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Fine-grained Lithofacies Types and Sedimentary Evolution Characteristics of the Lower Es3 to the Upper Es4 of the Eocene Shahejie Formation in Jiyang Depression

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Abstract

The lower Es3 to the upper Es4 of the Eocene Shahejie Formation in Jiyang Depression are the main layer for the development of fine-grained sedimentary rocks, with varying lithofacies types. Comprehensive use of a large number of analysis methods such as fine rock description, thin section identification and electron microscope observation, with fine-grained sedimentary rock composition as the first element, combined with rock type, color, sedimentary structure and micro-laminates to establish a fine-grained lithofacies division scheme. Taking Well NY 1 in Jiyang Depression as an example, the study area is divided into 8 lithofacies types. During the deposition process, the mineral components, environmental indicators, lithofacies and lithofacies combination of fine-grained sedimentary rocks changed frequently. Under the comprehensive control of paleo-water depth, paleo-salinity, paleo-climate, and paleo-redox environment, the Shahejie Formation Shahejie Formation Shahejie Formation was lowered to Sha4 The fine-grained rock depositional environment of the upper submember is divided into three stages: the first stage of dry and cold climate dominated by evaporation; the second stage of warm and humid climate affected by transgression and the third stage of relatively warm and humid climate. The difference in sedimentary environment affects the mineral composition, thereby controlling the type and development of lithofacies; lithofacies can also reflect changes in the depositional environment. Transgression caused changes in the sedimentary environment and fine-grained rocks in the second stage. Not all sedimentary processes will be affected by emergencies, which have the characteristics of accident and locality.

Keywords

Fine-grained Sedimentary Rocks; Lithofacies Types; Jiyang Depression; Shahejie Formation.

1. Introduction

In 1932, krumbein scholar put forward the concept of fine-grained sedimentary rocks in the analysis of rock grain size, which are clay grade and silt grade sediments with grain size less than 62.5 μ m, in which the clay grade sediments are less than 4 μ m, and the silt grade sediments have grain size ranging from 4 to 62.5 μ m, mainly composed of clay minerals, silt minerals, carbonate minerals and organic matter [1-5].Fine grained rock is widely distributed in sedimentary rocks, accounting for about

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two thirds of the total amount of sedimentary rock [6]. However, due to the small size, difficult observation and the limitation of ultra micro experimental conditions, the research of fine-grained rock has become a weak area in sedimentology and even geology [7-8].With the discovery and exploration of shale oil and gas resources, more and more attention has been paid to the fine-grained sedimentary rocks developed in deep water environment and rich in organic matter.Foreign research on fine-grained sedimentary rocks mainly focuses on marine shale, such as Williston Basin and Fort Worth basin in the United States. The mineral petrology characteristics of marine fine-grained sedimentary rocks are analyzed, and the lithofacies division scheme is established, which is named based on mineral composition, structure, biological characteristics, mineral size and rock color [9].The research scope of fine-grained sedimentary rocks in China is mainly lacustrine facies, and the lithofacies division and environmental interpretation of lacustrine fine-grained sedimentary rocks have been carried out in succession [10-16], and remarkable achievements have been made.There are the following schemes for the division of fine-grained lithofacies in the lower Es3-upper Es4 member of Shahejie Formation: the scheme for the division of fine-grained lithofacies is established based on the composition and sedimentary structure; the type of fine-grained lithofacies is divided on the basis of sedimentary structure and organic matter content with carbonate minerals, silt minerals and clay minerals as three end members [5].Jiyang depression is an important area for the exploration and development of continental shale oil in eastern China. Based on a large number of core and thin section observation data and test data, using sedimentology, petrology, geochemistry and other research methods, the fine-grained lithofacies division scheme of lower es3-upper Es4 member of Eocene Shahejie Formation in Jiyang depression is established, and the petrological characteristics, component composition and genesis are analyzed The sedimentary evolution characteristics of fine-grained rocks have important theoretical and application value for the exploration and development of continental shale oil in Jiyang depression.

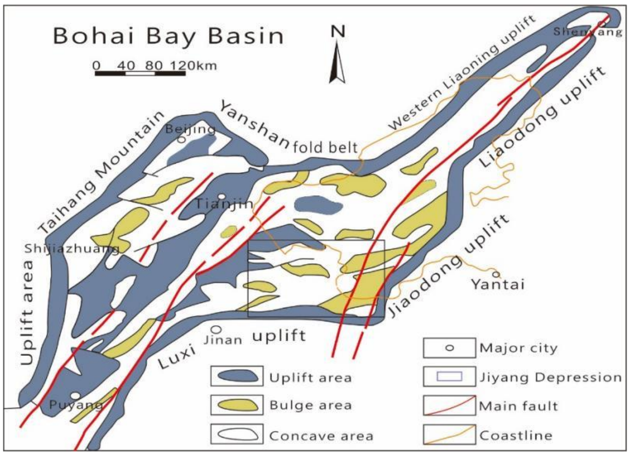

Fig. 1 Geographical location of Jiyang Depression(Modified according to reference [20])

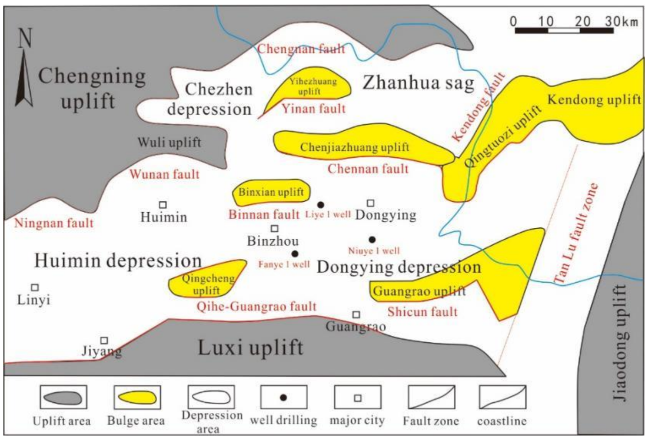

Fig. 2 Regional geological characteristics and drilling location in Jiyang Depression(Revised according to literature [21])

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2. Regional Geological Background

Jiyang depression is a typical continental basin in the southeast of Bohai Bay Basin (Fig. 1). It was formed at the end of Late Cretaceous and is one of the most oil-gas rich areas in Bohai Bay basin. Tanlu fault zone is developed in the East, chengning arc uplift zone is developed in the West and North, and Luxi uplift zone is adjacent to the south. The depression area is about 2.65 × 104km2, including four depressions: Dongying, Zhanhua, Huimin and Chezhen, and six uplifts: Guangrao uplift, Qingcheng uplift, Binxian uplift, Wudi uplift, Yihezhuang uplift and qingtuozi uplift (Fig. 2).

