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RESEARCH ARTICLE

The classification and significance of fine-grained deposits of micro-laminae rich in unconventional oil and gas resources

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Abstract In this study, an in-depth analysis of the types, characteristics, and formation mechanisms of micro-laminae and microscopic laminae was conducted in order to precisely examine the link or intersection of stratigraphy and petrology. This study was essentially a sedimentary examination of the minuteness-macro and micro-tiny layers between laminae and pore structure, as well as the types of structures and sedimentation. The results of this study bear important basic subject attributes and significance, as well as practical value for the basic theories and exploration applications of unconventional oil and gas geology. The quantitative data were obtained using the following: field macroscopic observations; measurements; intensive sampling processes; XRD mineral content analysis; scanning electron microscopy; high-power polarizing microscope observations; and micro-scale measurements. The quantitative parameters, such as laminae thicknesses, laminae properties, organic matter laminae, and laminae spatial distributions were unified within a framework, and the correlations among them were established for the purpose of forming a fine-grained deposition micro-laminae evaluation system. The results obtained in this research investigation established a basis for the classification of micro-laminae, and divided the micro-laminae into four categories and 20 sub-categories according to the development thicknesses, material compositions, organic matter content levels, and the spatial distributions of the micro-laminae. The classification scheme of the micro-laminae was divided into two categories and 12 sub-categories. Then, in accordance with the comprehensive characteristics of spatial morphology, the micro-laminae was further divided into the following categories: continuous horizontal laminae; near horizontal laminae; slow wavy laminae; wavy laminae; discontinuous laminae; and lenticular laminae. According to the structural properties of the laminae development, the micro-laminae was divided into the following categories: single laminae structures; laminated laminae structures; interlaminar structures; multiple mixed laminae structures; cyclic laminae structures; and progressive laminae structures. The research results were considered to be applicable for the scientific evaluations of reservoir spaces related to unconventional oil and gas resources.

Keywords fine-grained deposits, recognition of laminae types, microscopic laminae, recognition of fine laminae, laminae origins

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1 Introduction

Fine-grained deposition is very important in the study of shale oil and gas accumulations under geological conditions. Fine-grained deposition and fine-grained rock have become the frontier of sedimentology and petrology both in China and internationally (Aplin and Joe, 2011; Slatt and O'Brien, 2011; Hao et al., 2013; Jiang et al., 2013; Lazar et al., 2015; Zhang et al., 2015; Zhang et al., 2016). Shale gas mainly exists in shale formations in the form of adsorption states and free states. At the present time, reservoir formation and resource predictions and evaluations, as well as exploration and development methods, have become hot research topics (Bowker, 2007; Daniel and Ross, 2008; Daniel et al., 2007; Robert and Ruppel, 2007; Daniel et al., 2005; Zhang et al., 2011). A number of related basic research studies have also attracted the attention of researchers in the field. For example, fine-grained deposition and fine grain rock, shale formations, as well as fine-grained rock and shale classification research have become important basic scientific issues (Ma et al., 2018; Liu and Liu, 2019). The mineral composition, granularity, and diagenesis of sediment have been investigated in recent years in order reflect the formation processes of fine-grained rock (Aplin and Joe, 2011). It has been demonstrated that fine-grained deposition can be used to restore paleoenvironment and paleoecology conditions (Dill et al., 1996; Han and Ning, 2015).

The research, exploration, and development of unconventional oil and gas geology have further promoted the research regarding fine-grained deposition and argillaceous deposition (Han, 2017; Li et al., 2018). During the previous examinations of shale oil and gas reservoirs, it was determined that fine-grained rock formations are characterized by high content levels of organic matter, complex mineral composition, lamellar structural development, and small storage spaces (Yu, 2012, 2013). However, due to such unique factors as mineral compositions and rich organic matter in fine-grained rock and shale, different laminar assemblages may be formed (Wang, 2012; Song et al., 2015; Wang et al., 2015). As a result, the actual storage spaces of fine-grained rock and shale tend to be greatly improved, which then improves the storage capacities of the fine-grained rock and shale. Therefore, it is very urgent and important to study the formation and evolution of fine-grained sedimentary rock.

Sedimentologists and petroleum geologists have carried out in-depth discussions on the key issues related to the foundation of oil-bearing fine-grained sedimentary rock (Jiang et al., 2013; Liu et al., 2018; Wang et al., 2019). As a result, a lot of constructive and instructive suggestions have been put forward. In recent years, various research studies have identified Milankovich cycles using the changes in $CaCO_3$ content in strata. This has become a new method for fine-grained deposition astronomical periodic cycles. In particular, the study of the genetic and dynamic characteristics of fine-grained deposition and fine-grained rock laminae have been emphasized, as well as the mechanism of astronomical period influence. Therefore, attention should be paid to the tracking and development of similar new methods (Jin, 2017; Sun et al., 2017).

For example, there remains a lack of an important bridge between the study of the smallest unit of macroscopic strata and reservoir spaces, including detailed analyses of micro-laminae and micro-layers. Moreover, there are currently no hard theories or models for the fine-grained deposition of fine laminae structures, special fine-grained stratification types and spatial distributions, or their control mechanisms.

However, this study does not belong to the category of general stratigraphic classification and research, nor is it a simple petrology research investigation. The working features of the current study included the detailed analysis the types, characteristics, and formation mechanisms of fine-grained layers and micro-fine layers. The quantitative data were obtained via field macroscopic observations, measurements, intensive sampling processes, mineral content analysis, scanning electron microscopy, high-powered polarizing microscope observations, and micro-scaled measurements. Such quantitative parameters as laminae thicknesses, laminae properties, organic matter laminae, and laminae spatial distributions were unified in a framework, and the correlations between those parameters were established in order to form the fine-grained deposition of a fine laminae evaluation system.

2 Characteristics and classification of fine-grained sedimentary laminae

Fine-grained deposition in sedimentary sequences is a relative concept compared with coarse-grained deposition, such as sand and gravel, in conventional oil and gas reservoirs. Currently, there is no unified quantitative index for its dividing line, which is generally considered to be fine particles with particle sizes less than 0.0039 to 0.005 mm. The particle size analyses of modern argillaceous rock generally show that the majority of the particles with diameters less than 10 μm are deposited in the form of flocculation, while those with diameters larger than 10 μm are mainly deposited in the form of individual particles (Kranck et al., 1996a,1996b; Curran et al., 2002). Floccus processes provide a way to transport large quantities of sediment over long distances in marine basin environments (Macquaker and Adams, 2003). Fine-grained sediment in the oceans present complex sedimentation processes, and the granularity stratification of sediment is known to be closely related to the properties of viscous mud, coagulation, and turbidity currents (Curran et al., 2004).

Stratigraphic research units are generally composed of erathem, systems, series, formations, sections, layer systems, laminae systems, and laminae, among which, the laminae are most commonly the smallest research units. In the study of unconventional oil and gas geology, the concepts of fine-grained deposition and fine-grained rock have been put forward. Those concepts inevitably involve scientific issues between the smallest unit (laminae) of fine stratigraphy and the rock fabric and reservoir spaces. In other words, scientific issues between fine sedimentology and fine-grained petrology and reservoir geology. However, there are no clear frameworks for fine-grained facies or fine-grained micro-sequences or structures. Although the theories and research methods of sedimentology have been progressing rapidly, no scientific explanations for the sedimentary mechanisms have been established to date. The current research regarding the types, characteristics, and formation mechanisms of fine laminae, and the micro-fine laminae below the laminae is still weak.

This study should not be considered as a general stratigraphic classification and research category or general petrological research content, but a research investigation of the types, characteristics, and formation mechanisms of fine laminae and micro-fine laminae below the laminae, which is exactly at the link between stratigraphy and petrology. In other words, this study was an examination of the sedimentological characteristics of the sedimentary types and structures of the micro-micro laminae and macro-micro laminae between the laminae and pore structures. The content and scientific issues addressed in this study were considered to have important basic subject attributes and significance. The basic concepts associated with laminae are detailed in Table 1.

3 Samples and methods

In this study, qualitative and quantitative methods were used, along with and multi-disciplinary methods such as multi-leveled cycle recognition. This was achieved through traditional core sampling; outcrop detailed observation descriptions; high-precision microscope observations; scanning electron microscopy and field emission electron microscopy methods; fine-grained deposition microbe test analysis methods; geophysical identifications; and experimental testing methods. The method choices were based on the types of fine-grained sediment; properties of the fine-grained laminae; thickness values (including the micro-thicknesses); spatial distribution continuity, and so on. The fine-grained deposition of laminae layers, as well as the rock composition characteristics, were described in detail. A classification method for the main parameters and auxiliary descriptions was proposed, and such quantitative parameters as the laminar thicknesses, laminar attributes, organic matter laminar, and the laminar spatial distributions were unified in a framework. Then, the correlations between the parameters were identified in order to form a fine-grained deposition laminar evaluation system.

In this study, Phenom ProX and Leica DM4P polarizing microscopes developed in the Netherlands were mainly used as the experimental equipment, at magnifications of 20 to 8000 times. The samples examined in this study were mainly collected from mudstone, shale, and siltstone cores in the partial strata of Well Fan 1 and Niupain 1 of the core reservoir of the Shengli Oilfield in Shandong Province (Fig. 1(a)); mudstone and siltstone of Well ZK1 from the Longgu Coal Mine, Juye Coalfield, Heze (Fig. 1(b)); and siltstone from the Beilaishi Profile of Huangdao Lingshan Island (Fig. 1(c)).

4 Results

4.1 Determination of the classification basis of the fine laminae

The composition of the laminae, content levels of organic matter, spatial distributions of the laminae, and the classification criteria of the fine laminae were established based on the thickness values of the fine laminae. In the current investigation, the fine laminae were divided into four major classes and 20 minor classes, as detailed in Fig. 2 and Table 2.

1) Fine characterization and microscopic quantitative characterization methods of super-fine-grain laminae.

The quantitative characterization data were first obtained using a point system. For example, quantitative description methods and the law of micro-stratification were adopted in the field and in the laboratory for the purpose of measuring the thicknesses, particle sizes, and vertical distributions. In the macroscopic characterization process, sections of the rock were polished, and the actual measurements were made by the scale. For the laminae less than 1 mm, the scale below millimeter was used for measurements.

Table 1 Determination of several basic concepts related to lamination

Number	Classification	Implication
1	Laminae	The smallest unit of stratigraphic division in stratigraphy. From the perspective of stratigraphy and petrography, stratigraphy is the smallest unit of macroscopic stratigraphic identification.
2	Laminated composite	A group of laminae having similar features.
3	Laminated sequence	The phenomenon that several laminae are stacked regularly in the vertical direction.
4	Fine grain laminae	Refers especially to the various laminae in fine grain deposits
5	Superfine grain laminae	It refers to the laminae whose scale and thickness are smaller than the traditional laminae and can be recognized macroscopically.
6	Microscopic laminae	It refers to the smaller grades of laminae identified by the microscope, which can be characterized in terms of scale, thickness and composition, but does not belong to the category of petrology (rock ore appraisal).
7	Evaluation system of superfine grain laminae	It refers to the system to determine, classify and calculate the index of quantitative and scientific evaluation of sedimentary laminae.

