Geology of the Chang 7 Member oil shale of the Yanchang Formation of the Ordos Basin in central north China

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Abstract: We present a review of the Chang 7 Member oil shale, which occurs in the middle–late Triassic Yanchang Formation of the Ordos Basin in central north China. The oil shale has a thickness of 28 m (average), an area of around 30 000 km² and a Ladinian age. It is mainly brown-black to black in colour with a laminar structure. It is characterized by average values of 18 wt% TOC (total organic carbon), 8 wt% oil yield, a 8.35 MJ kg⁻¹ calorific value, 400 kg t⁻¹ hydrocarbon productivity and kerogen of type I–II, showing a medium quality. On average, it comprises 49% clay minerals, 29% quartz, 16% feldspar and some iron oxides, which is close to the average mineral composition of global shale. The total SiO₂ and Al₂O₃ comprise 63.69 wt% of the whole rock, indicating a medium ash type. The Sr/Ba is 0.33, the V/Ni is 7.8, the U/Th is 4.8 and the FeO/Fe₂O₃ is 0.5, indicating formation in a strongly reducing, freshwater or low-salinity sedimentary environment. Multilayered intermediate-acid tuff is developed in the basin, which may have promoted the formation of the oil shale. The Ordos Basin was formed during the northwards subduction of the Qinling oceanic plate during the Ladinian–Norian in a back-arc basin context. The oil shale of the Ordos Basin has a large potential for hydrocarbon generation.

Supplementary material: Tables of oil-shale geochemical composition, proximate and organic matter analyses from the Chang 7 Member oil shale, the Ordos Basin, Central north China are available at https://doi.org/10.6084/m9.figshare.c.4411703

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In addition to oil, natural gas, coal, coal-seam gas, uranium and groundwater resources, a large tonnage of oil shale is also present in the Ordos Basin (Fig. 1), which is one of the largest oil- and gas-bearing basins, ranked second in oil and gas resources, and first in annual production, in China (Pan 1934; Yang 1991, 2002; Wang et al. 1992; Guan et al. 1995; Zhang et al. 1995; Yang & Pei 1996; Li 2006; Chen 2002; Liu & Liu 2005; Lu et al. 2006; Liu et al. 2006; Yang et al. 2006, 2016a, b; Bai et al. 2006, 2009, 2010a, b, 2011; Liu et al. 2009; Qian 2009; Wang et al. 2016; Deng et al. 2017). The oil shale has attracted considerable interest in recent years in the context of global oil depletion and the search for unconventional energy resources. The commercial potential of the oil shale has been assessed and the resource might become more important as other energy reserves decline. Recent research undertaken by the Northwest Branch of the Research Institute of Petroleum Exploration and Development (NWGI), PetroChina, and others, has shown that the Ordos Basin contains more than 2000 × 10⁸ tonnes (t) of ‘shale oil’ predicted resources, of which the Chang 7 Member shale oil comprises more than 1000 × 10⁸ t: that is, 50% of that occurring at depths of 0–2000 m in the entire basin. The Chang 7 Member oil shale, also called ‘the Zhangjiatan shale’ in the northern Ordos Basin, has an area of around 30 000 km², an average thickness of 28 m and an average oil yield of 8 wt%. It is both a high-quality source rock and an oil shale with a high residual organic matter content, and is the most important oil-shale seam in the basin (Yang 2002; Duan et al. 2004; Bai et al. 2006; Yang et al. 2006, 2016a, b; Zhang et al. 2008b). It is located in the Yanchang Formation (Fig. 2), which was originally deposited over an area of c. 400 000 km² during the middle–late Triassic, with a current area of 250 000 km² and current thicknesses of 184–2060 m (Yang 2002; Bai et al. 2009).

The Yanchang Formation is a well-documented lithostratigraphic unit, first discovered in the northern Shaanxi in 1926 by M.L. Fuller and F.G. Clapp, who described it as a set of stratigraphic units including grey or green sandstone and shale (Fuller & Clapp 1926; Pan 1934; Yang 2002). Its reservoirs produce 90% of the oil in the Ordos Basin. It is a group of terrestrial sequences of middle–late Triassic age, and is composed of fluvial, delta plain and lake facies. The overlying strata of the Yanchang Formation are the Wayaobao Formation, which was a set of coal-bearing strata that originally belonged to the upper Yanchang Formation but was later separated from the Yanchang Formation. They contain 10 reservoir members, each including both reservoir sands and (oil) shales (Fig. 2). The units are numbered 1–10 from the top of the Wayaobao Formation to the bottom of the Yanchang Formation (i.e. opposite to the normal geological convention). Chang 1 is now contained in the Wayaobao Formation, but it is still called Chang 1 rather than the customary ‘Wa1’. Among them, the Chang 6 and 8 members are the two main oil reservoirs.

The Chang 7 Member oil shale is a high-quality source rock which supplies oil for the reservoirs of the Yanchang Formation, especially the Chang 6 Member and Chang 8 Member reservoirs, and it even supplies oil to reservoirs of the younger middle Jurassic Yanan Formation (Fig. 2). Yang et al. (2016a, b) discovered that the oil derived from the Chang 7 Member oil shale also fills internal nano-sized pores and pore throats to form ‘shale oil’, equivalent to tight oil occurring naturally in oil-bearing shales, which is different to ‘oil-shale-derived oils’ (‘oil shale’ is an organic-rich fine-grained sedimentary rock containing immature kerogen, a solid mixture of organic chemical compounds, from which liquid hydrocarbons, can be produced by low-temperature pyrolysis). The Chang 7 Member oil shale and its host stratum, the Yanchang Formation, have been investigated by the drilling of at least 57 boreholes in the basin interior (Fig. 1). Early in the last century, outcrops of the Chang 7 Member oil shale were investigated by Pan Zhongxiang (Pan 1934), who studied its distribution, occurrence and quality. In the 1960s, the Shaanxi Industrial Bureau commenced open-cast mining of the oil shale which outcrops in
Fig. 1. (a) Location map showing two cross-sections through the Ordos Basin X–X and Y–Y, together with outcrops of the middle–late Triassic and the oil shale. (i) Location map of the Ordos Basin in China and (ii) the location map for Figure 5. (b) Cross-sections X–X and (c) Y–Y through the Ordos Basin showing the spatial distribution of the Chang 7 Member oil shale and its host strata (modified and supplemented after Bai et al. 2009, 2010a). (b) Key: Q, Quaternary System; N, Neogene System; E, Paleogene System; Mz, Mesozoic; K, Cretaceous System; J, Jurassic System; T, Triassic System; C-P Carboniferous–Permian systems; E-O Cambrian–Ordovician systems; Pt, Proterozoic; Ar, Archean.
the Tongchuan area in the southern margin of the basin. They refined the oil shale using a cracking process but the annual shale oil production was only 80–90 t, and production was terminated because of water shortages and technological shortcomings (Bai et al. 2009). During 2000–08, several private enterprises attempted to initiate oil shale production using the Fushun Furnace, a small, low-temperature, pyrolysis furnace, but all of them failed. Since 2005, given the heightened imperative for seeking alternative energy sources, outcrops and drilling data for the oil shales in the region were reinvestigated (Liu & Liu 2005; Lu et al. 2006; Fig. 2).

![Stratigraphic chart summarizing the history of the Ordos Basin which is divided into five phases including the Meso-Neo Proterozoic, the early Paleozoic, the middle–late Triassic and the Jurassic–early Cretaceous (modified and supplemented after Bai et al. 2009, 2010b).](http://pg.lyellcollection.org/)

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Fig. 2. Stratigraphic chart summarizing the history of the Ordos Basin which is divided into five phases including the Meso-Neo Proterozoic, the early Paleozoic, the middle–late Triassic and the Jurassic–early Cretaceous (modified and supplemented after Bai et al. 2009, 2010b). (The width of the bars in the far-right column represents the importance of the resource.)
Liu et al. 2006, 2009; Qian 2009; Shu 2012; Bai et al. 2009, 2010a, b, 2011). Supported by PetroChina, Professor Bai Yunlai conducted a high-quality study (Bai et al. 2010b). However, in general, research on the oil shale of the region remains sporadic and unsystematic. This has hindered further exploration and exploitation of the oil shale resource; moreover, most of the research has been published in Chinese, making comparisons with comparable deposits elsewhere more difficult.

