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RESEARCH ARTICLE

Characteristics and significance of seismite of Silurian in member III at Shahejie Formation

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Abstract Based on studies of regional tectonic setting and the observation of drilling cores, the seismite is recognized in member III at Shahejie Formation in the Xianhe area of the Dongying sag. The principal mark of the seismite is the development of all kinds of soft sedimentary deformation structures, such as micro-step fault, intraformational minor fold, deformation, vibrational liquefied sandstone dike and seismic breccias. By observing the drilling cores of He 152, Wang 59, Niu 38, Niu 22 and so on, we found that the vertical sequences of the seismite are different because of the differences in structure and seismic intensity. We also found that different seismite structures are formed by different seismic intensities and that the relationships between seismite structures and paleoearthquakes were further confirmed by studying the relationship between all kinks of seismite structures and seismic intensity. Researches on reservoirs show that seismite can be an effective reservoir. These researches provide an important geological theoretical foundation for the study of the tectonic evolution of the Dongying sag and for seismite identification and description, and also supplies evidence for the researches of paleoearthquakes.

Keywords seismite, identification sign, seismite sequence, paleoearthquake, Dongying sag

1 Introduction

Seismite, first proposed by Seilacher, initially means a redeposited sedimentary layer formed by unconsolidated submarine deposit through seismic activity in a tectonically active region (Du and Han, 2000). As early as the mid 20th century, Heezen and Ewing studied earthquake displacement and sedimentary deformation in the marine strata and the turbid flow caused by the 1929 earthquake in Canada (Heeze and Dyke, 1964; Plaziat and Ahmamou, 1998). Afterwards, many scholars studied the sedimentary deformation caused by the seismic activities and its mechanism. Domestic studies toward seismite also made great progress. The study of the marine earthquake events of the Neoproterozoic and the Paleozoic eras in North China, South China and Southwest China made striking achievement (Song et al., 1988; Wu and Yin, 1992; Qiao et al., 1994; Qiao, 1996). In recent years, different kinds of seismites have been discovered in fluvial facies, lake facies and the outcrops in the marine strata by geologists, but the information left by the earthquake tended to be ignored and was not interpreted in the process of well drilling. The authors discovered a lot of abyssal soft sedimentary deformation structures and considered them as characteristics of seismite from the study of sedimentary facies and environments in member III at the Shahejie Formation of the Dongying sag, and from the further study of the relationship between the soft sedimentary deformation structure and the structure of the area, the sedimentary environment, the reservoir as well as the seismic intensity.

2 Regional structure background

Dongying sag is a typical open Meso–Cenozoic half sag. North of it is a discordogenic fault, contacted by the Chenjiazhuang bulge and the Binxian bump, the southern part is overlapped by the Luxi uplift and the Guangrao bump, the western part is adjacent to the Linfanjia structure-Gaoqing bump, and the east is adjacent to the Qingtuozi bump and the Qingdong sag. In the process of the formation and the evolution of the sag, the intense activity of the fracture in the north caused the formation of "fracture in the north, overlapping in the south", which makes the basin more typically compared with other sags in the Jiyang depression (Fig. 1).

In the sedimentary period of member IV–III–II at the Shahejie Formation, the deposition in the basin was controlled

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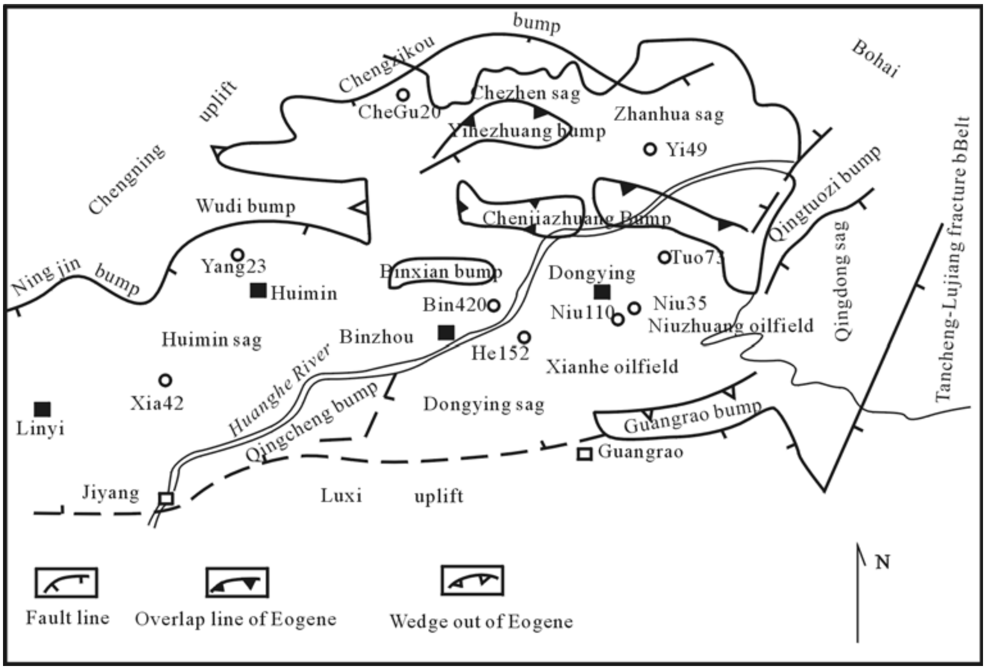

