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SEQUENCE STRATIGRAPHY AND SEDIMENTARY ENVIRONMENT OF THE EOCENE HUADIAN FORMATION IN THE HUADIAN BASIN (NE CHINA): IMPLICATIONS FOR OIL SHALE DISTRIBUTION

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The Huadian basin is a small, explored, coal and oil shale-bearing, Cenozoic fault basin in the middle part of the Fushun-Mishan Fault Zone, northeastern China. The basin primarily consists of the Eocene Huadian Formation and contains abundant oil shale resources. This basin is also one of the bases of underground oil shale mining at present. Based on core inspection and description from five wells and the analyses of hundreds of samples using various approaches, namely, thin section study, pollen identification and geochemical analyses (TOC, oil yield, trace elements (B, Mo, Sr/Ba, B/Ga, Sr/Cu, V/V+Ni and Ni/Co)), the sequence stratigraphy of the Eocene Huadian Formation has been established, and the sedimentary environment has been studied in this paper. Four third-order sequences and three types of sedimentary facies, including fan delta, lacustrine and subaqueous fan, are identified in the Huadian Formation. During the Eocene period, the basin experienced three sedimentary evolution stages: the initial subsidence stage mainly developed shore-shallow lake and fan delta sediments, the maximum subsidence stage is dominated by semi-deep and deep lake sediments, and the rapid downwarp filling stage mainly developed fan delta, limnetic and shore-shallow lake sediments. Oil shale mainly developed in the transgressive system tract (TST) and highstand system tract (HST) of sequence III (Oil shale member of semi-deep and deep lake facies). The TST developed the 7^{th} to 13^{th} layers of oil shale, characterized by thin beds, low to medium oil yield and, low to medium organic matter enrichment. The HST developed the 2^{nd} to 6^{th} layers of oil shale, characterized by widely distributed, thick beds, high oil yield and medium to high organic matter enrichment. In one parasequence, oil shale mainly developed in the lake flood period. High initial lake productivity and stable underlying water oxygen levels (lower decomposition rate) influenced by climate form the most favorable environment for oil shale formation.

***Key words*: Huadian Basin; Sequence stratigraphy; Sedimentary environment; Eocene; Oil shale.**

INTRODUCTION

The Huadian Basin is located in the middle part of the Fushun-Mishan Fault Zone (F_1 in Fig. 1), which is a northern branch of Tancheng-Lujiang Fault in China [1, 24]. A series of coal and oil shale-bearing basins such as the Xialiaohe, Fushun, Meihe, Huadian, Dunhua, Ermu, Jixi and Hulin basins are successively developed in the Fushun-Mishan Fault Zone from southwest to northeast, extending northward to Russia (Fig. 1). These basins are mainly filled with Paleocene sedimentary strata with abundant coal, oil shale, and oil and natural gas resources, which have become the important energy base of northeast China. The most representative, the Huadian Basin, is one of the typical fault basins that is rich in oil shale and coal; the oil shale is characterized by numerous seams (13 economically mineable layers), thin layers (generally 1–2 meters) and high oil yield (the highest comes to 24.8 %) [9]. This basin is also one of the bases of underground oil shale mining at present, and the produced oil (70000–80000 t/a) is used as ship fuel.

Previous research related to the oil shale member in the Huadian basin mainly focused on industrial utilization, clay minerals, biomarkers, trace and REE elements, flash pyrolysis mechanisms and the paleoproductivity and

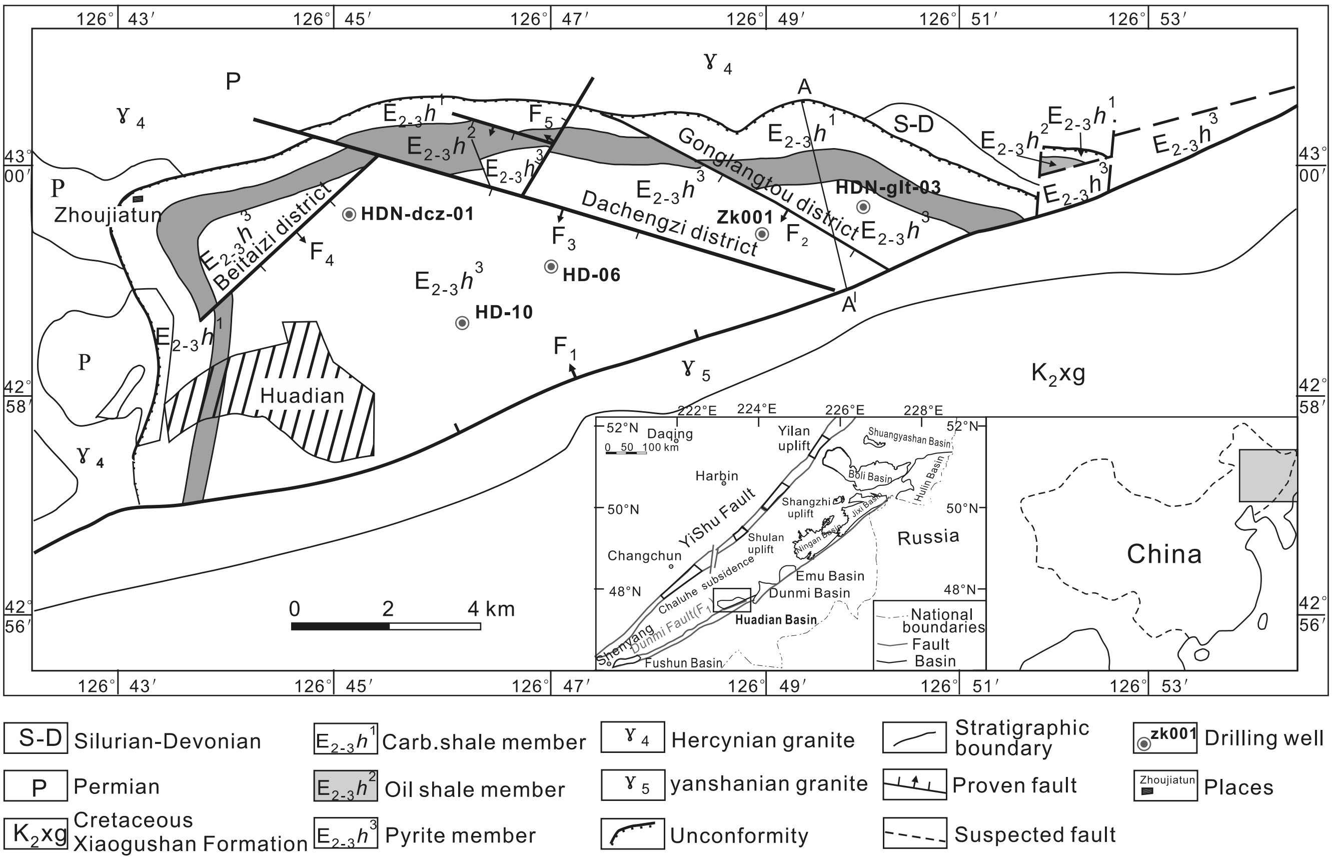

Fig. 1. Geological map of Huadian Basin.

water properties of the lake during the period of oil shale formation [4, 5, 11–13, 17, 18, 20, 22, 23, 26, and 28]. To our knowledge, to date no research has been undertaken on the sequence stratigraphy and sedimentary environment evolution during the depositional period of the Huadian Formation and their controls on oil shale distribution.

Hence, the main aim of our paper is to establish the sequence stratigraphic framework of the Huadian Formation and reconstruct the sedimentary environment of the Eocene basin, which produced the unique oil shale distribution. To reach the goal, detailed core evaluation together with thin section study and particle size analysis has been carried out in our study. Furthermore, TOC, oil yield, trace element and spore-pollen data were also applied to provide further information to establish sequence stratigraphic framework and evolution of oil shale accumulation. These results will have an important guiding role for the study of the enrichment, mineralization and predictive evaluation of oil shale, coal and other mineral resources in this area.

GEOLOGICAL SETTING AND STRATIGRAPHY

Controlled by the circum-Pacific tectonic domain, the tectonic evolution of the northern segment of Tancheng-Lujiang Fault Zone experienced five stages: namely, a left-lateral strike-slip tensile shear stage (the last stage of J_2), a left-lateral tenso-shear stage (the earlier-mid period of K_1), a right-lateral compression shear stage (of the later period of K_2/last stage of K_2), and a right-lateral strike-slip fault depression stage (E) and structural inversion (the end of E_3) [19]. The tectonic evolution of Huadian Basin is mainly controlled and influenced by the right-lateral compression shear stage and the right-lateral strike-slip fault depression stage and structural inversion; the main faults on the east and west sides of the Dunhua-Mishan Fault zone dip toward each other in an internal graben, which forms the "obsequent graben" fault system. The Huadian basin is part of a small strike-slip fault basin that trends EW. The formation strikes NE to NEE. The F_1 fault in the southern basin is part of the synsedimentary fault (Fig. 1) and its activity directly influences the tectonic subsidence and deposition of the basin; generally the sedimentary thickness tends to increase proximal to the basin-controlling fault.

The base of the Huadian basin is the Permo-Carboniferous metamorphic series. The unconformable overlying strata contain a Jurassic coal-bearing series (J), a Cretaceous glutenite series (K), the Eocene Huadian

Formation (E_{2-3}) and a Quaternary stratum (Q) (Fig. 2). The Huadian Formation comprises the main sedimentary strata in this area, and is divided into three members from bottom to top, including the Lower Pyrite Member ($E_{2-3}h^1$), the Middle Oil Shale Member ($E_{2-3}h^2$) and the Upper Carbonaceous Shale Member ($E_{2-3}h^3$).

The Lower Pyrite Member ($E_{2-3}h^1$), 250 to 320 m thick, is in unconformable contact with Cretaceous rocks. Its lower part is composed of gray mudstone intercalated with thin layers of sandstone containing pyrite layers (locally recoverable). The upper part is mainly brick red to purple and green mudstone, intercalated with thin layers of gypsum.

The Middle Oil Shale Member ($E_{2-3}h^2$), 75 to 300 m thick, is composed of gray to dark gray mudstone and oil shale, intercalated with thin layers of gray-white fine sandstone, and contains 8 to 26 oil shale layers. Of these, 6 to 13 layers contain recoverable oil shale and the oil yield is very high. Abundant fossils are also present in this member.

The Upper Carbonaceous Shale Member ($E_{2-3}h^3$) is 200 to 350 m thick and the upper part is composed of light gray mudstone interbedded with gray-white medium to fine sandstone. The middle part is thick mudstone and the lower part is gray mudstone interbedded with mainly medium-coarse sandstone with massive bedding, containing 18 thin layers of coal; 4 layers are recoverable locally.