Previous research focused primarily on the characteristics of the oil shale, especially its occurrence, volume and quality. However, little research has been conducted to address such key questions as: How and when did the oil shale form? Is it Triassic or middle–late Triassic in age? How did the basin accumulate such abundant oil and oil shale resources? What was the tectonic setting? What are the properties of the basin? Is it marine? Is it an intracratonic basin or a foreland basin (Li 2000; Yang 2002; Yang & Zhang 2005; Bai et al. 2006; Wang et al. 2017)? The present review seeks to address these questions.

The structure of the present study is to summarize pre-existing research, describe the characteristics of the Chang 7 Member oil shale, and to discuss the environment and processes of formation. The overall aim is to provide a basis for future investigations of the Ordos Basin oil shale and to facilitate comparisons with similar deposits elsewhere.

**Geological context**

**Tectonic setting**

The Ordos Lake was located in the SW part of the North China Plate and at the northern edge of the Qinling orogenic belt (Figs 1 and 3) (Yang 1991, 2002; Zhang et al. 1995; Yang & Pei 1996; Bai et al. 2006; Yang et al. 2006; James 2012). The Qinling Ocean Plate subducted beneath the North China Plate in the middle–late Triassic, forming a volcanic–magmatic arc and back-arc basin on the northern side of the volcanic–magmatic arc (Fig. 3) (Wan 2004; Chen 2010). Thick piedmont facies (up to 2400 m) are distributed in the SW Ordos Basin and are called the Kongtongshan conglomerates (the lower left part of Fig. 1 highlights their location). They are regarded as the remnants of the foredeep deposits of the back-arc foreland basin, most of which were destroyed subsequently. These suggest that the Ordos Lake environment was, in fact, a back-arc foreland basin, with a similar structural mechanism to the Karoo Basin in South Africa (Smith 1990).

**Sedimentary fill**

The Ordos Basin has a sedimentary fill with a maximum thickness of about 12 800 m, which has accumulated in varying tectonic settings and different climatic regimes since the Proterozoic era (Fig. 2). Broadly, the Ordos area has experienced five sedimentary cycles, including: (1) the Meso-Neo Proterozoic; (2) the early Paleozoic; (3) the late Paleozoic; (4) the middle–late Triassic; and (5) the Jurassic–early Cretaceous, and in only the last three phases was the oil shale formed. In the Meso-Proterozoic and the early Paleozoic, the marine facies carbonate sedimentary rocks accumulated on the Ordos area. In the late Paleozoic, 600–1400 m-thick deltaic and fluvial facies sandstone, mudstone, and coal and oil-shale seams formed in a paralic environment at first under humid, and later under dry and hot, conditions (Fig. 2). From the middle Triassic to the Jurassic, fluvial, deltaic and lacustrine facies sandstone, mudstone and oil shale accumulated in terrestrial environments in a damp hot phase, in general attaining 20–3000 m in thickness in the middle–late Triassic and 184–2060 m in the Jurassic. There is also an unconformable blanket of Cretaceous sandstone and mudstone (terrestrial facies) that covers the entire basin, varying from 600 to 3000 m in thickness (Fig. 2). Present day, the southern Ordos area is covered by nearly 100 m of Quaternary loess and the northern area is

![Fig. 3. Tectonic profiles and background during the middle–late Triassic (Ladinian–Norian) in the Ordos areas. The top sketch shows a back-arc foreland basin resulting from subduction of the Qinling oceanic plate and the bottom sketch shows the location of the Ordos Basin in the regional structure (after Wan 2004; Chen 2010; James 2012).](http://pg.lyellcollection.org/)

Legend and illustrations:
- gravelly and sandy deposits
- sandy and muddy deposits
- oil shale
- marine deposits and paralic deposits
- paralic deposits
- terrestrial deposits
- magmatic rock
- metamorphic rock
- volcanic
- subduction zone
- thrust belts
- oceanic crust
beneath the Mu Us Desert (Fig. 2) (Liu 1986; Bureau of Geology & Mineral Resources of Shaanxi Province (BGMRS) 1989, 1998; Yang 1991, 2002; Yang & Pei 1996; Zhang et al. 2005; Yang & Zhang 2005; Bai et al. 2006, 2013, 2014; Yang & Liu 2006; Yang et al. 2006, 2016a, b). Based on analyses of previous works on vitrinite reflectance, fluid inclusions and apatite fission tracks in the basin, Ren (1991) reconstructed the thermal history of the Ordos Basin, depicting a temperature gradient of 2.2–3.0°C/100 m from the Paleozoic to the early Mesozoic, which increased to 3.3–4.5°C/100 m in the late Mesozoic, gradually decreasing to 2.8°C/100 m during the Cenozoic. Research on the relationship between the thermal history and oil-gas accumulation of the Ordos Basin suggests that: (1) the low temperature gradient and low thermal maturation of gas resource rocks were favourable for the preservation of organic matter from the Paleozoic to the early Mesozoic; (2) the higher temperature gradient in the Cretaceous (>150 °C) was also responsible for maturing hydrocarbons and the lack of faults in the Ordos Basin are key factors in preserving the hydrocarbon accumulations.

Burial history analysis show that the strongest uplift and erosion event took place at the end of the later Cretaceous, and three weaker uplift and erosion events took place at the end of the late Triassic, the middle Jurassic and the late Jurassic (Chen et al. 2006).

**Characteristics of the oil shales and shale in different strata in the Ordos Basin**

Since the late Paleozoic, multiple oil-shale (shale) seams developed in different strata of the Ordos Basin, in the late Carboniferous–early Permian Taiyuan Formation, the middle–late Triassic (Ladinian–Norian) Yanchang Formation, the late Triassic (Rhaetian) Wayaobao Formation, the middle Jurassic (Aalenian–Bajocian) Yanan Formation and the middle Jurassic (Bathonian–Callovian) Anding Formation (Bai et al. 2009, 2010b).

The oil shales of the Taiyuan Formation were formed in a paralic environment. Because of deep burial, it is mature to overmature, with the vitrinite reflectance of the shale varying from 0.9–2.5% Ro, most of the kerogen was converted to gas. The oil shales and coals mainly crop out along the edge of the basin, with a burial depth greater than 600 m in the eastern part, near Hancheng, and attain a maximum burial depth of ≤3000 m in the mid-western part (Qingshen-2 well) (Fig. 1). The oil shale generally has a low oil yield (only 2.8 wt%) and thin seams (c. 2 m), forming a relatively low-grade resource (Bai et al. 2009).

The Jurassic oil-shale seams were mainly formed in a lake-delta environment, and are interbedded with coal seams. The oil-shale seams are thin and local, and therefore are of low economic value (Bai et al. 2009).

The Chang 9, 7, 4 + 5 and 1 Member oil shale (shale) occurred in the Yanchang Formation and the Wayaobao Formation.

The Chang 9 Member oil shale, also called ‘the Lijapan shale’ in the Ordos Basin, is present at the top of the Chang 9 Member of the Yanchang Formation. The oil shale is mainly distributed in the north-central basin, in Yanan, Zhidan and Ansai counties. It has an area of 4336 km², about one-seventh of the Chang 7 Member oil shale, with a limited thickness of about 6 m. It is characterized by a relatively large burial depth and a relatively low abundance of organic matter (c. 4.5 wt%), on average (Zhang et al. 2008a; Zhou et al. 2008). Its organic matter type is different to that of the Chang 7 Member oil shale: the sapropel content of the former is less than in the latter. A deep or semi-deep lake was formed during the interval of accumulation of the Chang 9 Member, which was supplied with large amounts of terrigenous material and a small amount of algal parent material. The frambooidal pyrite content is low. Although indicating an overall euxinic environment, the low frambooidal pyrite content in the Chang 9 Member oil shale indicates a weakly oxidizing–reducing environment.

