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RESEARCH ARTICLE

Deformation mechanism and hydrocarbon significance of Eocene organic-rich fine-grained soft sediments in the Leijia Region, Liaohe Depression

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Abstract The deformation structure of soft sediments has always been a research hotspot, which is of great significance for analyzing the tectonic and sedimentary evolution background of a basin, as well as the physical properties of reservoirs. Previous studies have reported that a large number of soft sediment deformation structures are developed in the western part of Liaohe depression. In this study, through core observation and thin section identification, various types of deformation structures are identified in the core samples which are collected from the upper Es4 in the Leijia region, western sag of Liaohe depression, such as liquefied dikes, liquefied breccia, convoluted laminae, annular bedding, synsedimentary faults, vein structures, etc. Based on the characteristics of core structure, single well profile and continuous well profile, combined with the regional background, this study clarifies that the deformation structure of soft sediments in the study area is mainly caused by seismic action. It is found that the permeability and porosity of deformation layers in the study area are higher than those of the undeformation layers, which proves that the deformation structure of soft sediments has a good effect on improving the physical properties of reservoirs.

Keywords soft sediment deformation structure, Liaohe depression, organic-rich fine-grained soft sediments, hydrocarbon significance

1 Introduction

The deformation structure of soft sediments refers to the deformation structure formed by external force acting on loose sediments, which is mainly due to the sudden and substantial increase of pore pressure in water-saturated sediments confined below the impermeable layer (Liu and Yu, 1990; Qiao et al., 2017; Su et al., 2022; Guo et al., 2023), which are widely developed in sedimentary basins (Van Loon, 2009; Li et al., 2019; Chen, 2020), especially in fluvial and lacustrine sedimentary basins (Moretti, 2000). They are of great significance to the analysis of the basin evolution background and oil and gas exploration (Du and Han, 2000; Chen et al., 2003; Hurst et al., 2003; Du et al., 2005; Qiao and Gao, 2007; Wei et al., 2007; Xia and Tian, 2007; Li et al., 2012; Chen, 2020). The formation mechanism of soft sediment deformation structure (SSDS) mainly includes external factors such as seismic action and internal factors such as gravity and tide (Owen and Moretti, 2011). Accurate identification of its formation mechanism is of great significance for understanding the type, occurrence time and intensity of tectonic activities in a basin (Guo et al., 2023), and clarifying the influence of SSDS on oil and gas reservoirs in the basin (Qiao et al., 2017; Liu et al., 2021). The sediments formed by deformation and redeposition due to seismic action transformation are called seismite (Törő and Pratt, 2016; Qiao et al., 2017). The original sedimentary structure of sediments is destroyed by the seismic action, formed a large number of interconnected structures, such as microfractures, thus improving the physical properties of the reservoir (Shao et al., 2014; Leila et al., 2022), but there is a lack of research on the seismite reservoir.

The upper Es4 member in the western sag of the Liaohe depression is one of the key exploration targets for shale oil in China, and high-yield industrial oil flow has been obtained in many wells. SSDS are widely developed in fine-grained sedimentary rocks in this area. In the current study, the SSDS in the Leijia region of Liaohe depression

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were studied by means of core observation and thin section identification. The formation mechanism of SSDS in this area was judged, and the influence of SSDS on shale oil reservoirs was discussed, which provides new evidence for the exploration and development of shale oil by studying the relationship between the formation of weak fine-grained sedimentary rocks and seismic events.

2 Geological setting

Liaohe depression is a Cenozoic rift faulted basin in the north-east of Bohai Bay Basin. It starts from the Liaodong depression in the east, with Yanshan subsidence zone in the west and Jiyang depression in the south, showing a structural pattern of “two grabens with one base” (Yu et al., 2007; Qi et al., 2013; Ji, 2016) (Fig. 1). The western sag is a secondary narrow and long half-graben-shaped sag which is distributed in the Liaohe depression in the north-east direction with an area of 2560 km^2. The western part is a slope landform, and the eastern side is a boundary fault (Chen et al., 2002; Shan et al., 2005). Leijia region is located in the northern part of the western sag, close to Taian-Dawa fault (Fig. 2(a)) (Li et al., 2022). Multistage extensional and transtensional tectonic activities controlled the formation and evolution of the Cenozoic Bohai Bay Basin (Zhang et al., 2017). The Eocene Shahejie (Es) Formation has experienced three stages of tectonic subsidence in the Leijia region (Fig. 2). The target layer of this study matches the first stage subsidence (The study layer is shown in Fig. 2(c)). During this period, volcanic and seismic activities were strong, and a large number of NNE-NE normal faults were developed and extended for a long time in the Leijia region. (Shan et al., 2005; Li et al., 2010; Qi et al., 2013) (Fig. 2(b)).

The strata in the western sag of Liaohe depression are relatively complex. The basement is mainly Archean strata, and the lithology is mainly granite and gneiss. Proterozoic and Paleozoic strata are developed in some areas (Wang, 2017; Wang et al., 2019). The Cenozoic sediments in the study area have a large sedimentation rate and many sedimentary cycles. The Eocene lacustrine sediments are mainly composed of Shahejie Formation, including Es1, Es2, Es3 and Es4 (Yang et al., 2006; Shan et al., 2014; Shan et al., 2017). In this study, the lowest member of Es4 is selected as research object. During this period, a large set of organic rich fine-grained sedimen-

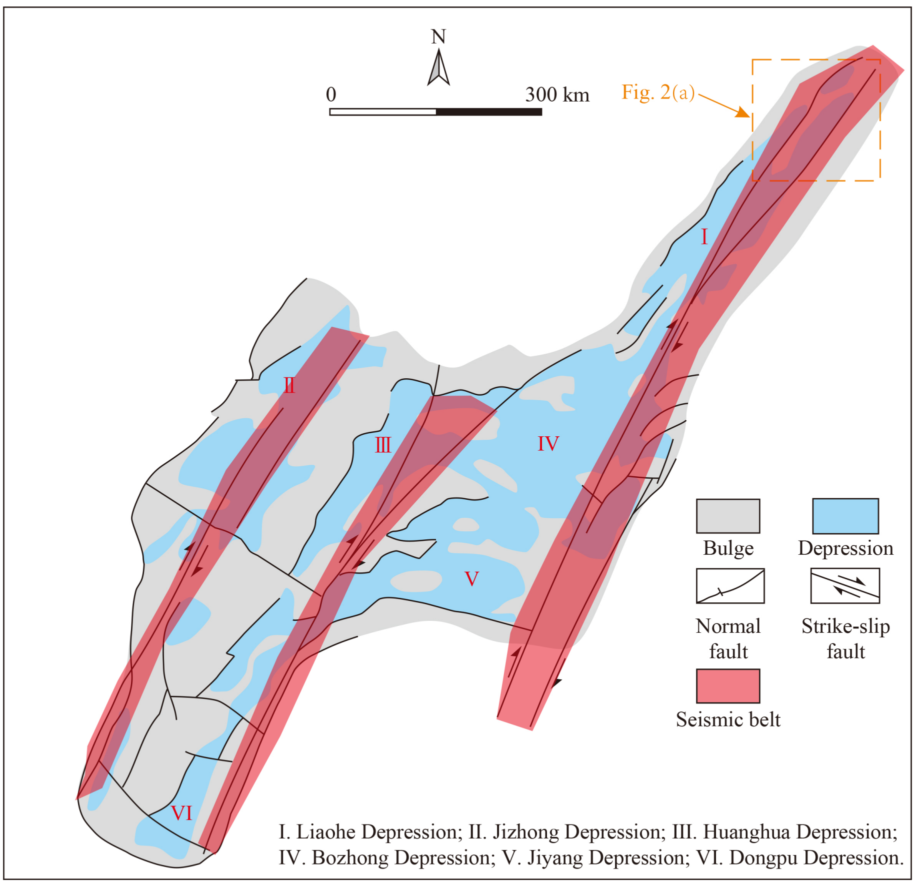

Fig. 1 Tectonic setting of the Eocene Bohai Bay Basin of north-east China, which is composed of six sub-basins, named as depressions I–VI. The three seismic belts belong to the Tanlu Fault Zone, and the study area is located in one of the seismic belts.