MATERIALS AND METHODS

Core from five wells situated in the Huadian Basin, namely, HDN-dcz-01, HDN-glt-03, HD-06, HD-10 and Zk001, was systematically inspected (Fig. 1) and seventy-seven samples taken for thin section identification. Systematic Total Organic Carbon (TOC) and oil yield data of wells HDN-dcz-01, HDN-glt-03 and ZK001 (each sample interval is approximately 1 m) were determined using a Leco CS-230 elemental analyzer and low-temperature retorting instrument at the Key-Lab for Oil Shale and Paragenetic Minerals of Jilin Province at Changchun, China. In addition, for Well HDN-glt-03, detailed pollen and trace elements analyses were conducted to obtain further information on climate change and sequence stratigraphy. Additionally, one hundred and one samples were analyzed for pollen identification at the Research Center of Paleontology and Stratigraphy at Jilin University in Changchun, China and trace element analysis was performed on one hundred and five samples at the Institute of Geophysical and

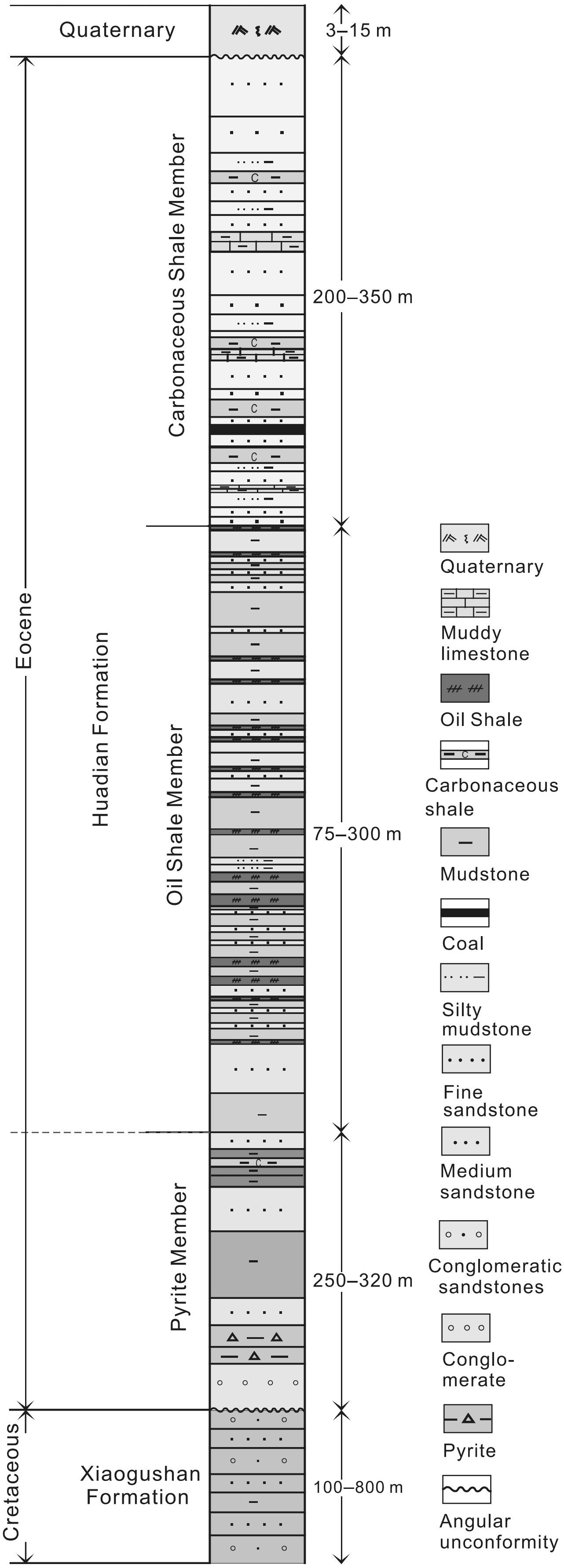

Fig. 2. Stratigraphic comprehensive histogram of Huadian Basin.

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SEQUENCE STRATIGRAPHIC CHARACTERISITICS

Due to limited outcrop and material restrictions, the Huadian Formation in the Huadain basin is divided in this paper into four third-order sequences using core, logging and geochemical data. Sequences Ⅰ and Ⅱ are developed in the Lower Pyrite Member, Sequence Ⅲ is developed in the Middle Oil Shale Member, and Sequence Ⅳ is developed in the Upper Carbonaceous Shale Member (Fig. 3).

Sequence Recognition Marks

The key problem in the study of sequence stratigraphy is to identify the boundaries of different order sequence stratigraphic units [26, 27]. In this paper, different identification methods and means are used for different order sequences. The identification of parasequences and parasequence sets is based on core and logging data and the identification of sequences is based on the criteria of rock associations, geochemistry and pollen assemblages.

Four sets of different rock assemblages separately developed in the upper, middle and lower members of Huadian Formation. Among them, the upper carbonaceous shale member consists of mudstone interbedded with medium to fine sandstone, and contains multi-layer minable coal seams. The oil shale deposit is mainly developed in the middle oil shale member. The lower part of the lower pyrite member is mainly formed by gray mudstone intercalated with thin layers of sandstone, and contains pyrite layers, but the upper part is formed by brick-red to purple and green mudstone intercalated with thin layers of gypsum (Fig. 3).

Trace elements such as B, Sr, Ba, V, Ni and related ratios not only can be used to distinguish between freshwater and seawater sediments but can also be used to estimate paleosalinity and analyze the paleoclimate [16, 21]. For terrestrial lakes, the change of evaporation/rainfall conditions directly causes a water salinity increase or decrease; the trend is consistent with the changes in evaporation/rainfall, so the paleosalinity changes can also lead to a base level change in the lake basin [6, 15]. Therefore, the response of trace elements and their ratios to climate change can be used as an auxiliary indicator for sequence stratigraphic units division. Fig. 4 shows the vertical distribution regularity of trace elements in the Huadian Formation at the interface between sequences Ⅱ, Ⅲ and Ⅳ. B, Mo and the Sr/Ba, Sr/Cu, V/V+Ni and Ni/Co ratios have obvious cut value changes, which reflect the control of climate on sequence.

In continental basins, the control of basement subsidence, sediment supply and climate on base level change and sequence are more apparent [8]. Additionally, changes in vegetation and sporopollen assemblage are caused by climate change, so sequence stratigraphy has a close relation with sporopollen assemblage [3, 10]. The percentages and concentrations of sporopollen are shown in Fig. 4. In sequence Ⅲ (Oil shale member), angiosperm pollen dominates, with mostly *Quercoidites*, *Ulmipollenites* and *Tiliaepollenites*; gymnosperm pollen is secondary. However, in sequence Ⅳ (Carbonaceous shale member), gymnosperm pollen dominates and is represented by *Abietineaepollenites* and *Pinuspollenites*. The obvious differences of sporopollen assemblages between the two sequences exactly reflect control by climate on the third-order sequence.

System Tract Recognition Marks

The four-division scheme of systems tracts within a third order sequence in continental basins proposed by [7, 8] is adopted in this paper. That is, a complete sequence consists of four system tracts, which are a lowstand system tract (LST), a transgressive system tract (TST), a highstand system tract (HST) and a regressive system tract (RST). In different system tracts, the characteristic parameters such as the grain sizes of lithologic assemblage, the sand-mud ratio, the thicknesses of parasequences and logging curves have a corresponding change [8]. Fig. 3 shows the typical characteristics of lithologic assemblage for each system tract in sequence Ⅲ of well HD3-glt-003. The LST develops fan delta plain deposits, and mainly consists of gray conglomeratic sandstones and coarse sandstones. The TST develops fan delta front and shore-shallow lake sediments, gradually becoming semi-deep deposits up section, with the 13^{th} oil shale layer as the first lake flooding surface and the 6^{th} oil shale layer as the maximum flooding surface, which is a typical retrogradational parasequence set. The HST is mainly composed of the semi-deep lake facies, developing the 2^{nd} to 6^{th} layers of oil shale. The RST transitions form the semi-deep facies to shallow-lake and progradational fan deltas.

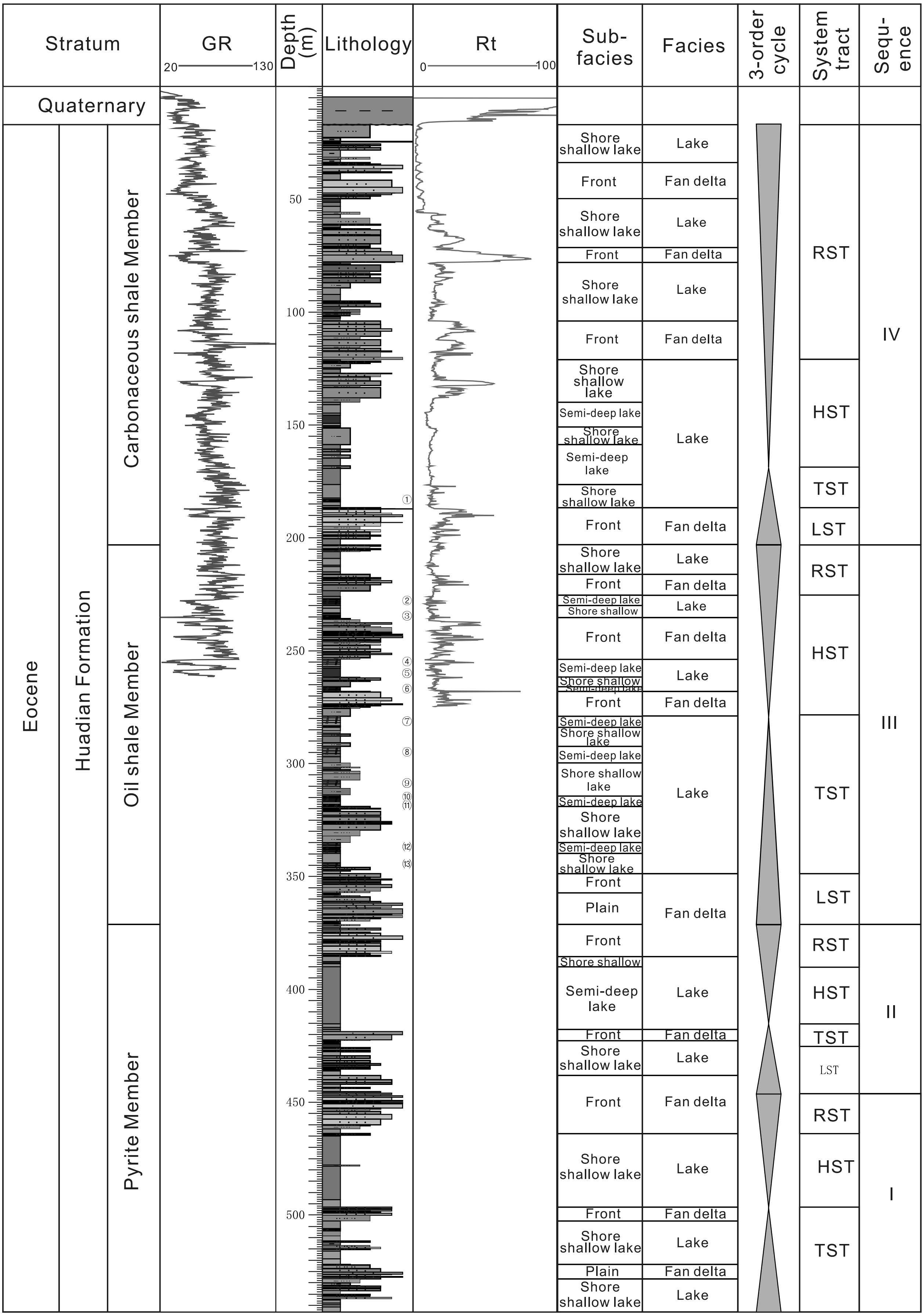
SEDIMENTARY FACIES

Based on the core and logging data, three types of sedimentary facies, including fan delta, lacustrine and subaqueous fan, are identified in the Huadian Basin.