The Chang 7 Member oil shale is widely distributed in the region, with an area of around 30 000 km² and a thickness of 28 m (average thickness). It developed in an anoxic, deep-lake environment (about 60 m depth: Yang et al. 2016a) and is rich in frambooidal pyrite; there is a relatively small amount of clay minerals and abundant algal material (Bi et al. 2007). Although some of the oil from the oil shales have been migrated into oil reservoirs of the oilfields, the residual organic matter content is still very high, about 18 wt% TOC (see below), and the in situ oil shale resources account for more than 50% of the total oil shale resources of the basin (Wang et al. 1992; Guan et al. 1995; Liu & Liu 2005; Liu et al. 2006, 2009; Lu et al. 2006; Bai et al. 2009, 2010a, b, 2011).

In addition to the Chang 7 and 9 Member oil shales, a shale seam is present in the Chang 4 + 5 Member of the Yanchang Formation with a wide distribution and a distinct response in wireline logs, and is known as the ‘thin neck section’, forming a regional marker. It was deposited in a shallow lake-delta environment and there is no kerogen in the shales, and therefore lacks the basic conditions for forming oil shale or hydrocarbon source rocks (Fu et al. 2012).

A thin oil-shale seam is present in the Chang 1 Member of the Wayaobao Formation, formed in the limnic and delta environment and interbedded with coal seams; it covers a limited area and is thin (Wang et al. 2007). The oil shale with coal had been mined, mainly used as fuel. In summary, the Chang 7 Member oil shale has a real significance for exploration and is quite different to the others.

**The Yanchang Formation: host rock of the Chang 7 Member oil shale**

The middle–late Triassic Yanchang Formation (Ty) mainly comprises carnation and celadon fine–coarse grain arkose, with interbeds of black shale, oil shale and andesitic to dacitic tuff (Fig. 4). It is an important oil-bearing formation.

The lower part of the Yanchang Formation consists of carnation and celadon medium–coarse grain arkose, fine sandstone, sand-wiched with siltite, argillaceous siltite, mudstone, oil shale (Chang 9 Member oil shale) and tuff; followed by oil shale (Chang 7 Member oil shale), black shale, interbedded with argillaceous siltite and tuff (Fig. 4).

The upper part of the Yanchang Formation is grey, celadon fine–medium grain arkose, black shale, mudstone, siltite, and interbedding of celadon sandstone and black silty mudstone (Fig. 4).

The Yanchang Formation has formable contacts with the overlying stratum (the Wayaobao Formation) and underlying stratum (the Ermaying Formation), and can be readily distinguished by its celadon, grey, black color. The base of the Yanchang Formation is marked by the disappearance of the crimson mudstone, which located the top of the Ermaying Formation, also known as the Zhifang Formation (T2). The top of the Yanchang Formation, or the base of the Wayaobao Formation, is marked by the occurrence of rhythmic layers of sandstone and mudstone containing coal seams or very thin coal seams (Fig. 4).

The Yanchang Formation contains abundant fossils (e.g. phytoliths, palynoflora, estheria, bivalves, insect, acritarchs and fish) and frambooidal pyrite (Liu 1986; Bai et al. 2006), and formed in fluviatile delta lake facies during the middle–late Triassic (BGMRS 1998; Bai et al. 2006, 2009; Deng et al. 2017). The age of the Yanchang Formation, which was regarded as Late Triassic (Yang 2002; Bai et al. 2006; Wang et al. 2017), has recently been determined to be middle–late Triassic (Deng et al. 2017).
The Yanchang Formation is a lithostratigraphic unit. According to the formal definition, it lacks coals. The coal-bearing section of the Chang 1 Member is therefore assigned to the Wayaobao Formation (BGMRSP 1998).

The Yanchang Formation experienced three lake transgressions, corresponding, respectively, to the Chang 9, Chang 7 and Chang 4 + 5 members (in terms of sedimentary cycles Ty1, Ty2, Ty3, respectively) (Figs 2 and 4).

In the Chang 10 Member, deposition comprised alluvial plain, deltaic plain and shallow lake facies. The lake facies covers a relatively small area. During deposition of the Chang 9 Member, the lacustrine area was significantly enlarged, with development of shallow lake and delta facies, while in some regions a deeper lake facies formed. The alluvial plain and alluvial fan facies became restricted. The Chang 9 Member represents the first lake transgression in the area. In the Chang 8 Member, although the lake area was wide, it was narrower and shallower than that of the Chang 9 Member. The deltaic sandstone deposited during this stage is one of the main reservoirs in the basin. This completes the first lake transgressive–regressive cycle (Ty1) (Deng et al. 2011).

In the Chang 7 Member, lacustrine facies dominated, and the deeper lake facies reached its maximum extent of c. 30 000 km² and possible water depth of about 60 m, representing a major lacustrine transgression. This was followed by the Chang 6 Member, where the lake shallowed and deltaic sand bodies developed to form another main reservoir. This represents the second lake transgressive–regressive cycle (Ty2) (Deng et al. 2011).

In the early stages of Chang 4 + 5 Member, the lake began to narrow considerably but was extended again in the middle of the interval. A mudstone-rich lake facies developed that formed the regional cap rocks. Subsequently, deltaic plain sand bodies developed again. In the Chang 3 and Chang 2 Member sedimentary intervals, the lake remained narrow and the deeper lake facies began to disappear. This represents the third lake transgressive–regressive cycle (Ty3) (Deng et al. 2011).

In the Wayaobao Formation, or the Chang 1 Member, the lake disappeared completely and there was extensive swamp development, with the deposition of some coal seams, some interbedding of oil shale, large amounts of charcoal debris and numerous plant fossils.

**Geological and geochemical characteristics of the Chang 7 Member oil shale**

**Spatial distribution**

The Chang 7 Member oil shale is present on a large scale, with an almost north–south-orientated asymmetrical syncline (Figs 1 and 5). The oil shales with the Yanchang Formation have been uplifted and eroded in the eastern, southern and western parts (arc distribution), and have subsided in the mid-western parts (including the Qingshen-2 well, Huangxian, Huachi and Qingyang counties, and Xifeng city: Figs 1 and 5). The deepest burial is in Huanxian County in Gansu Province (Fig. 5). In the western part of the Ordos Basin (including the Tiantan-1 well, west Huanxian County, Zhenyuan County and the Qingshen-2 well) (Figs 1 and 5), the oil-shale seams and its host rock are steeply uplifted and dip to the east, while in the eastern part (including Zhidan, Fuxian and Yanchang counties, and Yanan city) is gently uplifted and dips to the west (Figs 1 and 5). The structural contours in Figure 5 indicate the burial depth of the oil shales, which also reflects the structural characteristics of the oil-shale layers. Outcrops of both the oil shale and strata are mainly distributed in the east and south, in Yijun County.
County, Tongchuan city, Yaoqu town and Binxian County in northern Shaanxi (Fig. 1).

**Basic sequence of the Chang 7 Member**

The basic sequence of the Chang 7 Member consists of three parts: (1) oil shale, shale and mudstone; (2) sandstone and siltite; and (3) tuff (Fig. 4). The lower part of the Chang 7 Member consists of oil shale and tuff, with interbedded fine sandstone and siltite. The upper part consists of mudstone, shale and tuff, sandwiched with siltite and fine sandstone. The stratigraphic characteristics of the oil shales are clearly resolved in a well wireline logging; the oil shale being characterized by high natural gamma ray (GR) and resistivity of induction in lateral and deep (RILD) logs, low $\rho$ (density), and spontaneous potential (SP) logs (Fig. 6) (Yang & Zhang 2005; Wang 2007).