Fig. 1 Sketch of regional geology of Dongying sag

by the north-east, east-north-east and east-west fracture, and the basin was in a serious fault depression when member III deposited. In the early-middle period of the deposition of member III in the Shahejie Formation, the basement of the rift basin subsided continuously under the background of fast extension, and the sinking rate was bigger than the sedimentary imputing rate. Under humid climate and abundant water, a suit of dark grey mudstone and oil-shale and different kinds of gravity flow sedimentary formation were deposited. In the period of upper member III—lower member II at the Shahejie Formation, the fracture activity abated and the sinking of the basement slowed down. Intense structural activity and aphytal facies are in favor of the development and preservation of seismite.

3 Characteristics of seismite

In our domestic research, the main research object is carbonate rock and little seismite information was observed in well drilling. Yang et al. (2004) and Chen et al. (2003) discovered some seismite core information when they studied the Jiyang depression. Domestic and overseas researches indicated that step fault, intrafolial fold, pseudonodule, liquefied sandstone dike, sluicing structure as well as curled deformation structure and so on are principal marks to identify seismic record of terrestrial time (Smith, 1968; Chen et al., 2003; Yang et al., 2004; Yuan, 2004; Tian et al., 2005). These marks were discovered in Well He 152, Well Wang 59, Well Niu 38 and Well Niu 22 etc., and the characteristics of Well He 152 are the most obvious.

3.1 Structural characters

3.1.1 Sandstone dike

Sandstone dike, the most developed structure in seismite, is a kind of sandy dike which developed in sand-shale interlayered sediment and extends irregularly and cuts through the horizontal bedding (Fig. 2(a)) in the surrounding rock, which is the consequence of the liquidation of the soft sediment. The silt dike and fine sand dike discovered in the core were formed by the water rich sandy sediment. In earthquake activities, the water-rich sandy sediment diapired into the argillaceous sediment and formed the vein body (Plate 1) under pressure. The sandstone dikes have different sizes and irregular forms, generally, 0.5–5 cm wide, and one to dozens centimeter long. The lamina of the surrounding rock curved when sandstone dikes cut through the surrounding rocks. The sandstone dikes present different sizes of mottling and slabby in plan.

3.1.2 Micro fault

Micro fault is the small-scale fault formed in the layer in the process of liquefaction during earthquake shock. The micro fault, which is 1–5 cm long with a steep dip, is equivalent to the shatter stone proposed by Qiao et al. (1994) (Fig. 2(b)). The fault space is about 0.5–2 cm and the slip is 0.2–1 cm. They are mainly extensional faulting, step-shaped in the cross section. Most of them are normal faults, but the border fault can be abnormal fault because of the earthquake activity. For example, the micro fracture developed in the sand-shale interlayered rock observed in Well He 152 is vertical to the bed plane and can cut off the clay stone layer until the sandstone

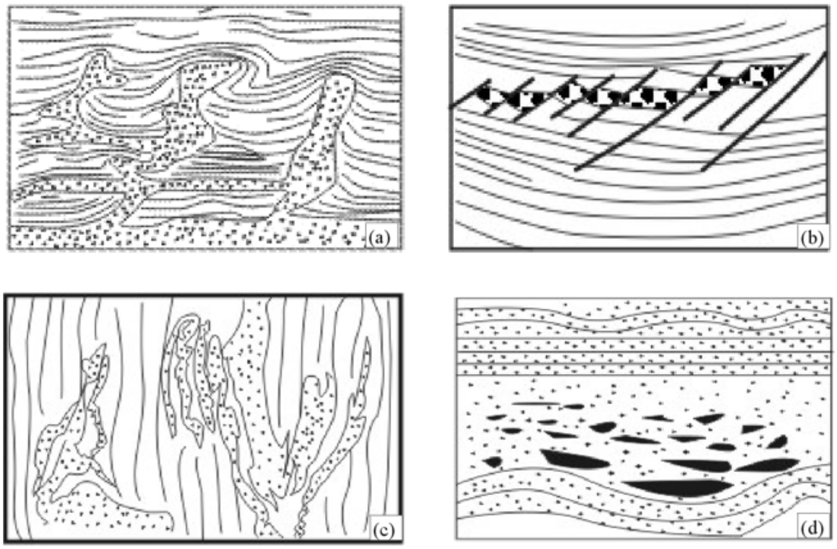

Fig. 2 Sketch showing of seismite character
(a) Fluidized sandstone dike; (b) step-shaped micro fault; (c) liquefied curled deformation; (d) earthquake inductive turbidite

layer. From the core we can see that the fracture and the liquefaction of the bottom sand-shale stone speed up the sinking of the upper block and lead to the formation of abnormal faults in the border (Plate 4).