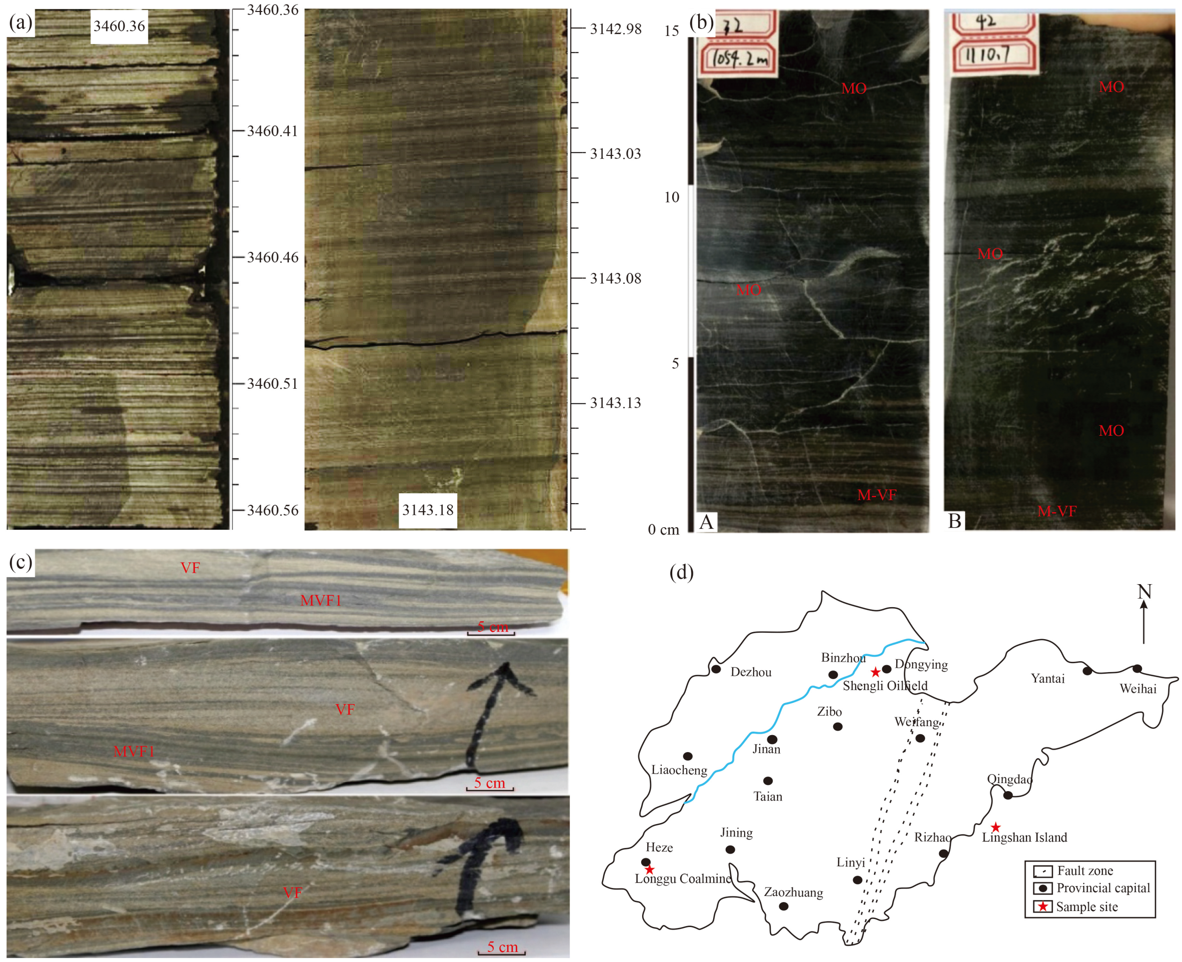

Fig. 1 Collection points and core characteristics of the fine-grained laminae samples. (a) Mud shale of Well NY 1 (left) and siltstone of Well FY 1 (right) of the Shengli Oilfield; (b) organic rich mudstone of Well ZK1 in the Longgu Coal Mine, Juye Coalfield, Heze City (left: 1054.2 m; right: 1110.7 m); (c) siltstone from the Beilaishi Profile of Huangdao Lingshan Island; (d) distribution of the sampling points.

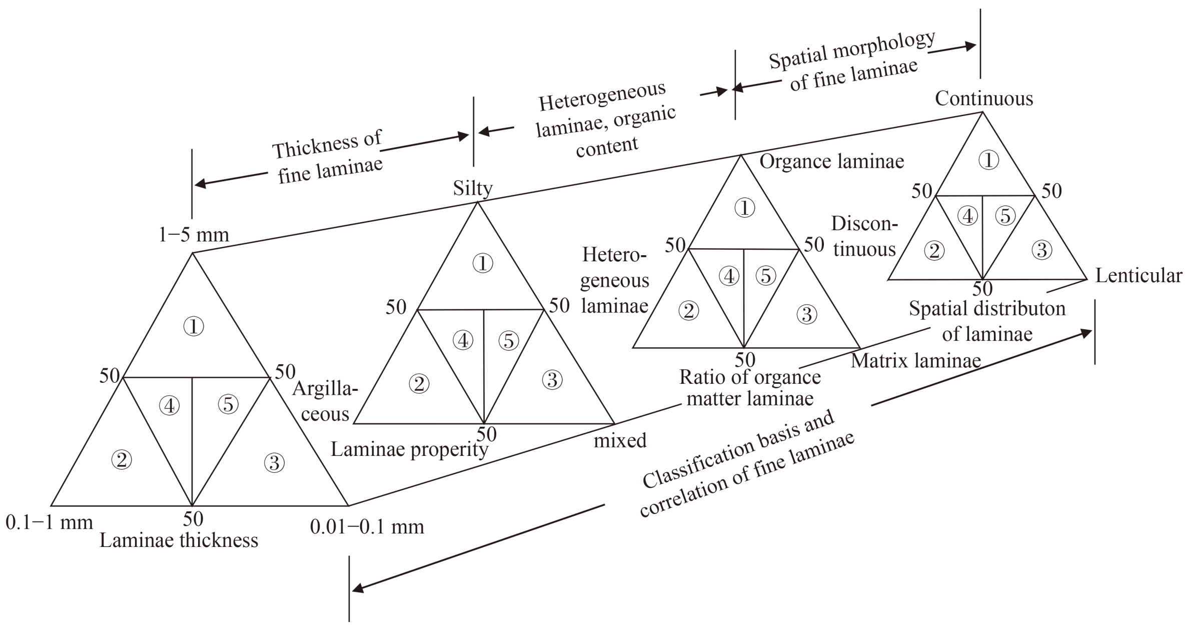

Fig. 2 Basic classification and observed correlations of the fine laminae.

Table 2 Classification basis and characteristics of fine laminae

Classification basis	Laminae types and characteristics
laminae thickness (Fig. 3)	①laminae:Single laminate thickness between 1–5 mm >50%; ②Thin laminae:Single laminate thickness between 0.1–1 mm >50%; ③Paper-thin laminae:with single laminate thickness between 0.01–0.1 mm >50%; ④Thinner laminae:thickness of single laminae between 1–5 mm, 0.1–1 mm, and 0.01–0.1 mm were all < 50%, and between 0.1–1 mm > between 0.01–0.1 mm;
laminae property (Fig. 4)	①Silt laminae:silty sand class >50%; ②laminae containing silt:argillaceous >50%; ③Mixed laminae:mixed layer >50%; ④Mixed-silt laminae:silty sand class <50%, argillaceous <50%, mixed layer <50%, and the content of silty sand class was higher than the argillaceous content; ⑤Silt-mixed laminae:silty sand class <50%, argillaceous <50, mixed layer <50%, and the argillaceous contentwas higher than the content of silty sand class.
Organic content (Fig. 5)	①Organic laminae:organic content >50%, the sum content of heterogeneous and matrix <50%; ②Heterogeneous laminae:Heterogeneous content >50%, the sum content of organic and matrix <50%; ③Matrix laminae:Matrix content >50%, the sum content of organic and heterogeneous <50%, actually an inconspicuous laminae; ④Organic-heterogeneous laminae:heterogeneous laminae <50%, organic laminae <50%, matrix laminae <50%, and heterogeneous laminae was more than matrix laminae; ⑤Organic-matrix laminae:heterogeneous laminae <50%, organic laminae <50%, matrix laminae <50%, and matrix laminae was more than heterogeneous laminae.
laminar spatial distribution (Fig. 6)	①Continuous laminae:heterogeneous components distributing continuously >50%; ②Discontinuous laminae:the discontinuous and stable heterogeneous components >50%; ③Lenticular laminae:the discontinuous and unstable heterogeneous components >50%; ④Continuous - discontinuous laminae:discontinuous laminae <50%, continuous laminae <50%, lenticular laminae <50%, and discontinuous laminae > lenticular laminae; ⑤Continuous - lenticular laminae:discontinuous laminae <50%, continuous laminae <50%, lenticular laminae <50%, and discontinuous laminae < lenticular laminae.

2) The identification and analysis of high-power micro-rock were carried out, and a fine-grained sedimentary classification process was carried out according to the new fine-grained sedimentary classification results. Then, the scale of the adopted microscope was used for the interpretations.

3) Quantitative descriptions of the laminar thicknesses were recorded, as shown in Fig. 3.

4) Quantitative classifications of the lamellar properties were established according to the different material properties of the laminae, and the laminae properties were characterized quantitatively, as detailed in Fig. 4.

5) Quantitative evaluations of the organic matter content levels of the laminae were performed. The types and characteristics of the laminae were quantitatively evaluated with organic matter as the main variable, as shown in Fig. 5.

6) Quantitative evaluations of the laminar spatial distributions were recorded according to the morphological characteristics of the spatial distributions, and quantitative evaluations and classifications of laminae were then carried out, as detailed in Fig. 6.

4.2 Establishment of the steps for the fine laminae classifications

The fine-grained sedimentary structures were first classified, and on that basis, the fine-grained sedimentary and fine-grained rhyolite properties were successfully identified and classified. The second step was considered to be the key step, in which the types of laminae were identified, classified and characterized individually. The goals were to measure and classify the thicknesses of the various laminas in the fine sediment and fine rock samples, in order to obtain the quantitative data. The data were then used to describe the morphological characteristics of the laminaes for the purpose of identifying and classifying the different types. Then, a classification system of the fine laminaes was established. Finally, a comprehensive index classification and evaluation procedure was determined, as detailed in Fig. 7 and Table 3.

4.3 Determination of a classification scheme for fine laminae

4.3.1 Property analyses of the fine laminae materials

This study's XRD mineral content analysis results, along with scanning electron microscope and polarizing microscope observations, revealed that the main mineral compositions of the fine-grained rock in the lower sub-member of the Shahejie 3 Formation (Es^{3L}) and the upper sub-member of the Shahejie 4 Formation (Es^{4U}) of Wells NY1, FY1, and LY1 included carbonate minerals, clay minerals, and clastic minerals (Table 4). It was observed that the carbonate minerals made up the greatest proportion of the total mineral content. The carbonate minerals mainly contained calcite, dolomite, and siderite, accounting for 40% to 50%; clay minerals composed of illite and small amounts of chlorite and iomc/montmorillonite accounted for approximately 25% to 35%; and clastic minerals (such as quartz minerals) composed more than 25% (Fig. 8). The secondary components included organic matter, sulfate minerals, and pyrite.

