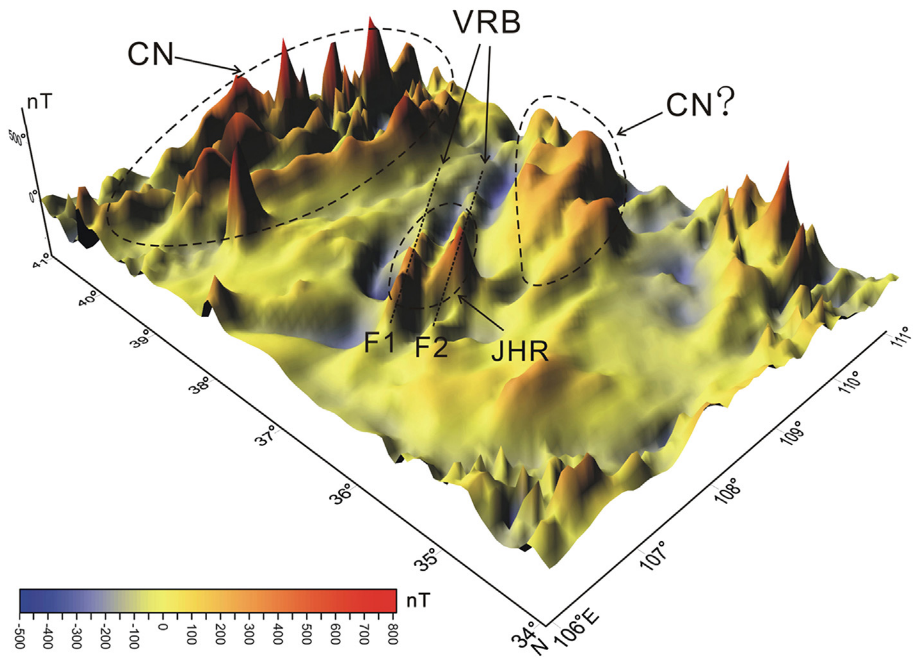

Figure 4. Map of aeromagnetic anomalies of the Ordos Basin and adjacent area. CN: continental nucleus, VRB: volcanic rocks belt, JHR: Jingbian–Huanxian region.

sources of data concerning its deep structure. Seismic tomographic studies, which reveal velocity structures of the crust and the upper mantle, have increased substantially in the Ordos Basin and adjacent areas (Wang et al., 2002; Wang et al., 2003; Guo et al., 2004; Chen et al., 2005; Wei et al., 2006; Teng et al., 2008; Wang et al., 2008; An et al., 2009; Chen, 2009; Chen et al., 2009a,b, 2010a,b; Ruan et al., 2009; Tian et al., 2009; Zheng et al., 2009; Fang, 2010; Zhao et al., 2010a,b; Li et al., 2011a,b; Lu et al., 2011; Zhu et al., 2011, 2012a,b; Li et al., 2012a,b,c; Yang et al., 2012; Zhou et al., 2012a,b; Cheng et al., 2013). These studies revealed enormous, thick, high-velocity anomalies beneath the Ordos block that can be interpreted as a thick lithosphere of the Ordos crust. Nevertheless, resolution of the velocity discontinuities is far from satisfactory (Guo and Xu, 2011). Furthermore, because the research area of the Ordos Basin is relatively small compared to that of the eastern NCC, revealing the fine structure of the crystalline basement rises and falls of the Ordos Basin is insufficient.

Significantly, Teng et al. (2008) reconstructed the rise and fall structures of the crystalline basement beneath the Ordos Basin from Yanchuan to Guyang with travel-time differential tomographic imaging (Fig. 5). Compared with the aeromagnetic anomaly map above, several points become apparent:

(1) A secondary uplift lies within the Yanchuan–Yulin depression. Its stake number is about 200 km, and it corresponds to the Mizhi high-positive anomaly zone in the aeromagnetic anomaly map. The scope, however, of this secondary uplift is smaller than the corresponding high anomaly zone. The reason may be that this uplift is covered by the thick, highly magnetic Wutai Group and/or Hutuo Group. Correlation indicates that F1 (Fig. 5), the Huanxian–Datong basement fault, corresponds to the deeply buried Yanchuan–Yulin depression. Yet, as mentioned above, it shows high positive anomalies. The most probable interpretation is that volcanic rock belts with high magnetism formed along F1.
(2) The Yulin–Daotu uplift is gentle and corresponds to negative anomalies. It is possible that this region is covered by the thick, lower Proterozoic Seertengshan Group, which has weak magnetism.
(3) The basement structure of the Yijinhuoluo depression is characterized by one wide and gentle uplift sandwiched between two narrow depressions with negative anomalies.
(4) The Dongsheng uplift corresponds to the Hangjinqi depression and the Yijinhuoluo uplift in velocity structure of the crust and upper mantle. They all display positive anomaly.
(5) A burial depth of 7–8 km for the Baotou Basin is between the stake numbers of 470–530 km; this region corresponds to negative anomalies.

The above results demonstrate that the basement rise and fall characteristics revealed by aeromagnetic data and seismic tomography are consistent. Specifically, positive anomalies always correspond to basement uplifts, and negative anomalies correspond to basement depressions, as illustrated by the E–W-trending Daluoshan–Lishi profile (C–D) (Fig. 5). The burial depth of the crystalline basement gradually increases from east to south in the profile, paralleling a gradual change from positive to negative anomalies on the aeromagnetic anomaly map.