Dongying sag is a typical asymmetric half graben depression, located in the south of Jiyang depression. It is a typical representative of oil-rich sag in Mesozoic Cenozoic continental fault basin in eastern China. The source rocks of Shahejie formation are well developed, and the main horizons of source rocks are lower es3-upper Es4[18]. Qingtuozi uplift is located in the east of the sag, Qingcheng uplift in the west, Luxi uplift and Guangrao uplift in the south, Chenjiazhuang uplift and Binxian uplift in the north, with nee strike, 90 km long from east to west, 65 km wide from north to south, with an area of about 5850 km2, which is characterized by "North Fault and South overlap, west fault and East overlap" [19]. From bottom to top, the strata are Kongdian formation, Shahejie formation, Dongying Formation, Guantao Formation and Minghuazhen Formation. The fine-grained sediments of Shahejie formation are widely distributed, which can be subdivided into the fourth member of Shahejie formation to the first member of Shahejie formation.

3. The basis of lithofacies Division

3.1 Mineral composition and rock type

In order to accurately study the composition characteristics of Oligocene continental fine-grained sedimentary rocks in Jiyang depression, well niuye-1, well fanye-1 and well liye-1 are selected as the research objects, and the core sections of Shahejie Formation in three wells are continuously and intensively sampled (the samples are taken from the core library of Shengli Oilfield Branch of Sinopec). Through XRD mineral content analysis and electron microscope observation, it is found that the main minerals in the study area are carbonate minerals, clay minerals and clastic minerals (Table 1). Carbonate minerals account for the main part, mainly including calcite, a small amount of dolomite and siderite, accounting for about 40% - 50%; clay minerals are mainly composed of illite, a small amount of chlorite and illite / montmorillonite mixed layer, accounting for about 25% - 35%; clastic minerals are mainly felsic minerals, accounting for more than 25%. Secondary components include organic matter, sulfate minerals and pyrite. Based on the carbonate, clay and clastic mineral contents of 486 samples from three wells, Niuye 1, Fanye 1 and Liye 1, the author draws a triangle (Fig. 3).

Table 1. The Main mineral compositions of fine grained sedimentary rocks

Well number	Carbonate minerals			clay mineral			Detrital minerals		
	Mean value	Maximum value	Minimum value	Mean value	Maximum value	Minimum value	Mean value	Maximum value	Minimum value
Niuye 1 well	45.49	93.00	1.00	35.57	83.70	2.90	26.23	51.40	4.10
Fanye 1 well	40.61	76.00	4.65	33.42	53.94	11.60	30.34	72.60	13.40
Liye 1 well	37.54	70.00	3.00	41.40	80.30	17.40	29.53	44.50	14.60

3.2 Sedimentary structure

Sedimentary structure refers to the arrangement and spatial distribution of different components of sedimentary rocks formed by physical, chemical and biological processes during or after deposition [5]. Sedimentary structure is one of the main factors for lithofacies classification. The fine-grained sedimentary rocks in the lower part of Shahejie formation, niuyi 1 well, Jiyang depression, are characterized by multi-stage paper stacking (FIG. 4A); the hillock interlayers are developed in shale, which are in erosion contact with the lower fine-grained sedimentary rocks (Fig. 4b); lens bedding is developed, which is mainly composed of calcite lenses, which are of different sizes and vertical

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orientation The results show that the structure is in sequence arrangement (Fig. 4C); the slow wave bedding is developed, and the wave characteristics can be observed under polarizing microscope, and the horizontal is undulating and the thickness is unstable (Fig. 4D); the S-shaped and W-shaped cladding bedding (Fig. 4e) is developed; and the block structure (Fig. 4) is developed.

