Vol. 92 No. 4 pp. 1627–1644 ACTA GEOLOGICA SINICA (English Edition) Aug. 2018

REVIEWS

Potash–Forming Regularity of the Ordovician Marine Northern Shaanxi Salt Basin: Insight from Review and Prospect of the Deep Geology of the Ordos Basin

WANG Zhentao * and ZHENG Mianping

Ministry of Natural Resources Key Laboratory of Saline Lake Resources and Environments, Institute of Mineral Resources, China Academy of Geological Sciences, Beijing 100037, China

Abstract: The Ordovician Northern Shaanxi Salt Basin (ONSSB), located in the east–central Ordos Basin, western North China Craton (NCC), is one of the largest marine salt basins yet discovered in China. A huge amount of halite deposited in the Mid-Ordovician Majiagou Formation, and potash-containing indication and local thin layer of potash seam were discovered in $O_2m_5^6$ (6^{th} submember, 5^{th} member of the Majiagou Formation). This makes ONSSB a rare Ordovician potash-containing basin in the world, and brings new hope for prospecting marine solid potash in this basin. However, several primary scientific problems, such as the coupling relationship between ONSSB and the continent nucleus, how the high-precision basement fold controls the ONSSB, and how the basement faults and relief control ONSSB, are still unclear due to the limitations of the knowledge about the basement of the Ordos Basin. This has become a barrier for understanding the potash-forming regularity in the continental nucleus (CN) area in marine salt basin in China. Up to now, the material accumulation has provided ripe conditions for the answers to these questions. Latest zircon U-Pb ages for the basement samples beneath the Ordos Basin reveal that there exists a continental nucleus (Yi-Meng CN) beneath the northern Ordos Basin. And this brings light into the fact that the ONSSB lies not overlying on the Yi-Meng CN but to south Yi-Meng CN. Both do not have superimposed relationship in space. And borehole penetrating into the basement reached Palaeoproterozoic meta-sedimentary rocks, which suggests the ONSSB is situated in the accretion belt of Yi-Meng CN during geological history. Basement relief beneath the ONSSB area revealed by seismic tomography and aeromagnetic anomaly confirms the existence of basement uplift and faults, which provides tectonic setting for sedimentary center migration of the ONSSB. Comparative research with various data sources indicates that the expanding strata in the ONSSB adopted the shape of the basement folds. We found that the orientations of the potash sags showed high correlation with those of several basement and sedimentary cover faults in the ONSSB. The secondary depressions are also controlled by the faults. Comparative research between all the global salt basins and continental nuclei distribution suggests that distribution of the former is controlled by the latter, and almost all the salt basins developed in or at the margin of the continental nucleus area. The nature of the tectonic basement exerts a key controlling effect on potash basin formation. And on this basis we analyzed in detail the geological conditions of salt-forming and potash-forming in the ONSSB.

Key words: Ordos Basin, Northern Shaanxi Salt Basin, continental nucleus, aeromagnetic anomaly, coupling relationship

1 Introduction

Massive potash deposits have been discovered in large, stable, cratonic basins worldwide (Haq et al., 1998, 2005; Hay et al., 2006; Condie, 2016). Compared with such cratons in North America and Siberia, the Precambrian landmass in China is much smaller (Ren Jishun et al., 2006; Li Jianghai et al., 2014). North America and Europe are dominated by large cratons, and have strong, stable, Archean–Proterozoic basements. Eastern Asia is a complex of the Sino–Korea, Yangtze, and Tarim cratons plus many micro–blocks and large–scale orogenic belts

* Corresponding author. E-mail: wangz@cags.ac.cn

(Wang Hongzhen, 1982, 2004; Deng Jinfu et al., 1996; Liu Qun et al., 1997; Ren Jishun et al., 2006; Chen Yuchuan et al., 2007). Marine and continental saline basins in China have varied and complex tectonic settings and intense tectonic instability (Li Jianghai et al., 2014).

Potash deposits are controlled by paleostructure, paleogeography, and paleoclimate. The nature of the tectonic basement has a critical role in marine potash basin formation. Metallogenic and salt- and potash-formation environments share some specific characteristics: multiple phases and ages of formation, migration and concentration of salts, diversity of component materials, and small, marine, saline basins, as well as significant, post-formational changes and the occurrence of liquid mineral deposits (Zheng Mianping et al., 2010). Proven potash reserves in China are distributed mainly in modern, continental salt lakes, such as the Qaidam Basin in Qinghai and Lop Nur in Xinjiang (Zheng Mianping et al., 2006; Wang Mili et al., 2001). Exploration for marine, large–scale, high–quality, solid potash deposits in China has not yet achieved a breakthrough. To this end, Zheng Mianping et al. (2012) presented a strategy to find potash deposits in marine evaporite salt basins.

Potash deposits are controlled by paleostructure, paleogeography, and paleoclimate. The nature of the tectonic basement has a critical role in marine potash basin formation. In the geological history, evaporite–forming conditions were poor globally in the Ordovician (Chen Wenxi and Yuan Heran, 2010; Zhang Yongsheng et al., 2015). Gypsum–rich strata were deposited in the Ordovician of the North China Craton (NCC), and massive halite was deposited in the east–central Ordos Basin of northern Shaanxi Province; evaporitic conditions in the latter even reached the depositional phase of potassium and magnesium salts (Zheng Mianping et al., 2010). The Ordos Basin meets the paleotectonic, paleoclimatic, and paleogeographic conditions for salt and potash formation, but the relationships between these conditions and the continental nucleus are unclear. Specifically, a coupling relationship, if one exists, between the basement features of the Ordos Basin and the ONSSB (Ordovician Northern Shaanxi Salt Basin) is unknown. Here we compile data from numerous sources to identify the distribution and boundaries of the continental nucleus beneath the Ordos Basin, probe the coupling relationship between the continental nucleus and the ONSSB, and identify the controlling effects of basement folds and basement/sedimentary cover faults to better understand salt and potash formation in the ONSSB.

2 Geologic Setting, Paleogeography, and Paleoclimate Conditions

The Ordos Basin is a cratonic basin (Yang Junjie, 2002) in the western NCC (Zhao Guochun et al., 2005) with a relatively stable sedimentary cover and a crystalline basement (Teng Jiwen et al., 2010). Mesoproterozoic to Cenozoic unmetamorphosed strata overlie Archean to Paleoproterozoic metamorphic basement of the NCC (Yang Yongtai et al., 2005; Wang Zhentao et al., 2016). Now there is a broad consensus that the NCC was formed by amalgamation of some micro-continental blocks (Zhao Guochun and Zhai Mingguo, 2013). A number of tectonic subdivision models were proposed to explain how many micro-continental blocks originally existed and when and how these micro-continental blocks were assembled to form the coherent basement of the NCC (Zhao Guochun and Zhai Mingguo, 2013; Kusky et al., 2016). A widely recognized model presented that the EW–trending Khondalite Belt separated the Western Block into the Yinshan Block in the north and the Ordos Block in the south (Fig. 1a). The basement of the Ordos Basin rarely outcropped due to the very thick sedimentary cover, and few boreholes penetrated into the basement. Thus, the composition and division of the basement of the Ordos Basin have been mainly inferred from the geophysical data, which is still uncertain in some extend (Wang Tao et al., 2007; Wang Zhentao et al., 2015). Recently, the petrologic features and latest zircon U-Pb ages for the basement samples beneath the Ordos Basin added direct evidence for the study of the basement of the Ordos Basin (Table 1).

