Journal of Palaeogeography, 2017, ■(■): 1—20

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: http://www.journals.elsevier.com/journal-of-palaeogeography/

Multi-origin of soft-sediment deformation structures and seismites

Soft-sediment deformation structures related to volcanic earthquakes of the Lower Cretaceous Qingshan Group in Lingshan Island, Shandong Province, East China

Yao-Qi Zhou [a,b,c,*], *Tian-Ming Peng* [a,b,c], *Teng-Fei Zhou* [a,b,c], *Zhen-Kai Zhang* [a,b,c], *Hui Tian* [d], *Wen-Dong Liang* [e], *Ting Yu* [f], *Li-Fu Sun* [a,g]

[a] *School of Geosciences, China University of Petroleum (East China), Qingdao 266580, China*
[b] *Laboratory of Geochemistry and Lithosphere Dynamics, China University of Petroleum (East China), Qingdao 266580, China*
[c] *Laboratory for Marine Mineral Resources, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266071, China*
[d] *Baikouquan Oil Production Plant of XinJiang Oilfield Company of CNPC, Karamay 834000, China*
[e] *Department of Earth and Environmental Sciences, University of Milano-Bicocca, Milano 20126, Italy*
[f] *College of Geosciences, China University of Petroleum (Beijing), Beijing 102249, China*
[g] *College of Geology and Mining Engineering, Xinjiang University, Urumqi 830046, China*

Abstract The study on soft-sediment deformation structures (SSDS) of Lingshan Island has been one of the hot topics of sedimentology researches in China in recent years, and SSDS developed in turbidite system in the Laiyang Group are widely known by domestic researchers. However, few studies were conducted on the SSDS in fan delta system in the Qingshan Group, Lingshan Island.

This study analyzes the classification and characteristics of SSDS especially their lithofacies association and lithologic characteristics through field outcrops investigation and thin section analysis as well. A conclusion was acquired that the paleoenvironment was a fan delta system with occurrence of several volcanic eruptions, where the water became gradually shallower.

The SSDS types in the Qingshan Group includes load and flame structure, ball and pillow structure, water-escape structure, hydroplastic deformation structure, plastic sandstone breccia structure, volcanic drop stone and V-shaped ground fissure mainly caused by volcanic earthquakes of three types: (1) seismic waves, (2) gravity and inertia effect of pyroclastic flows, (3) instant differential air pressure; which is different from slumping and tectonic earthquakes occurred in the Laiyang Group. In addition, with the lithofacies association analysis between pyroclastic flow and SSDS beds, a distribution model of SSDS related to volcanic earthquakes

* Corresponding author. School of Geosciences, China University of Petroleum (East China), Qingdao 266580, China.
E-mail address: zhouyq@upc.edu.cn (Y.-Q. Zhou).
Peer review under responsibility of China University of Petroleum (Beijing).
http://dx.doi.org/10.1016/j.jop.2017.02.002
2095-3836/© 2017 China University of Petroleum (Beijing). Production and hosting by Elsevier B.V. on behalf of China University of Petroleum (Beijing). This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Please cite this article in press as: Zhou, Y.-Q., et al., Soft-sediment deformation structures related to volcanic earthquakes of the Lower Cretaceous Qingshan Group in Lingshan Island, Shandong Province, East China, Journal of Palaeogeography (2017), http://dx.doi.org/10.1016/j.jop.2017.02.002

can be established: SSDS types changed gradually with their distance further away from the volcanic activity core. Brittle deformation which was common in the proximal zone disappeared gradually; liquefied and plastic SSDS continued to dominate in the medial zone; and slightly liquefied SSDS were developed in the distal zone. Meanwhile, the scale and size of SSDS is negatively correlated with the distance of SSDS depositional locations from the volcanic vent.

Keywords Lingshan Island, Qingshan Group, Yangjiaodong Section, Soft-sediment deformation structures, Volcanic earthquake, Early Cretaceous

© 2017 China University of Petroleum (Beijing). Production and hosting by Elsevier B.V. on behalf of China University of Petroleum (Beijing). This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Received 2 December 2016; accepted 22 February 2017; available online 7 April 2017

1. Introduction

Soft-sediment deformation structures (SSDS) were used to describe seismites at first; actually, they can be caused by various triggers and thus are of multi-origins (Allen, 1982; Owen *et al.*, 2011; Shanmugam, 2016), and now SSDS become a hotter interest in sedimentology.

In China, since Tian-Rui Song studied on the Proterozoic seismites in North China Plate (Song, 1988), lots of researches about SSDS and seismites were conducted in different ways in the last decade (Du, 2011; He *et al.*, 2010, 2012; Lü *et al.*, 2011; Qiao and Guo, 2011; Qiao and Li, 2008, 2009; Song and Liu, 2009; Yang *et al.*, 2008; Yuan *et al.*, 2006; Zhong, 2012), which is a significant and positive achievement (Feng *et al.*, 2016).

In traditional views, SSDS can be triggered by palaeoearthquake, tsunami, wave effect and so on, but the main mechanism is palaeoearthquake, which can cause differential compaction, liquefaction, slide and slip (Du, 2011). Soft-sediment deformation can be divided into liquefied deformation, thixotropic deformation, hydroplastic deformation, superimposed gravity driving deformation and brittle deformation (He and Qiao, 2015). And natural earthquakes commonly include three kinds: tectonic earthquake, volcanic earthquake, and collapse earthquake. Tectonic earthquake is the most common origin for forming SSDS according to the published papers about SSDS, and volcanic earthquake is another major origin for forming SSDS (Basilone *et al.*, 2014; Du *et al.*, 2005; Montenat *et al.*, 2007; Robertson, 1998; Wang *et al.*, 2010). However, SSDS are caused by multiple triggers except earthquakes; besides, the term “seismite” was overused (Shanmugam, 2016).

Abundant SSDS developed in Lingshan Island, and many academic achievements related with this research domain have been acquired (Dong *et al.*, 2013; Lü *et al.*, 2013; Shao *et al.*, 2014; Wang *et al.*, 2013, 2014; Zhong *et al.*, 2016; Zhou et al., 2015a). However these researches mainly focused on the SSDS developed in turbidite layers in the Laiyang Group, whereas few attentions were paid to SSDS developed in terrestrial clastic layers in the subsequent Qingshan Group. The difference of features between the SSDS in the Laiyang Group and those in the Qingshan Group attracts people's attention in considering their quite different palaeoenvironments and depositional backgrounds (Lü *et al.*, 2013; Zhou et al., 2015a,b).

This paper studied the SSDS developed in terrestrial clastic layers in the Qingshan Group, discussed the distribution of SSDS and their relationships with volcanic earthquake events; also analyzed the formation mechanism of SSDS and established a brief distribution model of the SSDS related to volcanic earthquakes.

2. Regional geology

2.1. *The Lower Cretaceous Qingshan Group in Lingshan Island*

Lingshan Island (35°45′01″N, 120°09′48″E) is located in the Yellow Sea, about 17 km southeast away from Qingdao City, Shandong Province, East China (Fig. 1).

The Lower Cretaceous stratigraphic sequence in Lingshan Island is divided into two groups: (1) the older is the Laiyang Group with turbidite layers, mainly developed in the west, including Beilaishi, Chuanchang, Dengta, Qiancengya, Laohuzui areas; (2) the younger is the Qingshan Group with terrestrial clastic layers and volcanic deposits, mainly developed in the east, including Gounanya, Wanghailou, Yangjiaodong areas (Fig. 2). This paper is mainly based on investigation of

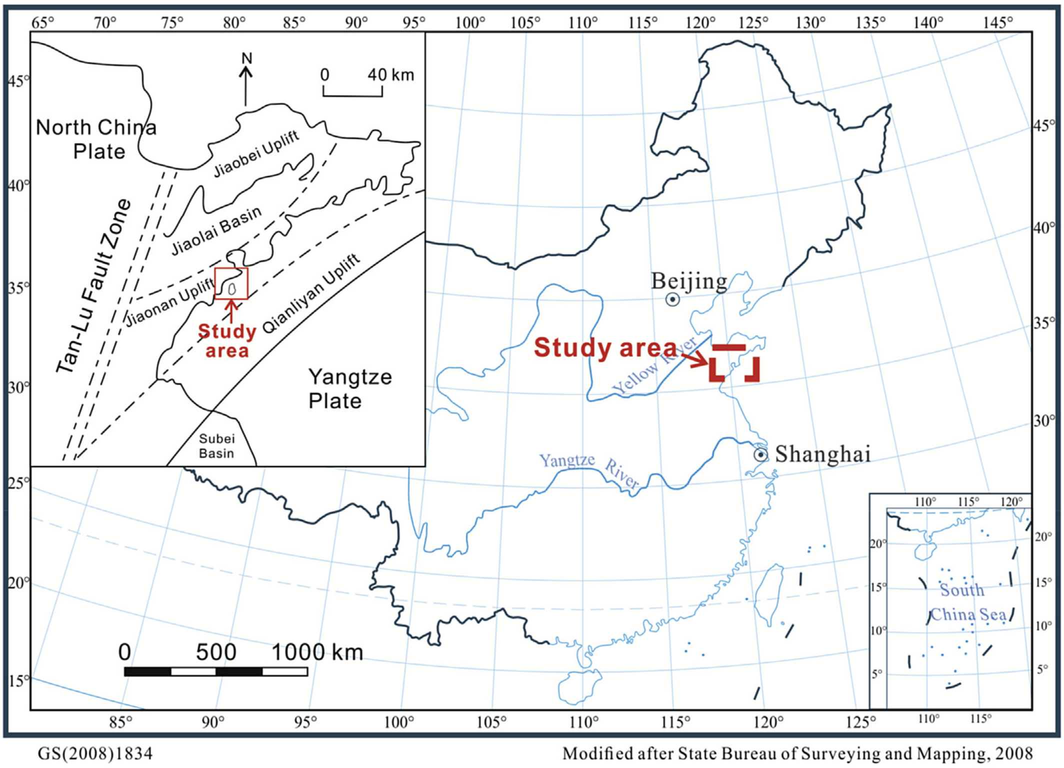

Fig. 1 Location and tectonics outline map of the study area.