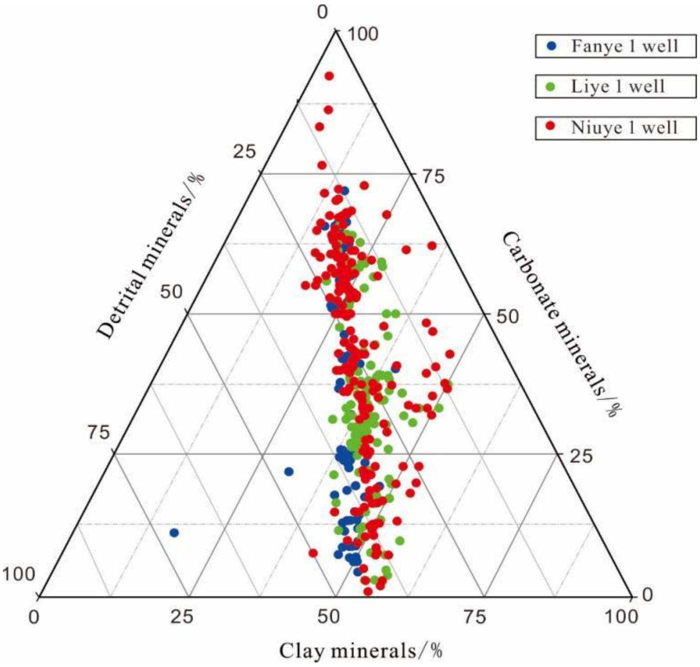
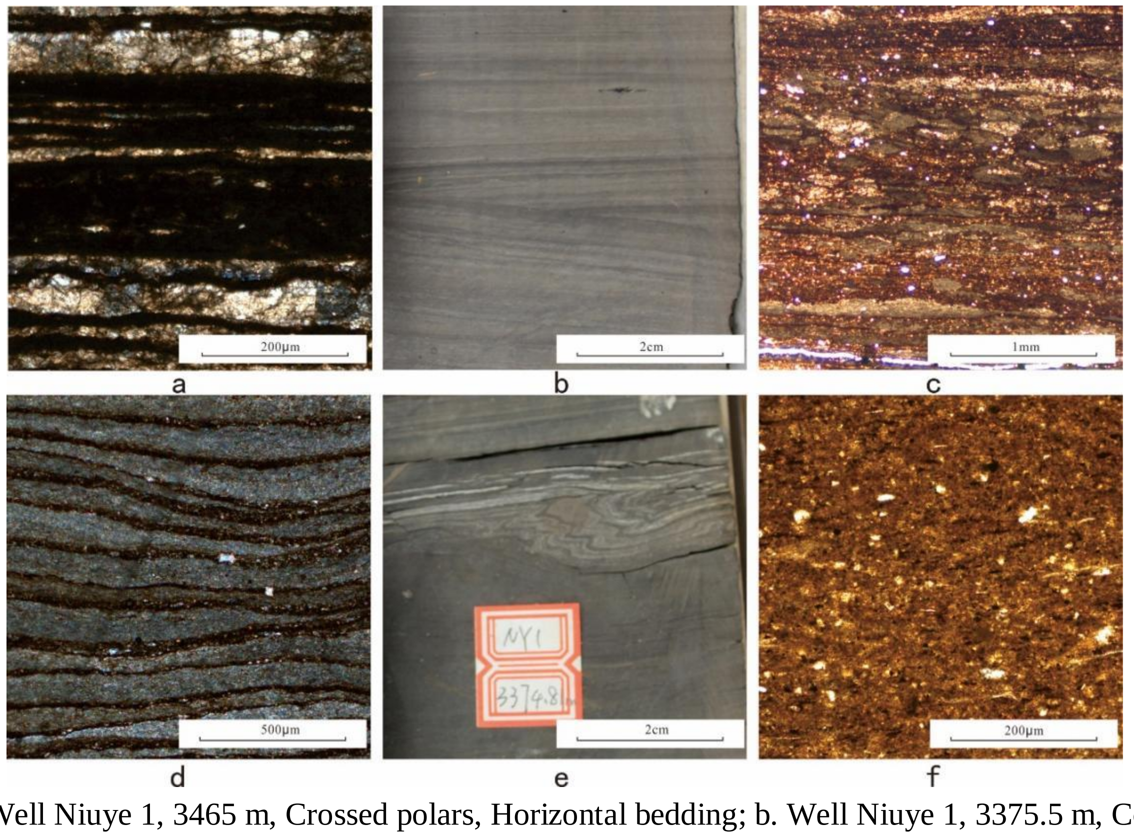


Fig. 3 Ternary diagram of the mineral composition



a. Well Niuye 1, 3465 m, Crossed polars, Horizontal bedding; b. Well Niuye 1, 3375.5 m, Core photos, Mound cross bedding; c. Fanye well 1, 3138.8 m, Cross-polarized light, Lenticular bedding; Niuye well 1, 3441.75 m, Cross-polarized light, Slow-wave bedding; Niuye well 1, 3374.8 m, Core photo, Wrap bedding; Fanye well 1, 3088.15 m, Single polarized light, Massive structure

Fig. 4 Fine-grained sedimenttectonic characteristics of the lower Es3 member-upper Es4 member

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3.3 Microlamination

The sedimentary structure of outcrop in the field is not obvious, and a series of sedimentary structure characteristics can be found after sampling and testing in the laboratory. The analysis of small-scale structures in rocks (a few millimeters or even a few centimeters) can explain the sedimentary conditions and related information of rock development [22]. The author takes lamina as one of the main basis of lithofacies division, which can better explain the sedimentary environment and reservoir space of fine-grained rocks. Based on the analysis of the lamina development in the study area, according to the lamina thickness, lamina properties, organic matter content and lamina spatial distribution, the micro lamina classification scheme is established, and the micro lamina is divided into four categories and nineteen sub categories.

3.3.1 Classification By Lamina Thickness

The striations with a single lamina thickness of more than 50% in the range of 1-5mm are named fine lamina; the striations with a single lamina thickness of more than 50% in the range of 0.1-1 mm are named thin lamina; the striations with a single lamina thickness of more than 50% in the range of 0.01-0.1 mm are named extremely thin lamina; the striations with a single lamina thickness of less than 50% in the range of 1-5 mm, 0.1-1 mm and 0.01-0.1 mm are all less than 50% and in the range of 0.1-1 mm The lamina between 0.01 mm and 0.1 mm is named thinner lamina.

3.3.2 Classification By Laminar Property

Those with the same or similar mineral composition of lamina are classified as one kind of lamina and measured and counted. The sand lamina is defined as the lamina with more than 50% silty lamina; the lamina with more than 50% argillaceous lamina is defined as the lamina with silt; the lamina with more than 50% mixed lamina is named as the mixed lamina; the lamina with less than 50% silt, less than 50% argillaceous, less than 50% mixed lamina and more than 50% argillaceous content is named as the mixed lamina silty lamina; the lamina with less than 50% silt, less than 50% argillaceous, less than 50% mixed lamina and more than 50% argillaceous content is named as the mixed lamina silty lamina The laminae with less than mud content is named Silt Mixed laminae.