**Age**

**Biostratigraphic age**

The biostratigraphy is based on phytoliths. The *Danaeopsis–Bernoullia* assemblage, with a Carnian–Norian age (Si 1956; BGMRSP 1989, 1998), occurs in the upper part of the Yanchang Formation, suggesting the upper part of the Yanchang Formation is of late Triassic (Carnian–Norian) age. The *Annalepis–Tongchuanophyllum* assemblage, with a Ladinian age (Si 1956), occurring in the lower part of the Yanchang Formation below the Chang 7 Member indicates an middle Triassic age for the lower part of the Yanchang Formation. The Chang 7 Member oil shale is therefore of Ladinian (i.e. middle Triassic) age.

**Zircon SHRIMP U–Pb ages**

Zircon SHRIMP U–Pb ages have recently been published for the lowermost tuff units ($K_0$) of the Chang 7 Member oil shale (stratigraphic horizon $K_0$, see Fig. 4) (Xie 2007; Wang et al. 2014). These ages range from 239.7 to 241.3 Ma, which are equivalent to the Ladinian age as indicated by the phytoliths.

In summary, the Yanchang Formation is middle–late Triassic (Ladinian–Norian) age, not just late Triassic age (Wang et al. 2017). The Chang 7 Member oil shale is of middle Triassic (Ladinian) age.

**Thickness**

Based on outcrops (Fig. 1) and logging data (Fig. 6), the thickness of the oil shale ranges from 0 to 61 m, with an average of c. 28 m
The areas with a thickness greater than 20 m are elongated approximately NW–SE, and include Huanxian, Huchi, Qingyang and Zhengning counties and Tongchuan city (Fig. 5). The oil shale is thin at the edge of the basin and thickest in the central part where it is more than 40 m in thickness near Huanxian County and more than 20 m thick to the NW of Tongchuan city (Fig. 5).

Petrological and geochemical characteristics

Petrological characteristics

The oil shales have a dark, greasy lustre with a maroon-coloured surface resulting from oxidation (Fig. 7). The fresh oil shales have a flakey, banded structure, uneven conchoidal fractures, low hardness and light brown streak.

The main components of the oil shale, by average, are 49% clays, 29% quartz, 16% feldspars and iron oxides. The composition falls within the muddy shale area in the shale classification scheme of Kuila & Prasad 2012 (Fig. 8). Carbonate minerals are rare. Clay minerals comprise mainly mixed-layer illite and smectite, followed by illite and chlorite, and are partially affected by sericitization. The clastic minerals are mainly quartz, followed by feldspars (Bai et al. 2009, 2010).

Iron oxides and organic matter fill the pore spaces between the clay minerals (Fig. 9a). The diameters of the detrital mineral grains vary from 0.03 to 0.06 mm (i.e. silt), occasionally up to 0.15 mm, Sand-size mineral grains are angular, subangular and rounded, and consist of quartz and feldspar (Fig. 9b); indicating a proximal provenance trait.

Chemical composition characteristics

The average chemical composition of the oil shale is shown in Table 1. Compared with ‘North American shale composite’ (NASC) (Gromet et al. 1984), the oil shale has higher P2O5 and Fe2O3; lower CaO, SiO2 and MgO; slightly lower Na2O and K2O; and similar Al2O3 and TiO2.

The concentrations of CaO, SiO2 and MgO in the oil shale are relatively low, which indicates limited terrigenous matter input into the lake. The concentrations of P2O5 and Fe2O3 in the oil shale is relatively high, if primary, indicating that the nutrient content of the lake water was relatively high, which may have been associated with volcanism to the south of the lake; numerous tuff layers are present in the oil-shale seams.

M (M = 100 × MgO/Al2O3) values of the shale could reflect the salinity of the lake water and the provenance; in general, M < 1 for freshwater environments, 1 < M < 10 for transitional environments, 10 < M < 500 for marine environments and M > 500 for epicontinental seas or lagoons (Liu 1984). M = 6.1 for the oil shale indicates a transitional brackish water environment. However, numerous specimens of *Leiosphaeridia* and *Micrhystridium* are preserved, which indicates that the lake was primarily freshwater (Ji et al. 2006). The Sr/Ba ratios cited below also support this conclusion.

The sum of SiO2 and Al2O3 reaches 63.69% of the whole-rock chemical composition, indicating a continental deposition. This corresponds to a siliceous ash on combustion (the criteria for siliceous ash-type oil shale are SiO2 (40–70 wt%), Al2O3 (8–50 wt%), Fe2O3 (<20 wt%) and CaO (1.20 wt%), (Zhao et al. 1991). The oil shales are slightly lower in SiO2 and Al2O3 than that of the Tertiary oil shales of the Fushun Basin, which consist of 61.59 wt% SiO2 and 23.36 wt% Al2O3 (Yuan et al. 1979; The Office of the National Committee of Mineral Reserves 1987), indicating that the latter have a more obvious continental deposition (Zhao et al. 1991).

Oil-shale fusibility can be expressed by (SiO2 + Al2O3)/(Fe2O3 + CaO + MgO) values, which are <5 for fusible ash, 5–9 for medium fusion ash and >9 for refractory ash (Zhao et al. 1991). Because the (SiO2 + Al2O3)/(Fe2O3 + CaO + MgO) value for the oil shales is 5.87, it belongs to a medium fusion ash.

Trace element characteristics

The average trace element concentrations of the oil shale are given in Table 1. Both Mn and Ni have enrichment coefficients (relative to NASC according to Gromet et al. 1984; see below) of less than 0.5; Ba, Zr, Rb, Cr, Co and Th have coefficients ranging from 0.5 to 1; Sr, V and Zn have coefficients ranging from 1 to 1.5; Pb has a coefficient of 1.7; and Cu has a coefficient 3.02. Both Mo and U are very strongly enriched. The strong enrichment of U, Mo, Cu and Pb,
if primary, shows that the lake was rich in organic nutrients. The eutrophic lake water would have enhanced the productivity, promoting algal booms and, at the same time, resulting in anoxia of the water. The enrichment of U, Mo, Pb and Cu is a positive relationship with TOC (Zhang et al. 2008b).

The Sr/Ba ratio of a shale, if primary, is proportional to the salinity of water; Sr/Ba >1 indicates a marine or saline lake environment, 0.5 < Sr/Ba < 1 indicates brackish water and Sr/Ba < 0.5 indicates freshwater (Liu 1984). The Sr/Ba ratio of 0.33 in the oil shale indicates that the lake was a freshwater environment.

The Mn content of lake water is positively correlated with water depth. The Mn abundance is about 10 ppm for lake shore, about 60 ppm for shallow lakes and about 400 ppm for semi-deep lakes to deep lakes (Liu 1984). The 313 ppm Mn of the Chang 7 Member oil shale indicates a semi-deep to deep lake environment.

The geochemical behaviour of the variable valence elements V and U is closely related to the sedimentary redox environment. In a reducing environment, V and U have a low valency, are less soluble and are readily enriched, so that the ratios of V/Ni, V/Cr and U/Th are often used as redox indicators (Lewan & Maynard 1982). The oil shale has a V/Ni ratio of 7.8 and a U/Th ratio of 4.8, indicating a strongly reducing environment.

The Sr/Cu ratio is climatically related. A Sr/Cu ratio of 1.3–5.0 indicates a warm and humid climate; a ratio value of >5 indicates a hot, dry climate; and a ratio of <1.3 indicates a cold, humid climate (Liu 1984). The Sr/Cu ratio of the oil shale is about 2, indicating a warm, humid climate.

