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# Re-discussion on the detrital zircon provenance of the lower Yanchang Formation in the southern Ordos Basin

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**Abstract:** The Ordos Basin is the second largest sedimentary basin in China. The Yanchang Formation is the key oil-bearing layer in the Ordos Basin. The stratigraphic time interval and the stratigraphic division of the Yanchang Formation has been highly debated with estimates ranging from Middle Triassic to Late Triassic. According to the latest studies on the stratigraphical division of Yanchang Formation, it was considered to be deposited as early as the Middle Triassic. Based on this new understanding, we re-examined the previous studies of the detrital zircons from the lower Yanchang Formation. The detrital zircons from the lower Yanchang Formation were divided into three groups based on their U-Pb ages: Paleozoic, Paleoproterozoic, and Neoarchean. The lack of Neoproterozoic U-Pb ages indicates no input from either the Qinling Orogen or the Qilian Orogen. The two older age groups (Paleoproterozoic, and Neoarchean) are likely derived from the North China Craton basement. The Paleozoic zircons were derived from the Inner Mongolia Paleo-uplift. The lower Yanchang Formation was mainly derived from the Inner Mongolia Paleo-uplift instead of being recycled from the previous sedimentary material from the central-eastern North China Craton as was previously hypothesized.

**Keywords:** Triassic; Ordos Basin; Detrital zircon; Provenance

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## 1 Introduction

The Ordos Basin is the second largest sedimentary basin in China with an area of 250,000 km$^2$. It lies in the west of the North China Craton (NCC). The NCC is an extensive epeiric platform (1500 km east-west and 1000 km north-south). The platform, which dates from the Precambrian, provided a stable setting upon which Cambrian through Middle Ordovician marine rocks were deposited [1]. A middle Paleozoic deformation resulted in a significant unconformity that separates these lower Paleozoic rocks from overlying middle Carboniferous rocks. After a platform-wide hiatus during the middle Paleozoic, alternating marine and terrestrial deposits accumulated on the platform during the Carboniferous and Permian [2]. Due to the regional uplift, continental conditions prevailed in the Triassic.

Provenance analysis is important for sedimentary basin analysis and is also the essential evidence for both the evolution and the depositional environment history of a basin [3, 4]. Our study focused on the early Yanchang Formation of the southern Ordos Basin. The Yangchang Formation is the key oil-bearing layer in the Ordos Basin. Much research has been done to determine the provenance of the Yanchang Formation. Traditional approaches were used in previous research, including petrographic, heavy mineral, geochemistry and clastic rock components methods [5–13]. It is still controversial whether the Qinling Orogen provided the source material for the lower Yanchang Formation in the southern Ordos Basin. With dramatic advances in analytical methodology, detrital-zircon geochronology has been widely applied in the reconstruction of sediment pathways between source areas and the Ordos Basin [14, 15]. Based on recent results from the detrital-zircon geochronology analysis, the lower Yanchang Formation was hypothesized to be mainly derived from recycled sediments of the central-eastern NCC [14, 15]. The data interpretations are new and challenge our traditional understanding. However, according to the latest studies on the stratigraphical division of Yanchang Formation [45, 50], the provenance of the Yanchang Forma-

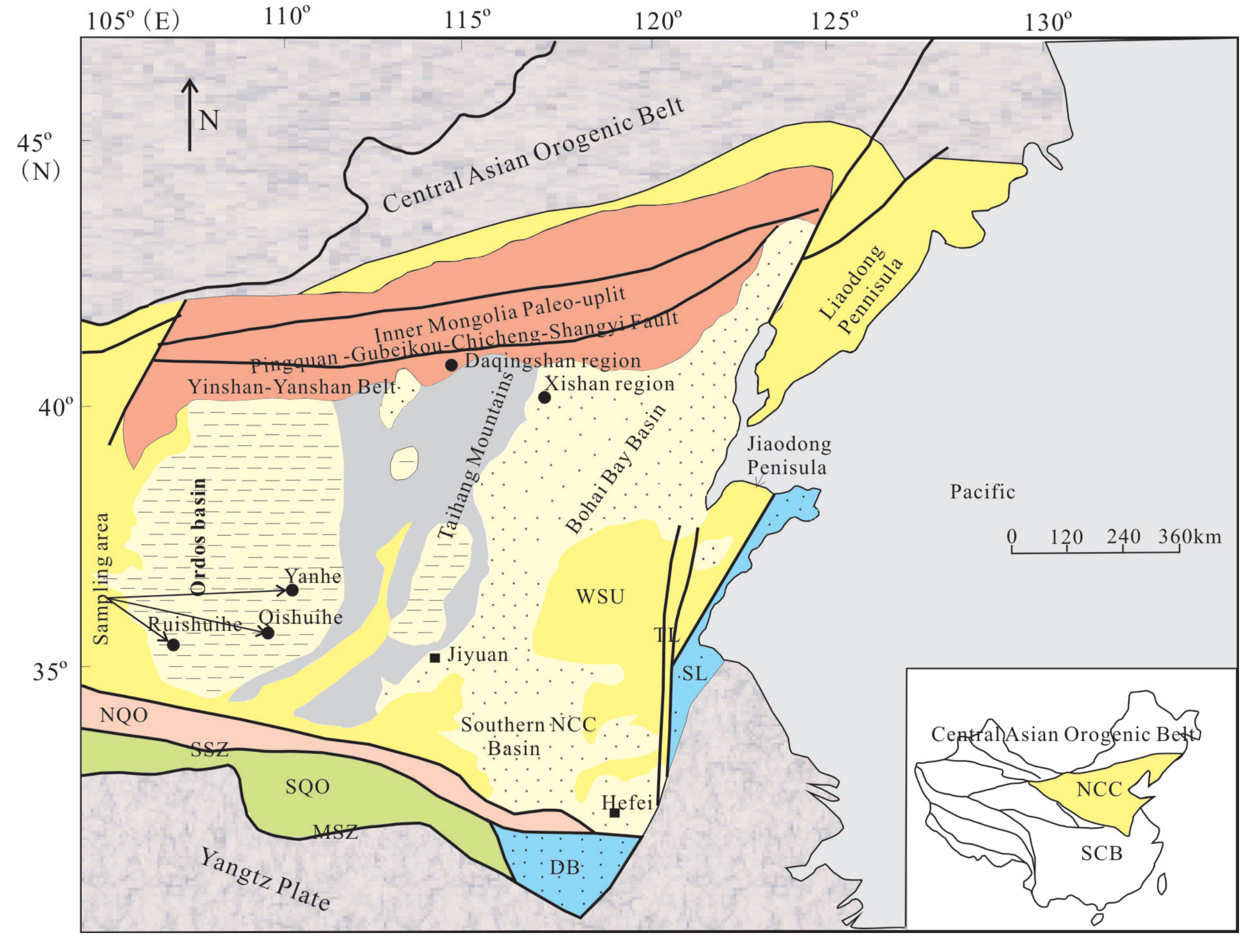


**Figure 1:** Simplified tectonic map of the North China Craton (modified after [6]). Abbreviations include: North China Craton (NCC), Northern Qinling Orogen (NQO), Southern Qinling Orogen (SQO), Shangdan suture zone (SSZ), Mianlue suture zone (MSZ), Dabie Orogen (DB), Sulu Orogen (SL), Tanlu fault zone (TL), Western Shandong Uplift (WSU).

tion is questionable and needs additional work. To study the provenance of the Yanchang Formation, we collected published data of the detrital zircons from the lower Yanchang Formation. We combined the data from multiple studies [14, 15], and reinterpreted and reanalyzed the results. The new results provide insight into the provenance, sediment dispersal pattern and sedimentary evolution of the Yanchang Formation.

