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Paleo-environmental constraints on uranium mineralization in the Ordos Basin: Evidence from the color zoning of U-bearing rock series

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ABSTRACT

Color zoning of strata of Mesozoic continental basins in North China is closely correlated with the sedimentary environments of sandstone-type uranium deposits. Systematic research has been conducted on the colors of U-bearing rock series within the Ordos Basin by using data of several ten thousands of drill holes from coal and oil fields. Taking an ore cluster as the unit, well-tie sections of deposit areas were compiled to analyze the vertical and lateral spatial variations in different color zones of rocks. Taking the basin as the unit, two typical well-tie sections in the central-northern basin were compiled in order to summarize the rock color zoning laws of U-bearing rock series within ore clusters and the entire basin. Lithogeochemical characteristics of different color zones in deposit areas and ore barren areas were studied. Especially, variations in trace elements in different color zones and the paleo-sedimentary environments they reflect were discussed. Within the Ordos Basin, from the basin margin to the center and from the U ore clusters to the ore barren areas, colors of the Zhiluo Formation U-bearing rock series generally display vertical zoning (i.e., from up downwards, red–green–gray [grayish black]) and show no lateral zoning characteristics. U ore beds mostly occur in the lower part of the green zone and the upper part of the gray zone. This conclusion differs greatly from the understanding on rock color zoning related to classic interlayer-oxidation-zone metallogenic theory. Hence, a correct understanding on color zoning of U-bearing rock series within the Ordos Basin is of great significance not only to U mineralization exploration but also to research on sandstone-type U mineralization theory.

1. Introduction

Color of sedimentary rock is one of the notable macroscopic characteristics used for rock identification and classification, stratigraphic correlation and analysis, and paleoclimate and paleo-environment determination. Additionally, color is also often utilized for paleoclimate and paleo-environment restoration or discussion of climate transformation events prior to the Quaternary (Song et al., 2005; Yan et al., 2017). In a sense, color indicates certain material sources of the formation of rocks (Huang et al., 2016).

Sandstone-type U deposits were formed by supergene fluidization with sandstone as their ore-hosting carrier. Formation of a U deposit is constrained by U source, paleoclimate, epigenetic fluid reworking, and other factors, wherein paleoclimate and paleo-sedimentary environment are some of the most significant conditions for sandstone-type U mineralization (Chen, 1994). Previous scholars have conducted considerable research on color zoning of strata regarding to typical sandstone-type U deposits mainly based on the interlayer-infiltration mineralization theory introduced by scholars from the former Soviet Union and USA (Finch, 1967). In the ideal ore-forming fluid infiltration model (Fig. 1), interlayer sands are horizontally divided into primary oxidation (brownish red), secondary oxidation (brownish yellow), and reduced (gray) zones (Adams and Smith, 1981; Hou et al.,2017) and further divided into four zones by Chinese scholars afterwards (Cai et al., 2006; Chen et al., 2006). Some scholars also proposed three zones for sandstone-type uranium deposits in the Ordos Basin (Yang et al., 2009; Miao et al., 2010). In their opinion, ore-bearing sands along the northeastern margin of the Ordos Basin show lateral zoning from north southwards, i.e., oxidation (brownish yellow and shallow grayish green), oxidation–reduction transitional (shallow gray), and reduction (gray) zones (Yang et al., 2009).

A database was established by using data of rock colors from exploring drill holes of several ten thousands of coal and oil fields within the Ordos Basin. Analysis and mapping of the different colored layers in

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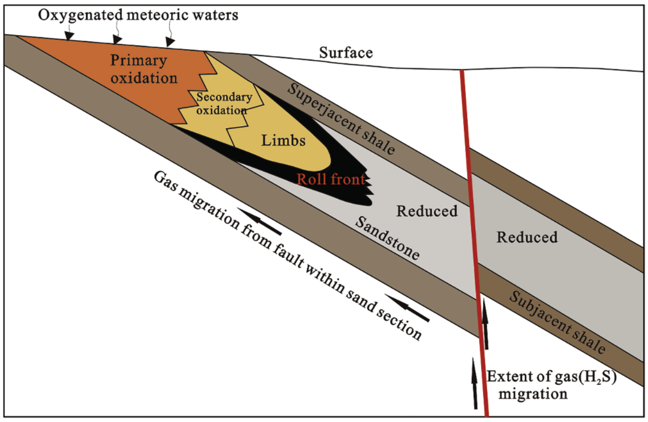

Fig. 1. Classic mineralization model of the interlayer oxidization zone (modified after Adams and Smith, 1981).

the uranium bearing Zhiluo Formation were carried out on ore clusters and basin, as the unit respectively. Regardless of the scale of an ore cluster or the entire basin, rock colors display vertical zoning characteristic, and geochemical data of different color zones also show typical vertical with weak lateral variations. Big data compiled from voluminous drill holes revealed the basic characteristics and laws, which are completely different from previous understandings on the formation of sandstone-type U deposits, and elucidated vertical color zoning that marks sedimentary environments for the first time. Papers about the specific characteristics of various major basins and the understandings on “large basin, large sands, and large mineralization,” as well as that on “supergene fluid contributing to sandstone-type U mineralization” within Mesozoic continental basins in China, will be published subsequently. Therefore, an objective understanding on the color occurrence laws of U-bearing rock series is of extremely great significance to the exploration of sandstone-type U deposits within the Ordos Basin and to the research on metallogenic theory of sandstone-type U deposits within continental facies basins.

2. Geological setting of the Ordos Basin

2.1. Evolution of Mesozoic-Cenozoic structures and strata

The Mesozoic continental sedimentary system is well developed within the Ordos Basin (Liu et al., 2008; Shamim et al., 2017; Yang et al., 2017). From lower upwards, the stratigraphic sequence comprises Triassic (T), Jurassic (J), Lower Cretaceous (K_1), and Cenozoic (E, N, and Q) strata, wherein the Mesozoic strata constitute the majority of the Ordos Basin sediments (Fig. 2). The Triassic strata are developed within and surrounding the basin, with clear sequence, from lower upwards, comprising the Lower Triassic Liujiagou and Heshanggou Formations, the Middle Triassic Ermaying Formation, and the Upper Triassic Yanchang Formation. Two stages of Indochina uplifting uplifted the basin and made the basin suffer from denudation and deformation, forming a paleotectonic framework where uplifts dominate the north with concaves occurring within the uplifts, sags dominate the center with convexes occurring within the sags, and uplifts dominate the south with alternated concaves (Wang, 2017). From Jurassic to Cretaceous, five tectonic episodes of Yanshanian movement occurred (Wang et al., 1996). Episode I occurred in a certain period during the sedimentation between the Yan’an Formation and the Zhiluo Formation with short hiatus. Consequently, the absent strata in Episode I are minimal, and upper and lower strata are consistent in attitude and in parallel unconformity. The Fuxian Formation sedimentation is featured by filling and supplementing, complex lithofacies, and great thick variations. The Yan’an Formation contains a set of stable lacustrine-swamp facies sediments and can be divided from lower upwards into ten individual members (Yan 1 to Yan 10), wherein the Yan 8 to Yan 6 Members represent a stable filling period of the basin evolution and corresponds to the main coal-forming period (Sun et al., 2016). Thick-bedded glutenite at the bottom of the Middle Jurassic Zhiluo Formation is the key period for sedimentary sequence conversion, and it represents the initial stage of the Middle-Late Jurassic tectonic event (Li et al., 2015). Episode II in the late stage of the Middle Jurassic was still dominated by large-scale uplifting and intense folding and faulting geological events, resulting in weak angle unconformity between the Fenfanghe Formation and the underlying Anding Formation. Episode III movement occurred between the Late Jurassic Fengfanghe Formation and the Early Cretaceous. This tectonism posed the greatest influence on this area, not only contributing to the formation of voluminous folds and faults, but also resulting into widespread unconformity between the Lower Cretaceous and its underlying strata. In the initial stage of Cretaceous, the basin subsided, and most area of the basin accepted Early Cretaceous sediments, forming the Zhidan Group strata. Episode IV movement occurred during the sedimentation between the Lower and Upper Cretaceous, resulted into a full uplifting of the entire basin and the termination of large-scaled depression sedimentary history of the Ordos Basin. Episode V uplifted the whole region. It led to the pre-Cenozoic strata suffering from denudation and the absence of Paleocene strata. In the Himalayan period, the collision between the Indian Ocean plate and the Eurasian Plate led the uplifting the intra-basin and the formation of a series of Cenozoic faulted basins in the periphery (Zhang et al., 2007).

2.2. Characteristics of the U-bearing rock series

U-bearing rock series within the basin is dominated by the Middle Jurassic Zhiluo Formation (Cai et al., 2007). Besides, the Yan’an Formation in the Ningdong area along the western margin and the Cretaceous Zhidan Group in the Jingchuan area along the southwestern margin are also significant ore-hosting horizons (Jin et al., 2016). U ore bodies are closely related to braided paleochannel bodies in space. Ore bodies generally occur along channel margins, or at turning points and lower reach bifurcations due to sand heterogeneity. U-rich ore bodies are generally present at bifurcations of the braided main channels and branch channels (Li et al., 2010).

After the deposition of the Yan’an Formation, due to the reworking of intense uplifting and denudation in the east and south and relatively weak of that in the west and north, the basin scope became larger in the early sedimentation stage of the Zhiluo Formation. Moreover, the sedimentary center was located in the eastern part of the present-day residual basin. Terrain relief was large along the basin margin, making the supply of sediment sources was sufficient. The climate was humid and warm at that time. The lower part of the central Lower Member constitutes a fluvial facies sedimentary lowstand system tract dominated by braided river sediments, and the lithology is mainly composed of gray and grayish white medium–coarse grained sandstone. The upper part of the Lower Member and the Upper Member constitutes a lacustrine transgressive system tract of meandering–lacustrine sediments and lithologically comprises grayish green medium–fine grained siltstone intercalated with argillaceous sandstone and silty mudstone. In the western and northeastern parts of the basin, the residual upper part of the Upper Member comprises sandstone-dominated, coarse clastic sediments of highstand system tract. During the late sedimentation period, terrain relief decreased in the periphery, and the climate was dry, leading to the insufficient supply of sediment sources. At the same time, the extent of the primary basin decreased, meandering and lacustrine sediments were dominated within the present-day basin, and the scale of delta was relatively small. The lithology consists of purple red, grayish purple argillaceous siltstone, silty mudstone intercalated with thin-bedded medium–fine grained sandstone and fine grained sandstone (Zhao et al., 2008).