Fan Delta Facies

Fan delta deposits are mainly distributed along the northeast and southwest margins of the basin and

Fig. 3. Sequence stratigraphic framework of Huadian Basin.


Stratum
GR
20
130
Depth (m)
Lithology
Rt
0
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Sub-facies
Facies
3-order cycle
System tract
Sequ-ence
Quaternary
Eocene
Huadian Formation
Carbonaceous shale Member
Oil shale Member
Pyrite Member
50
100
150
200
250
300
350
400
450
500
Shore shallow lake
Front
Semi-deep lake
Plain
Shore shallow
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Fan delta
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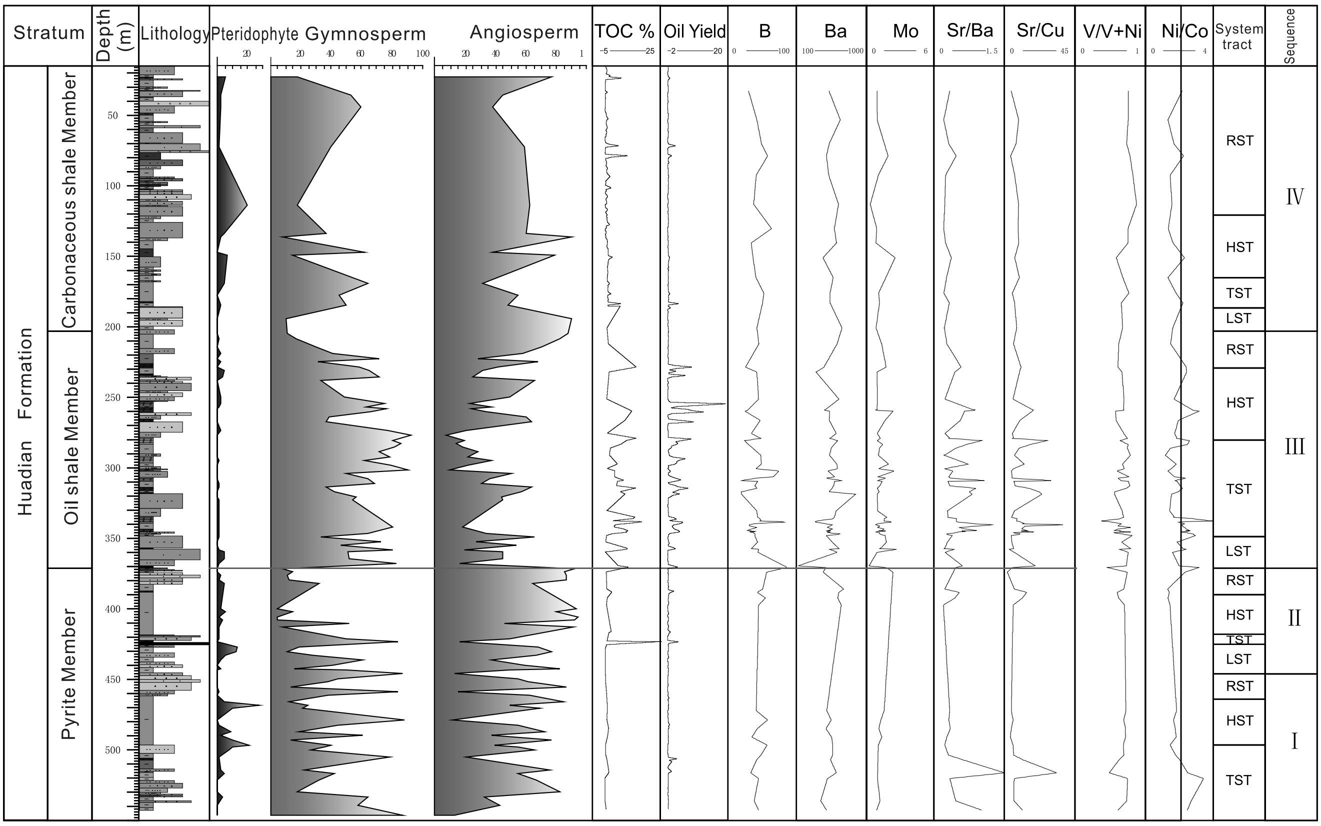


Fig. 4. Sequence division based on pollen assemblage and the vertical change of trace elements in Huadian Basin.

proximal to the basin-controlling fault, forming in the early and late stages of basin formation. They are divided into fan delta plain and fan delta front subfacies.

Three types of microfacies, upper-water distributary channel, upper-water interdistributary channel and swamp respectively, are identified in the fan delta plain subfacies. The upper-water distributary channel microfacies displays positive cycle features, in that the grain size is gradually smaller from bottom to top, and the sedimentary structures include trough cross-bedding, high-angle inclined bedding, and deformed bedding, as well as an erosional surface (Fig. 5). The upper-water interdistributary channel microfacies mainly consists of brownish red variegated mudstone, celandine green and gray massive silty mudstone, containing plant fossils and kish carbon, locally broken (Fig. 5). The swamp microfacies is composed of grayish black carbonaceous mudstone and coal seams.

The fan delta front subfacies can be divided into underwater distributary channel, underwater interdistributary channel and channel mouth bar microfacies (Fig. 6). The underwater distributary channel macrofacies mainly consists of grayish white conglomeratic sandstones, coarse sandstones, medium-fine sandstones and siltstones with normally graded vertical sequences (Fig. 6 A). The main sedimentary structures are medium-small scale trough cross-bedding, deformed bedding, and (locally) parallel bedding. The underwater interdistributary channel microfacies composed of gray mudstone or massive silty mudstone, containing kish carbon. Channel mouth bars mainly consist of gray siltstone and grayish white fine and medium sandstones with reverse grain size in ascending order; small cross-bedding, wavy bedding and parallel bedding are common (Fig. 6 B). Wormholes show that biological disturbance.

Lacustrine facies

The lacustrine facies is best developed in this area and is mainly divided into shore-shallow lake, semi-deep and deep lake subfacies.

The shore-shallow lake subfacies is located at the margin of the lake basin and is composed of limnetic lake, shore lake, muddy shallow lake, sandy shallow lake and beach bar microfacies.

The limnetic lake microfacies is one of the main environments for coal formation and is composed of gray black carbonaceous mudstone and coal in the study area. The shore lake microfacies generally consists of brownish red to purple red mudstone and silty mudstone and gray

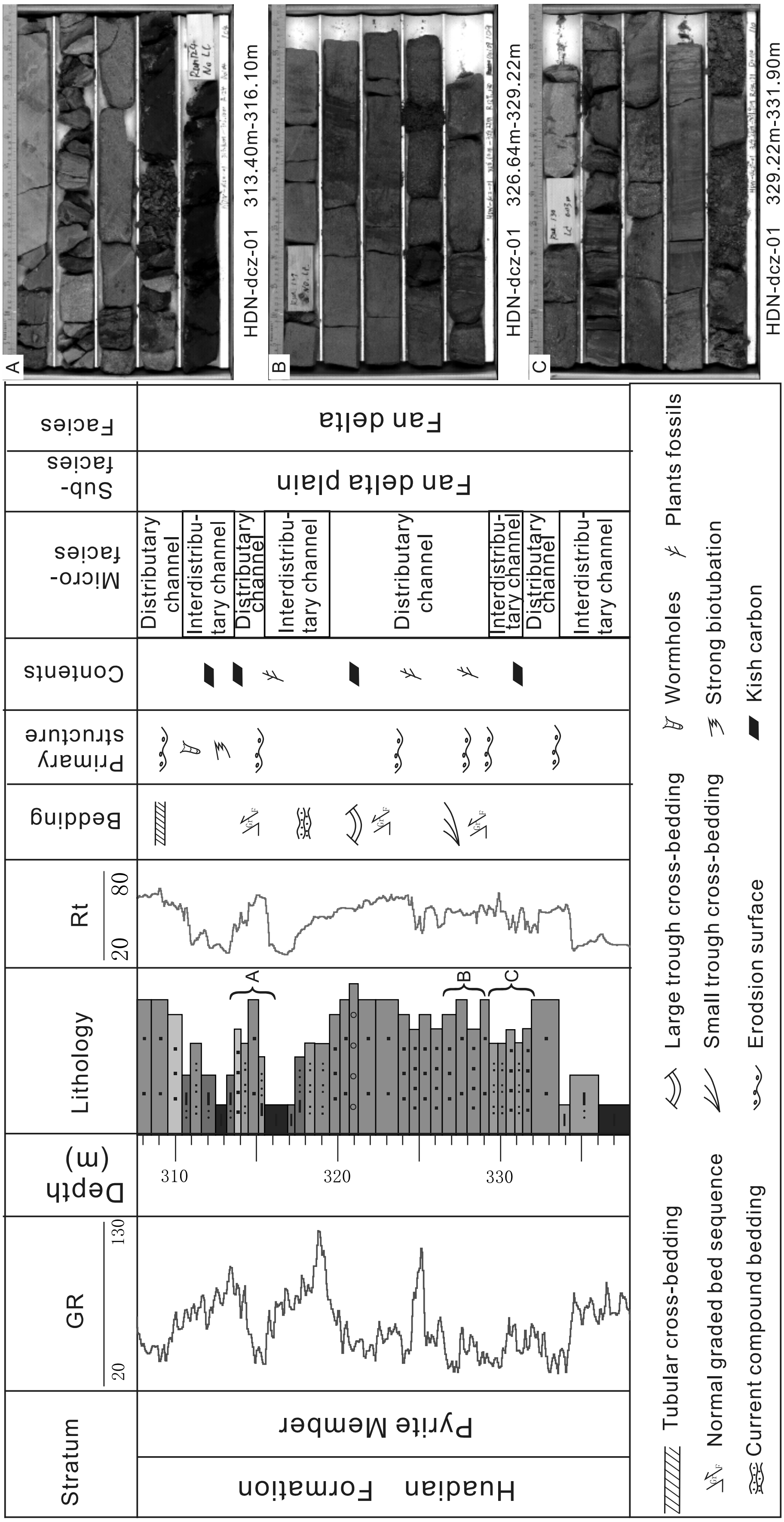


Fig. 5. Sedimentary characteristics of fan delta plain in well HDN-dcz-01(307.6 2m ~ 337.96 m).