## 2 Geological background

The Ordos Basin is a typical intracontinental basin situated in north central China (Fig. 1). The basin overlays the Archean granulites and lower Proterozoic greenschists of the North China Platform and was filled with Paleozoic to Cenozoic sedimentary rocks with thicknesses that exceed 8 km in the southwestern part [17]. Since the Mesoproterozoic, the Ordos area has experienced several multicycle tectonic stages.

Meso-Neoproterozoic volcano-clastic deposits are the first sedimentary cover in the basin during the Aulacogen period [18–20]. Prior to the Permian, the Ordos basin evolved as part of the North China block [14, 17, 21]. The Ordos Basin is superimposed on the marine basin in the Early Paleozoic. Massive marine sediments were deposited in the Early Paleozoic. The Cambrian-Ordovician formations consist predominantly of marine carbonates. Owing to the Caledonian movement, the basin experienced a long period of uplift and denudation during the Late Ordovician-Early Carboniferous [18]. As a result, the Silurian, Devonian, Lower Carboniferous and Upper Ordovician strata are missing [18, 21] (Fig. 2). Since the Late Carboniferous, the Ordos Basin experienced another marine transgression. It received paralic coal-bearing deposits during Late Paleozoic-Middle Triassic [23]. During the Middle to Late Triassic, the depositional environment com-

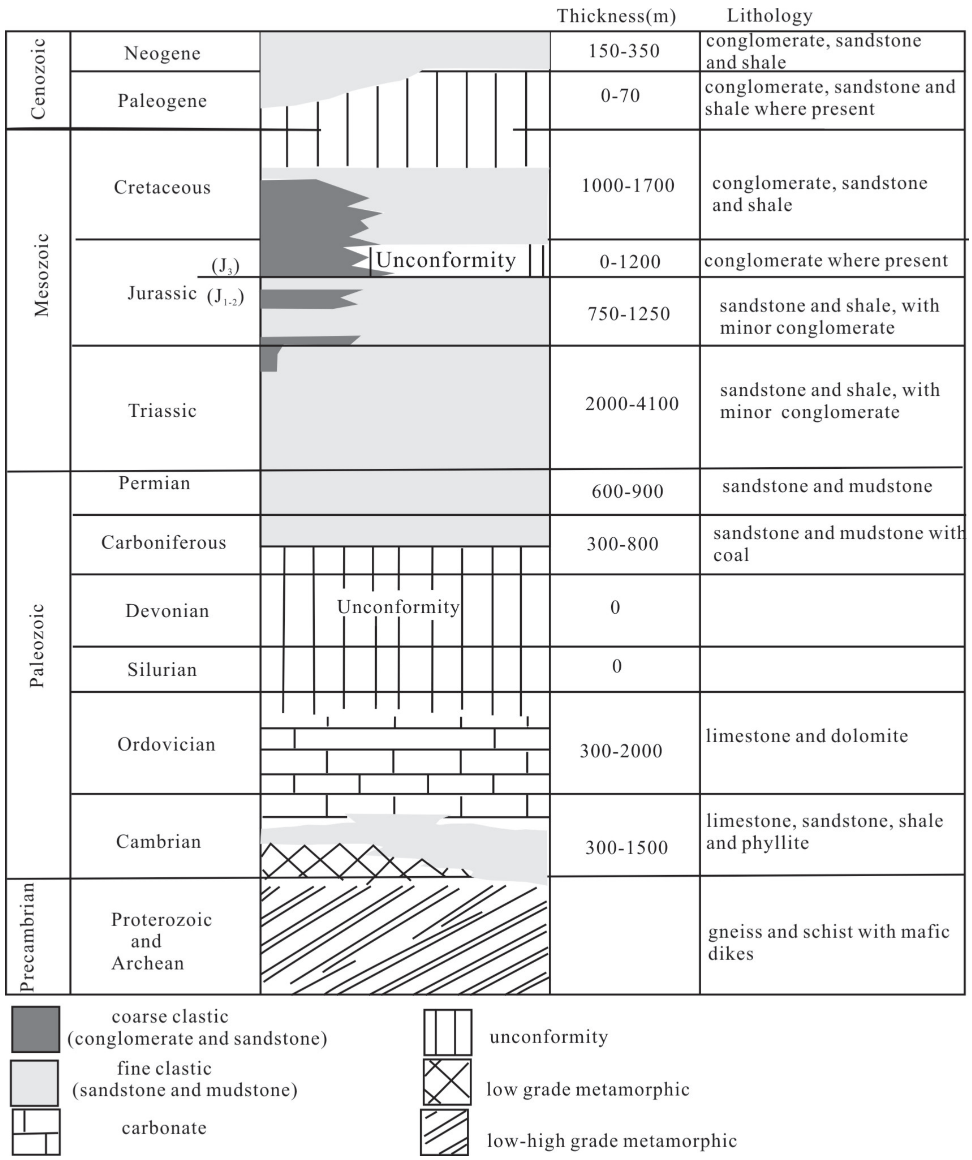


**Figure 2:** Generalized stratigraphic section for the Ordos Basin (modified after [22]). Data do not represent a complete stratigraphic column for any one part of the basin.

pletely changed from a marine-continental transitional depositional environment to a fluvial-deltaic-lacustrine depositional environment because of the collision between the North China Block and the South China Block. This event caused the depositional environment to change completely to that of a continental facies [14, 18, 24, 25]. In the Early Jurassic, the eastern margin of Asia became an active subduction zone [26, 27]. As a result, a series of orogenic processes and localized rifting around basin margins formed the modern Ordos Basin configuration [28, 29]. The Middle Jurassic strata in the basin are composed of fluvio-lacustrine clastic deposits [30]. In the Late Jurassic, the basin's eastern boundary was gradually uplifted and eroded [31]. The Early Cretaceous strata, characterized by red clastic deposits, are the last sedimentary sequence of the Ordos Basin [18, 32, 33]. Overall, the Late Triassic-Middle Jurassic formations are made up of fluvio-lacustrine clastic deposits. Many mineral deposits were formed in the sediments. Owing to the collision of India and Eurasia in the Middle-Late Eocene, most of the Ordos Basin lacks Late Cretaceous-Neogene sediments except for the western region [34]. In the Cenozoic, the Hetao graben system to the north and the Fenwei graben system to the south were produced by strike-slip movement and intraplate deformation [14]. Quaternary sediments are