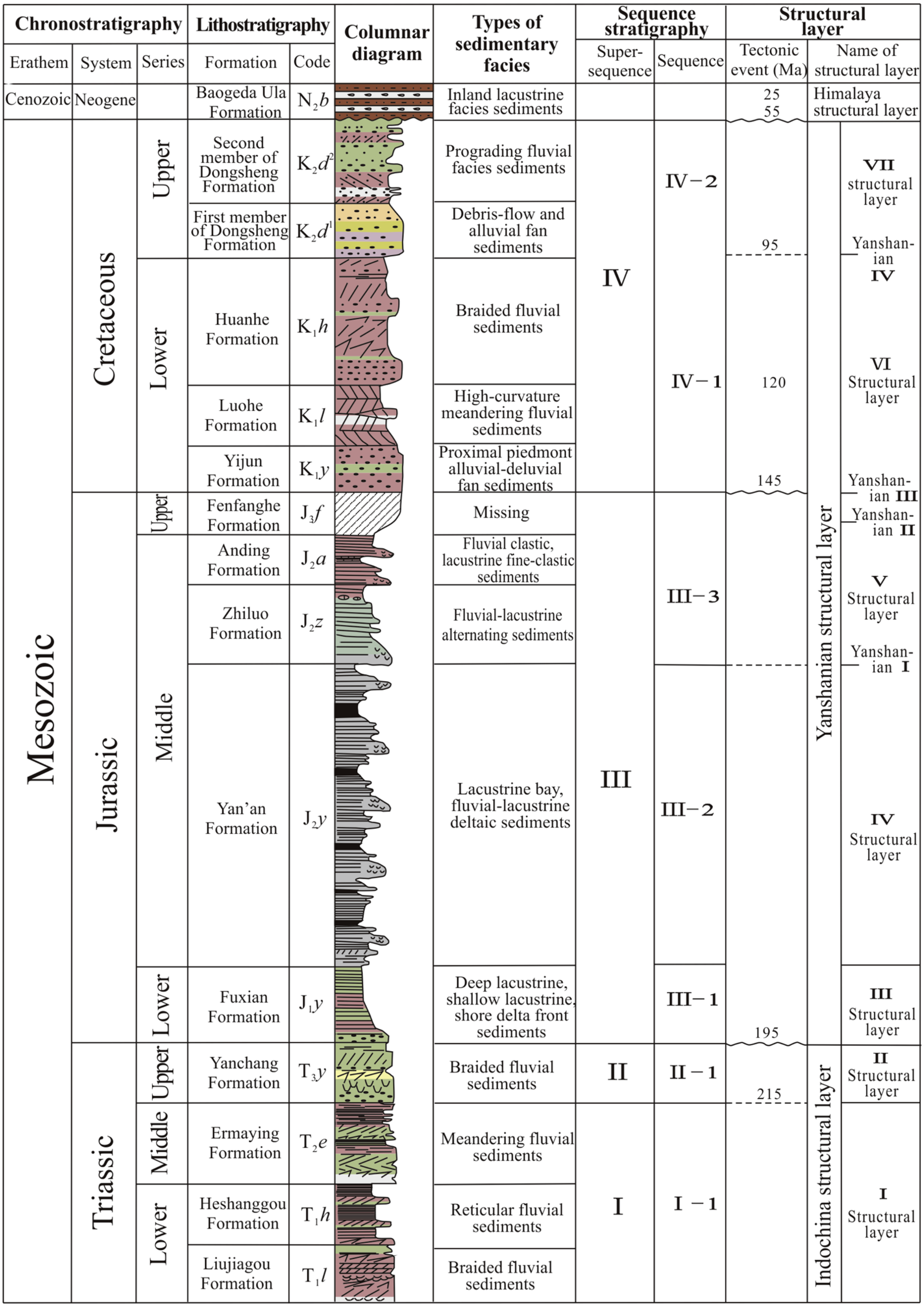

Fig. 2. The comprehensive columnar diagram of Mesozoic–Cenozoic strata along northeastern margin of the Ordos Basin.

3. Analytical methods

Detailed field observations and geological cataloguing were performed on drill core samples. Subsequently, the classification of strata in different colors was carried out and the unified working rules for color division of field core samples were established accordingly.

All the samples were collected from different color layers of different vertical drill holes in the ore cluster area. Sandstone samples from different color zones were selected for Fe^{3+}/Fe^{2+}, whole S content, TOC contents, and U content analyses. Experiments on samples from Huangling area were performed in Testing& Analysis Center, No. 203 Research Institute of Nuclear Industry. Major elements and whole S content analyses were carried out on ICPS-7510 plasma spectrometer and UV-2600 Analyzer manufactured by Shimadzu, Japan, respectively. TOC contents analyses were performed on a FD 125 Radon-Thorium Analyzer. U content analyses were conducted on a Laser induced Fluorescence Spectrometer manufactured by CNNC Beijing Research Institute of Uranium Geology. Pass ratio of all these tests were higher than 90%. Experiments on samples from Ningdong area were conducted in Geology and Mineral Resources Central Laboratory of Ningxia Hui Autonomous Region. Major elements, whole S contents and U content analyses were performed on type 6300-inductively coupled plasma atomic emission spectrometer (ICP-AES), high frequency infrared carbon sulfur analyzer and ZDD3902-low current multichannel gamma spectrometer, respectively. In terms of samples collected from the Tarangaole U deposit area, Bayannao–Naimada U anomaly area, and Uxin Banner ore barren area, relevant experiments were conducted in Tianjin Center, China Geological Survey. The major element analyses were carried out on X Ray Fluorescence, while trace element (including rare earth elements) analyses were performed on X inductively coupled plasma mass spectrometer (X series II ICP-MS). The analytical errors for major elements and trace elements (including rare earth elements) are less than 2% and 5% respectively.

4. Color zoning characteristics of U-bearing rock series of typical U deposits in the ore clusters

This work adopted an ore cluster as the unit to study mineralization and further investigate rock variation characteristics induced by mineralization. Mineralization was investigated by analyzing typical deposits and studying the spatio-temporal evolution characteristics of these deposits.

The known typical U deposits, ore spots, and mineralized occurrences within the Ordos Basin are mainly developed along the basin margin (Fig. 3), and U-mineralized bodies were also discovered in some oil fields within the basin. On the basis of different ore-controlling tectonic units, totally four ore clusters including the Dongsheng uplift, Ningdong fault-fold, Jingchuan fault uplift, and Weibei uplift ore clusters are found in the basin.

4.1. Dongsheng uplift ore cluster

The Dongsheng uplift ore cluster is distributed along the northeastern uplift of the basin, and it is a significant ore cluster of the Ordos Basin. For example, ultralarge, large-sized Daying, Nalinggou, and Zaohuohao U deposits, middle-sized Chaidenghao and Nongshengxin U deposits (Zhang et al., 2017), and recently discovered Tarangaole and Wulanxili ore-producing sites are distributed west of the Dongsheng uplift as a ring shape, similar to the extension direction of stratigraphic outcrop lines.

4.1.1. Daying U deposit

In the Daying U deposit, the Zhiluo Formation U-bearing rock series displays typical vertical color zoning. The red zone mainly lies in the central upper part of the Upper Member, Zhiluo Formation. In section, the burial depth of the red zone bottom gradually decreases from northeast toward southwest and varies within 450–550 m (Fig. 4A). Lithologically, the red zone comprises variegated sediments, including purple red, reddish brown sandstone and mudstone intercalated with green medium–coarse grained sandstone, and displays typical dual-structure characteristics.

The green zone mainly lies in the boundary between the bottom of the Upper Member and the top of the Lower Member, Zhiluo Formation, with a thickness varying within 50–90 m (relatively stable) and lithologically dominated by grayish green, shallow green medium–fine grained sandstone with silty mudstone. The sands are poorly connected and mostly occur as lenses.

The gray zone is distributed in the central lower part of the Lower Member, Zhiluo Formation. In section, it varies within 30–100 m in thickness and is lithologically composed of gray medium–coarse sandstone, with hysteretic gravels and boulder clay, coal dust commonly observable at the bottom, and often intercalated with calcareous sandstone. Vertically, the zone is constituted by overlapping of multiple coarse–fine grained positive rhythmic layers, and it is the area's main ore-hosting horizon.

The Daying U deposit spreads NE–SW–SE in plan and occurs as a U-type open toward NE that is approximately 20 km long and 400–2 km wide. In section, the ore bodies are distributed as plates in the lower and center parts of the Lower Member of the Zhiluo Formation.

4.1.2. Nalinggou U deposit

In the Nalinggou U deposit, the red zone of the Zhiluo Formation includes the upper part of the Upper Member of the Middle Jurassic Zhiluo Formation and minor top of the Lower Member of the Zhiluo Formation. From NW toward SE, the sediments have burial depths of 280–320 m and thicknesses of 40–100 m (Fig. 4B). The upper part of the Upper Member of the Zhiluo Formation is lithologically dominated by medium–fine grained sandstone and siltstone and mudstone interbeds cemented with argillaceous material. The mudstone and siltstone are pinkish, purplish, and grayish purple, containing blue to blue-green sandy lumps or nest-like sands, while the sandstone is purple, or grayish green, or grayish white. In the upper Member of the Zhiluo Formation in the Nalinggou and Daying areas, some coarse clastic rocks have been widely denudated. In most drill holes, the conglomerate bed at the bottom of the Middle and Lower Cretaceous strata directly overlies the set of variegated mudstone at the top of the Zhiluo Formation.

The green zone is widely developed in the area and mainly distributed in the central upper part of the Lower Member and the bottom of the Upper Member, Zhiluo Formation. It is relatively stable in thickness, varies toward south from 100 m to 140 m, and is lithologically dominated by grayish green medium–coarse grained sandstone. The bottom of the Upper Member contains alluvial flat sediments such as grayish green siltstone and argillaceous siltstone.

The gray zone is the major ore-bearing rock formation of the deposit area. It principally occurs in the lower part of the Lower Member, Zhiluo Formation, 20–80 m thick, and increases toward south. The lithology is dark gray–shallow gray lithic arkose with low degree of diagenesis and loose structure, and composed of multiple fining-upward sequence. Argillaceous formations are relatively thin or rarely developed, reflecting unstable channels and showing signatures of multiphased river channel sand sedimentation.

The Nalinggou ore bodies spread in plane NE–SW. In section, the U ore bodies are mainly platy and stratiform in the gray zone sands immediately underlain the green zone.

4.1.3. Zaohuohao U deposit

In the Zaohuohao U deposit, the red zone in the Zhiluo Formation is mainly distributed in the central upper part of the Upper Member and has a sedimentary thickness greatly varying from E to W within 10–80 m (Fig. 4C). The lithology is dominated by interbeds of purple red, reddish brown variegated mudstone and argillaceous siltstone, mingled with green sandstone, and cemented with argillaceous matrix. The bottom burial depth gradually decreases from W to E. The upper Cretaceous strata are less preserved. The central eastern section suffered from tectonic uplifting, while the Upper Member of the Zhiluo Formation suffered from intense oxidization and displays complex colors, and the central lower green zone has partially suffered from late-stage oxidization.

