

Paleogeographic framework and provenance features during Late Triassic Chang 9 time of the Yanchang Formation, Ordos Basin, China

Xiong Ding · Jingchun Tian · Jingshan Chen ·
Jingli Yao · Xiuqin Deng · Yuanhao Li

Received: 29 December 2013 / Accepted: 9 December 2014 / Published online: 28 December 2014
© Saudi Society for Geosciences 2014

Abstract The Chang 9 interval at the lower part of the Upper Triassic Yanchang Formation in the Ordos Basin is a new discovery sequence for strategy replacement in the oil exploration field. By conducting a comprehensive study of outcrop sections, well drilling, drill cores, well loggings, and test data, based on the relevant research achievements of some predecessors, and combined with the analysis of geological background of this basin, it is considered that the Ordos Basin is a broad and shallow lake basin with terrigenous clastic deposition during Late Triassic Chang 9 time. The lake basin had been supplied with multiple drainage systems and provenances. The lake water in this basin is inland freshwater to brackish water. Sedimentary framework is characterized by the development of “a lake surrounded by multiple deltas” pattern. On the basis of paleocurrent analysis, distribution of sedimentary facies and sand bodies, and the quantitative analysis results of rock fragment components and trace elements of Chang 9 sandstone, it is recognized comprehensively that the Chang 9 provenances have a close connection with the basin tectonic evolution and paleogeographic background. The provenance of the Ordos Basin in Chang 9 time can be divided into five provenance systems: i.e., the northeast,

north, northwest, southwest, and south provenance systems. Characteristics of rock fragment and trace element assemblages are documented in the individual provenance systems, respectively. It is inferred that terrigenous clastic sediments in Chang 9 interval mainly originate from the old lands around the basin. Parent rocks in these provenances are composed of a variety of rocks dominated by metamorphic rocks.

Keywords Paleogeographic framework · Provenance analysis · Sandstone · Chang 9 time · Ordos Basin

Introduction

The Ordos Basin is located in the vast loess plateau and desert steppe region of central China. Long-time extensive research has been carried into the paleogeography of the Ordos Basin during Late Triassic Yanchang age, gaining fruitful study results and knowledge (Chen et al. 2006; Fu et al. 2005; Liu et al. 2013; Zhang et al. 2013). Many of them hold that the Ordos Basin is overall characterized by huge dimension ($>25 \times 10^4$ km²), broad lake, shallow water depth, and flat terrain as well as little segmentation during Late Triassic Yanchang age, while its depositional boundaries far outreached the present layout of the Yanchang Formation strata of the Ordos Basin, with its north frontier being Yinshan Old Land, northwest frontier Alxa Old Land, southwest frontier Longxi Old Land, south frontier Qinling Old Land, and it could reach Shanxi, Henan and Hebei provinces eastward (Fig. 1). The eastern frontier is approximately located in the zone from Datong to Jining via Wutai, Shijiazhuang, and Handan, and further eastward came into realms of North China Old Land dominated by uplifting and denudation. Thus, the Ordos Basin is actually a part of North China Basin during the Late Triassic and has the features of inland basin “surrounded by mountains on all sides” (Fig. 1).

X. Ding (✉) · J. Tian
Chengdu University of Technology, Chengdu 610059, Sichuan,
China
e-mail: dingxiong_2007@126.com

X. Ding
State Key Laboratory of Oil and Gas Reservoir Geology and
Exploitation, Chengdu 610500, Sichuan, China

X. Ding · J. Chen
School of Geosciences and Technology, Southwest Petroleum
University, Chengdu 610500, Sichuan, China

J. Yao · X. Deng · Y. Li
Research Institute of Exploration and Development, PetroChina
Changqing Oilfield Company, Xi'an 710021, Shanxi, China

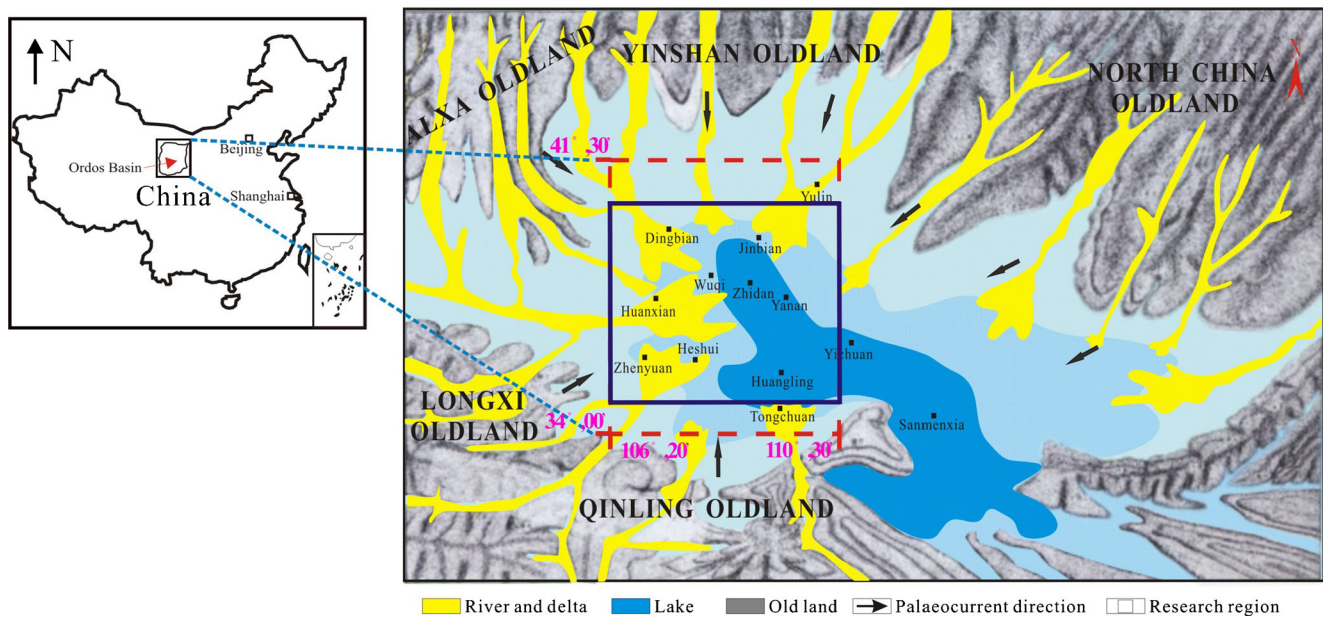


Fig. 1 Sketch showing paleogeographic framework during Late Triassic Chang 9 time, Ordos Basin

Paleotopography in this basin shows overall features of “higher in the northern part and lower in the southern part, north flank of less inclination, and steep inclined south flank.” Due to the stable subsidence of this sedimentary basin and abundant substance supply, huge thick terrigenous clastic sediments of alluvial fan, river, delta, and lake are accumulated within the basin, overall taking on a varying trend of thickening from east to west and from north to south. Coarse-grain clastic sediments with a thickness up to above 3000 m have been accumulated along the western margin of the basin, forming a large-scale subsidence zone in near north-south strike direction. At the same time, the southern zone from Tongchuan to Zhengzhou via Sanmenxia and Jiyuan is a great-scale subsidence center in near east-west strike direction, where clastic sediments have been deposited with over 2000 m thick (Chen et al. 2007; Huang et al. 2012; Liu and Yao 2000).

Geological setting

The Upper Triassic Yanchang Formation is one of the most important oil-producing sequences in the Ordos Basin. With the anew understanding of the petroleum geology of the Ordos Basin over the past few years, the new discovery and breakthrough in the oil exploration have been achieved in Chang 9 interval (hereinafter called “Chang 9” for short) at the lower part of the Yanchang Formation, which shows that this interval has good prospects for oil exploration (Ding et al. 2013). Certain basic researches on Chang 9 lithofacies paleogeography and sedimentary geology throughout the entire basin have been conducted in varying degrees, and some useful research

findings have been achieved (Ding et al. 2013; Fu et al. 2005). However, a further deep study is required due to a relatively small number of exploratory wells that penetrate the Chang 9 interval in this basin during early exploration, limited information available, and big controversy on some knowledge. Therefore, using new data and new ideas to re-recognize the paleogeography of whole basin in Chang 9 time, especially the distribution of provenances and sand bodies, will contribute to the proper guidance for Chang 9 oil exploration.