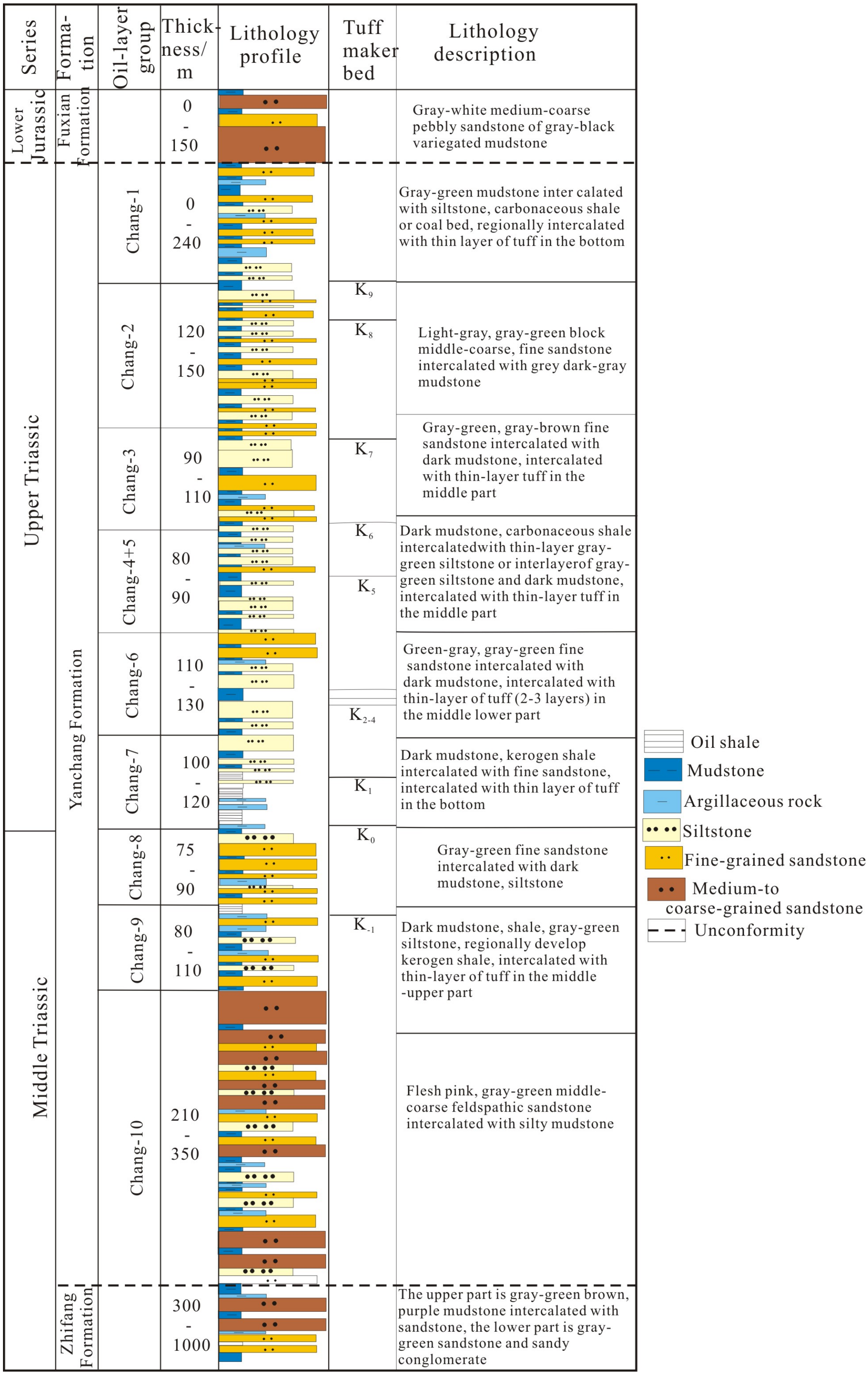


**Figure 3:** Stratigraphic column of the Yanchang Formation, Ordos Basin (after [35]).

characterized by loess deposits, especially in the Ordos Basin [18, 20].

The Yanchang Formation in the Ordos Basin consists lake deltaic deposits. It is formed by yellow sandstones and schists with thin coal beds in the upper part of the section. In terms of lithology, resistivity, and oil saturation, the Changqing Oilfield Company divides the Yanchang Formation into 10 members from the bottom to up: Chang-10–Chang-1 (Fig. 3). From Chang-10 to Chang-9 Units, the lake expanded rather quickly. From Chang-8 to Chang-7 periods, the lake basin expanded for the second time and thick sediment appeared in the central Ordos Basin. During the deposition of the Chang-7 unit, the Ordos Lake had the deepest water and widest surface. Huge source rocks were deposited. From Chang-6 to Chang-4+5 periods, the lake basin expanded again for a short time, especially in the southwestern Ordos Basin. In Chang-2+3 periods, the lake began to dry up. During the Chang-1 period, the deep lake returned and water levels started to fluctuate [19].

## 3 Methods

Zircon is a useful provenance proxy because of its durability and remarkable chemical stability over a wide range of lithospheric pressures, temperatures, and fluid/melt compositions [37]. The U-Pb age spectra of detrital zircons obtained from clastic sedimentary rocks provide important constraints for evaluating potential source regions [38, 39]. Furthermore, the youngest age of detrital zircons in clastic sedimentary rocks can be used as a constraint on the older age limit of deposition [40, 41].

An early attempt to use detrital zircons using large zircon fractions was applied to North American beaches and rivers [42]. With the advent of the sensitive high resolution ion micro-probe (SHRIMP) and laser ablation-inductively coupled plasma mass spectrometry (LA-ICP-MS), large populations of detrital zircon grains can be analyzed quickly. More recently, LA-ICP-MS U-Pb dating has been performed on detrital zircons from the Yanchang Formation in the southern Ordos Basin [14, 15]. Xie and Heller conducted LA-ICP-MS U-Pb dating at the GeoAnalytical Laboratory at Washington State University (Pullman, Washington, USA). Analyses were done using a New Wave UP-213 laser-ablation system in conjunction with a ThermoFinnigan Element2 single-collector double-focusing magnetic sector ICP-MS. Fixed 30 µm diameter spots were used with a laser frequency of either 10 or 5 Hz depending on estimated age and Pb abundance. Each analysis consisted of a 6-second warm-up period, with an 8-second delay in recording data to enable the samples to reach the plasma. Detailed procedures are similar to those described in [43]. Two hundred and fifty-eight (258) grains were analyzed from two samples. All analytical uncertainties in age were given with a 95% confidence level. One hundred and fifty-eight (158) grains gave concordant ages (concordance > 90%) [14]. Li and Huang [15] carried out the Zircon U-dating at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences in Wuhan. Laser sampling was conducted using a 193-nm GeoLas 2005 laser ablation system with a spot size of 32 µm. An Agilent 7500a ICP–MS instrument was used to acquire ion signal intensities. Each analysis incorporated an approximately 20s background acquisition (gas blank) followed by 50s of data acquisition from the sample. The operating conditions for the laser ablation system and the ICP–MS instrument and data reduction are the same as those described in [44]. Eighty (80) grains from the Yanchang Formation were analyzed and 67 grains gave concordant ages at the 90% confidence level [15].

## 4 State of knowledge

### 4.1 Yanchang Formation: Problematic Division

Yanchang Formation, which is situated in the Ordos Basin, is not only the first oil source and reservoir rock system in the Ordos Basin after its landlocked basin took form, but it also has the most extensive outcrops out. It is the earliest studied and the most completely developed stratotype section of continental Triassic strata in North China [45].

For a long time, however, the stratigraphic division of the Yanchang Formation has been highly debated (Tab. 1). Gan [51] subdivided the Yanchang Formation into members 1-5 in ascending order: the sandstone member ($T_3y^1$), the oil shale member ($T_3y^2$), the oil-bearing sandstone shale member ($T_3y^{3-4}$) and the coal-bearing rock member ($T_3y^5$). In a profile study on the strata in the east of the basin, the CAGS's Institute of Geology discovered that the floral assemblage of $T_3yn^{1-2}$ is not very diverse; it is dominated by Equisetites (*Equisetites brevidentatus*, *Neocalamites carcinoides*, *N. carrerei*), Marattiales (*Danaeopsis magnifolia)*, lycopods (*Pleuromeia*), and Pteridospermae (*Glossopteris* and *Tongchuanophyllum*). *Pleuromeia* and *Glossopteris* species are common and important components of the Early to Middle Triassic floras, and hence Institute of Geology, CAGS suggested naming $T_3yn^{1-2}$ the Middle Triassic Tongchuan Formation and placing