Table 1 Features and location of Precambrian rock samples beneath the Ordos Basin

Sample No.	Rock name	Depth (m)	Formation age (Ga)	Reference
S2-5	Biotite K-feldspar gneiss	1750–1758	2.5–2.45 or ~2.5	Wan Yusheng et al., 2013
H3-7	Banded two-mica K-feldspar gneiss	2985–2988	2.0–1.95 or ~2.0	Wan Yusheng et al., 2013
QT1-12b	Garnet-sillimanite-biotite gneiss	5229–5233	2.0–1.95	Wan Yusheng et al., 2013
LT1-11	Graphite-bearing two-mica two-feldspar gneiss	3560–3563	2.0–1.95	Wan Yusheng et al., 2013
QS1-18	Altered mica quartz feldspar gneiss	4609–4610	2.0–1.95 or ~2.0	Wan Yusheng et al., 2013
Sheng2-1	Gneissic granite	1749.5–1756.5	~2.5 (2499 Ma)	Zhang Chengli et al., 2015
Huo3-1	Monzogranite	2985.5–2987.5	2.04	Zhang Chengli et al., 2015
E1-2	Massive hornblende monzonite	2796–2797.5	2.025–2.19	Zhang Chengli et al., 2015
Longtan1-1	Massive monzogranite	3560–3563	2.067	Zhang Chengli et al., 2015
Qingsheng1-2	Gneissic granite	4069–4068	2.045, 2.003, and 1.844	Zhang Chengli et al., 2015
Long1-1	Gneissic two-mica granite	3495	2.035	Hu Jianmin et al., 2012
QI1-1	Garnet-sillimanite-biotite-plagioclase gneiss	5235	2.031	Hu Jianmin et al., 2012
Zhenjia1	Two-mica plagioclase gneiss and sillimanite gneisses	3443.6	1898.2–2047.2 Ma	Wu Sujuan et al., 2015

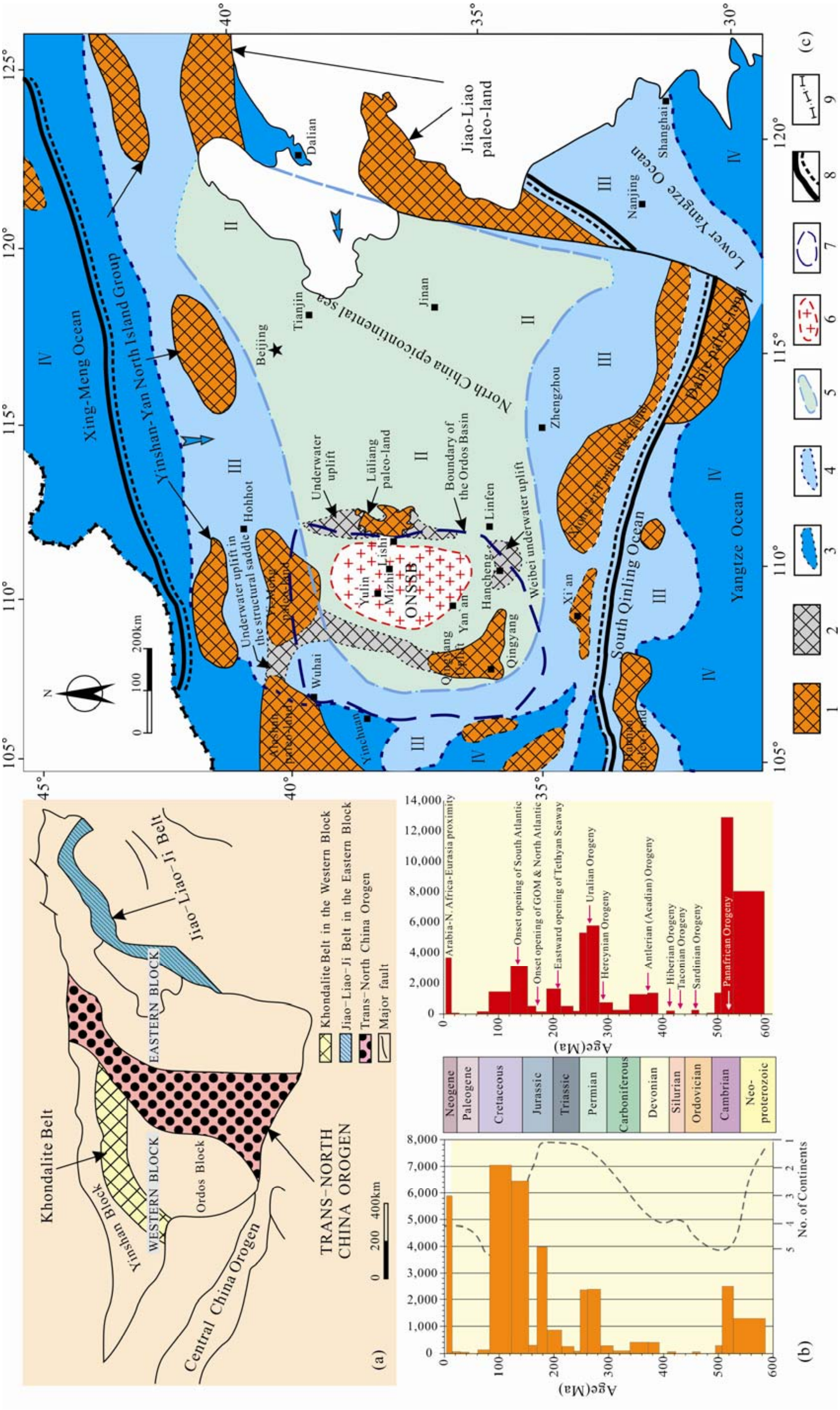

Fig. 1. (a), Tectonic subdivision of the North China Craton (after Zhao Guochun et al., 2005); (b), Mass (10^{15}kg) of Phanerozoic halite deposition and reconstructed original halite mass (after Waren, 2010); (c), The Middle Ordovician paleogeography of the NCC (after Wang Zhentao et al., 2016).

The Ordos Basin can be divided into six tectonic units: the Yimeng Uplift, the Weibei Uplift, the western margin thrust belt, the Tianhuan depression, the Yishan slope, and the Jinxi fault–fold belt. The ONSSB is located in the Yishan Slope unit and is one of the largest marine salt basins yet found in China. A great amount of rock salt accumulated in the Ordovician Majiagou Formation, and local, thin layers of potash seams were found in strata deposited during the $O_2m_5^6$ stage. The volume of halite and other evaporite sediments vary substantially and the volume were low for the Ordovician globally (Warren, 2010; Fig. 1b), which means that the Ordovician was not the prominent salt forming epoch in the world. During the Ordovician, the ONSSB was a graben basin with a gentle dip on the west side and steep dipon the east side. It is delimited by the Yimeng paleo–uplift in the north, the L–shaped Dingbian–Qingyang paleo–uplift in the southwest, and the Lüliang paleo–uplift in the east (Fig. 1c). During the early Paleozoic, the entire NCC, including the ONSSB, underlay a broad shelf facing the Qinling Ocean (Fig. 1c). Transgressions and regressions covered and exposed the Ordos Basin during the Ordovician (Li Wenhou et al., 2012). Large amounts of seawater entered the ONSSB during transgression, while the basin was isolated during regression. These transgressive–regressive cycles provided adequate provenance and tectonic conditions for salt deposition.

Potash forms in the last stage of evaporation in marine and continental basins. Potash deposition is favored under paleoclimatic conditions of extreme drought, which require both a particular paleolatitude and strong evaporation. In the oceans, the north and south Subtropical High atmospheric pressure belts correspond approximately to areas of maximum potential evaporation (Warren, 2010). On land, many of the deserts of the world are distributed within these two belts because the air is exceptionally dry. Favorable climate and hydrological conditions for potash deposition are thus concentrated in these latitudes. Conodont biogeography indicates that the NCC was located in warm, equatorial waters during the Early Ordovician, and stayed at low latitudes until the Middle Ordovician (Wang Chengyuan, 1998). Graptolite, cephalopod, and trilobite fossils and micrite, oolitic rocks, organic reefs, and bioherms throughout the North China Platform during the Ordovician reveal its low–latitude position (Zhou Zhiyi et al., 1989). Paleomagnetic data have also shown that the NCC was located in the middle–low latitudes of the Southern Hemisphere during the Ordovician (Zhai Yongjian and Zhou Yaoxiu et al., 1989; Zhu Rixiang et al., 1998; Huang Baochun et al., 2000, 2008, 2018; Li Desheng and He Dengfa, 2002), roughly at 18°S (Scotese et al., 1979) or 10.6°–14.4°S (Huang Baochun et al., 1999). Recently, Yan Maodu and Zhang Dawen (2014) evaluated and summarized existing paleomagnetic results to better resolve the paleolatitudes of potential potash– and halite–rich periods in the NCC, yielding results of 9.2°S to 14.2°S for the early–middle Ordovician. Based on the positions of Plume Generation Zones, paleomagnetic data, lithofacies analysis, and biogeographical information, Wang Honghao et al. (2016) suggested a revised paleoposition of the NCC during the Middle Ordovician, specifically a paleolatitude of approximately 16.6°–19.1°S. The NCC may have been within the subtropical high–pressure zone, experiencing favorable climatic conditions for potash deposition. More intuitive evidence is obtained from paleotemperatures. Petrographic research and homogenization temperature measurements of samples from the Zhenjia–1 core have been studied in detail (Hu Bin et al., 2014) and reveal paleotemperatures of 27°C–36.9°C in the ONSSB during the $O_2m_5^6$ stage. The paleoclimate thus was arid and hot in low latitudes of the Southern Hemisphere at this time.