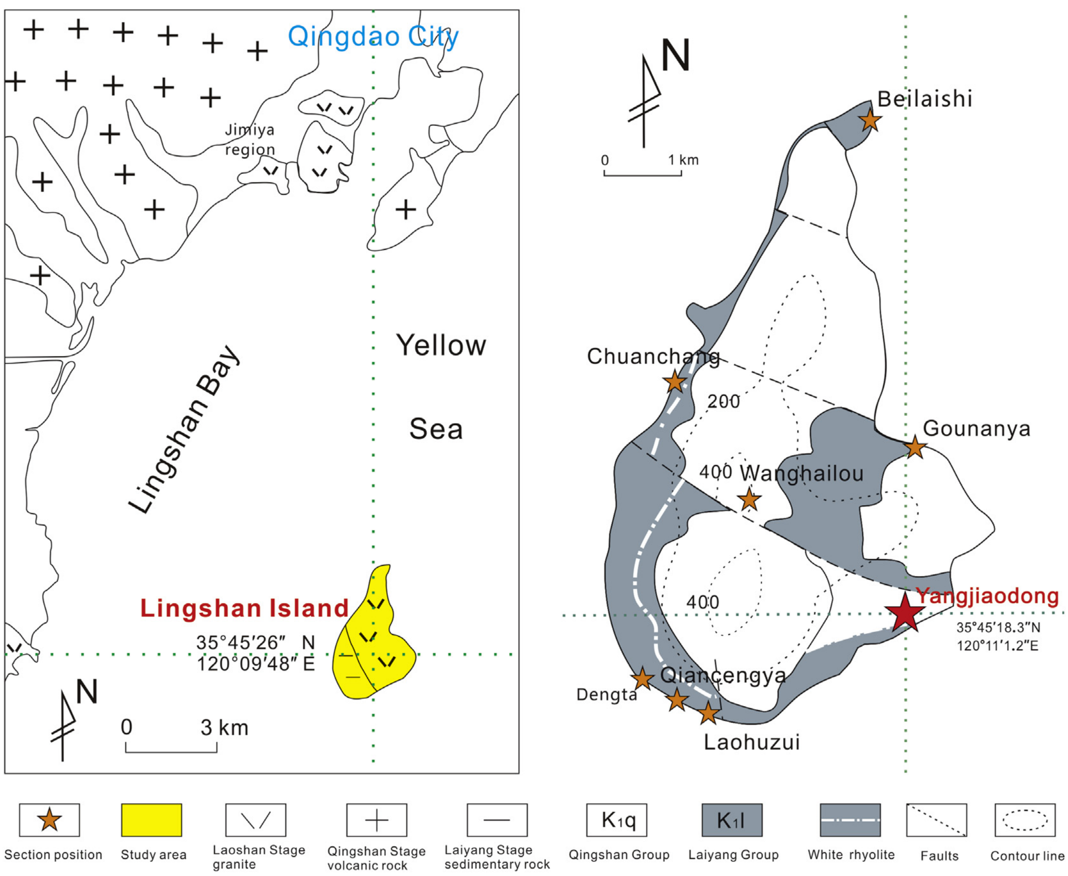

Fig. 2 Regional geological map and the locations of the Lower Cretaceous sections of Lingshan Island (modified from Luan *et al.*, 2010).

and sampled from the Yangjiaodong Section, Lingshan Island.

2.2. *The Yangjiaodong Section in Lingshan Island*

The Yangjiaodong Section is located in the southeast corner of Lingshan Island (35°45′18″N, 120°11′01″E), where a comparatively complete stratigraphic sequence of the Qingshan Group developed (Fig. 3).

From bottom to top of the Yangjiaodong Section, its lithology is mainly composed of pyroclastic rocks, conglomerate, glutenite, rhyolite, sandstone, mudstone, and andesite lava, which can be divided into four units (Fig. 4): (1) terrestrial clastic deposits of alluvial fan with volcanic breccia and proximal pyroclastics; (2) white rhyolites; (3) terrestrial clastic deposits of fan delta with pyroclastic flow interlayers; (4) andesite lava and pyroclastic sediments.

Fig. 3 Field outcrop photo showing the Yangjiaodong Section in Lingshan Island.

These four lithologic units of the Yangjiaodong Section were subdivided based on their different lithofacies and facies association, beginning with volcanic explosive facies as the first unit recorded by pyroclastic proximal deposits (Fig. 4). Volcanic effusive facies as the second unit overlaid upon volcanic explosive facies and was characterized by the thick-bedded white rhyolite with dated age of 119 Ma (Zhou et al., 2015b). Terrestrial clastic materials continually deposited during this period. Meanwhile, volcanic explosive facies was dominated by about 12 pyroclastic flow interlayers, which indicated that dozens of volcanic events happened, and deposited together with the fan delta facies as the third lithologic unit. The characteristics of fan delta facies in the third unit indicated that water became more and more shallower during the Qingshan Stage (Fig. 5; Yu, 2014). The fourth lithologic unit of the Yangjiaodong Section was dominated by huge andesite lava and pyroclastic rocks.

3. Types and characteristics of SSDS of the Yangjiaodong Section, Lingshan Island

A variety of SSDS were formed in the Lower Cretaceous Qingshan Group in Lingshan Island

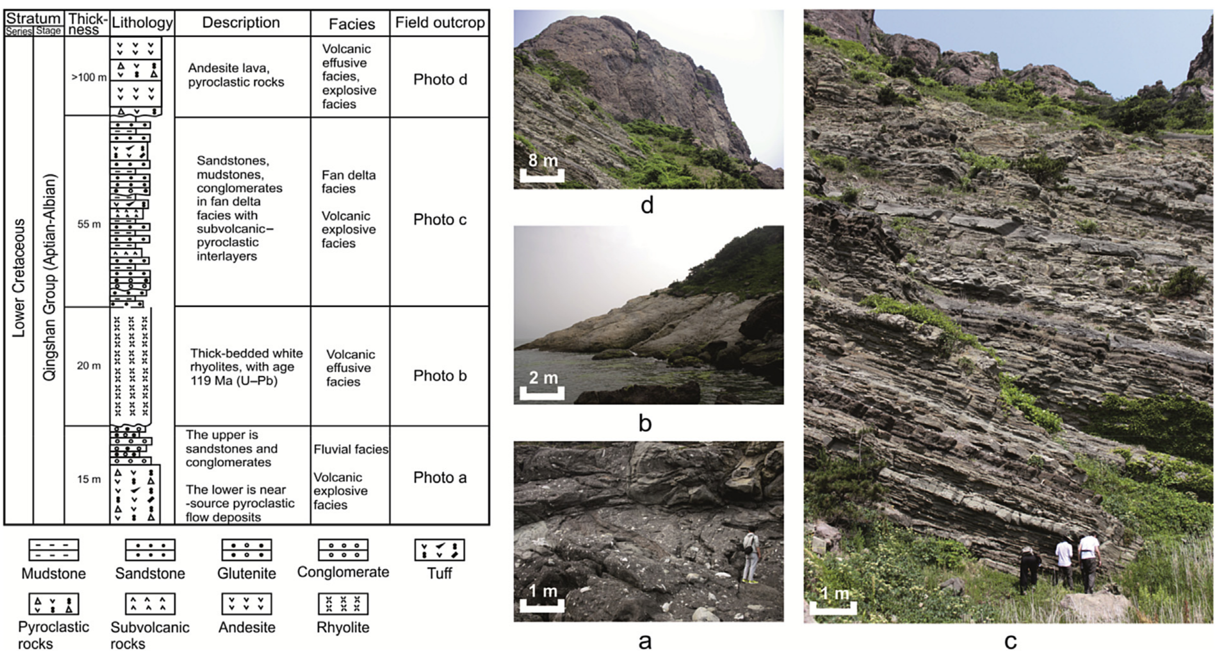

Fig. 4 Lithologic units and outcrop features of the Yangjiaodong Section in Lingshan Island.

Please cite this article in press as: Zhou, Y.-Q., et al., Soft-sediment deformation structures related to volcanic earthquakes of the Lower Cretaceous Qingshan Group in Lingshan Island, Shandong Province, East China, Journal of Palaeogeography (2017), http://dx.doi.org/10.1016/j.jop.2017.02.002

ARTICLE IN PRESS

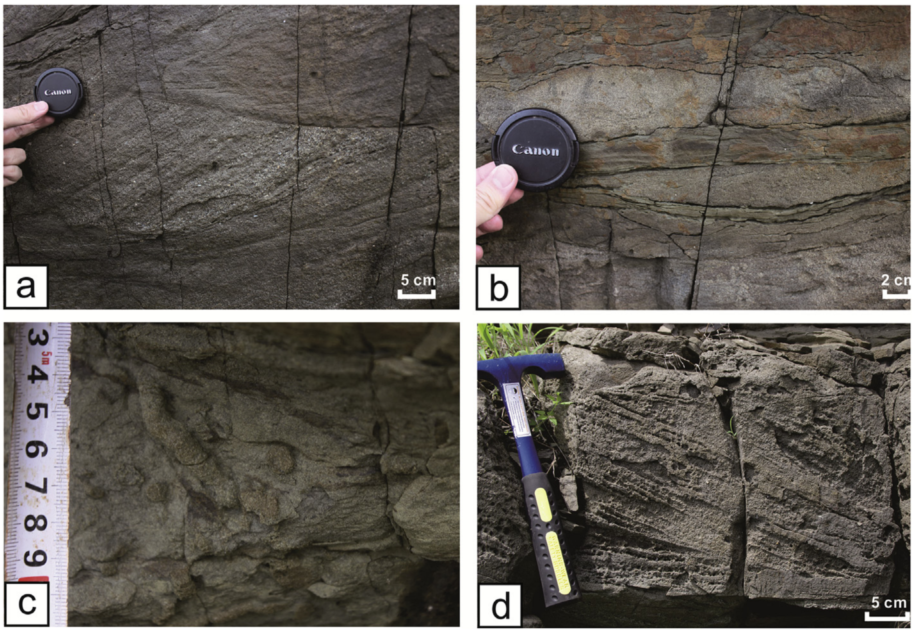

Fig. 5 Sedimentary characteristics (a-Trough cross-bedding; b-Lens structure; c-Burrow structure; d-Wedge cross-bedding) of the fan delta facies in the third lithologic unit of the Yangjiaodong Section in Lingshan Island.

respectively as (1) load structure, flame structure, ball and pillow structure, water-escape structure triggered by liquefaction deformation; (2) hydroplastic fold structure, plastic sandstone breccia, volcanic drop stone triggered by the plastic deformation; (3) V-shaped ground fissure triggered by brittle deformation.

3.1. Load and flame structures

Load and flame structures developed in terrestrial clastic deposits in the first and third lithologic units of the Yangjiaodong Section in the study area, especially in the layers underlying the pyroclastic flows.

The ordinary load structure was caused by earthquakes which led to the liquefaction of unconsolidated sandstone layers, and commonly developed along with flame structure (Fig. 6a and c; Table 1, Type I). Another kind of load structure was caused by gravity and inertia effect of pyroclastic deposition when high-density pyroclastic flow flew upon the sedimentary layer, and usually was not associating with flame structure (Fig. 6b; Table 1, Type II).

When earthquakes happened, the overlying unconsolidated sandstone layers of the load structure were liquefied, and the fine-grained sediments injected into the overlying sandstone layers affected by liquefaction and differential compaction and thus formed flame structure (Fig. 7). Thus, flame structure usually develops along with load structure.

SSDS of the Qingshan Group in Lingshan Island were in “flame” and “sharp” shape. Especially, when the pyroclastic flows that acted as the host layer of the flame structure flew far away from the volcanic vent, the size of the host layer became smaller and the density decreased as well. And then, when the host layer composed by pyroclastic flows was lower than the overlying sandstone layer, it was liquefied and injected into the unconsolidated sandstone layer, and formed load and flame structures (Fig. 8).

3.2. Pillow structure and ball—pillow structure

Pillow structure and ball—pillow structure are two types of SSDS with absolutely different characteristics in morphological feature, occurrence mode and deformation mechanism (Qiao and Li, 2008).

Pillow structure is defined as a suit of deformed concave-upward sand bodies whose original layer is bent, and is parallel with the basal surface and truncated at the top surface. Pillow structure of the Yangjiaodong Section was triggered by liquefaction of some definite layers within package of layered sandstone that was forced to fold (Fig. 9a).