**Table 1:** The Triassic tectonic sequence framework in the southern Ordos Basin.

<table>
<tr><th colspan="2">Pan[46]</th><th colspan="2">Xie et al. [47]</th><th colspan="2">Institute of Geology of CAGS[48]</th><th colspan="2">Regional Geological Memoir Compilation Group of Shaanxi Province[49]</th><th colspan="2">Yang[29]</th><th>Deng et al. [50]</th></tr>
<tr><td>Jurassic system</td><td>Wayaobao series</td><td rowspan="9">Upper Triassic Yanchang Formation</td><td>$T_3y^5$</td><td rowspan="6">Upper Triassic</td><td rowspan="6">Yanchang Formation</td><td rowspan="6">Upper Triassic</td><td>Wayaobao Fromation</td><td>Chang-1</td><td rowspan="6">Upper Triassic</td><td>Chang-1</td></tr>
<tr><td rowspan="8">Upper Triassic</td><td rowspan="8">Yanchang Formation</td><td rowspan="2">$T_3y^4$</td><td rowspan="2">Yongping Formation</td><td>Chang-2</td><td>Chang-2</td></tr>
<tr><td>Chang-3</td><td>Chang-3</td></tr>
<tr><td rowspan="3">$T_3y^3$</td><td rowspan="3">Hujiacun Formation</td><td>Chang-4+5</td><td>Chang-4+5</td></tr>
<tr><td>Chang-6</td><td>Chang-6</td></tr>
<tr><td>Chang-7</td><td>Chang-7</td></tr>
<tr><td rowspan="2">$T_3y^2$</td><td rowspan="3">Middle Triassic</td><td rowspan="3">Tongchuan Formation</td><td rowspan="3">Middle Triassic</td><td rowspan="3">Tongchuan Formation</td><td>Chang-8</td><td rowspan="3">Middle Triassic</td><td>Chang-8</td></tr>
<tr><td>Chang-9</td><td>Chang-9</td></tr>
<tr><td>$T_3y^1$</td><td>Chang-10</td><td>Chang-10</td></tr>
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$T_3yn^{3-5}$ in the Upper Triassic Yanchang Formation *sensu stricto* [48]. In contrast, the Shaanxi Regional Geological Memoir Compilation Group, did not think that the Yanchang flora included all of the Tongchuan Formation flora and suggested renaming the first and the second members of Gan's "five-part division" as the Middle Triassic Tongchuan Formation and calling the third to fifth members the Upper Triassic Hujiacun Formation, Yongping Formation, and Wayaobao Formation, respectively [49]. On the basis of the five-part division, the Changqing Oilfield subdivides the Yanchang Formation into ten members on the basis of marker beds (from bottom to top, member Chang-10 to 1), dating them to the Late Triassic. However, the latest studies show that the Yanchang Formation was deposited as early as the Middle Triassic time [45, 50, 52]. Based on observations from the sporo-pollen assemblage, petrology and the depositional environment of Yanchang Formation, Deng *et al.* [50] found significant differences between Chang-10–Chang-8 and Chang-7–Chang-1. The Chang-8–Chang-10 members have low sandstone maturity and the depositional environment is characterized by well-developed rivers, deltas and shallow lakes. The sporo-pollen assemblage is dominated by a Pteridophyta spore, with high content of *Punctatisporites*. From the Chang-7 depositional period, the deep lake expeditiously expanded. The quartz content in the Chang-7 sandstone is significantly more than in previous units, which results in a corresponding change of rock types in the west and the southwest. The sedimentary system in the west and southwest margins of the basin transitioned to an alluvial fan and fan delta environment. The biotic comunity is characterized by the appearance of *Duplexisporites*, which is an important member of sporo-pollen assemblages in the Late Triassic. Deng *et al.* [50] suggested that the stratigraphical boundary between Chang-7 and Chang-8 member could be regarded as the boundary between the Middle Triassic and Upper Triassic time in the Ordos Basin. Chen *et al.* [52] discovered the climax of sedimentation in the Yanchang Formation is concentrated at the initial stage of the Chang-7 member, and suggested that the boundary between the Middle Triassic and Upper Triassic might be equivalent to that between the Chang-7 and the Chang-8 members. Furthermore, zircon U-Pb dating was performed on the tephra at the bottom of the Chang 7 member. Wang *et al.* [45] reported SHRIMP U-Pb zircon ages from the Ordos Basin, ranging from 239.7±1.7 to 241.3±2.4 Ma, which overlaps with the boundary age between the Ladinian and the Carnian stages (within the error range). In general, these findings have confirmed the presence of Middle Triassic strata at the bottom of Yanchang Formation. In other words, the Yanchang Formation is somewhat diachronous. The lower Yanchang Formation (Chang-10–Chang-8) was assigned as Middle Triassic, and the middle-upper Yanchang Formation (Chang-7–Chang-1) was regarded as Upper Triassic.

## 4.2 The detrital zircon studies of the Yanchang Formation

With the development of new analytical methods, detrital-zircon geochronology has been widely applied in the reconstruction of sediment pathways between sources and the Ordos Basin [14, 15]. Xie and Heller [14] reported detrital zircon age spectra for the early Yanchang Formation