3 Methods

The Ordos Basin has rarely outcropped basement and the basin-wide sedimentary cover has a thickness of 4000–5000 m (Yang Junjie, 2002), which results in many difficulties for unveiling the true face of the basement. Magnetic susceptibility is an important indicator to reflect the crystalline basement. The basic principle is that the magnetic anomalies of the Ordos Basin are mainly from the strongly magnetic metamorphic and igneous rock of the crystalline basement, whereas the contribution of sedimentary rocks to the magnetic anomalies is small (Li Ming and Gao Jianrong, 2010).

The aeromagnetic data presented in 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. Details of the aeromagnetic data processing, as well as the software used, are after Wang Zhentao et al. (2015). Besides, we collected the latest research results from zircon U-Pb ages of the basement and sedimentary cover samples, basement faults and sedimentary cover faults, the Ordovician paleoclimatic information, the geophysical, seismic, and drilling data of the Ordos Basin.

4 Spatial Distribution of the Continental Nucleus beneath the Ordos Basin

The basement nature plays a decisive role in the formation of a potash-containing basin (Jia Chengzao et al., 2007; Zheng Mianping et al., 2010). Therefore, to identify the coupling relationship between continental nucleus beneath the Ordos Basin and the ONSSB, we must first determine the spatial distribution and boundaries of its underlying continental nucleus or nuclei. In the early days, based on the geophysical method, Chinese geologists did much research on the basement of the Ordos Basin, and they speculated that a continental nucleus existed beneath the Ordos Basin. Researchers, however, have not yet reached consensus on the number and locations of continental nuclei beneath the Ordos Basin. Zhang Wenyou (1980), Zhang Kang (1983), Wang Hongzhen et al. (1990, 2006), Wang Hongzhen and Mo Xuanxue (1996), and Yang Sennan et al. (1990) held that just only one continental nucleus was concentrated in the northern Ordos Basin; while Huang Jiqing (1984) thought that an Archean continental nucleus existed in the Inner Mongolian axis (on the northern margin of the Sino–Korean paraplat form) in the southern Ordos Basin. According to the depth of the deep–magnetic interface (Guan Zhining et al., 1987) and regional foliation trends in the Archean rocks, Bai Jin et al. (1996) divided the North China block into six Archean continental nuclei. We superimposed the boundary of the Ordos Basin over the six continental nuclei, and found that the Ordos Basin spanned the Dongsheng and Linfen continental nuclei. These were welded together along a northwest–trending greenstone belt in the Datong–Yulin–Dingbian area. Shen Qihan and Qian Xianglin (1996) and Deng Jinfu et al. (1999) inferred that a Mesoarchean continental nucleus existed beneath the Ordos Basin, but its position was unclear. In addition, Bai Jin et al. (1996) proposed that another, unidentified continental nucleus, beyond the ones already identified, may still exist in the Ordos Basin.

In the last two decades, with the accumulation of extensive field-based structural, metamorphic, geochemical, geochronological and geophysical data on the basement rocks of the NCC, researchers have reached a consensus that the NCC was formed by amalgamation of some micro-continental blocks, and proposed a number of tectonic subdivision models (Zhao Guochun et al., 2005; Zhai Mingguo et al., 2000; Zhai Mingguo and Liu Wenjun, 2003; Santosh, 2007; Zhao Guochun and Zhai Mingguo, 2013; Kusky et al., 2016). Almost all the models regard the Ordos Block as a single and unbroken Archaean continental blocks (continental nuclei). The crystalline basement beneath the Ordos Basin has been reached by petroleum companies drilling in some regions. The basement consists of Paleoproterozoic granites or granitic gneisses with small amounts of parametamorphic rocks. For a long time, rocks older than 2.3 Ga, let alone Archean in age, have not been found. The ages and compositions of these basement rocks suggest that they may be not part of a continental nucleus. Zircon $^{207}Pb/^{206}Pb$ ages were obtained from two drill cores in the basement of the Ordos Basin (Hu Jianmin et al., 2013). A garnet–sillimanite–biotite–plagioclase gneiss from the western Ordos Basin basement yielded an average age of 2031±10 Ma. A gneissic, two–mica granite from the eastern Ordos Basin basement yielded an average age of 2035±10 Ma. Both are consistent with magmatism in the Proterozoic orogenic belt in the neighboring region (Zhao Guochun et al., 2002, 2010a, 2010b; Xia Xiaoping et al., 2006a, 2006b; Santosh et al., 2007; Yin Changqing et al., 2009, 2011). This indicates the existence of an active, Paleoproterozoic tectonic belt. Hu Jianming et al. (2013) argued that the Ordos block was probably not completely Archean. Wan Yusheng et al. (2013) reported SHRIMP zircon ages and Hf-in-zircon isotopic compositions for five drill holes samples that penetrated into the Ordos basement, and presented that the Ordos basement is not an Archean cratonic block. Change came when Zhang Chengli et al. (2015) confirmed that there existed a Neoarchean crust in the Ordos Block through zircon U–Pb geochronology and Hf isotopes for gneissic granitoids of the basement. Meanwhile, Wan Yusheng et al. (2018) identified three continental blocks older than 2.6 Ga in the NCC (Fig. 2), which form the basis for the late Neoarchean plate tectonics of the NCC. Based on the U-Pb dating of detrital zircons of the metamorphic basement (Wu Sujuan et al., 2015), It could be found that the basement beneath the ONSSB was Paleoproterozoic meta-sedimentary rock system. Thus, in the Fig. 2, the ONSSB was not located upon the continental nucleus but besides them. This provides detailed geological background for finding potash–forming regularity in the continental nuclei region.

Detrital zircon ages provide further significant information. In earlier research, the large proportion of Early Proterozoic age detrital zircons in the Proterozoic to Ordovician samples may suggest that much of the NCC basement is Early Proterozoic in age (Darby and Gehrels, 2006). Then, however, a 3.5 Ga detrital–zircon age was obtained from Paleozoic rocks in the southeastern Ordos Basin (Chen Ling et al., 2009a, 2009b). Archean detrital zircons have also been found in metamorphic sandstones in the Shangdu–Huade region of Inner Mongolia (Hu Bo et al., 2009). A detrital–zircon U–Pb age of 3691±25 Ma was obtained from arkose in a drill core from the Yanchang Group on the northern border of the Ordos Basin (Zhai Mingguo, 2010). More recently, more than 2000 detrital zircons were extracted from modern fluvial sands and metasedimentary rocks in the region (Diwu Chunrong et al., 2012). And a lot of ＞2.5 Ga detrital