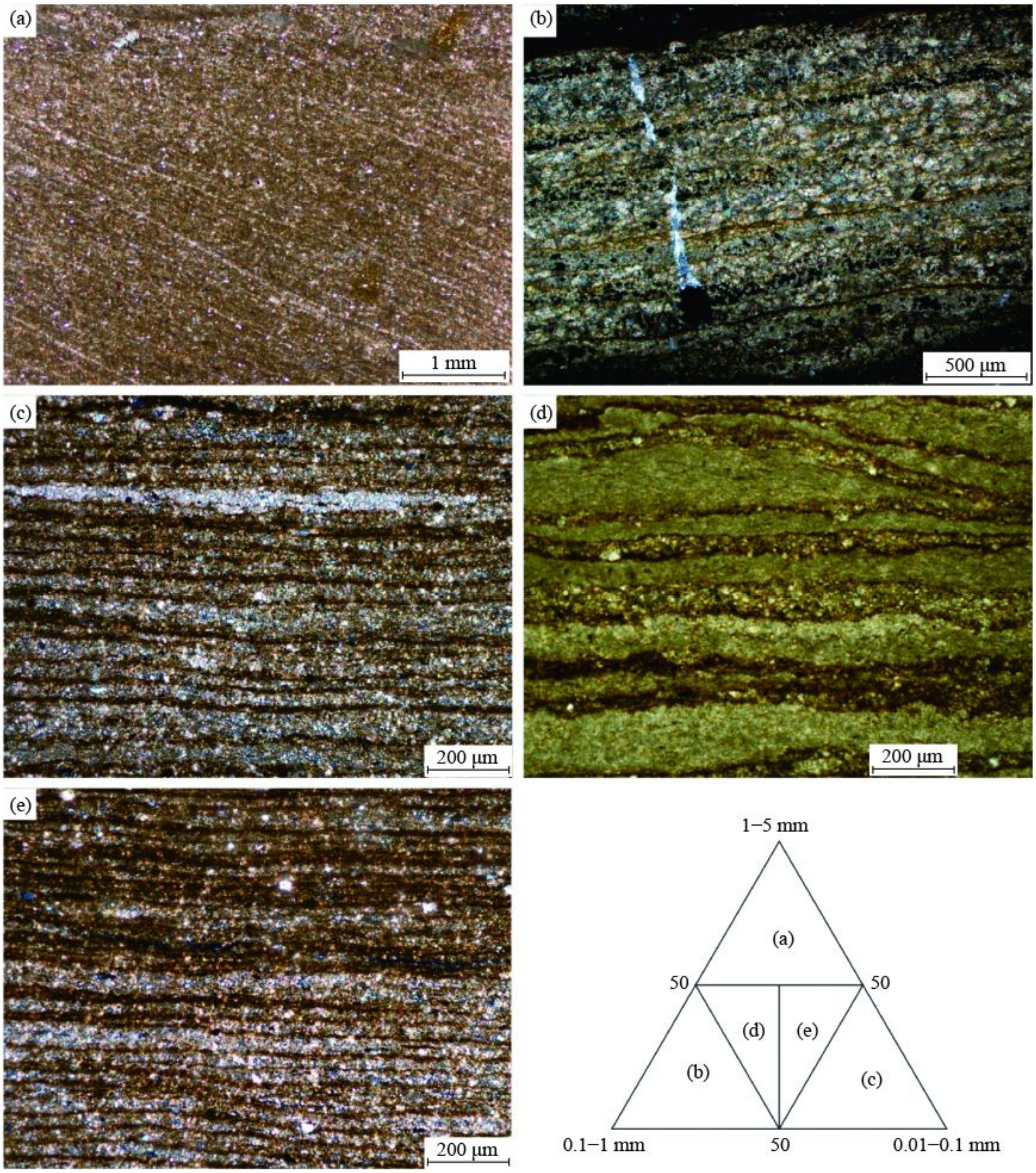

Fig. 3 Quantitative description of the laminae thicknesses in Wells FY 1 and NY 1. (a) Laminae (Well FY 1; 3143.4 m); (b) thin laminae (Well NY 1; 3,419.94 m); (c) paper-thin laminae (Well NY 1; 3,499.95 m); (d) thinner laminae (Well NY 1; 441.75 m); (e) thinner laminae (Well NY 1; 3499.95 m).

As the main component of fine-grained rock, clay minerals are generally smaller than 2 microns in size. In the Es^{3L}–Es^{4U}, the content of clay rocks was greater than 90%. Under scanning electron microscopy, it was observed that the clay mineral composition of Well NY1 mainly included illite and montmorillonite, the majority of which were in the form of imonite (Fig. 9(a)), with small amounts in the form of chlorite and kaolinite. The dominant characteristics of the chlorite and illite content in the composition of the clay minerals indicated that the media conditions for the formation of the clay minerals were mainly weakly alkaline (Zhang et al., 2007). The imomalt was the intermediate product of the transformation process from montmorillonite to illite. The illite was mainly presented in stratified or lineated clay mineral micro-layers, and the majority were observed to be interbedded with organic matter. The occurrence of the clay minerals was caused by the syngenetic clastic formations, and the sections and lineation of the vertical bedding were clear. However, the mineral morphology was difficult to identify. The results of this study's energy spectrum analysis mainly included Si and Al. The morphology of the clastic

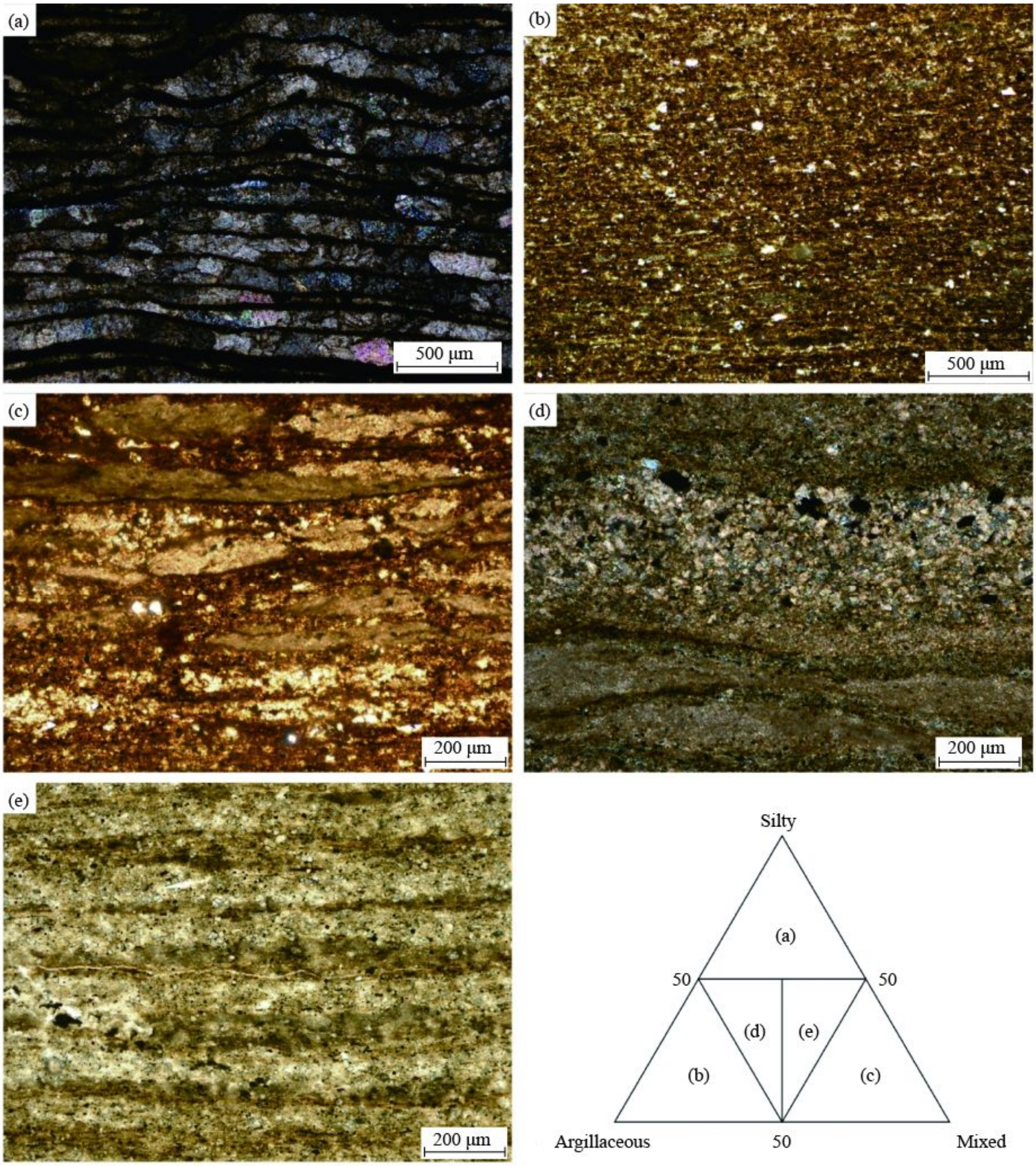

Fig. 4 Quantitative classifications of the laminae properties in Wells FY 1 and NY 1. (a) Silt laminae (Well NY 1; 3465 m); (b) laminae containing silt (Well FY 1; 3127.74 m); (c) mixed laminae (Well FY 1; 3138.8 m); (d) mixed-silt laminae (Well NY 1; 3325.5 m); (e) silt-mixed laminae (Well NY 1; 3575.8 m).

mineral monomers was relatively obvious. It was found that the illite was mainly presented in flakes or curled shapes (Fig. 9(b)). The montmorillonite was flocculent shaped (Fig. 9(c)), and the kaolinite was visible as hexagonal or rounded shapes (Fig. 9(d)). In addition, there were observed to be some autolitic clay minerals dispersed and developed in the pores of the reservoir, which mainly included chlorite in the form of flowers (Fig. 9(e)) and fibers (Fig. 9(f)).

The amount of organic matter content is reflected in the color of the shale, which can be better reflected under polarized light microscopy. In this investigation, both core (Fig. 10(c)) and thin sections were used to determine that the organic matter was distributed in layers, most of which being interbedded with carbonate minerals or claystone minerals, as indicated by the black bands