3.3.3 Classification By Organic Matter Content

The laminae with more than 50% organic matter content and less than 50% sum of heterogeneous and matrix is named as organic laminae; the laminae with more than 50% heterogeneous component and less than 50% sum of organic matter and matrix is named as heterogeneous laminae; the laminae with more than 50% matrix and less than 50% sum of organic matter and heterogeneous laminae is named as matrix laminae, which is actually not obvious laminae; the laminae with less than 50% heterogeneous component and less than 50% sum of organic matter and matrix is named as heterogeneous laminae The lamina with matrix < 50% and heterogeneous lamina > matrix is named organic matter heterogeneous lamina; the lamina with heterogeneous lamina < 50%, organic lamina < 50%, matrix < 50% and matrix > heterogeneous is named organic matter matrix lamina.

3.3.4 Classification By Lamina Spatial Distribution

The striations with continuous distribution of heterogeneous components > 50% are named as continuous layer; the Interlaminal layer with discontinuous but stable heterogeneity > 50% is named as the continuous layer; the non continuous and unstable grain layer > 50% is named as lenticular layer; the Interlaminal layer is less than 50%, the continuous layer is less than 50%, the lenticular layer is less than 50%, and the Interlaminal layer is more than lenticular layer. The striated layer is more than lenticular layer The Interlaminal layer is named continuous discontinuous layer, the continuous layer is less than 50%, the continuous layer is less than 50%, the lenticular layer is less than 50%, and the Interlaminal layer is less than the lenticular layer. The layer is named continuous lens layer.

4. Types and Characteristics of Fine-grained Lithofacies

In continental sedimentary basins, fine-grained sedimentary rocks account for a high proportion, which are characterized by complex lithofacies, fast phase transformation and heterogeneity. The

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study of fine-grained rocks in deep water is still in an exploratory stage. With the opening up of a new field of oil and gas exploration in the center of the lake basin, the basic research on the types and facies of fine-grained rocks has been strengthened at home and abroad. The analysis of petrological characteristics, composition and genesis is of guiding significance for oil and gas exploration[12].

4.1 Division scheme

Based on the previous study on the division scheme of fine-grained lithofacies [16], the fine description of core, thin section identification and electron microscope observation and analysis, combined with the composition, color, structure and texture of fine-grained sedimentary rocks in the paper, the lithofacies division scheme of fine-grained sedimentary rocks in the lower part of sha3-shasi upper sub section of niuyi 1 well in Jiyang depression is established. The division principle is as follows: 1) in the previous study, the lithofacies division scheme of fine-grained sedimentary rocks in the lower part of Shasan to upper part of Shasi in niuyi 1 well in Jiyang Depression The paper proposes a division scheme for the research results of the lower and lower Shahejie upper sub sections of shasansi formation; 2) the paper emphasizes the significance of the characteristics of the striated layer in fine-grained rocks, strengthens the role of the identification and type division of the striations in the lithofacies division; 3) the paper improves the importance of fine-grained sedimentary structure in the lithofacies division. Finally, fine-grained sedimentary rocks in the study area are divided into 8 lithofacies types by the way of the pattern type (form) + sedimentary structure + lithology.

4.1.1 Carbonate Rocks

Organic matter laminar massive limestone facies (Fig. 5a): massive structure is developed, mineral composition is mainly calcite, carbonate composition is evenly distributed, argillaceous is second, dense, hard, medium brittleness, flat fracture, poor water absorption, strong foaming after dropping hydrochloric acid. The massive limestone is mainly controlled by primary sedimentation and formed in semi deep lake environment.

Horizontal organic matter heterogeneous laminar argillaceous limestone facies (Fig. 5b): horizontal bedding and wavy bedding are developed. Carbonate lamina and organic lamina are interbedded, and they occur alternately. The carbonate laminar minerals are mainly composed of bright calcite and a small amount of cryptocrystalline calcite, which are formed by recrystallization during diagenesis. The sedimentary environment of this kind of microfacies is mainly the deposition of biomass in the lake, and the lamina contains a very small amount of terrigenous clastic material, which is related to the light, climate and other factors in the sedimentary stage [23].

Table 2. Lithofacies categories

Major categories	Category	Lamina type	Sedimentary structure
Carbonate rock	Organic laminar massive limestone facies	Stromal lamina	Massive structure
	Horizontal organic matter heterogeneous bedded argillaceous limestone facies	Heterogeneous lamina Lamella	Horizontal bedding Wavy bedding
Clay rock	Intermittent clayey layered mudstone facies	Intermittent lamina Lenticular lamina	Horizontal bedding Lenticular bedding
	Laminar calcareous mudstone facies of horizontal organic matter	Heterogeneous lamina Lamella	Horizontal bedding Gentle wave bedding
	Organic matter continuous laminar shale facies	Organic texture layer Continuous lamina	Page management
	Horizontal clayey layer with carbonate layered calcareous mudstone phase	Mixed lamina	Horizontal bedding Roll bedding
Siltstone group	Horizontal fine grained bedded siltstone facies	Microlamina	Horizontal bedding Wavy bedding Cross bedding
Mixed fine-grained sedimentary rocks	Massive limestone migmatite facies	Mixed lamina Silt Mixed lamina	Massive structure

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4.1.2 Clay Rock

Intermittent clayline bedded mudstone facies (Fig. 5C): horizontal bedding and lenticular bedding are developed. Clay grain layer accounts for most of them, and the polymerization force of fine-grained materials is large, which leads to the small part of calcite grain which completes the sedimentation after being broken, and the majority of particles are gathered in one piece, which is represented by calcite lens [24]. Therefore, there are a large number of carbonate lenses in the clay grain layer. The water body in the sedimentary period was layered. Under the condition of that time, the bottom flow scour was existed in the half deep lake and deep lake, which resulted in intermittent and lenticular layers. Meanwhile, the storm and other actions make the sediment at the bottom of the lake suspended, which causes the striated layer to break, and intermittent striated layer can be formed when the sedimentation again[11].