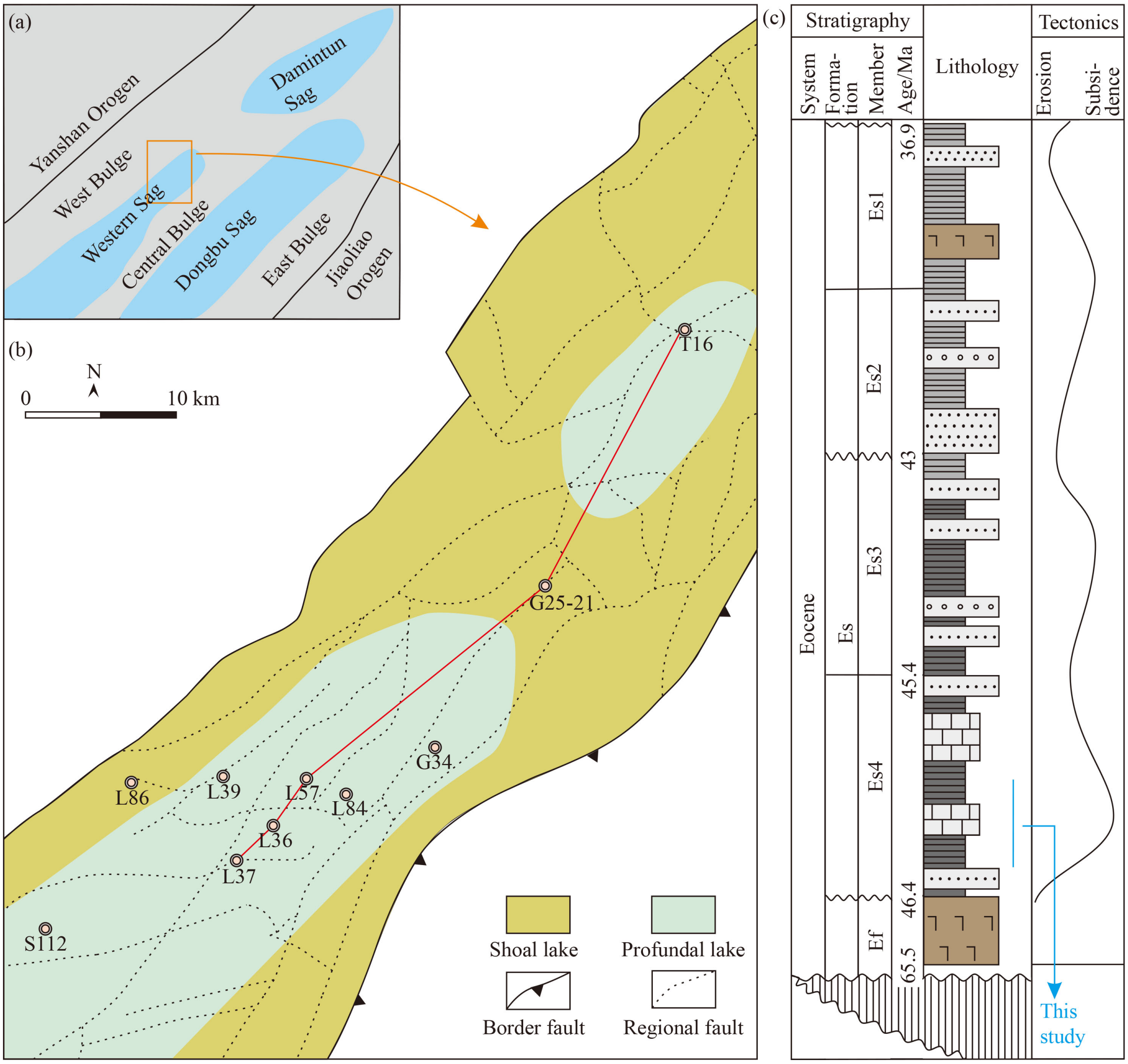

Fig. 2 (a) Geological setting of Leijia region in the western sag; (b) structural image of Leijia region in the western sag, with the location of well section; (c) Tertiary stratigraphy and tectonic evolution in the western sag.

tary rocks were developed in the deep lake area of Leijia region, and oolitic carbonate rocks, conglomerates and sandstones were developed in some areas.

3 Methods

In this study, the characteristics of SSDS in core samples collected from wells of L36, L37, L39, L57, L84, T16, and G25-21 are described in detail. The characteristics of SSDS in single well section and connected well profile are compared, which is used to study the vertical and lateral distribution characteristics of SSDS. The cores collected in this study are 10 cm in diameter. For selected cores, approximately 700 high-resolution photos were taken, and for important cores, photos were taken from different angles to cover the entire core. Moreover, some identified SSDS were sketched for better observation.

4 Deformation structures

4.1 Classification of SSDS

Many deformation sedimentary structures are preserved in the sedimentary rocks of the upper Es4 member in the western sag. According to their development characteristics, they are divided into two categories: soft sediment deformation and brittle deformation. The research area includes six types of SSDS: liquefied dikes, liquefied breccia, convoluted laminae, annular bedding, synsedimentary faults, and vein structures.

4.1.1 Liquefied dikes

Liquefied dikes refer to the dikes in which the liquefied flow of sand layer in the sediment intrudes into adjacent sedimentary layers, which are generally connected with the liquefied lithofacies strata (Qiao et al., 2017). Liquefied dikes in the study area are generally developed in the upper of Es4. The dikes are mostly sandstone-bearing coarse-grained clay to fine-grained sandstone, with colors ranging from light gray to gray. They are typically composed of soft sediment injections that crosscut the laminated strata. The orientation of the dike body is inclined or horizontal to the long axis and the shape includes radial, banded, tadpole, etc (Figs. 3(a)–3(d)). The dick length varies from 0.5 cm to 3 cm and extends vertically more than 10 cm. Its tail end is gradually pinched out, and the surrounding rock is in traction bending shape with liquefaction flow (Figs. 3(e) and 3(f)).

4.1.2 Liquefied breccia

Liquefied breccia is a deformation structure formed by the liquefied sand layer penetrating the adjacent argillaceous layer (Qiao et al., 2017). The lithology of liquefied breccia in the study area is mainly siltstone or argillaceous carbonate rock, which is intruded and cut by mudstone. Gray siltstone and gray white argillaceous carbonate rock are occur in breccia. The shape is mostly ellipsoidal, the angular angle of breccia is not obvious, and the size varies from several millimeters to several centimeters (Fig. 4). Some breccias show obvious drag marks or are separated into reticular patterns under microscope (Fig. 4(d)). Distinctive liquefied deformation features can be seen below the edge slide, and the micro breccia formed after thin layer liquefaction of argillaceous calcite can be seen (Figs. 4(d)–4(f)).

4.1.3 Convoluted laminae

The convoluted laminae in the study area is developed in laminated shale. The convoluted laminae layer is sandwiched between the undeformation layers, the thickness of the deformation layer is about 1–30 cm (Figs. 5(a)–5(g)), and small related folds are developed at the top. The convoluted laminae are irregular in shape (Fig. 5(a)), with some folds and some undulations (Figs. 5(c)–5(g)). The flank of the anticline is gentle, with no obvious sliding structure and injection vein. The orientation of fold axes varies from inclined to nearly horizontal and the fold amplitudes are about 2 cm, and partial dislocation is visible. Recumbent folds are developed in the horizontal direction, with an average fold amplitude of 5–10 cm, gentle wings, and no obvious sliding structures and injection veins (Figs. 5(h) and 5(i)).