Redox conditions in the original water settings controlled the concentrations of some major and trace elements in sediments and sedimentary rocks. Thus, their concentration could be used to reconstruct the redox of the original water (Liu 1984; Tribovillard et al. 2006). Because of fine particles, compacting construction and very low porosity of the oil shale, the concentration and ratios of some major and trace elements are very small change in the diagenetic alteration, and could be used to indicating sedimentary environment (Liu 1984).

**Rare earth element characteristics**

The amount of REE in the oil shales is slightly higher than the average amount of REE (146.4 ppm) in the upper crust and slightly lower than that (197 ppm) in NASC (Gromet et al. 1984). The amount of both REE and TOC in the deposits of the warm, damp climate environments is, generally, higher than that in arid and cold climate environments. The amount of REE is relatively high in the oil shale, which shows that the warm and damp climate prevailed during the middle Triassic, favouring biological productivity.

The REE distribution patterns of the oil shales are characteristic rich in LREEs (light REE) and have a weakly negative Eu anomaly, similar to that of the upper crust (Fu & Qi 1995), which suggests the degree of differentiation of REE is relatively high and the deposition rate is relatively low in the lake, which favoured enrichment in organic matter (Fu & Qi 1995).

In sedimentary systems, the Ce anomaly may reflect changes in the redox conditions in water, $\text{Ce}_{\text{anom}} = \log [3\text{Ce}_n/(2\text{La}_n + \text{Nd}_n)]$ (the subscript $n$ is standardized values for NASC). $\text{Ce}_{\text{anom}} > -0.1$ reflects a reducing water body and $\text{Ce}_{\text{anom}} < -0.1$ reflects an
oxidized water body (Fu & Qi 1995). The oil shale has Ce anomaly greater than $-0.1$ (Ma et al. 2016).

The oil shales have very similar REE characteristics to chondrite distribution patterns among the different samples (Fig. 10). The coherence of the REE distribution patterns indicates a consistent provenance.

**Organic geochemistry characteristics**

The oil shale has a high residual organic matter content, with an average TOC content of 18 wt% (Table 2). The main component (kerogen) of the organic matter has reached maturity, with a $R_o$ value of 0.9–1.15% ($T_{max} = 445–455^\circ$C), a residual chloroform bitumen ‘A’ content of 0.1–0.4 wt% (chloroform bitumen is a soluble organic matter in rocks that can be dissolved in chloroform, composed of saturated hydrocarbon, aromatic hydrocarbon, gum and asphaltene; generally, chloroform bitumen ‘A’ is the ratio of the extracted bitumen mass to the mass of rock sample), a hydrocarbons content of 0.3–0.6 wt% and a pyrolytic hydrocarbon-generation potential ($S_1 + S_2$) content of about 70 mg HC/g rock (Table 2). The yield of the oil shale is up to 400 mg HC/g rock. $I_O$ has two interval values (bimodal) of 200–300 and 600–650 mg HC/g TOC, and $I_O$ also has two interval values, $<5$ and 50–100 mg CO$_2$/g TOC (Yang & Zhang 2005; Ma et al. 2016), which suggest that the kerogens come from a variety of sources. The residual ‘chloroform bitumen A’ conversion rates (A/TOC) are 3.14–9.84 and the hydrocarbon conversion rates (HC/TOC) are 2.11–5.77 (Yang & Zhang 2005). The hydrocarbon-expulsion efficiency reaches an average of 72% (Mu et al. 2001; Yang & Zhang 2005; Zhang et al. 2006, 2008b).

![Fig. 9. The characteristics of the oil shale under a light microscope (after Bai et al. 2009, 2010b). (a) Remaining argillaceous texture, slab structure, weak sericitization (perpendicular polarized light). (b) Angular, subangular and rounded silt-sized mineral grains (feldspars) (perpendicular polarized light).](http://pg.lyellcollection.org/Downloaded from)
The kerogens mainly consist of amorphous lipids, with a few Hystrichosphaera and spores, and are characterized by a uniform, monotonous biological component (Mu et al. 2001; Yang & Zhang 2005; Ji et al. 2007). They lack aryl isoprenoid alkane complexes, which shows that the kerogens are mainly derived from algal material of lacustrine origin, of the I–II1 type (Mu et al. 2001; Yang & Zhang 2005; Ji et al. 2007; Ma et al. 2016). The high residual organic matter content, good-quality kerogens with 0.9–1.05% Ro but low (S1 + S2) values (Table 2) indicate that the oil shales (source rocks) underwent strong hydrocarbon expulsion, and a low ratio of saturated hydrocarbon/aromatic hydrocarbon (SH/AH of 0.86–3.0) also suggests this (Yang & Zhang 2005).

### Table 1. Major, trace and rare-earth element analyses from the Chang 7 Member oil shale

<table>
<thead>
<tr>
<th>Oxide</th>
<th>Chang 7 Member oil shale (average, N = 54)1</th>
<th>Trace elements (ppm)</th>
<th>Chang 7 Member oil shale (average, N = 43)2</th>
<th>Rare-earth elements (ppm)</th>
<th>Chang 7 Member oil shale (average, N = 8)3</th>
<th>Chondrite4</th>
<th>NASC5</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>48.69</td>
<td>Na</td>
<td>58.10</td>
<td></td>
<td>La</td>
<td>31.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Al2O3</td>
<td>14.40</td>
<td>Sr</td>
<td>15.40</td>
<td></td>
<td>Ce</td>
<td>56.0</td>
<td>1.0</td>
</tr>
<tr>
<td>TiO2</td>
<td>0.51</td>
<td>Ca</td>
<td>0.65</td>
<td></td>
<td>Pr</td>
<td>6.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>8.54</td>
<td>V</td>
<td>4.02</td>
<td></td>
<td>Nd</td>
<td>24.0</td>
<td>0.7</td>
</tr>
<tr>
<td>MgO</td>
<td>0.97</td>
<td>Zr</td>
<td>3.44</td>
<td></td>
<td>Sm</td>
<td>4.4</td>
<td>0.2</td>
</tr>
<tr>
<td>CaO</td>
<td>1.14</td>
<td>Rb</td>
<td>3.11</td>
<td></td>
<td>Eu</td>
<td>0.9</td>
<td>0.1</td>
</tr>
<tr>
<td>Na2O</td>
<td>0.96</td>
<td>Cu</td>
<td>1.30</td>
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<td>Gd</td>
<td>3.9</td>
<td>0.3</td>
</tr>
<tr>
<td>K2O</td>
<td>2.72</td>
<td>Pb</td>
<td>3.24</td>
<td></td>
<td>Tb</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>FeO</td>
<td>4.00</td>
<td>Zn</td>
<td>3.24</td>
<td></td>
<td>Dy</td>
<td>3.6</td>
<td>0.9</td>
</tr>
<tr>
<td>P2O5</td>
<td>0.30</td>
<td>Cr</td>
<td>0.17</td>
<td></td>
<td>Ho</td>
<td>0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>Ni</td>
<td>22.5</td>
<td>Co</td>
<td>58.0</td>
<td></td>
<td>Er</td>
<td>2.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Mo</td>
<td>59.1</td>
<td>Mo</td>
<td>3.1</td>
<td></td>
<td>Yb</td>
<td>2.5</td>
<td>0.2</td>
</tr>
<tr>
<td>U</td>
<td>31.9</td>
<td>Th</td>
<td>3.0</td>
<td></td>
<td>Lu</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Th</td>
<td>6.6</td>
<td></td>
<td>12.3</td>
<td></td>
<td>Y</td>
<td>2.3</td>
<td>1.9</td>
</tr>
<tr>
<td>∑REE</td>
<td>160.5</td>
<td></td>
<td>160.5</td>
<td></td>
<td></td>
<td>197.0</td>
<td></td>
</tr>
</tbody>
</table>

N, number of samples.