Laminar calcareous mudstone facies of horizontal organic matter (Fig. 5d): horizontal bedding and gentle wave bedding are developed. The bedding is composed of black organic matter lamina, grayish yellow clay lamina and light color carbonate lamina. The thickness of the fine layer ranges from 1.0 mm to 2.0 mm. The carbonate lamina is in parallel plane shape with good continuity and is generally interbedded with clay lamina. This kind of microfacies composed of three different laminae is also called three terminal laminae. The formation of three terminal lamina is due to the flocculation of clay minerals, which adsorbs organic matter produced by algae or plankton, and Ca ions which are easy to form carbonate minerals. In the process of deposition, as a typical seasonal lamina, the three terminal lamina was completely preserved under the changeable climatic conditions [25].

Organic matter continuous laminar shale facies (Fig. 5e): developed foliation structure, with a thickness of 0.1-0.55mm. The foliation is mainly composed of dark gray argillaceous and brown gray lamina, with uniform distribution of gray matter, relatively hard, high brittleness, and rich in organic mineral components. During the development of the strata, the deposition rate of oil shale is lower than that of mudstone, which indicates that it was in still water environment at that time. Jiyang depression in the lower es3-upper Es4 sedimentary period is in the dry period to the wet period of the paleoclimatic environment, which makes the ancient lake system produce salinity stratification. In the deep lake environment with high salinity and hypoxia, the deposition rate of suspended matter is slow, the lake basin presents the state of under compensation, and the layered structure of the water body makes the organic matter in the sediment be effectively preserved [26].

Horizontal clay lamina intercalated with carbonate lamina calcareous mudstone facies (Fig. 5F): horizontal bedding and convolution bedding are developed. The components are mainly dark gray clayey thin laminae with gray white carbonate laminae, and there is an obvious boundary between the two laminae. The massive calcite in the carbonate lamina is similar to the lump or semicircle in shape, and the minerals in the clay lamina deposit in the form of flocculation, indicating that some carbonate minerals were adsorbed in the process of deposition.

4.1.3 Siltstone

Fine grained bedded siltstone facies (Fig. 5g): horizontal bedding, wavy bedding and cross bedding are developed, which are mainly composed of heterogeneous siltstone, showing light gray or grayish yellow, indicating that the fine grained layer and mud rich thin layer are closely interbedded at that time. Combined with the sedimentary characteristics of lithofacies, it shows that the sedimentary environment at that time was semi deep lake sedimentary facies belt or semi deep lake shallow lake sedimentary facies belt with insufficient provenance [27].

4.1.4 Mixed Fine Grained Sedimentary Rock

Massive limestone migmatite facies (Fig. 5H): massive structure is developed, which is composed of uniformly distributed siltstone and gypsum. The formation of massive migmatite facies is due to the rapid accumulation of sediments under the action of gravity flow, which is the product of deep lake turbidite. The gypsum deposit is formed in the dry climate environment because of the strong evaporation of ancient lakes, insufficient supply of material sources, high salinity and rich in chloride ions, resulting in the enhanced reducibility.

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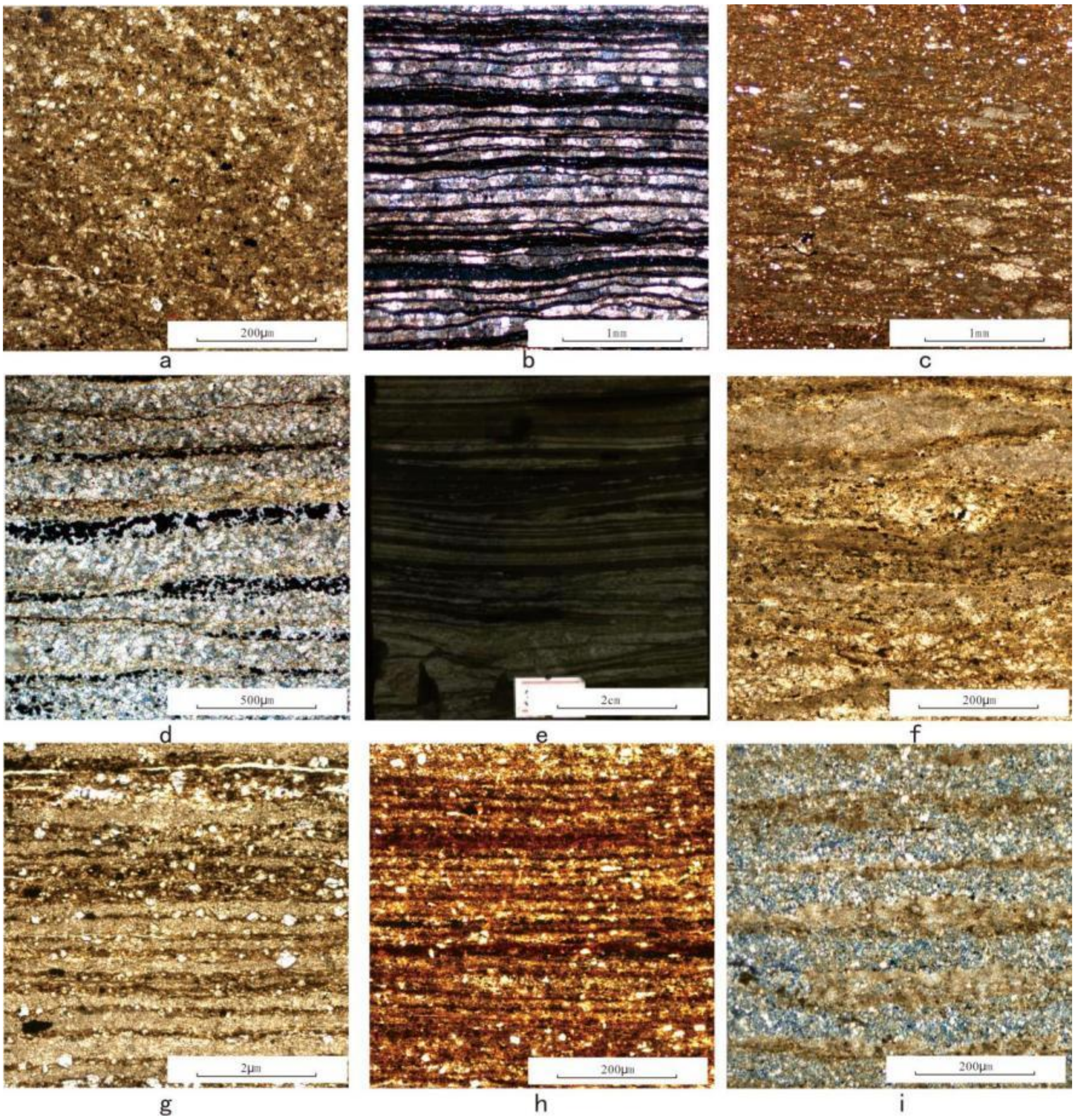