6. Conclusions

An aeromagnetic map provides valuable information on the basement geology and deep structure of the Ordos Basin area.

Based on the pattern and distribution of aeromagnetic anomalies, the Ordos Basin is divided into three high magnetic anomaly zones (YMR, JHR and LMYR) and two low magnetic anomaly zones (SYDR and SCBR). Among them, the YMR alternately exhibits positive and negative anomalies along a roughly E–W trend. They may be influenced by amalgamation of the Ordos Terrane and Yinshan Terrane. The high anomalies in the YMR may result from the existing paleocontinental nucleus. The JHR consists of two banded anomaly zones representing volcanic rock basement and underlying basement faults that acted as magma upwelling channels during a volcanic emplacement event in the Paleoproterozoic era. The LMYR is characterized by continuous and widespread high anomaly

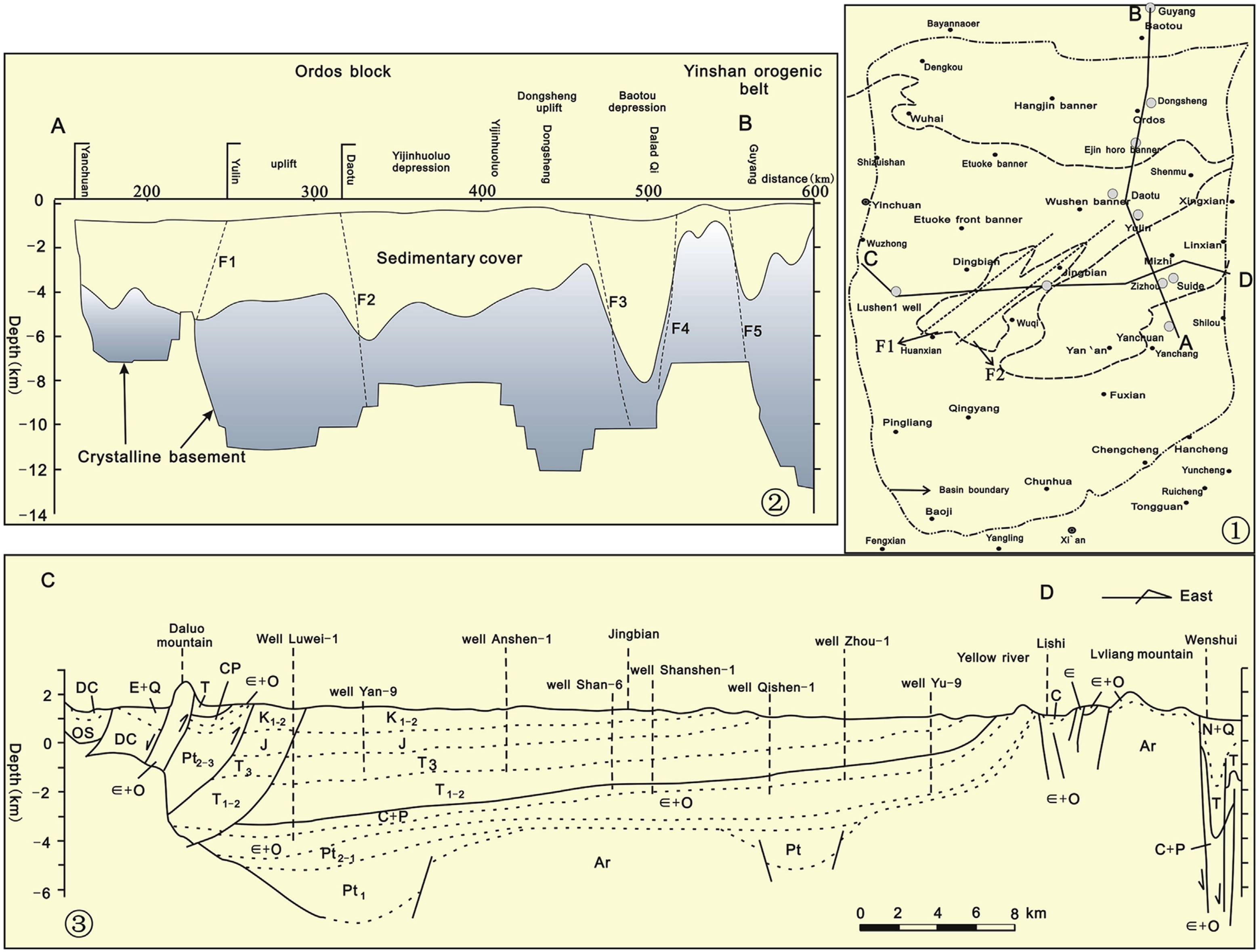

Figure 5. Basement relief characteristics of the Ordos Basin revealed by seismic tomography and drilling wells ① per this paper; ② after Teng et al., 2008; ③ after Jia et al., 2007; F1–F5 are faults.

areas, suggesting the presence of another continental nucleus in this region. Seismic tomography and drilling results indicate the aeromagnetic anomalies are also influenced by buried depth of the crystalline basement.

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