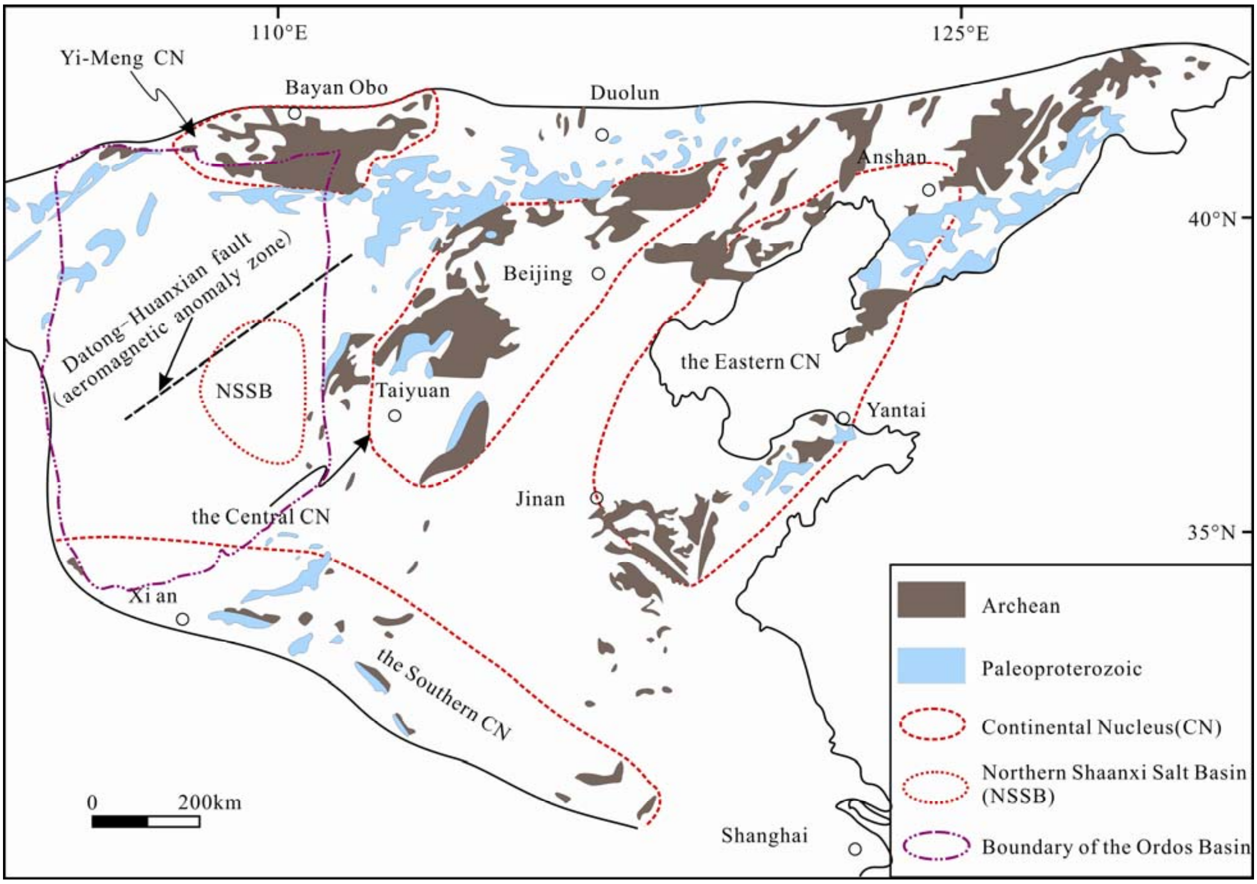

Fig. 2. Spatial distribution of ancient blocks in the North China Craton (>2.6 Ga) (after Wan Yusheng et al., 2018). In which, the position of the Datong–Huanxian fault was revealed by aeromagnetic anomalies (after Peng Peng et al., 2014).

zircons were found in the Middle Ordovician rocks in the western NCC (Wang Zhentao et al., 2016). The distribution of detrital zircon ages means that more than one Archean continental nucleus probably lies beneath the Ordos Basin.

Recently, Wang Zhentao et al. (2015) and Peng Peng et al. (2014) concluded that the Ordos block is not completely Archean. Wang Zhentao et al. (2015) divided the basement of the Ordos Basin through interpretation of high–precision aeromagnetic anomalies (Fig. 3). The Jingbian–Huanxian high anomaly consists of two parallel–banded anomaly zones trending northeast, which correspond to the Wangjiachuan–Diaotu (F1) and Huanxian–Datong (F2) basement faults. F1 and F2 may have functioned as magma upwelling channels during the Paleoproterozoic granite emplacement event (approximately 2035–2030 Ma) (Hu Jianmin et al., 2013), which suggests that the two basement faults appeared when the continental nuclei rejoined and the basement formed, prior to the Paleoproterozoic (Li Ming and Gao Jianrong, 2010). Therefore, the crystalline basement of the Ordos Basin consists of at least two parts. Another continental nucleus may exist, corresponding to the Linxian–Mizhi–Yan'an high anomaly region (Fig. 3), east of the two faults. Additionally, the aeromagnetic anomaly map clearly shows the Datong–Huanxian anomaly zone, which means that the Datong–Huanxian fault marks the Trans–North China Orogen formed by amalgamation of the Western NCC and Eastern NCC (Peng Peng et al., 2014). We regard this as evidence that the Ordos block is not entirely Archean.

5 Basement Relief Features

There are substantial structural variations among different parts of the NCC. The Bohai Bay Basin in the eastern NCC is underlain by thin crust (~30 km) with relatively low velocities and large, positive, radial anisotropy in the middle to lower crust (Cheng Cheng et al., 2013). Beneath the Ordos Basin in the western NCC, the crust is relatively thicker (≥40 km) and well stratified, and presents a large low velocity zone in the mid–lower crust and overall weak radial anisotropy except for a localized lower crust anomaly (Cheng Cheng et al., 2013). The structural features of this region resemble those of typical Precambrian shields, supporting the long–term stability of the region. This is also supported by thevelocity structure of the crust and upper mantle in the

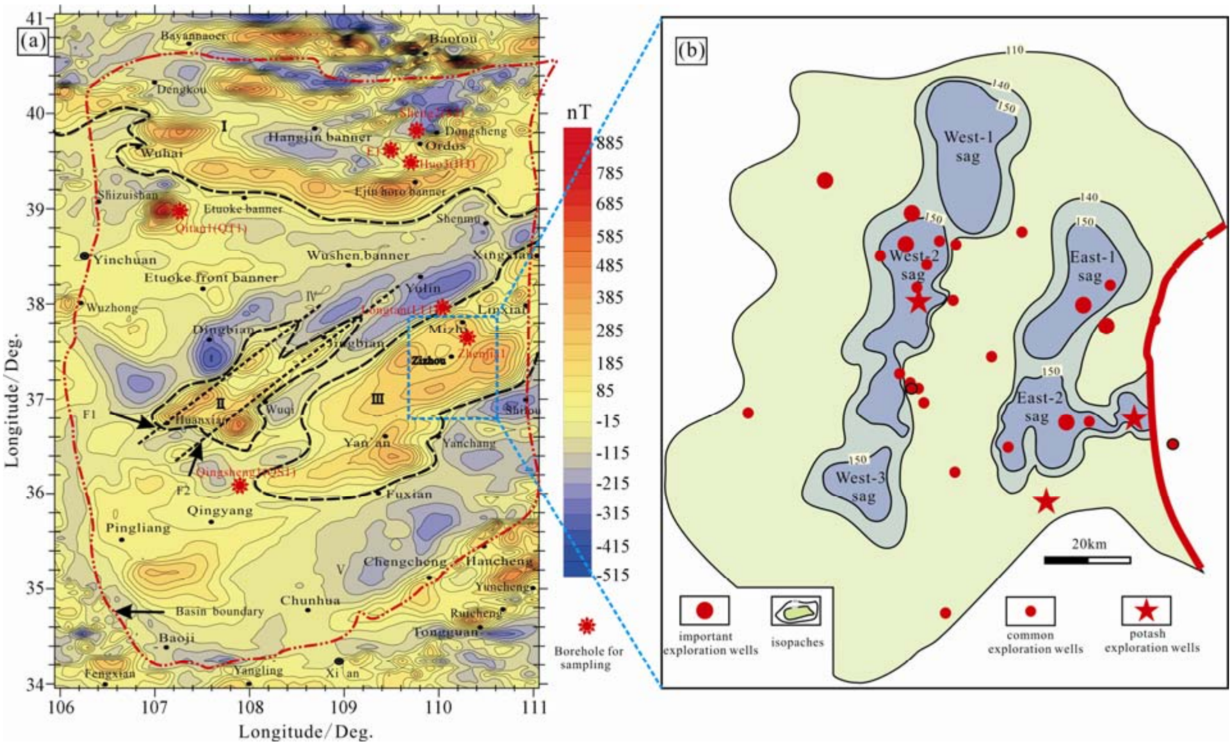

Fig. 3. (a), Aeromagnetic anomaly map of the Ordos Basin (after Wang Zhentao et al., 2015) and (b), the secondary depression of the ONSSB (after Zhang Yongsheng et al., 2013).
I, Yimeng region; II, Jingbian–Huanxian region; III, Linxian–Mizhi–Yan'an region; IV, Shenmu–Yulin–Dingbian region; V, Shilou–Chunhua–Baoji region; F1, Wangjiachuan–Daotu basement fault; F2, Huanxian–Datong basement fault.