The green zone mainly comprises the Upper Member and the upper part of the Lower Member of the Zhiluo Formation, extending 30–50 m thick and stably. The lithology is dominated by grayish green medium–fine grained sandstone with silty mudstone; two to three sand beds

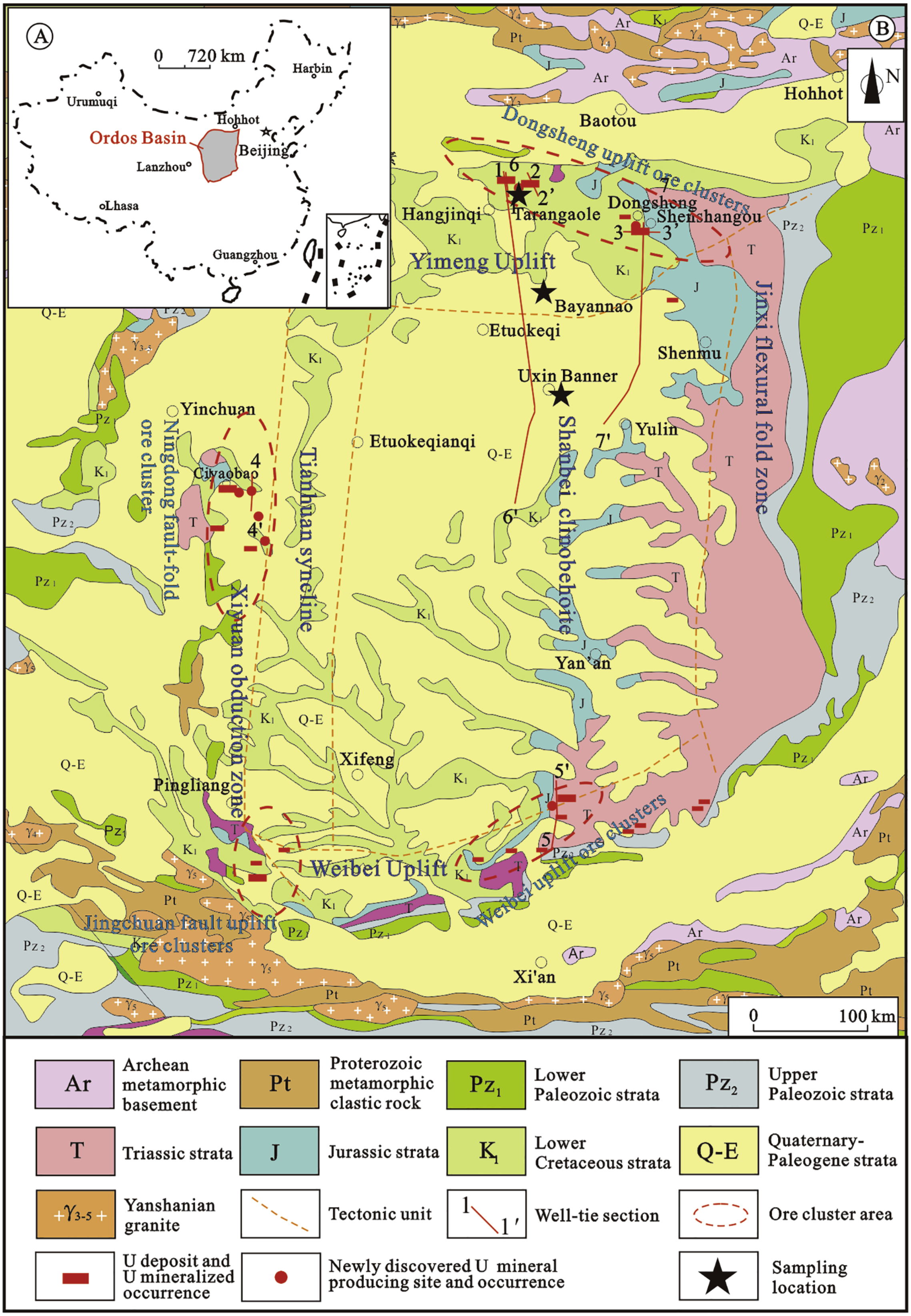

Fig. 3. (A) Generalized map showing the position of the Ordos Basin; (B) Schematic map showing the geology and deposit distribution of the Ordos Basin (modified after Sun et al., 2017). The Lower Paleozoic strata are mainly composed by shale, siliceous rock, etc, while the Upper Paleozoic strata are dominantly composed by carbonate rock and coal-bearing clastic rock. The Triassic strata are composed by terrestrial clastic rock. The Jurassic strata are mainly composed by variegated clastic and carbonate rocks. The Lower Cretaceous strata is typically composed by brick red and variegated clastic rocks, marl, and volcanic rocks. The Cenozoic strata (Q–E) are dominantly composed by sandstone, mudstone, clay, etc.

are generally observable, showing a typical dual structure. The upper part of the Lower Member of the Zhiluo Formation is dominated by grayish green medium–coarse grained sandstone and relatively developed in the central western deposit area.

The gray zone is mainly distributed in the central lower part of the Lower Member of the Zhiluo Formation, with a thickness of 10–30 m. The lithology comprises dark gray-shallow gray lithic arkose, with a loose texture. This zone is composed of multiple upward-fining normal cycles, with very thin or rarely developed argillaceous beds. Especially, the bottom part contains abundant podzolized phytoclasts and organic matter.

The Zaohuohao U ore bodies occur as nearly EW discontinuous bands in plan and mainly as platy and stratiform shapes in section. These ore bodies are distributed at the contact interface between green and gray zones in organic-rich or argillaceous-rich bands.

4.2. Ningdong fault-fold ore cluster

The Ningdong fault-fold ore cluster lies along the western basin margin, including the middle-sized Ciyaobao and Huianbao U deposits, and the newly discovered large–middle-sized Shicaocun, Jinjiaqu, Maiduoshan, and Yangchangwan producing sites in the Ningdong area. The occurrence positions of ore bodies are controlled by NS-trending fault-fold zones and display multiphased, multi-horizon, and flank mineralization characteristics.

In the Ningdong U deposit area, in addition to red, green, and gray zones, green and gray zones are also locally intercalated with yellow lenticular sand beds (Fig. 4D). In the area, NS-trending thrust nappe structures are well developed. The upper strata are seriously denudated, and the Cretaceous strata are basically absent. The red zone mainly occurs in the upper part of the Upper Member of the Zhiluo Formation, and the bottom of the red zone has a burial depth varying within 280–70 m from N to S and a sedimentary thickness varying within 50–120 m. The lithology is dominated by yellowish brown, green, purple red, and reddish brown siltstone and fine grained sandstone, with typically interclacted thin-bedded medium grained feldspar–quartz sandstone and mudstone. The sand–mudstone interbedded structure is typical.

The green zone is widely distributed within the area and mainly developed in the central upper part of the Upper Member and the Lower Member of the Zhiluo Formation. The lithology is dominated by grayish green siltstone and fine grained sandstone, with gray thin-bedded medium grained sandstone. The thickness varies greatly within 130–350 m, and the green zone in Drill Hole SCZK03 in the Shicaocun area has an accumulative thickness of up to 350 m. Of the zone, two sets of yellow lenticular sand beds are developed with thicknesses of 3–5 m and located at the bottom of the Upper Member and the central part of the Zhiluo Formation, respectively.

The gray zone is mainly developed in the central lower part of the Lower Member of the Zhiluo Formation, with a thickness of 50–180 m. The lithology is dominated by gray, grayish white medium–coarse grained sandstone and is the main ore-bearing horizon. At the upper contact of ore bodies, one bed of yellow (with red) sands is observable. This bed is 2–5 m thick, relatively stable, and distributed in the Shicaocun area, and can be considered a prospecting indicator of the area.

The Ningdong U ore bodies are controlled by NS-trending reverse fault-fold zones and generally spread N–S. The ore bodies are mainly hosted in the Lower Member sands of the Middle Jurassic Zhiluo and Yan'an Formations. The ore bodies strike consistently with anticlinal axes. Vertically, the ore bodies contain multiple beds and mainly occur in the grayish white coarse sandstone at the bottom of the Zhiluo Formation. These ore bodies occur as stratiform and platy shapes, with minor lenses.

4.3. Weibei uplift ore cluster

The Weibei uplift ore cluster lies along the eastern basin edge. It mainly includes the middle–small-sized Shuanglong and Diantou U deposits, the Jiaoping- and Miaowan-mineralized occurrences, and the Huangling mineral-producing site, which is newly discovered. In plan, the cluster occurs in the northern Weibei uplift and the Tongchuan uplift tectonic slope.

In the Huangling U deposit area, the Zhiluo Formation is dominated by red and gray zones, wherein the green zone is thin but relatively stable (Fig. 4E). The burial depth from NE toward SW gradually decreases. The red zone is mainly distributed in the Upper Member of and the top of the partial Lower Member of the Zhiluo Formation, with a relatively stable sedimentary thickness of 80–100 m. The Upper Member of the Zhiluo Formation is dominated by purple red mudstone

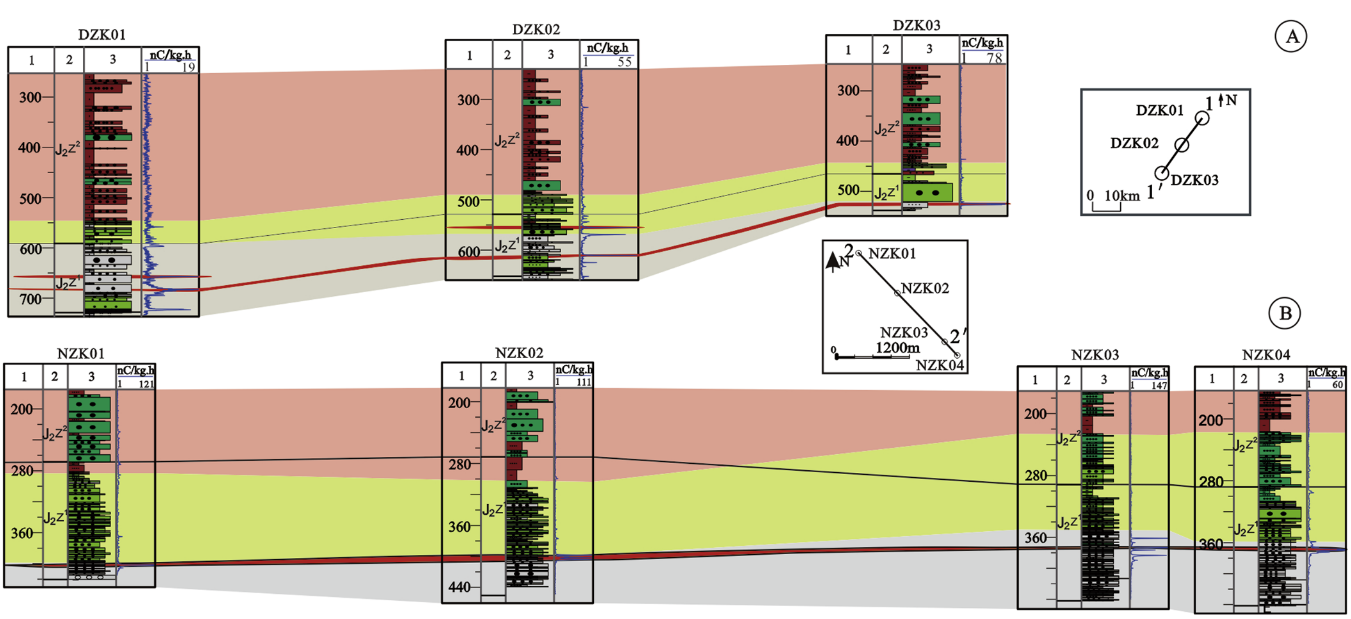

Fig. 4. Well-tie sections of typical U deposits within the Ordos Basin. (A) 1–1′well-tie section, Daying U deposit; (B) 2–2′well-tie section, Nalinggou U deposit; (C) 3–3′well-tie section, Zaohuohao U deposit; (D) 4–4′well-tie section, Ningdong U deposit; (E) 5–5′well-tie section, Huangling U deposit area.