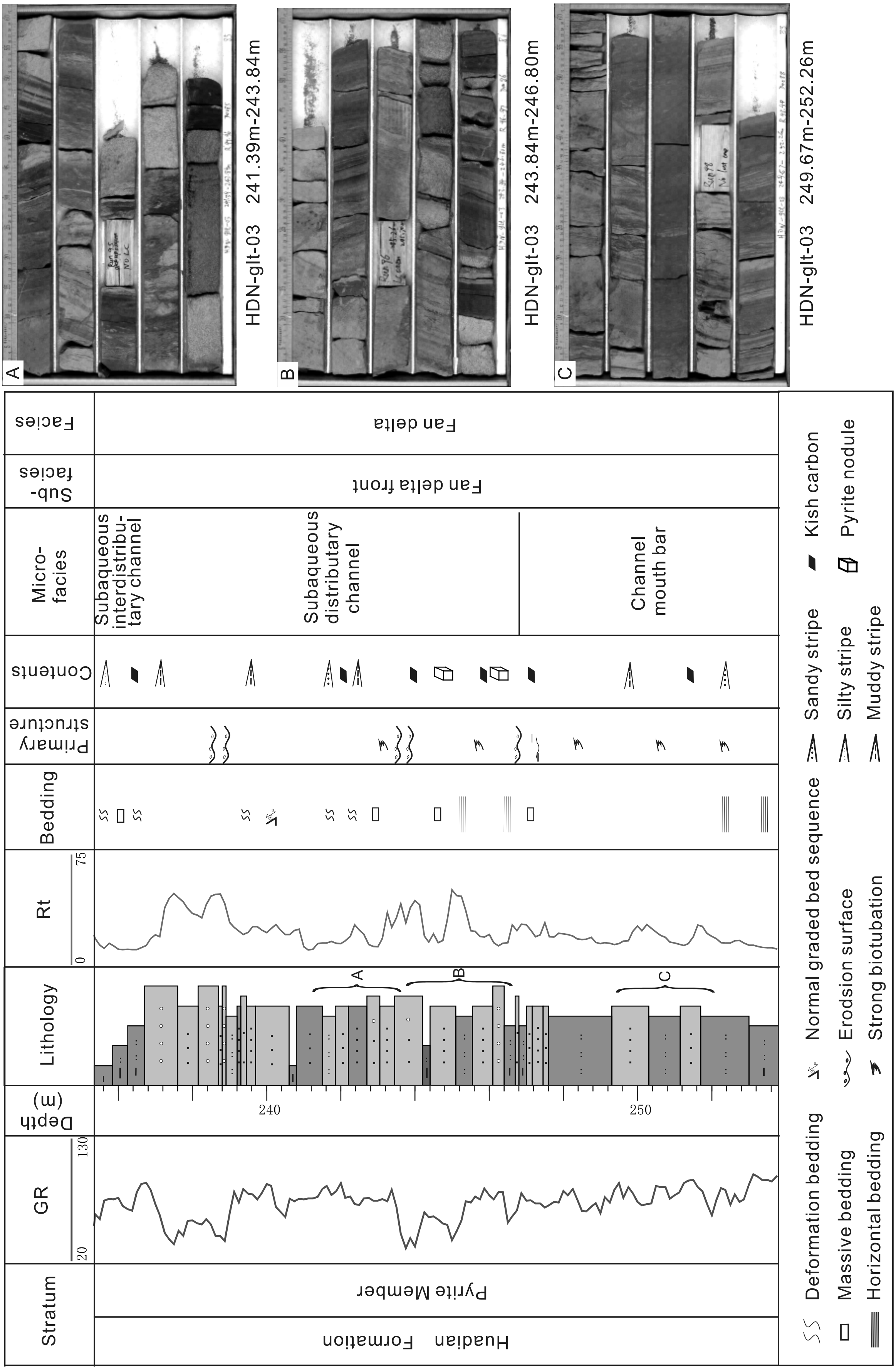


Fig. 6. Sedimentary characteristics of fan delta front in HDN-glt-03 (235.35 m ~ 253.8 m).

green siltstone and fine sandstone with better sorting and rounding (Fig. 7 A). The sandy shallow lake microfacies is composed of gray green and gray fine sandstone, siltstone and muddy siltstone; the muddy shallow lake microfacies is made up of gray green and gray silty mudstone and mudstone (Fig. 7 B). The bioturbation in the shore-shallow lake subfacies is stronger and wormholes are common (Fig. 7 E).

The beach bar microfacies in the shore-shallow lake subfacies is the more common sandstone body in this area and formed in the rift expansion stage of the fault lake basin with the relatively flat shore terrain. It consists of gray siltstone and fine sandstone interbedded with mudstone, which are reversely graded in ascending order.

The semi-deep and deep lake subfacies are mainly composed of dark gray to gray black mudstone and grayish brown to brownish black oil shale. The sediments of the semi-deep and deep lake subfacies in the middle oil shale member and upper carbonaceous shale member have certain differences. The semi-deep and deep lake subfacies in the middle oil shale member consist of dark gray to gray black mudstone intercalated with multiple-layers of oil shale deposits (Fig. 7 C) and contain abundant typical gastropods fossils including *Planorbarius subdiscus*, *Australorbis* cf. *hebeiensis* and *Hydrobia zhuoxianensis* that represents the Eocene freshwater lakes (Fig. 7 G), and ostracoda and plant fossils are also found in gray black mudstone and oil shale; horizontal bedding and rhythmic layering are prominently developed (Fig. 7 F). The sediments of the semi-deep and deep lake subfacies in the upper carbonaceous shale member are mainly gray black and dark gray mudstones intercalated with thin sandy layers (Fig. 7 D) containing abundant kish carbon; the thickness is relatively less than that of the oil shale member and oil shale is poor developed.

Subaqueous fan facies

The subaqueous fan facies in this area mainly consists of middle fan and outer fan sediments. The main middle fan sediments are braided channel deposits, which consist of fine conglomerate, greywacke and coarse sandstones, with massive bedding that indicates rapid deposition. Liquefaction deformed and graded bedding is occasionally seen (Fig. 7 H). The outer fan sediments are mainly typical turbidites and form the BCDE member of Bouma sequence, which is composed of medium-fine sandstones with parallel bedding, fine sandstone with wavy bedding and deformed bedding and mudstone and muddy sandstone with parallel and massive bedding (Fig. 7 I). Load cast and sandball structures are visible on the contact surface with bottom mudstone.

SEDIMENTARY EVOLUTION AND ITS CONTROL ON OIL SHALE MINERALIZATION

Sedimentary evolution

Stratigraphic thickness, sandstone thickness, sand-strata ratios and distribution characteristics of sedimentary facies of the Huadian Formation show that it has experienced three sedimentary evolution stages:

(1) The initial subsidence stage of the lake basin (equal to the depositional period of the lower pyrite member)

During the initial subsidence stage of the Huadian basin, the thickest strata were deposited in the northeast margin of the basin (Fig. 8 A). Corresponding sandstone thickness and sand-strata ratio values are high (Fig. 8 B, C), which indicate that the basin provenance was mainly from the northeast. In addition, high values of strata thickness, sandstone thickness and the sand-strata ratio are also found in the northwest and western parts of the basin, which shows that there also exist two minor provenances in these two directions (Fig. 8 C).

During this period, the lake basin was in a state of over-compensation deposition and mostly filled with sand bodies. The lake area was very small with the water mainly concentrated in the middle and eastern basin. Fan delta deposits are present in the northeast basin, shore-shallow lake deposits are widely distributed, and the semi-deep lake facies is only present in the middle part close to the contact with the basin fault. The provenance areas in the northwest and western basin are underlain by alluvial fan deposits (Fig. 8 D).

(2) The maximum subsidence stage of the lake basin (equal to the depositional period of the middle oil shale member)

At this stage, the values of strata thickness, sandstone thickness and the sand-strata ratio are high in the eastern and middle basin (Fig. 9 A) and show a decreasing trend from the northeast to southwest, which indicates that the basin provenance is still from the northeast (Fig. 9 B, C) with the deposition of small scale of fan deltas. Shore-shallow lake deposits developed in the ramp belt of the basin with less provenance supply and gradually transition to semi-deep and deep lake deposits proximal to the basin-controlling fault (Fig. 9 D).

During this period, the influence of provenance is the weakest and the areal extent of the lake is at its largest with a stable water environment. The lake basin is in a stable state of under-compensation deposition, which provides favorable conditions for economic oil shale formation, but frequent changes in climate led to the multiple-layers of oil shale deposition.

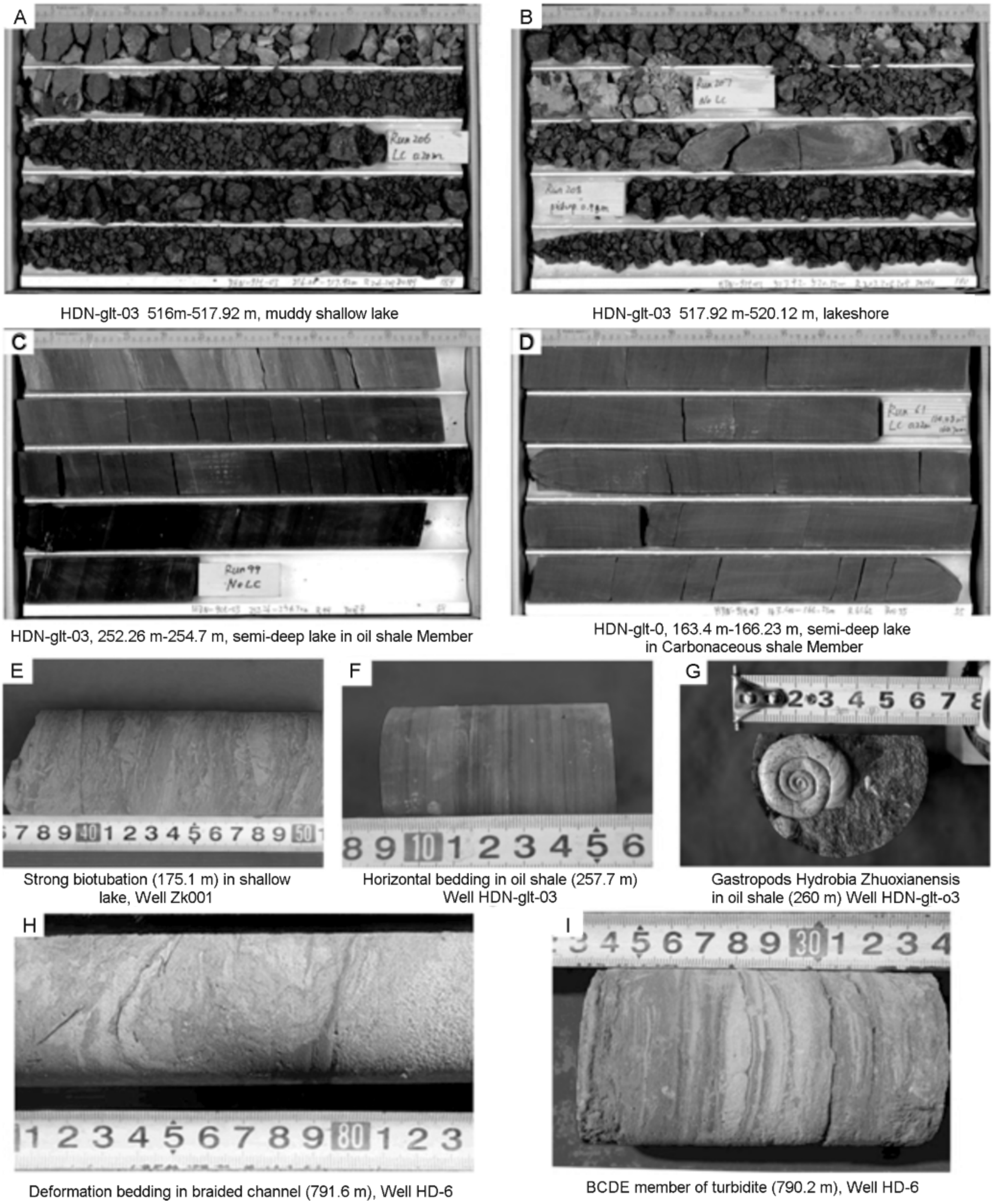


Fig. 7. Sedimentary characteristics of lacustrine and subagueous fan facies.

