Tectonic Taphrogenesis and Paleoseismic Records from the Yishu Fault Zone in the Initial Stage of the Caledonian Movement

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Abstract: The Yishu fault zone (mid-segment of the Tanlu fault zone) was formed in the Presinian. Periodic tectonic activities and strong seismic events have occurred along the fault zone. During the initial stage of the Caledonian Movement, with the proceeding of the marine transgression from the Yishu paleo-channel to the western Shandong, uneven thick sediments, composed mainly of sand, mud and carbonates of littoral, lagoon, and neritic facies, were deposited in the Yishu fault zone and western Shandong, and constructed the bottom part of the Lower Cambrian consisting of the Liguan and Zhushadong formations. Through field observations and the lab-examinations, various paleoseismic records have been discovered in the Liguan Formation and the Zhushadong Formations of the Yishu fault zone and its vicinity, including some layers with syn-sedimentary deformation structures that were triggered by strong earthquakes (i.e. seismites, seismo-olistostrome, and seismo-turbidite). Paleoseismic records developed in the Zhushadong Formation are mainly seismites with soft-sediment deformation structures, such as liquefied diapir, small liquefied-carbonate lime-mud volcano, liquefied vein, liquefied breccia, convolute deformation (seismic fold), graded fault, soft siliceous vein, and deformation stromatolite, as well as seismites with brittle deformation structures of semiconsolidated sediments. Paleoseismic records preserved in the Liguan Formation are not only seismo-olistostrome with a slump fold, load structure, and ball-and-pillows, but also seismo-turbidite with convolution bedding, graded bedding and wavy-bedding. However, in the western Shandong area, the closer to the Yishu fault zone, the greater the thickness of the Liguan Formation and the Zhushadong Formation, the greater the number and type of layers with paleoseismic records, and the higher the earthquake intensity reflected by associations of seismic records. This evidence indicates that tectonic taphrogenesis accompanied by strong earthquake events occurred in the Yishu fault zone during the initial stage of the Caledonian Movement, which embodied the break-up of the Sino-Korean Plate along the Paleo-Tanlu fault zone at that time.

Key words: Caledonian Movement, paleoseismic record, tectonic taphrogenesis, Yishu fault zone

1 Introduction

The Yishu fault zone belongs to the mid-segment of the Tanlu fault zone, which is the biggest deep fault zone in eastern China. The Tanlu fault zone was formed in the Presinian, and since its formation, there have been periodic violent tectonic and seismic activities along the fault zone (Zhang et al., 1984; Qiao et al., 2001; Qiao and Zhang, 2002; Luo et al., 2008). Several types of seismogenesis rocks, including seismites, seismic volcanic rock and seismic fault-tectonic rock were formed within the Yishu fault zone and its periphery in different geologic ages, in which seismite is the most predominant paleoseismic rock record because it is most widely distributive and not to be transformed by later strong earthquake activities (Tian et al., 2007). Since the end of the 20th century, some paleoseismic event beds consisting of seismites of different geologic times have been discovered in the fault zone and its vicinity (Qiao et al., 1994, 2001; Chen et al., 2003; Tian et al., 2003, 2005, 2006, 2007; Yuan, 2004; Yin and Yang, 2005; Yang et al., 2006; Tian and Zhang, 2007). In recent years, through field surveys, lab examinations, and correlation research, we identified some layers with syn-
sedimentary deformation structures triggered by earthquakes from the Liguan Fm to the Zhushadong Fm in the researched area (Fig. 1), that were seismite, seismoturbidite, and seismo-olistostrome. We selected profiles from Dongxiugou of Yishui County, Liushan in Linyi City, Jiulongshan in Laiwu City, Mantoushan and Hongyegu in Jinan City for our detailed analysis and research.