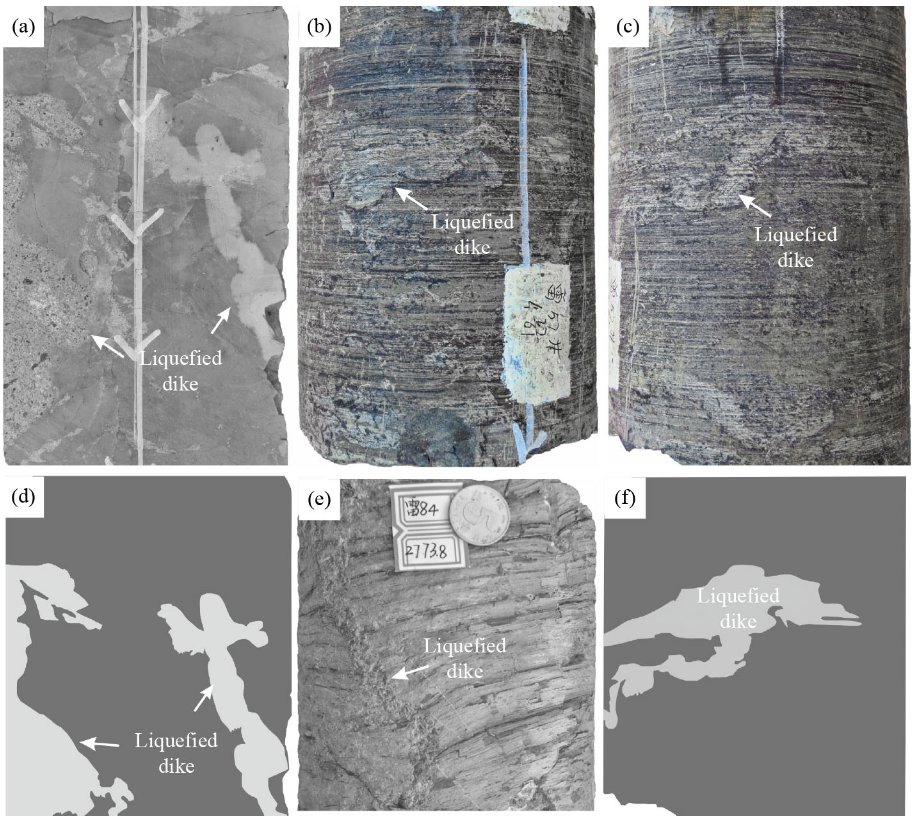

Fig. 3 Core and thin-section characteristics of liquefied dikes structure. (a) Well G21-25, 1871.10 m, liquefied argillaceous dike and liquefied sandstone dike; (b) and (c) Well L57, 2366.65 m, liquefied sandstone dike, emplaced from bottom to top, in the shape of mushroom cloud; (d) taken from Fig. 3(a); (e) Well L84, 2773.8 m, a liquefied argillaceous siltstone dike. The dikes gradually become thinner from top to bottom and pierces the original horizontal lamina, resulting in traction structure; (f) taken from Fig. 3(c), mushroom liquefied dike.

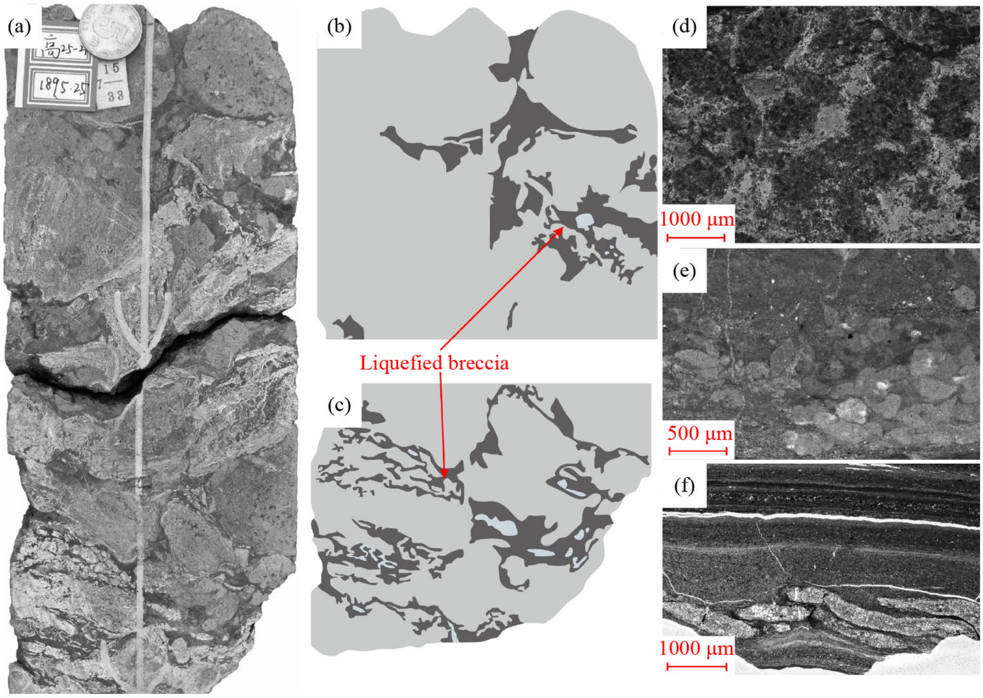

Fig. 4 Core and thin-section characteristics of liquefied breccia. (a) Well G21-25, 1895.25 m, liquefied breccia, dark green mudstone. vein in a reticulated pattern, pierces the dark gray surrounding rock and makes it brecciated; (b) and (c) from Fig. 4(a); (d) Well L57, 2359.8 m, thin section characteristics of liquefied breccia structure; (e) Well L57, 2372 m, thin section characteristics of liquefied breccia structure; (f) Well L57, 2368.25 m, thin section characteristics of liquefied breccia structure, the breccia is oval.

4.1.4 Annular bedding

Annular bedding is a circular structure connected by the curling deformation of multiple thin rock layers (Qiao et al., 2017). Annular bedding is mostly distributed in bedded argillaceous siltstone, showing the characteristics of multiple annular layers nested. The diameter of the inner sheath is about 1 cm, and the that of the outer ring sheath is 2–10 cm (Fig. 6). Light crystalline calcite veins are developed along the annular laminae and a small number of micro faults are associated with the annular layer (Figs. 6(c) and 6(d)).

4.1.5 Synsedimentary faults

Synsedimentary faults are usually developed locally in shale, showing a group or a series of parallel normal faults, and moving to loose strata vertically or at a certain angle. Most synsedimentary faults are normal faults developed between unaffected upper and lower strata. The lithology of deformation sediments is generally composed of fine to medium-grained calcareous clastic rocks and local argillaceous limestone, some of which carbonate gravels of pebble size. The synsedimentary fault has a large dip of about 50°– 80° with an offset between 0.2 cm and 2 cm, and there is a certain gap in the thick layer of the fault (Fig. 7). The combination of graben and barrier is also developed in the synsedimentary fault (Figs. 7(e) and 7(f)). The dip angle of the fault plane is large and the fault scale is small. There is a strong liquefaction flow along the fault, and the thickness of the upper plate of the contemporaneous sedimentary layer is obviously greater than that of the lower plate (Figs. 7(c) and 7(f)).

4.1.6 Vein structures

Vein structure is a group of fine veins arranged in parallel, which is small in size, several microns to several millimeters in width and several microns to several centimeters in height. Each vein is filled with fractures commented by dark fine particles, mainly clay or mica minerals (Figs. 8(a)–8(c)). They appear as a group of S- or X-shaped (double S-crossing pattern) veins, usually without cutting the bedding plane (Fig. 8(d)). The veins are regularly arranged, and the interval between them is generally one to several millimeters wide, which is generally in high angle contact or sub-parallel arrangement with the bedding (Fig. 8(d)).