Ball—pillow structure is the result of the system unbalance to rebalance between the overlying coarse-grained sediments and the underlying fine-grained sediments. The structure was shown as the “ball”

Please cite this article in press as: Zhou, Y.-Q., et al., Soft-sediment deformation structures related to volcanic earthquakes of the Lower Cretaceous Qingshan Group in Lingshan Island, Shandong Province, East China, Journal of Palaeogeography (2017), http://dx.doi.org/10.1016/j.jop.2017.02.002

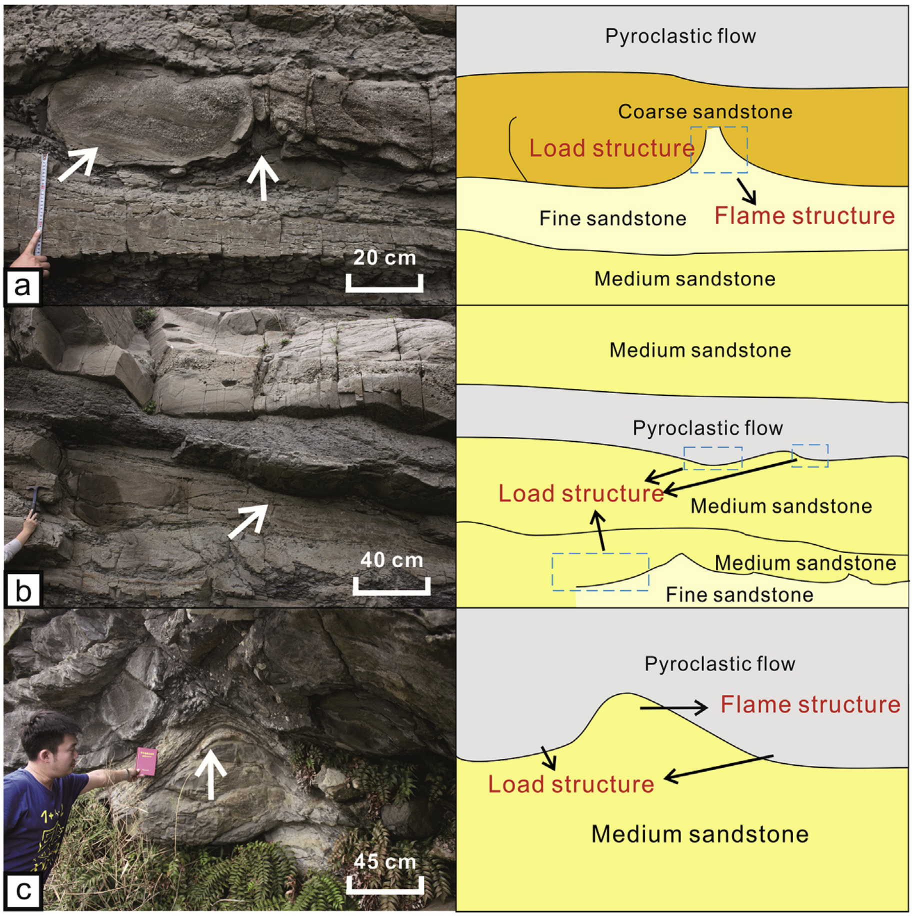

Fig. 6 Load structures developed in terrestrial clastic deposits of the Yangjiaodong Section in Lingshan Island and their formation mechanism. a—Load structure developed along with flame structure; b—Load structure developed not associating with flame structure; c—Huge load structure causing diaper structure of the underlying layer.

composed by coarse-grained sediments falling into the underlying fine-grained layer (Fig. 9b and c).

3.3. *Water-escape structure*

Water-escape structure is a common type of SSDS formed by the liquefied sandstone layer. When volcanic earthquakes happened, unconsolidated sandstone layers were full of water, and the water escaped from bottom to top across the layer without injecting action, and thus formed water-escape structure and pillows (Fig. 10).

3.4. *Hydroplastic deformation structure*

Hydroplastic deformation is a kind of plastic deformation caused by the extrusion stress when or after an earthquake happens. Generally, the forming process of hydroplastic deformation does not need water participation, but the sedimentary layer usually becomes slightly liquefied even full of water for the reason that the sedimentary layer will be dragged by flowing water. In the study area, this type of hydroplastic deformation mainly involves laminated convolution deformation (Fig. 11a) and fold deformation (Fig. 11b).

3.5. *Plastic sandstone breccia structure*

Plastic sandstone breccia structure is different from the liquefied breccia. It is not only one type of the specific SSDS related to volcanic earthquakes, but also one kind of the specific structure of proximal volcanic deposits. When a volcano erupts, the high-density pyroclastic flows flow across the unconsolidated sandstone layers with high speed, and the generated erosion effect involves some unconsolidated sandstones from the underlying layer and cools them down to form plastic sandstone breccia in the pyroclastic flows. Plastic sandstone breccia structure keeps the

Please cite this article in press as: Zhou, Y.-Q., et al., Soft-sediment deformation structures related to volcanic earthquakes of the Lower Cretaceous Qingshan Group in Lingshan Island, Shandong Province, East China, Journal of Palaeogeography (2017), http://dx.doi.org/10.1016/j.jop.2017.02.002

ARTICLE IN PRESS

Table 1 Comparison between the ordinary load structure developed along with flame structure (Type I) and the load structure developed not associating with flame structure (Type II) in the Yangjiaodong Section in Lingshan Island.

Load structure	Type I	Type II
Material composition	The host layer is mainly composed of relatively coarse-grained sandstones; The underlying layer is composed of relatively fine-grained sandstones and mudstones.	The host layer is composed of pyroclastic flow deposits; The underlying layer is mainly composed of sandstones.
Shape	Different kinds	Relatively flat
Structure characteristic	Developed along with flame structure	Developed not associating with flame structure
Triggering mechanism	Liquefaction	Gravity and inertia effect of pyroclastic flows
Field photo	Fig. 6a and c	Fig. 6b

characteristics of both the original sedimentary structure and deformation structure such as bedding and fold (Fig. 12).

3.6. *Volcanic drop stone deformation structure*

Du *et al.* (2005) studied the volcanic drop stone deformation structure of the Late Pleistocene in Weizhou Island, Guangxi, and discussed the genesis of the volcanic drop stone and its process of falling into the common sedimentary layers around the volcanic vent.

The volcanic drop stone deformation is a specific type of SSDS caused by volcanic earthquakes, especially by the explosive volcanic eruption. When a volcano erupts, the explosive rocks fly out and fall into the surrounding sedimentary layers and this process will lead to brittle deformation or plastic deformation which depends on the status (consolidated or unconsolidated) of the sedimentary layers where the explosive rocks falling into and depositing.

As Fig. 12b shows, volcanic rock flew out and fell into an unconsolidated sandstone layer, forming the volcanic drop stone deformation; and then, pyroclastic flows flew across some part of the unconsolidated sedimentary layer and huge plastic sandstone breccia was formed. So the volcanic drop stone deformation and the plastic sandstone breccia are obviously two different types of SSDS formed in two stages and caused by different geneses.

3.7. *Ground fissure*

Ground fissure usually formed by earthquakes which happened in semi-consolidated sediments on the ground, is a type of brittle deformation structure and is filled with common surrounding sediments or pyroclastic deposits. It is mainly V-shaped and develops in the layer under the proximal—medial pyroclastic flows.

Ground fissures showed in Fig. 13 were shaped as upside-down cones, with width changing from 20 cm (top) to 3 cm (bottom); and the grid of sediments in this kind of inverted cone shows a sieve deposition progress.

4. Distribution of SSDS and its relationship with pyroclastic flows

4.1. *Distribution of SSDS and pyroclastic flows at the Yangjiaodong Section*

More than 10 interlayers of pyroclastic flows developed at the Yangjiaodong Section, which respectively corresponded to a series of volcanic events that happened during this period (after 119 Ma). In field outcrop (Fig. 14) pyroclastic flow interlayers developed in association with the gray layers and intermediate—basic subvolcanic rocks the brown layers, and the rest is terrestrial sediment of fan delta. Palaeoenvironment changed from deep-water to shallow-water.

The analysis of the relationship between pyroclastic flows and SSDS-developed layers revealed that most SSDS-developed layers developed in strata underlying the strata with pyroclastic flows. This study observed 10 SSDS-developed layers, 15 volcanic depositional layers, and 10 sets of pyroclastic flows in the vertical stratum of the Yangjiaodong Section (Fig. 15). Characteristics, types, scales of SSDS indicated differences between the two kinds of host rocks changing from pyroclastic flows themselves to the underlying sandstone layers (Table 2). In addition, even the same type of SSDS developed in different layers, were quite different in their scale and shape of load and flame structures.

The observation and statistical analysis of SSDS-developed layers illustrated that the differences among them derived from different force conditions

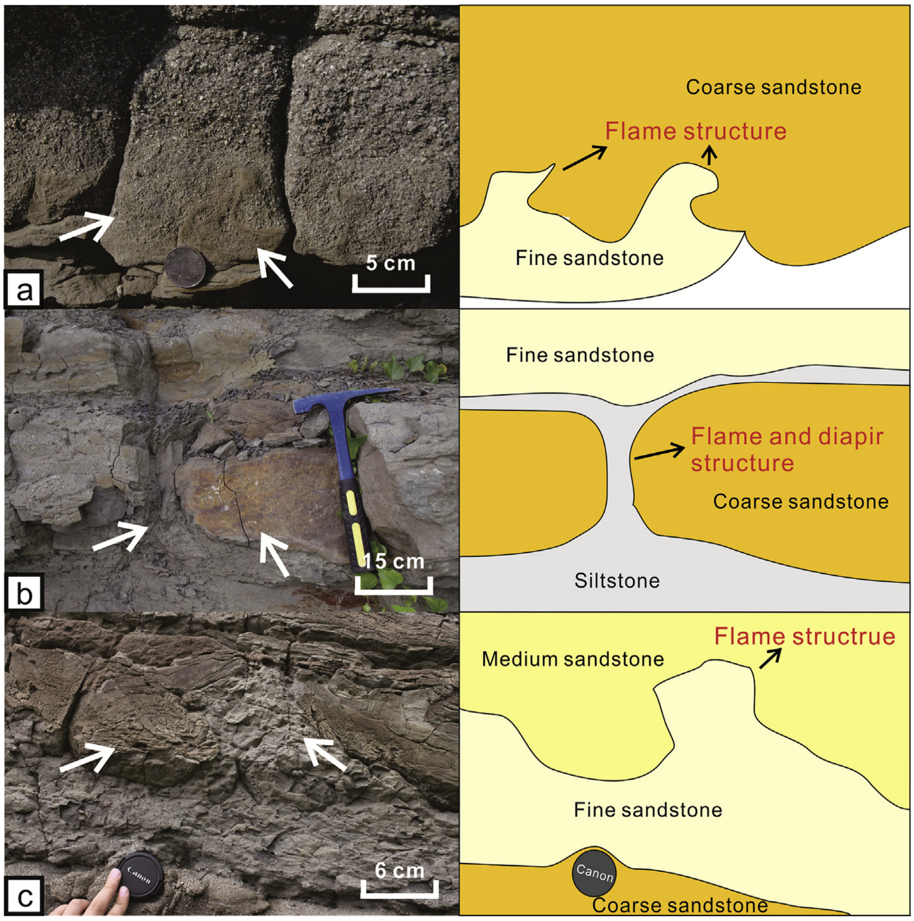

Fig. 7 Flame structures developed in terrestrial clastic deposits of the Yangjiaodong Section in Lingshan Island and their formation mechanism. a—Flame structure caused by liquefaction of the overlying sandstone layer; b and c—Diaper structure and flame structure caused by liquefaction and differential compaction that triggered the underlying layer inserting into the upper layer.

caused by different levels of volcanic earthquakes. The earthquake intensity decreased with the increasing distance from the paleo-volcanic vent; and the volcanic earthquake source was usually 0—10 km beneath the volcanic vent (Zobin, 2003). It is obvious that the distance from the volcanic vent was an important factor affecting the SSDS related to volcanic earthquakes.