The Upper Triassic Yanchang Formation in Ordos Basin may commonly be divided into five lithological members and ten oil-bearing intervals in accordance with lithological association and hydrocarbon-bearing property (Ding et al. 2013; Fu et al. 2005). The Chang 9 situated in the lower part of the Yanchang Formation is mainly composed of continental sandstone and mudstone with complicated and varied lithological characters. It mainly shows alternating layers of pale-, brownish-, and greenish-gray glutenite; sandstone; gray siltstone; and black- and dark-gray mudstone and shale in various thicknesses and contains interlayers of black-gray carbonaceous mudstone, coal streak, and/or thin coal seam, while it still contains interlayers of gray-brown oil shale in the east, pale-gray tuff and tuffaceous mudstone. The Chang 9 ranges from 80 to 125 m in thickness and makes conformable contact with underlying Chang 10 interval and overlaying Chang 8 interval, respectively (Table 1).

Paleogeographic framework

The paleotopography and sedimentary framework of the Ordos Basin during Chang 9 time are basically similar to

Table 1 Stratigraphic chart of the Upper Triassic Yanchang Formation, Ordos Basin

Stratigraphic system				Thickness (m)	Lithologic description	
System	Series	Formation	Member	Oil-bearing interval		
Jurassic	Lower	Fuxian			0~150	
Triassic	Upper	Yanchang	Fifth (T ₃ y5)	Chang 1	0~240	Dark gray-green silty mudstone and argillaceous siltstone interbedded with fine sandstone and thin coal seams partially
			Fourth (T ₃ y4)	Chang 2	120~150	Gray-green medium-fine sandstone interbedded with dark gray mudstone
				Chang 3	90~110	
			Third (T ₃ y3)	Chang 4+5	80~90	Light-colored sandstone interbedded with unequal thick dark mudstone. “Zhangjiatan Shale” of Chang-7, developed in south part, is the major source rock; mudstone and shale are mainly developed in Chang 4+5
				Chang 6	110~130	
			Second (T ₃ y2)	Chang 7	100~120	Light-colored sandstone interbedded with dark mudstone
				Chang 8	75~90	
			First (T ₃ y1)	Chang 9	80~125	Light gray, brown-gray, green-gray coarse-fine sandstone and gray siltstone interbedded with dark gray mudstone and shale; “Lijiapan Shale” developed at the top of this interval
				Chang 10	300~400	
				Middle	Zhifang	

those throughout the whole Late Triassic (Chen et al. 2007; Ding et al. 2013; Huang et al. 2012; Liu and Yao 2000). However, due to Chang 9 time is at the early development and evolution stage, therefore, the basin at this stage has its specific characteristics mainly in a smaller domain of the stable lake than that in the ultimate development period (Chang 7 time) of the lake basin. Based on the existing research achievements, and combined with the comprehensive analysis of the paleogeographic background, material source, depositional features, and sedimentary geochemistry, the paleogeographic framework of the Ordos Basin during Chang 9 time is described as follows.

Broad and shallow lake basin with the supply of multiple drainage systems and provenances

Vast old lands are distributed around the sedimentary basin in Ordos and its neighboring areas (Fig. 1). The Alxa Old Land is located at the northwest of this basin, Yinshan Old Land at the north, North China Old Land to the northeast, Longxi Old Land at the southwest, and Qinling Old Land at the south. The paleotopography here is of a layout with old lands all around and sedimentary basin in the middle. The paleotopography shows an overall developing trend from high terrain at north to low basin in the middle before high south again and from high terrain at west to low terrain at east. The stable lake of small domain within the basin, which approximately extends in NW-SE strike direction, expands mainly at the southeast area of the Ordos Basin which is to the east of Wuqi-Zhengning

line, opening to the southeast and extending to the western area of Henan Province. While the old lands around the basin is in the period of continuous uplifting and denudation, the numerous rivers deriving from them steadily ensure supply of adequate fresh water and rich terrigenous detrital materials for the confluence basin of stable subsidence, and paleocurrent has dominantly three flow directions: the one from north to south, the one from west to east, and another from south to north. In conclusion, the Ordos Basin is a terrigenous clastic depositional basin with supply of multiple drainage systems and provenances during the Chang 9 time. There are a variety of technologies and methods to determine and recover the water depth of ancient sedimentary basins (Abdalla et al. 2014; Decarlis and Lualdi 2011; Stern and Wagreich 2013), such as lithology, authigenic mineral, sedimentary structure, fossil category and assemblage, trace fossil, ichnofacies, and others, but these technologies and methods, which basically belong to qualitative analysis, and accurate quantitative judgment are still very difficult to be made available. According to core observation, tubular dwelling and feeding burrows (Fig. 2a) are commonly seen in sandstone and mudstone of Chang 9 delta front. They belong to Skolithos ichnofacies and mainly are distributed in high-energy shallow-water environment of shallow lakes, so the ancient water depth is estimated to be 2 to 5 m (Chen et al. 2007; Huang et al. 2012). Secondly, small-scale wave-ripple bedding (Fig. 2b) can be seen in delta front siltstone, which indicates that they are formed in the high-energy shallow-water environment above the normal wave base, so the ancient water depth is estimated to be 10 m at most. Thirdly, phylogenetic upright root traces in situ

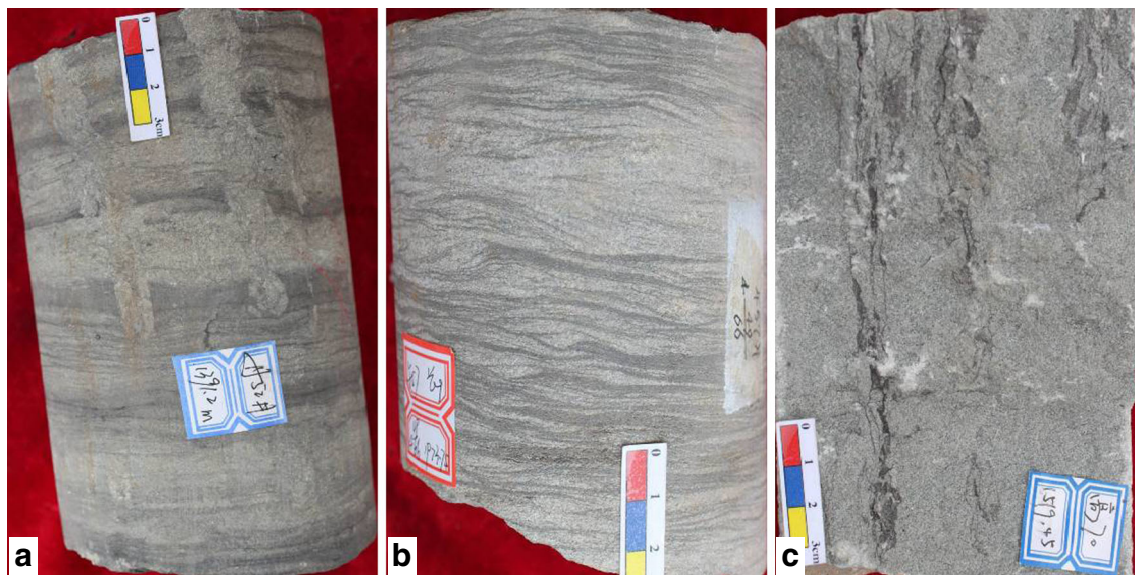


Fig. 2 Core photos showing sedimentary structures in sandstone and mudstone in Chang 9 time, Ordos Basin. **a** Light gray siltstone interbedded with dark gray mudstone of delta front, the vertical tubular burrows can be seen. Well Dan 52, 1,391.2 m; **b** light gray siltstone with

argillaceous stripes of delta front, small-scale wave-ripple bedding is developed. Well Wu 57, 1,973.75 m; **c** light gray medium to fine sandstone of delta front, phylogenetic upright root traces can be seen. Well Gao 70, 1,519.45 m

(Fig. 2c) are often seen in the sandy sediments of delta front. They belong to Rihizoliths ichnofacies and indicate that the original underwater sediments were uplifted above the lake level with relative descending of the secondary lake level and the delta front environment was changed into the delta plain environment suitable for the rooting and growth of plants. This reflects from another side that the delta front environment water depth is not deep, so the water depth is estimated to be several meters. Based on the above analysis, it may be considered that the Ordos Basin during Chang 9 time is a shallow lake basin, and the lake is mainly dominated by shore-shallow lake environment. Inferred water depth ranges from 0 to 10 m. It is worth noting that, with subsidence of the basin basement and relative rise of the lake level, the lake in the eastern part of the basin evolved to semi-deep lake to deep lake environment with the “Lijiapan Shale” as the representative (Chen et al. 2007; Ding et al. 2013; Huang et al. 2012) during late Chang 9 time.