(a) NY Well 1, 3336.00m, organic matrix lamina; (b) NY Well 1, 3465.00m, heterogeneous laminae of organic matter and thin laminae;

(c) NY Well 1, 3313.80m, intermittent lamina and lenticular lamina; (d) NY Well 1, 3419.94m, heterogeneous lamina and thin lamina; (e)NY Well 1, 3453.46, m, core photo; (f) NY well 1, 3325.50m, clay laminae intercalated with carbonate laminae; (g) NY Well 1, 3460.50m, fine lamina; (h) NY Well 1, 3499.95m, mixed lamina; (i) NY Well 1, 3575.80m, silty sand mixed lamina

Fig. 5 Microfacies characteristics of fine grained sedimentary rocks from lower Es3 to upper Es4 of well Niuye 1

5. Sedimentary Environment and Genetic Model

5.1 Sedimentary environment and its evolution characteristics

Fine grained sedimentary rocks in different sedimentary environments have different characteristics in mineral composition, lithofacies assemblage and sedimentary structure. The essence of the difference is that different sedimentary basins show different geochemical environments, and the law of element enrichment is also quite different. Therefore, the ratio of elements and element combinations can be used as a criterion for distinguishing sedimentary environments [28]. In this paper, the fine-grained rocks from the lower Es3 to the upper Es4 of well niuye-1 in Jiyang depression are

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taken as the research object, and the elements at different depths and their ratios are used to represent the sedimentary evolution characteristics of the fine-grained rocks, such as paleoclimate, paleowater depth and paleosalinity, so as to further explain the changes of sedimentary environment (Fig. 6).

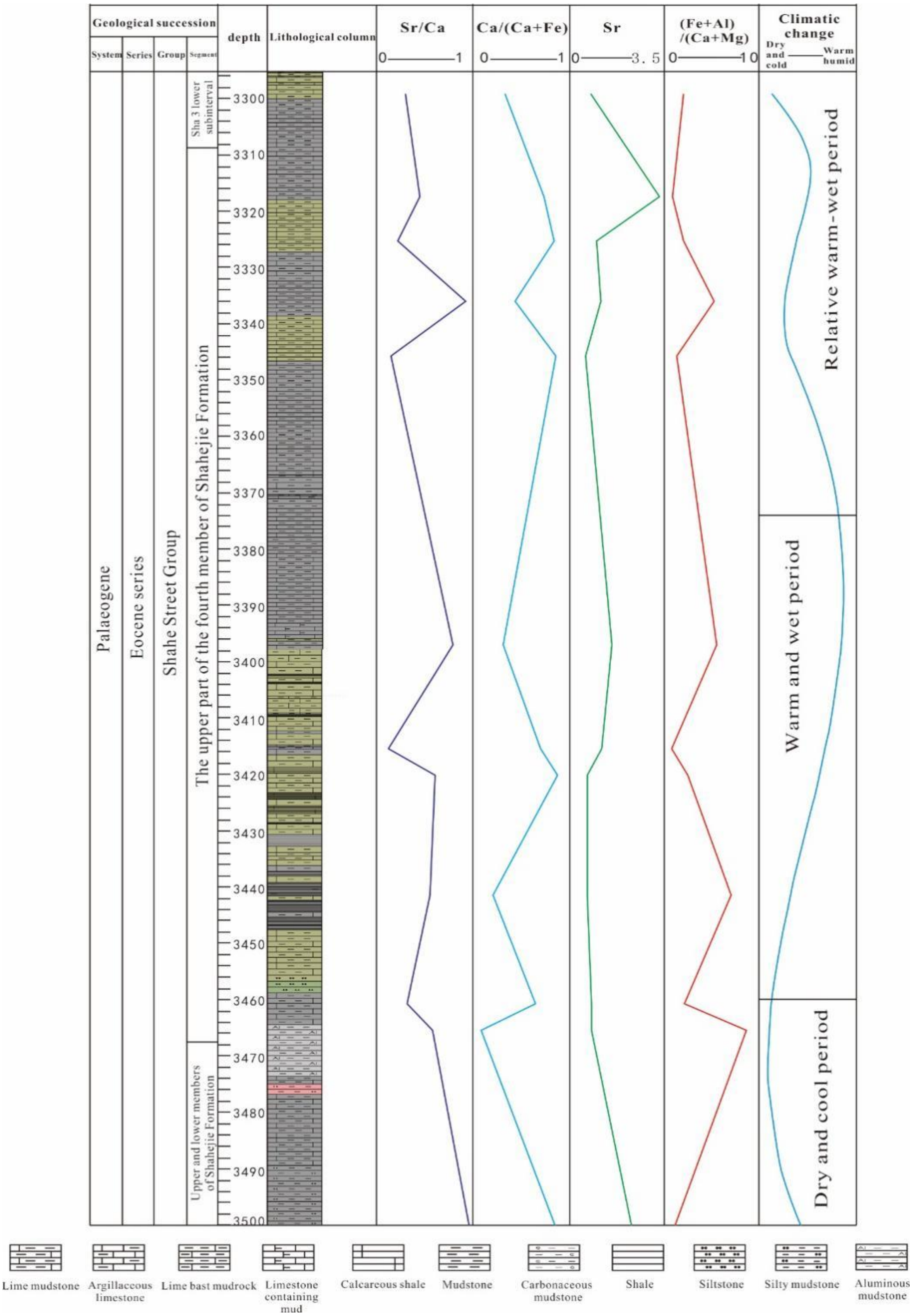

Fig. 6 Geochemical analysis of fine granulite elements in the lower submember of lower Es3 member-upper Es4 member, NY-1 well