4.2 Temporal and spatial characteristics of SSDS

Based on the cores collected from six wells of L37, L36, L39, L84, T16, and G25-21, the well profile is established (the location is shown in Fig. 2). The plane and vertical distribution characteristics of deformation structures and sedimentary sequences are analyzed through a cross-section.

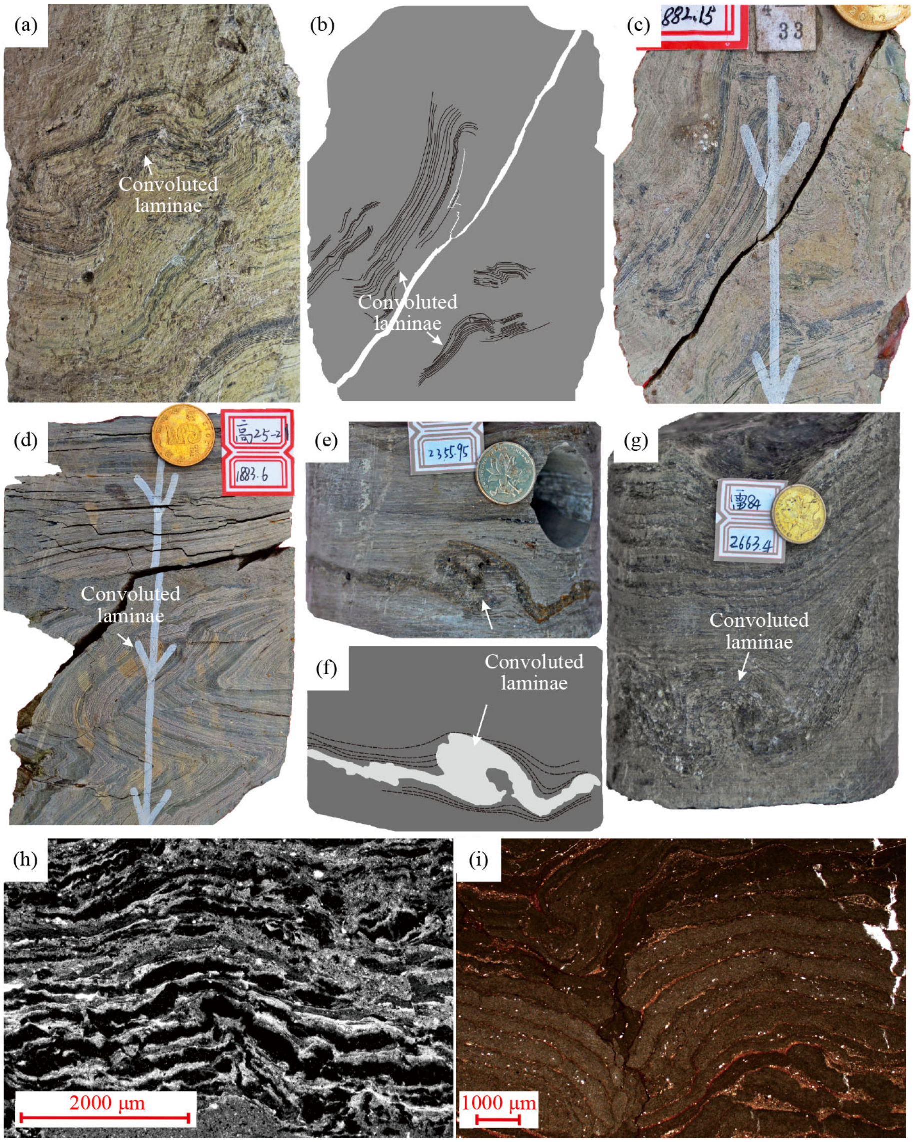

Fig. 5 Core and thin-section characteristics of convoluted laminae. (a) Well G25-21, 1881.95 m, with an irregular shape and curved laminae; (b) taken from Fig. 5(c); (c) Well G21-25, 1882.15 m, where the grain layer has bending deformation; (d) Well G21-25, 1883.6 m, the bottom layer is deformation, and top layer is undeformation; (e) Well L57, 2355.95 m, bending striation, and it should be noted that the upper and lower parts of bending striation are undeformation layers, with the same lithology as deformation layers; (f) taken from Fig. 5(e); (g) Well L84, 2663.4 m. folds developed, axially almost vertical; (h) Taken from Well L36, 2528.1 m, bent laminae, deformation layer between undeformation layers and identical lithology; (i) taken from Fig. 5(e). Layers bend to form folds.

4.2.1 Lateral characteristics

The deformation layer is widely distributed along the fault zone and various types of SSDS are developed (Fig. 9). The deformation layer is controlled by the Tanlu Fault Zone and extends north-eastward along the fault zone. In areas with strong tectonic activity, the deformation structure types are diverse and the thickness of soft sediments is large. In areas with weak tectonic activity, the deformation structure types of soft sediments are single and the thickness is small. This large-scale distribution of SSDS is likely to be caused by seismic action. Affected by the fault zone, many high-intensity and multi-period episodic earthquakes occur, which can form a large-scale distribution of deformation layer. The SSDS caused by gravity can only be developed locally, and the extension is not far, without large-scale distribution. Therefore, it can be inferred that the SSDS in the study area may be caused by seismic action.

4.2.2 Vertical characteristics

It can be seen from the single well profile that the deformation layer and the undeformation layer appear alternately in the vertical direction, showing the characteristics of multi-stage superposition (Fig. 10). The adjacent deformation layers are separated by the undeformation layers in a certain degree of circulation. In

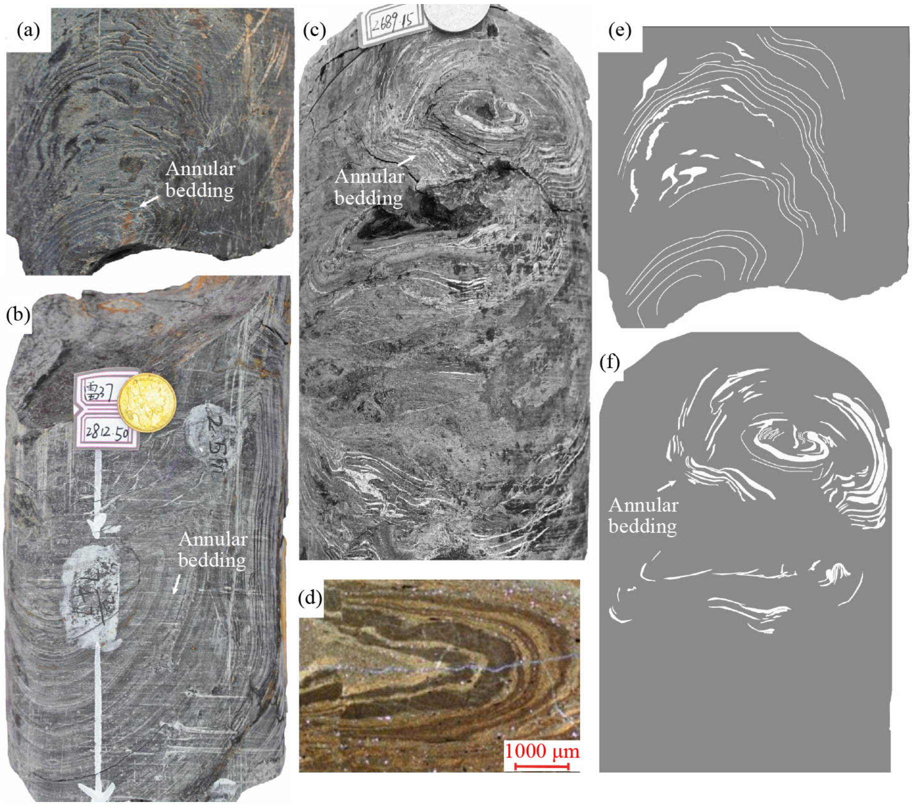

Fig. 6 Core and thin-section characteristics of annular bedding. (a) Well L39, 2380.05 m, annular bedding, mainly composed of mud silty carbonate rock; (b) Well L37, 2812.5 m, annular bedding; (c) Well L36, 2689.15 m, annular bedding, a few calcite veins are visible in the annular laminae. The annular layer is represented by the interbedding of bright carbonate vein layer and mud silty layer; (d) taken from well L36, 2367.7 m, annular bedding and micro faults; (e) taken from Fig. 6(a); (f) taken from Fig. 6(c), a few calcite veins are visible in the annular laminae.