(3) The rapid downwarp filling stage of the lake basin (equal to the depositional period of the carbonaceous shale member)

The activities of the basin-controlling fault during this stage are more pronounced than during that of the oil shale member, and the thickest strata are located proximal to the basin-controlling fault (Fig. 10 A), with obviously higher values of sandstone thickness and sand-strata ratio (Fig. 10 B and C). This illustrates that the provenance has changed from the northeast basin to the edge of the basin-controlling fault on the southern margin, accompanied by the deposition of large volumes of fan delta sediments. During this period, the lake basin is in a state of over-compensation deposition. The provenance on the margin of the ramp belt gradually shrinks and the principal deposits change to limnetic lake and shore-shallow lake sediments (Fig. 10 D). With the basin filled with the sediments, the area covered by lakes rapidly decreases. A large volume of input terrigenous clastic particles is not favorable for oil shale formation and peat bogs developed in places, with the local development of a minable seam.

Areal distribution characteristics of oil shale within the sequence framework

The oil shale member of the Huadian Formation is a whole third-order sequence (sequence Ⅲ). Within an isochronous stratigraphic framework, the changes between tectonic subsidence rate and sediment supply rate control the development characteristics of each system tract. Oil shale mainly develops in the TST and HST, and is not developed in the RST and LST (Fig. 11). The content of organic matter is mainly controlled by the deposition rate at the interface between sediment and oxygenated water; a low deposition rate is beneficial for the preservation of organic matter [2]. This means that once the oxygen interface forms, the deposition rate becomes the main factor that controls the preservation of organic matter.

The TST is formed during the period of lake-level rise, with the first lake flooding surface and maximum lake flooding surface as its boundaries and the first lake flooding forming the 13th layer of oil shale. During this period, the tectonic subsidence rate is greater than the sediment supply rate ($\Delta A/\Delta S > 1$), the accommodation space increases and the shallow and semi-deep lake facies are dominant in the area of the lake basin, benefiting the accumulation of organic matter. Semi-deep lake sediments mainly develop proximal to the basin-controlling fault with greater tectonic subsidence and the facies range gradually expands with the increase of lake flooding, which controls the distribution range of oil shale. However, because of the relatively quick subsidence of the basin basement and the high accumulation rate of sediments, the accumulation ratio of organic matter is relatively low; only poor grayish brown and dark gray oil shale is formed, characterized by thin beds (0.7 m~1.3 m), low to medium oil yield (3.5 % ~ 7.1 %) and low to medium enrichment of organic matter (TOC is between 8.0 % and 17.3 %, humic-sapropel organic matter) (Fig. 4 and 12).

The HST is formed in the relatively static high lake-level period, with the maximum lake flooding surface (the 6th layer of oil shale) as its lower boundary and the regressive downlap surface as its upper boundary. During this period, the tectonic subsidence rate is equal to the sediment supply rate ($\Delta A/\Delta S = 1$). The accommodation space is essentially unchanged and has the stacking pattern of a typical aggradational parasequence set. In lake basin area, the HST mainly consists of stable semi-deep lake facies sedimentary systems. The accumulation rate of the sediments is relatively slow and the organic matter has a relatively high accumulation ratio and is preserved very well, so that the 2nd to 6th layers of black brown and brownish black color rich oil shale form and are evenly distributed through the whole area. The oil shale is characterized by thick beds (1.3 m ~ 3.5 m), medium to high oil yield (8 % ~ 19.8 %) and medium to high enrichment of organic matter (TOC is between 8.9 % and 30.3 %, sapropel organic matter). However, in the late stage of the HST, the parasequence is converted from aggradation to progradation. The oil yield and thickness of oil shale show a tendency of gradual decrease (Fig. 4 and 12).

During the period of the LST and HST, the tectonic subsidence rate is lower than the sediment supply rate and the accommodation space decreases. The lake-level falls and the climate is relatively arid. The sediment supply rate increases due to progradation, rapidly diluting organic carbon. The rich organic lithofacies duration is thereby shorter, which does not benefit the formation and preservation of organic matter. Thus, oil shale is not developed in these two system tracts.

Organic matter enrichment of oil shale within the parasequence

Oil shale mainly develops in the lake flood period of each parasequence within the TST and HST. In a parasequence, paleoclimatic parameters including mean annual temperature (MAT/°C), mean annual precipitation (MAP/mm) and precipitation of the warmest month (WMP/mm) are calculated by the method of the Coexistence approach (CA) [14] utilizing spore-pollen data. This indicates that the precipitation during oil shale formation is greater than during the time of the deposition of the mudstones at the top and bottom. During the initial stage of the parasequence (the lake flood period), precipitation is greater than evaporation. Adequate nutrients make plankton flourish in the lakes, greatly increasing the initial lake

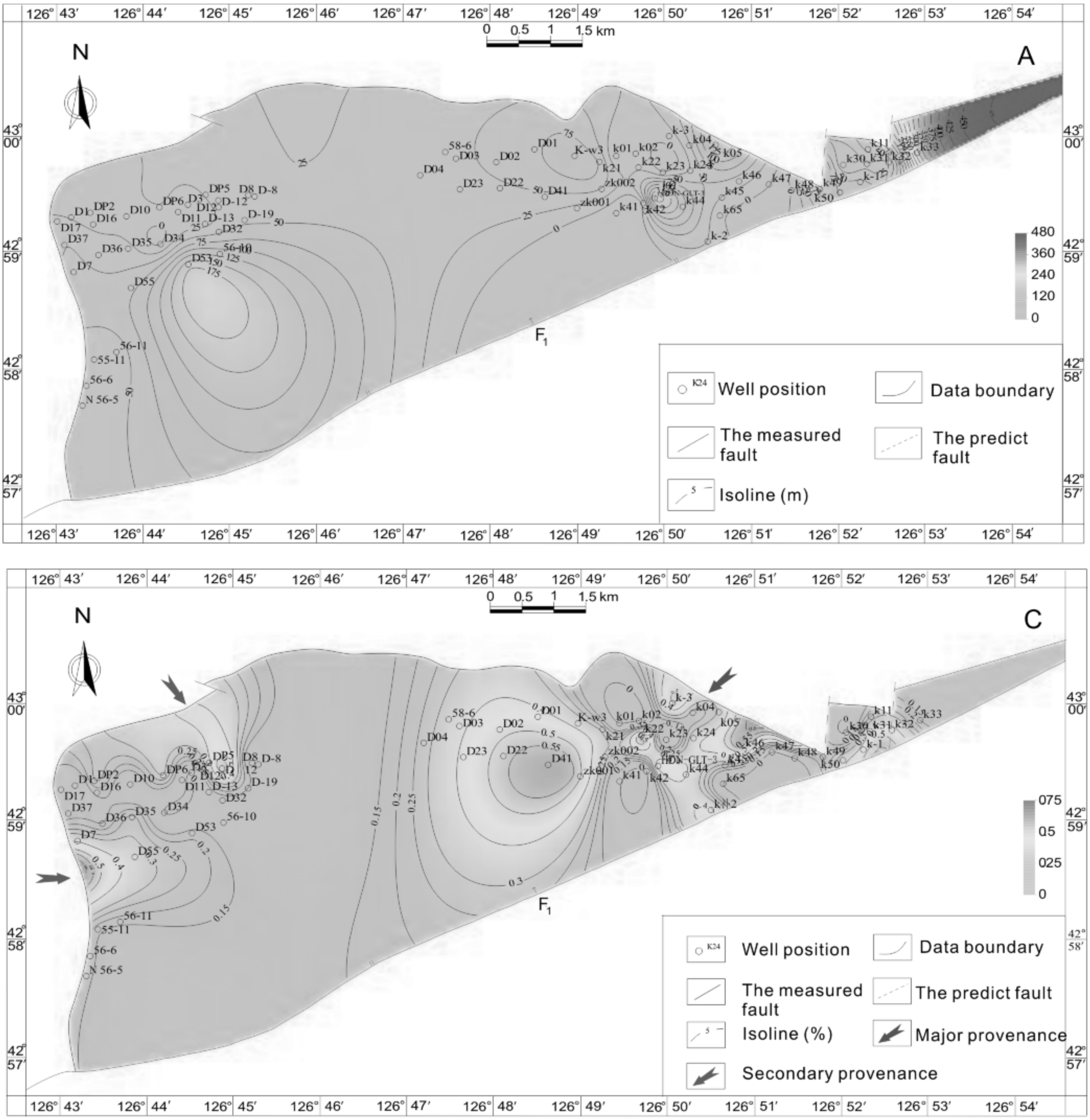
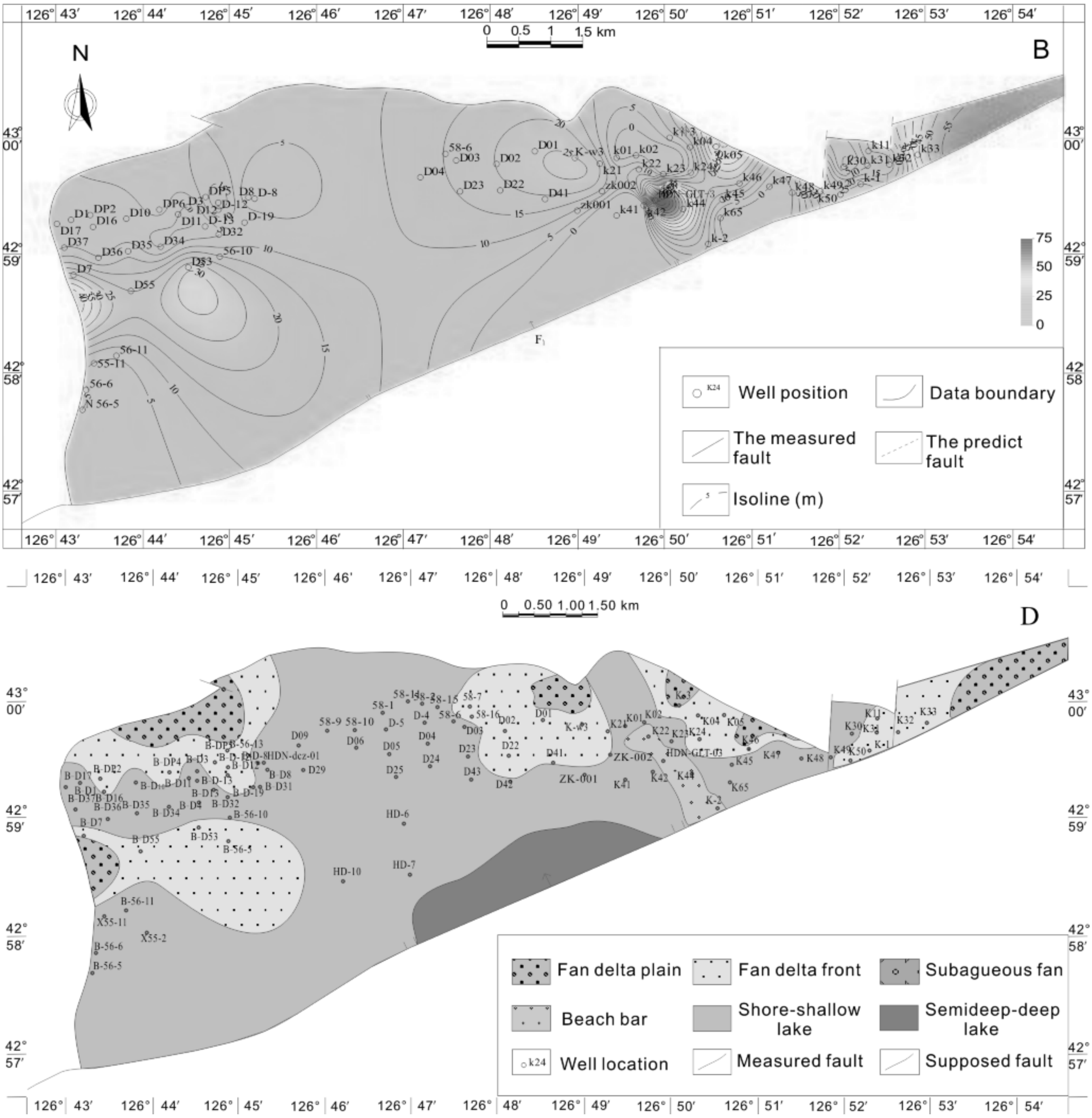


Fig. 8. Composition graphs of sedimentary facies analysis of the lower pyrite member in Huadian Basin.