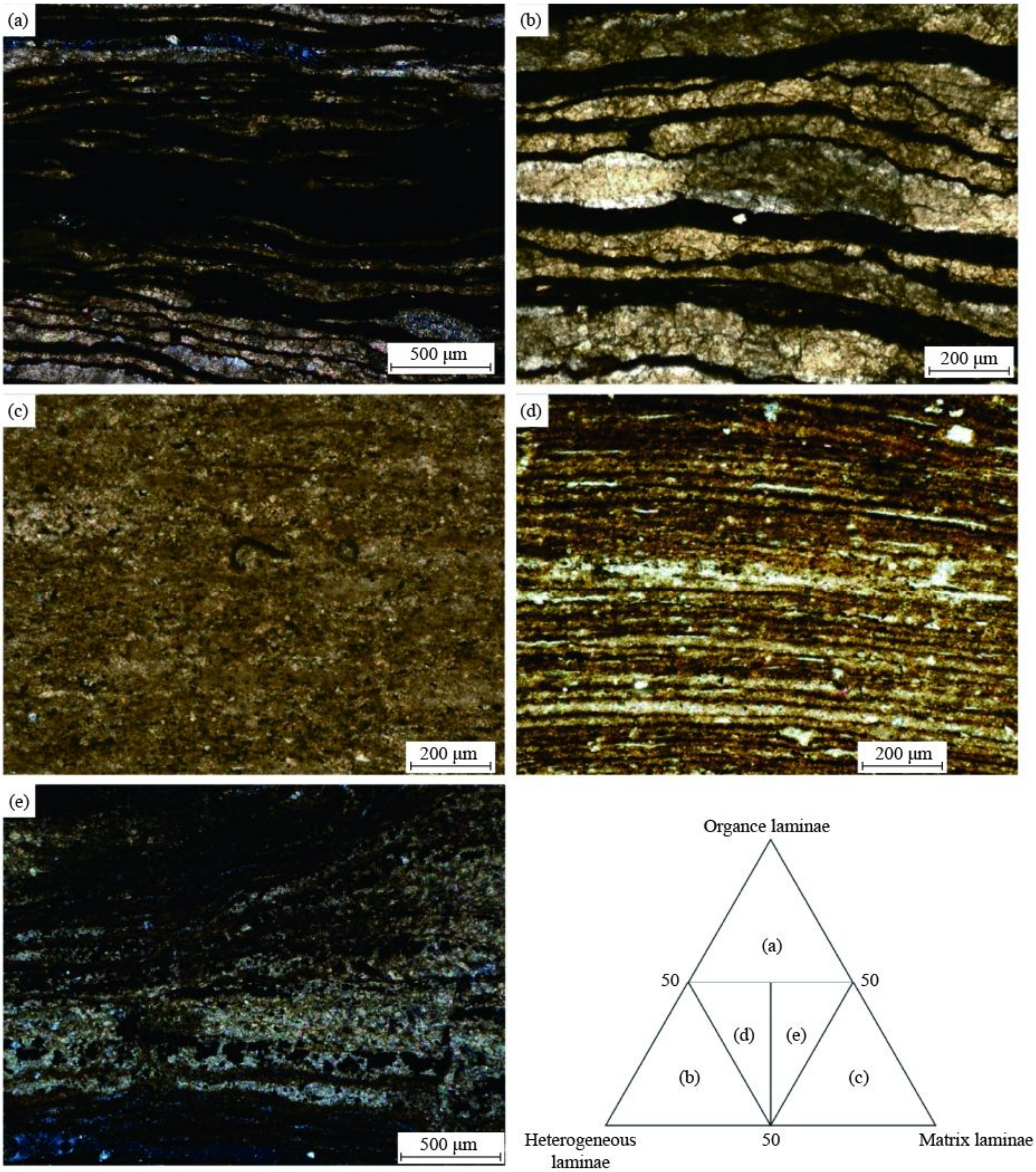

Fig. 5 Classifications of the organic matter content in Wells FY 1 and NY 1. (a) Organic laminae (Well NY 1; 3465 m); (b) heterogeneous laminae (Well NY 1; 3465 m); (c) matrix laminae (Well NY 1; 3325.5 m); (d) organic-heterogeneous laminae (Well NY 1; 3419.94 m); (e) organic-matrix laminae (Well NY 1; 3419.94).

shown in Fig. 10(a). A small number were determined to be scattered in clay stones (Fig. 10(b)). Under the SEM backscattering, the organic matter appeared as bright black surrounded by the clay minerals (Fig. 10(d)). After imaging with secondary electrons, the organic matter presented a bright state color (Fig. 10(e)). The most direct manifestation of the identification of the organic matter was the extremely high content of C element in the energy spectrum analysis results, at up to 90%. Planktonic algae were determined to be the main sources of organic matter in Es^{3L}–Es^{4U} in the study area. They included coccolithophores, dinoflagellates, and so on. It was observed that coccolithecia and dinoflagellates alternated to form calcareous laminae shale, and the

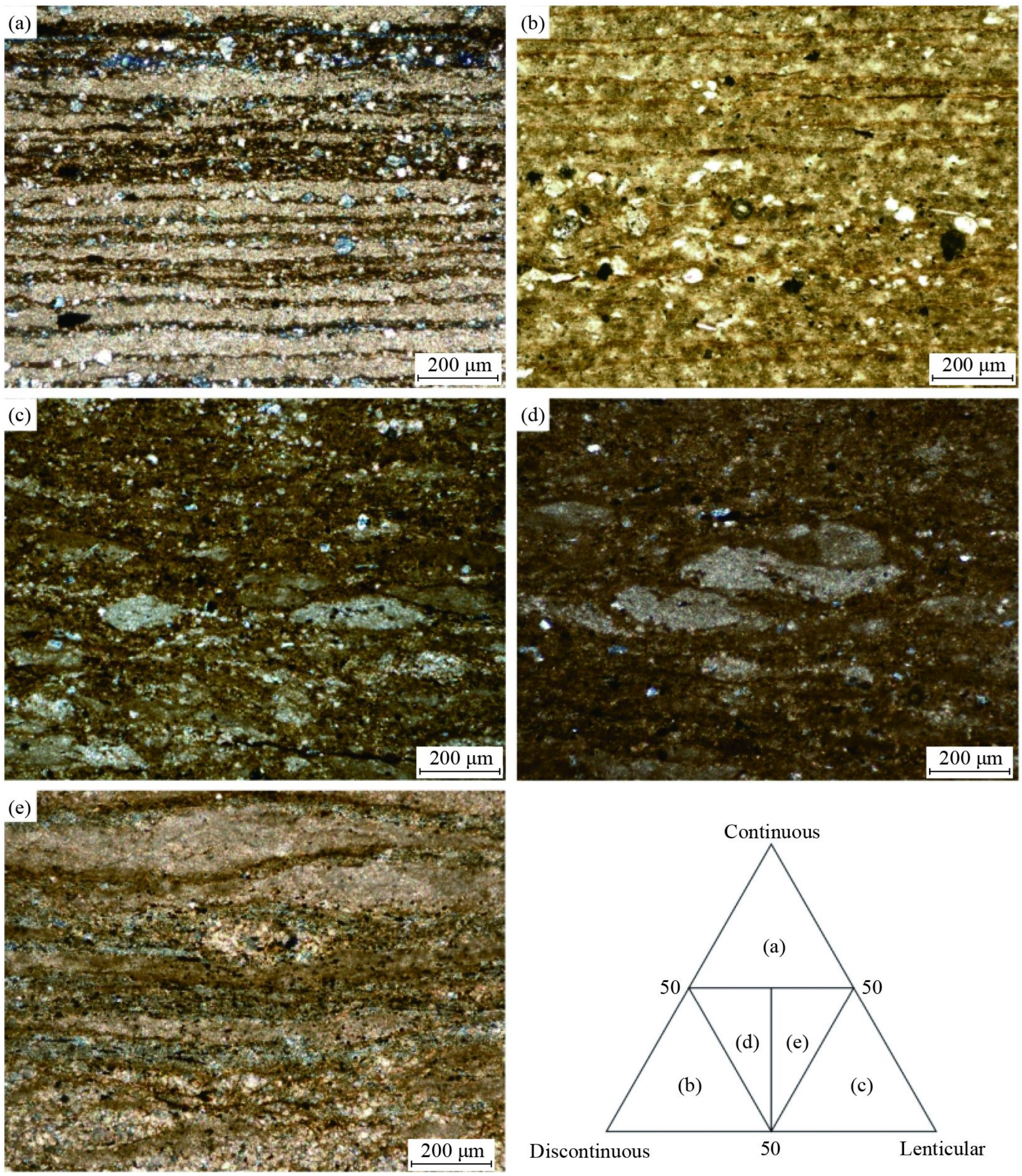

Fig. 6 Spatial distributions of the laminae in Wells FY 1 and NY 1. (a) Continuous laminae (Well NY 1; 3460.5 m); (b) discontinuous laminae (Well NY 1; 3415.04 m); (c) lenticular laminae (Well NY 1; 3317.3 m); (d) continuous-discontinuous laminae (Well FY 1; 3113.8 m);(e) continuous-lenticular laminae (Well NY 1; 3325.5 m).

dinoflagellates also induced fine calcite laminae to precipitate. In addition, due to the high productivity of the algae growth, a large amount of algae was deposited. Then, as a result of microbial degradation, amorphous organic matter had finally formed. The amorphous organic matter was distributed in layers, and together with the clay mineral laminae formed organic match-rich laminates shale (Liu et al., 2001).

4.3.2 Description of the fine core lamination features

In this study, the Paleogene Shahejie Formation of Well NY1 was selected as the research object. This study utilized detailed descriptions of cores of the 3417.7 m to 3500 m of Es^{3L}–Es^{4U} (Table 5). The core descriptions were then used to quantitatively characterize the fine sedimentary sequence features (Fig. 11). This study's laboratory analysis results of the macro and micro combinations; combinations of petrology and geophysics; combinations of the qualitative and quantitative; close combinations of outdoor and indoor research; and the combinations of the fine-grained mineral composition images, rock trace element analysis results.

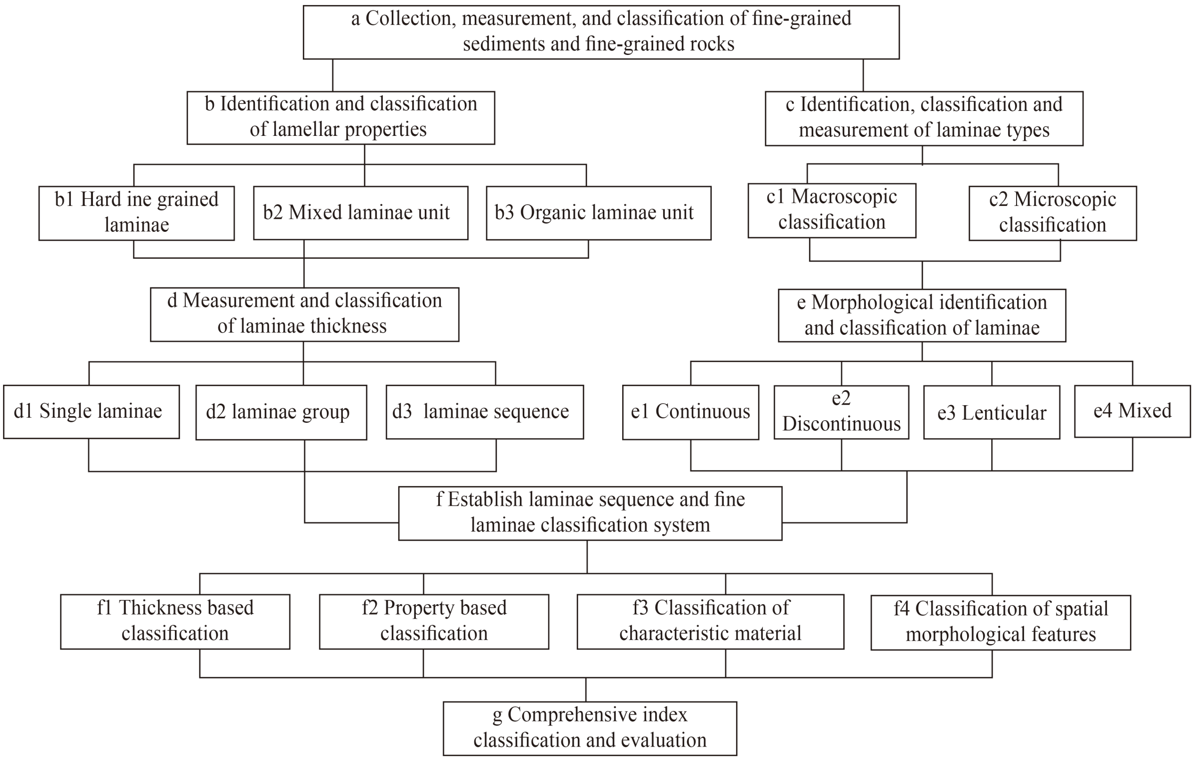

Fig. 7 Comprehensive index and classification procedure for fine laminae classification.