2 Geological Background

The Yishu fault zone is 330-km long and 20—80-km wide, and is a deep-fault assemblage containing two grabens and a horst which pass through the mid-east part of Shandong province in China. The studied area in the present study (Fig. 1) lies in western Shandong. The Paleozoic erathem is especially developed in western Shandong, but absent in the eastern area of the Yishu fault zone (the eastern Shandong area). The Yishu area was drawn apart to form the Yishu channel during the Jinning Tectonic Cycle. Subsequently, sediments composed of argillo-arenaceous clastic and carbonate of marine facies of the Tumen Group was deposited c. 600 m thick (Song and Wang, 2003). Paleoseismic records composed mainly of liquefied carbonate lime-mud veins were produced by strong seismic depositional events of the Yishu fault zone in the Sinian, which are preserved in the Shiwangzhuang Formation (Qiao et al., 1994, 2001). By the end of the Sinian, the Yishu channel became a continent, but the subsidence took place here again in the Early Cambrian, resulting in the reappearance of the Yishu channel. Marine transgression and the on-lap type sedimentation occurred toward the west, and as a result, unequal thick sediment layers of marine facies of the Lower Cambrian were deposited in the western Shandong.

The Lower Cambrian, from bottom to top, is divided into the Liguan Formation, the Zhushadong Formation and the Shidian Member of the Mantou Formation. Contact between the three is conformable (Zhang and Liu, 1996). The Liguan Formation, which is 0–24.4-m thick, is mainly composed of sandy conglomerate, sandstone, silt, sandy shale and muddy dolomite of littoral to neritic facies, which belongs to the Canglangpu stage and overlay discordantly the Precambrian. The sedimentary facies and the thickness of the Zhushadong Formation change obviously from east to west. The Zhushadong Formation consists of limestone, laminated limestone with chert, dolomite, marl and shale of neritic facies, which is 90–160-m thick, and belongs to the Canglangpu and Longwangmiao stages near the Yishu fault (in the eastern area of the Qingzhou–Yiyuan–Mengyin line) (Fig. 1), but in the western area of the Qingzhou–Yiyuan–Mengyin line, it consists of laminated dolomite, dolomite with chert mass, muddy dolomite of tidal flat lagoon, and contained diatom stromatolite, 10–30-m thick only, and belongs to the Longwangmiao stage. The Shidian member of the Mantou Formation is composed of laminated muddy dolomite with intercalated limestone and shale, which belongs to the upper part of the Longwangmiao stage. Its overlying stratum is the shale member of the Mantou Formation, which belongs to the mid Cambrian.

3 Paleoseismic Records: Syn-sedimentary Deformation Structures Triggered by Earthquakes

Paleoseismic records are synsedimentary deformation structures triggered by earthquakes. There are various
deformations of sediments produced by seismic vibration or shock in the depositional basin near the epicenter. Most of them are intralayer deformation structures of soft sediments, which are the main bases in which seismites are identified. Differences in lithology and the thickness of the Liguan Formation and Zhushadong Formation, and in which types and assemblages of paleoseismic records exist in the studied area, are shown in Fig. 2.

3.1 Paleoseismic records in the Zhushadong Formation

3.1.1 Liquefied diapir structure

The liquefied diapir structure of soft sediment was well known as a paleoseismic record, which was detailed by geologists of China and abroad (Qiao et al., 2006, 2007; Montenat et al., 2007; Qiao and Li, 2009). Some diapir structures of liquefied lime-mud (micrite) developed in the top part of the Zhushadong Formation, and in which types and assemblages of paleoseismic records exist in the studied area, are shown in Fig. 2 of the Liushan section, in Linyi city. The one illustrated in Fig. 3 is representative of this. In the vertical section, there exists an intrusive body that looks like a tongue with a narrow top and wide bottom, and there is a distinct boundary between the intrusive body and its host rocks. There are some line marks resembling tree-roots in the lower part of the intrusive body, which are flow lines produced by the upward injection of liquefied lime-mud. Fig. 3 indicates that liquefied lime mud gushing upward cut through lithic sand layers, not only causing nearby layers to form drag flexures, but also causing the overlying layers (thin-bedded limestone with intercalated marl) approximately 15-cm thick, to produce arched deformation. The top interface of the arched layers is ancient ground, and undeformed layers (knot-like limestone) overlie the ancient ground. The tensile stress derived by the arched deformation produced a lot of tensile badinage structures. Based on the flowing lines of the intrusive body, as well as the deformation features of the host rock, it is confirmed that the formation process of the diapir structure mentioned in this study is as follows. First, the liquefaction of saturated limemud was caused by a strong earthquake, and then, under seismic lateral pressure, liquefied lime-mud gushed and injected upward into the overlying sediment layers.

