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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

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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

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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

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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