3.1.3 Liquefied curled deformation

The liquefied curled deformation structure is formed in the fast accumulated sediment. Influenced by the seismic wave, the effective pressure imposed on grain supported sediment is transmitted into the pore fluid and generates extra high excess pore pressure which makes the sediment liquefied and form a series of mini close folds. These curled structures, which are also called “ptygmatic structures” (Fig. 2(c)), connect with each other, while the lamina in the upper and lower layers remain stationary. They are equivalent to the seismic fold proposed by Qiao (1996). Liquefied deformation occurs a lot in this area, such as 3,232.5 and 3,089.67 m of Well He 152 (Plates 2 and 3). They have poor directivity, narrow and long, and are confined to thin beds which are merely several centimeters thick. Many scholars have described it and thought it was the product of the earthquake. Qiao et al. (1994) successfully simulated it in the laboratory.

3.1.4 Seismic breccias

Seismic breccias, namely clastic breccia, refer to primarily fractured breccia formed by the destruction of the former sedimentary layer in the earthquake. They are formed by the shattered autochthonal consolidated and semi-consolidated layers. The gravels distribute irregularly and are poorly sorted. Some breccias become smooth because of liquefaction, indicating that they were semi-consolidated at that time. Sometimes the adjacent breccias can piece together completely, which can reflect the original state of the sediment clearly (Plates 4 and 5). In Plate 4, seismic breccias formed when the micro fracture developed at the bottom of the core. The diameter of the rubble of the clastic breccia is about 1.0–5.0 cm.

3.1.5 Fiamme structure

Fiamme structures are hummocky or irregular nodules at the bottom of the sandstone layer overlying the mudstone. The height of the fiamme structure is several millimeters to several centimeters. The sandstone cannot be liquefied when the earthquake activity is weak. The influence of the seismic wave can only cause the load pressure to be uneven and make the overlying sandy sediment sink into the underlying plastic mud and the fiamme structure is formed (Plate 6).

3.1.6 Earthquake inductive turbidite

The member III of the Shahejie Formation at the Xianhe area is deep lake deposition. The intense seismic activity stirred the lake water and the earthquake inductive turbidite deposition was formed (Plate 7). Scour channels were formed due to the erosion of turbulent water and the clast formed as the eroding process filled into the scour channels and formed the washing-packing structure (Fig. 2(d)). Mud pebbles, graded bedding or rhythmic bedding occur with the washing plane, and other sedimental structures are mainly syngenetic deformation structures. After sedimentation and before diagenesis, the watery sediment deforms easily because of quakes and forms the syngenetic deformation structure. The deformation degrees can vary from slight deformation to complex fold, shatter layer and shift layer. Syngenetic deformation structures occur a lot in research areas and reconstruct beddings obviously. The syngenetic deformation structure often occurs in argillaceous siltstones and silty claystones, and the liquefaction of sandy sediment is the main distortion way.