![Fig. 2. Columns of the Lower Cambrian from Liguan Formation to Zhushadong Formation in the western Shandong, China (section positions as marked in Fig. 1)](image-url)

$\gamma^1$, Neo-archean gneissic granite; Zt and Zf, Tongjiazhuang Formation and Fulaishan Formation of the Sinian Tumen Group; $\Gamma_1$, Liguan Formation; $\Gamma_2$, Zhushadong Formation; $\Gamma_3$, Mantou Formation.
3.1.2 Lime-mud volcano

According to the Chinese seismic intensity scale (GB/T17742-2008), liquefaction of saturated sand soil and sand volcanos occur in regions with earthquake intensity \( \geq \text{VI} \) degrees, which is caused by strong earthquakes. Paleoseismic sand volcanos were reported at home and abroad (Purser et al., 1993; Qiao et al., 2006; Du et al., 2007; Montenat et al., 2007). Some lime-mud volcanos distributed linearly occurred in the Zhushadong Formation of Liushan in Linyi city, and were accompanied by liquefied veins that did not erupt. The distance between every two volcanos in the Zhushadong Formation was 30–50 cm. The top part of two volcanos was exposed to the ground surface for the denudation (Fig. 4). Their ejecta, channel filler and source layer are all composed of micrite (CaCO\(_3\) lime-mud sediment), which have a distinct boundary with the host rock. Their bottom part is connected with the source layer. Vertical line marks within lime-mud volcanos and their channels should be flow lines of liquefied carbonate lime-mud. Their characteristics are quite similar to the Neogene sand volcanos in the Red Sea rift (Purser et al., 1993). The formative process of lime-mud volcanos mentioned in the present study is as follows. The liquefaction of saturated lime-mud in the source layer was induced by strong seismic shock; meanwhile, the overlying semiconsolidated layers were shattered, and then liquefied lime-mud was ejected from the ground along seismic fissures, with many shocks, enlargement of fissures, and eruption of lime–mud, which resulted in the formation of lime–mud volcanos. After the earthquakes stopped, calderas were formed by the subsidence of the lime-mud volcanic craters.

3.1.3 Liquefied vein, liquefied breccia, convolute deformation, graded micro-fault and syn-depositional fault

Liquefied veins and liquefied breccias mainly appear within the Yishu fault zone and its adjacent area (Fig. 2). Liquefied veins are composed of micrite dolomite, which are 5–8 mm wide and 5–15 cm long in the section. The borderline between veins and host rocks is distinct. Veins pierced into the laminated carbonate rock. Because laminated beddings were pierced and became flexures, laminated host rocks became soft plastic (Fig. 5a). Their formation mechanism is that saturated lime-mud was liquefied by seismic shaking, and liquefied lime-mud invaded the host rocks along seismic fissures so as to induce water escaping out of the saturated lime-mud. Therefore, liquefied veins are also called “water escape veins”.

Under strong earthquakes, interbed or interbedded liquefied and non-liquefied sediments most easily form liquefied breccias. Non-liquefied layers (e.g. muddy sediment) form angular breccias, and liquefied sediments (e.g. saturated sand and carbonate sediment) invade into interspaces among breccias (Qiao et al., 2001, 2006; Qiao and Li, 2009). The basic characteristic of liquefied breccias is that their liquefied veins or masses are filled in interspaces among angular seismic breccias of the non-liquefied sediment. The liquefied breccia shown in Fig. 5B is in accordance with the aforementioned characteristic, that is, the light-colored liquefied dolomite veins filled in intervals of brown angular breccias of the calcareous mudstone.