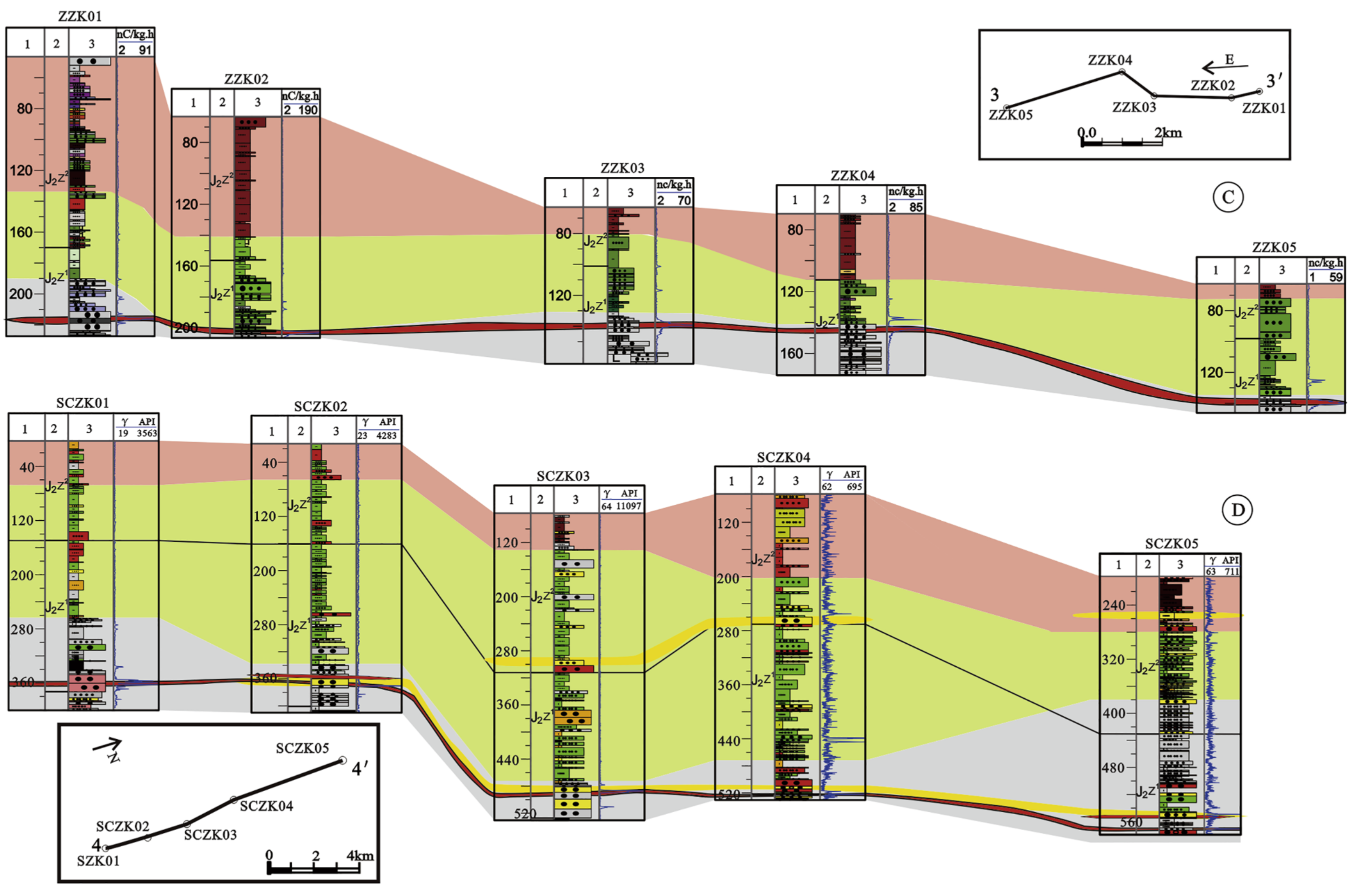

Fig. 4. (*continued*)

and argillaceous siltstone, with thin-bedded grayish green, reddish brown variegated sandstone and gypsum. R66 Drill hole is close to the Weibei Uplift, and the Lower Member of the Zhiluo Formation has mostly been oxidized.

The green zone is mainly distributed in the upper part of the Lower Member of the Zhiluo Formation. It is lithologically composed of grayish green mudstone and argillaceous siltstone with purple red sandstone. The thickness varies within 10–30 m, which is small but relatively stable. This zone is often used as a marker of the Upper and Lower Sub-members of the Lower Member of the Zhiluo Formation in the area.

The gray zone is distributed in the central lower part of the Lower Member of the Zhiluo Formation, with a thickness of 30–50 m. The lithology is dominantly shallow gray or grayish white medium–fine grained sandstone, with a high degree of siliceous cementing. The lithology is rich in organic lamina, with oil spots and traces observable in local sandstone, and is in scouring contact with the underlying strata.

The Huangling U ore bodies in plan occur as NE-SW-trending and discontinuous bands, whereas those in section mainly occur as platy and stratiform configuration with minor lenses. There are two major mineralization beds. The first bed of U ore bodies (mineralized bodies) lies in the central green zone of the Lower Member, while the lower ore bodies lie in the gray zone channel sands.

5. Color variation characteristics of rocks within the basin

Research in sedimentary environments with a basin as the unit is conducted to compare and study the similarities and differences in sedimentary environments of ore-forming areas and ore barren areas. Results can be used to distinguish ore-forming settings and relics left by mineralization.

Two large NS-trending representative ore clusters crossed sections with complete data were selected for studies of color variations (6-6′ and 7-7′; Fig. 5). Section 6-6′ starts from the northern Daying U deposit in the Yimeng Uplift and southwards to the end at the Uxin Banner coalfield exploration area of the Yishan Slope in the central basin, extending 280 km from S to N (Fig. 5A). Section 7-7′ starts from Gaojialiang in northern Zaohuohao and southwards to end at the Balasu coal field exploration area in Yulin, extending nearly 200 km from S to N (Fig. 5B). From the scale of the entire basin, comprehensively elaborate analysis to the variation characteristics of rock colors of U-bearing rock series was carried out by compiling the macroscopic characteristics of field core.

5.1. Vertical variation characteristics of colors in Section 6-6′

In section, from N to S, the red zone is mainly distributed in the Upper Member of the Zhiluo Formation, and its color is mainly variegated. The thickness gradually decreases within 300–50 m, and the lithology gradually transitions from medium–fine grained sandstone to fine sandstone and argillaceous siltstone. The northern part of the green zone mainly lies in the lower part of the Upper Member and the upper part of the Lower Member of the Zhiluo Formation, with a thickness of 50–90 m. The lithology is dominated by medium–fine grained sandstone, locally with purple red mudstone. Lateral sediments along river channels result into fine grained sediments successively overlapping above coarse sediments, forming multiple cycles of coarse–fine grained, dual-structure sedimentary sequence. Southwards, the zone mainly occurs in the central lower part of the Lower Member of the Zhiluo Formation, with a thickness of 150–300 m that gradually increases. The gray zone lies in the lower part of the Lower Member of the Zhiluo Formation and varies greatly in thickness (20–100 m thick in the

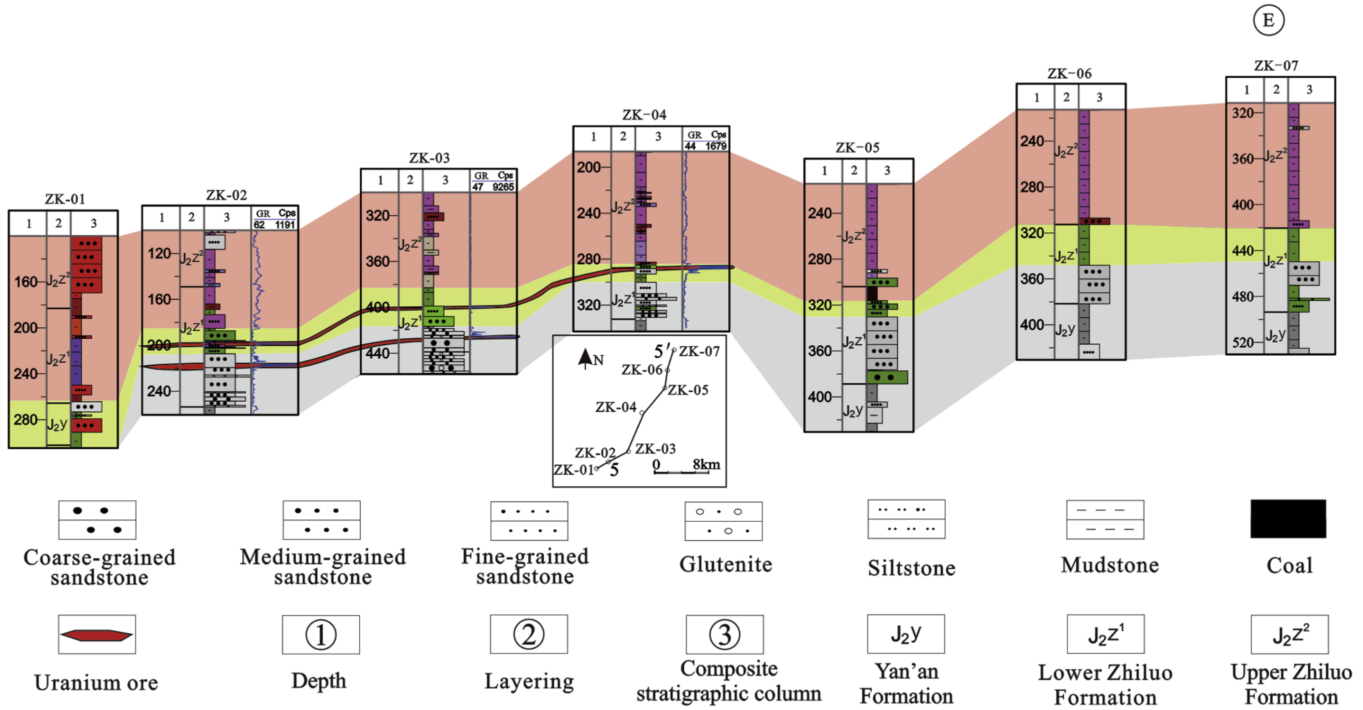

Fig. 4. (*continued*)

northern Daying area). Medium–coarse grained sandstone (containing gravels) is developed, and the Lower Member sandstone beds and thickness are in typical positive correlation. The stratal thickness is small, the number of sandstone beds is low, the sand-bearing percentage is high, and braided river sedimentary systems are developed. In the southern Uxin Banner area, which is relatively far from the provenance area, the Lower Member gray zone of the Zhiluo Formation is lithologically dominated by medium-fine sandstone, with siltstone developed locally.