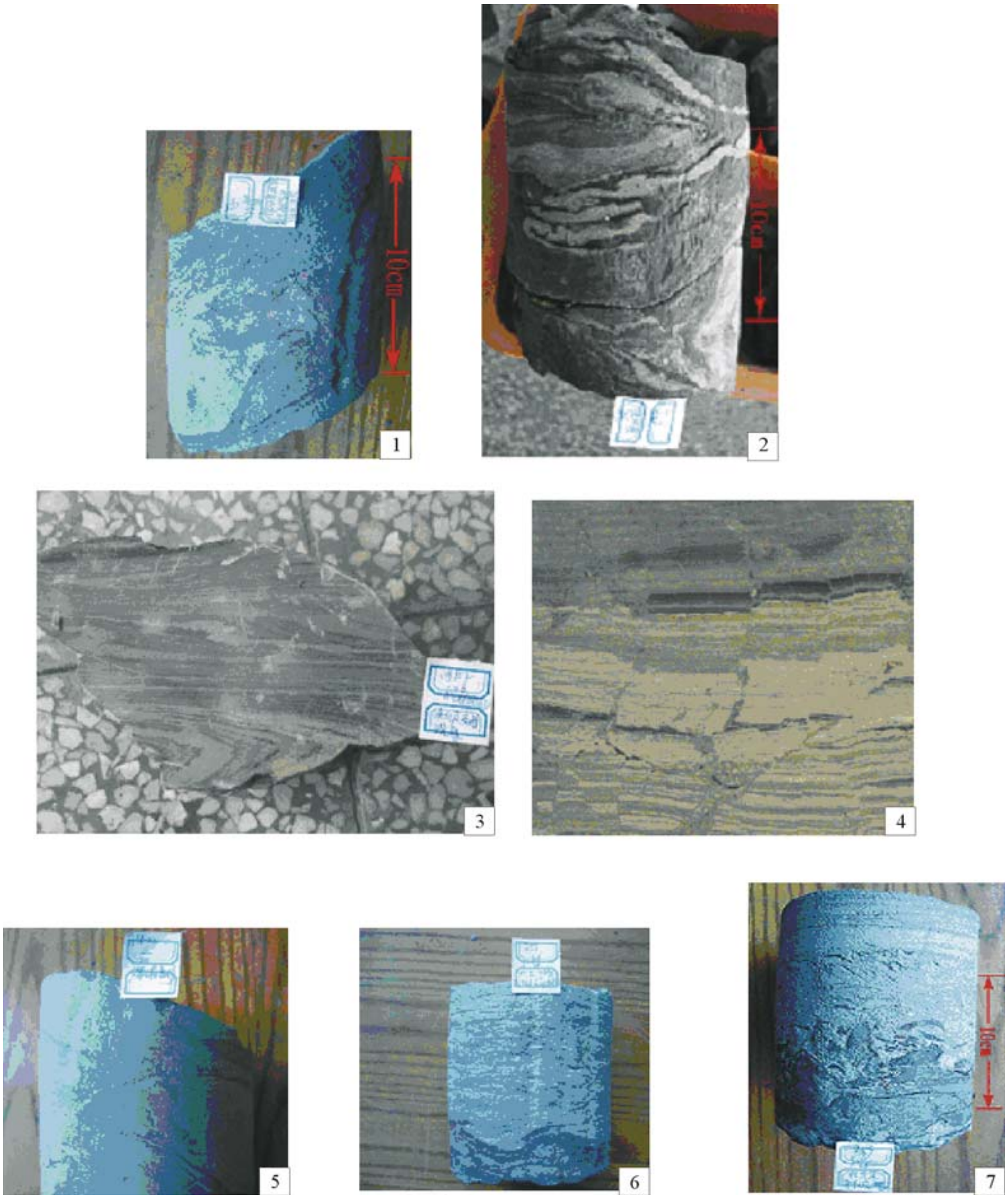

Plate I. 1. Liquefied sand dikes, the depth of 3,322.3 m in the Well Wang 59; 2. Enterolithic structure, forming intrastratal fold and a series of different confining fold, convolute structures join each other, the depth of 3,232.5 m in the Well He 152; 3. Liquefied convolute deformation, the depth of 3,089.67 m in the Well He 152; 4. Step-shaped micro fault, seismic breccias are at the bottom, the depth of 3,078.1 m in the Well He 152; 5. Seismic breccias, the depth of 3,207.2 m in the Well Niu22; 6. Luggage and fiamme structure, the depth of 3,325.1 m in the Well Wang 59; 7. Earthquake inductive turbidite, the depth of 3,302.5 m in the Well Wang 59

3.2 Size characteristics

The special grain-size probability curves are caused by the special genetic conditions of seismites which are characterized by low inclined two-stage and multiple-stage. The low inclined two-stage is composed of saltation secondary population and suspension secondary population and their intersection is between 2φ and 3φ. The poor saltation secondary population with a low slope has a poor sort in general, while the suspension secondary population can add up to 50% or more, but still has a poor sort. The characters reflect the features of the sandstone dike in the seismite, similar to the turbidite deposit plane. In the multiple-stage (Fig. 3(b)), the saltation population develops to many reflux washing points, the suspension population manifests the reconstruction characteristics after deposition indicating that it is the result of the preexisting sediment reconstruction when the earthquake happens.

4 Preservation conditions of seismite

The identification of seismite cannot rely on the sedimentary structures only, but should analyze whether there are conditions to preserve seismite, combining the sedimental background and structure characters. The study indicates that the liquefied sandstone dikes develop in the arenaceous pelitic facies which contain parallel beddings, while seismic breccias and liquefied distortion deformation mainly exist in steep environment. Therefore, the analysis of sedimental background is in favor of the study of seismite. For example, nowadays many studies hold that the sedimental environment of the lower member III of the Shahejie Formation at the Xianhe area pertains to lacustrine sedimentation and is in abyss. However, the authors found the existence of bimodal current in the core observation, and calculated by the Sahu size identification functional approach. The calculation result shows that Well He 152 is a turbidite deposition and fluvial (delta) deposition, Well Niu 22 is a turbidite deposition, also slight fluvial (delta) deposition, while Well Niu 105 is completely fluvial (delta) deposition. The above-mentioned grain size data are collected from a small area, the strata between these wells distribute steadily, and the lithologic characters are almost the same, whereas the calculation results are different. The relevant graphical solution of the Sahu function is summed up from the analysis of large quantities of recent sediment from the whole world. The result should be universal and this contradictory phenomenon should not occur. The difference will be easier to interpret if the sedimentary structure characters and the structural background are taken into consideration, because the liquefied deformation structures occupied a lot in sedimental structures, and the sedimentary structures are usually relevant to the deformation or slump activity of sediment before consolidation. All these demonstrate that there are special geologic activities caused by seismic activities. Therefore, the seismite study should closely combine with the study of depositional environment and the tectonic setting, to confirm the possibility of its existence.