4.2. Pyroclastic flow deposits of the Yangjiaodong Section

The volcanic deposits are good indicators to indicate the transportation distance of themselves from their sources (volcanic vent; Bai *et al.*, 2006; Sun *et al.*, 2001; Xie, 1994; Zhao, 2010). The pyroclastic flow deposits can be divided into 3 types according to their transportation distance. With the increasing transportation distance, they are respectively named as volcanic explosive-collapse facies (Type 1); pyroclastic flow facies (Type 2); fallout facies (Type 3). All kinds of facies of pyroclastic flows deposits developed in the study area, with Type 2 as the major one and Type 3 as the secondary type. The pyroclastic flow deposits (Type 2) in the study area can be further subdivided to proximal and medial deposits, according to their transportation distance. The proximal deposits, lava like, were composed of pyroclasts with taxitic structure. If proximal deposits deposited closer to the volcanic vent, the facies transferred to eruptive-collapse facies (Type 1), so it is common that some volcanic bombs and volcanic breccia occasionally occurred in the proximal pyroclastic flow deposits. The medial pyroclastic flow deposits usually developed as thick layers (10—20 cm) with massive structure and abundant debris (Zhao, 2010). Some of the debris occurred as good orientation arrangement of volcanic pebbles. These features of medial pyroclastic flow deposits suggest that the pyroclastic flows are of high density and fluid property. With the increasing

ARTICLE IN PRESS

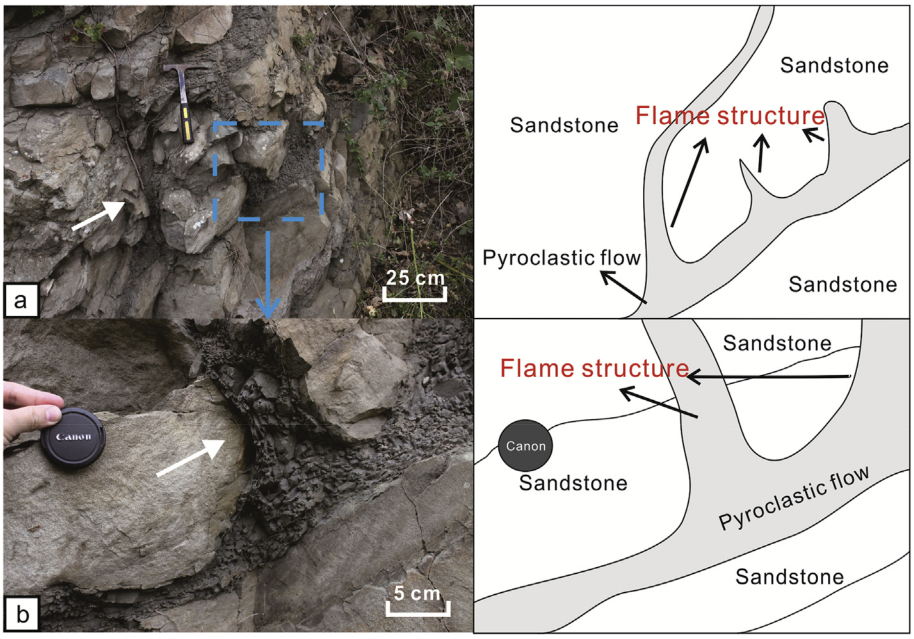

Fig. 8 Flame structures developed in the pyroclastic distal deposits of the Yangjiaodong Section in Lingshan Island and their formation mechanism. a and b— Flame structures caused by liquefaction that triggered the underlying host layer of pyroclastic flows inserting into the upper unconsolidated sandstone layer.

transportation distance, the transportation capacity of pyroclastic flow decreased, and the maximum size of pebbles in the flow were important indicators of transportation capacity and distance.

As shown in Table 3, the maximum sizes of pebbles are distinctly different among different layers of pyroclastic flow deposits, which means that each layer of pyroclastic flow deposits has different transportation distance from the volcanic vent. Base on the features of pebbles shown in Table 3 and Fig. 16, we proposed that the layer 5 m below the rhyolite (the second lithologic unit of the Yangjiaodong Section) belonged to proximal deposits, the layers 7 and 8 belonged to proximal—medial deposits, while the rest layers belonged to medial deposits.

The layer of pyroclastic flow deposits 5 m below the rhyolite (the second lithologic unit of the Yangjiaodong Section), was deposited in alluvial fan environment associating with some alluvial deposits. Since the depositional locations were close to the volcanic vent, the released energy of paleo-volcano eruption was huge, and therefore volcanic drop stone associated with huge plastic sandstone breccia bearing large-scale load and flame structures can be observed. In the layers 1—6 and the layer 2 m below the andesite (the fourth lithologic unit of the Yangjiaodong Section), various types of SSDS, including load and flame, ball and pillow, hydroplastic fold deformation, and water-escape structures in their adjacent layers were found. In the layers 7 and 8, SSDS including V-shaped ground fissure, plastic sandstone breccia structure and volcanic drop stone structure were found in the host rocks (pyroclastic rocks and sandstones) (Table 1; Fig. 15).

4.3. Distribution model of the SSDS related to volcanic earthquakes

Based on the analysis of pyroclastic flows, volcanic eruption types and SSDS, we can easily establish a close relationship among them. The scale of SSDS mainly depended on the types of volcanic eruption and explosive intensity. We primarily concluded that the SSDS related to volcanic eruption had a larger scale than those related to effusive volcanic eruption (Tables 4 and 5). Basically, the scale of SSDS was positively correlated with the volcanic explosive intensity. In addition, the specific type and scale of SSDS were affected by the increasing distance from the vent as energy decreased.

Based on comprehensive analyses (Tables 1 and 2; Figs. 15 and 17), this study indicated that SSDS were significantly different as distance from the volcanic vent changed. Deformations including brittle deformation, plastic deformation or liquefied deformation were developed which depended on the change of distance from proximal to distal part. In the proximal zone, brittle deformation was much more frequently

Please cite this article in press as: Zhou, Y.-Q., et al., Soft-sediment deformation structures related to volcanic earthquakes of the Lower Cretaceous Qingshan Group in Lingshan Island, Shandong Province, East China, Journal of Palaeogeography (2017), http://dx.doi.org/10.1016/j.jop.2017.02.002

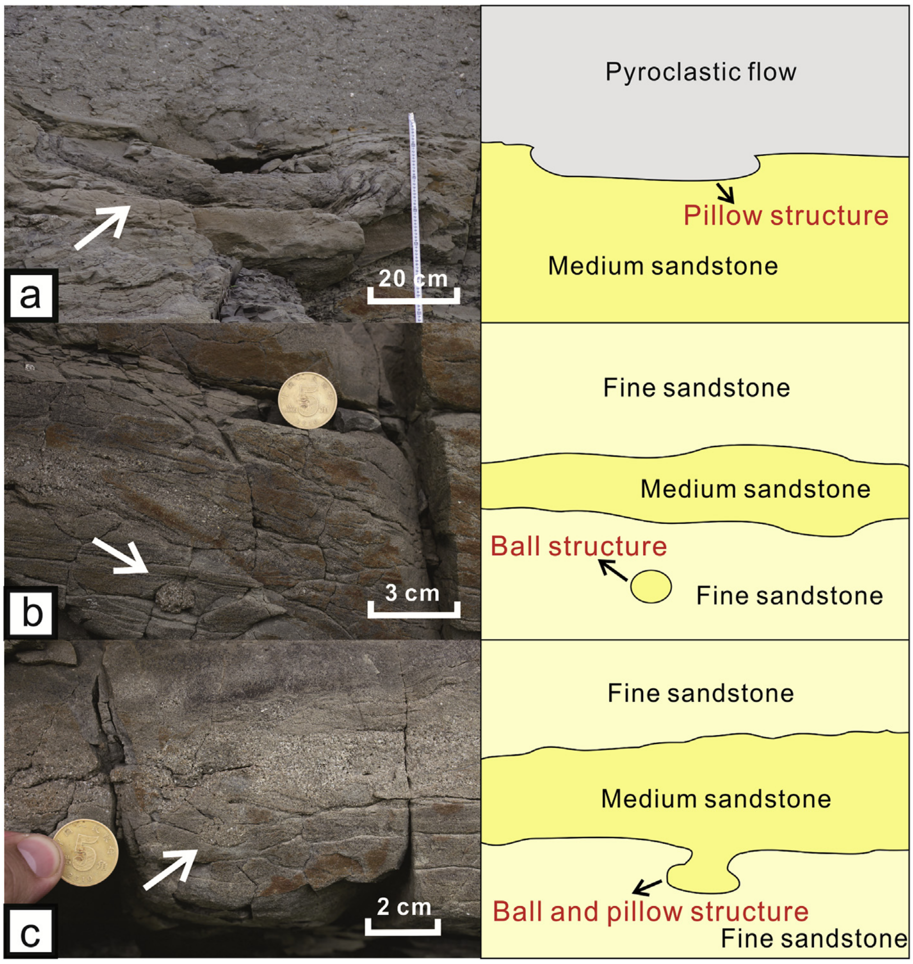

Fig. 9 Sand pillow and ball–pillow structures developed in the Yangjiaodong Section in Lingshan Island and formation mechanism.

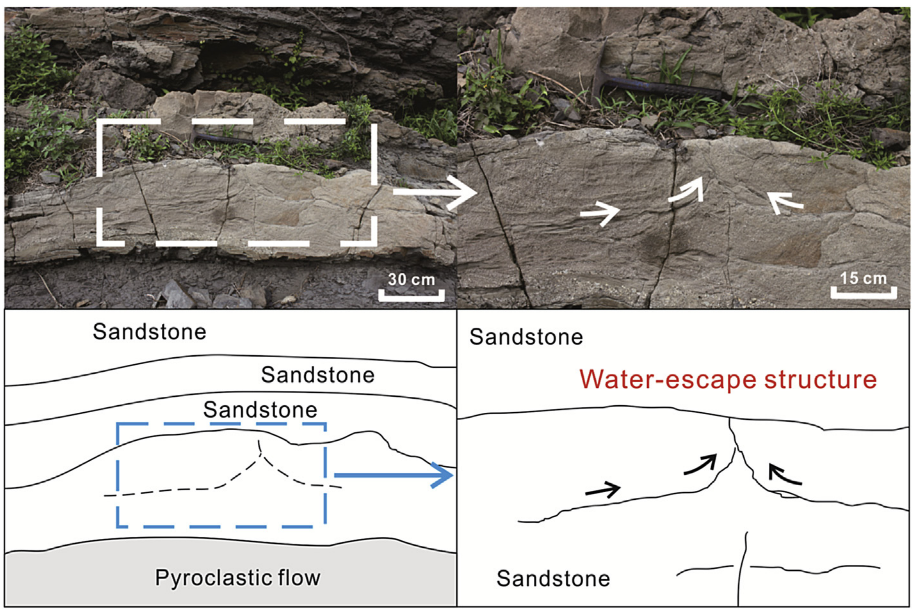

Fig. 10 Water-escape structure developed in the liquefied sandstone layers of the Yangjiaodong Section in Lingshan Island. Note the water escape path in the sandstone layer, and that the pillow structures developed in pairs were separated with each other by the water-escape structure.