5.2. Vertical variation characteristics of colors in Section 7-7′

The red zone mainly occurs in the Upper Member of the Zhiluo Formation, with a thickness gradually decreasing from the northern Zaohuohao southwards the Chahasu area. The strata in northern Gaojialiang and Zaohuohao deposit areas are similar to those in the Daying area. As this study area was affected by tectonic uplifting, the Cretaceous strata have been mostly denudated, and the Zhiluo Formation has a small burial depth and a thickness of 30–80 m. In the southern Yulin area, the Upper Member of the Zhiluo Formation has no observable red zone.

From north to south of the green zone, its spatial distribution location varies greatly, while its thickness varies within 20–180 m. The northern green zone mainly occurs in the Lower Member of the Zhiluo Formation. The green zone in the area suffered from late-stage oxidation and varies weakly in thickness. The southern green zone is distributed in the Upper and Lower Members of the Zhiluo Formation, and a thick green zone is observable in the Zhidan Group. In the southern Chahasu area, the Lower Member of the Zhiluo Formation is a delta plain sedimentary system. The Lower Member of the Zhiluo Formation is basically a green zone, with a thickness of 30–100 m. The lithology is mainly composed of fine grained sandstone and siltstone. In the Yulin area at the southern end of the section, the Lower and Upper Members of the Zhiluo Formation are dominated by medium–fine grained sandstone, and their sedimentary facies belong to a meandering river sedimentary system. The color basically exhibit a green tone with small red interbeds locally.

The northern part of the gray zone lies mainly in the central lower part of the Lower Member of the Zhiluo Formation, wherein the thickness is larger in the Zaohuohao area than in other sections. Its southern part mainly occurs in the thin-bedded glutenite formation at the bottom of the Lower Member of the Zhiluo Formation.

6. Geochemical characteristics reflected by color zoning

Geochemical characteristics of sedimentary rocks are good indicators for deducing the paleo-environment and paleoclimate of a sedimentary period. Various major and trace element characteristics of sedimentary rocks or sediments were investigated to trace a paleo-sedimentary environment to understand the sedimentary characteristics (Spirakis, 1996; Min et al., 2005a,b; Xiong and Xiao, 2011; Liu et al., 2018).

6.1. Sedimentary environment reflected by vertical color variation in a deposit

This round of U deposit survey results, in combination with previous research data of different color strata (Table 1), revealed that the Fe^{3+}/Fe^{2+} ratio, whole S content, TOC content, and U content in the peripheral deposits of the basin show typical differences vertically, whereas environmental indexes of different deposit areas show similar characteristics in the same color intervals/zones (Fig. 6). Thus, geochemical zoning and color zoning are in good correlation. In general, Fe^{3+}/Fe^{2+} ratio is an indicator for distinguishing redox environment. If the ratio is far less than 1, it hints a reducing environment. When the ratio is slightly less than 1, it indicates a weak reducing environment. Similarly, ratio value of 1, slightly greater than 1, far greater than 1 represents neutral environment, weak oxidation environment and oxidation environment, respectively. Uranium is usually behaved as soluble under the oxidation condition and insoluble under the reduction condition during sedimentation. Low whole S content and TOC content imply that voluminous of low valence sulfur and organic matter has been consumed by oxidation. Consequently, the low contents of whole S and TOC could denote a oxidation environment, and conversely, it

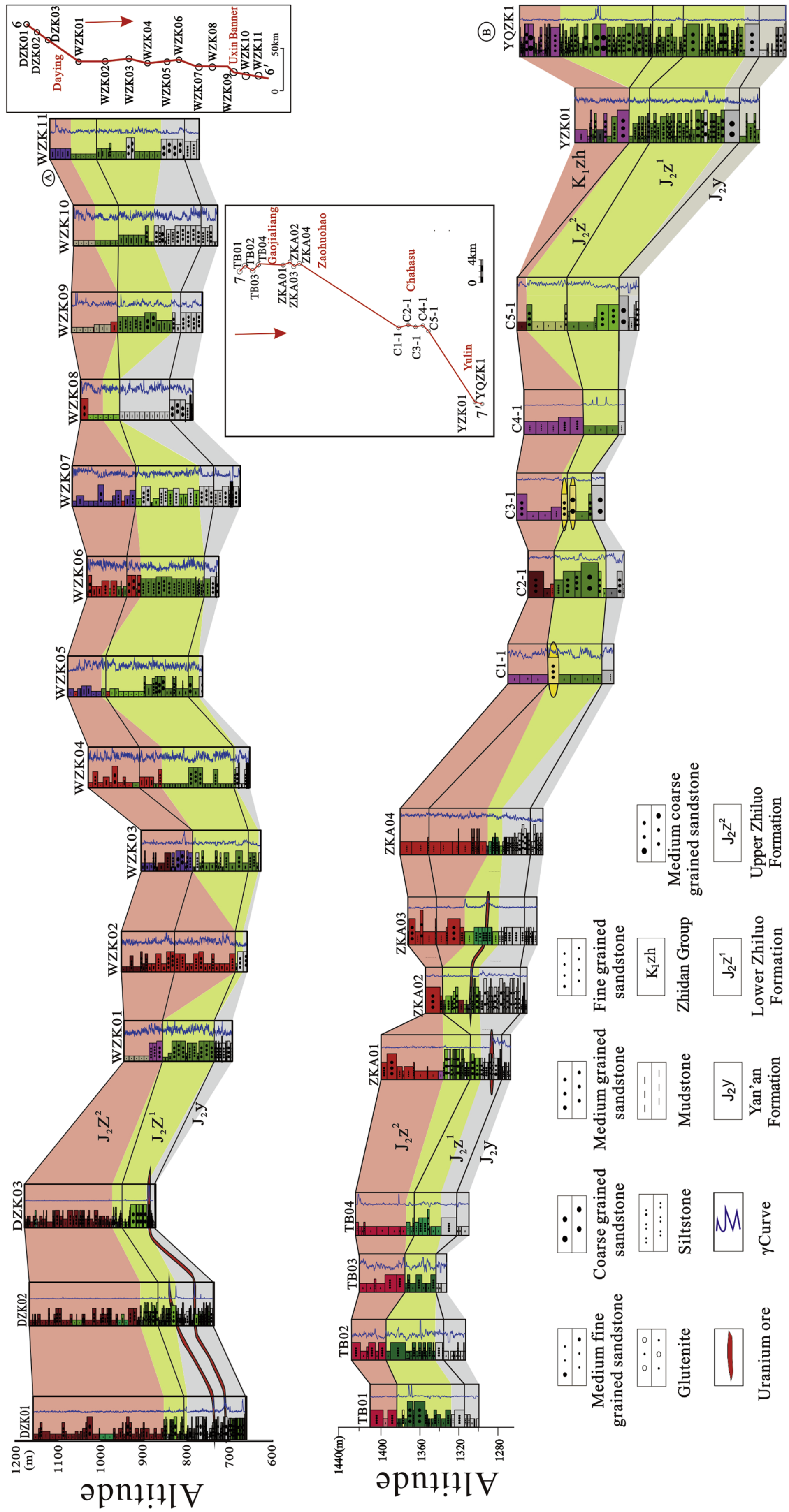

Fig. 5. The 6–6′ (A) and 7–7′(B) Drill hole well-tie sections along the northeastern edge of the Ordos Basin.

Table 1
Geochemical parameters of various color zones in the Zhiluo Formation in different deposit areas.

Color Zoning	Daying deposit area				Nalinggou deposit area				Zaohuohao deposit area	
	Red zone	Green zone	Ore Block	Gray zone	Red zone	Green zone	Ore Block	Gray zone	Red zone	Green zone
Average ω(U) (μg/g)	7.84 (20)	17.79 (46)	1734.74 (38)	26.77 (72)	4.19 (5)	27.84 (21)	769.48 (29)	26.61 (51)	4.2 (4)	3.67 (7)
Average Fe^{3+}/Fe^{2+} ratio	1.11 (15)	0.51 (43)	1.11 (31)	0.48 (60)	1.63 (5)	0.51 (34)	0.8 (19)	0.56 (25)	5.76 (4)	1.15 (7)
Average ω(whole S)/%	0.11 (10)	0.03 (20)	0.39 (28)	0.42 (28)	0.01 (5)	0.13 (20)	0.15 (25)	0.38 (26)	0.03 (4)	0.02 (7)
Average ω(TOC)/%	0.04 (3)	0.18 (11)	0.59 (21)	0.3 (24)	0.3 (5)	0.12 (35)	0.31 (24)	0.1 (29)	0.08 (4)	0.03 (7)

Color Zoning	Zaohuohao deposit area		Ningdong deposit area				Huangling deposit area			
	Ore Block	Gray zone	Red zone	Green zone	Ore Block	Gray zone	Red zone	Green zone	Ore Block	Gray zone
Average ω(U) (μg/g)	115.97 (8)	5.55 (6)	2 (27)	4 (58)	234 (37)	45 (72)	–	–	–	–
Average Fe^{3+}/Fe^{2+} ratio	2.14 (8)	1.48 (6)	2.2 (27)	0.94 (58)	1.1 (37)	0.59 (72)	5.28 (5)	0.55 (14)	1 (16)	0.37 (39)
Average ω(whole S)/%	0.63 (8)	0.44 (6)	0.02 (27)	0.39 (58)	0.7 (37)	0.7 (72)	0.42 (5)	0.06 (14)	0.48 (16)	0.25 (39)
Average ω(TOC)/%	0.26 (8)	0.09 (6)	0.03 (27)	0.2 (58)	0.6 (37)	0.4 (72)	0.11 (5)	0.1 (14)	1.16 (16)	0.25 (39)

Note: 7.84 (20) denotes that the total number is 20, and the average is 7.84. Data of Daying and Nalinggou deposit areas are from Li et al. (2016). Data of Zaohuohao deposit area are from Hu (2010). Data of Ningdong and Huangling deposit areas are from the Ningdong U Deposit Survey Results Report, and the Survey Results Report of U deposits in Huangling area, Shaanxi Province, respectively.

represents reducing environment (Zhang et al., 2016).