In summary, a conclusion may be drawn that the Ordos Basin is a broad and shallow lake basin with the terrigenous clastic sedimentation and the supply of multiple drainage systems and provenances during Chang 9 time.

The nature of water body

Drilling cuttings and cores reveal that the Chang 9 interval consists of terrigenous clastic rocks which have been deposited in fluvial, deltaic, and lacustrine environments in the study area. It ranges commonly from 80 to 120 m in thickness.

The Chang 9 lithology is complicated and varied; mainly includes pebbly sandstone, sandstone, siltstone, dark mudstone, and shale being rich in organic matter and fossils; and contains interlayers of carbonaceous mudstone, coal streak, and/or thin coal seam. The algae, bivalve, Ostracoda, *Estheria*, fish fossils, etc. can be seen in cores. Carbonized plant fragments and plant root traces are common. The paleophytology is characterized by the development of *Danaeopsis* flora fossil assemblage (Liu and Yao 2000). From all the lithological and paleontological assemblages, it shows that the Ordos Basin was in the condition of humid and temperate paleoclimate (Chen et al. 2007; Ding et al. 2013; Huang et al. 2012; Liu and Yao 2000), with abundant rainfall and luxuriant vegetation during Chang 9 time. The paleolatitude recovered based on paleomagnetism also prove that the Ordos Basin was in the north temperate zone during the Late Triassic, for example, the Tongchuan region almost was located in north latitude 34°, 33' at that time (Liu and Yao 2000). According to the results of quantitative analysis on trace elements of 31 samples from Chang 9 mudstone (Table 2), it shows that boron content ranges from 15.0 to 58.6 $\mu\text{g/g}$ and is 36.95 $\mu\text{g/g}$ on the average, which is lower than the threshold value (60 $\mu\text{g/g}$) for discriminating between marine and continental strata. The ratio of B/Ga ranges from 0.94 to 2.32 and is 1.46 on the average, which is lower than the threshold value (3.3) for discriminating between marine and continental strata. The ratio of Sr/Ba ranges from 0.22 to 0.40 and is 0.32 on the average, which is also lower than the threshold value (1.0) for discriminating between marine and continental strata. The content of other trace elements, such as Cr, Cu, Ni, V, and so on, is a little lower, which also reflects the continental

Table 2 Results on trace elemental analysis of 31 samples from mudstones in Chang 9 time, Ordos Basin

Trace elements	Range of values ($\mu\text{g/g}$)	Mean ($\mu\text{g/g}$)	Ratio of trace elements	Range of values	Mean
B (boron)	15.0~58.6	36.95	B/Ga ^a	0.94~2.32	1.46
Ga (gallium)	16.1~30.8	25.27	Sr/Ba ^b	0.22~0.40	0.32
Rb (rubidium)	57.4~203	153.88	V/(V+Ni)	0.69~0.83	0.75
Sr (strontium)	148~400	262	U/Th ^c	0.12~0.44	0.24
Ba (barium)	452~1466	814			
V (vanadium)	95.2~176	136.49			
Ni (nickel)	31.4~65.1	45.50			
U (uranium)	2.28~4.79	3.37			
Th (thorium)	11.0~19.3	14.2			

^a B/Ga ratio, <3.3: continental freshwater deposition; >4.5: marine deposition

^b Sr/Ba ratio, <1: continental freshwater deposition; >1: marine deposition

^c U/Th ratio, <0.75: normal oxygen; range of 0.75~1.25: poor-oxygen; >1.25: anaerobic

freshwater sedimentary characteristics. Therefore, it may be inferred that the water body within the Ordos Basin was inland freshwater to brackish water during Chang 9 time since fossils occurring in Chang 9 formation belong to freshwater organisms. For all 31 mudstone samples, the ratio of U/Th ranges from 0.12 to 0.44 and is 0.24 on the average, which reflects the sedimentary environment being normal oxygen during Chang 9 time.

Sedimentary framework of “a lake surrounded by multiple deltas”

As mentioned above, large mounts of terrigenous clastics from old lands around the Ordos Basin, which are in the state of being continuously uplifted and denudated, are carried by many rivers originated from different drainage areas and pour into the Ordos Lake from all directions. As a result of the surface gradient becoming smaller, the current velocity becoming slower, and the current dispersing, large mounts of terrigenous clastics carried by river, especially the sandy sediments, have been deposited at the river mouth in the form of delta and construct many large- and medium-scale delta bodies mainly made up of sandy sediments. In order to describe the plane distribution of these sandy delta bodies, the isopach map of Chang 9 sandstone is drawn according to the calculated thickness of sandstone based on the data from drilling and well logging, and then the map of Chang 9 delta distribution (Fig. 3) is planned by way of the division of deltaic depositional systems referring to the “watershed principle.”

The plane distribution of Chang 9 sandstone shows obvious “one divides into two” feature in the Ordos Basin (Fig. 3): one is that the sandstone in the west is relatively thicker with more sand and less mud; another is that the sandstone is relatively thinner in the east with less sand and more mud.

Nine larger-scale lake deltas are developed in the lake basin margin. Jiyuan and Dingbian deltas are distributed in the northwest and their strike is NW-SE direction; Anbian delta is distributed in the middle north and its strike is nearly NS direction; Wuqi, Zhidan, and Ansai deltas are distributed in the northeast and their strike is in NE-SW direction; Yanwu and Qingyang deltas are distributed in the southwest and their strike is SW-NE direction; Zhengning delta is distributed in the middle south and its strike is nearly SN direction. The single delta is more than 100 km in the length, is about tens of kilometers in the width, and is more than a thousand to thousands of square kilometers in area. These deltas show active progradation toward the lake direction, and are elongated, lobate or bird-foot shapes. Two adjacent deltas always get cross-linked. The steady lake area is mainly located in the southeast part of the Ordos Basin from Wuqi to Fuxiang via Yongning. It behaves as a shore-shallow lake environment in the early Chang 9 time (Fig. 4) and evolves into a semi-deep to deep lake environment represented by the “Lijiapan Shale” with basin subsidence and lake transgression in late Chang 9 time (Fig. 4). Thus, the sedimentary framework of the Ordos Basin is characterized by the development of the “a lake surrounded by multiple deltas” pattern during Chang 9 time.