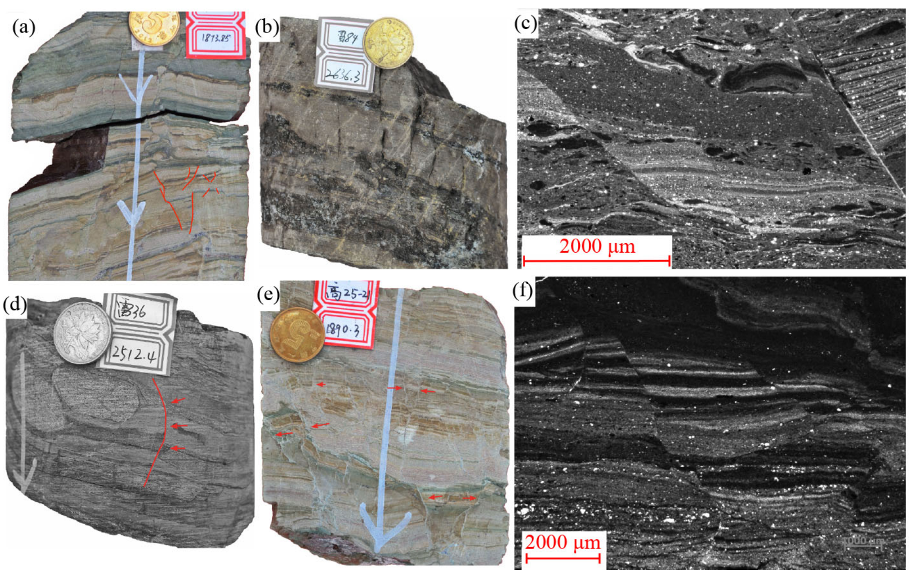

Fig. 7 Core and thin-section characteristics of synsedimentary faults. (a) Well G25-21, 1873.85 m, synsedimentary faults, ladder graben and horst assemblages within layers; (b) Well L84, 2636.3 m, the fault is nearly vertical, a series of faults parallel arrangement; (c) taken from Well L36, 2512.4 m, two sets of stepped micro-faults; (d) Well L36, 2512.4 m, micro-fault (red dotted line position); (e) Well G25-21, 1890.3 m, a series of faults (shown by red arrows) can be seen under the core, with some sections straight but some sections bent; (f) taken from Well L57, 2382.5 m, stepped micro-faults, with relatively straight cross-section.

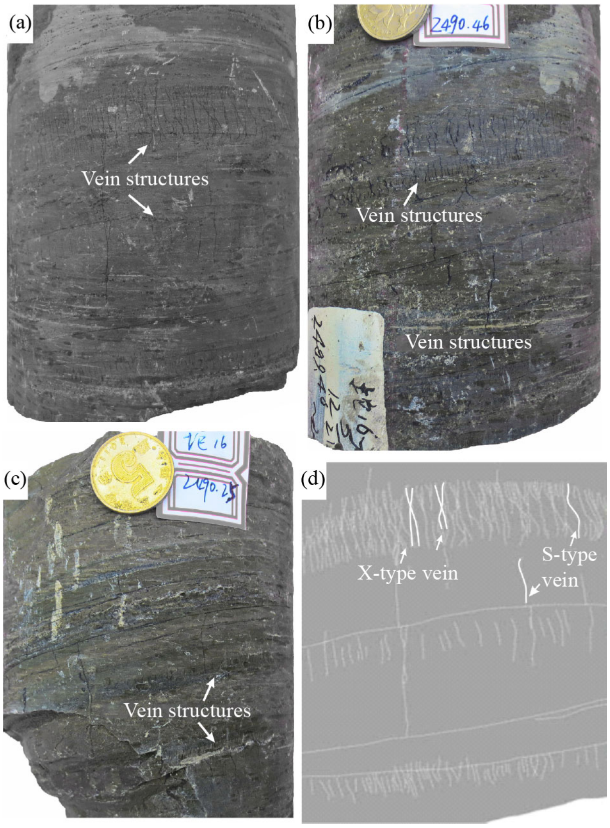

Fig. 8 Core characteristics of vein structure. (a) Well T16, 2490.46 m, vein structure; (b) Well T16, 2490.42 m, vein structure; (c) Well T16, 2490.25 m, the vein body is in the shape of "X" or "S", and the vein body and the laminar intersect at a large angle; (d) taken from Fig. 8(a).

the deformation layer, the distribution of various deformation structures has certain regularity. The top of the deformation layer is convoluted laminae, and the bottom is seismic breccia or synsedimentary fault, which also has certain cyclicity. Strata with the same lithology above and below the deformation layer, one part deforms under the influence of deformation structure, and the other part does not deform (Figs. 5(d) and 10). When the seismic activity ends, the overlying strata are usually deposited on the deformation layer, resulting in the same lithology of the upper and lower strata, but only the lower strata deform.

5 Discussion

5.1 Formation mechanism of SSDS

Morphological characteristics of deformation structures in soft sediments depend on lithology, physical properties and driving force systems of sediments (Ezquerro et al., 2015; Törő et al., 2015). Most of the deformation structures undergo fluidization or liquefaction deformation due to the decrease of sedimentary strength (Owen et al., 2011), or brittle deformation of the sedimentary layer under the effect of external stress. However, both the decrease of sedimentary strength and the generation of external stress require the function of triggering mechanism. The triggering mechanism of SSDS mainly includes external triggering factors such as seismic action, and internal triggering factors such as storm, tide and gravity (Du et al., 2001, 2007). However, it is difficult to distinguish between seismic and non-seismic deformation structures only from the external morphology (Owen and Moretti, 2011; Feng et al., 2016). Morphological analysis of deformation structures combined with sedimentary and structural settings help to determine the mechanism of sediment deformation (Törő et al., 2015; Törő and Pratt, 2015) (Table 1).

According to previous studies, the characteristics of SSDS caused by seismic action generally have the following characteristics: 1) it is a small deformation structure between the undeformation layers, and the deformation layers and the undeformation layers have similar lithology and sedimentary facies; 2) its spatial distribution has the characteristics of lateral continuity and vertical periodicity, and its distribution area is often large; 3) its deformation intensity and deformation frequency are obviously related to the fault. In general, the closer to the fault, the greater the deformation strength. (Hilbert-Wolf et al., 2009; Van Loon, 2009; Owen et al., 2011; Qiao et al., 2017).