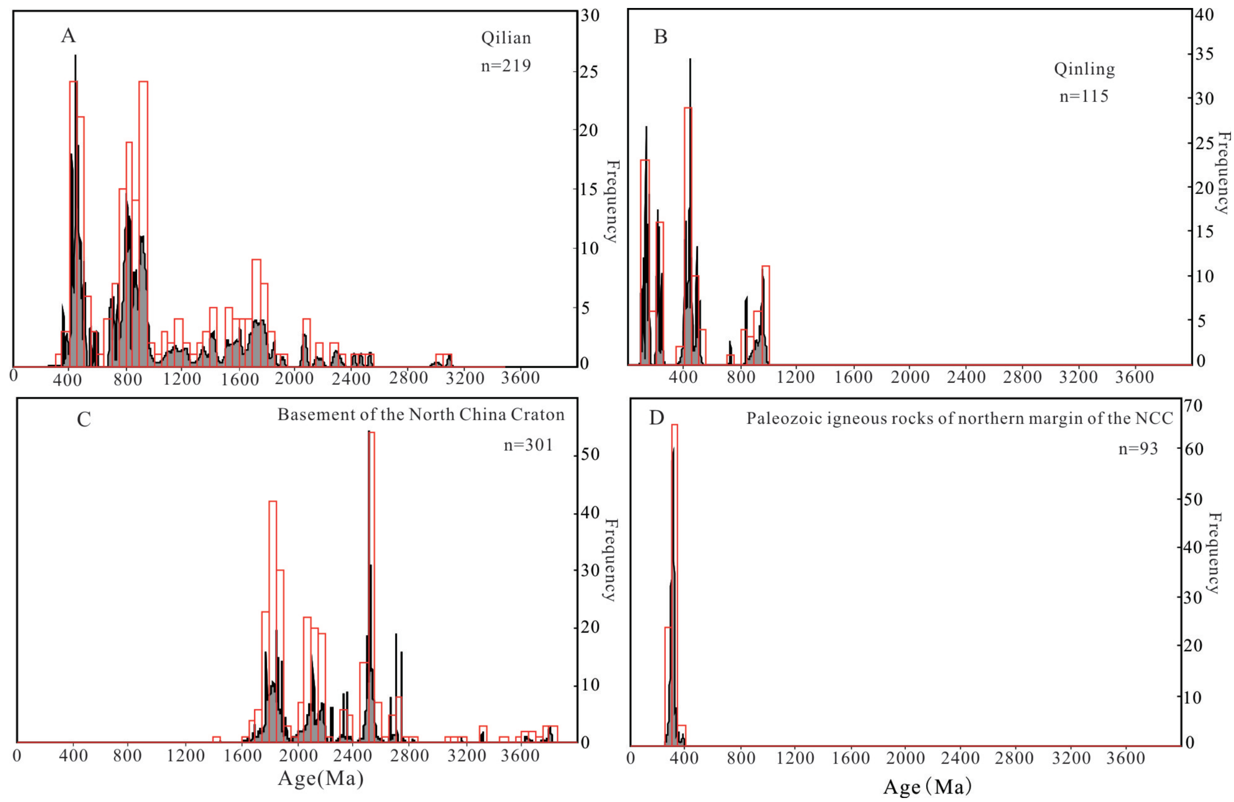


**Figure 4:** Relative probability density diagram of the ages for potential source regions (after [54]).

in the southern Ordos Basin and suggested it was likely recycled from previous sedimentary rocks from the North China block. Li and Huang [15] reported detrital zircon age spectra for the Yanchang Formation in the Yan'an area, and they suggested that the Yanchang Formation is mainly derived from recycled sediments of the central-eastern NCC. Their data interpretations are new and challenge the traditional concept. Previous studies suggested that the Qinlin-Qilian Orogen and the Inner Mongolia Paleo-uplift provided the source for the Yanchang Formation. Few researchers have suggested the Yanchang Formation was derived from recycled sediments of the NCC.

## 5 Results

The material comprising the sedimentary rocks is mainly derived from three major sources: high-grade metamorphic rocks of the deeply eroded cratonic basement, young volcanics from arcs and accretionary basins along active continental margins and recycled rock complexes of old crustal sections [53]. The NCC, the Inner Mongolia Paleo-uplift, the Qinling Orogen, the Qilian Orogen and the pre-Triassic sediments of the NCC constitute the potential source areas for the southern Ordos Basin during the Triassic. To determine the source of the sediment, we compiled the ages of magmatic events and built the age spectrum of the adjacent tectonic units of the southern Ordos Basin (Fig. 4). The North Qilian Belt is characterized by Early Paleozoic ages, whereas the Central Qilian Belt is characterized by Proterozoic ages (Fig. 4A). The Qinling Belt is characterized by Early Paleozoic igneous rocks. In addition, there are some Mesozoic ages and Neoproterozoic ages (Fig. 4B). The ~2500 and ~1800 Ma tectonothermal events are typically attributed to the NCC (Fig. 4C). Late Paleozoic magmatic activity within the NCC occurs mainly in the Inner Mongolia Paleo-uplift (Fig. 4D). In addition, the pre-Middle Triassic sedimentary rocks of the NCC might be the potential sediment source for the southern Ordos Basin in the Middle-Late Triassic. The Carboniferous to Permian strata from the northern margin of the NCC constrain three groups of detrital zircons (250–400 Ma, 1500–1950 Ma, and 2400–2700 Ma; Fig. 5). Meanwhile, we collected the previous detrital zircons data from the lower Yanchang Formation (Fig. 6). The detrital zircon U-Pb age patterns of the three samples show the same distributions, indicating that the three samples have similar provenance. The detrital zircons from the lower Yanchang Formation were divided into three groups based on their U-Pb ages: Pa-

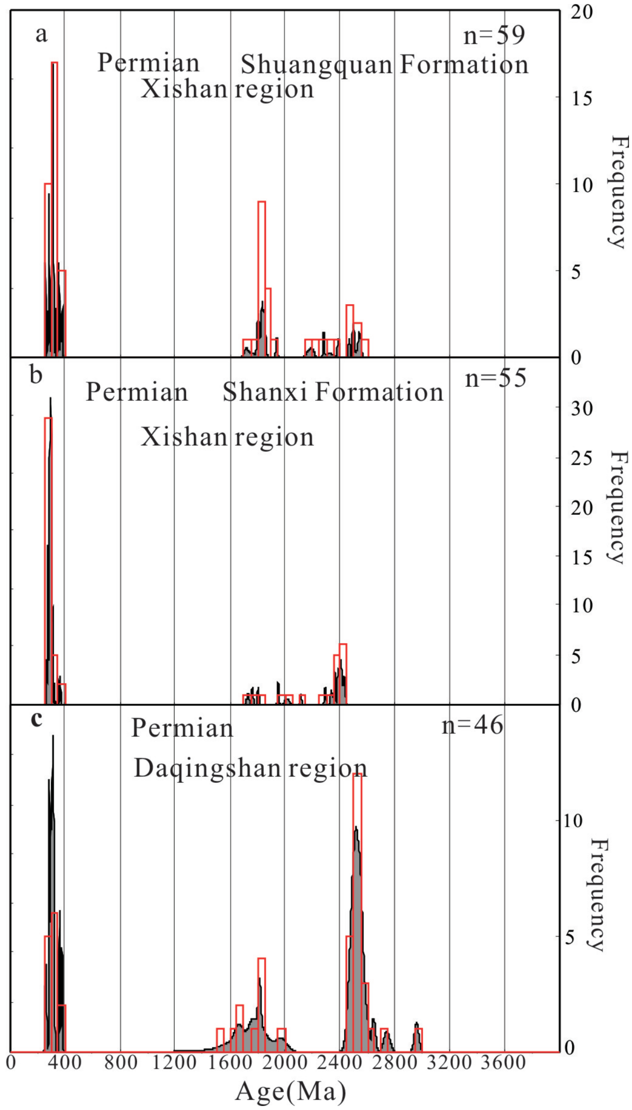


**Figure 5:** Relative probability density diagram of ages for the Permian section from the North China Craton. Data sources are [55, 56].

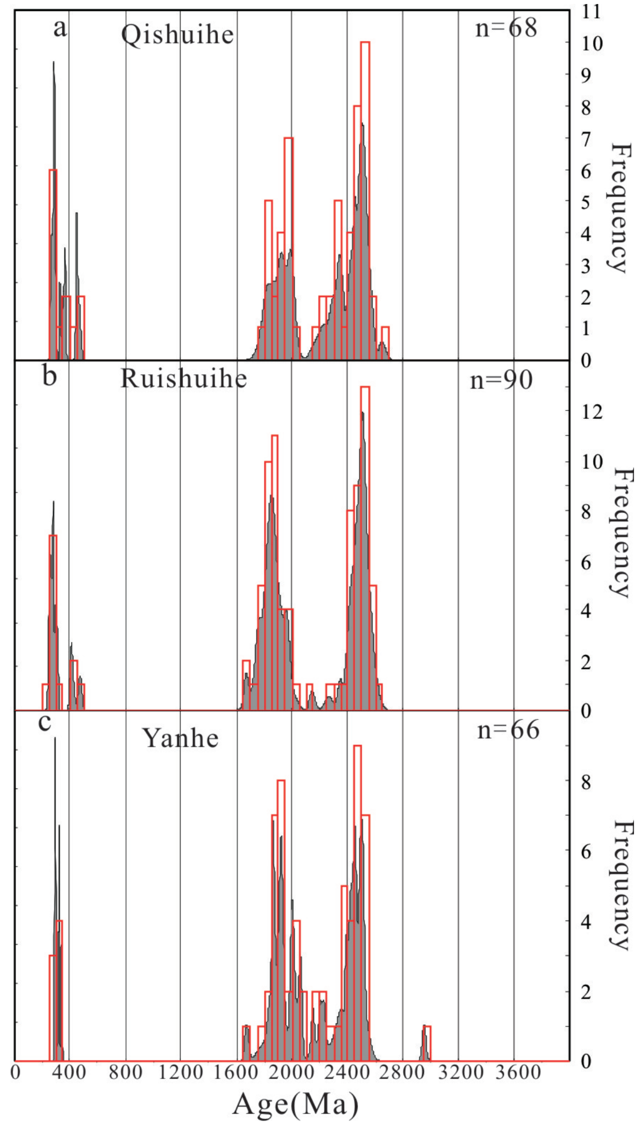


**Figure 6:** Relative probability density diagram of ages for the early Yanchang Formation. Data sources are [14, 15].

leozoic, Paleoproterozoic, and Neoarchean (Fig. 6). Most grains belong to the two older age groups (Paleoproterozoic and Neoarchean). No grains fall within ages between 500 Ma to 1.5 Ga.