Analysis of provenance

The provenance analysis plays an important role in identifying the provenance location, the nature of parent rock, and the transporting paths of sediments. Moreover, it is of great significance in discriminating the sedimentation and tectonic evolution of the whole basin. Nowadays, there are lots of ways to do analysis on provenance, such as the measurement of paleocurrent direction with primary directional structure, sandstone component, rock fragment composition,

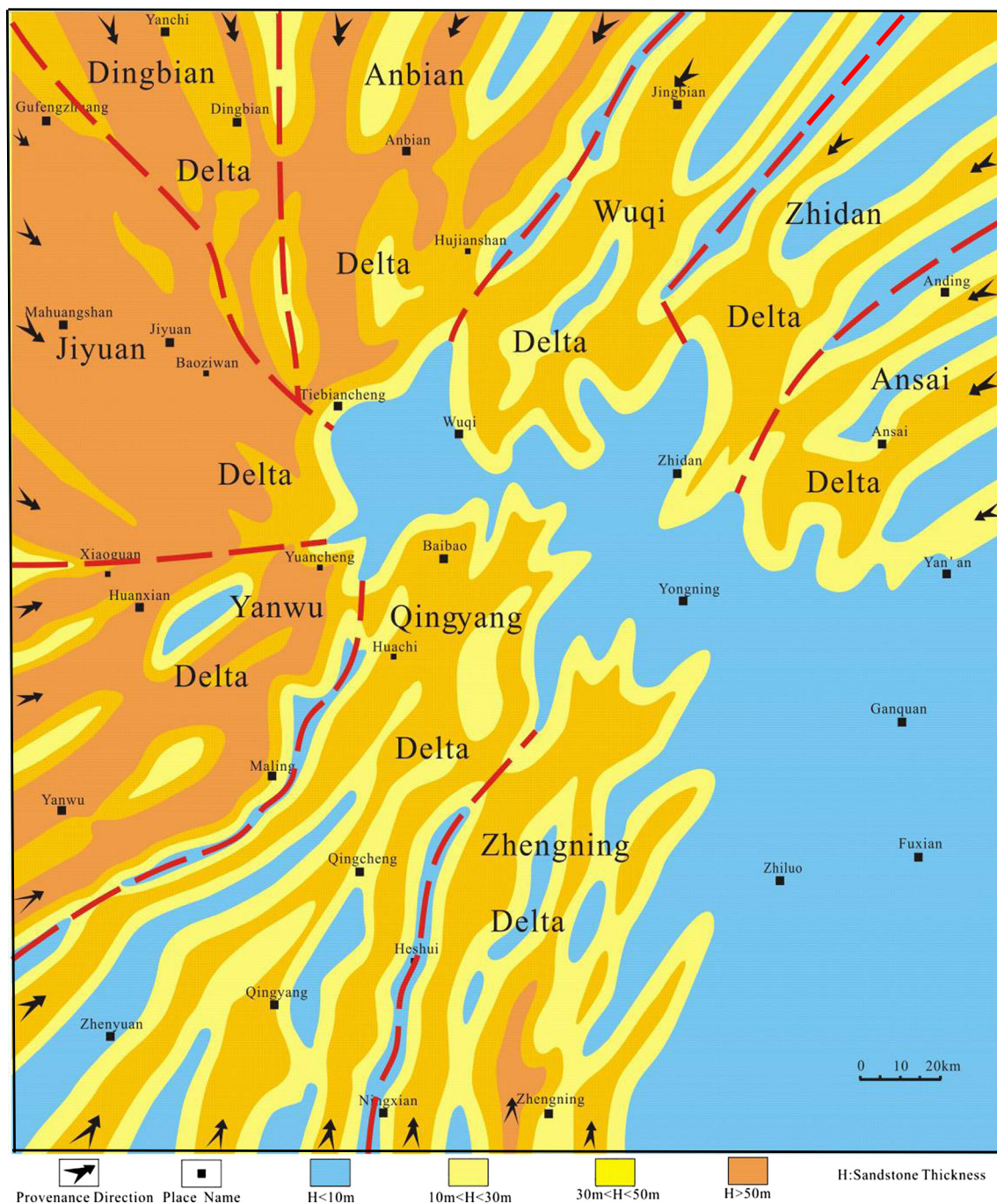


Fig. 3 Schematic diagram showing distribution of deltas in Chang 9 time, Ordos Basin

sedimentary geochemical analysis, etc. (Khan and Anis 2014; Abhik et al. 2012; A. N. Filippov et al. 2012; Bhatia 1983; Das and Haake 2003; Choi et al. 2012; Elias et al. 2014; Brust et al. 2011; Zhao et al. 2003). However, in order to gain satisfied result, comprehensive analysis on all these ways should be done combining with the tectonic background, the sedimentary geological background, as well as the reconstruction of lithofacies paleogeography. A lot of deeper researches on provenance of the Ordos Basin have been done by some predecessors who also have achieved fruitful results (Chen

et al. 2007; Ding et al. 2013; Huang et al. 2012; Liu et al. 2000). Although they use different methods and the research area and horizon chosen by them are different, many of them think that the provenance of the Upper Triassic Yanchang Formation generally can be divided into two main branches: northeast and southwest provenances, while the provenances from other directions are seen as the supplement to the whole supply system. Certainly, there are different cognition and controversy, especially on the issue of provenance in the western part. However, the research specifically on Chang 9

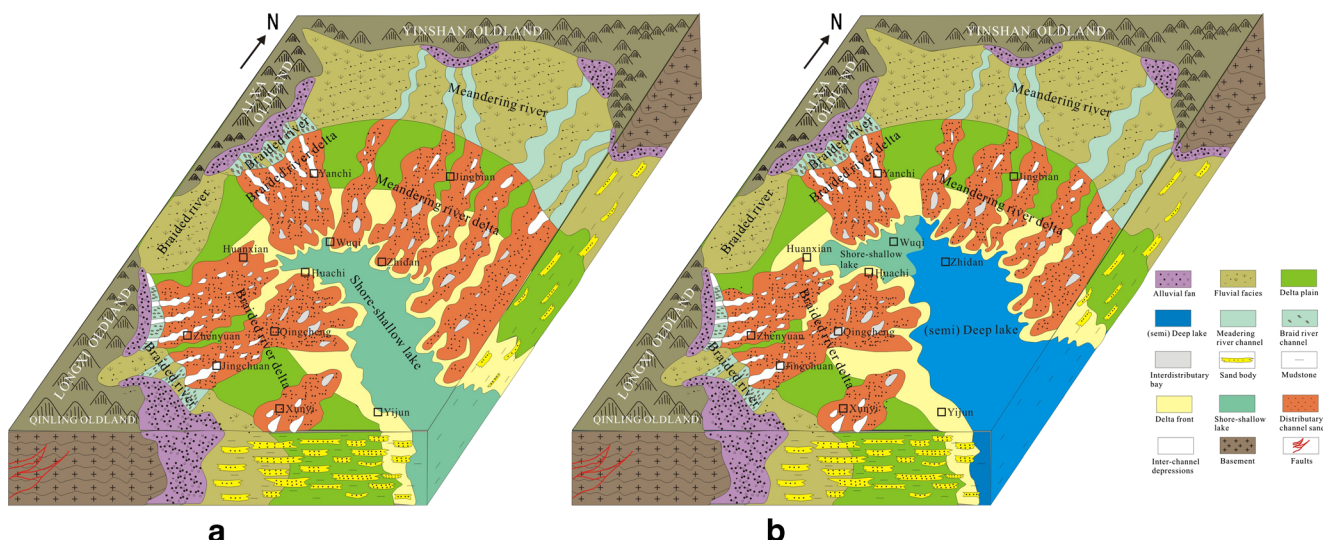


Fig. 4 Schematic mode diagram of sedimentary facies in Chang 9 time, Ordos Basin. **a** Schematic mode diagram of sedimentary facies in the early Chang 9 time, Ordos Basin. **b** Schematic mode diagram of sedimentary facies in the late Chang 9 time, Ordos Basin

provenance is really rare. The comprehensive discrimination on Chang 9 provenance would be done in the following based on some existing relevant research results, measurement of paleocurrent, distribution characteristics of sand bodies and sedimentary facies, and the quantitative analysis of rock fragment composition and trace elements in sandstone with closely combining with paleogeographic background.

Division of provenance system

Obviously, the accumulation location of sandy clastics and the extend direction of sand bodies in sedimentary basin is closely related to provenance and paleocurrent direction (Apurba et al. 2010; Konstantopoulos et al., 2013; Degryse et al., 2003; Jalal and Ghosh 2012). Therefore, it is helpful to discriminate provenance direction by analyzing the distribution characteristics of sedimentary facies and sand bodies. The large number of thick sand bodies extends from the margin to the center of lake basin in elongated shape and radial-inward shape (Fig. 5). This reflects there are multiple drainage systems with different current directions and multiple provenances with different positions during the Chang 9 time. The lake district in which the cumulative thickness of Chang 9 sandstone is less than 10 m and the muddy deposition is predominant is roughly distributed in northwest-southeast trend along a belt from Wuqi to Fuxian via Yongning, which might be the “water-shed” between north and south provenance influence extents.