Ordos block and adjacent areas, documented by seismic tomography (Wang Suyun et al., 2002, 2003; Chen Jiuhui et al., 2005; Wei Wenbo et al., 2006; Teng Jiwen et al., 2008; An Meijian et al., 2009; Chen Ling, 2009; Chen Ling et al., 2009a, 2009b; Tian You et al., 2009; Chen Ling et al., 2010a, 2010b; Fang Lihua et al., 2010; Li Zhiwei et al., 2011; Lu Yifeng et al., 2011; Zhu Rixiang et al., 2011, 2012; Li Sanzhong et al., 2012; Li Shaohua et al., 2012; Yang Ting et al., 2012; Zhou Lihong et al., 2012; Cheng Cheng et al., 2013). The results show high–speed anomalies, interpreted as thick crustal lithosphere beneath the Ordos block. Although numerous studies have been done on the basement relief of the Ordos Basin (Tang Yizhi et al., 1978; Zhang Kang, 1983; Zhao Chongyuan et al., 1988; Tang Xiyuan et al., 1993; Wei Wenbo et al., 1993; Ding Yanyun, 2000), the resolution is not very good. Furthermore, limited knowledge of the composition, ages, and relief features of the Ordos Basin basement constrains our understanding of how the overlying sedimentary cover is controlled by the basement. In recent years, fine lithospheric structures along the Mandula–Ordos–Yulin–Yanchuan and Yulin–Xianyang profiles have been obtained from high–resolution, wide–angle reflection and refraction seismic sounding（Teng Jiwen et al., 2008, 2010, 2014; Zhang Yongqian et al., 2011; Xu Shubin et al., 2013; Hu Guoze et al., 2014). This adds more sophisticated and reliable constraints on aeromagnetic interpretations of the Ordos Basin basement. Wang Zhentao et al. (2015) compared the aeromagnetic anomaly map with the reconstructed the rise and fall structures of the Ordos Basin crystalline basement from Yanchuan to Guyang with travel–time differential tomographic imaging (Teng Jiwen et al., 2008). Moreover, this paper compared and analysed the rise and fall structures of the crystalline basement from Yulin to Xianyang (Teng Jiwen et al., 2014) and the distribution map of crystalline basement burial depth inverted from 1:100,000 and 1:200,000 scale aeromagnetic anomaly data (Fig. 4). The result clearly shows the topography of the Southern Ordos Basin basement is significant and uneven, and there is a significant basement relief and two basement faults beneath the ONSSB (Fig. 5). The Yulin–Jingbian negative aeromagnetic anomaly corresponds to a tectonic depression, while the Mizhi–Zizhou–Yanchang–Yan'an positive anomaly corresponds to a crystalline basement uplift beneath the ONSSB, and the Yichuan–Tongchuan negative anomaly corresponds to a tectonic depression. The crystalline basement uplift, instead of a tectonic depression, makes the depocenter of the ONSSB shift much easier. Actually, the ONSSB started to form in the Cambrian, reached its peak during the Middle Ordovician, and perished in the late Paleozoic, and its

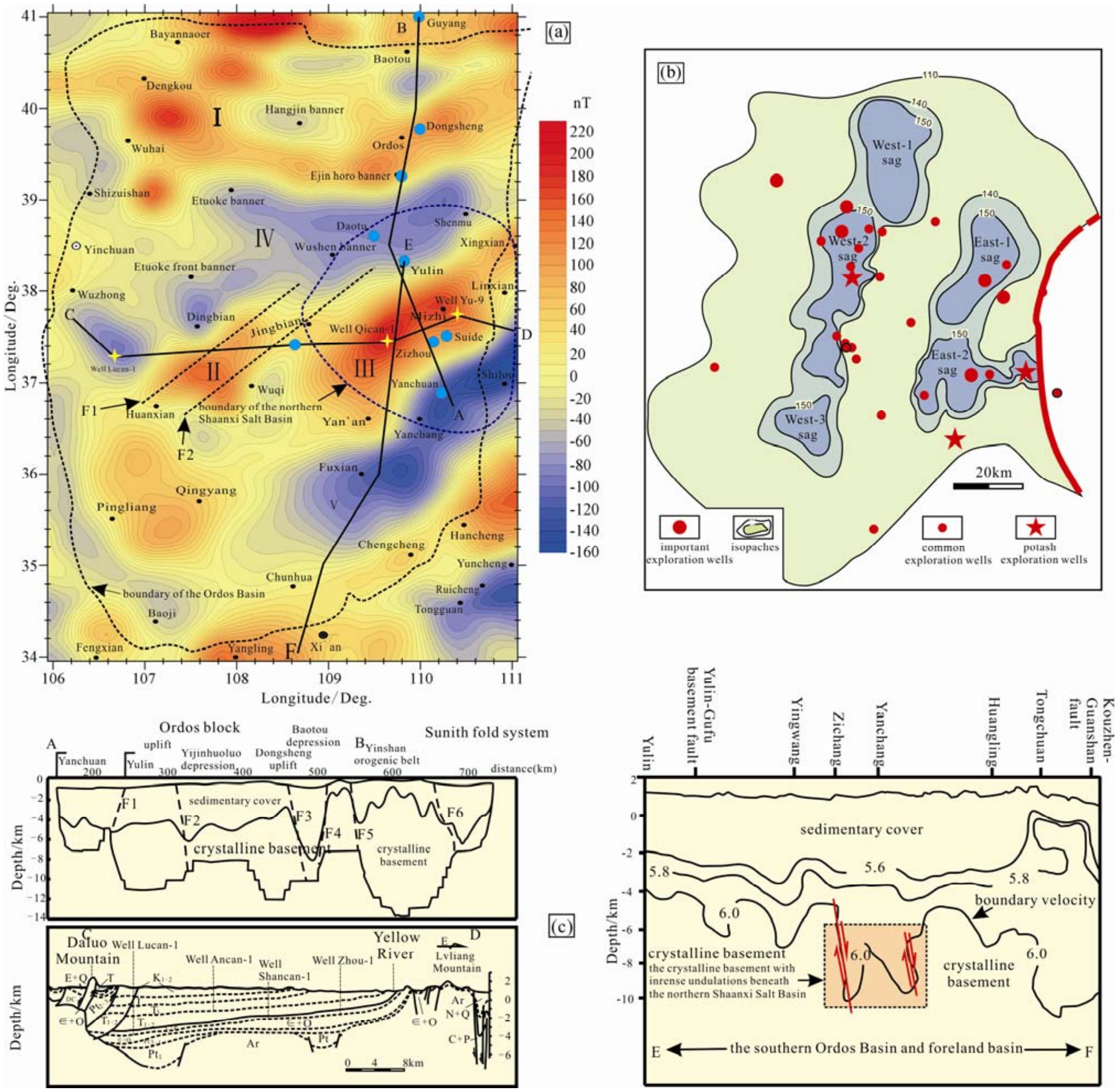

Fig. 4. (a), The contour map of aeromagnetic anomalies after reduction to the pole and upward continuation to 20 km (Wang Zhentao et al., 2015); (b), see Fig.3; and (c), the basement-relief characteristics of the Ordos Basin revealed by seismic tomography and drilling wells (Jia Chengzao et al., 2007;Teng Jiwen et al., 2008, 2014); Profile A–B after Teng Jiwen et al., 2008; Profile C–D after Jia Chengzao et al., 2007; Profile E–F after Teng Jiwen et al., 2014; F1–F6 are deep faults.

depocenter migrated from north to south (Yang Junjie, 2002). This provides foundations for tectonic differentiation of the ONSSB and brine migration.

