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Seismically induced soft-sediment deformation structures in the Palaeogene deposits of the Liaodong Bay Depression in the Bohai Bay basin and their spatial stratigraphic distribution

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ABSTRACT

Soft-sediment deformation structures (SSDS) have been identified from well cores in the Palaeogene deposits of the Liaodong Bay Depression in the Bohai Bay basin, China. These deposits formed as interbedded sand and mud at a delta front or on the slope toe of the prodelta. According to criteria proposed by previous research, we established that these SSDS were induced by earthquakes and that they can be divided into two groups: ductile deformation structures (plastic intrusions, ball-and-pillow structures, flame structures, boudinage structures, irregular convolute stratifications, and synsedimentary faults and folds) and brittle deformation structures (sand dykes and autoclastic breccias). Based on their level of deformation, size, and complexity, the SSDS were divided into three Groups, from weak to strong, to reflect the intensity of palaeo-earthquakes. With consideration of the palaeo-sedimentary environment, we proposed a model to account for the production and preservation of these SSDS. According to the classification adopted in this study and the spatial stratigraphic distribution of the SSDS, the tectonic activities of the Tan–Lu faults in the Bohai Bay basin were investigated. The A and B oilfields (assumed names) are located in the tectonically active zones of the west and east branches of these faults, respectively. The extension tectonic activities in the A oilfield region exhibit a sharply decreasing trend from E_2s^3 to E_2s^1, and increase again in E_3d^2; whereas the strike–slip tectonic activities in the B oilfield region exhibit an increasing trend from E_2s^3 to E_2s^1, and finally, reach a maximum to E_3d^3. The results of this study show that the method of analysis of the spatial stratigraphic distribution of SSDS is suitable for determining the evolution of tectonic activity and thus, it can provide a new perspective for basin analysis.

1. Introduction

Soft-sediment deformation structures (SSDS) and well cores can provide information of depositional history and reveal aspects of basin evolution. These deformation structures can form when sediments are unconsolidated or shortly after consolidation via many processes, e.g., earthquakes, rapid deposition in slumping environments, and storm waves (Owen, 1987, 1996; Allen, 1982). Whatever the trigger mechanism, the cause of SSDS can be attributed to a decrease of shear resistance and a collapse of the grain framework (Chaney and Fang, 1991). The types and scales of SSDS depend on the intensity of the trigger mechanism, physical properties of the sediments, and sedimentary environment (Berra and Felletti, 2011). SSDS have been observed and studied in many areas in various sedimentary environments, especially lacustrine (Scott and Price, 1988; Rodríguez-Pascua et al., 2000; Galli, 2000). Because of the diversity of trigger mechanisms, it is especially important to judge their origin by the distinguishing criteria. The criteria, proposed and elucidated by Sims (1975), Owen and Moretti (2011), used to identify palaeo-earthquakes are as follows. (1) SSDS are deformed in a tectonically active basin near an active fault. (2) SSDS recur in the vertical direction, separated by undeformed beds, and develop continuously in the lateral direction. (3) The morphologies of SSDS are comparable with deformation structures confirmed from active earthquake belts. (4) SSDS occur in complex combinations. (5) Both deformed and undeformed beds develop in similar lithologies and facies (Montenat et al., 2007; Owen et al., 2011). It is necessary to exclude all other possible trigger mechanisms before SSDS can be identified as induced by earthquake. The indicator for storm-induced SSDS is the presence of typical storm deposits (hummocky cross bedding), which mainly develop in a marine basin. It is almost impossible that storm deposits could be observed in a palaeo-lake

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environment because of the shallowness and the spatial dimension (Taşgın, 2011). The presence of coarse sediments can be indicative of rapid deposition in a slumping environment. Coarse sediments mainly develop with processes of mass transport, e.g., slumping, sandy debris, and turbidites or with over-steepening of depositional slopes (Owen and Moretti, 2011; Oliveira et al., 2011; Van Loon and Pisarska-Jamrozy, 2014). Rapid sedimentation can only be preserved well where the overlying sediments are thick, massive and without grain size variation (Ghosh et al., 2010). The SSDS induced by earthquakes are seismites, which is a term proposed by Seilacher (1969) to describe layers that record palaeo-earthquake events. The theory of seismogenesis has been quoted frequently as the most appropriate for the interpretation of numerous SSDS (Alfaro et al., 2002; Jewell and Ettensohn, 2004; Bachmann and Aref, 2005; Zhang et al., 2007; Ghosh et al., 2010; Berra and Felletti, 2011; Kundu et al., 2011; Martín-Chivelet et al., 2011; Moretti and Ronchi, 2011; Van Loon and Pisarska-Jamrozy, 2014).

Various SSDS that present both as ductile and brittle deformation structures have been identified from well cores in the Palaeogene deposits of the Liaodong Bay Depression in the Bohai Bay basin (China). The characteristics of these SSDS accord with the criteria above; however, the possibility of the presence of storm or gravity deposits is discounted because of the absence of evidential indicators in study area. The absence of any evidence of hummocky cross bedding in the area excludes storm activities, and rapid deposition can be excluded because of the absence of coarse sediments, gravity flows, and the over-steepening of depositional slopes. Based on the criteria proposed by Montenat et al. (2007) and by Owen et al. (2011), it can be confirmed that the SSDS in the study area were induced by palaeo-earthquakes. In addition, analysis of their morphologies is useful in determining the mechanism of their formation. Many studies on seismites and palaeo-earthquakes have been conducted in other regions of the Bohai Bay basin, which have focused on the characteristic features of the seismites and on their development sequence (Chen et al., 2003; Yuan, 2004; Lu, 2004; Shi et al., 2009;). However, few studies have considered the characteristics of the SSDS in the Liaodong Bay Depression or discussed their trigger mechanism (Wang et al., 2008). A seismite sequence can reveal the process of an earthquake; however, it does not have the general applicability of the Bouma Sequence. This is because SSDS in different regions could have different sequences. Depending on the degree of consolidation of the deposits, seismic shock can cause different types of deformation structure, ranging from ductile to brittle. Therefore, based on the degree of liquefaction and deformation, the magnitudes and epicentres of palaeo-earthquakes can be deduced (Rodríguez-Pascua et al., 2010; Berra and Felletti, 2011; Põldsaar and Ainsaar, 2015).