1. Northeast provenance system is represented by forming Wuqi, Ansai, and Zhidan meandering river deltas. It is located in northeastern part of this basin and is distributed in Ordos City-Yulin-Jingbian-Zhidan belt roughly in the NE-SW trend. The length of this system is about 500 km

from north to south with big distribution area. The paleotopography is a large-scale moderate slope inclined toward south-southwest direction. During Chang 9 time, meandering river were developed in the northern part, and meandering-river delta were constructed in the southern part. The sediment transporting directions measured from outcrop sections are mainly southwestward, for example, the transporting direction of fluvial sediments is 200° on average in Yulin area.

2. North provenance system is characterized by constructing Anbian delta. This system, adjacent to northeast provenance system and connected with northwest provenance system, is located in the northern middle part and is distributed in Hangjinqi-Etuoke Banner-Anbian area roughly in N-S trend. The length of this system is more than 300 km from north to south. The paleotopography is a large-scale slope inclined toward south-southwest direction. During Chang 9 time, braided river were developed in the northern part, and braided river delta were constructed in the southern part. Although there is no measured data about transporting direction of terrigenous sediments, according to channel sand bodies in Chang 9 Anbian delta are distributed in shoestring shape from north to south, it can be speculated that paleocurrent and sediment transporting direction should be southward.
3. Northwest provenance system is represented by accumulating Dingbian and Jiyuan braided river deltas. This system is located in the northwestern part, with north provenance system in its east and southwest provenance system in its south, roughly displaying the NW-SE trend and spreading in Yinchuan-Yanchi-Dingbian belt and its south region. Its length is up to 200 km from north to south, and its area is relatively large. The paleotopography overall is a large-scale slope steeply tilting to southeast

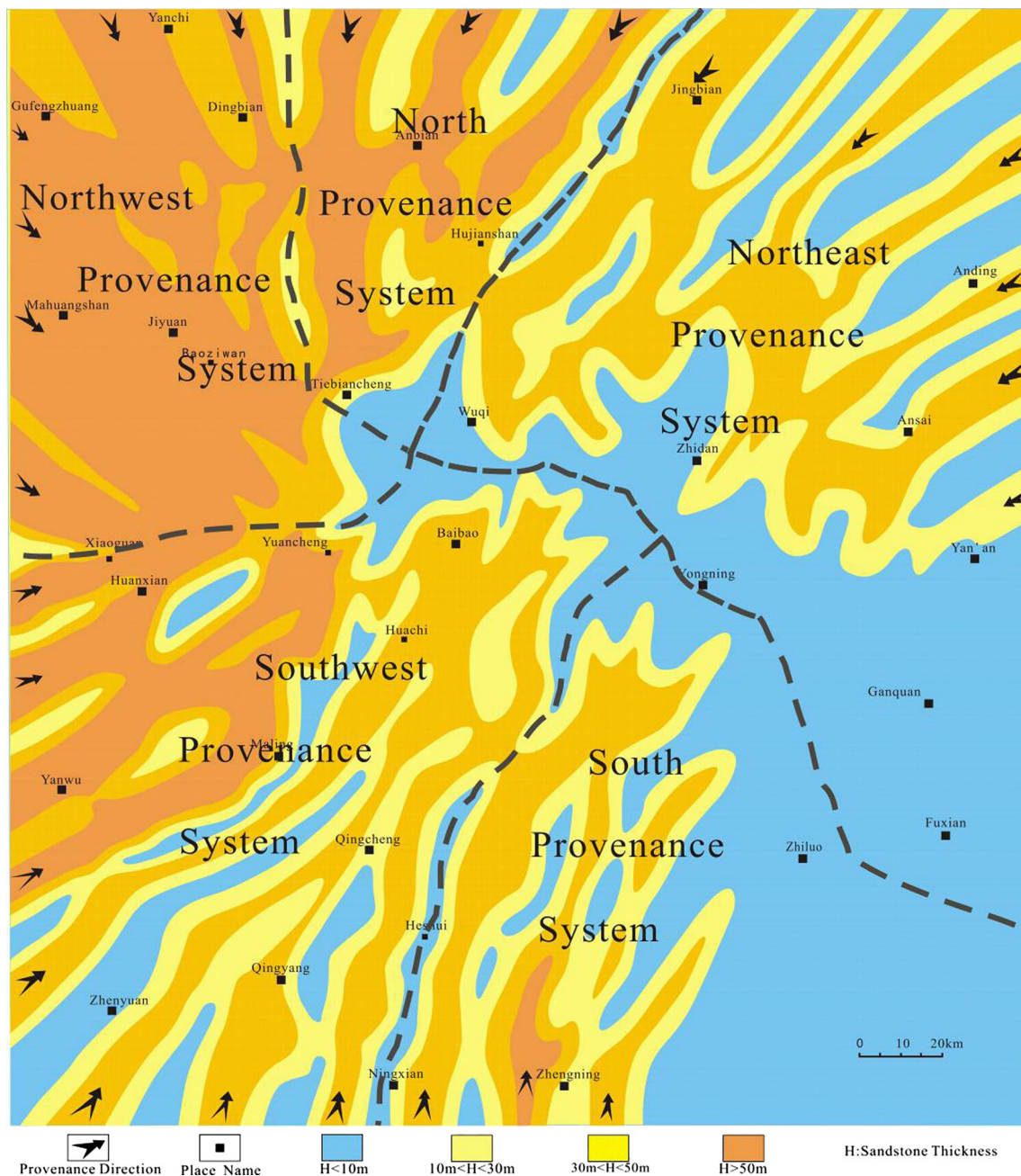


Fig. 5 Schematic diagram showing distribution of provenance systems in Chang 9 time, Ordos Basin

direction. The Chang 9 time is characterized by the development of alluvial fan, braided river, and braided river delta, having relatively coarse sediment and relatively thick sandstone. The paleocurrent direction measured from outcrop sections is predominantly southeastward, averagely 105° .

- Southwest provenance system is represented by developing Yanwu and Qingyang deltas. This system is located in the southwestern part, with northwest provenance system in its north and south provenance system in its east, roughly displaying the SW-NE trend and spreading in Pingliang-Zhenyuan-Huachi areas. Its length is more than

200 km from southwest to northeast, and its area is relatively large. The paleotopography overall is a large-scale slope tilting to northeast direction. The Chang 9 time is characterized by the development of alluvial fan and braided river in the southwestern part and the construction of braided river delta in the northeastern part. The paleocurrent and sediment transport direction measured from outcrop sections is scattered, for example, the paleocurrent direction in Pingliang-Huating area is about 110° , the paleocurrent direction in Longxian and Linyou areas is northwestward, but totally with 30° – 35° as its predominant direction.

5. South provenance system makes a feature of constructing Zhengning braided river delta. This system is located in the southern part, roughly displaying the south-north trend and spreading in Xunyi-Zhengning-Yongning areas. Its length is less than 200 km from south to north, and its area is relatively small. The paleotopography overall is a slope tilting to the north direction. The Chang 9 time is characterized by the development of braided river delta. The paleocurrent and sediment transport direction measured from outcrop sections is also scattered, for example, the average paleocurrent direction in Tongchuan area is 320° , but based on delta extension direction and sand body distribution trends, the general paleocurrent should be northerly orientation as its predominant direction.

According to thickness and distribution of Chang 9 sand bodies, northeast, northwest, and southwest provenances made relatively large contribution, but south and north provenances made less contribution.