6 Basement Folds Constrain Sedimentary Cover

Huang (1945) introduced the concept of basement folds and the idea that basement folds are the folds of a continent itself, and cover folds are the surface forms of basement folds (Ren Jishun, 2004). The Changcheng–Ji'xian System, Cambrian and Ordovician marine strata, Carboniferous and Permian marine–terrigenous strata, and Mesozoic–Cenozoic continental strata developed over Archean and Lower Proterozoic metamorphic rocks in the Ordos Basin. During different stages of geological development, sedimentary associations, boundary conditions, and basin–mountain couplings developed in the Ordos Basin. Different geodynamic settings and tectonic stress fields in different basin types result in

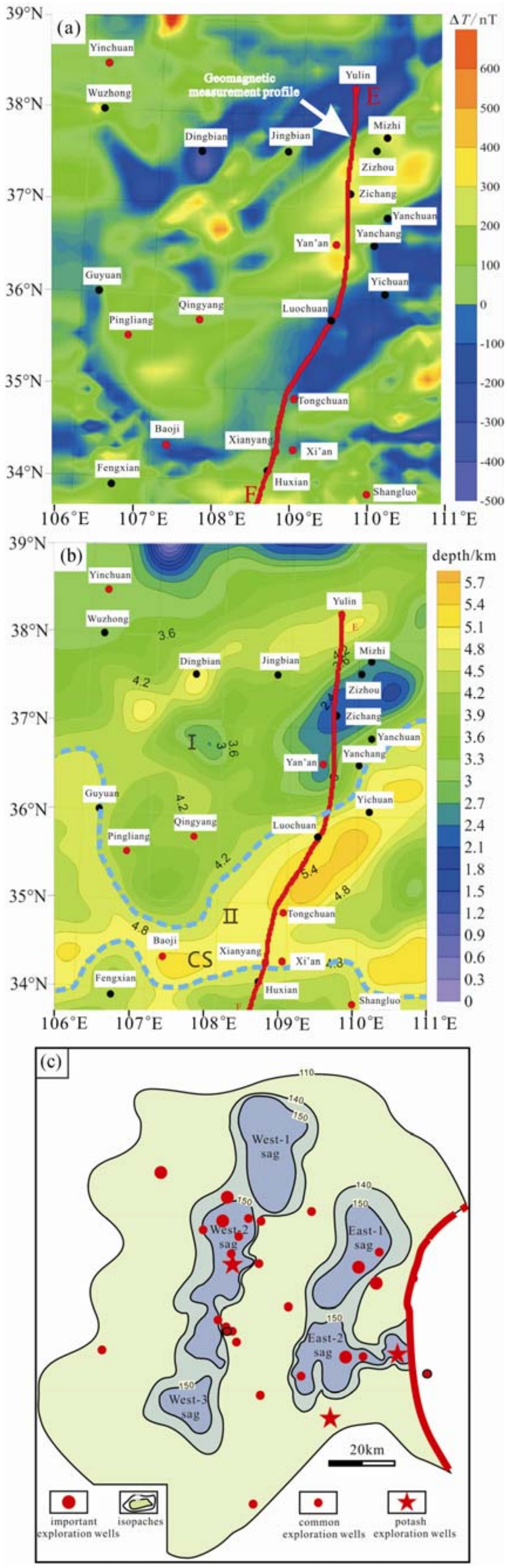

Fig.5. (a) and (b), Aeromagnetic anomaly contourmap and crystalline basement burial depth inferred from aeromagnetic data in the southern Ordos Basin (after Hu Guoze et al., 2014); (c), see Fig.3.

intricate tectonic deformations. The evolution of the basement always plays an important role in controlling deformation of the sedimentary cover. Folds in the sedimentary cover are distributed over the surface of the basement folds. The overall patterns and local shapes of the sedimentary cover in the Ordos Basin are controlled by the tectonic framework of the basement (Deng Jun et al., 2005).

The fluctuating features of the Precambrian metamorphosed basement and the depth change of the sedimentary cover are of great importance for geological structure research and energy and resources exploration (Xiong Shengqing et al., 2014). Along discontinuity between Cambrian strata and the underlying basement has been confirmed through well drilling in the Ordos Basin. Two boreholes drilled into the basement in the western and eastern Ordos Basin (Hu Jianmin et al., 2013) reveal the same stratigraphic break (both missing the Mid–Neoproterozoic strata) with good horizontal contrast. Both show the Middle Cambrian Xuzhuang Formation in direct contact with the metamorphic rocks of the basement. A thickness map reveals that Cambrian–Ordovician strata are widely distributed in the northern Ordos Basin (Ding Yanyun, 2000). As the first sediments over the crystalline basement in the Ordos Basin, the Cambrian–Ordovician strata should inherit the patterns of the basement. On the basis of 11 outcrop sections, 18 drilling profiles, and the thicknesses at 236 seismic points, Feng Zengzhao et al. (1999) compiled a sedimentary–thickness isoline graph of Lower Cambrian stratigraphic units in the Ordos Basin (Fig. 6), indicating that one uplift and three depressions emerged during the Cambrian. These facts tally with the Cambrian–Ordovician tectonic features presented by Li Ming and Hu Jianmin (2010) using residual thicknesses. It should be noted that although there are certain differences between the paleotectonic patterns during the Ordovician and the Cambrian, on the whole they inherited the Precambrian tectonic pattern (Fig. 7). Therefore, it is easy to draw the conclusion that the forming process of the ONSSB was affected by the basement relief.

7 Coupling Relationship between Stable Continental Nucleus and the ONSSB

Basement relief affects and controls the development of tectonic features and sedimentary cover, and also the migration and accumulation of oil and gas or brine. Basement faults play an important role in development of the overlying sedimentary cover and secondary depressions. Early Paleozoic sediments in the Ordos Basin inherited the tectonic framework of their basement. Maximum sediment thicknesses and their trends were both associated with the deep depressions of the basement. The sediments were of significantly reduced thickness or even absent on the basement uplifts. As part of the Paleoproterozoic crustal–scale, transtensional Western Shear System of northern China, the conspicuous northeast–trending Datong–Huanxian fault in the central Ordos Basin controlled the sedimentary and structural evolution of ensialic mobile belts (Zhang Jiasheng et al., 1999, 2007). A shear zone produces friction and extrusion between blocks on both sides and forms complex structural phenomena, such as secondary fractures, uplifts on the boundaries, and shearing corrugations, which generally lead to inherited structures in the overlying sedimentary cover. The ONSSB is close to the Datong–Huanxian fault and we infer that this salt basin is influenced bythis fault at the regional scale. Studies by Hu Guoze et al. (2014) and Zhang Yongsheng et al. (2013) provide detailed, high–resolution geophysical data to depict the underlying basement relief and faults. Using the variable velocity method, an isopach map of the potash–rich Ordovician $O_2m_5^6$ saliferous strata in the ONSSB was developed from drilling logs and integrated seismic data interpretation (Zhang Yongsheng et al., 2013). Tectonic differentiation in this region was also discussed (Zhang Yongsheng et al., 2013). In the $O_2m_5^6$ period, this salt basin exhibited two depressions and one uplift (Fig. 7). In addition, Hu Guoze et al. (2014) revealed that basement uplift existed beneath the secondary depressions of the ONSSB.

The Ordos Basin has generally been considered to be rigid for a long time (Wang Tao et al., 2007). But in recent years, a variety of aeromagnetic, gravitational, and magnetotelluric data, and satellite photos have identifiedmany large–scale basement faults in the Ordos Basin and its adjacent areas, especially the Datong–Huanxian fault in the central Ordos Basin (Ma Xingyuan et al., 1979; He Zixin et al., 2003; Zhao Wenzhi et al., 2003; Li Ming and Gao Jianrong, 2010). He Zixin et al. (2003) suggested that 37 basement faults developed in the Ordos Basin. Later, Li Ming and Gao Jianrong (2010) made a more detailed study in the Yulin–Yanchuan region and identified 78 basement faults. Li Ming and Gao Jianrong recognized seven faults in the sedimentary cover, F10–F16, and nine basement faults, F1–F9 in the Salt Basin region (Fig. 8). Basement faults F1, F2, F3, and F8 have not cut through the sedimentary cover, butthe others have extended up to the sedimentary cover. The orientations of the basement faults and fractures beneath the salt bed suggest that the Ordovician strata were controlled by the basement faults (Li Ming and Gao Jianrong, 2010). Comparing the secondary depressions mentioned above and the underlying basement and