Convolute deformations are intralayer folds formed by seism vibration acting on soft sediment (especially soft
Fig. 4. Contrasting lime-mud volcanoes in the research area with sand volcanoes in the Red Sea rift. All vertical section. Pictures (1) and (2), Lime-mud volcanoes of Liushan (present study). ①, liquefied lime mud (CaCO₃) layer; ②, a liquefied vein, not spewed out, and the traction bend of the host rock punctured by the vein; ③, semi-consolidated and laminated marl with intercalated mudstone; ④, lime mud volcano; ⑤, caldera; ⑥, lime mud bar. Pencil is 11cm long. Pictures (3), Sand volcanoes in the Red Sea rift (Purser et al., 1993). ①, fine sand; ②, liquefied fine sand; ③, non-liquefied sand with seismic cracks; ④, sand volcano; ⑤, Brecciated laminate; ⑥, laminated silt and clay.

laminated sediment), which is also called seismic folds, seismic fold layers or microcrrugated lamination. There are some convolute deformations in every section of the studied area (Figs. 2, 5a, c, d), which are 10–50cm thick and 10–100cm long. Their axial planes are without fixed attitude, however, which not to change attitudes of overlying and underlying layers. They can be associated with liquefied veins, siliceous veins and graded micro-faults.

The scale of graded micro-faults is rather small in general, and is 3–15-cm long; the fault throws are 0.5–5mm. Graded micro-faults are generally ladder-like assemblages in the section (Figs. 2, 5c). They are intralayer faults induced by the adjustment of destroyed sediments after the cessation of ancient earthquakes, and were widely distributed. They were geologic indicators cognized as seismite at their earliest by a geologist (Seilacher, 1969). Soft sediment deformation structures caused by earthquakes are always accompanied by graded micro-faults or synsedimentary faults (Wheeler, 2002; Du et al., 2009).

Synsedimentary faults developed in the lower part of the Zhushadong Formation, from Dongxiagou to Jiulongshan of this studied area, are bigger size than graded micro-faults. Their fracture surfaces are steep, and the fault-throws are 15–40 cm (Fig. 2). They belong mostly to tensional normal faults, in which the filler is similar to the overlying or underlying soft sediment.

3.1.4 Soft-sediment deformation structures related to siliceous rocks

Dolomite and limestone with chert mass (or band) and siliceous stromatolite exist in the Zhushadong Formation in the research area (Di et al., 1996; Song and Wang, 2003), in which chert mass and siliceous stromatolite belong to siliceous rocks. There exists multiplicity on the genesis of siliceous rocks, such as siliceous metasomatism in the diagenesis stage, chemical precipitation and syngenetic biodeposition (Liu, 1980). However, the present study has proven that siliceous rocks of Zhushadong Formation in the western Shandong were formed by syngenetic biochemical genesis (Di et al., 1996), which is mainly based on chert masses or bands being distributed along bedding, some connected with each other, and extending stably, and host rock bedding surrounding chert masses, in which there are diatom filaments. This shows that original siliceous rock was soft sediment, which is also the precondition of forming seismo-genesis deformation structures. Liu (1980) noted that quite soft chert could be seen coming from the deep drilling, the initial composition of which was hydrous SiO₂ (silica colloid, SiO₂·nH₂O), chalcedony and quartz were formed through the dehydration of soft chert, and it would take over 10⁵ years for soft chert to dehydrate completely during the diagenetic process.