From the tectonic setting, the optimal triggering mechanism of these deformation structures can be interpreted as synsedimentary to post-depositional seismic action. The following factors indicate that these deformation structures may be triggered by seismic action. 1) The liquefied breccia in the study area is splicable, indicating that the breccia has no obvious displacement and belongs to *in situ* or near-*in situ* deposition. It is obviously different from the off-site sedimentary liquefied breccia caused by gravity flow or storms, which is consistent with the characteristics of liquefied breccia formed by seismic action (Kahle, 2002; el Taki and Pratt, 2012; Wallace and Eyles, 2015) (Fig. 4); In addition, there is no clear direction of the fold axial plane of the convoluted laminae layer in the study area, which does not conform to characteristic of the convoluted laminae (has the same axial plane) that formed due to gravity. In conclusion, the liquefied deformation structure in the study area is formed by seismic action. 2) There is a systematic and constant spacing between the continuous vein structures in the study area (Fig. 8). This phenomenon is caused by the shock wave generated by resonance (Mazumder et al., 2016). The shock wave can be generated by seismic action and gravity action, but no evidence of gravity action is found in the study interval. Therefore, the vein structure in the study area is most

Table 1 Summary table of deformation structure formation mechanism of soft sediments

Formation mechanism	Genesis	Constructed type	Features	Reference
Glacial activity	Unstable moraine deposits are formed due to glacial activities	Disharmonic folds	Lithology dominated by glutenite, poor sorting, no orientation	Greb and Archer (2007)
Hydraulic fracturing	Due to the rupture of high-pressure fluid sac in sedimentary rock	Rock vein, diapir structure, hydraulic fracture breccia	Generally formed vein, layered veins, fluid containing metal elements	Greb and Archer (2007); Moretti and Sabato (2007)
Landslide and debris flow	As a result of a large number of gravity flow deposits and accumulations, SSDS are formed due to instability	Distorted folds, involved structures	Generally formed curl deformation and fold	Greb and Archer (2007); Chen et al. (2011)
Liquefaction	As the water in the upper strata (such as high pressure mudstone layer) is pressed into the sandstone layer, the water content of the sandstone layer increases and the sandstone particles are suspended in the water	Drainage structure, liquefied sandstone dike, enclave bedding	Generally developed in siltstone and fine sandstone, but not in mudstone	Greb and Archer (2007)
Seismic action	1) Shear causeds by seismic action; 2) change of pore fluid pressure due to wave	Load structure, flame structure, needle structure, spherical structure, liquefied veins, liquefied breccia, etc.	The deformation layer is widely distributed along the fault zone, with the strength of seismic action	Qiao et al. (2001); Pratt (2002); Becker et al. (2005)

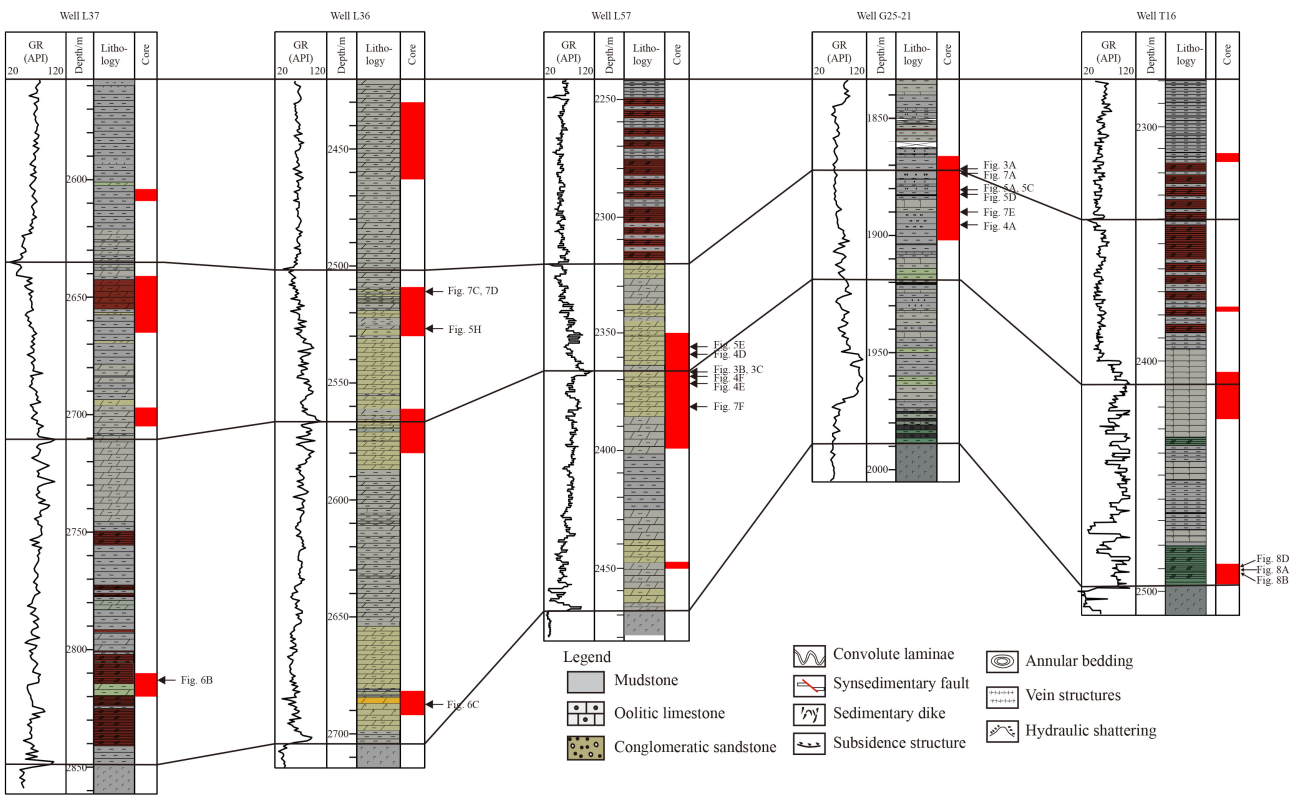

Fig. 9 The profile from well L37 to well L16, showing the distribution of deformation layers. The red rectangle represents the coring position.

likely to be formed by seismic action. 3) The SSDS is widely distributed in wells of L36, L37, L39, L84, L86, G25-21, and T16, which is consistent with the large-scale distribution of deformation structures caused by seismic action. This is obviously different from the deformation structure caused by gravity flow which only develops locally (Rossetti et al., 2011; Li et al., 2012). 4) In the vertical direction, multiple sets of superimposed SSDS are separated by undeformation strata, and the deformation structures show a certain degree of cyclicity (Fig. 10). Its top is generally convoluted laminae, and the bottom is generally fractured breccia or liquefied breccia. Meanwhile, the lithology of the deformation layer is the same as that of the adjacent undeformation layer (Figs. 5(d) and 5(h)). This phenomenon is most likely caused by seismic action which leads to the destruction of the first deposited