5 Seismite vertical succession

The characteristics and vertical succession of seismite are different with the difference of the distance to the mobile belt or the earthquake intensity. The complete characteristics (Fig. 4(a)) of vertical succession observed from the core are as follows (Liang et al., 1994; Cao et al., 2004).

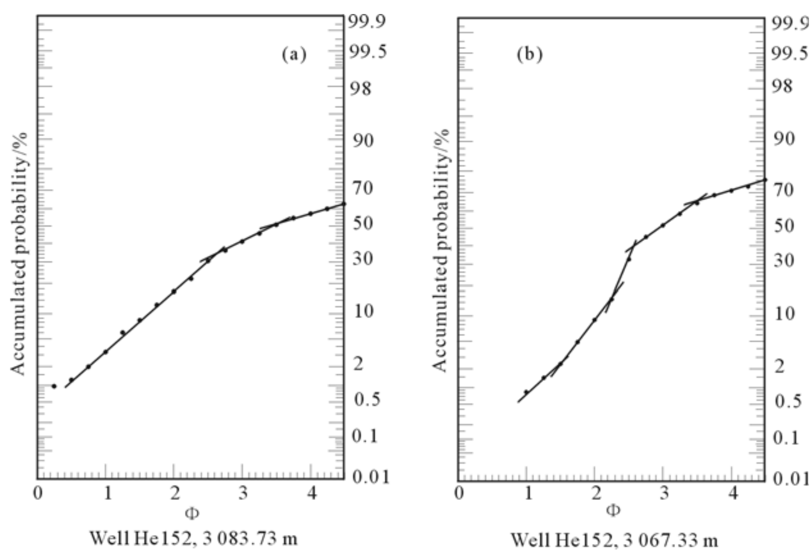

Fig. 3 Grain-size probability curves
(a) Low inclined two-stage; (b) multiple-stage