Under the action of strong paleo earthquake, the original and soft chert masses were shaken to form plastic bending siliceous veins (Fig. 6a–c) in the Zhushadong Formation, in which soft siliceous stromatolite was staggered and contorted (Fig. 2), and a soft siliceous layer was shaken and compressed to produce a diapir structure resembling a mushroom (Fig. 6d) and intralayer micro-fault. The deformations of the soft siliceous sediment are always associated with graded micro-faults (Fig. 2). Based on the phenomenon of siliceous veins coming from chert masses and their feature of plastic bending (Figs. 5d, 6a, c), the seismogenesis mechanism and formation process of siliceous veins is confirmed in Fig. 7.
3.1.5 Brittle deformations

Brittle deformations are sediments in the incompletely consolidated (or semiconsolidated) state that are shattered or broken by the seismic action, which belong to brittle seismites (Duan et al., 2002; Tian et al., 2006, 2007; Qiao and Li, 2009; Liang et al., 2010). There are two types of brittle deformations: the shattered rock (Fig. 8a) and the seismic breccia (Fig. 8b), which mainly occur in the Zhushadong Formation in the western area of Jiulongshan (Fig. 2). The common ground for both is their brittle, broken feature, which contains angular breccias. The first difference between them is that the shattered rock is formed in situ, while the seismic breccia belongs to seismites of the alien place system; that is, the latter is the accumulation of breccias broken down by earthquakes, in which the short displacement took place under gravitational action. The other differences between them are that the former has many seismic fissures, consisting of approximately splicing breccias of simple composition; however, the latter’s breccias are of complex composition, with no splicing property and seismic fissures (Fig. 8b). Fig. 8b shows the seismic breccia filled into paleoseismic V-shaped cracks. Present day seismic cracks are open, in general; however, paleoseismic cracks were always filled with the overlying sediment.

3.2 Paleoseismic records in the Liguan Formation

Based on the old stratigraphic division scheme, Yan et al. (2005) identified olistostrome and turbidite from the bottom part of the Mantou Formation, mainly composed of elastic rocks in the areas of Hongyegu and Jiulongshan. At present, the elastic rock stratum of the bottom part of the Mantou Formation of the old scheme is designated to the Liguan Formation (Song and Wang, 2003). The present
Fig. 6. Siliceous soft-sediment deformation structures in the Zhushadong Formation.

a. Siliceous veins come from the chert mass.  
b. Plastic curved siliceous veins under microscope (cross polarized, ×20), which consists of chalcedony and microcrystal quartz.  
c. Soft siliceous veins come from the soft chert mass on the polished surface of the rock sample. Scale object is 3cm long.  
d. Diapir structure like mushroom shape. Locations: Hongyegu, Jinan. Pen is 14.5cm long. All vertical section pictures.

Fig. 7. Seismogenesis mechanism and deformation process of siliceous veins.

(1) Soft chert mass before the earthquake;  
(2) When vibrating energy of a strong earthquake was transferred into the soft mass, some seismic fissures were produced in host rock;  
(3) Under sustained and intense earthquake action, silica gel with high energy in the chert mass jetted into fissures of host rocks, forming soft siliceous veins (injection structure);  
(4) After the earthquake, veins became more winding for soft siliceous veins accepted gravity compaction of overlying layers.

The study confirms the existence of olistostrome and turbidite (Fig. 2). Dip directions of the folds’ axial planes in Fig. 9 (b, c) are identical, which indicates their feature of slump genesis. Turbidites in the Liguan Formation consist of sandy conglomerate or pebbly sandstone with the normal graded bedding (Fig. 9f), siltstone with the convolution
Fig. 8. Brittle deformations: shattered rock and seismic breccias in the Zhushadong Formation.

2.1 shattered rock, semisolidified dolomite with chert masses was shaken to form an approximately splicing breccias of a simple composition, in which the blacks represent silicious veins and remaining chert masses, and the arrow is pointing to a silicious vein connected with a chert mass. b. seismic breccia, consisting of more than two kinds of angulate rock-breccias without splicing features (b), filled in the paleoseismic crack of the underlying layer (a), and overlaid by the unshaken layer (c). location: Mantoushan, Jinan.