5.1.1 Sr

Sr element is more sensitive to the change of paleoclimate, and it occurs stably in weathering. Its relative enrichment may be the result of lake water concentration and precipitation under dry and hot conditions [29]. When the paleoclimate is dry and hot, the content of Sr is higher, when the paleoclimate is warm and humid, the content of Sr is lower. Therefore, the content of Sr is positively correlated with paleoclimate. In this paper, the content of Sr element decreases first and then increases, which indicates that the climate of the upper pure lower sub segment of the fourth member of the Shahejie formation changes from dry and hot to warm and humid, and the climate of the upper pure upper sub segment of the fourth member of the Shahejie formation changes from humid to dry and then to humid rapidly.

5.1.2 Sr/Ca

The change of Sr / Ca index can reflect the paleosalinity of the lake basin, which has a positive correlation. The high index indicates that the lake is in a saline environment, and the low value indicates that the lake is in a freshwater environment [29]. In this paper, the Sr / Ca index shows a trend of first decreasing, then increasing and then decreasing, which indicates that the salinity of water body in sedimentary environment first decreases, then increases and then decreases. The periodic change of salinity is not only related to the change of dry and wet climate, but also caused by the fourth seawater intrusion.

5.1.3 Ca/(Ca+Fe)

The Ca / (Ca + Fe) index is used to judge the sedimentary environment by the relationship between the relative ratio of Ca to Fe and paleosalinity, which is the sedimentary phosphate method. When the index is greater than 0.8, it indicates salt water deposition; when the index is less than 0.4, it indicates fresh water deposition; when the index is between 0.4-0.8, it indicates brackish water deposition [30]. In this paper, the Ca / (Ca + Fe) index is between 0.19 and 0.8, and the ratio is generally high, mostly in brackish saline water environment.

5.1.4 (Fe+Al)/(Ca+Mg)

The content of Fe and Al in terrigenous clastic sediments is relatively high. When the content of carbonate minerals such as calcite increases, the enrichment degree of Fe and Al in shale decreases; on the contrary, the enrichment degree of Ca and Mg increases with the increase of carbonate minerals [31]. Therefore, the input of terrigenous detritus can be judged by the ratio of (Fe + Al) / (Ca + Mg). Generally, the deeper the water depth is, the more difficult it is for terrigenous clasts to reach. In this paper, the ratio of (Fe + Al) / (Ca + Mg) is oscillatory in the study section, but from the top to the bottom, the input of terrigenous detritus first increases and then decreases, that is to say, the overall change trend of water depth from deep to shallow can be distinguished.

5.2 Sedimentary model and its evolution characteristics

Paleo water depth, paleo salinity, paleo climate and paleo redox environment control the sedimentary evolution of fine-grained rocks. Climate and water depth affect the types of sedimentary structures, and climate changes lead to lithology changes. The change of sedimentary environment is mainly due to the variability of climate. With the change of climate from dry and cold to warm and wet to relatively warm and wet from bottom to top, the water depth gradually increases, the salinity decreases, the reducibility of sedimentary environment gradually weakens, and the paleoproductivity changes from high to high to low [32]. Based on the lithology analysis, fine-grained lithofacies division, element geochemical characteristics analysis and sedimentary environment identification of niuye-1 well in Jiyang depression, the mineral composition, environmental indicators, lithofacies and lithofacies assemblage of fine-grained rocks in the sedimentary stage of the lower Es3 ~ upper Es4 sub members are frequently changing. Combined with the formation environment of lamina, the changes of lithofacies and environmental indicators, etc The sedimentary environment of the area is divided into three stages (Fig. 7).

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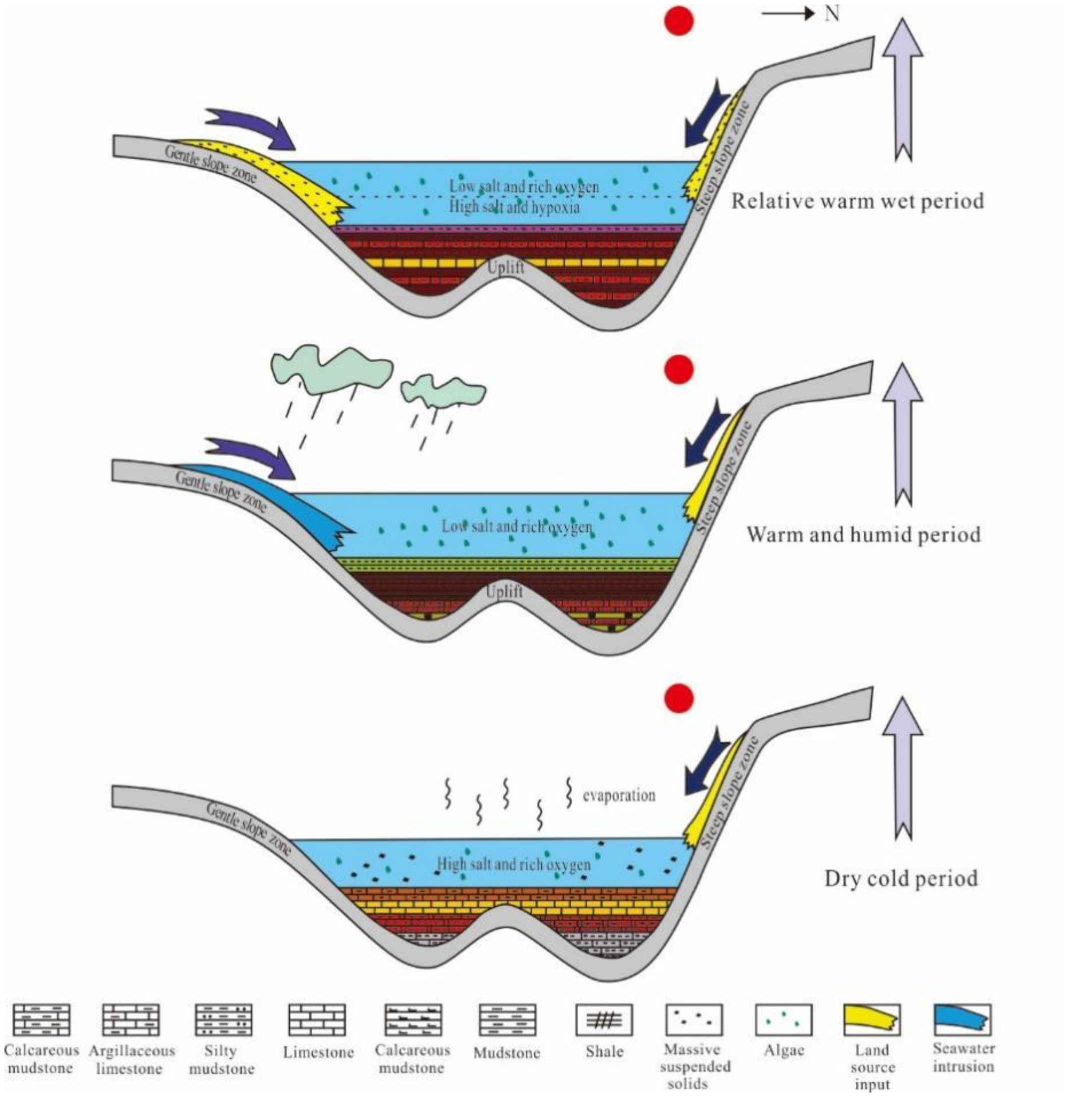