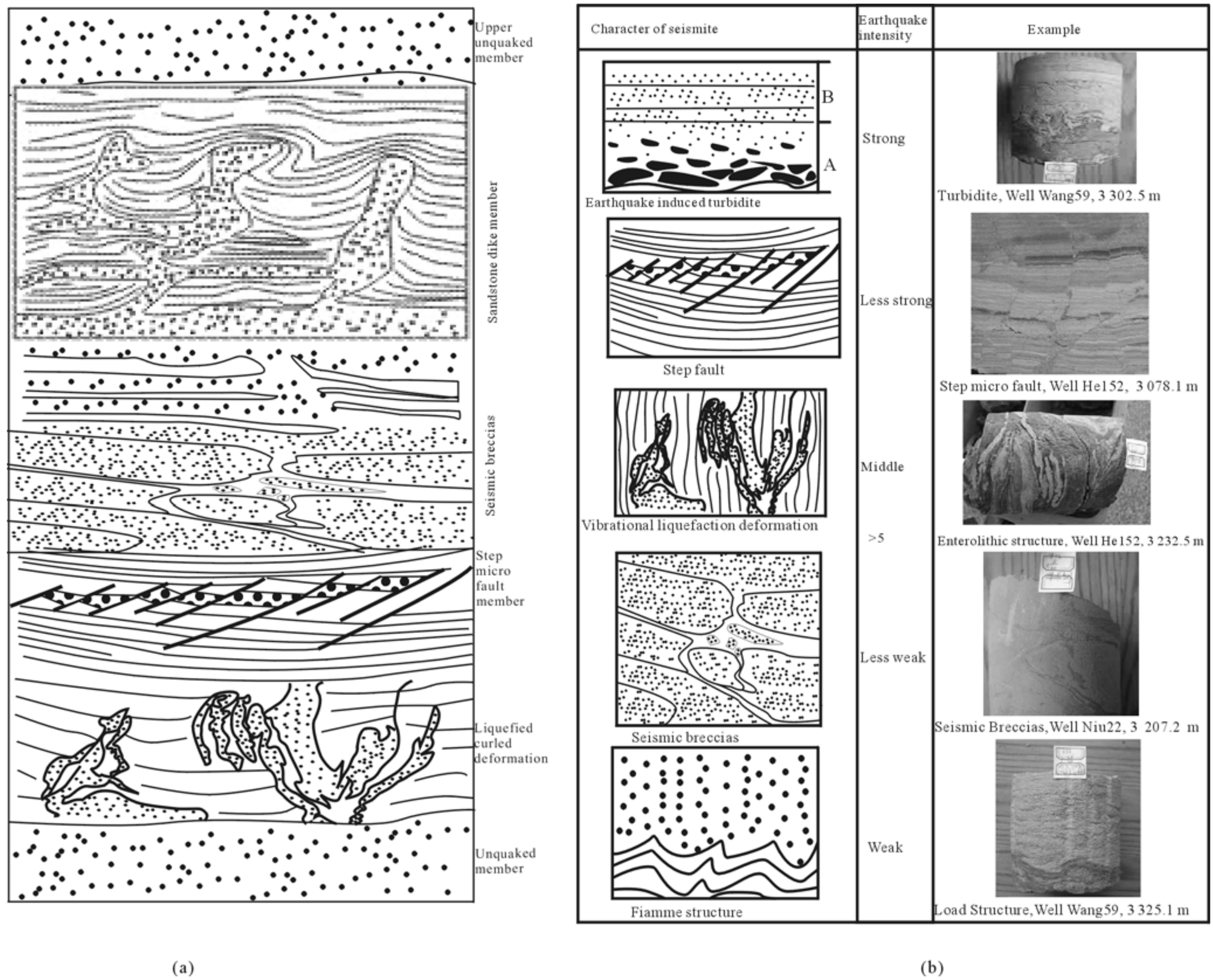

Fig. 4 (a) Seismite vertical succession; (b) relationship between seismite and seismic intensity

(1) Bottom unquaked member: located out of the range of the seismic wave, the lithology is dark grey mudstone with thin interbedded sand, not disturbed by any shake, and the original horizontal bedding and ripple cross bedding are preserved well.

(2) Liquefied curled deformation member: thin mudstone and sandy mudstone curled and formed a series of connected close microfolds, while the lamina in the upper and lower layers remains stationary.

(3) Step microfault member: 5–15 cm thick, the fault density can measure up to 5–10 pieces/10 cm, and the fault displacement is small.

(4) Seismic breccias member: 5–20 cm thick, chunks are mostly sandstone, with curved beddings, the fragments are weakly liquefied, upward fining in different orientations, and vanish when accessing the liquefied uniform layer.

(5) Sandstone dike member: this member appears in many drilling wells, 5–30 cm thick. The sandstone dikes don't have uniform strikes in plane, presenting complex space morphology. There are tearing traces in the border. Multiple thin sand beds can liquefy simultaneously and participate in the formation of sandstone dikes together.

(6) Upper unquaked member: with the decrease of the seismic energy, the upper member cannot be affected by the earthquake and continues the original deposition again. This member does not possess the seismite characteristics any more.

Just as Fig. 4(a) shows, the bottom is an unquaked member, and there is a vibratory liquefied distorted deformation, and step micro fault upward in turn. Both the scale and the fault displacement are small, but the deformation distorts intensely. The middle member is a seismic breccias member, and the sand bed is mingled with a 1–10 cm size conglomerate. The upper member is a distorted deformation member, and the deformation degree is weaker than that of the underlying. Just as Fig. 5 shows, the seismite vertical succession in Well He 152 are ptygmatic structure, liquefied deformation lenticular bedding and load structure upward in turn.