Trace elements of Chang 9 sandstone and provenance discrimination

The geochemical composition of terrigenous clastic rock not only can be used to reshape the tectonic setting of orogenic belt and sedimentary basin (Maslov et al. 2006; Bhatia et al. 1986; Black et al. 2004; Yudovskaya et al., 2013; Julleh Jalalur Rahman et al. 2014) but also can well reflect the characteristics of provenance province for the reconstruction of ancient environments (Dasgupta et al., 2005, Littke et al. 2005; Utkin et al. 2007). According to the results of quantitative analysis on trace elements from 30 samples of Chang 9 sandstone by using ICP-MS method, it suggests that there is almost no difference in magnitude in terms of the minimum, maximum, and average abundance of each remaining 24 kinds of trace elements except the six elements (Cd, In, Sb, Ta, Tl, Bi) with their contents less than $1 \mu\text{g/g}$, respectively; therefore, it is difficult to analyze their distribution characteristics. The priority method based on the abundance of trace element is used here to study the distribution characteristics and district naming of trace elements in Chang 9 sandstone (Table 3).

1. The multiple trace element assemblage with high abundance is distributed in northeast provenance system. In this assemblage, 16 kinds of trace elements, i.e., B, Li, Be, Sc, V, Co, Cu, Zn, Ga, Rb, Cs, Ba, Pb, U, Zr, and Hf, are very high in average abundance, while the ratio between 16 trace elements with average maximum abundance and all 24 trace elements is 0.67. Therefore, it becomes apparent that both the categories and average abundance of trace elements ranked first in the whole basin without trace elements with minimum average abundance. It

clearly reflects that this trace element assemblage may be derived from the parent rocks which are rich in trace elements. By tracing the source, it is inferred that this trace element assemblage is closely affiliated with the Proterozoic or Cambrian-Ordovician Baiyunobo rocks (Ding et al. 2013; Huang et al. 2012; Liu et al. 2000). The Baiyunobo formation is rich in rare earth and trace elements and is distributed in Yinshan Old Land along the north side of this basin. On these grounds, it is inferred that northeast provenance mainly originated from parent rocks made up of Baiyunobo low-grade metamorphic rocks and Archean high-grade regional metamorphic rocks and igneous rocks in Yinshan Old Land.

2. Rich thorium and poor tungsten assemblage is distributed in northwest provenance system. Only the average abundance of thorium is the highest in this assemblage. The ratio between the one trace element with average maximum abundance and all 24 trace elements is 4.16 %. There are five elements with lowest average abundance: Ga, Sr, Mo, W, and Pb, which accounts for 20.83 % of 24 all trace elements. It clearly reflects that this trace element assemblage is derived from the parent rock which is rich in thorium element. On these grounds, it is inferred that this assemblage has a close affiliation with the parent rocks made up of Archean and Proterozoic migmatite, gneiss, schist, and other metamorphic rocks in Alxa Old Land.
3. Rich nickel+molybdenum+tungsten assemblage is distributed in north provenance system. The average abundance values of Ni, Mo, and W are the highest in this assemblage. The ratio between 3 trace elements with average maximum abundance and all 24 trace elements is 0.125. There are ten elements with lowest average abundance: Li, Be, Sc, V, Zn, Y, Nb, Cs, Th, and U, which accounts for 41.67 % of all 24 trace elements. The characteristics of this assemblage are obviously different from two former assemblages. This reflects this provenance system has certain particularity despite it is influenced by mixed effects from northeast and northwest provenances more or less. Meanwhile, this conclusion is totally identical with former deduction based on the distribution of sand bodies. It is inferred that this assemblage mainly comes from the parent rocks in Yinshan Old Land and is influenced by mixed effects from northeast and northwest provenances.
4. Rich niobium and poor chromium assemblage is distributed in southwest provenance system. In this assemblage, only the average abundance of niobium is the highest among all trace elements. The ratio between one trace element with average maximum abundance and all 24 trace elements is 0.0417. These are the elements with lowest average abundance: Ni, Ba, and Cr, which accounts for 12.5 % of 24 all trace elements. It clearly

Table 3 Abundance distribution of trace elements from sandstone in Chang 9 time, Ordos Basin

Provenance system	Northeast	North	Northwest	Southwest	South
Sample number	7	3	9	8	3
Trace elements with highest abundance	B, Li, Be, Sc, V, Co, Cu, Zn, Ga, Rb, Cs, Ba, Pb, U, Zr, Hf	Ni, Mo, W	Th	Nb	Cr, Sr, Y
Trace elements with lowest abundance	/	Li, Be, Sc, V, Zn, Y, Nb, Cs, Th, U	Ga, Sr, Mo, W, Pb	Ni, Ba, Cr	B, Co, Cu Rb, Zr, Hf
Number percent of trace elements with highest abundance (%)	66.67	12.50	4.17	4.17	12.50
Number percent of trace elements with lowest abundance (%)	0	41.67	20.83	12.50	25.00
Trace element assemblage	Multiple trace elements with high abundance	Rich Ni+Mo+W	Rich Th and poor W	Rich Nb and poor Cr	Rich Cr+Sr+Y

reflects that this assemblage has a close affiliation with the parent rock which is rich in niobium element. Combined with the abovementioned provenance analysis results, it is also inferred that its parent rock is mainly composed of granite, intermediate and basic rocks, gneiss, schist, phyllite, slate, volcanic rock, clastic, and carbonate rocks in Longxi Old Land.

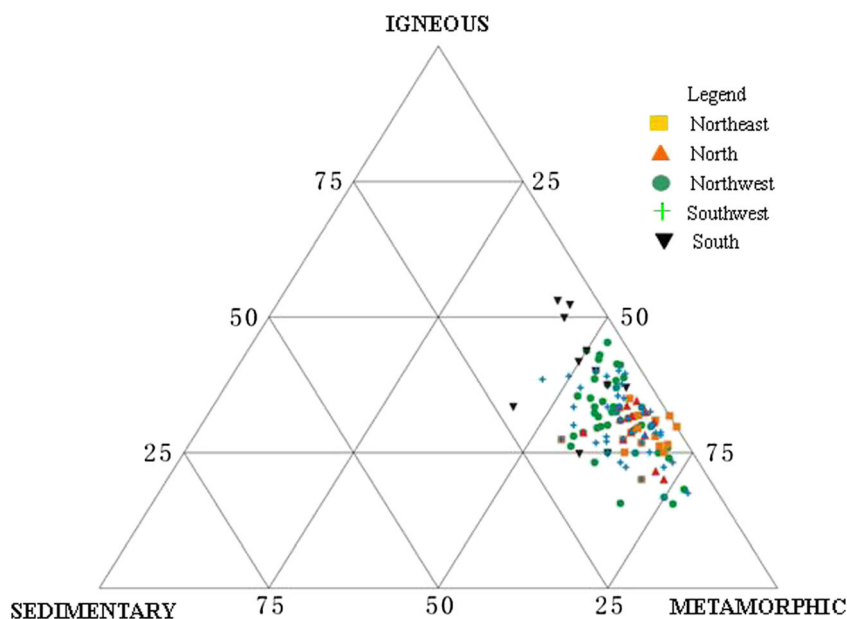
- Rich chromium+strontium+ytterbium assemblage is distributed in south provenance system. The average abundance of Cr, Sr, and Y is the highest in this assemblage. The ratio between the three trace elements with average maximum abundance and all 24 trace elements is 0.125. There are six elements with lowest average abundance: B, Co, Cu, Rb, Zr, and Hf, which accounts for 25 % of all 24 trace elements. It clearly reflects that this assemblage has close affiliation with the parent rock which is rich in chromium, strontium, and ytterbium. Combined with the abovementioned provenance analysis results, it is inferred

that its parent rock is made up of Proterozoic and early Paleozoic metamorphic and igneous rocks in Qinling Old Land.