Please cite this article in press as: Zhou, Y.-Q., et al., Soft-sediment deformation structures related to volcanic earthquakes of the Lower Cretaceous Qingshan Group in Lingshan Island, Shandong Province, East China, Journal of Palaeogeography (2017), http://dx.doi.org/10.1016/j.jop.2017.02.002

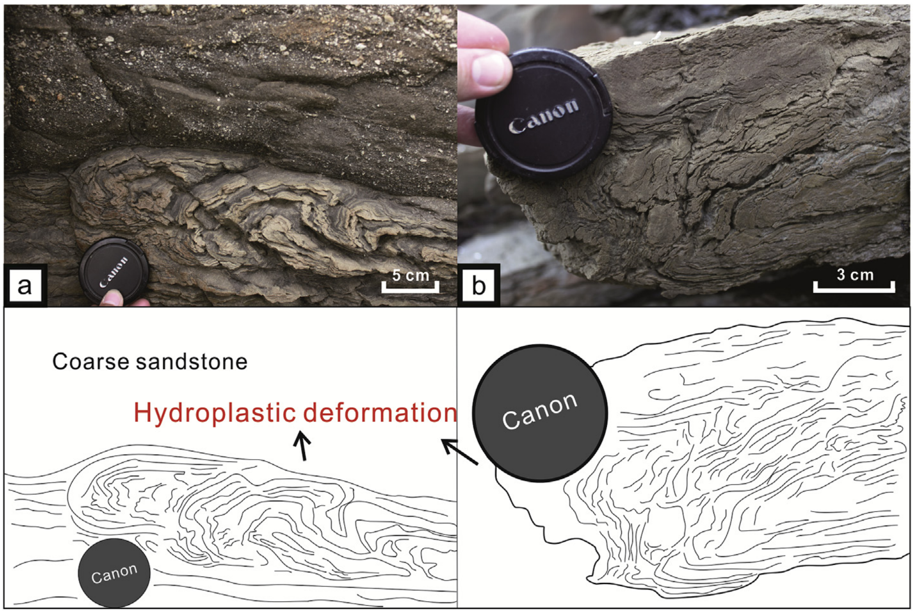

Fig. 11 Hydroplastic deformation developed in the liquefied sandstone layers of the Yangjiaodong Section in Lingshan Island. Note the two types of hydroplastic deformation: a—Laminated convolution deformation; b—Hydroplastic fold deformation.

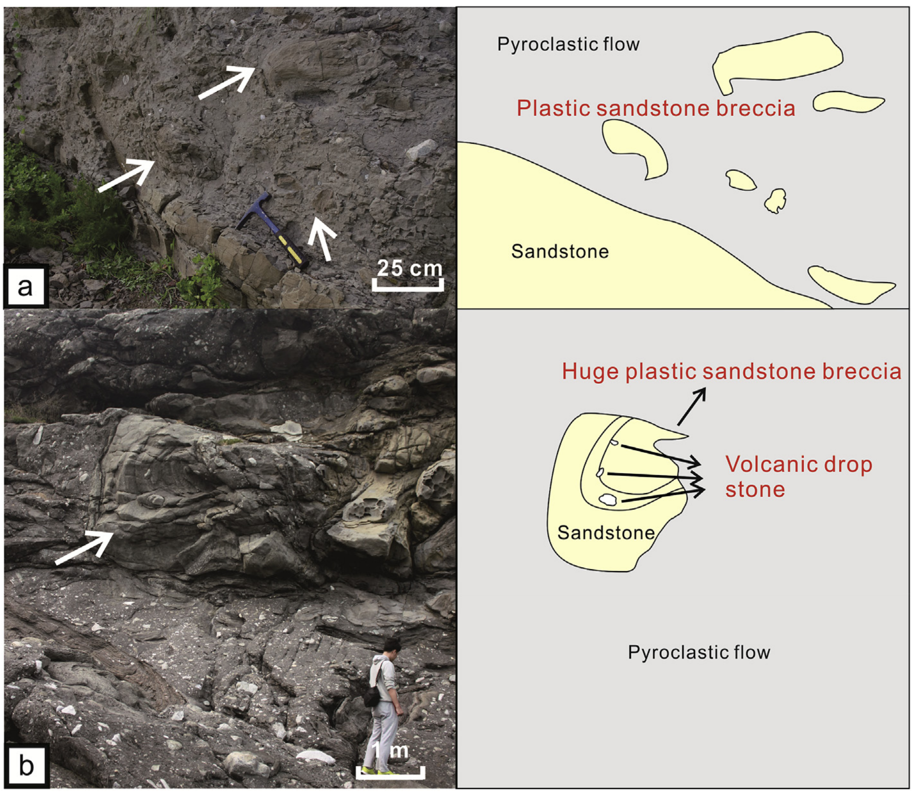

Fig. 12 Plastic sandstone breccia and volcanic drop stone deformation developed in the pyroclastic flows of the Yangjiaodong Section in Lingshan Island and their formation mechanism.

developed than in other farther zones, while the scale of plastic deformation and liquefied deformation was larger, with typical SSDS such as volcanic drop stone structure and plastic sandstone breccia bearing structure. In the medial zone, brittle deformation quantity decreased rapidly, and its scale tended to be smaller. However, the plastic deformation and liquefied deformation developed steadily and became

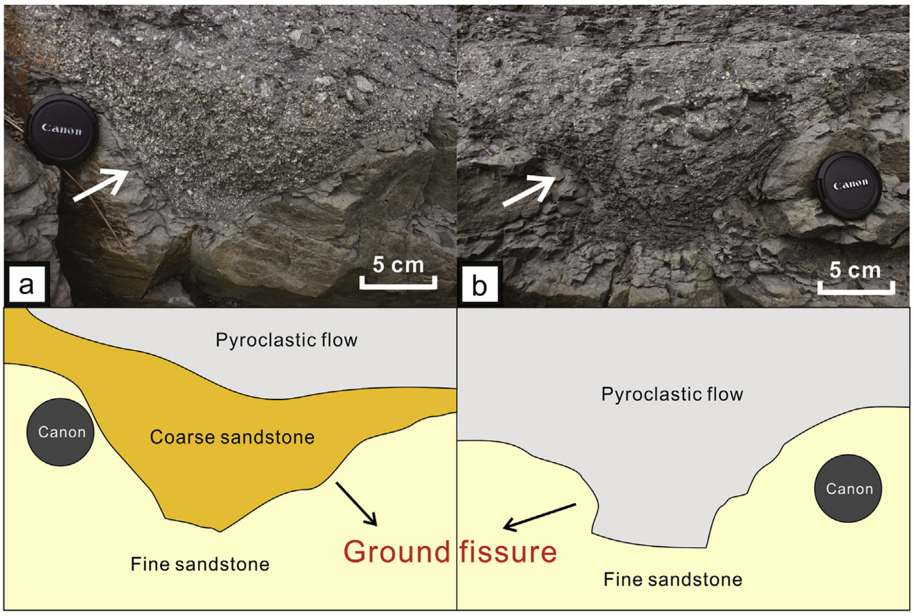

Fig. 13 V-shaped ground fissures developed in the semi-consolidated sediments of the Yangjiaodong Section in Lingshan Island and their formation mechanism.

Fig. 14 Field outcrop photo showing the third lithologic unit (refer to Fig. 4) of the Yangjiaodong Section in Lingshan Island.

dominant types. In the distal zone, with the decreasing energy of volcanic earthquake, only a few water-escape structure and load and flame structure developed. The distribution model of SSDS related to volcanic earthquakes in the Qingshan Stage in Lingshan Island was drawn in Table 6 and Fig. 18 as a conclusion.

Types, characteristics, shapes and scales of SSDS changed gradually with the increase of distance. It must be emphasized again that the definition of proximal, medial and distal was based on comprehensive statistic data including volcanic sedimentology and volcanic petrogeochemistry. Furthermore, to find more information about the SSDS related to volcanic earthquakes, it is essential to discuss in details about different study area and different types of volcanic eruptions with different magmatism characteristics.

5. Formation mechanism of the SSDS related to volcanic earthquakes

Compared with SSDS in turbidite system in the Laiyang Group, the SSDS related to the volcanic eruption in the Qingshan Group were obviously different in their types, characteristics, size and distribution density: (1) two groups of specific SSDS, *i.e.*, fold modified beddings and V-shaped ground fissures were developed in the Laiyang Group; (2) V-shaped ground fissures in the Laiyang Group were of different sizes, and the sizes of load structures in the Laiyang Group were from millimeters to tens of centimeters; but the sizes of load structures in the Qingshan Group were much bigger, and in different shapes; (3) Most SSDS of the Laiyang Group developed continuously, so they can be easily traced horizontally; however, SSDS of the Qingshan Group rarely appeared continuously.

This study thus led to the following summarizations: (1) Lithological associations were different due to different lithofacies palaeogeographic characteristics; (2) Different seismic features between tectonic earthquakes and volcanic earthquakes influenced characteristics of the two types of SSDS related to earthquakes.