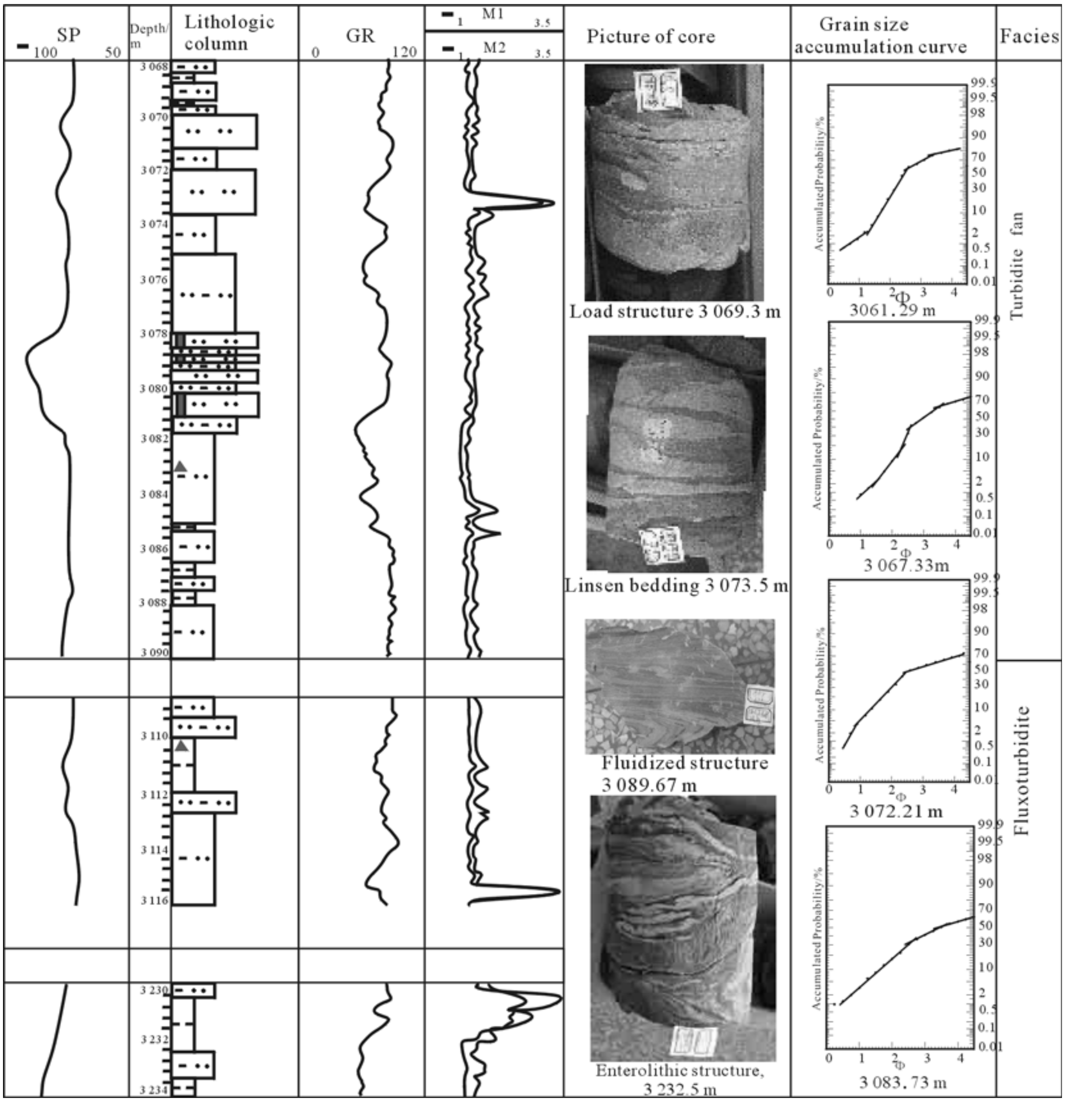

Fig. 5 Sedimentary facies of drilling segment of coring in Well He 152

6 Significance

The authors hold that we can know the active time of the paleo earthquake in terrestrial time by studying the time distribution law of seismite, recover the paleoenvironment and the intense degree of tectonic activities by studying the developmental conditions of seismite, and identify the law of paleoearthquake activities by studying the relationship between seismite and seismic intensity, and that the seismite is likely to be a favorable reservoir.

6.1 Seismite study supplies an effective means for the paleoearthquake study

We can know the global paleoearthquake belts by studying the seismite space distribution law, and know the active period of the paleoearthquake of terrestrial time. When the datum is abundant, we can know the periodic law of the alternation between the active period and the quiet period of the paleoearthquake, then identify the earthquake law diagram and reflect the earthly natural law from a new aspect. Of course we also can study the structural history and the active law of a basin. The authors hold that, different seismite structural characteristics reflect different seismic intensities by studying the seismite of member III of the Shahejie Formation at the Xianhe area in the Dongying sag. Based on the theory that liquefication does not occur until the magnitude attains Richter 5 level, we made the figure of the relationship between seismite and the seismic intensity. The seismic intensity is divided into five levels. The weak seismic activity can only affect the bearer uniformity of the sediment, and the uneven load pressure makes the overlying sandy sediment sink into the underlying watery plastic mud and form the load structure and the fiamme structure. With the increase of the seismic activity, the thin mudstone and sandstone fold and form liquefied distorted deformation. Intense seismic activity can make the consolidated and semi-consolidated sediment break and form step micro-fault. The water will be stirred and earthquake inductive turbidite will be formed if the seismic intensity is strong enough. The seismite can be a paleoearthquake mark. As Fig. 5 shows, with the increase of the distance to the earthquake center, the deformation and liquefied degree decrease. When the seismic intensity could not cause the liquefaction, the load structure formed and became normal sedimentation at last.

6.2 Appearance of seismite is the symbol to ascertain the tectonically active period

The present earthquake mainly occurs at the extensional zone in and on the margin of plate. According to uniformitarianism, earthquakes occurring in sedimentary basins should bear some relation to tectonic activities such that faults influence the sedimentary process. Therefore, seismite research can help us to resume the history of the tectonic activity, and then to have cognition of the tectonic setting of the sedimentary basin. Researches show that the second episode of the Yanshan Movement which occurred in the Early–Middle Jurassic formed the embryo of the Dongying sag, and the basal structure of the Dongying sag was controlled by the basal reversion which occurred during the TV episode of the Yanshan Movement because of the compression. And the Tertiary rift basin developed on the basis of the negative reversion basin of the Late Jurassic–Early Cretaceous. Two evolution periods of this Tertiary rift basin can be divided according to the tectonic development, basin-infill characteristics and volcanic activities, namely the chasmic stage in the Early Tertiary and the depression stage in the Late Tertiary. The episodic movement of the Himalayan orogeny results in the stepped characters of the Early Tertiary rift basin, including the following four periods: initial rift—intensive rift—secondary rift—fade rift, and formed an intact sedimentary cycle, including fluvial facies—shallow lake facie—deep lake facies—fluvial facies. The development of the seismite in the member III of the Shahejie Formation is an indication of intensive tectonic period.