Fig. 9. Slump fold, load structure, ball-and-pillow and graded bedding in the Liguan Formation.

a. Liguan Formation and its boundary with the Zhushadong Formation, the cypress is 1.5m in height, photos b–d were all taken here. b. The slump fold is a recumbent and compound anticline which contains second class small folds with the same dip directions of axial planes (---), developing a pillow mass (p) below the slump fold. White scale object is 30cm long. c. Slump folds with the same attitudes of axial planes (---) are on the right of the recumbent fold shown by photo b in the field. d. Load structures (a) sited on the left side of the recumbent fold shown in photo B, and the upper parts of two load bodies are connected. Their lower edge is arc shaped, and beddings present a syncline type flexure within load bodies. A flame structure (f) exists between both load bodies. e. load structures (a) and ball-and-pillow (b). f. graded bedding layer of turbidite (1.9 m thick) at the bottom of the Liguan Formation. location: a–d,Hongyegu; e, Qixingtai between JiuLongshan and Hongyegu; f, JiuLongshan.

bedding, and sandy mudstone with parallel bedding and ripples (Fig. 2).

The new discoveries in the present study are that load structures, ball-and-pillow structures, or pillow bodies associated with slump folds exist in the Liguan Formation (Fig. 9b, d, e). These types of soft sediment deformation structures have been affirmed as paleoseismic records by geologists (Rodriguez-Pascua et al., 2000; Moretti et al.,
2002; Qiao and Li, 2008, 2009; Du et al., 2009; Liang et al., 2010), Therefore, the olistostrome in the Liguan Formation should be seismo-olistostrome, which might be similar to the seismic slump folds and blocks discovered by Lü et al. (2006) in inner Mongolia.

Load structures (Fig. 9d, e) were formed by the subsidence of non-liquefied sediment with high density under seismic vibration and gravity. In the process of subsidence, bedding within load body moved downwards like a syncline; the underlying saturated soft sediment with lower density moved upwards because of bearing extrusions, and formed a flame structure (Fig. 9d) between both load bodies. The lower part of the load body was shaken to separate from the matrix, and then fell, which produced ball, ellipsoid, and pillow (Fig. 9b, 9e), also known as the ball-and-pillow structure.

In the Early Cambrian, turbidites developed in the eastern area of Jiulongshan where was the littoral and neritic sedimentary setting of the paleo-continental margin extended eastwards to the Yishu fault zone. In the Liguan Formation, the number of turbidite graded beds and their thickness increased from west to east (Fig. 2), indicating that these turbidites in the continental margin are large scale basin. As huge turbidites deposited in the continental margin basin are cognized as seismo-turbidite (Mutti et al., 1984; Sun et al., 1995), and other aforementioned seismic records exist in the Liguan Formation, turbidites of the Liguan Formation should be seismogenesis, which belong to shallow-water turbidites, as discussed by Liu (1980).

4 Discussions

4.1 Forming model of seismic sedimentary deformations and tectonic taphrogenesis

Assemblage, distribution, and the forming model of seismic sedimentary deformation structures from the Liguan Formation to the Zhushadong Formation in the studied area are shown in Fig. 10. Epicentral distance, sedimentary setting, sediment property, and the paleo-seabed slope were the main factors that affected assemblage, distribution, and change of seismic sedimentary deformation structures at that time. The features of paleoseismic records differ according to sedimentary stage. In the sedimentary stage of the Liguan Formation, paleoseismic records were mainly seismo-turbidite, seismo-olistostrome, with a slump fold, load structure, and ball and pillow. However, in the sedimentary stage of the Zhushadong Formation, those records were mainly liquefied diapir, liquefied lime-mud volcano, liquefied breccia, liquefied vein, soft siliceous vein, convolute deformation, and graded fault. According to Figs. 2 and 10, it can be seen nearer to the Yishu fault zone that the greater the thickness of the Liguan and Zhushadong formations, the greater the number and type of layers with paleoseismic records, and the higher the earthquake intensity reflected by the association of seismic records. This evidence shows that tensile taphrogenesis activities occurred frequently in the paleo-Yishu fault zone in the Early Cambrian during the initial Caledonian Movement. Taphrogenesis activities of this fault zone caused several

![Fig.10. Formation model of seismic deposition deformations of the Lower Cambrian from the Liguan Formation to the Zhushadong Formation in the Paleo-Yishu fault zone and its western vicinity.](image-url)
episodes of strong earthquakes, and the epicenter areas were located in the paleo-Yishu fault zone and its adjacent belt.