4.3.3 Comprehensive classifications

In accordance with the characteristics of the thicknesses and granularity of the fine-grained laminae, along with the continuity of the laminae development, the laminae were divided into the following groups: continuous horizontal laminae; near-horizontal sandwiched laminae; gently undulate laminae; wavy laminae; intermittent laminae; and lenticular laminae based on the comprehensive characteristics of their spatial morphology (Table 6; Fig. 12).

In addition, according to the laminate properties and the correlations between the adjacent laminates, the comprehensive characteristics of the laminate structure types were divided into single laminate structures; sandwich laminate structures; cross laminate structures; multiple mixed laminate structures; circular laminate structures; and progressive laminate structures, as presented in Table 7 and Fig. 13.

5 Discussion

In this research investigation, through recognizing the fine-grained lithography types and identifying the fine-grained lithology of Es^{3L}–Es^{4U} in the Jiyang Depression, complemented with the data regarding the mineral compositions, material sources, and features of the fine-grained rock, the genetic mechanisms of the fine-grained sedimentary rock in the study area were analyzed in detail, as shown in Fig. 14. Then, a genetic model of the continental fine-grained rock in the Jiyang Depression was established, as detailed in Fig. 15. It was determined that the research results were applicable to the scientific evaluations of unconventional oil and gas storage spaces. It was found that, due to the changes in climate temperature, dryness or wetness conditions, and land source inputs, the sedimentary water environments of the fine-grained sedimentary rock could be divided into muddy water stages, semi-muddy water stages, and clear water stages. Variations in the durations of each stage were found to lead to different laminar assemblages during the sedimentary stages. For example, combinations of carbonate rock lamination and clay mineral lamination with good continuity mainly developed during the muddy water stages and the clean water stages, rather than during the semi-muddy water stages. It was found that the mixed laminae were generally not able to develop during the semi-muddy water stages, and the durations of the muddy water stages were usually short, which allowed for the easy accumulation of organic substances. The laminae formed during the semi-muddy water stages usually contained low content levels of organic matter and were characterized by dispersed distributions. As a result,

Table 3 Steps for fine-grain deposition and fine laminae classification

Step	Methods	Research content
a	The information of fine grained sediments and small sedimentary structures in fine grained rocks is collected, measured, classified.	There are many small structures in fine-grained sediments and fine-grained rocks, so it is necessary to collect, measure, screen, remove the false and retain the true, and classify and analyze the laminae and micro-fine laminae.
b	Fine grained deposition and identification and classification of fine grained lithostratigraphic properties	laminae properties are the basis of lamellar classification, properties are the characteristics of all the laminae.
	b1. laminae and fine laminae dominated by rigid fine particles, including small quartz particles, other hard minerals and cutting materials;	
	b2. The laminae and fine laminae units formed by the mixed layer, that is, the main body of the laminae and fine laminae is mixed material, and all kinds of substances are in the same proportion;	
	b3. The lamination unit is the lamination and fine lamination mainly composed of organic matter, which are the unique properties of fine grain sediments and fine grained rocks, especially the lamination in coal-bearing strata.	
c	Layer types are identified, classified and measured one by one.	Mainly from the following two aspects of screening, classification and measurement.
	c1. Macroscopic classification refers to laminae and fine laminae which can be measured and identified by naked eyes;	
	c2. Microclassification is the identification, classification and measurement of laminae at a smaller level by means of microscope and other instruments.	
d	The thickness of fine grained deposits and various laminates in fine grained rocks are measured and classified.	The laminar thickness is the key data to reflect the laminar characteristics and to evaluate the shale oil and gas reservoir characteristics.
	d1. Measure and count the thickness of single laminae observed and screened one by one;	
	d2. laminae with the same or similar properties were classified into a laminae group and measured and counted respectively;	
	d3. For those with the same or similar properties on the whole and with certain distribution rules or overlapping forms in space, they are classified as a lamellar sequence for measurement and statistics.	
e	The lamellar morphological features are identified and classified.	laminate morphology is related to the genesis of laminate formation, morphological characteristics play an important role in evaluating the practical value of laminae.
	e1. Continuous laminae, that is, laminae and fine laminae are continuously distributed within a certain range, with small intervals and relatively stable laminae thickness;	
	e2. Discontinuous laminae, that is, laminae and fine laminae are distributed intermittently within a certain range, with discontinuity, but can be tracked and distributed along a certain direction and space generally;	
	e3. Lenticular laminae, that is, laminae and fine laminae are lenticular in a certain range, with significant intervals. laminae are lenticular bodies, but generally they can be tracked and distributed along a certain direction and space;	
	e4. Mixed laminae, that is, the material composition of the laminae is mixed, and the laminae are diversified in distribution, which may be traced from a continuous transition to a discontinuous or lenticular body in space.	
f	Identify the lamellar sequence.	Establish the classification system of fine laminae.
	f1. laminae and fine laminae thickness classification, that is, take the thickness data as the main variable to carry out the thickness classification, supplemented by the description of properties and substances;	
	f2. Classification of laminae and fine laminae is mainly based on property characteristics, with thickness as an auxiliary parameter;	
	f3. Classification of material arrangement of laminae and fine laminae, i.e., classification of material characteristics, with thickness as auxiliary parameter and attribute as description content;	
	f4. The classification of laminae and fine laminae spatial morphological characteristics, namely, quantitative description by thickness and laminae spacing parameters, supplemented by description of properties and material characteristics.	
g	Comprehensive index classification and evaluation.	On the basis of the above steps, the classification scheme is finally made by integrating the qualitative and quantitative classification attribution and evaluation, and finally make classification scheme.

Table 4 Main mineral compositions of the fine-grained sedimentary rock

Well number	Carbonate mineral content/%			Clay mineral content/%			Clastic mineral content/%		
	Mean value	Maximum value	Minimum value	Mean value	Maximum value	Minimum value	Mean value	Maximum value	Minimum value
NY 1	45.49	93.00	1.00	35.57	83.70	2.90	26.23	51.40	4.10
FY 1	40.61	76.00	4.65	33.42	53.94	11.60	30.34	72.60	13.40
LY 1	37.54	70.00	3.00	41.40	80.30	17.40	29.53	44.50	14.60

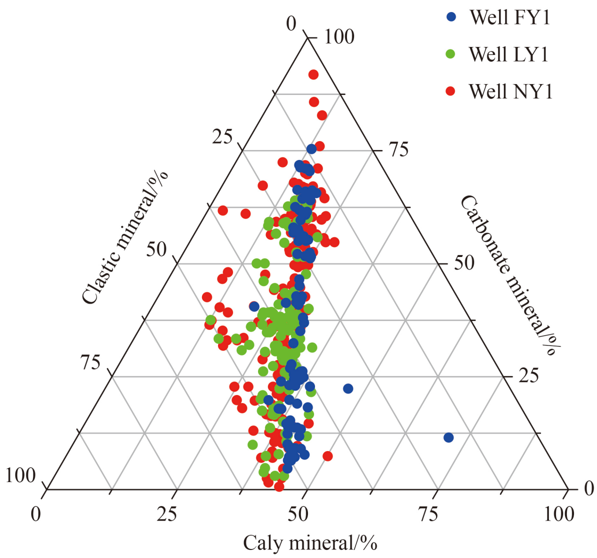

Fig. 8 Ternary diagram of the mineral compositions.

stable organic matter laminae could not be formed. The combinations of mixed laminae and organic matter laminae indicated that the scale of the flooding was not often frequent, and the periodic flooding outbreaks resulted the land source materials being continuously input into the lake basin, with the lake water body in a muddy water stage for long periods of time. The combinations of clay lamination and mixed lamination indicated that the flooding was small in scale and lasted for a relatively long period of time. Also, the flooding had been frequent. This study's results also revealed that the clay lamination had formed during the muddy water stages, while the mixed lamination had formed during the semi-muddy water stages. Prior to the transitions to the clean water stages, a muddy water stage had appeared once again. It was considered that the combinations of carbonate laminae and organic laminae may have been related to climate changes. The climate conditions were probably relatively dry, and the provenance area may have suffered from relatively weak weathering which had not provided very much terrestrial debris. However, the influencing effects of monsoons may have led to increased precipitation, but the scale of the precipitation was believed to have been relatively small. Therefore, the muddy water stages would have lasted for only short periods of time, directly transferring to clean water stages without experiencing semi-muddy water stages. The laminae with poor continuity were caused by the effects of bottom flow, storms, and various living species during or after the laminae formation (Peng, 2017). This study's model of the muddy water-semi-muddy water-clear water stages is the basic laminar genesis of the fine-grained sedimentary rock in the Es^{3L}–Es^{4U} of the Jiyang Depression, as detailed in Fig. 14.

In the current study, based on detailed analysis of the fine-grained lithofacies of Well NY1, it was determined that from the mineral compositions, environmental index, lithofacies, and combination changes of the fine-grained lithofacies of Es^{3L}–Es^{4U} during the sedimentary stage, it could be concluded that the fine-grained sedimentary model accurately represented the Es^{3L}–Es^{4U} in the Dongying Sag. The dry and cold periods were the initial deposition period of the Es^{4U}, during which the supplies of terrestrial clastic materials were relatively sufficient. However, flooding brought a large number of minerals including the clay, clastic, and organic matter of the lake basin. Furthermore, silty sediment had easily developed in the basin margins due to the strong land input. It was determined that due to the weak reducibility of the water, the algae supply was small and difficult to preserve, resulting in low organic matter content in the sediment. The environmental conditions also influenced the composition and content of the fine-grain deposits, which determined the development of the mixed block microfacies, striated silty mudstone microfacies, and block limestone microfacies during the early stages of the dry and cool depositions (Fig. 15(a)). Then, during the warm and wet periods, when the temperature fluctuation changes tended to be larger, the climatic conditions has been changeful but generally tended to be warm, wet, and humid. Due to the increases in rainfall, the amount of fresh-water input had risen. However, due to the large amounts of seawater intrusion, the amount of seawater was much larger than the fresh-water supplements, resulting in the salinity levels of the lake water not decreasing. Those findings indicated that the influencing effects of climate on the water depths, reducibility, and salinity had still existed during that period, but the controlling effects of transgression