Volcanic earthquakes usually acted in two ways as magmatic active earthquakes and volcanic eruption

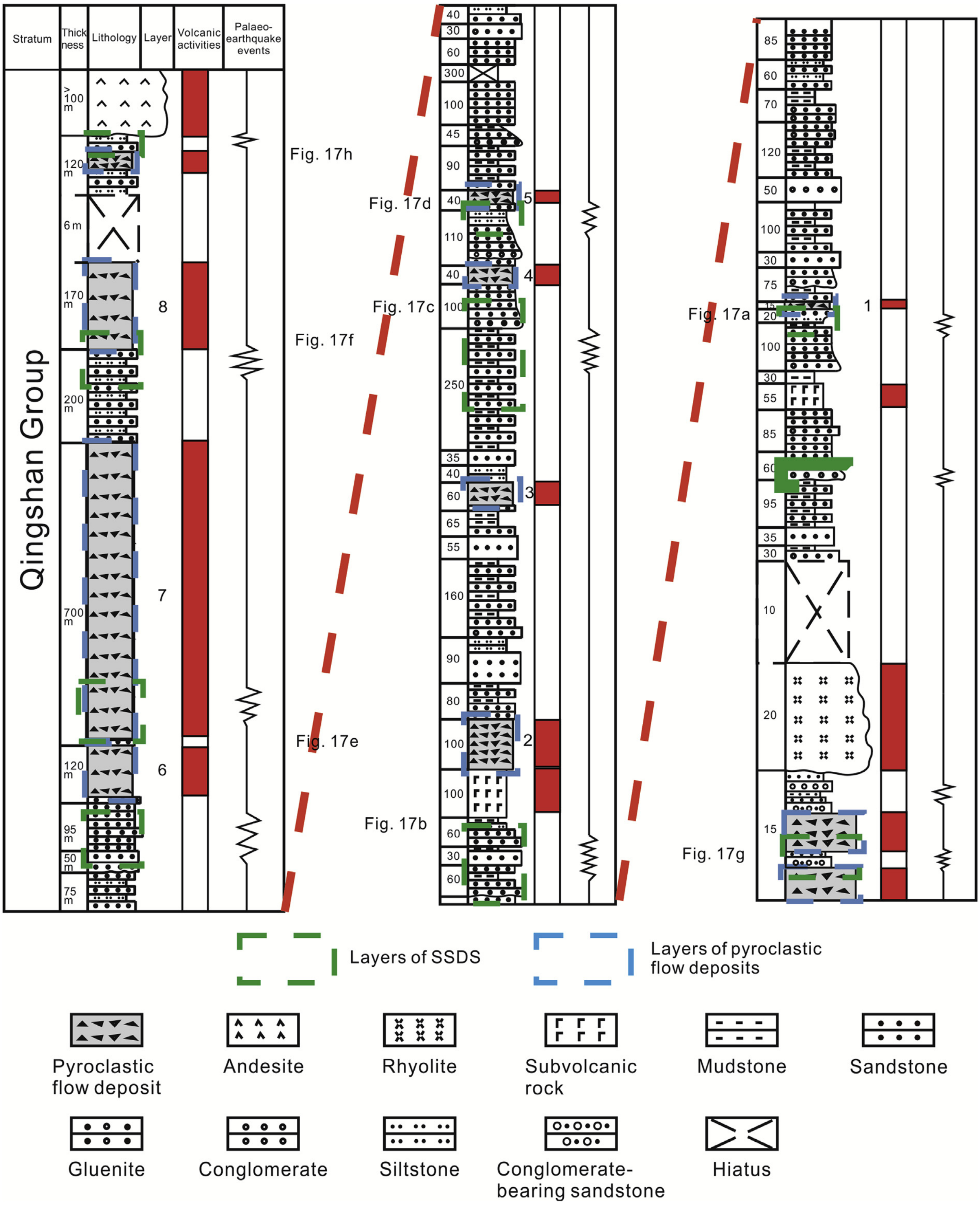

Fig. 15 Relationship between pyroclastic flows and SSDS-developed layers of the Yangjiaodong Section in Lingshan Island.

earthquakes. The former was caused by the underground magma activities, which did not eject across the surface; the latter was characterized by volcanic eruptions with magma ejecting across the surface. It is useful for investigating the SSDS related to volcanic earthquakes if the distinction between these two types of volcanic earthquakes clearly understood.

Volcanic activities occurred in the Qingshan Stage were mainly recorded by the intermediate—acid extrusive rocks that belonged to the Jiaodong volcanic

ARTICLE IN PRESS

Table 2 Relationship between layers of pyroclastic flows deposits and SSDS-developed layers of the Yangjiaodong Section in Lingshan Island.

Layers of pyroclastic flow deposits	Thickness	Underlying layers	Types of SSDS
The layer below the rhyolite (5 m below the second lithologic unit)	8 m	Beneath the horizon, the overlying layer is gluenite of fluvial fan	Huge plastic sandstone breccia, volcanic drop stone deformation structure, load structure
1	0.2 m	Sedimentary layer	Flame structure
2	1 m	Subvolcanic rock layer, and sedimentary layer	Load and flame structures, ground fissure (both in the pyroclastic flow layer and the underlying layer)
3	0.6 m	Sedimentary layer	None SSDS
4	0.4 m	Sedimentary layer	Load and flame structure, pillow structure, V-shaped ground fissure
5	0.5 m	Sedimentary layer	Flame structure
6	0.8 m	Sedimentary layer	Load and flame structure, hydroplastic sandstone deformation
7	7 m	Pyroclastic flow layer	Volcanic drop stone structure, plastic sandtone breccia
8	2 m	Sedimentary layer	V-shaped ground fissure
The layer below the andesite (2 m below the fourth lithologic unit)	0.3 m	Sedimentary layer	Water-escape structure, pillow structure

Table 3 Statistics of maximum grain size of breccia in pyroclastic flow deposits of the Yangjiaodong Section in Lingshan Island.

Layers of pyroclastic flow deposits	Thickness	Maximum size of pebbles
The one below the rhyolite (5 m under the second unit)	8 m	60 cm
1	0.2 m	1 cm
2	1 m	2.5 cm
3	0.6 m	1.5 cm
4	0.4 m	1.5 cm
5	0.5 m	1.6 cm
6	0.8 m	2 cm
7	7 m	40 cm
8	2 m	20 cm
The one below the andesite (2 m below the fourth lithologic unit)	0.3 m	1 cm

area. Lithogeochemistry characteristics of the volcanic rocks in the Jiaodong Peninsula indicated that their origin was that the magmatic melting source transferred from the mantle to the lower crust under the effect of magma differentiation due to the subduction of the Pacific Plate (Cao et al., 2014; Kuang et al., 2012). Zobin (2003) worked on the andesitic eruption activities in El Chichon volcano, Mexico and Sakurajima volcano, Japan and associated modern volcanic earthquakes, and found that explosive volcanic earthquakes occurred commonly in the shallow strata with depth of 0—20 km in the andesitic area where volcanic eruptions were more intense. In this sense, the heavy volcanic agglomerate, volcanic breccia and andesitic lava in Lingshan Island also reflected the strong volcanic eruption which happened during the Qingshan Stage.

During the Early Cretaceous, the palaeoenvironment of Lingshan Island gradually transferred from the deep-water depositional environment of the Laiyang Stage to the shallow-water depositional environment of the Qingshan Stage. Accompanied by increased participation of water, volcanic eruptions occurred more frequently with higher intensity, and magmatic volatiles increased. Volcanic eruptions caused volcanic earthquakes, and then volcanic earthquakes triggered the deformation of semi-consolidated and unconsolidated sediments. Each set of the pyroclastic flow and the SSDS-developed layer correspondingly recorded a series of ancient volcanic earthquake events.

Volcanic earthquakes triggered SSDS mainly through the following three factors: the spread of seismic waves within underlying rocks, the gravity and inertia of pyroclastic flows, and the instantaneous differential pressure. The seismic waves caused by shallow earthquakes from volcanic activity spread along near-surface rocks, which has almost the same mechanism as SSDS caused by earthquakes. The inertia of pyroclastics gravity during accumulation, and the initial movement of the pyroclastic flows caused by volcanic eruption, and the erosion, denudation and differential compaction of the underlying layers, led to the development of SSDS. Due to volcanic eruptions, an instantaneous change of air pressure near surface occurred. Generally, the gas pressure of high-speed movement was smaller than the surrounding pressure, which therefore led to instantaneous pressure

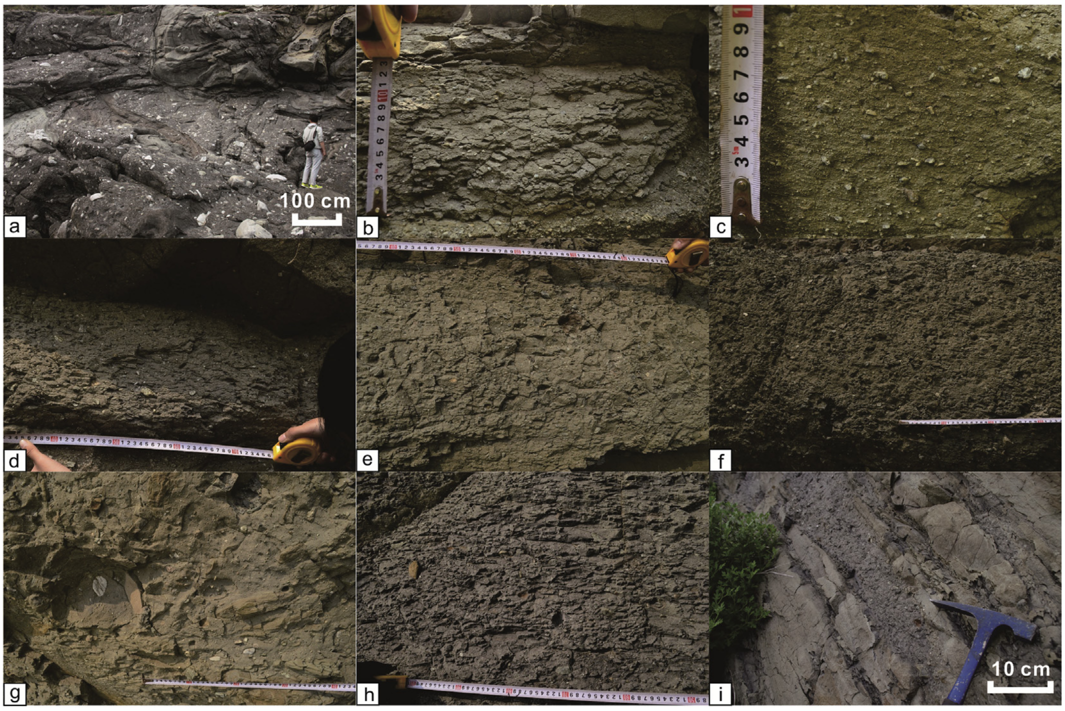

Fig. 16 Field photographs showing pyroclastic flow deposits of the Yangjiaodong Section in Lingshan Island. a—The layer below the rhyolite (5 m below the second lithologic unit); b and c—Type 1 and type 2 pyroclastic flow deposits, respectively; d—h—The layers 4—8 pyroclastic flow deposits, respectively (refer to Table 3); i—The layer below the andesite (2 m below the second lithologic unit).

imbalance, and thus caused the unconsolidated sediments to "swarm" upwards and interact with the sediment gravitation, and resulted in vibration effects. Then the accumulation of pyroclastic flows accompanied by seismic waves, together formed SSDS in the neighbouring layers. Analysis of the location and specific type of SSDS will illustrate the dominant factor. Three circumstances were summarized. First, in general, the SSDS which do not develop in the neighbouring layers of pyroclastic flows, are mainly triggered by seismic waves; Second, the SSDS in pyroclastic flow deposits are triggered mainly by the inertia of pyroclastics own gravity during accumulation; Third, the SSDS in the neighbouring layers of pyroclastic flows are affected by differential pressure, which leads to the vibration of unconsolidated sediments, and then triggered by the other two factors together. The influence of the first two circumstances to form SSDS, has been relatively clear. However, the third one still needs further study.

Table 4 Relationship between volcanic deposits and the SSDS which developed beneath or in the layer of the volcanic deposits.

Type of volcanic deposits	Type of SSDS
Andesite pyroclastic rocks	Water-escape structure and pillow structure
Rhyolite	Hardly to observe any SSDS
Pyroclastic flows	Almost every type of SSDS that can be observed in the study area developed here (listed in Table 2).

Table 5 Relationship between scale of volcanic-earthquake-related SSDS and type of volcanic eruption (including explosive intensity).

Type of volcanic eruption	Scale of SSDS
Effusive eruption	SSDS were not developed or occasionally occurred in small scales.
Explosive eruption	SSDS were developed and their scales increased with the increase of explosive intensity.