1) Red zone: The average Fe^{3+}/Fe^{2+} ratios range within 5–6 in the Huangling deposit along the southeastern margin and in the Zaohuohao deposit along the northeastern margin. These ratios are greatly higher than those of other deposit areas because most of the Upper Zhiluo Formation has been denudated, and ore horizons are shallowly buried in the area. The average whole S contents range within 0.01%–0.02%, wherein the whole S content of the red zone in the Huangling area differs weakly from and is slightly higher than that of other areas. This difference may be due to obvious oil and gas reduction of the area. Shallow intervals of drill holes show many oil spots and gypsum. The TOC contents are obviously low and range within 0.03%–0.4%. The average U contents range within $1–10 \times 10^{-6}$, indicating typical oxidation environment signatures.
2) Green zone: The Fe^{3+}/Fe^{2+} ratios, whole S contents, TOC contents, and U contents of the green zone vary weakly among different deposits within the basin compared to those of the red zone. However, the Fe^{3+}/Fe^{2+} ratios gradually decrease, and the whole S, TOC, and U contents gradually increase toward the ore horizon. In general, the green zone displays signatures of a weak reduction environment.
3) Ore horizon: This horizon mainly occurs in the gray zone, and part of the ore horizon is developed in the green zone. The most obvious characteristics of the ore horizon are the highest TOC and U contents when compared with those of other rock formations. Thus, the content of organic carbon is positively correlated with the U content in sandstone.
4) Gray zone: The Fe^{3+}/Fe^{2+} ratios, TOC content, and U content decrease correspondingly, whereas the whole S content increases. The gray primary sandstone is typically characterized by the highest whole S content, thereby indicating that this zone has not suffered from late-stage oxygenated water reworking, retains primary characteristics of sandstone, and represents reduction environment characteristics.

   In summary, within Ordos Basin, the red zone basically represents an oxidation environment, the green zone represents a weak reduction environment, and the gray zone rich in pyrite represents a strong reduction environment.

6.2. Sedimentary environment reflected by vertical color variation within the basin

Previous research has revealed geochemical characteristics, provenance, and paleo-sedimentary environment restoration by using mudstone and fine grained sandstone samples from the Yan'an and Zhiluo Formations (Lei et al., 2017; Zhang et al., 2016; Sun et al., 2017). Researchers believe that the coal-forming and diagenetic stage after the Yan'an Formation deposition formed a regional primary reducing zone, while the red zone in the Upper Member of the Zhiluo Formation was in an intense oxidizing environment (Zhang et al., 2016). Dissolubility of some trace elements is controlled by the reducing/oxidizing state of an sedimentary environment, and trace elements easily migrate toward reducing waters and sediments and precipitate as sulfides by authigenic accumulation (Francois, 1988; Calvert and Pedersen, 1993; Russell and Morford, 2001; Algeo and Maynard, 2004; Tribovillard et al., 2006), such as U, Th, V, Cr, Fe, Co, Cu, Zn, and Mo. Cr, U, and V are highly charged ions that can be reduced and accumulate under oxygen-deficient denitration environments (Timofeev et al., 2018), whereas Ni, Cu, Co, Zn, Cd, and Mo mainly accumulate in sulfate reduction environments. Th and U show similar geochemical properties under reducing conditions and differ greatly under oxidizing conditions (Mclennan and Taylor, 1979). Therefore, contents or ratios of these elements are often considered significant indexes for the discrimination of oxidation and reduction environments.

Criteria for discrimination: V/Cr, Ni/Co, and U/Th ratios that

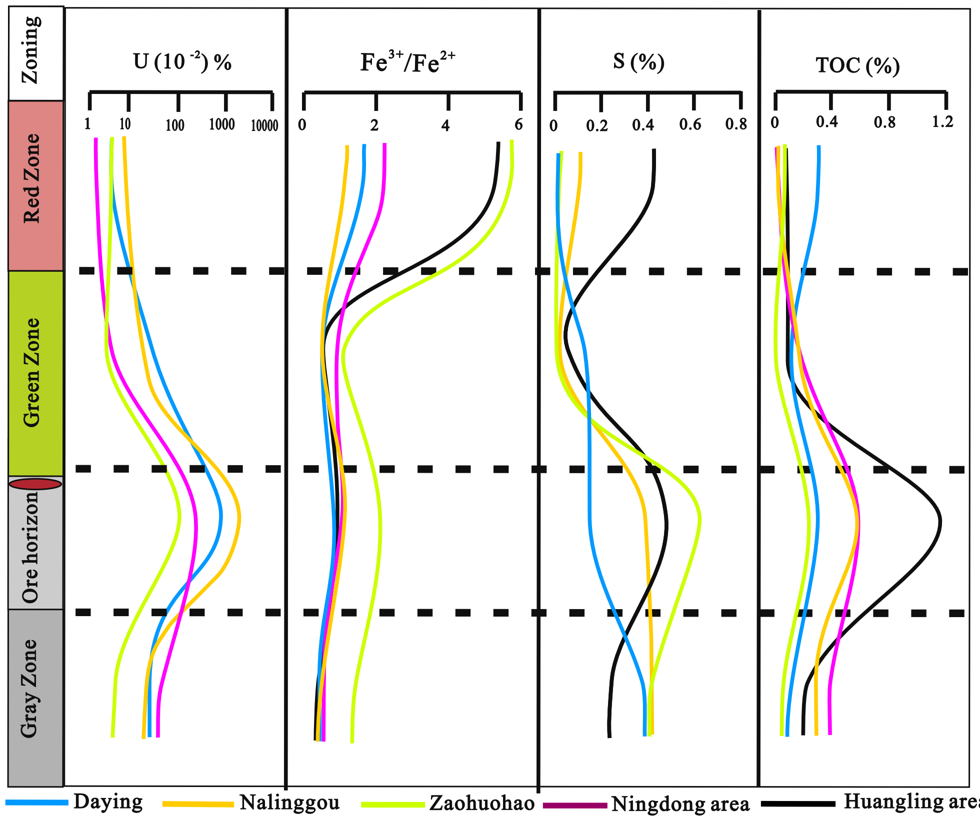

Fig. 6. Geochemical zoning characteristics of key deposit areas within the Ordos Basin.

are > 4.25, > 7, and > 1.25, respectively, indicate sub-oxidizing, oxygen-deficient (reducing) environments. While those that are less than 2, 5, and less than 0.75, respectively, corresponding to oxidizing environments, and those between these values represent oxygen-poor environments (Jones and Manning, 1994). The V/(V + Ni) ratio is often used to discriminate the degree of layering of water at the sediment bottom (Hatch and Leventhal, 1992). The V/(V + Ni) ratio of less than 0.84 indicates an intense layering and oxygen-deficient environment with H_2S, 0.6–0.84 indicates moderate layering, and 0.4–0.6 indicates weak layering. The Cu/Zn ratio varies with medium oxygen fugacity; a high value indicates a reduction environment, and a low value indicates an oxidation environment (Dypvik, 1984).

To discuss the geochemical characteristics and sedimentary environment variations from the basin margin to the center, samples from Zhiluo Formation with different colors from several drill holes of the Tarangaole U deposit area, Bayannao–Naimada U anomaly, and Uxin Banner ore barren area were selected. Sampling locations are shown in Fig. 3. Moreover, major and trace elements were tested with results listed in Table 2. The results demonstrated that ratios of the aforementioned elements show similarities in the vertical variations of different color zones among the three different areas, and a comparison of vertical evolution curves revealed the following results (Fig. 7):

1) Red zone: The average Fe^{2+}/Fe^{3+}, Ni/Co, and V/Cr ratios of the three areas vary within 0.48–0.53, 1.69–2.12, and 1.0–1.36, respectively. The average V/(Ni + V), U/Th, and Cu/Zn ratios vary within 0.73–0.78, 0.16–0.39, and 0.26–0.39, respectively. From the basin margin toward the center, these ratios indicate the red color of the Zhiluo Formation shows an oxidation environment and moderate layering of water at the bottom during sediment deposition. The Cu/Zn ratios show a weakly oxidizing environment. Compared with the inner basin, the Tarangaole area shows a higher degree of oxidation.
2) Green zone: In the three areas, the average Fe^{2+}/Fe^{3+}, Ni/Co, and V/Cr ratios range within 0.71–1.44, 1.89–2.05, and 1.33–1.53, respectively. Moreover, the average V/(Ni + V), U/Th, and Cu/Zn ratios range within 0.76–0.83, 0.22–28.8, and 0.26–0.46, respectively. The green zone is of stronger reduction degree than the red zone. The upper green and red zones in the Tarangaole area show that the formations have high U contents, which is possibly because the epigenetic U-rich supergene fluid reaction and reducing fluids lead to a large variation range in U/Th ratios. Some of the samples have high Fe^{2+} contents, which hindered the indication to sedimentary environments. In the other two areas, the U/Th ratio curves vertically change weakly. Thus, related parameters generally reflect that the green zone indicates a weak reducing environment.
3) Gray zone: Given that the Zhiluo Formation gray zone lies in the lower part of the Lower Member, the lithology is mainly medium–coarse grained sandstone with minor fine grained clasts. Sediments components are easily affected by exotic provenance. In this work, a few fine grained samples were collected, which may not precisely reflect the sedimentary environment of paleowater. However, according to the aforementioned ratios of elements, the average Fe^{2+}/Fe^{3+} ratios range within 0.69–1.06, the average Ni/Co ratios range within 1.62–1.84, the average V/Cr ratios range within 1.53–1.63, the average V/(Ni + V) ratios range within 0.77–0.82, the average U/Th ratios range within 0.22–7.05, and the average Cu/Zn ratios range within 0.12–0.42.

Hence, from the deposit areas along the basin margin to the ore barren areas inside the basin, from up downwards, the vertical "red–-green–gray" geochemical characteristics of different color zones reflect a paleo-sedimentary environment transition from "oxidation to weakly reduction to reduction." The same color zones show weakly differed lateral geochemical signatures.

Above all, this study believes that color variation is the most visual

Table 2
Representative major and trace concentrations of rocks from the Zhiluo Formation in the central north of the Ordos Basin.