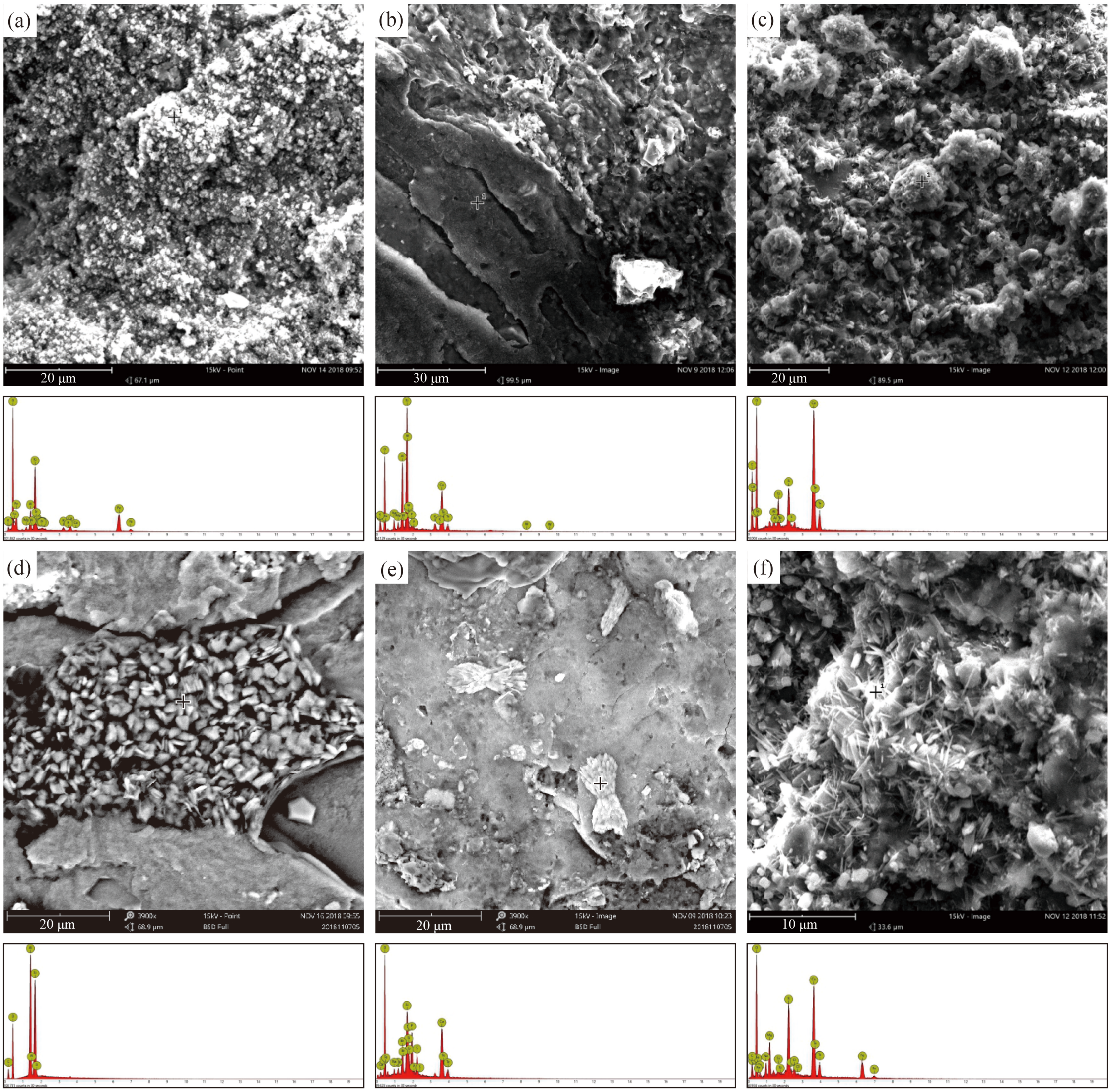

Fig. 9 Characteristics of the clay minerals as viewed using scanning electron microscopy (SEM). (a) Well NY 1, 3465 m, secondary electrons, illite/smectite formation; (b) Well NY 1, 3336 m, secondary electrons, sheet illite; (c) Well NY 1, 3345.7 m, secondary electrons, flocculent montmorillonite; (d) Well FY 1, 3100.6 m, back scattering, flaked kaolinite; (e) Well NY 1, 3441.75 m, back scattering, flower-like chlorite; (f) Well NY 1, 3345.7 m, secondary electrons, fibrous chlorite.

were more obvious. Moreover, with the end of the transgression period and the diluting effects of large amounts of fresh-water input, the salinity of lake basin gradually decreased and returned to normal lake levels. Overall, the lake presented a state of low salt and rich oxygen (Fig. 15(b)). During the warm and wet periods, the amount of land source input tended to be stable, while the amounts of fresh-water input and rainfall decreased. As a result, the salinity levels were further decreased (Fig. 15(c)).

Under the background of humid climate conditions, the lake water body appeared to become stratified. The lower part was in a high-salt and oxygen-deficient environment, and the upper part was in a low-salt and oxygen-enriched environment. This was due to the fact that the rainfall carried large amounts of fresh-water and nutrients into the lake system, causing rapid rises in the lake level and the promotion of the stratification of the lake (Bohacs et al., 2000; Jiang et al., 2007; Ma et al., 2016). Therefore, it was evident that the sedimentary environment of the fine-grained sedimentary rock was closely related to the paleo-climate conditions, and its sedimentary characteristics changed with the evolution of the sedimentary environment.

6 Conclusions

In this study, the quantitative parameters, such as the

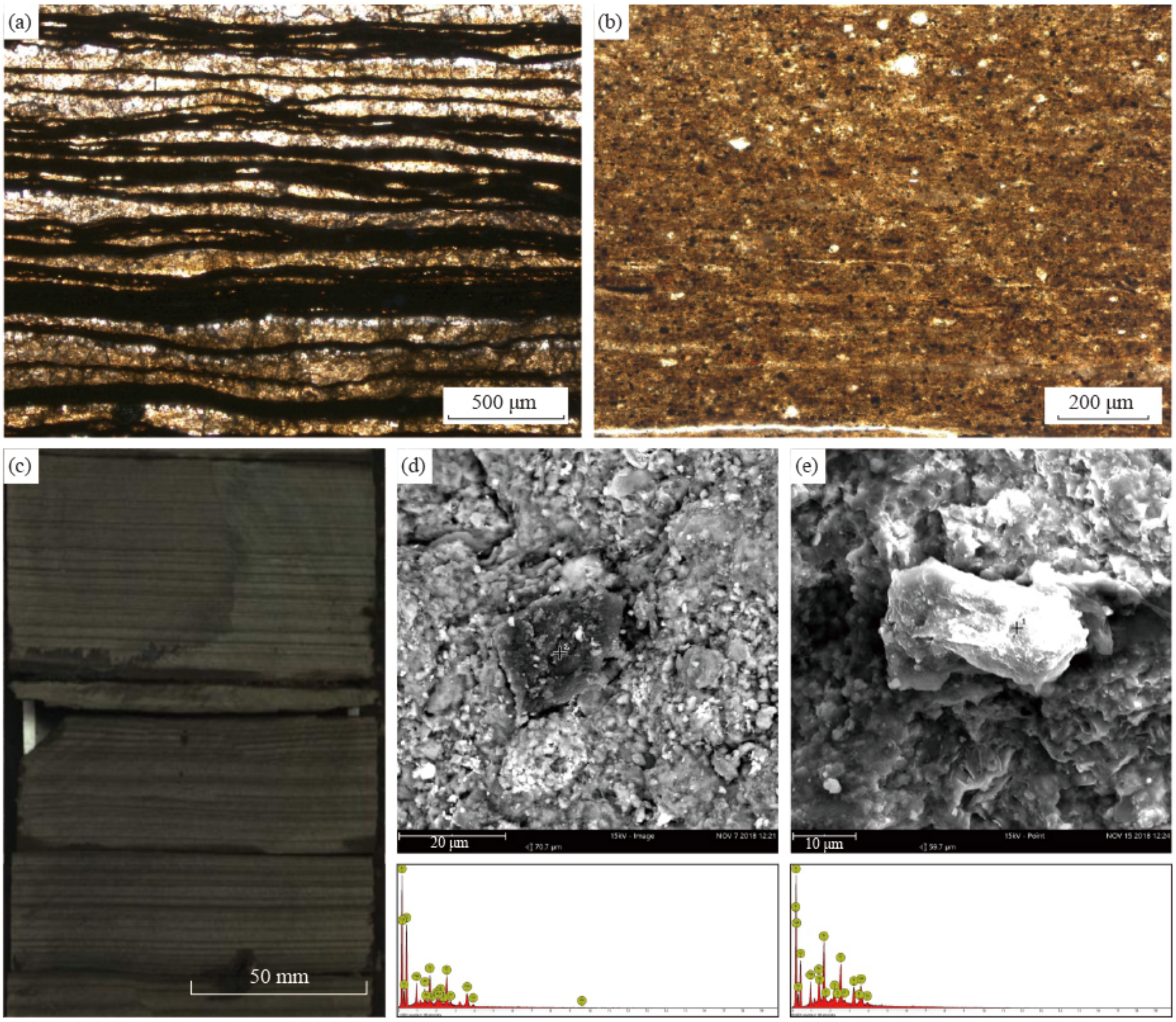

Fig. 10 Organic core and microscopic characteristics. (a) Well NY 1, 3465 m, single polarization, black bands interlayered with carbonate minerals; (b) Well NY 1, 3336 m, single polarization, organic matter is scattered in the clay rock; (c) Well NY 1, 3465 m, core photographs, organic laminae; (d) Well NY 1, 3325.5 m, back scattering, dispersed organic matter; (e) Well FY 1, 3088.15 m, secondary electrons, dispersed organic matter.

thicknesses of the fine laminae, laminae properties, organic matter laminae, and laminae spatial distributions could be unified within the established framework in order to identify mutual relationships. Subsequently, an evaluation system for the fine-grained deposition of micro-laminae was formed as follows.

1) A basis for accurate micro-laminae classification was established, and the criteria for the classifications of micro-laminae were determined. The micro-laminae were divided into four major categories and 20 minor categories.

2) The working steps and classification methods including information collection, measurement, characterization, identification and classification of laminae attributes are proposed, and based on this, the classification and evaluation system of lamina comprehensive indexes is established.

3) A micro-laminae classification scheme was successfully identified as two major categories and 12 sub-categories. The first category was classified according to the comprehensive characteristics of spatial morphology, and the second category was classified according to the comprehensive characteristics of laminae developmental structural attributes.