## 6 Discussion

In general, the NCC is mainly characterized by a Neoarchean and Paleoproterozoic basement [57–60]. The Late Paleoproterozoic (1.8 Ga) and Neoarchean (2.5 Ga) detrital zircon age clusters of the lower Yanchang Formation may ultimately match that of the basement rocks of the NCC. Therefore, we suggest that the detrital zircons of the two old age groups (Paleoproterozoic, and Neoarchean) are likely derived from the NCC basement.

The Phanerozoic zircons were only derived from the orogens surrounding the NCC, and these Phanerozoic orogens have distinctive zircon U-Pb ages. Thus the source of sediments can be constrained according to the Phanerozoic zircons accumulated in the sediments [15, 55]. The lack of Neoproterozoic U-Pb ages indicates that no input from the Qinling Orogen or Qilian Orogen occurred, because both of these two source areas are characterized by Paleozoic and Neoproterozoic ages [14, 61]. Although, the lower Yanchang Formation shares a similar age spectra with the pre-middle Triassic sediments (Fig. 5, Fig. 6), we suggest that the lower Yanchang Formation is mainly derived from the Inner Mongolia Palaeo-uplift (IMPU) rather than from the recycled sediments of the central-eastern NCC, given the following lines of evidence:

1. The eastern NCC uplifted and eroded in the Late Triassic [62–64]. In spite of the similar age spectra of detrital zircons, it is impossible that the eastern NCC provided a potential source area for the southern Ordos Basin in the Middle Triassic. Moreover, considering the fact that there is no large-scale erosion around the Ordos Basin in the Middle Triassic, the lower Yanchang Formation could not be primarily derived from recycled sediments.
2. Most of Paleozoic zircons are very similar to the known Late Paleozoic igneous zircons from the Inner Mongolia Paleo-uplift. The Late Paleozoic magmatic activity within the NCC occurs mainly in the Inner Mongolia Paleo-uplift and is of Andean type [65, 66]. U-Pb ages of the Phanerozoic zircons from the Inner Mongolia Paleo-uplift range from 395 to 107 Ma [55]. The IMPU is located on the northern margin of the NCC (Fig. 1). It is a Late Palaeozoic Andean-style continental arc and is characterized by Late Paleozoic magmatic activity [65] (Fig. 4D). The IMPU is a tectonic province with extensive early Precambrian high-grade basement rocks that are unconformably overlain by Jurassic-Cretaceous volcanic and sedimentary rocks. Given the fact that the Late Paleozoic igneous rocks in the NCC are primarily distributed in the IMPU, we infer that the detrital zircons of the Paleozoic zircons mainly came from the IMPU.

   The sedimentary evidence indicates that the uplift and erosion between the Inner Mongolia Paleo-uplift and the Yanshan fold-and-thrust belt was distinct during the Late Paleozoic to Early Mesozoic [67]. The IMPU was an erosion area during the early Mesozoic. The strong differential uplift and erosion led to the lack of Mesoproterozoic-Paleozoic sedimentary rocks in the IMPU. The exhumation of the basement crystalline rocks and absence of the Meso-Neoproterozoic and Paleozoic sedimentary rocks in the IMPU are likely a result of these strong differential uplift and exhumation during the Late Paleozoic to Early Mesozoic [67]. The present IMPU is the consequence of major uplift and erosion between the Carboniferous and the Early Mesozoic. Thus, we infer that the Paleoproterozoic and Neoarchean detrital zircons have mainly been derived from the denudation of the IMPU basement, although the possibility that a small amount of source material came from the recycling of previous sedimentary rocks cannot be fully excluded.
3. Paleocurrent analysis revealed that the southern Ordos Basin mainly received easterly and northeasterly derived detritus during the deposition of the lower Yanchang Formation [68], which provides important evidence for the transport of materials from the IMPU to the southern Ordos Basin during the Middle Triassic. Furthermore, the analysis of the sandstones detrital modes indicates the provenance of the lower Yanchang Formation mainly came from the ancient mountains surrounding the basin [52], which is consistent with the tectono-sedimentary setting in the northern margin of NCC where the IMPU had been deeply eroded from the Late Carboniferous to the Early Jurassic [65, 66].

In summary, we suggest that the IMPU may be the main source area for the lower Yanchang Formation. Moreover, the possibility that a small amount of source material came from the recycling of previous sedimentary rocks cannot be ignored. In the Late Triassic, due to the Indosinian movement, the Qinling Orogen belt uplifted rapidly and provided the main source for the southern Ordos Basin. Certainly, IMPU and the pre-Late Triassic sediments of the NCC also constitute potential sedimentary source areas for the southern Ordos Basin. Further studies are needed to fully understand the provenance evolution of the Yanchang Formation.

## 7 Conclusions

The Yanchang Formation was deposited as early as the Middle Triassic. The detrital zircons from the lower Yanchang Formation were divided into three groups based on their U-Pb ages: Paleozoic, Paleoproterozoic, and Neoarchean. The youngest age group shows strong resemblance to those of Paleozoic igneous zircons from the IMPU on the northern margin of the NCC. The two older age groups are reflective of the provenance from the NCC basement. The IMPU may be the main source area for the lower Yanchang Formation.

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# References


[1] Johnson E.A., Liu S., Zhang Y.L., Depositional environments and tectonic controls on the coal-bearing Lower to Middle Jurassic Yan'an Formation, southern Ordos Basin, China. Geology, 1989, 17, 1123-1126

[2] Chen J.T., Lee J.H., Woo J., Formative mechanisms, depositional processes, and geological implications of Furongian (Late Cambrian) reefs in the North China Platform. Palaeogeography, Palaeoclimatology, Palaeoecology, 2014, 414, 246-259

[3] Xu Y.J., Du Y.S., Yang J.H., Prospects of Sediment Provenance Analysis. Geological Science and Technology Information, 2007, 26(3), 26-32 (in Chinese with English summary)

[4] Yang R.C., Li J.B., Fan A.P., Zong M., Zhang T., Research Progress and Development Tendency of Provenance Analysis on Terrigenous Sedimentary Rocks. Acta Sedimentologica Sinica, 2013, 31(1), 99-107 (in Chinese with English summary)

[5] Song K., Lv J.W., Du J.L., Wang H.K., Source direction analysis and delta depositional systems of Yanchang formation of the upper Triassic in the central Ordos Basin. Journal of Palaeogeography, 2002, 4(3), 59-66 (in Chinese with English abstract)

[6] Lv Q., Zhao J.X., Chen C.D., Shen X.L., Luo Y., Analysis of the provenance and basin bottom shape of Yanchang epoch of Mesozoic in Ordos Basin, China. Journal of Chendu University of Technology (Science & Technology Edition), 2008, 35(6), 610-616 (in Chinese with English summary)

[7] Nie Y.S., Tian J.C., Xia Q.S., Dou W.T., Song J.H., Source analysis of Yanchang Formation in Baibao-Jiyuan region, Ordos Basin. Petroleum Geology and recovery Efficiency, 2004, 11(5), 4-6 (in Chinese with English summary)