1Chang 7 Member oil shale (N = 54) data were compiled from Miao et al. (2005), Changqing Oilfield Company, PetroChina (2008), Bai et al. (2009), Zhang et al. (2013), Sun et al. (2015) and Wang et al. (2016).

2NASC according to Gromet et al. (1984).

3Chang 7 Member oil shale (N = 43) data were compiled from Miao et al. (2005), Zhang et al. (2008a, b), Bai et al. (2009), Zhang et al. (2013), Sun et al. (2015) and Ma et al. (2016).

4NASC according to Gromet et al. (1984).

5Chang 7 Member oil shale (N = 8) data were compiled from Bai et al. (2009) and Ma et al. (2016).

6Chondrite according to Taylor & Melean (1985).

7NASC according to Gromet et al. (1984). Analytical methods: the analytical method for major elements uses X-ray fluorescence (XRF) in different laboratories following Chinese standards GB/T 14506.14-2010 (AQSIQ & SAC 2010c) and GB/T 14506.28-2010 (AQSIQ & SAC 2010b); the analytical method for microelements uses XRF and inductively coupled plasma mass spectrometry (ICP-MS) following Chinese standard GB/T 14506.30-2010 (AQSIQ & SAC 2010a); and the analytical method for rare earth elements uses XRF and ICP-MS in different laboratories following Chinese standard GB/T 14506.30-2010 (AQSIQ & SAC 2010a).

Fig. 10. Chondrite-normalized REE distribution patterns of the Chang 7 Member oil shale.
Table 2. Proximate and organic matter analysis from the Chang 7 Member oil shale

<table>
<thead>
<tr>
<th>Proximate analysis items</th>
<th>Chang 7 Member oil shale average, N = 35</th>
<th>Organic matter abundance analysis items</th>
<th>Chang 7 Member oil shale average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil yield (wt%)</td>
<td>8.00</td>
<td>TOC (wt%)</td>
<td>17.76 (N = 72)</td>
</tr>
<tr>
<td>Qnet,v,ar (MJ kg⁻¹)</td>
<td>8.35</td>
<td>Chloroform bitumen A (wt%)</td>
<td>0.4–1</td>
</tr>
<tr>
<td>Aₐ (wt%)</td>
<td>69.24</td>
<td>S₁ (mg HC/g rock)</td>
<td>3.06 (N = 41)</td>
</tr>
<tr>
<td>S₁ (wt%)</td>
<td>4.69</td>
<td>S₂ (mg HC/g rock)</td>
<td>60.51 (N = 40)</td>
</tr>
<tr>
<td>Mₐ (wt%)</td>
<td>3.37</td>
<td>S₃ (mg CO₂/g rock)</td>
<td>7.78 (N = 41)</td>
</tr>
<tr>
<td>Vₐ (wt%)</td>
<td>68.16</td>
<td>S₁ + S₂ (HC/g rock)</td>
<td>70.00 (N = 76)</td>
</tr>
<tr>
<td>Cₐ (wt%)</td>
<td>19.08</td>
<td>Iₐ (mg/g)</td>
<td>407.80 (N = 434)</td>
</tr>
<tr>
<td>H₂O (wt%)</td>
<td>2.13</td>
<td>Iₒ (mg/g)</td>
<td>63.39 (N = 19)</td>
</tr>
<tr>
<td>ARD (g cm⁻³)</td>
<td>1.77</td>
<td>N, number of samples</td>
<td></td>
</tr>
</tbody>
</table>

¹Proximate analysis: Qnet,v,ar, net calorific value at constant volume; Aₐ, ash content (dry basis); S₁, sulphur content (dry basis); Mₐ, total moisture; Vₐ, volatile (dry ash-free basis); Cₐ, carbon (air dry basis); H₂O, hydrogen (air dry basis); ARD, apparent density.

²Chang 7 Member oil shale data were compiled from Liu et al. (2006), Zhang et al. (2006), Ren (2007), Changing Oilfield Company, PetroChina (2008), Bai et al. (2009) and Zhang et al. (2013). Analytical methods: the analytical method for the oil yield uses Gray–King low-temperature distillation in different laboratories following Chinese standard GB-T 1341-2007 (AQSIO & SAC 2007); the analytical method for ash yield uses the fast ashing method in different laboratories following Chinese standard GB/T 212-2008 (AQSIO & SAC 2008a); and the analytical method for chloroform bitumen A value uses the environmental isothermal automatic oxygen bomb calorimeter in different laboratories following Chinese standard GB/T 213-2008 (AQSIO & SAC 2008b). Organic matter abundance analysis: TOC (total organic carbon) is the content of residual organic matter in oil shale (%); chloroform bitumen A (%) is the ratio of the extracted bitumen mass to the mass of rock sample; S₁ is the content of soluble hydrocarbon in oil shale (mg HC/g rock); S₂ is the content of pyrolytic hydrocarbon in oil shale (mg HC/g rock); S₃ is the content of pyrolytic carbon dioxide in oil shale (mg CO₂/g rock); S₁ + S₂ is the potential amount of hydrocarbon generation (mg HC/g rock); Iₐ = Qₐ / COT × 100 and Iₒ = Qₒ / COT × 100 (where Qₐ is hydrocarbon from kerogen pyrolysis and extractable hydrocarbon components; COT is total organic carbon; and Qₒ is the amount of CO₂). Analytical methods: the analytical method for total organic carbon (TOC) uses the Carbon/Sulfur Determinator in different laboratories following Chinese standards GB/T 19145-2003 (AQSIO & SAC 2003); the analytical method for chloroform bitumen A analysis uses Soxhlet extraction equipment in different laboratories following the Chinese enterprise standard of CN-PC SY/T5118-2005 (NDRC 2005); and the analytical method for rock pyrolysis analysis uses Rock-Eval pyrolysis apparatus in different laboratories following Chinese standard GB/T 18602-2012 (AQSIO & SAC 2012). Chang 7 Member oil shale data were compiled from Yang & Zhang (2005), Ren (2007), Changing Oilfield Company, PetroChina (2008), Bai et al. (2009), Zhang et al. (2013), Ma et al. (2016) and Yang et al. (2016).

The Chang 7 Member oil shale kerogen and ‘chloroform bitumen’ are enriched in the light carbon isotope ¹²C. The kerogen and ‘chloroform bitumen’ have a limited range of ³¹C values, which are −30.00 to −28.5 and −33.00 to 32.2‰ (Yang & Zhang 2005), respectively, which shows that the kerogen formed in a terrestrial, freshwater to low-salinity water body. Gas chromatography shows that the saturated hydrocarbon chromatogram is of unimodal type, and the main carbon peak is nC₁₇−nC₁₉, showing an odd–even equilibrium with an OEP (odd–even performance) of 0.95−1.21. Pr/Ph is 0.56–1.17, Pr/nC₁₇ is 0.11−0.33 and Pr/nC₁₈ is 0.16–0.40, which also indicates a reducing environment. The low Pr/Ph, lower Pr/nC₁₇ and Pr/nC₁₈ ratios indicate that the sedimentary environment was a deep reducing water body, and the source of the organic material was primarily lower aquatic organisms; in addition, it has reached the peak of the oil source maturity phase (Yang & Zhang 2005; Zhang et al. 2006; Ji & Xu 2007; Ji et al. 2007).

Hopane is composed primarily of C₃₀βββ. The content of gammacerane and tricyclic terpane is low, and the content of Ts is high. Sterane is given priority to with regular Sterane, with C₁₉, C₂₀, C₂₁, C₂₂, C₂₃, C₂₄, and C₂₅ steranes in the oil shale.