4.2 Division about the paleoseismic active period

The length of time about a paleoseismic active period is over multimillion years, which reflects a long cycle of paleoseismic activities (Qiao et al., 2006). Relative dense layers of seismic sedimentary deformation structures record a paleoseismic episode, and ancient earthquake records of a paleoseismic episode reflect more than several paleoseismic events (Qiao et al., 2006). An assemblage of seismic sedimentary deformation structures is a record of a paleoseismic episode, as shown in Fig. 2. As the geological history from the Liguan Formation to the Zhushadong Formation is only approximately 5 Ma (525–520 Ma), all seismic sedimentary deformation structures identified by this study are records of the same paleoseismic active period that could be called the Liguan–Zhushadong paleoseismic active period, in which approximately five-to-seven paleoseismic episodes corresponded with taphrogenesis activities of the paleo-Yishu fault zone. However, records of the latest three paleoseismic episodes of the paleoseismic active period in the Laiwu–Jinnan area exist.

4.3 Ancient earthquake intensity

By means of the Chinese seismic intensity scale (GB/T17742-2008), the seismic intensity reflected by a great deal of landfall and landslide induced by an earthquake is referred to as XI degree. The slump is a type of slope failure; first sliding and then collapsing, which has features of both a landfall and landslide (Shi, 2007). During the deposition of the Liguan Formation, seismic slumping took place in the western area of Jiulongshan, which showed seismic intensity of XI degree, thus epicenter intensity should be XII degree or so. According to the relation formula of the epicenter intensity ($I_o$) with the Richter magnitude ($M$) – $M = 0.66I_o + 0.98$ (Shi, 2007), a Richter magnitude of the ancient earthquake obtained by the formula is 8.9 scale.

As the minimum magnitude to make liquefaction of saturated soft sediment is Richter magnitude 5.0 and the magnitude reflected by the liquefied diapir structure is Richter magnitude 8.0 (Rodriguez-Pascua et al., 2000), the ancient earthquake intensity was Richter magnitude 5.0–8.0 in the deposition time of the Zhushadong Formation.

5 Conclusions

During the initial stage of the Caledonian Movement, the western Shandong area was littoral-neritic setting, and the paleo-Yishu fault zone lied in the Yishu channel of the eastern margin of the area. Tensile taphrogenesis activities of the paleo-fault zone caused several episodes of strong earthquakes for Richter magnitude 5.0–8.9, and the epicenter areas were located in the paleo-fault zone and its adjacent belt. Strong earthquakes made sedimentary layers of littoral-neritic facies form various synsedimentary deformations (i.e. paleoseismic records) within 180-km range from the paleo-fault zone to west, which were preserved in the Liguan and Zhushadong formations, approximately 525–520 Ma. Paleoseismic records developed in the Zhushadong Formation are mainly seismites with soft-sediment deformation structures, including liquefied diapir, small liquefied-carbonate lime-mud volcano, liquefied vein, liquefied breccia, seismic fold, graded fault, soft siliceous vein, and deformation stromatolite. Paleoseismic records preserved in the Liguan Formation are not only seismo-olistostrome with a slump fold, load structure, and ball-and-pillows, but also seismo-turbidite with convolution bedding, graded bedding and wavy-bedding.

The aforesaid seismic records in this paper, with strong paleoseismic records of the Mantou paleoseismic active period (~515–510 Ma), preserved in the top part of the Lower Cambrian in the western Shandong (Tian et al., 2003; Song and Wang, 2003), are evidence of the tectonic activities in the paleo-Tanlu fault zone in the initial stage of the Caledonian Movement. The taphrogenesis in the Yishu fault zone should have embodied the break-up of the Sino–Korean plate along the Paleo–Tanlu fault zone (Qiao et al., 1994; 2001).

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