[8] Chen F, Fan T.L., Gao Z.Q., Yu X.T., Pang Z.L., Analysis of the provenance direction and the depositional systems of Yanchang Formation of Upper Triassic in the southern Ordos Basin. Journal of Xi'an Shiyou University (Natural Science Edition), 2009, 24(6), 24-32 (in Chinese with English summary)

[9] Zhu Z.L., Li W.H., Li K.Y., Chen Q.H., Guo Y.Q., Yuan Z., Provenance Analysis of Late Triassic Sediments in the Southern Ordos Basin. Geological Journal of China Universities, 2010, 16(4), 547-555 (in Chinese with English abstract)

[10] Han T.Y., Li H., Li W.H., Tian T.Q., Liu G.L., Ma H.Y., Li J.H., Distribution Characteristics and Geological Significance of U-Pb Age of Detrital Zircon in Yanchang Formation of Yanhe Strata Section of Ordos Basin. Northwest Geology, 2011, 44(1), 105-111 (in Chinese with English abstract)

[11] Deng K., Zhang S.N., Ding X.Q., Wan Y.L., Provenance analysis of Chang 8 and Chang 6 Members of Yanchang Formation in Fuxian exploration area of Ordos basin-From lithogeochmeistry and heavy minerals analysis. Journal of Guilin University of Technology, 2012, 32(1), 29-35 (in Chinese with English summary)

[12] Shang T., Chen G., Li W.H., Wu H.Y., Wang R.G., Zhang R., Provenance analysis of Chang 6 reservoir in Fuhuang exploration area of Ordos Basin. Geological Science and Technology Information, 2012, 31(1), 33-40 (in Chinese with English summary)

[13] Zhao Y.X., Wang J.F., Ding X., Liu Y.B., Yao J.L., Li S.X., Provenance analysis of Upper Triassic Chang 9 reservoir in Ordos Basin. Journal of Oil and Gas Technology, 2012, 34(4), 7-13 (in Chinese with English abstract)

[14] Xie X.Y., Heller P.L., U-Pb Detrital zircon geochronology and its implications: the early Late Triassic Yanchang Formation, south Ordos Basin, China. Journal of Asian Earth Sciences, 2013, 64, 86-98

[15] Li H.Y., Huang X.L., Constraints on the paleogeographic evolution of the North China Craton during the Late Triassic–Jurassic. Journal of Asian Earth Sciences 2013, 70-71, 308-320

[16] Li H.Y., He B., Xu Y.G., Huang X.L., U-Pb and Hf isotope analyses of detrital zircons from Late Paleozoic sediments: Insights into interactions of the North China Craton with surrounding plates. Journal of Asian Earth Sciences, 2010, 39, 335-346

[17] Ji L.M., Yan K., Meng F.W., Zhao M., The oleaginous Botryococcus from the Triassic Yanchang Formation in Ordos Basin, Northwestern China: Morphology and its paleoenvironmental significance. Journal of Asian Earth Sciences, 2010, 38, 175-185

[18] Yuan Y.S., Hu S.B., Wang H.J., Sun F.J., Meso-Cenozoic tectonothermal evolution of Ordos Basin, central China: Insights from newly acquired vitrinite reflectance data and a revision of existing paleothermal indicator data. Journal of Geodynamics, 2007, 44, 33-46

[19] Zhang, F.L., Huang, S.X., Yang, C.G., Gas Geology of Ordos Basin. Geological Press, Beijing, 1994 (in Chinese)

[20] Yang M.H., Li L., Zhou J., Jia H.C., Sun X., Qu X.Y., Zhou D., Ting Gong b, Ding C., Mesozoic structural evolution of the Hangjinqi area in the northern Ordos Basin, North China. Marine and Petroleum Geology, 2015, 66, 695-710

[21] Liu C.Y., Zhao H.G., Sun Y.Z., Tectonic background of Ordos Basin and its controlling role for basin evolution and energy mineral deposits. Energy Exploration & Exploitation, 2009, 27(1), 15-27

[22] Zhang L.P., Bai G.P., Zhao K.B., Sun C.Q., Restudy of acid-extractable hydrocarbon data from surface geochemical survey in the Yimeng Uplift of the Ordos Basin, China: Impro vement of geochemical prospecting for hydrocarbons. Marine and Petroleum Geology, 2006, 23, 529-542

[23] Zhang F.L., Relation of multicyles to oil and natural gas in Ordos Basin. Petro. Geo. Exp., 2004, 26, 138-142

[24] Liu S., The coupling mechanism of basin and orogen in the western Ordos Basin and adjacent regions of China. Journal of Asian Earth Sciences, 1998, 16, 369-383

[25] Liao C.Z., Zhang Y.Q., Wen C.S., Structural styles of the eastern boundary zone of the Ordos Basin and its regional tectonic significance. Acta Geologica Sinica, 2007, 81, 466-474 (in Chinese with English summary)

[26] Maruyama, S., Isozaki, Y., Kimura, G., Terabayashi, M., Paleogeographic maps of the Japanese islands: plate tectonic systhesis from 750 Ma to the present. Island Arc, 1997, 6, 121-142

[27] Isozaki Y., Aoki K., Nakama T., Yanai S., New insight into a subductionrelated orogen: a reappraisal of the geotectonic framework and evolution of the Japanese Islands. Gondwana Research, 2010, 18, 82-105

[28] Yang Y.T., Li W., Long M., Tectonic and stratigraphic controls of hydrocarbon systems in the Ordos Basin: a multicycle cratonic basin in central China. Am. AAPG Bull, 2005, 89(2), 255-269

[29] Yang J.J., Tectonic evolution and distribution pattern of oil and gas of Ordos Basin. Petroleum Industry Press, Beijing, 2002 (in Chinese)

[30] Yang M.H., Liu C.Y., Sequence stratigraphic framework and its control on accumulation of various energy resources in the Mesozoic continental basins in Ordos. Oil Gas Geology, 2006, 27, 563-570