Sample No.	Sample location (depth)	Rock type	FeO	Fe_2O_3	Ni	Co	V	Cr	U	Th	Cu	Zn	Fe^{2+}/Fe^{3+}	Ni/Co	V/Cr	V/(Ni + V)	U/Th	Cu/Zn
			wt.%		ppm													
Tarangaole Area																		
UZK2-23	290.45 m	Reddish brown coarse sandstone	0.73	2.7	10.2	6.77	32.2	38.2	1.6	2.72	5.7	17.6	0.3	1.51	0.84	0.76	0.59	0.32
UZK2-26	320 m	Reddish brown mudstone	0.72	6.23	42.2	26.1	103	83.4	3.75	11.2	62.3	90.3	0.13	1.62	1.24	0.71	0.33	0.69
UZK2-28	343 m	Green mudstone	3.2	3.35	18.8	19.4	58.9	92.1	4.98	7.08	13.6	26.8	1.06	0.97	0.64	0.76	0.7	0.51
UZK2-31	377 m	Grayish green medium grained sandstone	1.7	2.26	37.4	19.4	84.6	88.6	2.19	9.64	16.5	77.4	0.84	1.93	0.95	0.69	0.23	0.21
UZK2-34	391.3 m	Reddish brown mudstone	1.52	6.2	49	21.9	122	117	3.14	14	24.5	94.8	0.27	2.24	1.04	0.71	0.22	0.26
UZK2-36	407.59 m	Dark purple mudstone	4.42	8.24	44.9	24	126	98.5	3.91	16.1	37.7	102	0.6	1.87	1.28	0.74	0.24	0.37
Average			**2.05**	**4.83**	**33.75**	**19.6**	**87.78**	**86.3**	**3.26**	**10.12**	**26.72**	**68.15**	**0.53**	**1.69**	**1**	**0.73**	**0.39**	**0.39**
UZK2-43	480.98 m	Grayish green coarse sandstone	2.68	2.77	17.1	7.9	67.9	59.3	11.9	10.3	14.1	46.4	1.08	2.16	1.15	0.8	1.16	0.3
UZK4-1	616.4 m	Shallow grayish green medium–coarse grained sandstone	1.38	4.6	17.8	9.01	74.3	69.7	14.4	6.66	16.4	60.5	0.33	1.98	1.07	0.81	2.16	0.27
UZK4-2	615.4 m	Shallow grayish green medium–coarse grained sandstone	2.38	0.45	11.5	5.88	145	58	1.97	6.24	7.95	32.1	5.88	1.96	2.5	0.93	0.32	0.25
UZK4-3	620.5 m	Grayish white fine sandstone	1.21	4.44	17	8.78	82.4	68.7	29	6.08	14.4	39.8	0.3	1.94	1.2	0.83	4.77	0.36
UZK4-4	624.7 m	Grayish green fine sandstone (ore block)	1.39	0.95	11.3	6.82	68.8	37.5	166	4.69	8.7	28.5	1.63	1.66	1.83	0.86	35.39	0.31
UZK4-5	626.1 m	Grayish green fine sandstone (ore block)	0.76	1.83	21.3	12.2	75	56.9	1280	8.38	11.3	60.8	0.46	1.75	1.32	0.78	152.74	0.19
UZK4-6	627.15 m	Grayish green medium–fine sandstone	0.68	0.84	9.63	4.58	34.6	29.3	14.6	3.63	6.63	37.5	0.9	2.1	1.18	0.78	4.02	0.18
UZK4-7	631 m	Grayish green fine sandstone (ore block)	0.59	0.67	10.3	6.46	46.6	23	100	3.35	5.43	22.9	0.98	1.59	2.03	0.82	29.85	0.24
Average			**1.38**	**2.07**	**14.49**	**7.7**	**74.33**	**50.3**	**202.23**	**6.17**	**10.61**	**41.06**	**1.44**	**1.89**	**1.53**	**0.83**	**28.8**	**0.26**
UZK4-9	642.1 m	Grayish white medium–coarse sandstone	0.84	0.96	10.7	7.12	50	34.5	44.4	3.82	6.69	23.2	0.97	1.5	1.45	0.82	11.62	0.29
UZK4-10	643.19 m	Grayish white medium–coarse sandstone	0.27	1.48	10.2	7.4	36.1	28.8	3.98	3.45	6.63	25.3	0.2	1.38	1.25	0.78	1.15	0.26
UZK27-1	621.3 m	Grayish white fine sandstone	2.22	1.68	20.2	11.3	189	78.4	4.66	3.24	13.1	52.2	1.47	1.79	2.41	0.9	1.44	0.25
UZK27-2	622.3 m	Grayish white fine sandstone	1.51	1.99	16.9	9.7	64.4	49.1	1.29	3.52	11.8	33.7	0.84	1.74	1.31	0.79	0.37	0.35
UZK27-3	6223.3 m	Grayish white medium sandstone	1.46	0.96	9.99	5.94	45.5	34.6	53.5	3.11	7.8	26.9	1.69	1.68	1.32	0.82	17.2	0.29
UZK27-4	624.5 m	Grayish white medium–coarse sandstone	1.02	0.98	8.4	5.16	31.4	22.2	18.7	1.78	4.77	14.3	1.16	1.63	1.41	0.79	10.51	0.33
Average			**1.22**	**1.34**	**12.73**	**7.77**	**69.4**	**41.27**	**21.09**	**3.15**	**8.47**	**29.27**	**1.06**	**1.62**	**1.53**	**0.82**	**7.05**	**0.3**
Bayannao-Naimadai area																		
U6-3-Z1	40.5 m	Brownish red siltstone	0.67	1.89	11.1	6.39	32.1	33.5	1.21	11.8	7.68	37.4	0.39	1.74	0.96	0.74	0.1	0.21
U6-3-Z2	75.4 m	Brownish red medium grained sandstone	1.91	2.13	9.77	7.38	47.9	42.9	1.59	13.3	13	72.4	1	1.32	1.12	0.83	0.12	0.18
U6-3-Z3	103.7 m	Brownish red mudstone	0.76	3.03	21.2	11.4	48.2	54.2	1.5	10.7	16.3	63.1	0.28	1.86	0.89	0.69	0.14	0.26
U6-3-Z4	172.6 m	Brownish red medium sandstone	0.58	2.96	11.9	8.24	59.1	35	1.2	6.23	23.3	40.7	0.22	1.44	1.69	0.83	0.19	0.57
U6-3-Z5	218.7 m	Brownish red coarse sandstone	0.59	2.34	11.8	7.56	46.1	29	1.44	8.06	17.6	42.2	0.28	1.56	1.59	0.8	0.18	0.42
U6-3-Z6	290.8 m	Brownish red coarse sandstone	1.59	2.15	8.01	6.4	39.4	31	1.31	9.67	14.3	55.9	0.82	1.25	1.27	0.83	0.14	0.26
U6-3-Z7	468.4 m	Brownish red coarse sandstone	1.24	2.04	8.61	6.69	37.4	53.2	1.5	8.79	9.93	50	0.68	1.29	0.7	0.81	0.17	0.2
U6-3-Z8	379.1 m	Brownish red medium sandstone	1.34	2.55	11.3	7.91	47	53.4	1.77	8.55	11	49.6	0.58	1.43	0.88	0.81	0.21	0.22
U6-3-Z9	452 m	Brownish red medium sandstone	0.82	1.32	7.05	4.88	20	19.4	0.9	5.59	5.28	39.6	0.69	1.44	1.03	0.74	0.16	0.13
U6-3-Z10	507 m	Brownish red mudstone	0.26	4.16	17.8	9.77	50.8	52.6	1.14	7.38	12.6	48	0.07	1.82	0.97	0.74	0.15	0.26
U6-3-Z11	546.7 m	Brownish red coarse sandstone	0.35	4.5	19.4	11.4	51.4	59.6	2.03	9.47	13.6	49.3	0.09	1.7	0.86	0.73	0.21	0.28
U12-2-Z3	520.5 m	Brownish red coarse sandstone	1.1	1.83	10.3	6.61	32.1	23.6	1.22	8.1	6.49	35.6	0.67	1.56	1.36	0.76	0.15	0.18
Average			**0.93**	**2.58**	**12.35**	**7.89**	**42.63**	**40.62**	**1.4**	**8.97**	**12.59**	**48.65**	**0.48**	**1.53**	**1.11**	**0.78**	**0.16**	**0.26**
U6-3-Z12	601.5 m	Grayish green mudstone	1.35	8.35	49.5	25.8	138	116	2.51	19.2	56	130	0.18	1.92	1.19	0.74	0.13	0.43
U6-3-Z13	606 m	Grayish white fine grained sandstone	2.41	5	50.8	24.2	112	91	1.49	18.8	40.8	130	0.54	2.1	1.23	0.69	0.08	0.31
U6-3-Z14	614.1 m	Grayish green mudstone	2.54	4.05	28.3	12	264	77.7	4.5	13.8	59.6	97.6	0.7	2.36	3.4	0.9	0.33	0.61
U6-3-Z15	630 m	Grayish green mudstone	3.55	3.37	40.6	19	104	94.6	2.68	15	33.4	95.7	1.17	2.14	1.1	0.72	0.18	0.35
U6-3-Z16	632.5 m	Grayish green mudstone	2.94	4.19	47.2	21.2	117	100	2.69	20.3	45.4	124	0.78	2.23	1.17	0.71	0.13	0.37
U12-2-Z4	667.3 m	Grayish green medium sandstone	0.64	1.31	9.77	5.75	45.2	36.1	1.55	4.98	5.78	23.5	0.54	1.7	1.25	0.82	0.31	0.25
U12-2-Z5	681.7 m	Grayish green medium sandstone	2.8	2.9	32.3	16.6	115	136	5.29	13.2	24.4	82.9	1.07	1.95	0.85	0.78	0.4	0.29

(*continued on next page*)

Table 2 (*continued*)