Table 5 Fine description of the core of the Es3L - Es4U, Well NY 1

Strata: System	Series	Group	Section	Depth/m	Lithology	Core sampling	Detailed description of core
Paleogene	Oligocene	Shahejie Formation	Chunxia submember of Es^{4U}	3417.7	Lime mudstone	▲	The lamellar deformation was relatively consistent at 3417.7 m. Folds and rolls were developed in the lower lamellar group (Fig. 11) with a thickness of 2 mm. A small soft deformation fracture was observed in the upper layer, and the sausage-like lamellar group was broken.
				3419.94	Calcareous mudstone	▲	This depth is about 17 cm up and down, which is the same depositional deformation. Now it occurs between flat layers, and the laminae bend and the laminae thickness changes. The main laminae deformation is basically in the same phase, also develop wrap and flow structure (Fig. 11), which reflected that the slight slope change caused by differential compaction and the change of unconsolidated sediments caused by gravity in thick sediments. The main laminate is about 1−2 mm, and most fine laminates are less than 1 mm. The flow pattern deformation laminae are found between the upper and lower normal layers (flat).
				3434.5	Calcareous shale intercalated with calcareous shale		It is mainly composed of very fine gray laminae, with light gray laminae sandwiched between them. Most of the laminae show transitional contact, and the color division lines are not obvious. However, the cycle of laminae group could be identified by the location of gray laminae. laminae are mostly composed of laminae less than 1 mm and more than 2 mm, and some laminae show slow wave shape. The laminae of less developed organic matter are similar in color and horizontal in shape.
				3437.13	Calcareous mudstone		The laminae containing organic matter are the main laminae, and several laminae group cycles can be identified, with a single cycle thickness ranging from 1 cm to 3 cm. The inner laminae of the cycle are well developed and easy to be recognized. The gray and white laminations are calcareous laminations, and the gray laminations are fine grain components. The individual laminations (parts) are less than 1 mm, presenting a horizontal shape. There is a thickness change in the thicker laminae, calcite laminae is mostly stable, but also lenticular. There are small synsedimentary faults, which are limited by fine cycles of laminae.
				3449.98	Calcareous mudstone	▲	There are many fine laminae in the deformation section, and the fine laminae show sliding deformation along the same direction of the laminae formation, and the folds go along the laminae, and the deformation is severe and sharp, and the deposition breaks off and the sliding deformation occurs (Fig. 11). Flow plastic deformation of suspected soft sediments in the direction of bedding force (Fig. 11). The upper and lower laminae are held apart. Small soft fault deformation also developed.
				3452.04	Shale		The lamellar lamination is developed horizontally, the lamination thickness is < 1 mm, and there are organic laminae. The horizontal texture reflects the development of small cycles and is easy to identify, and can be recognized easily, interspersed with deep gray laminae (where fine laminae develop). The laminae of light gray are intermittently extended, but not in large proportion. laminar thickness is approximately <1 mm.
				3460.5	Siltstone calcareous cement	▲	Grey/brown grey interleaved with light grey (organic matter laminae), the lamination cycle is clear, and the lamination surface is clear and can be opened along the lamination of organic matter. lamination is about 1mm thick, with horizontal, flat page.
				3467.4	Calcareous mudstone intercalated with siltstone		Stratified siltstones are developed from 3460.5 to 3462.5 m, and the laminar thickness is 0.1−0.3 mm, which is horizontal. The grey-black clay rock veins are interbedded with the grey-yellow siltstones (Fig. 11), And then the grain size becomes fine and turns into gray mudstone siltstone bands and organic matter bands alternately (Fig. 11), with obvious cyclicity.
			Chunxia submember of Es^{4U}	3475.8	Aluminous mudstone		This section of 3467.6−3475.8 m is mainly composed of light gray aluminum-soil mudstone with massive bedding (Fig. 11), and some areas have weak laminates
				3500	Silty mudstone intercalated with lime mudstone	▲	The upper part contains 2 m pink siltstone, calcareous cement, good continuity, horizontal bedding, rhythmic bedding. Gray laminae are deformed (Fig. 11), with gray laminae sandwiched inside. Although the contact surface is clear, it is not smooth, and there is sliding change along the laminae.3490.28 m. The following are dark gray silty mudstones (Fig. 11).

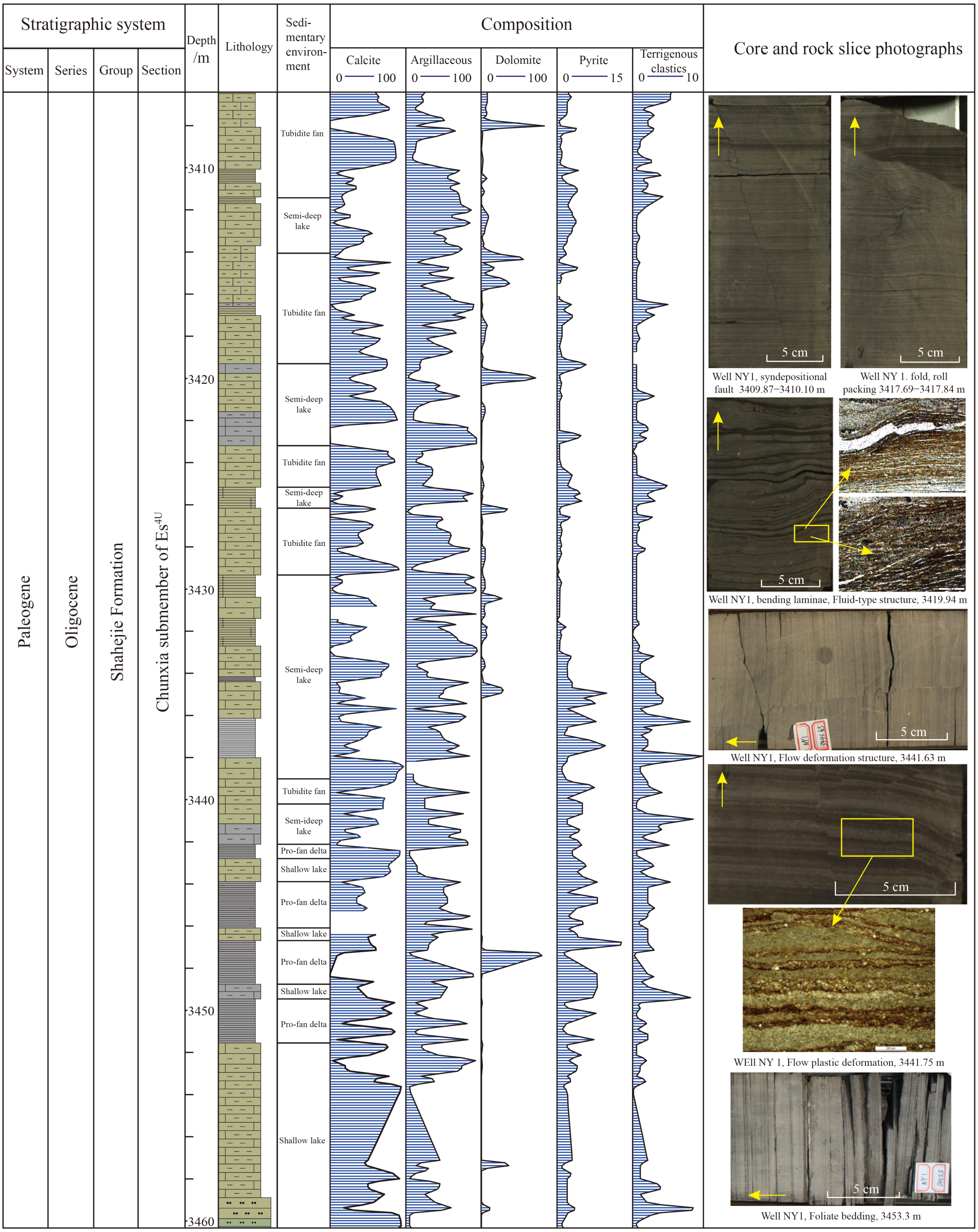

Fig. 11 Comprehensive column of Well NY-1.

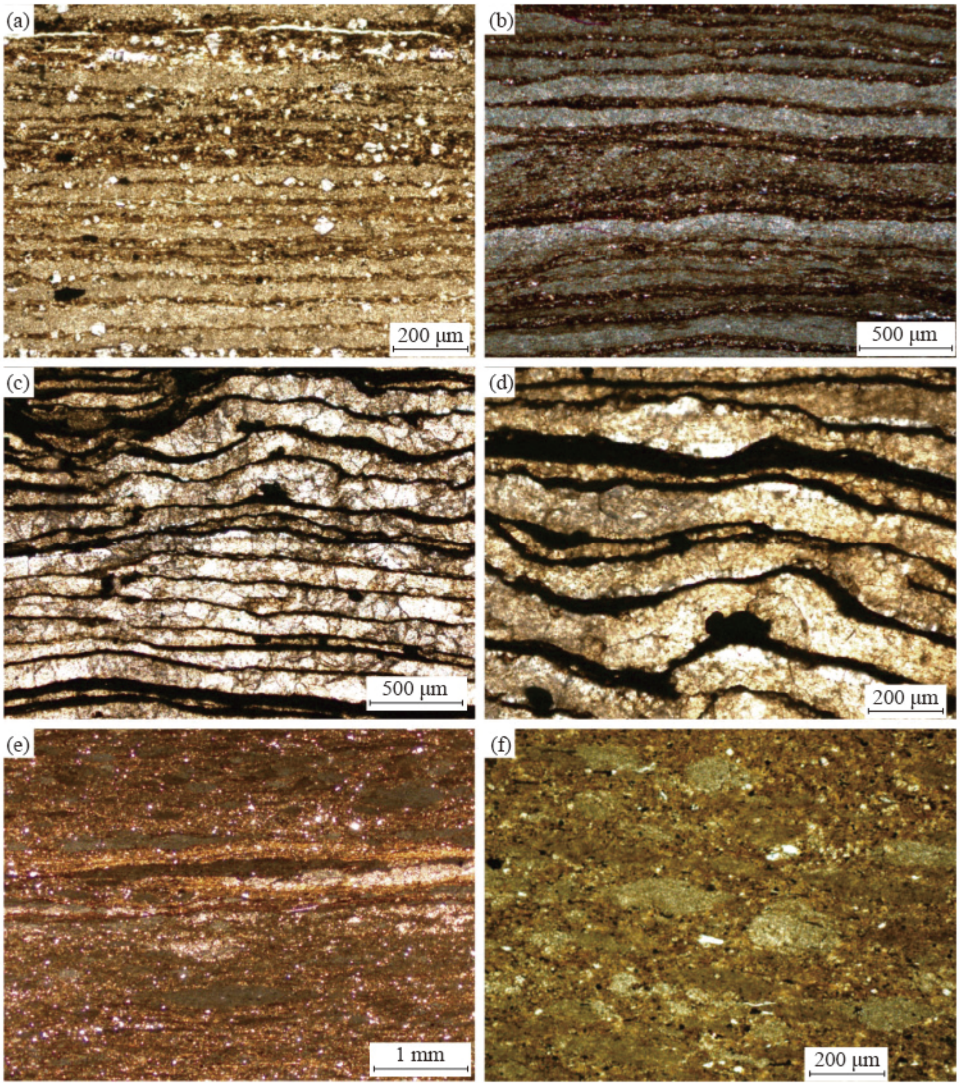

Fig. 12 Fine lamina types classified based on spatial morphology. (a) Continuous horizontal laminae (Well NY1; 3,460.5 m); (b) near-horizontal laminaeted layers (Well NY1; 3,441.75 m); (c) gently undulate laminae (Well NY1; 3,465 m); (d) wavy laminae (Well NY1; 3,465 m); (e) interrupted laminae (Well FY1; 3,132.68 m); (f) lenticular laminae (Well NY1; 3,317.3 m).

Table 6 Types and characteristics of fine laminae are classified based on spatial morphology (including microlaminae)

Classification	Characteristics
Continuous horizontal laminae	The laminae are continuously and stably distributed, such as fine silty laminae and unstable micro-shells of organisms, which are generally horizontal, without obvious peaks and troughs (Fig. 12(a)).
Near-horizontal laminated layer	The laminae are continuously and stably distributed, such as the fine silty laminae which are stable, and the delicate biological shells which are unstable. There are some peaks and troughs, but the overall shape is nearly horizontal (Fig. 12(b)).
Gently undulate laminae	The laminae are continuously and stably distributed, such as stable fine silty laminae and unstable biofilm shells, showing obvious characteristics of wave peaks and troughs, but the overall laminae have moderate changes, and the peak height/wave distance ratio is less than 1/4 (Fig. 12(c)).
Wavy laminae	The laminae are continuously and stably distributed, such as stable fine silty laminae and unstable biological fine shells, showing obvious characteristics of wave peaks and troughs. The overall laminae have obvious changes, and the peak height/wave distance ratio is greater than 1/4 (Fig. 12(d)).
Interrupted laminae	The laminae are discontinuous, but generally traceable (Fig. 12(e)).
Lenticular laminae	The laminae are discontinuously distributed and dominated by matrix (Fig. 12(f)).