Type of rock fragments and provenance discrimination

Rock fragments are mineral aggregate and are terrigenous clastic materials which are directly brought into the sedimentary basin after the weathering of parent rocks (Madhavaraju et al. 2006; Benayad et al., 2014; Tan et al. 2000; Weltje et al. 2004). Due to retention of parent rock composition and structure, rock fragments have more provenance information than other detrital grains. Thus, the type and content of rock fragments can accurately reflect the petrology of parent rock in the provenance province, the type and degree of weathering and

Fig. 6 The triangular diagram showing rock fragment components of sandstone in Chang 9 time, Ordos Basin



transport distance, etc., and it is the most direct evidence for determining the source direction and the nature of parent rock. According to the identification results of 157 thin sections from the sandstone, the rock fragments are not only very common but also are widely distributed in Chang 9 sandstone. From north to south and from west to east, the rock fragments are easily visible, with their content basically ranging from 10 to 20 %. Chang 9 sandstone has many types of rock fragments, among which, igneous, metamorphic, and sedimentary fragments are the three major categories of existence. As a whole, each region is mainly covered by the metamorphic fragments, with the average content of 10.75 %, followed by igneous fragments, with the average content of 5.39 %, while the sedimentary fragments are much less in the amount, with the average content only of 0.29 % (Fig. 6). This reflects that parent rocks in Chang 9 provenances, no matter the northern part or the southern part, are mainly composed of a variety of rock types with the metamorphic rock as the dominant type.

According to the statistical results of the composition and content of rock fragments from different provenances (Table 4), it may be showed that (1) rock fragment assemblage of northeast provenance system is characterized by rich metamorphic fragments which accounts for 72.23 % on average in this assemblage. They mainly are fragments of high-grade metamorphic rocks (gneiss, schist, quartzite) and medium- and low-grade metamorphic rocks (phyllite, slate, and metamorphic siltstone). The content of igneous fragments accounts for 26.60 % on average. Fragments of granite and diorite are common in igneous fragments. The content of sedimentary fragments is low and accounts for 1.17 % on average, mainly fragments of clastic and carbonate rocks. (2) Rock fragment assemblage of north provenance system is characterized by the higher content of metamorphic and igneous fragments. Metamorphic fragments mainly include fragments of gneiss, schist, quartzite, slate, and others and account for 67.66 % on average in this assemblage. Igneous fragments account for 29.65 % on average and granite fragments are common in this assemblage. Sedimentary fragments are very low in the content and account for 2.69 % on average in this assemblage.

Table 4 Composition and content of rock fragments from sandstone Chang 9 time, Ordos Basin

Provenance system	Sample number	Rock fragment (%)		
		Metamorphic	Igneous	Sedimentary
Northeast	38	72.23	26.60	1.17
North	16	67.66	29.65	2.69
Northwest	53	72.24	26.83	0.93
Southwest	20	59.64	37.71	2.65
South	30	48.95	50.00	1.05

Table 5 Partition and characteristics of provenance systems in Chang 9 time, Ordos Basin

Provenance system	Northeast	North	Northwest	Southwest	South
Average paleocurrent direction	210°~215°	Partial southward is the dominant direction	105°	30°~35°	Partial northward is the dominant direction
Trace element assemblage	Multiple trace elements with high abundance	Rich Ni+Mo+W	Rich Th and poor W	Rich Nb and poor Cr	Rich Cr+Sr+Y
Rock fragment assemblage	Rich metamorphic fragments	With higher content of metamorphic and igneous fragments	Rich metamorphic fragments and poor sedimentary fragments	With higher content of metamorphic and igneous fragments	Rich igneous fragments
Inferred provenance location	Yinshan Old Land	Yinshan and Alxa Old Land	Alxa Old Land	Longxi Old Land	Qinling Old Land
Inferred parent rocks	High-grade metamorphic and igneous rock assemblage, mainly granulite, gneiss, schist, quartzite, gabbro, diorite, granite, etc.	High-grade metamorphic and igneous rock assemblage, mainly gneiss, schist, quartzite, phyllite, slate, gabbro, diorite, granite, etc.	Metamorphic rock assemblage, mainly pre-Sinian and Sinian gneiss, schist, migmatite, quartzite, slate, and others	Granite, medium and basic rocks, gneiss, schist, phyllite, slate, volcanic, clastic and carbonate rocks, and others	Gneiss, schist, marble, meta clastic rock, volcanic rock, pyroclastic rock, clastic and carbonate rocks, and others

(3) Rock fragment assemblage of northwest provenance system is characterized by rich metamorphic fragments and poor sedimentary fragments. Metamorphic fragments mainly include fragments of gneiss, schist, quartzite, slate, and others and account for 72.24 % on average in this assemblage. Igneous fragments account for 26.83 % on average and granite fragments are common in this assemblage. Sedimentary fragments are very low in the content and account for 0.93 % on average in this assemblage. (4) Rock fragment assemblage of southwest provenance system is also characterized by the higher content of metamorphic and igneous fragments. Metamorphic fragments account for 59.64 % on average in this assemblage. Not only gneiss, schist, quartzite, and other high-grade metamorphic fragments can be easily found but also phyllite, slate, and other medium- and low-grade metamorphic fragments are common in this assemblage. Igneous fragments account for 37.71 % on average and granite and volcanic fragments are common in this assemblage. Sedimentary fragments are very low in the content, account for 2.65 % on average in this assemblage, and mainly are fragments of clastic and carbonate rocks. (5) Rock fragment assemblage of south provenance system is characterized by rich igneous fragments. They account for 48.95 % on average in this assemblage and mainly include fragments of acid effusive rock and aphanite and a little amount of granite fragments. Metamorphic fragments account for 50 % on average in this assemblage and mainly are fragments of slate, phyllite, schist, and metaquartzite. Sedimentary fragments are very low in the content, account for 1.05 % on average in this assemblage, and mainly are dolostone fragments and a little amount of siltstone fragments.

The main characteristics of every provenance system and their deduced locations as well as the types of parent rock are summarized in Table 5 according to abovementioned analysis results on paleocurrent direction, sand body distribution, rock fragment component, trace elements, and their provenance discrimination and associated with the analysis of regional geological background.

Conclusion

This study presents an example of analysis of paleogeographic framework and provenance features during Late Triassic Chang 9 time of the Yanchang Formation in the Ordos Basin.

Ordos Basin is a broad and shallow lake basin with the terrigenous clastic deposition and the supply of multiple drainage systems and provenances during Late Triassic Chang 9 time. Sedimentary framework is characterized by the development of “a lake surrounded by multiple deltas” pattern. Lake water is inland freshwater to brackish water.

The Chang 9 provenance in Ordos Basin can be divided into five systems: northeast, north, northwest, southwest, and

south provenance systems. (1) Northeast provenance system is characterized by multiple trace element assemblage with high abundance. They are presumably derived from parent rocks dominantly composited of metamorphic and igneous rocks in Yinshan Old Land. (2) North provenance system is characterized by higher content of metamorphic and igneous fragments, as well as rich Ni+Mo+W assemblage. They are presumably originated from parent rocks dominantly composited of metamorphic and igneous rocks in Yinshan and Alxa Old Land. (3) Northwest provenance system is characterized by rich metamorphic fragment and poor sedimentary fragment and rich thorium and poor tungsten assemblages. They are presumably stemmed from parent rocks dominantly composited of metamorphic rocks in Alxa Old Land. (4) Southwest provenance system is characterized by higher content of metamorphic and igneous fragments, rich niobium and poor chromium assemblage. They are presumably derived from parent rocks dominantly composited of metamorphic and igneous rocks in Longxi Old Land. (5) South provenance system is characterized by rich igneous fragment and rich Cr+Sr+Y assemblages. They are presumably originated from parent rocks dominantly composited of metamorphic and igneous rocks in Qinling Old Land.

Acknowledgments This work was initially carried out with the support from CNPC, with further supports from Major Project (2011E-13-2). Lab work was assisted by Heyun (rock fragments analysis), HanMeimei (trace elements analysis) from State Key Lab of Oil/Gas Reservoir Geology and Exploitation at Southwest Petroleum University, China.