Sample No.	Sample location (depth)	Rock type	FeO	Fe_2O_3	Ni	Co	V	Cr	U	Th	Cu	Zn	Fe^{2+}/Fe^{3+}	Ni/Co	V/Cr	V/(Ni + V)	U/Th	Cu/Zn
			wt.%		ppm													
Average			**2.32**	**4.17**	**36.92**	**17.79**	**127.89**	**93.06**	**2.96**	**15.04**	**37.91**	**97.67**	**0.71**	**2.05**	**1.46**	**0.77**	**0.22**	**0.37**
U12-2-Z1	664.27 m	Grayish white medium sandstone	0.45	1.31	10.5	5.81	34.6	41.4	0.88	3.26	3.37	21.9	0.38	1.81	0.84	0.77	0.27	0.15
U12-2-Z2	659.79 m	Grayish white medium sandstone	0.84	0.93	13	8.2	63.6	28.2	0.72	4.18	5.74	63	1	1.59	2.26	0.83	0.17	0.09
Average			**0.65**	**1.12**	**11.75**	**7.01**	**49.1**	**34.8**	**0.8**	**3.72**	**4.56**	**42.45**	**0.69**	**1.7**	**1.55**	**0.8**	**0.22**	**0.12**
Uxin Banner area																		
B3311-18	581 m	Purple red mudstone	0.57	8.83	44.7	19.9	132	101	1.76	9.72	19.6	73.4	0.07	2.25	1.31	0.75	0.18	0.27
B3311-5	590.5 m	Purple red mudstone	0.6	4.7	31.3	14.6	68.4	67.5	1.14	7.62	9.86	53	0.14	2.14	1.01	0.69	0.15	0.19
B3311-6	596.5 m	Variegated siltstone	1.47	8.8	45.4	21.1	157	98.5	1.56	10	35.2	86.1	0.19	2.15	1.59	0.78	0.16	0.41
B3311-7	604 m	Green siltstone	1.66	4.76	52.2	19.9	123	103	2.25	9.6	17.8	64.2	0.39	2.62	1.19	0.7	0.23	0.28
B3311-3	620 m	Variegated sandstone	1.48	7.15	37	16.9	112	86.2	1.85	8.82	19.4	65	0.23	2.19	1.3	0.75	0.21	0.3
B3311-21	621 m	Green silty mudstone	4.16	4.1	55.1	26.7	150	121	1.65	11.5	50.2	104	1.13	2.06	1.24	0.73	0.14	0.48
B3311-13	624.4 m	Green siltstone	3.07	4.88	46.2	22.1	145	104	1.35	8.44	36.1	83	0.7	2.09	1.39	0.76	0.16	0.43
B3311-11	628.3 m	Green siltstone	2.95	3.88	44.3	28.4	127	84.7	1.34	7.7	50.4	88.4	0.84	1.56	1.5	0.74	0.17	0.57
B3311-16	629 m	Green mudstone	5.07	4.23	59.1	29.4	140	110	1.86	17.1	59.4	110	1.33	2.01	1.27	0.7	0.11	0.54
B3311-4	630.5 m	Green mudstone	1.75	6.34	50.5	22.1	217	89.3	3.1	8.39	24.1	65.7	0.31	2.29	2.43	0.81	0.37	0.37
B3311-12	631.5 m	Purple red coarse sandstone	0.36	3.72	15.7	8.27	52.9	44	1	4.73	7.76	30.3	0.11	1.9	1.2	0.77	0.21	0.26
B3311-23	664.5 m	Green silty mudstone	4.31	5.19	46.5	26.3	147	115	1.88	7.07	41.4	99.7	0.92	1.77	1.28	0.76	0.27	0.42
B3311-22	666.2 m	Purple red siltstone	0.58	3.02	17.2	7.88	57.2	49.2	2.8	4.47	7.21	34	0.21	2.18	1.16	0.77	0.63	0.21
B3311-15	669.3 m	Red coarse sandstone	0.34	1.76	14.4	5.96	39	32.8	1.57	3.44	6.32	25.4	0.21	2.42	1.19	0.73	0.46	0.25
Average			**2.03**	**5.1**	**39.97**	**19.25**	**119.11**	**86.16**	**1.79**	**8.47**	**27.48**	**70.16**	**0.48**	**2.12**	**1.36**	**0.75**	**0.25**	**0.35**
B3311-14	671.5 m	Grayish green siltstone	3.52	3.95	34.3	17.6	125	83.4	2.02	12.1	31	89.7	0.99	1.95	1.5	0.78	0.17	0.35
B3311-20	674.5 m	Green silty mudstone	2.62	3.94	44	26.2	126	93	3.16	8.84	49.2	74.6	0.74	1.68	1.35	0.74	0.36	0.66
B3311-24	737.0 m	Green mudstone	4.14	3.69	45.4	19.7	115	101	1.62	12.4	44.3	94.7	1.25	2.3	1.14	0.72	0.13	0.47
B3311-8	744.8 m	Grayish green fine sandstone	2.55	1.63	18.8	9.58	56.4	47.1	1.11	6.92	15.4	39.8	1.74	1.96	1.2	0.75	0.16	0.39
B3311-17	779.0 m	Grayish green mudstone	2.48	3.57	27	12	95.7	90	1.99	11.3	30.9	45.5	0.77	2.25	1.06	0.78	0.18	0.68
B3311-25	781.5 m	Grayish green medium sandstone	1.31	2.02	17.7	11.1	75.4	44.4	3.35	4.76	7.32	35.6	0.72	1.59	1.7	0.81	0.7	0.21
Average			**2.77**	**3.13**	**31.2**	**16.03**	**98.92**	**76.48**	**2.21**	**9.39**	**29.69**	**63.32**	**1.03**	**1.96**	**1.33**	**0.76**	**0.28**	**0.46**
B3311-26	790.2 m	Grayish white coarse sandstone	11.58	8.02	65.8	59.2	195	111	6.48	10.9	32.8	85.8	1.6	1.11	1.76	0.75	0.59	0.38
B3311-27	790.3 m	Green mudstone	5.25	21.72	44	46.7	74.3	31.8	1.45	6.82	15.1	45.8	0.27	0.94	2.34	0.63	0.21	0.33
B3311-9	796 m	White coarse sandstone	0.69	0.83	14.6	6.45	36.8	26.4	0.67	3.41	6.72	22	0.92	2.26	1.39	0.72	0.2	0.31
B3311-10	797.5 m	Grayish white coarse sandstone	4.07	10.48	37.9	19.1	228	100	2.8	12.8	20.8	48.2	0.43	1.98	2.28	0.86	0.22	0.43
B3311-1	800 m	Grayish white coarse sandstone	0.9	1.22	13	7.98	52.6	33.4	0.72	3.86	8.91	27.5	0.82	1.63	1.57	0.8	0.19	0.32
B3311-2	805 m	Carbon clast	2.05	2	29.6	10.6	204	162	2.72	18.2	53.3	65.2	1.14	2.79	1.26	0.87	0.15	0.82
B3311-29	811.5 m	Grayish white coarse sandstone	0.73	1	13.2	6.55	46.7	36.2	0.9	5.14	10.3	44.1	0.81	2.02	1.29	0.78	0.18	0.23
B3311-28	813 m	Gray mudstone	2.94	2.78	40.4	20	118	101	3.47	13.5	40.9	79.7	1.18	2.02	1.17	0.74	0.26	0.51
Average			**3.53**	**6.01**	**32.31**	**22.07**	**119.43**	**75.23**	**2.4**	**9.33**	**23.6**	**52.29**	**0.9**	**1.84**	**1.63**	**0.77**	**0.25**	**0.42**

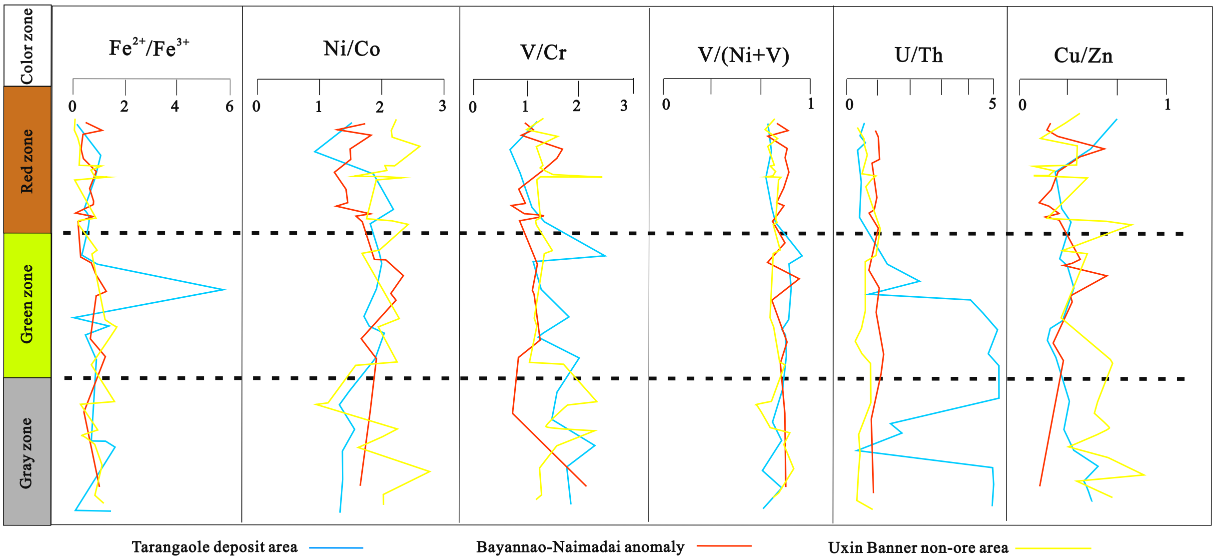

Fig. 7. Discrimination diagram using trace element ratios for the central northern Ordos Basin.

and direct evidence for climate changes and sedimentary environment evolution. Geochemical distribution and vertical stratigraphic color variations in the Zhiluo Formation are correlated in space. From the basin margin to the center, and from the U ore clusters to the non-U ore clusters, vertical red (yellow)–green–gray zoning and geochemical variation characteristics show relatively well stability, while little lateral zoning and typical geochemical characteristics variation are observable. Although laterally, water level fluctuation, basin margin oxidization, and reducing fluid geochemical barriers form small-scale color mixing and abrupt changes. The color layer thickness is changed, but large-scale regular color tonal variation or the disappearance of a certain color does not occur.

7. Discussion

Based on research results above, it is considered that color variations in the strata is the most direct evidence of climate change and sedimentary environment evolution. The Fe^{3+}/Fe^{2+} values, whole S contents, TOC contents, and U contents for sandstones from vertically red (yellow)–green–gray color zoning strata in the ore clusters show corresponded distinctly vertical variations, characterized by gradually decreased Fe^{3+}/Fe^{2+} values, but gradually increased whole S contents and TOC contents. In general, ore-bearing layers exhibit relatively higher whole S contents and TOC contents, directly indicating positive correlations between uranium metallogenic enrichment and the volume of pyrite, organic matter such as carbonaceous clastics, and indirectly hinting spatial correlation between vertical geochemical feature and color variations for Zhiluo Formation. For the four ore clusters in the basin, the vertical morphological changes of environmental index parameters have similar characteristics in the corresponding color layer, demonstrating that same color strata should display the same sedimentary environment, as characterized by red layer basically representing oxidizing environment, green layer representing weak reduction environment, and pyrite bearing gray layer representing strong reduction environment.

Regarding to the entire basin, from marginal U deposit area to the inner ore barren areas, the Zhiluo Formations not only show vertically identical red (yellow)–green–gray color variations, but also display resemble redox index, such as those chemical components including U, Th, V, Cr, Fe, Co, Cu, Zn and Mo concentrations. Though small scale of color mixture mutation and color zoning thickness variations induced by horizontally water-level fluctuation is visible, on the whole, there is no wide range of regular horizontal color changes and/or no wedging out of some kind of color. The above vertical color variations represent their primarily sedimentary environments other than posterior multiple stages of mineralization.

In summary, the vertical color variations and its significance are different from transverse color zoning derived from interlayer oxidation zone metallogenic theory, and opinions on three different color zoning proposed by previous research (Yang et al., 2009; Miao et al., 2010). The newly discovered color variation features can be used as a standard for uranium prospecting and exploration instead of previous idea of "redox front line".

8. Conclusions

1) From the margin to the center and from the ore clusters to the ore barren areas across the Ordos Basin, the Zhiluo Formation displays vertical color variation, i.e., red (yellow)–green–gray color zoning with little variations in lateral color zoning.
2) The vertical color variation in the Ordos Basin represents the response to paleo-sedimentary environments. The vertical geochemical characteristics and color variations of the Zhiluo Formation show good corresponding relationships. The red zone and green zone represent an oxidation environment and a weak reduction environment respectively, while the gray (grayish black) zone represents a reduction environment. The lower upwards color variations entirely reflect a paleo-sedimentary environment evolution gradually transitioning from reduction to oxidation.
3) This research believes that the U ore bodies within the Ordos Basin mainly occur as platy and stratiform configuration, and no roll-type ore bodies have been discovered. The U ore bodies are mainly distributed near the gray zone at the contact between the green zone and the gray zone of the Middle Jurassic Zhiluo Formation, and they are partially developed in the green zone.

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