Quality

Oil yield and calorific value are the most common parameters for evaluating oil shales (Yuan et al. 1979; Smith 1980; The Office of the National Committee of Mineral Reserved 1987; Zhao et al. 1991; Zhao & Liu 1992; Guan et al. 1995; Diny 2006a, b; Liu et al. 2006, 2009). The oil yield of the oil shale was measured by the Gray–King low-temperature dry distillation assay method following Chinese standard methods (GB/T 1341-2007) (AQSIO & SAC 2007), and the calorific value of the oil shale was measured by isothermal oxidation bomb calorimetry following Chinese standard methods GB/T 213-2008 (AQSIO & SAC 2008a, b).

Based on our own and previously published data, the oil shale has an average oil yield of 8 wt%, a calorific value of 8.35 MJ kg⁻¹ (net calorific value at constant volume) and an apparent specific gravity of 1.79 (Table 2).

The grade of oil shale can be divided into three types by oil yield of oil shale (dry basis), which is, respectively, low (3.5 wt% < oil yield ≤ 5 wt%), medium (5 wt% < oil yield ≥ 10 wt%), and high (oil yield >10 wt%) (Liu et al. 2009). The oil shale is medium quality.

The calorific value is useful for determining the quality of oil shale that is burned directly in a power plant to produce electricity. The calorific value of a given oil shale is a useful and fundamental property of the rock, although it does not provide information on the amounts of shale oil or combustible gas that would be yielded by retorting (destructive distillation). The oil shale is high grade compared with other Chinese oil-shale deposits, which have average calorific values of 5.7 MJ kg⁻¹ (Fushun), 7.3 MJ kg⁻¹ (Maoming), 7.0 MJ kg⁻¹ (Yaojie), 3.6 MJ kg⁻¹ (Nongan), 4.2 MJ kg⁻¹ (Dongsheng), 6.6 MJ kg⁻¹ (Huidian) and 4.2–5.0 MJ kg⁻¹ (Guyang), respectively (Zhao et al. 1991; Liu et al. 2009), but it is low grade compared with the high-grade kükersite oil shale of Estonia, which fuels several electric power plants and has a calorific value of about 10.03–12.62 MJ kg⁻¹ on a dry-weight basis (Diny 2006a, b). The higher calorific value are linked to the higher oil yields, TOC and lower Ad (ash content, dry basis) in the oil shale (Fig. 11a–c).

The oil shale averages 69 wt% ash yield (dry basis); a high ash type (Zhao et al. 1991; Liu et al. 2009). The higher ash yield is linked to the lower calorific value and oil yield (Fig. 11b and d). Considering the above data of the oil shale fusibility, it is a medium fusion, high ash type.

The data analysis indicates that there is an obvious positive correlation between the oil yields and C₃₀βββ (carbon, air dry basis) (Fig. 10c). The higher the total sulphur content, the greater the potential environmental pollution in oil-shale utilization. Oil shale can be divided into five levels: ultra-low sulphur (≤1.0 wt%), low sulphur oil shale (1.0–1.5 wt%), medium sulphur (1.5–2.5 wt%), rich sulphur (2.5–4.0 wt%) and high sulphur (>4.0 wt%) (The Office of the National Committee of Mineral Reserves 1987). The total sulphur is 4.69 wt%: indicating a high sulphur oil shale.
Oil shale can be divided on moisture content into high moisture content (Mt of 20–30 wt%), medium moisture content (Mt of 10–20 wt%), low moisture content (Mt of less than 10 wt%) (The Office of the National Committee of Mineral Reserves 1987). The oil shale has Mt of 3.37 wt%, a low moisture content.

The oil shale has an average density of 1.77 kg m$^{-3}$, which is quite high, related to the higher silicon and aluminum components; this means a lower oil yield per tonne.

The oil shale has an average V$\text{daf}$ (volatile, dry ash-free basis) of 68 wt%, which is quite high, related to the higher silicon and aluminum components; this means a lower oil yield per tonne.

The average TOC of the oil shale is high (Table 2). The correlation between the TOC and oil yield in the outcrop oil shale samples is very obvious (Fig. 11f), but there is no obvious correlation between TOC and (S$_1$ + S$_2$).

The average content of C$_\text{ad}$ (carbon, air dry basis) and H$_\text{ad}$ (hydrogen, air dry basis) in the oil shale are, respectively, 19.08 and 2.13 wt% (Table 2), so an average H/C ratio of 1.4 is obtained. Ma et al. (2016) pointed out that the oil shale has average H/C and O/C ratios of 1.34 and 0.1, respectively. Therefore, the organic matter of the oil shale belongs to Type I and II$_1$. Tissot & Welte (1978) stated that the Type I kerogen has a H/C ratio of >1.5, a O/C ratio of <0.1, and the precursors of the kerogen are mainly from marine or continental deep-water lake algae and bacteria; the Type II kerogen has a H/C ratio of 1.0–1.5, a O/C ratio of 0.1–0.2, and the precursors of the kerogen are mainly from continental deep-bathyal lake spores and pollen, plankton, micro-organisms, and other mixed organic matter; and the Type III kerogen has has a H/C ratio of <1.0, a O/C
ratio of >0.2 and the precursors of the kerogen are mainly from terrestrial higher plants. Based on content of $C_{spec}$ and $H_{spec}$ and the H/C and O/C ratios in the oil shale, the organic matter is mainly derived from lacustrine algae, spores and pollen. Thus, 'carbon' in the organic matter of the oil shale is unlikely to have been derived from seawater or carbonate minerals, with a probable lake water origin.

**Origin**

**Classification of the Ordos Basin oil shale**

Oil shales can be classified by their depositional environment (e.g. large lake, shallow marine, deltaic and lagoonal/small lake settings) (Carman & Bayes 1961; Surdam & Woflbauer 1975; Yuan et al. 1979; Macauley 1981; Boyer 1982; Francis & Miknis 1983; Hutton 1987; Brendow 2003; Altun et al. 2006; Dyni 2006a, b; Ots et al. 2007; Lu et al. 2006; Durham 2010). Oil shales of great lakes have large thicknesses and areas, and are of good quality. A typical example is the Green River oil shale in the NW USA, which is black in colour with a thickness of several hundred metres, and with an oil yield of generally <15 wt% (Surdam & Woflbauer 1975; Smith 1980; Boyer 1982; Dyni 2006a, b).

Shallow sea and continental shelf oil shales are generally much thinner than the large lake deposits, and are associated with carbonates, siliceous and phosphatic facies. They do not exceed 2–3 m in thickness and are distributed over very large areas, up to thousands of square kilometres (Hutton 1987). They are black to light brown in colour with a high oil yield (c. 20 wt%). A typical example is the Kukersite oil shale of Ordovician age in Estonia, which is in a single calcareous layer, 2.5–3 m in thickness, with an average oil yield of 20 wt%. Most of the organic matter is derived from green algae (Hutton 1987).

Oil shales deposited in lagoonal or small lake environments are rarely extensive and are often associated. Despite having a high oil yield, they are thin and are unlikely candidates for commercial exploitation. A typical example is the Yaojie oil shale of Jurassic age in NW China, which is black in colour, 4–11 m thick, with an oil yield of 4.6–8.9 wt%, and most of the organic matter is derived from macrophytes (Bai et al. 2010b).

The Chang 7 Member oil shale formed in a larger-scale lake setting. The ‘Ordos Lake’ itself covers an area of 400 000 km² with a maximum water depth of about 60 m (Yang et al. 2010a) during the middle Triassic, resembling the Green River oil shale (Smith 1980; Boyer 1982; Dyni 2006a, b). The oil shale covers an area of around 30 000 km², has an average thickness of 28 m and an average oil yield of 8 wt%.

The Chang 7 Member oil-shale clay mineral content of 49% is similar to the composition of the Darden Gulch oil-shale seam of the Green River, which has a clay mineral content of 40–70%. However, it differs from the Kuksite oil shale in Estonia, which has a clay mineral content of only 13.9% and a carbonate mineral content of 56.1% (Hutton 1987).