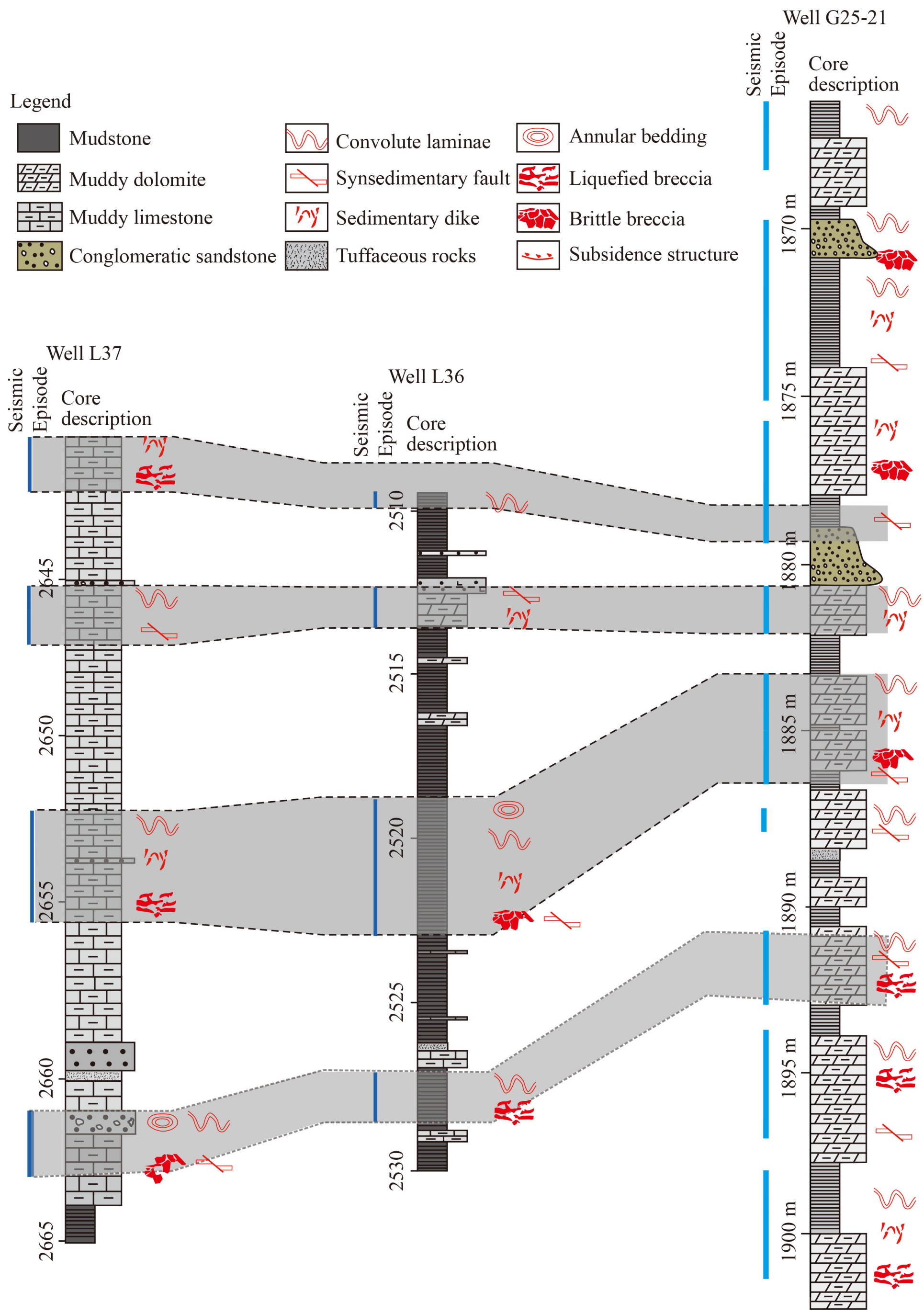

Fig. 10 Comparison of SSDS in different wells, showing the deformation layer and undeformation layer appear alternately in the vertical direction.

rock layer, forming a deformation layer. When the seismic activity ends, the normal sedimentary load will continue to be above the deformation layer. 5) During the sedimentary period of Es4 in the western sag, strong unbalanced fault block movements and a large number of active faults were developed, indicating that these faults may control the topographic relief in the basin and have a great influence on the distribution and deformation of sediments. In this period, the western sag was the main source supply area, forming a lake basin, which had the prerequisite for SSDS caused by seismic action. 6) Paleogene seismites have also been found in the eastern sag of Liaohe depression, including drainage structure, load structure, flame structure, spherical pillow structure and synsedimentary faults. The structure of the western sag is similar to that of the eastern sag (Liu et al., 2015). Therefore, the simultaneous development of SSDS in the western sag is likely to be the cause of seismic action; 7) In the study area, the tidal effect was weak during the sedimentary period of Es4, and large-scale deformation structure layers could not be formed, so the tidal effect could be excluded to form deformation structures. And during this period, the basin is in a deep lake environment, and the deformation structure caused by groundwater intrusion is generally formed in a river environment, so it does not exist in the lake environment of this study.

Similar to modern earthquakes, paleoearthquakes may be episodic, and there are usually multiple continuous events during seismic activity, and sedimentary deformation structures are one of the good records (Qiao et al., 2006; Qiao and Guo, 2013). Several soft sediment deformation layers are separated by undeformation layers, which can be regarded as an earthquake episode. When the time interval between two earthquake episodes is longer than the time interval between the respective earthquake sedimentary records, many earthquake episodes constitute an active period. The thicker undeformation sediment layer between earthquake episodes indicate a longer time interval. In core observation, if multiple soft sediment deformation layers and brittle deformation layers occur continuously, the deformation is most likely caused by paleoearthquakes rather than other factors (Qiao et al., 2017).

In summary, a small part of the SSDS in the study area may be causeed by internal triggering factors, but extensive deformation structures are mainly caused by seismic action.

5.2 Effect of SSDS on reservoir quality

5.2.1 Pore characteristics of rocks developed in SSDS

By comparing the permeability and porosity of the undeformation and deformation layers in the study area, it is found that the porosity and permeability of the deformation layer are significantly higher than those of the undeformation layer. The porosity of the undeformation layer in the study area is 0.64%−17.55% (mean 10.32%), and the permeability is 0.0008−0.73 × 10^{-3} μm^2 (mean 0.125 × 10^{-3} μm^2). However, the porosity of the deformation layer is 3.73%−29.25% (mean 18.94%), and the permeability of the deformation zone is 0.0016−0.96 × 10^{-3} μm^2 (mean 0.175 × 10^{-3} μm^2) (Table 2).

A large number of identifiable pores and fractures can be seen in the deformation layers. The width of fractures ranges from tens of microns to hundreds of millimeters, including both brittle fracture and plastic deformation (Fig. 11). A large number of pores formed after brecciation of fine sediments can be seen under thin sections, with pore diameters of several hundred microns. This shows that the seismic action has a direct transformation effect on the reservoir, and the formed fractures have a significant effect on connecting pores and improving reservoir permeability. At the same time, it is also conducive to the activities of pore water and groundwater, thus promoting the development of dissolution pores and formed a unified pore, hole and fracture system.

In the core, fractures and liquefaction channels can connect with pores, thereby improving the permeability of reservoirs. Cores fractures are developed in seismite strata of wells L36 and L57, and there are different degrees of oil and gas reservoirs on the surface of cores, and even asphalt occurs along the fractures on the surface of dark shale. The reservoir shows heterogeneity after transformation, and the liquefied dikes can invade and pierce the surrounding rock. For example, after the carbonate veins invade the shale strata with poor permeability, the effective porosity and permeability of the reservoir increase, making the originally dense fine-grained sediments a good reservoir after transformation (Fig. 12). These phenomena suggest that seismic action improves the reservoir properties of fine-grained reservoirs in the study area.

The micro-fractures formed by the seismic action provide channels for the later fluid seepage, which in turn to form dissolution pores and improve the porosity of the reservoir. In thin section observation, a series of dissolution pores are developed along the fractures in shale, which effectively increases the porosity of reservoir and provides a good place for oil and gas accumulation.

Table 2 Physical property table of core in study area

Well	Depth/m	Lithologic characters	Average porosity/%		Average permeability/(10^{-3} μm^2)	
			Deformation segment	Undeformation layers	Deformation segment	Undeformation layers
L84	2625−2786.5	Mainly limestone	18.50	10.21	0.172	0.112
L37	2540.8−2857.2	Limestone and argillaceous limestone	20.80	11.94	0.183	0.124
L39	2331.4−2394	Mainly mudstone and marl	17.80	9.88	0.168	0.134
L57	2351.5−2450	Mainly argillaceous limestone and argillaceous limestone	18.45	8.34	0.177	0.142
T16	2407.5−2550.8	Limestone and limestone	17.60	10.63	0.182	0.121
G25-21	1866−1902	Mainly mudstone and sandstone	20.48	10.87	0.165	0.117