Fig. 7 Fine-grained sedimentary model of the NY-1 well in Jiyang Depression(Modified according to literature [33])

The first stage: the climate is dry and cold, and the evaporation of the lake water is large. With the increase of evaporation, the salinity of the lake water increases, while the depth of the water body is shallow, the rainfall is less, and the input of surface fresh water is limited, so the discharge is far greater than the input, and the salinity increases, which leads to the water body's reversion. The formation of massive gypsum and dolomite in migmatite. When the input of terrigenous detritus is sufficient, the flood will bring clay, detritus and organic matter into the lake basin. Due to the enhanced reducibility of water, algae are less and difficult to preserve, and massive suspended solids are more developed. The sedimentary environment affects the composition and content of fine-grained rocks, which determines the development of massive migmatite facies, laminar silty mudstone facies and massive limestone facies in dry cold period. Under the dry and cold climate, the lake water is affected by periodic floods, and the water body is turbid, which shows the salt lake environment of high salt and oxygen enrichment. The second stage: the climate is changeable and tends to be warm and humid as a whole. However, due to the large amount of seawater intrusion in the fourth stage, the input of seawater was greater than that of fresh water, resulting in the enhancement of water reducibility and the development of lithofacies such as algae and clayey laminated mudstone. With the end of the transgression, the fresh water input makes the salinity of the water decrease and change to the normal lake, and the water body presents a state of low salinity and rich oxygen. The third stage: temperature and humidity showed a downward trend, compared with

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the second stage, this period showed a relatively warm and humid climate. The input of terrigenous detritus tends to be stable, and the input of fresh water and rainfall show a decreasing trend, which leads to the decrease of water depth and reducibility. Meanwhile, the decrease of water salinity leads to the development of algae, organic laminar limestone mudstone facies and intermittent clayey laminar mudstone facies. Under the relatively warm and humid climate, the lake water body is stratified. The upper layer is in a low salt and oxygen rich environment, and the lower layer is in a high salt and oxygen deficient environment. The reason for this phenomenon is that rainfall carries a large amount of fresh water and nutrients into the lake, causing the lake level to rise, thus forming the stratification of the lake. Generally speaking, the development of fine-grained rock changes with the change of sedimentary environment.

6. Conclusion

(1) There are 8 kinds of lithofacies in Shahejie formation of Niuye 1 well, Jiyang depression: organic matter laminar massive limestone facies, horizontal organic matter heterogeneous laminar argillaceous limestone facies, intermittent clayey laminar mudstone facies, horizontal organic matter laminar calcareous mudstone facies, organic matter continuous laminar shale facies, horizontal clayey laminar interbedded with carbonate laminar calcareous mudstone facies Horizontal fine grained bedded siltstone facies and massive calcareous migmatite facies.

(2) The sedimentary environment evolution of fine-grained rocks in the lower es3-upper Es4 sub member of Shahejie Formation in Niuye 1 well of Jiyang depression is characterized by stages, and the paleoclimate has experienced the characteristics of dry cold warm wet relative warm wet. In the first stage, the water body is reductive due to evaporation, and the climate is dry and cold; in the second stage, the reductive water body is weakened due to transgression, and the climate is warm and humid, and in the third stage, the climate is relatively warm and humid. Generally speaking, the sedimentary environment controls the type and relative content of fine-grained lithofacies components, resulting in the development of different lithofacies, and the stage and cycle of sedimentary environment cause the overlapping characteristics and evolution of lithofacies; the sedimentary environment controls the development of lithofacies, on the contrary, lithofacies reflects the change of sedimentary environment. These findings provide a basis for the study of lithofacies division, environmental interpretation and sedimentary evolution characteristics, and also provide a theoretical basis for the lithofacies classification of fine-grained sedimentary rocks in Jiyang depression, Bohai Bay basin.

(3) Transgression occurred in the process of fine-grained rock deposition, resulting in the change of sedimentary environment and fine-grained rock in the second stage. Emergencies have the characteristics of contingency and locality. Not all the fine-grained sedimentary rocks are affected by transgression or other emergencies during the sedimentary period, so as to avoid the limitation of the development of fine-grained sedimentary rocks.

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