A– atrata thickness contour map; B – sandstone thickness contour map; C– sandstone-strata ratio contour map; D – the plane graph of sedimentary facies.


B
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Well position
Data boundary
The measured fault
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Fan delta plain
Fan delta front
Subagueous fan
Beach bar
Shore-shallow lake
Semideep-deep lake
Well location
Measured fault
Supposed fault

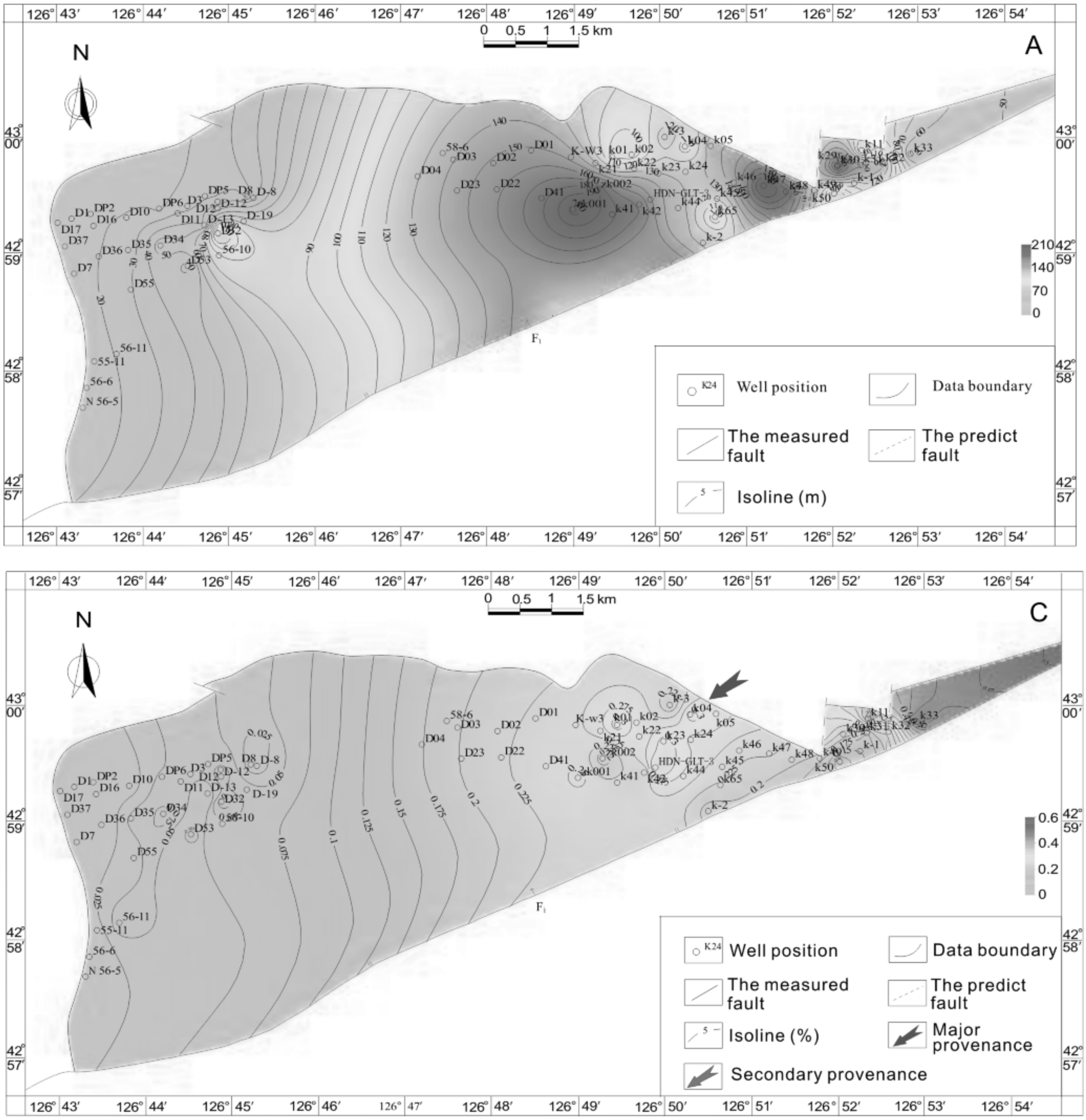
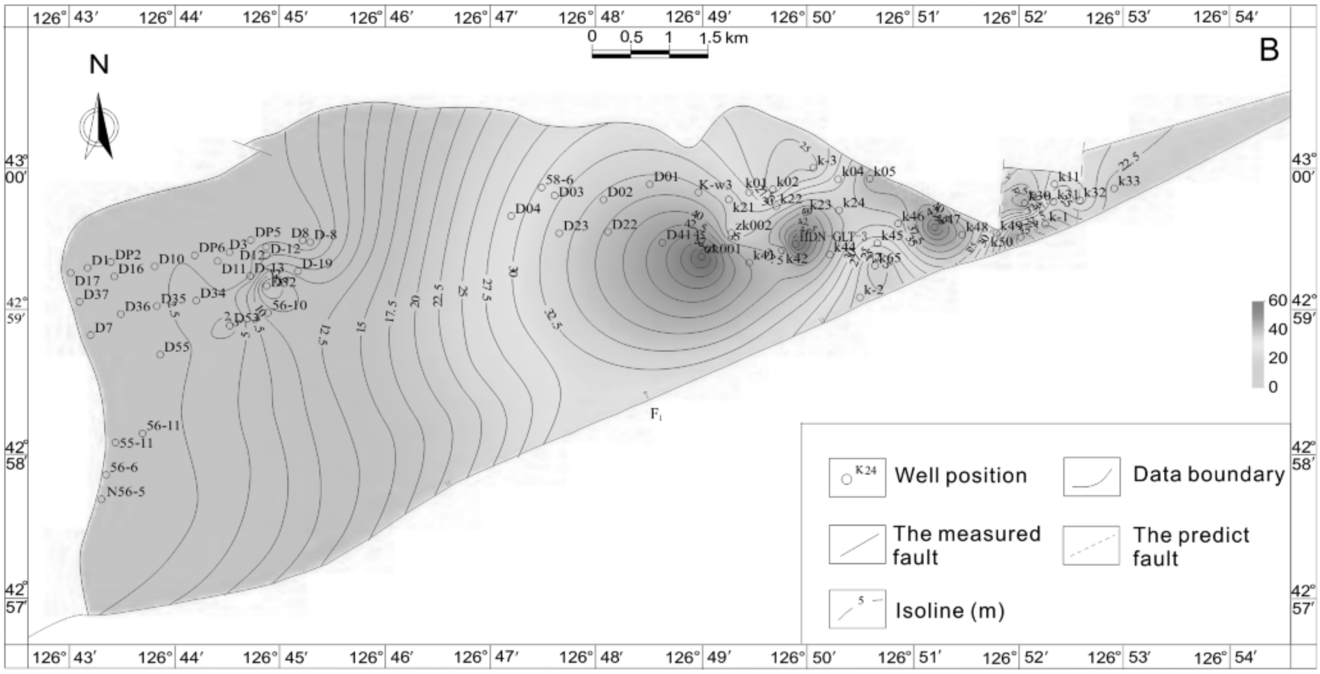
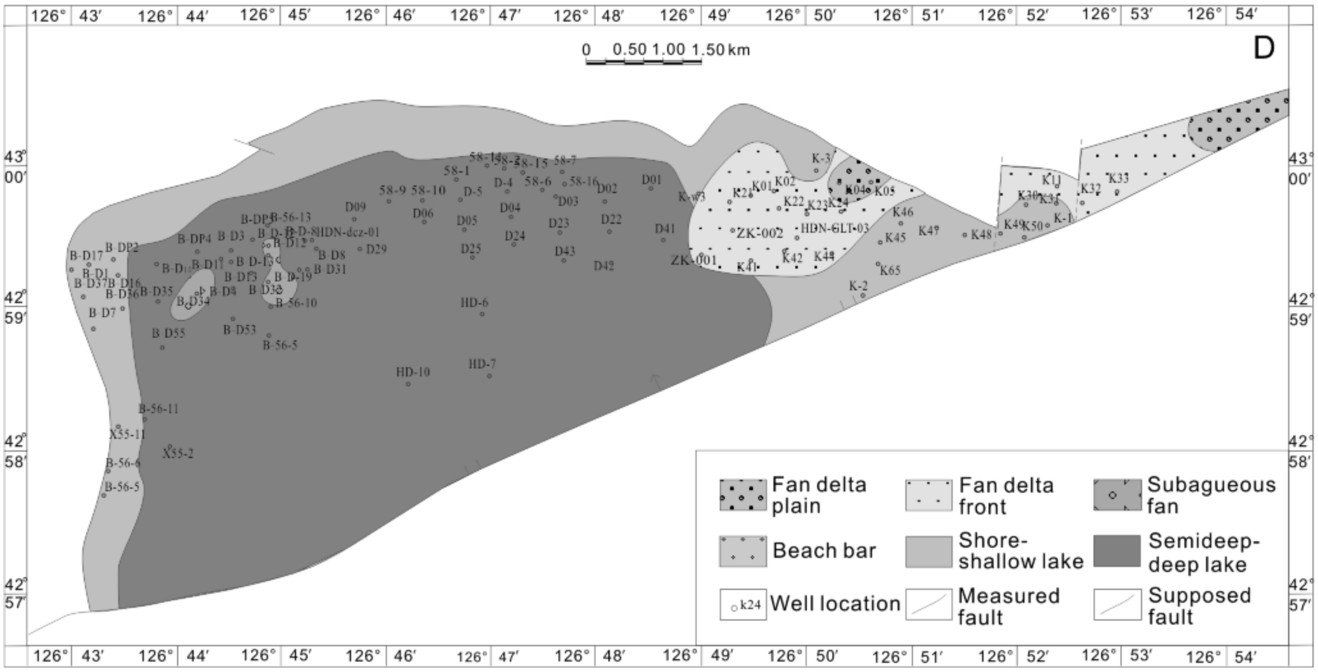


Fig. 9. Composition graphs of sedimentary facies analysis of the middle oil shale member in Huadian Basin.

A – strata thickness contour map; B – sandstone thickness contour map; C – sandstone-strata ratio contour map; D – the plane graph of sedimentary facies.