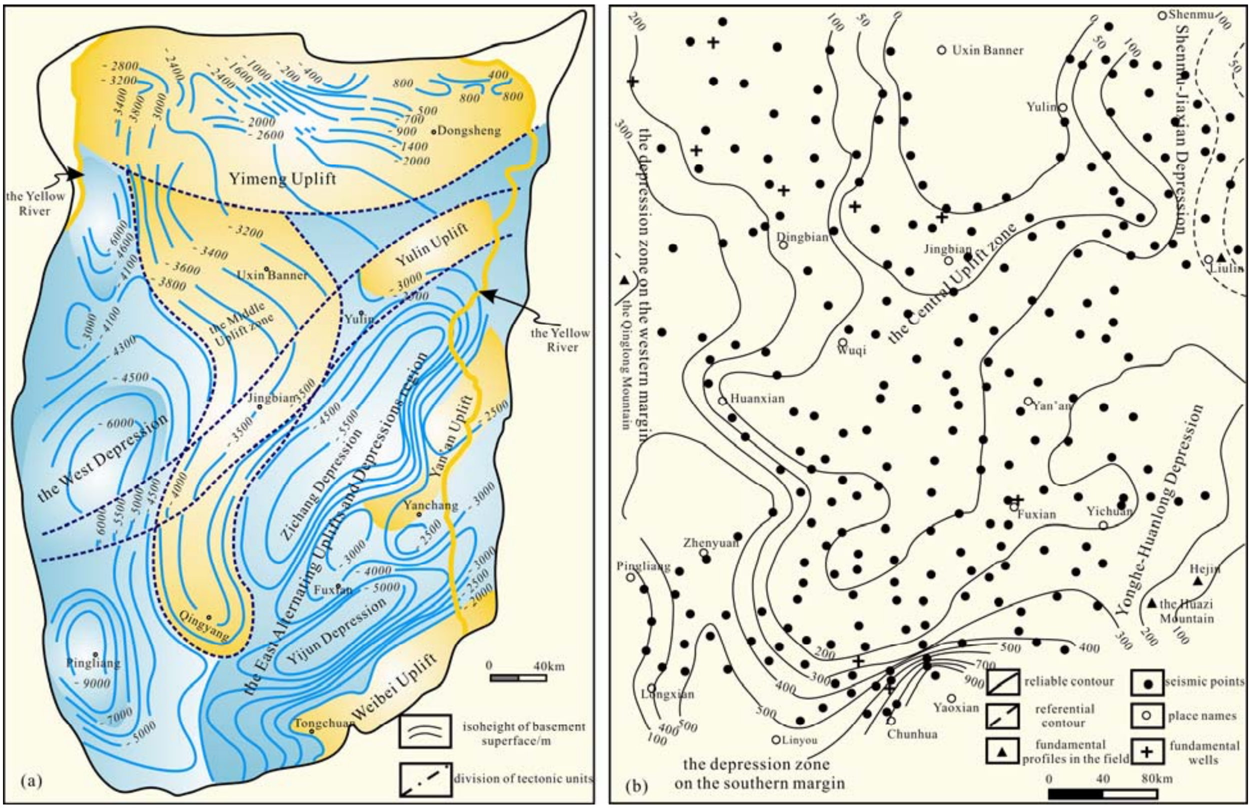

Fig. 6. (a), Tectonic framework of basement beneath the Ordos Basin; (b), Isopach map of the lower and middle Cambrian in the Ordos Basin (after Yang Junjie, 2002; Feng Zengzhao et al., 1999).

sedimentary cover faults shows that the orientation of depression West–1 with respect to West–2 is entirely consistent with that of F17 and F18 revealed by seismic interpretation and with sedimentary fault F13, and that the secondary depressions are cut through by basement fault F16 and sedimentary fault F12. The orientation of depression East–1 with respect to East–2 is consistent with that of the F19 revealed by seismic interpretation, and the depression and the fracture are cut through by basement fault F7 and sedimentary fault F15. From the spatial relationships between the basement faults and the sedimentary cover, Li Ming and Gao Jianrong (2010) deemed that the fractures and faults F10, F15, and F16 that cut through the secondary depressions played a role in the formation and evolution of those secondary depressions.

8 Potash–Forming Regularity of the Marine Salt Basin in the Continental Nuclei Region

On a global scale, the distribution of the large-scale salt basin shows the positive correlation with the continental nucleus. It means that the salt basin was located either on or besides the continental nucleus. Large–scale, marine salt deposits develop in relatively stable continental nuclei in China (Zheng Mianping et al., 2010). For instance, the Triassic salt basin in the Yangtze region overlies a continental nucleus (Wang Hongzhen, 2004; Huang Jianguo, 1998), and salt basins in the Tethyan tectonic domain developed in the relatively stable Northern Qiang–Western Yunnan tectonic sub–domain, where a large number of small landmasses are distributed (Li Yongtie et al., 2006; Zheng Mianping et al., 2010).

Little is known about the basement of the Ordos Basin because of an extensive and very thick sedimentary cover. This hampers the understanding of the salt– and potash–forming regularity in the ONSSB. As mentioned above, the Ordos

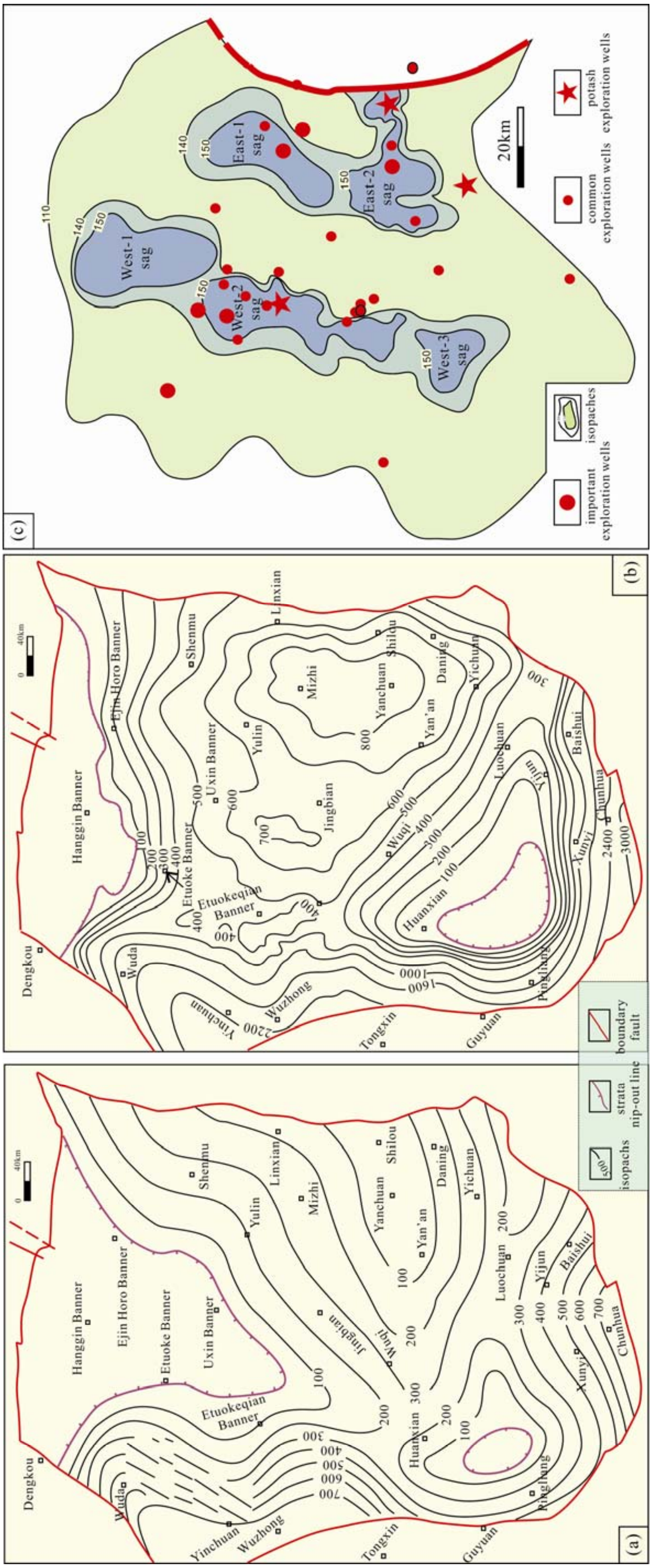

Fig. 7. (a), Residual thickness of the Cambrian in the Ordos Basin; (b), Residual thickness of the Ordovician in the Ordos Basin (after Li Zhenhong and Hu Jianmin, 2010); (c), see Fig.3.