The relatively low concentration of CaO, SiO₂ and MgO, and the relatively high concentration of P₂O₅ and Fe₂O₃ and MgO/Al₂O₃ ratio show that the lake was a coastal lake, lacked significant terrigenous matter inputs and that the lake water had a high nutrient content. The coherence of the REE distribution patterns among the different samples indicates a consistent provenance. The Pr/Ph, Pr/InC17 and Pr/InC18 ratios also indicate that the biological source material is dominated by lower aquatic organisms (Yang & Zhang 2005; Ji & Xu 2007; Ji et al. 2007).

The oil shale formed in a reducing environment. Its surface is maroon after oxidation, indicating enrichment in Fe²⁺, and thus a deep-water reducing environment. Pb, Cu, Mo and U are strongly enriched, the the ratios of V/Ni, U/Th, FeO/Fe₂O₃, Pr/Ph, Pr/InC17 and Pr/InC18 also indicate that the lake was a strongly reducing environment.

The lake where the oil shale formed may have been a freshwater to brackish water environment. The Sr/Ba ratio indicates that the lake was a freshwater lake, but the M value of the oil shale indicates a transitional brackish water environment. Both the low content of gammacerane and high content of diasteranes also indicates that the oil shale formed in a low-salinity sedimentary environment (Yang & Zhang 2005).

The Sr/Cu ratio indicates a warm, humid climate.

Recent research shows that the sapropel group in the kerogens in the Chang 7 Member oil shale contains abundant Leiosphaeridia, which is multicellular macro red algae and/or chlorophytes, rooted in the lacustrine macroscopic algae, fomed in a freshwater environment, different to the Proterozoic and Paleozoic Leiosphaeridia which is commonly thought as a marine unicellular phytoplankton (Ji & Xu 2007; Ji et al. 2007). Although Leiosphaeridia is abundant in the area, it is not only monotone in species but also conspicuous in echinulate process, suggesting that some marine acanthomorphic acritarchs survived in freshwater and had experienced long-term evolution. Therefore, the sedimentary environment of the Chang 7 Member oil shale is a lacustrine environment, which turned into the climax of lake transgression in the Chang 7 sedimentary interval, indicating the supply of a large-scale lake water body that came from rivers rather than from a rise in sea level (Ji & Xu 2007; Ji et al. 2007).

The limited range of δ¹³C values of ‘chloroform bitumen’ shows that the kerogen formed in a deep, reducing, low-salinity water body. Considering that the composition of the kerogen is monotonous, it is conjectured that the water body of the Ordos Basin was indistinctly stratified (Yang & Zhang 2005). A low gammacerane content and the absence of aryl isoprenoid compounds in the kerogen structure of the oil shale also indicate that the lake basin was not significantly delaminated (Zhang et al. 2008b). Both the low content of gammacerane and the high content of diasteranes indicate that the oil shale formed in a low-salinity sedimentary environment (Yang & Zhang 2005). The Pr/Ph, Pr/InC17 and Pr/InC18 ratios also indicate a reducing deep-water environment within which the biological source material was dominated by lower aquatic organisms (Yang & Zhang 2005; Ji & Xu 2007; Ji et al. 2007).

To sum up, the Ordos Basin oil shale formed in a deep-water reducing environment with a warm, humid climate context. The lake may have been freshwater or brackish water and was indistinctly stratified. The biological source material was dominated by lower aquatic organisms.

**Volcanism in the Ordos area**

The andesitic–dacitic tuff interbeds in the Chang 7 Member oil-shale seams and the Yanchang Formation (Fig. 7c) indicate its formation close to a volcanic arc, and that the lake was a relatively high-energy environment. In addition, the sandstone types in the upper and lower host layers of the oil-shale seams are mostly feldspar quartz sandstone and arkose, also indicating a relatively high-energy environment. The Ordos Basin was not a stable intracratonic basin (Yang 2002), and was subject to relatively energetic sedimentary processes. Moreover, the angular sandy debris grains suggest a proximal provenance (Fig. 9b).

As stated above, the Ordos Lake was a reducing sedimentary environment; however, the atmospheric oxygen level was not low at the time of the oil-shale formation and questions arise regarding the origin of the reducing lake environment. Multiple layers of andesitic acid tuff (Figs 4 and 7c) are present in the Yanchang Formation and the oil-shale seams; therefore, it is possible that their deposition was to some extent responsible for the reducing conditions in the lake basin. There may have been a catastrophic death of organisms due to...
ash falls, which may be the main reason why organic matter was enriched in the lake. At the same time, the tuff layers also provided nutrients for the next cycle of oil-shale formation (Yang & Zhang 2005).

Marine facies or lacustrine facies?

It is problematic that recently one paper proposed that the Chang 7 Member oil shale in the Ordos Basin was deposited in a marine intrusion (Wang et al. 2017). Their evidence is a typical marine coelacanth fossil with a rounded tail that was found in the late Triassic stratum in the Huachui County area; a broken marine coelacanth fossil was discovered in Tongchuan city area about 20 years ago by Liu et al. (1999). The research shows that these marine organisms actually belong to a “terrestrial organism with sea origin” rather than a marine organism (Liu et al. 1999; Wang 1995), and the terrestrial organism with a sea origin represents the survival of early marine creatures in the lake and does not represent a seawater intrusion. In combination with the geochemical evidence described above (Sr/Ba ratio of 0.33), it is proposed that the Chang 7 Member oil shale in the Ordos Basin was principally deposited in a freshwater or brackish water body, neither marine environment nor saltwater lake.

In fact, the North China Plate, including the Ordos Basin, suffered the subduction of the Qinling oceanic plate in the middle–late Triassic, resulting in a decline in sea level; in such a tectonic setting, the subduction of the Qinling oceanic plate in the middle–late Triassic stratum in the Huachui County area; a broken marine coelacanth fossil was discovered in Tongchuan city area about 20 years ago by Liu et al. (1999). The research shows that these marine organisms actually belong to a “terrestrial organism with sea origin” rather than a marine organism (Liu et al. 1999; Wang 1995), and the terrestrial organism with a sea origin represents the survival of early marine creatures in the lake and does not represent a seawater intrusion. In combination with the geochemical evidence described above (Sr/Ba ratio of 0.33), it is proposed that the Chang 7 Member oil shale in the Ordos Basin was principally deposited in a freshwater or brackish water body, neither marine environment nor saltwater lake.

In fact, the North China Plate, including the Ordos Basin, suffered the subduction of the Qinling oceanic plate in the middle–late Triassic, resulting in a decline in sea level; in such a tectonic setting, how did seawater rise over the island arc belt and invade the area?

Conclusion

Oil-shale resources are abundant in the Ordos Basin in central north China. There are multiple oil-shale seams in the basin, but the Chang 7 Member oil-shale seam is the main oil shale seam (MOSS), with a thickness of 28 m and an area of around 30 000 km². The oil shale is usually found in layers developed at the top of the lower part of the Yanchang Formation of middle Triassic (Ladinian) age. The Yanchang Formation was deposited in a great lake in the middle–late Triassic (Ladinian–Norian). The oil shale is mainly brown-black to black in colour, of a medium ash type with a TOC of 18 wt%, an oil yield of 8 wt%, a calorific value of 8.35 MJ kg⁻¹, and a relatively high P₂O₅ and Fe₂O₃ content. It is strongly enriched in Mo, U and LREE, and is kerosene type I–II. Volcanism may have favoured the formation of the oil shale. The oil shale formed in a large, deep to moderately deep lake, the Ordos Lake, with a low input of terrigenous material but abundant algal growth. The water is freshwater or brackish and strongly reducing. The tectonic context of the lake is a back-arc basin which was formed by the northwards subduction of the Qinling oceanic lithosphere beneath the southern margin of the Ordos Kraton during the middle–late Triassic (T₂–T₃).
Ordos oil shale