B
N
0 0.5 1 1.5 km
Well position
Data boundary
The measured fault
The predict fault
Isoline (m)
F₁


D
0 0.50 1.00 1.50 km
Fan delta plain
Fan delta front
Subagueous fan
Beach bar
Shore-shallow lake
Semideep-deep lake
Well location
Measured fault
Supposed fault

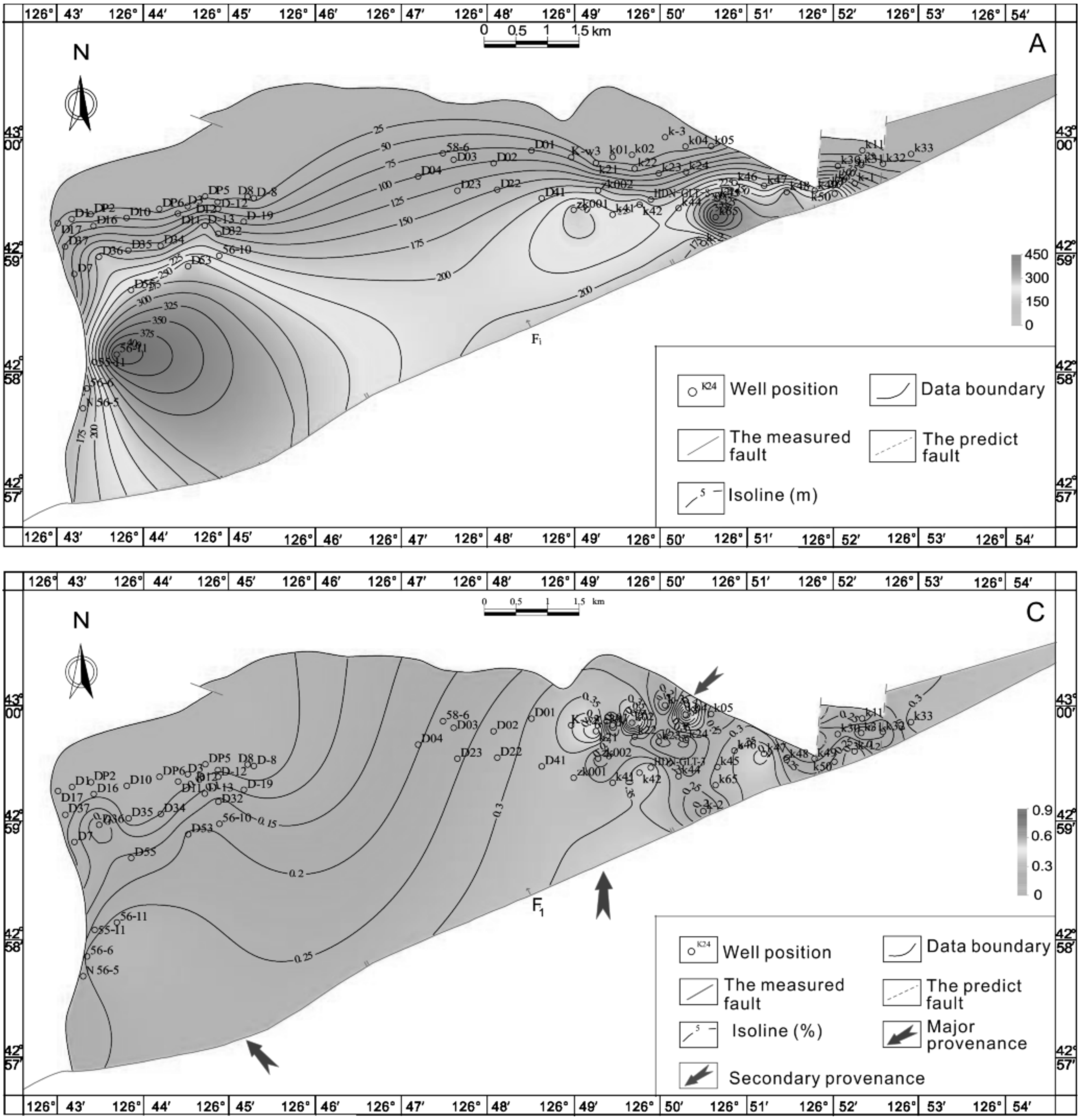
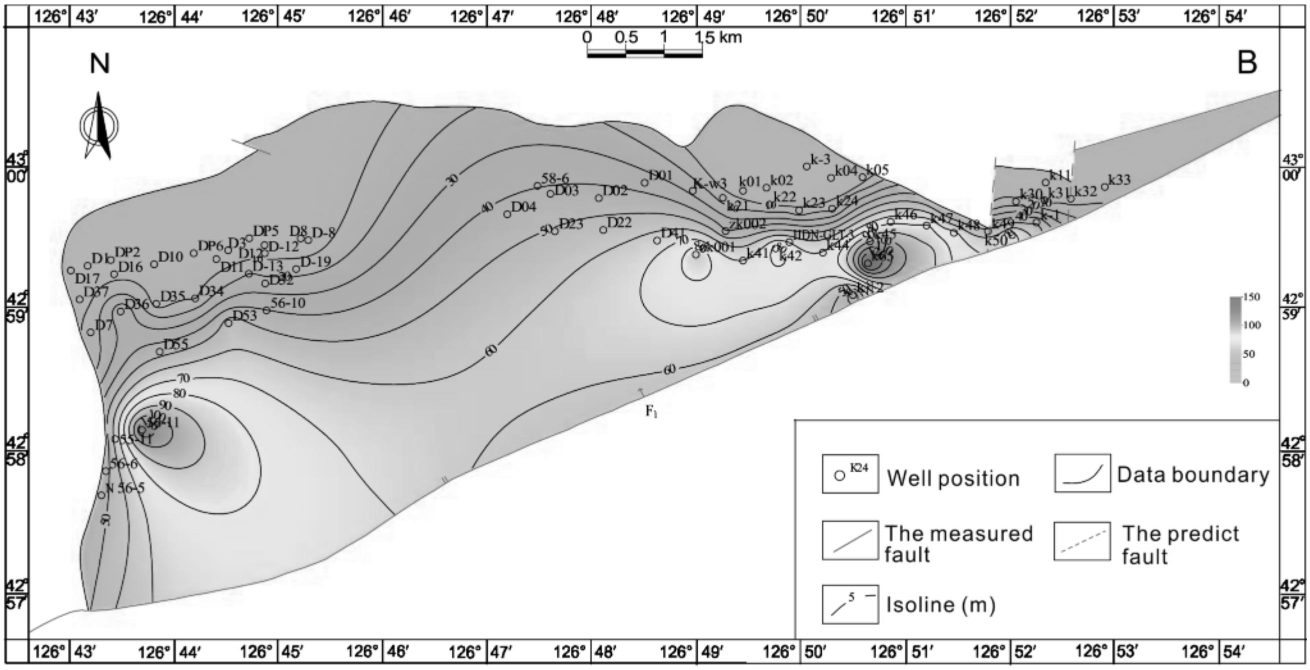
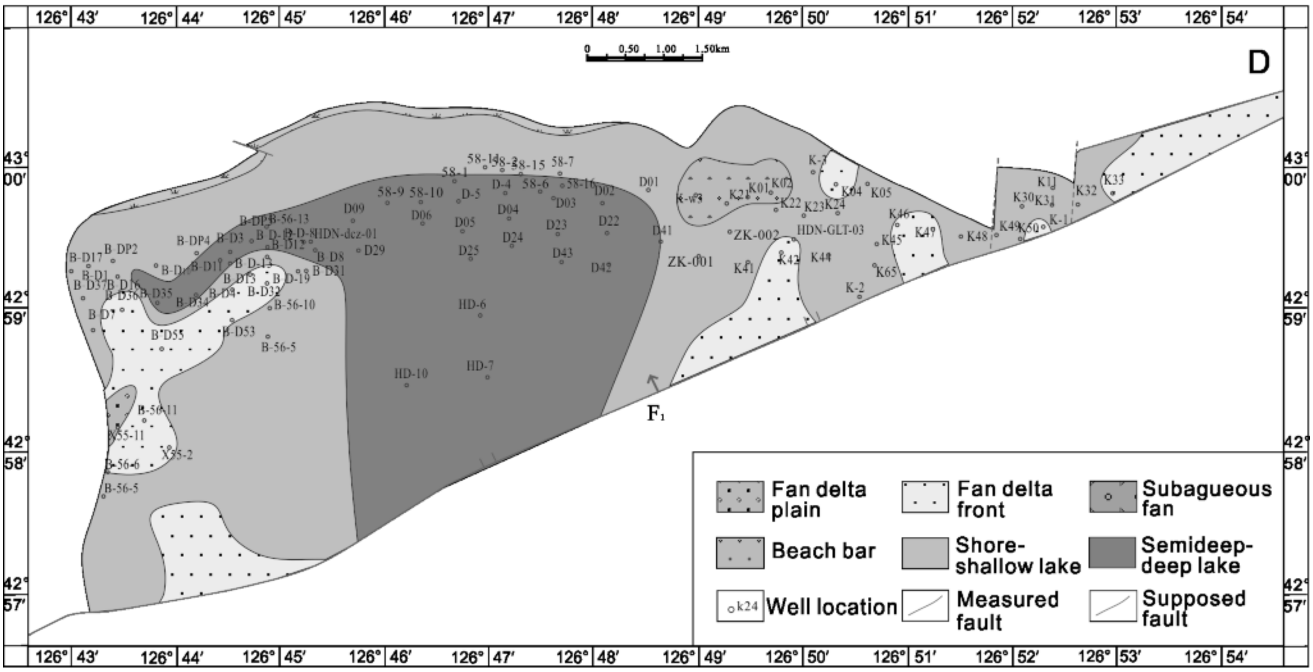


Fig. 10. Composition graphs of sedimentary facies analysis of the Upper Carbonaceous shale member in Huadian Basin.

A – strata thickness contour map; B – sandstone thickness contour map; C – sandstone-strata ratio contour map; D – the plane graph of sedimentary facies.


B
N
0 0.5 1 1.5 km
Well position
Data boundary
The measured fault
The predict fault
Isoline (m)
F1


D
0 0.50 1.00 1.50km
Fan delta plain
Fan delta front
Subagueous fan
Beach bar
Shore-shallow lake
Semideep-deep lake
Well location
Measured fault
Supposed fault
F1

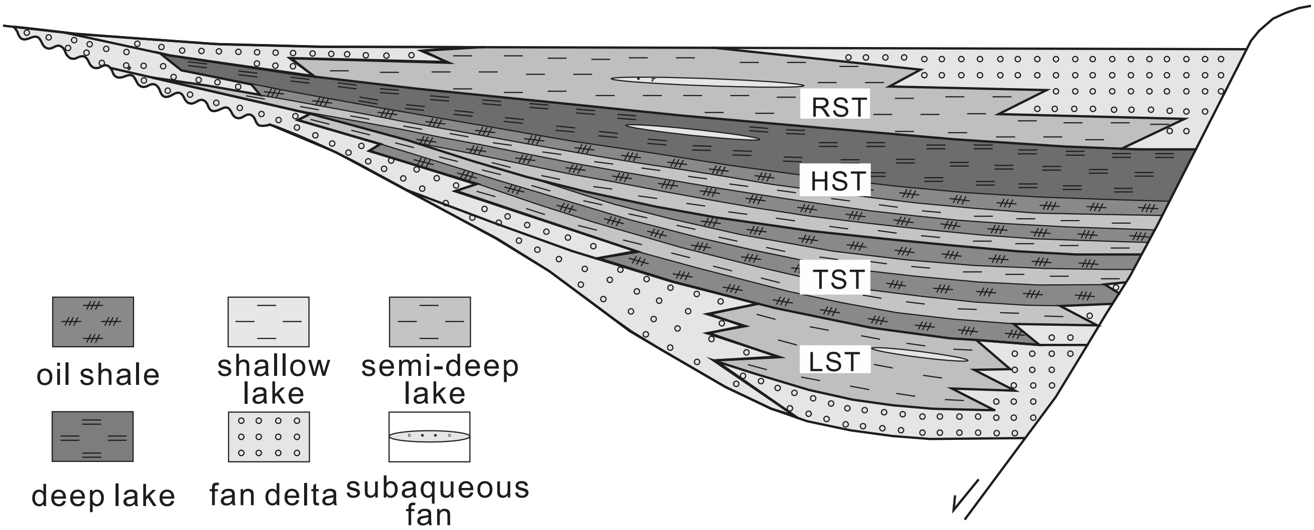


Fig. 11. Metallogenic model of oil shale in Huadian Basin.