6. Conclusions

Following conclusions can be drawn from this study:

1) Soft-sedimentary deformation structures (SSDS) were well developed in the Lower Cretaceous Qingshan Group. Compared with the slumping structures triggered by tectonic earthquakes in the earlier Laiyang Stage, the triggering mechanism of

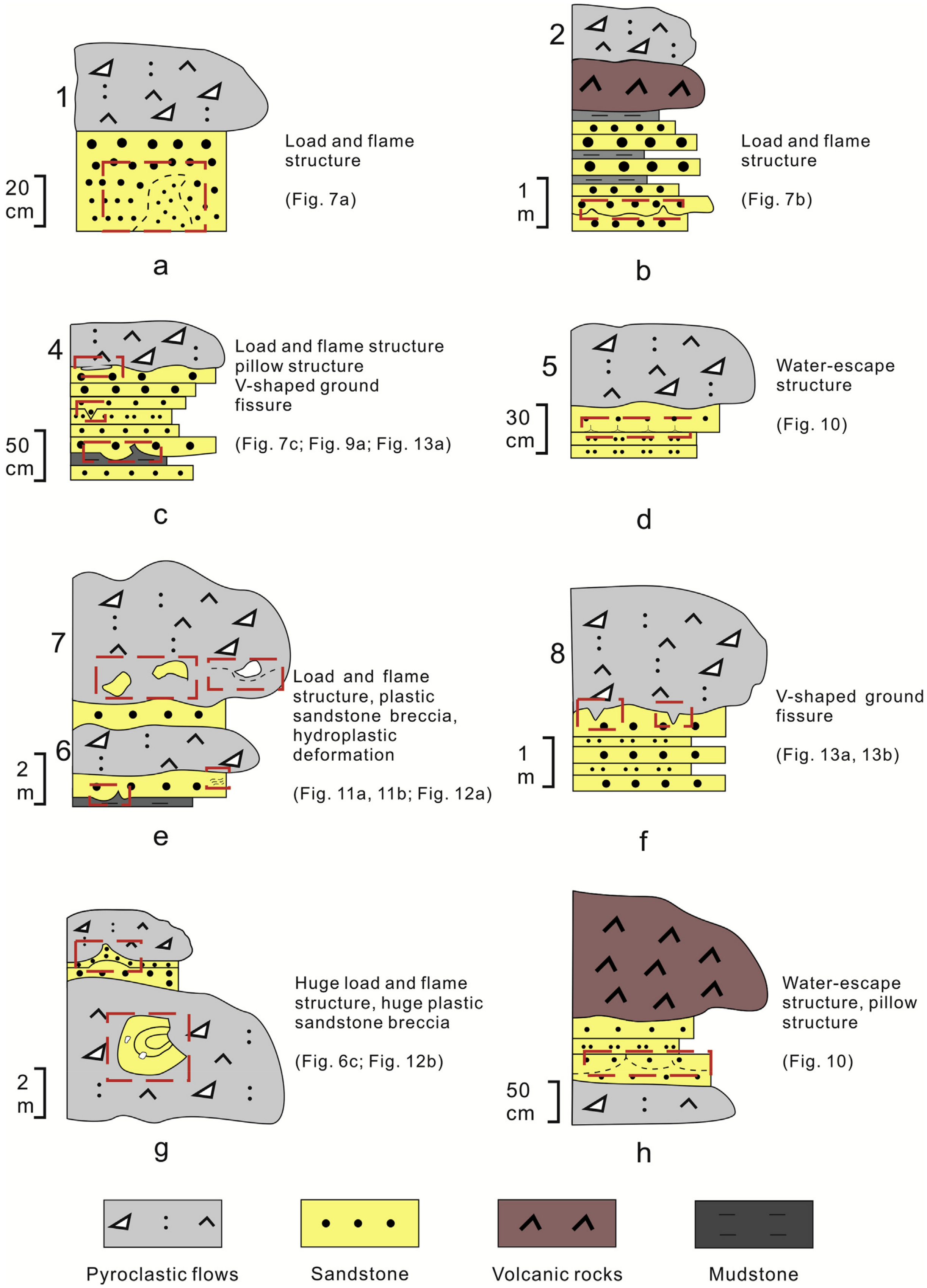

Fig. 17 SSDS types developed in pyroclastic flow deposits of the Yangjiaodong Section in Lingshan Island. See Fig. 15 for the position of pyroclastic flow deposits. SSDS are marked out by red rectangles.

Table 6 Relationship between the distance of SSDS depositional locations from the volcanic vent and the SSDS types in the Yangjiaodong Section in Lingshan Island.

Distance of SSDS depositional locations from volcanic vent	Types of SSDS
Proximal zone	Volcanic drop stone structure, huge load structure, V-shaped ground fissure, plastic sandstone breccia structure
Medial zone	Load and flame structure, ball—pillow structure, pillow structure, hydroplastic deformation structure, water-escape structure, V-shaped ground fissure
Distal zone	Load and flame structure, water-escape structure (slightly)

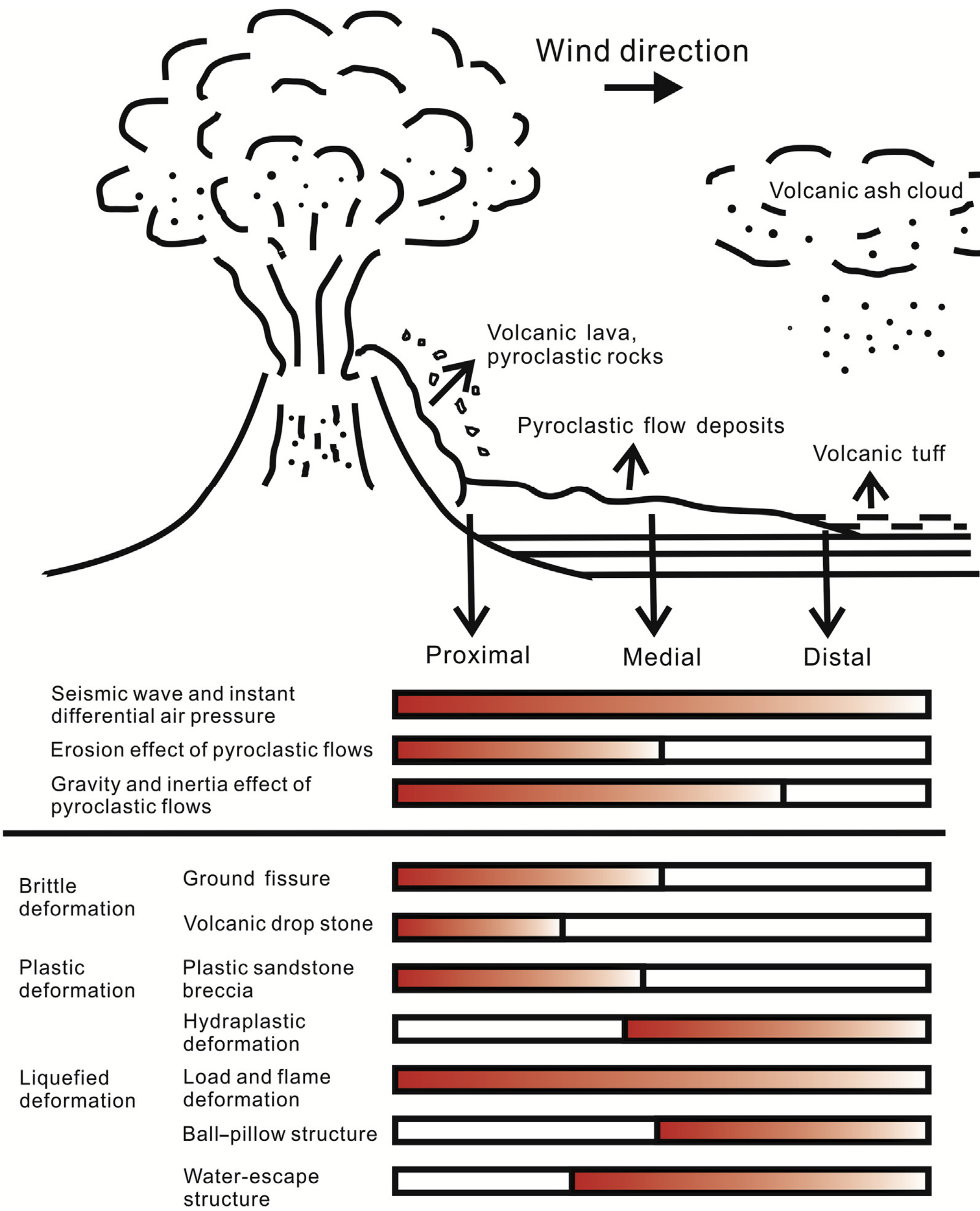

Fig. 18 Distribution model of SSDS related to volcanic earthquakes in the Yangjiaodong Section in Lingshan Island (ranging according to the distance of SSDS depositional locations from volcanic vent).

Please cite this article in press as: Zhou, Y.-Q., et al., Soft-sediment deformation structures related to volcanic earthquakes of the Lower Cretaceous Qingshan Group in Lingshan Island, Shandong Province, East China, Journal of Palaeogeography (2017), http://dx.doi.org/10.1016/j.jop.2017.02.002

SSDS of the Qingshan Group is attributed to volcanic earthquakes. The SSDS caused by volcanic earthquakes had their unique characteristics regarding type, scale and distribution, but the SSDS caused by the tectonic slip and slump and tectonic earthquakes were more diverse in type and scale, and had greater distribution density.

2) SSDS of the Qingshan Group caused by volcanic earthquakes were divided into different types with different characteristics in accordance with different distances of SSDS depositional locations from or different range of the volcanic earthquake. The large-scaled load and flame structures, volcanic drop stone structure, and plastic sandstone breccia structure were well developed in the proximal area. The load and flame structure formed by differential compaction due to high-density pyroclastic flows, pillow and ball—pillow structure, and water-escape structure were mainly developed in the medial source area. In the distal zone, the scale of load and flame structure and water-escape structure obviously decreased; especially the distal pyroclastic flow deposits were liquefied and inserted into the upper sandstone layer which formed a special flame structure.
3) The erosion effect of high-density pyroclastic flows has been proved to be an important trigger for plastic sandstone breccias as well as plastic sandstone breccia structure. Furthermore, we proposed that all kinds of the high-density debris flow erosion, whether from pyroclastic flows or from sandy debris flows, can cause such soft-sediment deformation structures. SSDS triggered by the high-density debris flow erosion like the plastic sandstone breccia structure are the typical deformation structures related to volcanic earthquakes in the proximal source area and the proximal—medial source transitional area, where high-density debris flows exist.
4) The triggering mechanism for the SSDS that developed in the neighbouring layer of the pyroclastic flow is a confluence of three ways of forces including seismic wave, gravity and inertial effect of pyroclastic flows, and instantaneous differential pressure. The influence degree of these three forces on the SSDS related to volcanic earthquakes generally depends on the vertical relative position relationship between SSDS and pyroclastic deposits. Further analysis is necessary.
5) Scales, types and characteristics of the SSDS related to volcanic earthquakes are affected by the type of volcanic eruption and its explosive intensity, as well as the distance from the volcanic vent. Scale of the SSDS related to explosive eruption is larger than that of the SSDS related to effusive eruption. And along with the incremental distance from the volcanic vent, scale of SSDS becomes smaller, and types change.