Table 7 Structure types and characteristics of fine laminae are classified based on their properties and correlations (including microscopic laminae)

Classification	Characteristics
Single lamellar structure	The argillaceous matrix is composed of only one stable distribution of characteristic laminae, such as fine silty laminae (Fig. 13(a)).
laminated structure	It is mainly characterized by one iconic laminae and distributed by one or more other laminae, such as stable fine silty laminae and unstable micro-shells of organisms (Fig. 13(b)).
Interlaminar structure	It is characterized by the interaction of two iconic laminae (Fig. 13(c)).
Multicomponent hybrid lamellar structure	Non-cyclic mixing of three or more characteristic laminae (Fig. 13(d)).
Circular lamellar structure	Two or more iconic lamellar features occur regularly (Fig. 13(e)).
Gradation lamellar structure	One or more of the iconic lamellar features show obvious change trend from bottom to top (Fig. 13(f)).

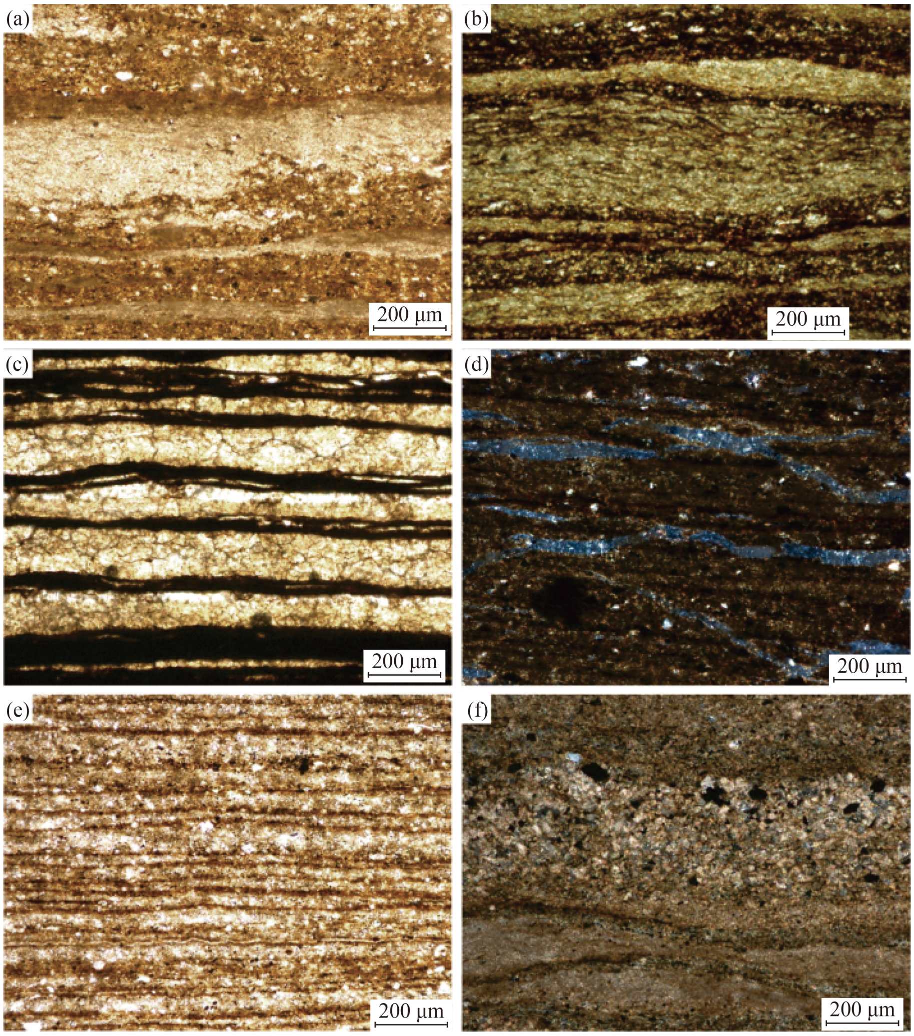

Fig. 13 Fine laminae structural types classified based on their properties and correlations. (a) Single lamellar structure (Well FY1; 3125 m); (b) laminated structure (Well NY1; 3441.75 m); (c) inter-laminae structure (Well NY1; 3465 m); (d) multiple component hybrid lamellar structure (Well NY1; 3396.65 m); (e) circular lamellar structure (Well NY1; 3499.95 m); (f) gradation lamellar structure (Well NY1; 3325.5 m).

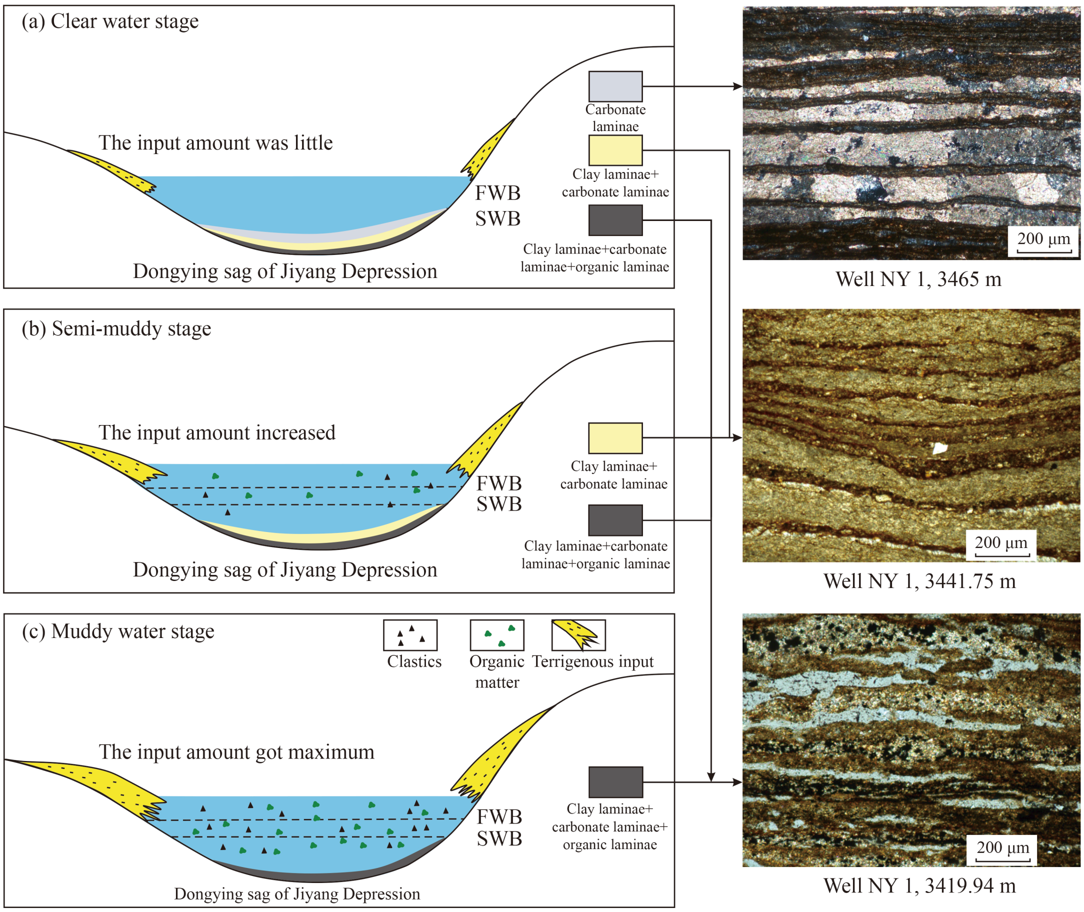

Fig. 14 Genetic pattern diagram of the fine-grain layered.

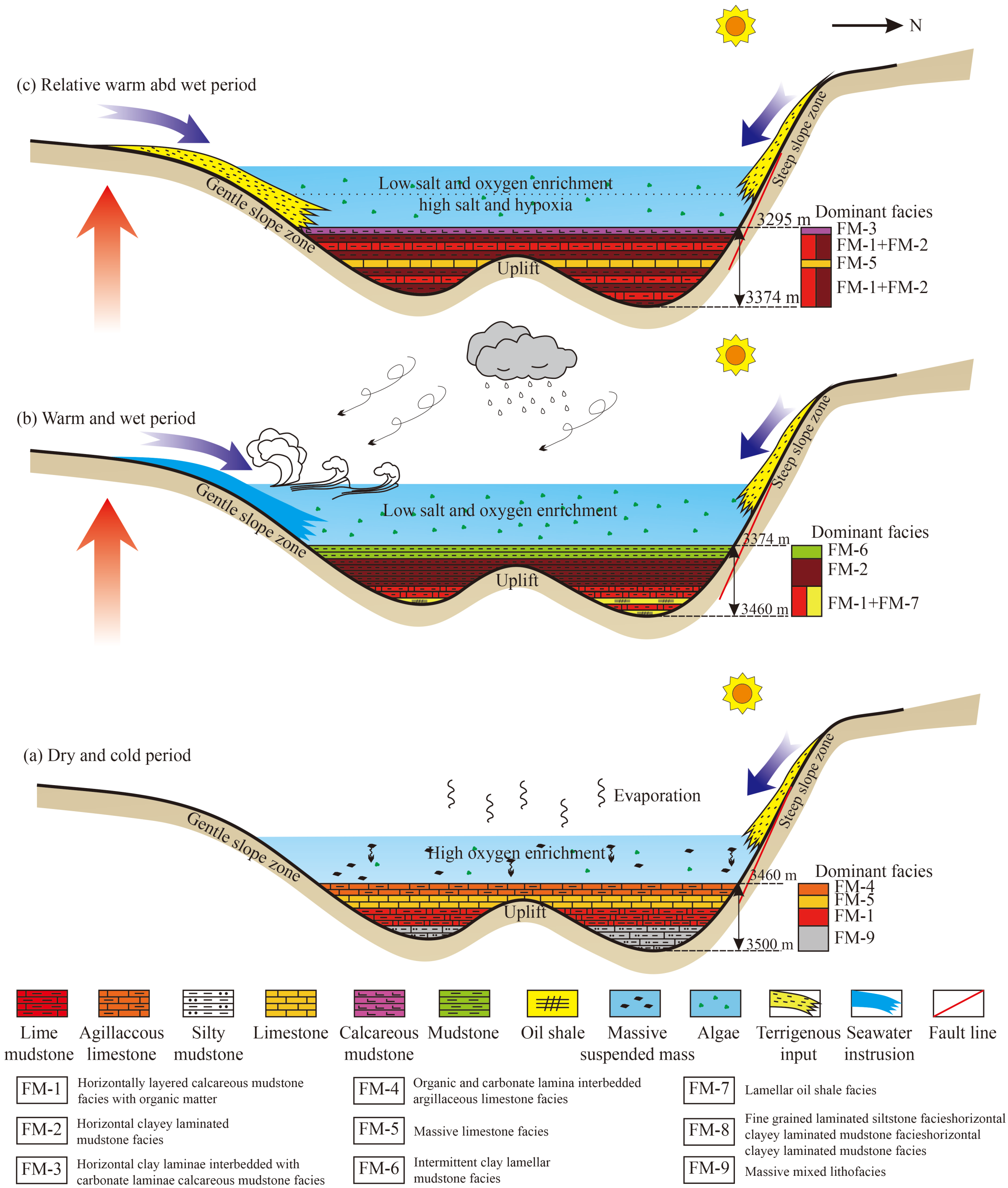

Fig. 15 Continental depression lacustrine fine-grained rock sedimentary model.

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