The main objectives of this work are to identify typical deformation structures of the Palaeogene deposits of the Liaodong Bay Depression, analyse their sedimentary environments, and summarise their spatial stratigraphic distribution to deduce the palaeo-earthquake activity of the study area. These data and methods could be beneficial in further analyses of the tectonic evolution of the Liaodong Bay Depression and the characteristics of the tectonic activity of the basin-controlling Tan–Lu faults.

2. Study area

2.1. Geological setting

The Liaodong Bay Depression, which is a secondary tectonic unit of the Bohai Bay basin, is located in the northeast of the Bohai Bay basin in China. The Bohai Bay basin is a typical rifted basin on the North China Craton that is controlled by the Tan–Lu faults (Fig. 1a). The Liaodong Bay Depression is a deep and narrow rifted basin that has developed in alignment with the NE-trending Tan–Lu faults.

Multi-stage extensional and strike–slip fault activities have led to the special tectonic characteristics of the Liaodong Bay Depression, which consist of three uplifts and two sags. From west to east, these are arranged as the Liaoxi Sag, Liaoxi Uplift, Liaozhong Sag, Liaodong Uplift and Liaodong Sag. The Tan–Lu faults developed across the Liaoxi and Liaozhong sags in a NE direction, bifurcating into two branched faults in the Palaeogene (Fig. 1b). These branched faults are dextral slip faults that have been studied by other researchers (Xu et al., 2005; Gong et al., 2007). The western faults predominantly exhibit extensional activity, whereas the eastern faults predominantly exhibit strike–slip activity. The Liaozhong Sag has the largest sedimentary thickness of the three sags, followed by the Liaoxi and Liaodong sags. Each tectonic unit has developed in the NE direction and they are aligned parallel to each other. The tectonic evolution of the Liaodong Bay Depression in the Palaeogene was related closely to the tectonic setting of the Bohai Bay basin, and controlled by the dextral strike–slip activity of the Tan–Lu faults. The tectonic evolution can be divided into three stages: extension and rifting in the Palaeocene to middle Eocene (56–38 Ma), post-rift thermal subsidence in the late Eocene to early Oligocene (38–32.8 Ma), and strike–slip and rifting activity in the Dongying period of the Oligocene (32.8–24.6 Ma) (Zhu et al., 2008; Zhao et al., 1996) (Fig. 2).

2.2. Material and methods

The depositional characteristics of SSDS and their spatial stratigraphic distribution in the Palaeogene deposits of the Liaodong Bay Depression can be analysed based on observations and statistics of the core intervals in this area. These core intervals were obtained by the Tianjin Branch of CNOOC China Ltd. There have been 213 exploration and development wells drilled in the Liaodong Bay Depression and we used cores from 102 wells, whose intervals included Palaeogene deposits. However, of these, only 92 cores were available because some cores were destroyed or sealed by natural or human factors. Granulometry, sedimentary facies and structures were recorded in detail together with the description of SSDS. In the majority of available cores, there was no core loss. The lengths of the core intervals in the cored wells ranged from 0.86 to 143.38 m, with diameters of either 80 mm (slabbed) or 100 mm (not slabbed). Cores were split lengthwise, photographed with digital camera. Overall, over 80% of wells had core intervals of $<$40 m. The wells were distributed mainly in the Liaoxi Uplift, Liaozhong Sag, and Liaodong Uplift, and concentrated in the horizons of E_2s^3, E_2s^2, E_2s^1, E_3d^3, and E_3d^2 of the Palaeogene. SSDS were observed in 33 core intervals from 25 wells. Among these, 5 core intervals were located in E_2s^3; 7 core intervals were located in E_2s^2; 5 core intervals were located in E_2s^1; 4 core intervals were located in E_3d^3; and 12 core intervals were located in E_3d^2. The depths, horizons, sedimentary environments, and specific deformation structures of these core intervals with developed SSDS are shown in Table 1 to explain the depositional environments, trigger mechanisms, and distribution horizons of the SSDS. All the data gave significant information to analyse sedimentary characteristics of SSDS and helped deduce tectonic activities in spatial and stratigraphic aspects.

2.3. Sedimentological setting

The Palaeogene strata that (from old to new) consist of the Kongdian, Shahejie, and Dongying formations form the object of this research. The SSDS are concentrated mainly in the Shahejie and Dongying formations. The strata of the Shahejie Fm. can be divided into E_2s^4, E_2s^3, E_2s^2 , and E_2s^1 and the strata of the Dongying Fm. can be divided into E_3d^3, E_3d^2 , and E_3d^1 (Fig. 2).

The sedimentary deposits of E_{1-2} k to E_2s^4 are small-sized lacustrine facies and alluvial fan facies, the main lithologies of which are mudstone and carbonatite, formed in the early chasmic stage of the basin under a dry climatic background (Zhu et al., 2008). The shale or mudstone lithologies of E_2s^3 are lacustrine facies that formed in the centre of the lake basin. In addition, fan-delta and near-bank submerged alluvial fan deposits are developed on the edge of the lake basin (Dong et al.,