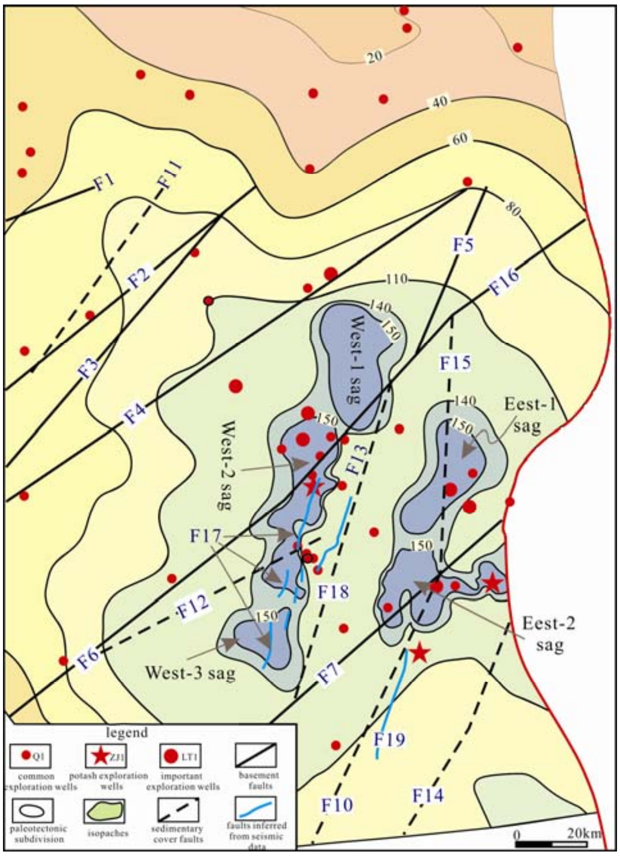

Fig. 8. Paleotectonic map of the Ordovician $O_2m_5^6$ stage in the Ordovician Northern Shaanxi Salt Basin and underlying faults (Li Ming and Gao Jianrong, 2010; Zhang Yongsheng et al., 2013).

Block is not an unbroken Archean cratonic block but has mosaic structure with distinct relief on the basement surface. What`s more, the basement faults and sedimentary faults develop widely beneath the ONSSB, which breaks the knowledge that the ONSSB was only affected by the extreme arid climate and lithofacies paleogeography. Based on drilling and seismic data and the variable velocity mapping method, Zhang Yongsheng et al. (2013) presented that the ONSSB shows “two depressions and one uplift” during the $O_2m_5^6$ stage of Ordovician period, which means that some salt sub-depressions formed in the ONSSB. And these sub-depressions correspond to the basement uplift below (Hu Guoze et al., 2014).

Before the basement of the Ordos Basin formed, its unique tectonic framework, of a hard core with soft sides, it consisted of a hard, continental nucleus (or nuclei) and a collage of soft, surrounding materials (Deng Jun et al., 2005). The compressive strength of the continental nucleus is greater than that of the surrounding rocks. The continental nucleus beneath the ONSSB provided a stable tectonic setting during formation and evolution of the salt basin. The basement faults controlling the sub-depressions in the salt basin provide a relative, active tectonic setting for brine migration, and syngenetic faults in the sedimentary cover are likely to favor migration and consolidation of the later potash–containing brine. This unique tectonic setting, a relatively active, quasi–stable region in a stable tectonic region, is important for salt formation and potash concentration and preservation in the ONSSB.

9 Discussions

Theoretically, the available ore-forming space in the Earth is 10,000 m below the surface. At present, advanced global exploration and mining has reached 2,500 to 4,000 m, but most companies in China have only reached less than 500 m. Therefore, penetrating deeper into the Earth is a strategic science and technology goal on which it would be beneficial to make progress. Additionally, to study the lithosphere and deeper interior of the Earth and gain fundamental insights into how the Earth operates is a common interest to geoscientists worldwide (Condie, 2016).

The Ordos Basin is the second largest sedimentary basin in China with an area of ~400,000 km^2. It has a wide distribution of resources, including complete energy and mineral resources, large resource potential and large reserves (Liu Guangdi et al., 2013; Zhao Xiaoming et al., 2014; Zhang Yongsheng et al., 2015; Sheng Jun et al., 2018). Additionally, it is one of the largest known marine salt basins in China. Huge deposits of rock salt and a small quantity of potash salts, such as sylvite, carnallite and rinneite, were discovered in the Ordovician age Majiagou Formation on the eastern side of the ONSSB (Chen Yuhua et al., 1998; Zhang Yongsheng et al., 2014). This indicates that the Ordos Basin has potash potential. However, the salt deposits developed in the Majiagou Formation are at more than 2,000 m depth (Zhang Yongsheng et al., 2014). Thus, it is necessary to first understand some basic characteristics of deep geology in salt-forming basins.

Basement relief is thought to control the distribution and shape of the overlying sedimentary cover. However, the metamorphic basement of the ONSSB is covered by thick Cambrian to Cenozoic non-metamorphosed strata (Hu Jianmin et al., 2013; Wu Sujuan et al., 2015). To-date, only two boreholes drilled in the ONSSB have encountered basement rocks (Wan Yusheng et al., 2013; Wu Sujuan et al., 2015). This means that detailed geological characteristics of the Ordos Basin are still unknown and unlikely to be described as a result of drilling operations alone. However, geophysical methods could play an important role in describing some basic deep geology parameters of the Ordos Basin (Li Ming and Gao

Jianrong, 2010; Wang Zhentao et al., 2015). There are now multiple geophysical methods that can be combined with other multidisciplinary data for a comprehensive study of the deep geology of the ONSSB. Zhang Yongsheng et al. (2013) defined a more precise distribution shape through drilling and seismic data, and the variable velocity mapping method. Based on passive adaptation of the sedimentary cover to the basement folds, it was speculated that there is a basement depression beneath the salt basin. However, the aeromagnetic anomaly map (Hu Guoze et al., 2014; Wang Zhentao et al., 2015) and travel-time differential tomographic imaging (Teng Jiwen et al., 2008) both showed that there is a significant basement relief instead of a tectonic depression, as well as two basement faults. This was subsequently confirmed with drilling data (Wang Zhentao et al., 2016), suggesting that the ONSSB sedimentary center was not originally at its present position, but that basin migration occurred earlier. Therefore, accurately defining the formation mechanism, scope and migration path of the ONSSB are important scientific topics to be investigated. It is difficult to determine whether the main controlling factor in ONSSB formation is the basement/ sedimentary fault or basement fold. The results of Hu Guoze et al. (2014) indicated that the basement fold did not always determine the shape of the sedimentary cover. Thus, the importance of the basement/sedimentary fault is reflected by two aspects: (1) that it may play a controlling role in the formation of the basin, and/or (2) there is a migration channel in the salt deposit. This second aspect may play an important role.

10 Conclusions

Based on the comparative study on the basement relief, ages of the basement rocks, basement faults, sedimentary faults, and geophysical data of the Ordos Basin, we made a new understanding of the following:

(1) Continental nucleus, basement, and sedimentary cover faults exist beneath the ONSSB. And, the potash sags in the ONSSB correspond to a crystalline basement uplift.

(2) The expanding Early Paleozoic strata adopted the shape of underlying basement folds. And, the orientations of the potash sags correlate well with those of several basement and sedimentary cover faults in the ONSSB.

(3) The basement faults controlling the secondary depressions in the salt basin provide a relative active tectonic setting for brine migration, and syngenetic faults in the sedimentary cover are likely to favor migration and consolidation of the later potash–containing brine.

Acknowledgments

This work was financially supported by the National Key R&D Program of China (grant No. 2017YFC0602806) and the National Basic Research Program of China (973 program, grant No. 2011CB403001). Thanks are given to Professor Jerry D. Harris at the Department of Paleontology Science, Dixie State University, for his great help in improving the manuscript. And we would like to thank Dr. Yan Maodu at the Institute of Tibetan Plateau Research, China Academy of Science, and other reviewers for their valuable comments and suggestions.

Manuscript received Feb. 15, 2017
accepted Oct. 8, 2017
edited by Hao Qingqing

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About the first author

WANG Zhentao, male; born in 1986, Qingfeng County, Henan Province; an assistant research fellow from the Institute of Mineral Resources, China Academy of Geological Sciences. He received his BSc (2009) and PhD (2014) from China University of Geosciences, Beijing. He finished his postdoc research at the Institute of Mineral Resources, China Academy of Geological Sciences in 2016. His primary research interests focus on the Paleozoic-Mesozoic tectonics and sedimentary evolution of the western North China Craton and Yangtze Craton. E-mail: wangz@cags.ac.cn