[31] Zhao H.G., Liu C.Y., Wang J.Q., Gui X.J., Yue L.P., Weng W.F., Liang M.Y., Structural reverse and its significance to oil and gas accumulation in Ordos block in Neogene. Energy Exploration & Exploitation, 2009, 27(3), 167-180
[32] Zheng X.Q., Yan G., Types of hydrocarbon traps in Hangjinqi area of northern Ordos Basin.Progress in Exploration Geophysics, 2006, 29, 279-284.
[33] Xue H., Zhang, J.C., Wang, Y., Xu, B., Guo, H.Q., Relationship between tectonic evolution and hydrocarbon in Hangjinqi block of north Ordos Basin. Geotect. Metallogenia, 2009, 33, 206-214
[34] Li R.X., Li Y.Z., Tectonic evolution of the western margin of the Ordos Basin, central China. Russian Geology and Geophysics, 2008, 49, 23-27
[35] Yang H., Deng X.Q., Deposition of Yanchang Formation deep-water sandstone under the control of tectonic events in the Ordos Basin. Petroleum Exploration and Development, 2013, 40(5), 549-557
[36] Chen Q.H., Li W.H, Gao Y.X., Guo Y.Q., Feng J.P., Zhang D.F.3, Cao H.X., Liang J.W., The deep-lake deposit in the Upper Triassic Yanchang Formation in Ordos Basin, China and its significance for oil-gas accumulation. Science in China Series D: Earth Sciences, 2007, 50(Supp. II), 47-58
[37] Moecher, D.P., Samson, S.D., Differential zircon fertility of source terranes and natural bias in the detrital zircon record: Implication s for sedimentary provenance analysis. Earth and Planetary Science Letters, 2006, 247, 252-266
[38] Dickinson, W.R., Gehrels, G.E., U-Pb ages of detrital zircons in Jurassic eolian and associated sandstones of the Colorado Plateau: Evidence for transcontinental dispersal and intraregional recycling of sediment. Geological Society of America Bulletin, 2009, 121, 408-433
[39] Zhang Y., Wang D.Y., Yang H., Xin B.S., Fu J.H., Yao J.L., Provenance analysis of Nanyinger Group in the North Qilian Belt: constraints from zircon U–Pb geochronology. Arabian Journal of Geosciences, 2015, 8, 3403-3416
[40] Wilde S.A., Valley J., Peck W.H., Graham C.M., Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago. Nature, 2001, 409, 175-178
[41] Fedo C.M., Sircombe K.N., Rainbird R.H., Detrital Zircon Analysis of the Sedimentary Record. Reviews in Mineralogy and Geochemistry, 2003, 53, 277-303
[42] Ledent D., Patterson C., Tilton G.R, Ages of zircon and feldspar concentrates from North American beach and river sands. Journal of Geology, 1964, 72, 112-122
[43] Chang Z., Vervoort, J.D., McClelland, W.C., Knaack, C., U-Pb Dating ofZircon by La-Icp-Ms. Geochemistry, Geophysics, Geosystems, 2006, 7, 5-14
[44] Yuan H.L., Gao S., Liu X.M., Li H.M., Günther D., Wu F.Y., Accurate U–Pb age and trace element determinations of zircon by laser ablation-Inductively Coupled Plasma Mass Spectrometry. Geostandards and Geoanalytical Research, 2004, 28, 353-370
[45] Wang D.Y., Xin B.S., Yang H, Fu J.H., Yao J.L., Zhang Y., Zircon SHRIMP U-Pb age and geological implications of tuff at the Bottom of Chang-7 Member of Yanchang Formation in Ordos Basin. Science China: Earth Sciences, 2014, doi: 10.1007/s11430-014-4979-0
[46] Pan Z.X., Phytolite in Mesozoic in north Shaanxi. China Palaeophyte, 1936, 4, 1-49 (in Chinese)
[47] Xie Q.Y., Sun G.F., Li Y.L., The petroleum geological survey summary report of Ordos Basin. Oil Survey Team of Shaanxi Provincial Geology Bureau, 1974 (in Chinese)
[48] Institute of Geology Chinese Academy of Geological Sciences (CAGS). Stratigraphy and Palaeontology in Mesozoic Ordos Basin. Geological Publishing House, Beijing, 1980 (in Chinese)
[49] Regional Geological Memoir Compilation Group of Shaanxi Province, Regional geology of Shaanxi Province. Geological Publishing House, Beijing, 1989 (in Chinese)
[50] Deng X.Q., Li W.H., Liu X.S., Pang J.L., Liu X., Discussion on the stratigraphic boundary between Middle Triassic and Upper Triassic. Acta Geologic Sinica, 2009, 83, 1089-1096 (in Chinese with English summary)
[51] Gan K.W., A preliminary study summary report on Sinian to Jurassic stratum of Northwestern and Northern Ordos platform. Yinchuan petroleum Administration of Ministry of Petroleum Industry, 1959, (internal report) (in Chinese)
[52] Chen A.Q., Chen H.D., Hou M.C., Lou Z.H., Xu S.L., Li J., Su Z.T., The Middle-Late Triassic Event Sediments in Ordos Basin: Indicators for Episode I of the Indosinian Movement. Acta Geologica Sinica, 2011, 85, 1681-1690 (in Chinese with English summary)
[53] Zhu X.Y., Chen F.K., Li S.Q., Yang Y.Z., Nie H., Siebel W., Zhai M.G., Crustal evolution of the North Qinling terrain of the Qinling Orogen, China: Evidence from detrital zircon U-Pb ages and Hf isotopic composition. Gondwana Research, 2011, 20, 194-204.
[54] Zhang Y., The Research of Sequence Stratigraphy and Provenance of the Early-Middle Triassic in the Southeastern Margin of Ordos Basin and Its Adjacent Region. PhD thesis, Beijing Normal, China, 2014 (in Chinese with English summary)
[55] Yang J.H., Wu F.Y., Shao J.A., Wilde S.A., Xie L.W., Liu X.M., Constraints on the timing of uplift of the Yanshan Fold and Thrust Belt, North China. Earth and Planet Science Letters, 2006, 246(3-4), 336-352
[56] Cope T., Ritts B.D., Darby B.J., Late Paleozoic sedimentation on the northern margin of the North China Block: implications for regional tectonics and climate change. International Geology Review, 2005, 47, 270-296
[57] Zhai M.G., Guo J.H., Liu W.J., Neoarchean to Paleoproterozoic continental evolution and tectonic history of the North China Craton: a review. Journal of Asian Earth Sciences, 2005, 24, 547-561
[58] Zhao G.C., Sun M., Wilde S.A., Li S.Z., Late Archean to Paleoproterozoic evolution of the North China Craton: key issues revisited. Precambrian Research, 2005, 136, 177-202
[59] Zhai M.G., Santosh M., The early Precambrian odyssey of North China Craton: a synoptic overview. Gondwana Research, 2011, 20, 6-25
[60] Darby B.J., Gehrels J., Detrital zircon reference for the North China block. Journal of Asian Earth Sciences, 2006, 26, 637-648
[61] Wang T., Wang X.X., Tian W., Zhang C.L., Li W.P., Li S., North Qinling Paleozoic granite associations and their variation in space and time: Implications for orogenic processes in the orogens of central China. Science China Earth Sciences, 2009, 52(9), 1359-1384
[62] Qi J.F., Yu F.S., Lu K.Z., Zhou J.X., Wang Z.Y., Yang Q., Conspectus on Mesozoic basins in Bohai Bay province. Earth Science Frontiers, 2003, 10 (Suppl.), 199-206 (in Chinese with English summary)
[63] Ji Y.L., Hu G.M., Huang J.J., Wu Z.P., Eroded strata thickness of Mesozoic and evolution of Mesozoic and Cenozoic basins in the Bohai Bay basin area. Acta Geologica Sinica, 2006, 80(3), 351-358 (in Chinese with English summary)

[64] Yang M.H., Liu C.Y., Zeng P., Bai H., Zhou J., Prototypes of Late Triassic Sedimentary Basins of North China Craton (NCC) and Deformation Pattern of Its Early Destruction. Geological Review, 2012, 58(1), 1-18 (in Chinese with English abstract)
[65] Zhang S.H., Zhao Y., Song B., Yang Y.H., Zircon SHRIMP U-Pb and in-situ Lu-Hf isotope analyses of a tuff from Western Beijing: Evidence for missing Late Paleozoic arc volcano eruptions at the northern margin of the North China block. Gondwana Research, 2007, 12, 157-165
[66] Zhang S.H., Zhao Y., Song B., Yang Z.Y., Hu J.M., Wu H., Carboniferous granitic plutons from the northern margin of the North China block: implications for a late Palaeozoic active continental margin. Journal of the Geological Society, 2007, 164, 451-463
[67] Zhang S.H., Zhao Y., Liu J., Hu J.M., Chen Z.L., Li M., Pei J.L., Zhou J.X., Emplacement depths of the Late Paleozoic-Mesozoic granitoid intrusions from the northern North China block and their tectonic implications. Acta Petrologica Sinica, 2007c, 23, 625-638 (in Chinese with English abstract)
[68] Luo J.L., Li Z.X., Shi C.E., Li J., Han Y.L., Wang H.H., Li J.B., Wang C.Y., Depositional system sand provenance directions for the Chang 6 and C hang 8 reservoir groups of the Upper Triassic Yanchang Formation in the southwestern Ordos Basin, China. Geological Bulletin of China, 2008, 27(1), 101-111 (in Chinese with English summary)