Acknowledgements

This work is funded by NSFC (Project No. 42172123).

Many thanks to Prof. Zeng-Zhao Feng, the Editor-in-Chief of the *Journal of Palaeogeography*, for inviting our research team to attend the 14th National Conference of Palaeogeography and Sedimentology to present our research results at both the symposium of “Multi-origins of soft-sediment deformation structures and seismites” and the *Journal of Palaeogeography*.

Thanks are given to the good advice from Prof. Zeng-Zhao Feng and other reviewers whose comments are greatly helpful for improving the quality of the original version of this paper.

References

Allen, J.R.L., 1982. Sedimentary structures, their character and physical basis. *Earth-Science Reviews*, 19(4), 362—363.

Bai, Z.D., Xu, D.B., Zhang, B.L., Zhang, T., Bu, J., 2006. Study on type and phase of Quaternary explosive volcanism in Longgang volcanic cluster. *Acta Petrologica Sinica*, 22(6), 1473—1480 (in Chinese with English Abstract).

Basilone, L., Lena, G., Gasparo-Morticelli, M., 2014. Synsedimentary-tectonic, soft-sediment deformation and volcanism in the rifted Tethyan margin from the Upper Triassic—Middle Jurassic deep-water carbonates in Central Sicily. *Sedimentary Geology*, 308(7), 63—79.

Cao, G.Y., Xue, H.M., Wang, J.G., 2014. Zircon U—Pb age and geochemistry of Mesozoic intermediate and acidic volcanic rocks from the Shandong segment (Jiaodong area) of the Tan-Lu fault. *Acta Petrologica ET Mineralogica*, 33(06), 1019—1038 (in Chinese with English Abstract).

Dong, X.P., Lü, H.B., Zhang, X., Zhang, H.C., Wang, J., Zhang, S.J., 2013. Stage analysis on the soft-sediment deformation in the Early Cretaceous Flysch, Lingshan Island, Shandong Province. *Geological Review*, 59(6), 1060—1067 (in Chinese with English Abstract).

Du, Y.S., 2011. Discussion about studies of earthquake event deposit in China. *Journal of Palaeogeography (Chinese Edition)*, 13(6), 581—590 (in Chinese with English Abstract).

Du, Y.S., Peng, B.X., Han, X., 2005. Syn-depositional deformation structures by earthquake related to volcanic activity of the Late Pleistocene in Weizhou Island, Beihai City, Guangxi. *Acta Sedimentologica Sinica*, 23(2), 203—209 (in Chinese with English Abstract).

ARTICLE IN PRESS

Feng, Z.Z., Bao, Z.D., Zheng, X.J., Wang, Y., 2016. Researches of soft-sediment deformation structures and seismites in China — a brief review. *Journal of Palaeogeography*, 5(4), 311—317.

He, B.Z., Qiao, X.F., 2015. Advances and overview of the study on paleo-earthquake events: a review of seismites. *Acta Geologica Sinica (English Edition)*, 89(5), 1702—1746.

He, B.Z., Qiao, X.F., Tian, H.S., Zhang, Y.X., 2012. Paleoearthquake events of Early Cretaceous Laiyang stage and dinosaur migration in Zhucheng, Shandong Province, Eastern China. *Acta Geologica Sinica*, 86(8), 1320—1330 (in Chinese with English Abstract).

He, B.Z., Qiao, X.F., Xu, Z.Q., Jiao, C.L., Cai, Z.H., Zhang, Y.L., Su, D.C., 2010. Late Ordovician paleoseismic records of the Manjiaer Depression and adjacent areas in Tarim Basin, Xinjiang, and its geologic significance. *Acta Geologica Sinica*, 84(12), 1805—1816 (in Chinese with English Abstract).

Kuang, Y.S., Pang, C.J., Luo, Z.Y., Hong, L.B., Zhong, Y.T., Qiu, H.N., Xu, Y.G., 2012. $^{40}Ar—^{39}Ar$ geochronology and geochemistry of mafic rocks from Qingshan Group, Jiaodong area: implications for the destruction of the North China Craton. *Acta Petrologica Sinica*, 28(4), 1073—1091 (in Chinese with English Abstract).

Lü, H.B., Wang, J., Zhang, H.C., 2011. Shandong Lingshan Island Late Mesozoic tectonic significance of the sliding layer and collapse area. *Acta Geologica Sinica*, 85(6), 938—946 (in Chinese with English Abstract).

Lü, H.B., Zhang, H.C., Wang, J., Zhang, S.J., Dong, X.P., Zhang, X., 2013. Lingshan Island Early Cretaceous flysch not intracontinental delta: a reply to Professor Zhong Jianhua. *Geological Review*, 59(1), 11—14 (in Chinese with English Abstract).

Luan, G.Z., Li, A.L., Wang, J., Li, G., Xie, R.J., 2010. The geological origin division of the main sea island in Qingdao area and environment analysis. *Periodical of Ocean University of China*, 40(8), 111—116 (in Chinese with English Abstract).

Montenat, C., Barrier, P., Ott D'Estevou, P., Hibsch, C., 2007. Seismites: an attempt at critical analysis and classification. *Sedimentary Geology*, 196, 5—30.

Owen, G., Moretti, M., Alfaro, P., 2011. Recognising triggers for soft-sediment deformation: current understanding and future directions. *Sedimentary Geology*, 235, 133—140.

Qiao, X.F., Guo, X.P., 2011. On the Lower Jurassic soft-sediment deformation of southwestern Tianshan Mountains, Xinjiang, China. *Geological Review*, 57(6), 761—769 (in Chinese with English Abstract).

Qiao, X.F., Li, H.B., 2008. Pillow, ball-and-pillow structures: paleo-seismic records within strata. *Geological Review*, 54(6), 721—730 (in Chinese with English Abstract).

Qiao, X.F., Li, H.B., 2009. Effect of earthquake and ancient earthquake on sediments. *Journal of Palaeogeography (Chinese Edition)*, 11(6), 593—610 (in Chinese with English Abstract).

Robertson, A., 1998. Rift-related sedimentation and volcanism of the north-Indian margin inferred from a Permian—Triassic exotic block at Lamayuru, Indus suture zone (Ladakh Himalaya) and regional comparisons. *Journal of Asian Earth Sciences*, 16(2), 159—172.

Shanmugam, 2016. The seismite problem. *Journal of Palaeogeography*, 5(4), 318—362.

Shao, Z.F., Zhong, J.H., Li, Y., Mao, C., Liu, S.X., Ni, L.T., Tian, Y., Cui, X.Y., Liu, Y.T., Wang, X.N., Li, W.H., Ling, G.S., 2014. Characteristics and sedimentary processes of lamina-controlled sand-particle imbricate structure in deposits on Lingshan Island, Qingdao, China. *Science China Earth Science*, 57(5), 1061—1076.

Song, T.R., 1988. A probable seismic-tsunami sequence in carbonate formation of Precambrian in Beijing Ming Dynasty Tombs. *Chinese Science Bulletin*, 38(8), 609—611 (in Chinese with English Abstract).

Song, T.R., Liu, Y.X., 2009. Ancient earthquake records and litho-paleogeography. *Acta Sedimentologica Sinica*, 27(5), 872—879 (in Chinese with English Abstract).

Sun, S.P., Liu, Y.S., Zhong, R., Bai, Z.D., Li, J.Z., Wei, H.Q., Zhu, Q.W., 2001. Classification of pyroclastic rocks and trend of volcanic sedimentology: a review. *Acta Petrologica ET Mineralogica*, 20(3), 313—317 (in Chinese with English Abstract).

Wang, A.D., Zhou, Y.Q., Yan, H., Wang, R., Zhang, Z.K., Wang, Z.Y., 2013. Shandong Province Lingshan Island Early Cretaceous tectonic deformation characteristics of soft sediments. *Journal of Palaeogeography (Chinese Edition)*, 15(5), 718—728 (in Chinese with English Abstract).

Wang, A.D., Zhou, Y.Q., Zhang, Z.K., Yu, S.S., Wang, Z.Y., 2014. Nonfracture characteristics and significance of structure of Shandong Lingshan Island Laiyang Group under the water. *Acta Geoscientia Sinica*, 35(3), 321—328 (in Chinese with English Abstract).

Wang, G.D., Cheng, R.H., Wang, P.J., Gao, Y.F., 2010. Coniacian seismites: structure, sequence and volcanogenic origin of Qingshankou Formation in the Cretaceous Songliao Basin. *Acta Petrologica Sinica*, 26(1), 121—129 (in Chinese with English Abstract).

Xie, J.Y., 1994. Pyroclastic flow and pyroclastic flow deposits. *Volcanology and Mineral Resources*, 15(3), 53—54 (in Chinese with English Abstract).

Yang, J.P., Nie, L.L., Yang, J., 2008. Soft-sediment deformation structures of Neogene related to earthquake and its geological significance in the southwestern margin of Qaidam Basin. *Acta Sedimentologica Sinica*, 26(6), 967—974 (in Chinese with English Abstract).

Yu, S.S., 2014. *Research on the Sedimentary Facies of Late Mesozoic Rift Basin in the Offshore Area of Eastern Shandong*. Dissertation, China University of Petroleum (in Chinese with English Abstract).

Yuan, J., Chen, X., Tian, H.S., 2006. Formation of loop bedding in Jiyang sub-basin, Paleogene. *Acta Sedimentologica Sinica*, 24(5), 666—671 (in Chinese with English Abstract).

Zhao, B., 2010. *Characteristics of Pyroclastic-flow Facies in Millennium Eruption and Study on Pyroclastic-flow Hazard Zonation in Tianchi Volcano, Changbai Mountains*. Ph.D. Dissertation, Institute of Geology, China Earthquake Administration (in Chinese with English Abstract).

Zhong, J.H., 2012. Lingshan Island Mesozoic sedimentary rocks in deep water far source turbidite or continental delta deposits? A discussion with Professor Lü Hongbo.

Geological Review, 58(6), 1180—1182 (in Chinese with English Abstract).

Zhong, J.H., Ni, L.T., Shao, Z.F., Li, Y., Liu, X., Mao, C., Liu, S.X., Sun, N.L., Chen, B., Wang, K., Luo, K., Wang, S.J., Liu, C., Liu, B., Xiong, Z.Q., 2016. Tempestites and storm deposites in the Lower Cretaceous from Lingshan Island, Qingdao. *Journal of Palaeogeography (Chinese Edition)*, 18(3), 381—398 (in Chinese with English Abstract).

Zhou, Y.Q., Zhang, Z.K., Xu, H., Wang, A.D., Wei, K., Zhang, Y.C., Wang, Z.Y., Li, D., Chen, Y.Z., Liu, Y., Yu, S.S., Gao, X.J., 2015a. Soft-sediment deformation structure in the sediments at Lingshan Island. *Marine Geology Frontiers*, 31(4), 42—54 (in Chinese with English Abstract).

Zhou, Y.Q., Zhang, Z.K., Liang, W.D., Li, S., Yue, H.W., 2015b. Late Mesozoic tectono-magmatic activities and prototype basin restoration in eastern Shandong Province, China. *Earth Science Frontiers*, 22(1), 137—156 (in Chinese with English Abstract).

Zobin, V.M., 2003. *Introduction to Volcanic Seismology*. Elsevier, pp. 93—113.