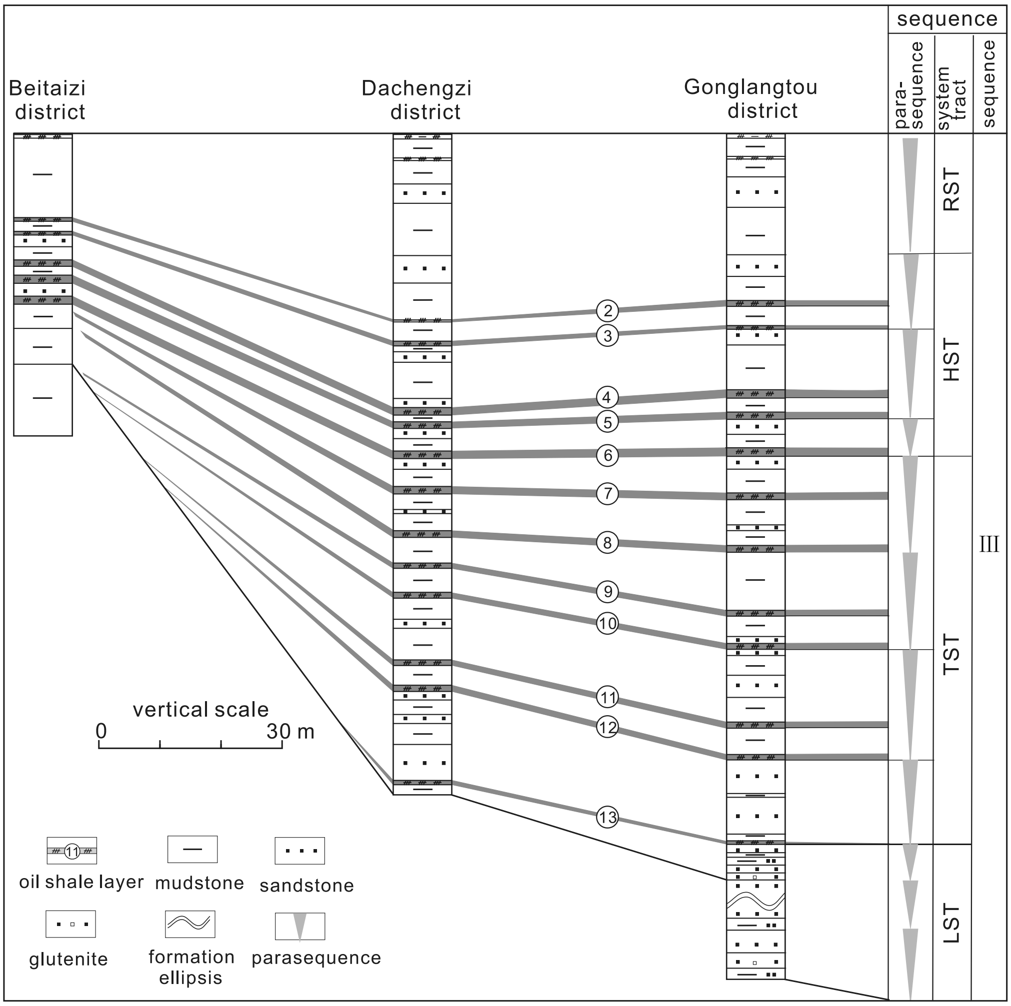


Fig. 12. Oil shale layers distributed in Sequence III.

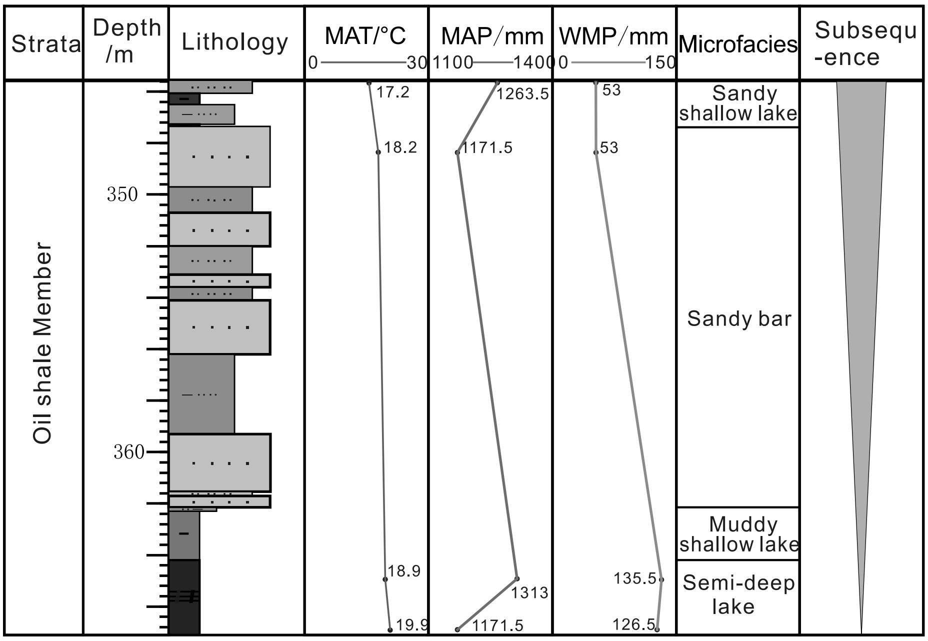


Fig.13. Palaeoclimatic parameters changes in one subsequence.

productivity. Meanwhile, the lake flooding effect causes the water depth to increase abruptly, leading to the rapid death of biota and providing abundant organic matter for oil shale formation. During the late stage of the parasequence, precipitation is lower than evaporation and the lake level fall. The geochemical parameters, including Sr/Ba, B and B/Ga show that the water is brackish (Fig. 4), which is conducive to forming a certain degree of salinity stratification and creating a reducing environment in the water near the bottom. This results in the formation of an anoxic layer restricting the oxygenolysis of organic matter deposited on the bottom, preserving the rapidly accumulated organic matter to a high degree and forming the economic oil shale deposits.

CONCLUSIONS

(1) The sequence stratigraphic framework of the Huadian Basin has been established using rock association, spore-pollen and geochemical data. Four third-order sequences are identified in the Huadian Formation. Sequences Ⅰ and Ⅱ are developed in the lower pyrite member of the Huadian Formation, sequence Ⅲ is developed in the middle oil shale member, and sequence Ⅳ is developed in the upper carbonaceous shale member.

(2) Three types of sedimentary facies, including fan delta, lacustrine and subaqueous fan, are identified in the Huadian Basin; the seare further sub divided into six subfacies and fourteen microfacies. Oil shale is mainly developed in the semi-deep and deep lake subfacies.

(3) The Huadian Formation experienced three sedimentary evolution stages; the initial subsidence stage of the lake basin (corresponding to the pyrite member) mainly developed shore-shallow lake and fan delta sediments.The maximum subsidence stage (corresponding to the oil shale member) was dominated by semi-deep and deep lake sediments.The rapid downwarp filling stage (corresponding to the carbonaceous member) mainly developed fan delta, limnetic and shore-shallow lake sediments.

(4) The oil shale memberic, developed in a whole third-order sequence. Oil shale mainly developed in the transgressive system tract (TST) and highstand system tract (HST). The TST developed the 7th to 13th layers of the oil shale,which exhibit thin beds, low to medium oil yield and low to medium organic matter enrichment. The HST developed the 2nd to 6th layers of oil shale, displaying widely distributed, thick beds, high oil yield and medium to high organic matter enrichment.

(5) In one parasequence, oil shale mainly developed in the lake flood period. High initial lake productivity and stable underlying water oxygen levels (lower decomposition rate) influenced by climate produce the most favorable conditions for oil shale formation.

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Секвенсстратиграфия и обстановка седиментацииэоценовой формации Хуадянь, бассейн Хуадянь (СВ Китая): перспективы для поисков горючих сланцев

Бассейн Хуадянь – небольшая, угле- и горюче-сланцевая кайнозойская сбросовая впадина в средней части зоны разлома Фушунь-Мишань, св Китая. Бассейн в основном состоит из палеоценовой формации Хуадянь и содержит огромные запасы горючих сланцев. В настоящее время бассейн также является одной из баз подземной разработки сланцев месторождений. В данной статье установлена секвенсстратиграфия эоценовой формации Хуадянь и изучена осадочная обстановка по результатам изучения керна и описания пяти скважин, а также анализов образцов с использованием различных подходов (изучение шлифов, определение пыльцы и химические анализы (общий органический углерод, дебит нефти и рассеянные элементы (B, Mo, Sr/Ba, B/Ga, Sr/Cu, V/V+Ni и Ni/Co). Четыре последовательности третьего порядка и три типа осадочных фаций, включая дельтовый конус выноса, озерный и подводный конусы выноса, были идентифицированы в формации Хуадянь. В эоцене бассейн испытал три этапа осадочной эволюции: на начальном этапе оседания развивались осадки мелководного прибрежного озера и дельтового конуса выноса, на максимальном этапе оседания преобладали осадки полуглубокого и глубоководного озера и на этапе резкого заполнения прогнутой области образовались отложения дельтового конуса выноса, пресного и мелководного прибрежного озера. Горючие сланцы формировались в основном в трансгрессивном фациальном ряду и полосе систем высокого стояния последовательности III (фациальная пачка горючего сланца полуглубокого и глубоководного озера). Трансгрессивный фациальный ряд образовал 7–13 слои горючего сланца, которые характеризуются маломощными слоями, низким до среднего дебитом нефти и слабым - средним обогащением органическим веществом. В полосе систем высокого стояния образовались со 2-го по 6-й слои горючего сланца, которые характеризуются широко распространенными, мощными слоями, высоким дебитом нефти и средним – высоким обогащением органическим веществом. В одном парасеквенсе горючий сланец формировался в период повышения уровня воды в озере. Высокая начальная продуктивность озера и стабильные кислородные уровни нижележащих вод (более низкая скорость химического выветривания) под воздействием климата создают очень благоприятную обстановку для формирования горючих сланцев.

Ключевые слова: **бассейн Хуадянь, секвенсстратиграфия, осадочная обстановка, эоцен, горючий сланец.**