References

- Abhik K, Abdul M, Malay M (2012) Depositional environment and provenance of Middle Siwalik sediments in Tista valley, Darjiling District, Eastern Himalaya, India. *J Earth Syst Sci* 121:73–89
- Apurba B, Banerjee DM (2010) Modal analysis and geochemistry of two sandstones of the Bhandar Group (Late Neoproterozoic) in parts of the Central Indian Vindhyan basin and their bearing on the provenance and tectonics. *J Earth Syst Sci* 119(6):825–839
- Benayad S, Park Y-S, Chaouchi R, Kherfi N (2014) Parameters controlling the quality of the Hamra Quartzite reservoir, southern Hassi Messaoud, Algeria: insights from a petrographic, geochemical, and provenance study. *Arab J Geosci* 7:1541–1557
- Bhatia MR (1983) Plate tectonics and geochemical composition of sandstones. *J Geol* 91(6):611–627
- Bhatia MR, Crook KAW (1986) Trace element characteristics of graywacke and tectonic of sedimentary basins. *Contrib Mineral Petrol* 92:181–193
- Black LP, Kamo SL, Allen CM, Davis DW, Aleinikoff JN, Valley JW, Mundil R, Campbell IH, Korsch RJ, Williams IS (2004) Improved ²⁰⁶Pb/²³⁸U microprobe geochronology by the monitoring of a trace-element-related matrix effect; SHRIMP, IDETIMS, ELAeICPeMS and oxygen isotope documentation for a series of zircon standards. *Chem Geol* 205:115–140
- Brust J, Hüneke H, Meschede M, Sommer M (2011) Facies and provenance of basin-margin deposits in the Los Palacios Basin (Capdevila Formation, Cuba). *Facies* 57:73–92

- Chen RY, Luo XR, Chen ZK, Wang ZM, Zhou B (2006) Estimation of denudation thickness of mesozoic strata in the Ordos Basin and its geological significance. *Acta Geol Sin* 80:685–692
- Chen QH, Li WH, Gao YX, Guo YQ, Feng JP, Zhang DF, Cao HX, Liang JW (2007) The deep-lake deposit in the Upper Triassic Yanchang Formation in Ordos Basin, China and its significance for oil-gas accumulation. *Sci China Ser D Earth Sci* 50:47–58
- Choi DK, Woo J, Park T-y (2012) The Okcheon Supergroup in the Lake Chungju area, Korea: Neoproterozoic volcanic and glaciogenic sedimentary successions in a rift basin. *Geosci J* 16:229–252
- Das BK, Haake B-G (2003) Geochemistry of Rewalsar Lake sediment, Lesser Himalaya, India: implications for source-area weathering, provenance and tectonic setting. *Geosci J* 7(4):299–312
- Dasgupta P (2005) Facies pattern of the middle Permian Barren Measures Formation, Jharia basin, India: the sedimentary response to basin tectonics. *J Earth Syst Sci* 114(3):287–302
- Decarli A, Lualdi A (2011) Synrift sedimentation on the northern Tethys margin: an example from the Ligurian Alps (Upper Triassic to Lower Cretaceous, Prepyrenean domain, Italy). *Int J Earth Sci* 100:1589–1604
- Degryse P, Muchez P, Loots L, Vandeput L, Waelkens M (2003) The building stones of Roman Sagalassos (SW Turkey): facies analysis and provenance. *Facies* 48:9–22
- Ding XQ, Han MM, Zhang SN (2013) The role of provenance in the diagenesis of siliciclastic reservoirs in the Upper Triassic Yanchang Formation, Ordos Basin. *China Pet Sci* 10:149–160
- Elias EM, Al-Jubory ZJ (2014) Provenance and tectonic setting of the metapelites deposits in the Bulfat Complex NE-Iraq. *Arab J Geosci* 7:3589–3598
- Elsheikh AEM, Zeinelabdein KAE, Khidir SOHE, Ibrahim AE (2014) The geometric configuration of the newly discovered Abu Deleig sedimentary sub-basin, Central Sudan, using remote sensing, structural analysis, and geophysical survey. *Arab J Geosci* 7:789–797
- Filippov AN (2012) Composition and provenances of Mesozoic sandstones in Sikhote Alin. *Lithol Miner Resour* 47(1):78–97
- Fu JH, Guo ZQ, Deng XQ (2005) Sedimentary facies of the Yanchang Formation of Upper Triassic and petroleum geological implication in southwestern Ordos Basin. *J Palaeogeogr* 7(1):34–44 (in Chinese with English abstract)
- Huang JP, Li XB, Chen QL, Yang ZL, Wan YR, Wei LH, Long LW, Liu XG (2012) The origin and accumulation model of crude oils from oil reservoirs Chang 9 and Chang 10 in the Yanchang Formation of the Ordos Basin. *Chin J Geochem* 31:327–339
- Jalal P, Ghosh SK (2012) Provenance of the Late Neogene Siwalik sandstone, Kumaun Himalayan Foreland Basin: Constraints from the metamorphic rank and index of detrital rock fragments. *J Earth Syst Sci* 121(3):781–792
- Julleh Jalalur Rahman M, Sayem ASM, McCann T (2014) Geochemistry and provenance of the Miocene sandstones of the Surma group from the Sitapahar anticline, Southeastern Bengal Basin, Bangladesh. *J Geol Soc India* 83:447–456
- Khan A, Anis SR (2014) Petrofacies, provenance, and paleocurrent analysis of Pachmarhi sandstone (Early Triassic), Satpura basin. Central India *Arab J Geosci* 7:3548–3556
- Konstantopoulos PA, Zeliglidis A (2013) Provenance analysis of Eocene–Oligocene turbidite deposits in Pindos Foreland Basin, fold and thrust belt of SW Greece: constraints from framework petrography and bulk-rock geochemistry. *Arab J Geosci* 6:4671–4700
- Littke R, Bayer U, Gajewski D (2005) Dynamics of sedimentary basins: the example of the Central European Basin system. *Int J Earth Sci* 94:779–781
- Liu HL, Yao JL (2000) Depositional feature and material source analysis of Yanchang Group in Ordos Basin. *J Xi'an Petroleum Institute (Natural Science Edition)* 15(5):7–9 (in Chinese with English abstract)
- Liu GD, Sun ML, Zhao ZY, Wang XB, Wu SH (2013) Characteristics and accumulation mechanism of tight sandstone gas reservoirs in the Upper Paleozoic, northern Ordos Basin. *China Pet Sci* 10:442–449
- Madhavaraju J, Yong II L, Armstrong-Altrin JS, Hussain SM (2006) Microtextures on detrital quartz grains of upper Maastrichtian–Danian rocks of the Cauvery Basin, Southeastern India: implications for provenance and depositional environments. *Geosci J* 10(1):23–24
- Maslov AV, Ronkin YL, Krupenin MT, Petrov GA, Kornilova AY, Lepikhina OP, Popova OY (2006) Systematics of rare earth elements, Th, Hf, Sc, Co, Cr, and Ni in the vendian pelitic rocks of the Serebryanka and Sylvitsa groups from the western slope of the Central Urals: a tool for monitoring provenance composition. *Geochem Int* 44(6):559–580
- Stern G, Wagneich M (2013) Provenance of the Upper Cretaceous to Eocene Gosau Group around and beneath the Vienna Basin (Austria and Slovakia). *Swiss J Geosci* 106:505–527
- Tan LK, Shi TZ (2000) Discovery and significance of small shelly fossils in the Baiyunobo Group in Shangdu, Inner Mongolia. *Geol Rev* 46(6):573–593 (in Chinese with English abstract)
- Utkin VP, Khanchuk AI, Kasatkin SA, Dong-Woo L (2007) Formation geodynamics of the infrastructure of the Cretaceous Kongju sedimentary basin (South Korea). *Dokl Earth Sci* 416(2):236–240
- Weltje GJ, von Eynatten H (2004) Quantitative provenance analysis of sediments: review and outlook. *Sediment Geol* 171(1/4):1–11
- Yudovskaya M, Kinnaird J, Naldrett AJ, Rodionov N, Antonov A, Simakin S, Kuzmin D (2013) Trace-element study and age dating of zircon from chromitites of the Bushveld Complex (South Africa). *Miner Petrol* 107:915–942
- Zhang XL, Feng Q, Feng QH, Liu JJ, Liu GW, Yan YZ (2013) Genesis of the high gamma sandstone of the Yanchang Formation in the Ordos Basin. China: A reply *Pet Sci* 10:55–57
- Zhao HG, Liu CY (2003) Approaches and prospects of provenance analysis. *Acta Sedimentol Sin* 21(3):409–415 (in Chinese with English abstract)