6.3 Appearance of seismite is a symbol of facies

Special tectonic settings are necessary during the formation process of the seismite while special sedimentary settings are also indispensable during its conservation. It is difficult to preserve the seismite's tectonic characteristics in mudstones or sandstones which have large thickness. The Silurian seismite in Tarim basin and the Eogene seismite in Jiyang depression which were found at present all exist in the interbedded structure of sand and shale. This kind of sedimentary structure can well preserve the seismite's characteristics. According to the analysis of tectonic settings in which the seismite developed, we found that the seismite mainly developed in the slope gradient environment, and combined with the tectonic settings and sedimentary structures, we can ascertain the sedimentary facies more easily. Therefore, the seismite could be a symbol to indicate the sedimentary facies.

6.4 Seismite can be used as excellent reservoir

The lower member III of the Shahejie Formation in the Xianhe area belongs to lacustrine sedimentation, and in theory, its physical property should be poor because of the deep lake sedimentary setting. However, because the seism caused landsliding, sandstones at the upper member slumped to the deep lake and formed good reservoirs. Micro faults and micro cracks formed in cores increased the effective porosity, and moreover, source rocks are abundant in the deep lake facies, so favorable source-reservoir-cap combination formed. For example, the Well He 152 at 3,060–3,080 m are cemented by carbonates and the average porosity is only 10% or so, but nearly all sandstones are oil-immersed (Fig. 5). According to the research on carbonate seismite of the Dongying Formation in the Upper Sinian at Dayong, Xiangxi which was conducted by Guo et al. (1999), the shatter breccia is a kind of favorable reservoir. Therefore, seismites are good reservoirs and are the key bed in the deep lake depositional environment which is not favorable to the development of seismite.

References

Cao G Q, Chen S Y, Yan J H, et al (2004). The Early Tertiary sedimentary sequence of earthquake events in Jiyang depression. Geology Exploration Commention, 19(4): 252–256 (in Chinese with English abstract)

Chen S Y, Yuan W F, Yan J H, et al (2003). Discovery and significance of earthquake event deposits of Early Tertiary in the Jiyang depression. Chinese Journal of Geology, 38(3): 413–424 (in Chinese with English abstract)

Du Y S, Han X (2000). Study on seismite action and seismite. Advances in Earth Science, 15(4): 389–394 (in Chinese with English abstract)

Guo J H, Wang F P, Liu G, et al (1999). Shattered breccia of the Upper Sinian Dengying Formation in Dayong, West Hunan Province. Petroleum Geology and Experiment, 21(3): 219–224 (in Chinese with English abstract)

Heezen B C, Dyke C L (1964). Grand bank slump. Bull Am Ass Petrol Grol, 48(2): 221–225

Liang D Y, Nie Z T, Song Z M, et al (1994). A re-study on seisnite and seismite-unconformity. Earth Science—Journal of China University of Geosciences, 19(6): 845–851 (in Chinese with English abstract)

Plaziat J C, Ahmamou M (1998). Mechanic processes active in seismites: Their identification and tectonic significance in the Pliocene basin of the Sais of Fes and Meknes. Geodynamic Acta, 11(4): 183–203

Qiao X F (1996). Study of seismites of China and its prospects. Geol Rev, 42(4): 317–320 (in Chinese with English abstract)

Qiao X F, Song T R, Gao L Z, et al (1994). Seismic sequence in carbonate rocks by vibrational liquefaction. Acta Geologica Sinica, 68(1): 16–32 (in Chinese with English abstract)

Smith A G (1968). The origin and deformation of some "molar tooth" structure in the Precambrian belt Purcel Super Group. Journal of Geology, 76(4): 426–443

Song T R, He Z J, Ding X Z, et al (1988). A possible seismic-tsunami sequence in Precambrian carbonate stratigraphy in Shisanling area, Beijing. Chinese Sci Bull, 38(8): 609–611 (in Chinese)

Tian H S, Wang J G, Lu M Y, et al (2005). Seismic records in Paleogene alluvial layers in Anqiu, Shangdong. Acta Sedimentologica Sinica, 23(3): 447–453 (in Chinese with English abstract)

Wu X T, Yin G X (1992). Features and significance of seismite from Upper Jurassic lacustrine deposits of Emei, Sichuan Province. Acta Sedimentologica Sinica, 10(3): 19–24 (in Chinese with English abstract)

Yang J P, Wang H, Chen S Y, et al (2004). The features of seismites in Jiyang sub-basin, Paleogene. Acta Sedimentologica Sinica, 22(2): 281–287 (in Chinese with English abstract)

Yuan J (2004). The property and geological significance of seismites of Paleogene in Huimin sag, Shandong Province. Acta Sedimentologica Sinica, 22(1): 41–46 (in Chinese with English abstract)