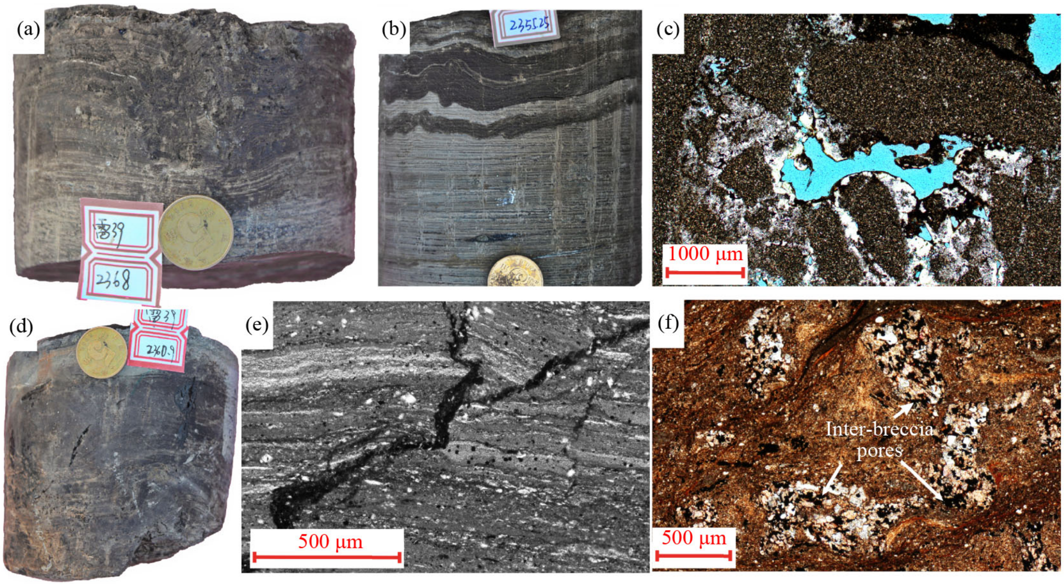

Fig. 11 Oil-gas bearing characteristics of deformation structures in soft sediments. (a) Well L39, 2368 m, has good oil-bearing property in the strong deformation section of the upper core, while poor oil-bearing property in the weak deformation section of the lower core; (b) Well L57, 2355.25 m, the upper part of the core has oil-bearing property, while the lower undeformation layer has poor oil-bearing property; (c) from Well L39, 2368 m, the pores with hundreds of microns in diameter (blue casting) are distributed among the breccias formed by the seismic action; (d) Well L39, 2360 m, has good oil-bearing property in the strong deformation section from the bottom to the middle and upper part of the core, but poor oil-bearing property in the weak deformation section at the top; (e) from Well L57, 2355.25 m, organic matter is distributed in the micro-fractures formed by soft sediment deformation; (f) from Well L39, 2360 m, hundreds of microns in diameter of pores distributed between breccias formed by seismic action.

The upper member of Es4 in the study area belongs to deep lake facies, and a set of fine-grained sediments containing carbonate shale is deposited. In theory, the reservoir conditions should be poor. However, seismic action can make tight reservoirs form fractures and secondary pores, thus improving the physical properties of fine-grained reservoirs.

5.2.2 Significance of shale reservoir exploration

The shale oil resources of fine-grained reservoirs are abundant (Jiang et al., 2022). However, its ultra-low porosity and ultra-low permeability are the bottleneck that restrict the exploration and development of shale oil. This study found that the porosity and permeability of the deformation layer in the study area are better than those of the undeformation layer, indicating that the seismic SSDS has an important influence on the physical properties of shale oil reservoirs, which is of great significance for the exploration and development of shale oil (reservoir physical contrast see Section 5.2.1). In China, seismites have been found and reported in the fine-grained reservoir strata of several major petroliferous basins, such as Yanchang Formation in Ordos Basin, Xujiahe Formation in Sichuan Basin, Qingshankou Formation in Songliao Basin, and Shahejie Formation in Bohai Bay Basin (Wei et al., 2007; Zhang et al., 2007; Yang et al., 2008a, 2008b; Shao et al., 2014; Zhao et al., 2019). The above basins are also the key targets of shale oil exploration in China. The relationship between seismites and shale reservoirs is worthy of attention in future research. Identifying this relationship directly determines exploration deployment and dessert prediction. For shale oil reservoirs controlled by seismic action, favorable exploration targets may be fine-grained reservoirs developed along seismic zones.

6 Conclusions

1) A variety of soft sedimentary deformation structures such as liquefied dikes, liquefied breccia, convoluted laminae, annular bedding, synsedimentary faults and vein structures were identified in the study area. These structures are widely distributed in the horizontal direction, and have the characteristics of multi-stage superposition in the vertical direction. Most of the deformation structures are in situ deformation structures, and their structural characteristics conform to the characteristics of SSDS caused by seismic action, indicating that seismic action is the main driving force for the formation of these structures.

2) The micro-fractures and faults generated by seismic action can become good oil and gas migration channels, and provide channels for later fluid seepage, formed dissolution pores in the formation, and improving the

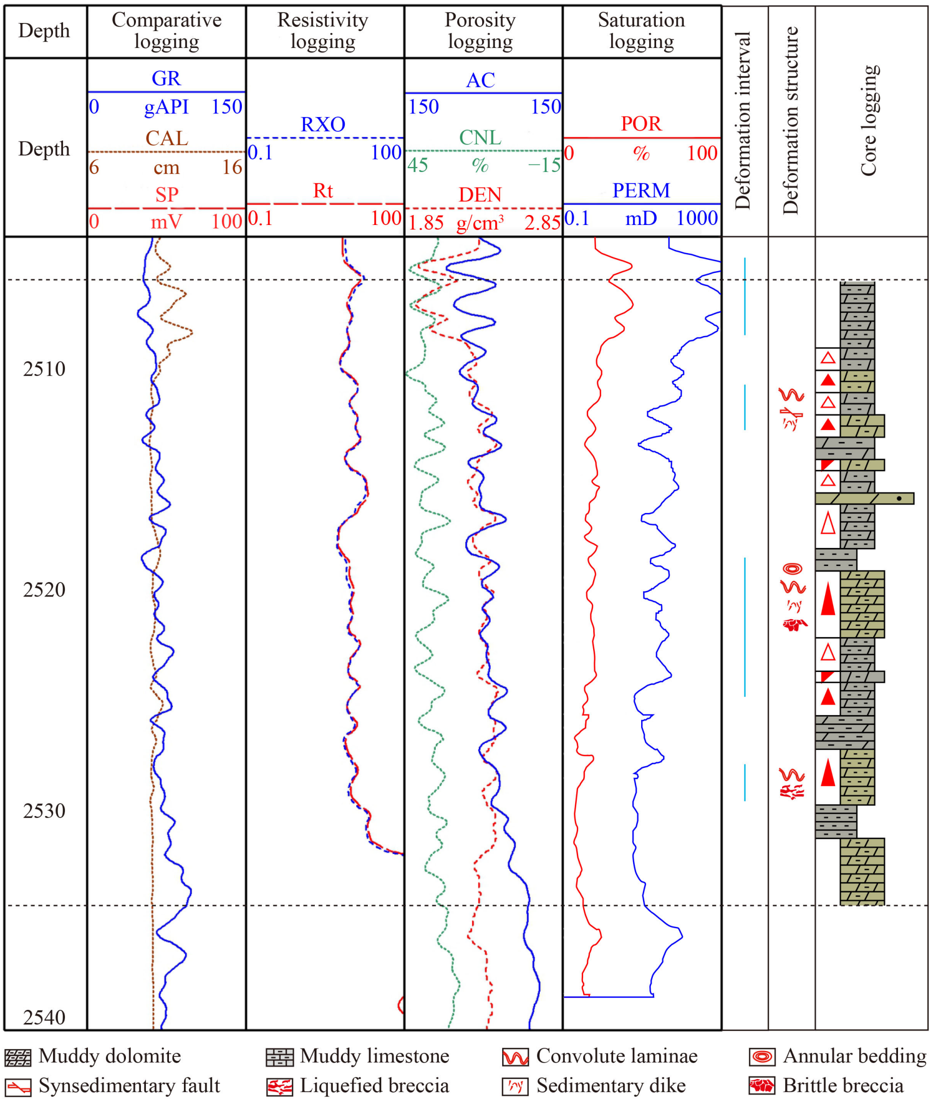

Fig. 12 Single well profile of L36, showing the porosity and permeability of deformation and undeformation layers.

permeability and porosity of tight fine-grained sedimentary rock reservoirs. Therefore, the seismic SSDS is of great significance for the exploration of shale oil reservoirs.

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