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Soft-sediment deformation structures in Cambrian siliciclastic and carbonate storm deposits (Shandong Province, China): Differential liquefaction and fluidization triggered by storm-wave loading

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ABSTRACT

This paper focuses on soft-sediment deformation structures (SSDS) in both siliciclastic and carbonate storm deposits of the Cambrian Mantou and Chaomidian formations (Shandong Province, China) in order to understand their deformation mechanisms and possible triggers. Siliciclastic SSDS (e.g., sand volcanoes and pillows) and carbonate SSDS (e.g., sedimentary dykes, grainstone-matrix breccias, deformed cross-beddings, and marlstone-matrix breccias) occur exclusively in hummocky cross-stratified fine sandstone and peloidal grainstone, respectively. The siliciclastic SSDS formed in porous and permeable surface sediment, whereas the carbonate SSDS formed under shallow burial conditions when early marine cementation prevailed. The various deformation structures resulted mainly from differences between siliciclastic and carbonate sediment conditions and resulting deformation mechanisms. Sand volcanoes formed by upward extrusion of over-pressured fluidized sandy sediment, whereas sand pillows resulted from upward injection of lower density muddy sediment into overlying liquefied sandy sediment. Sedimentary dykes and grainstone-matrix limestone breccias formed as a result of differential liquefaction and fluidization of heterogeneously cemented carbonate sediment, whereas deformed cross-beddings and marlstone-matrix limestone breccias developed by the thixotropic liquidization and injection of clayey sediment, and further disruption of thin peloidal layers. Sedimentary facies analysis and analysis of the physical processes indicate that the SSDS were most likely caused by cyclic loading of storm waves.

1. Introduction

Soft-sediment deformation structures (SSDS) commonly form in unconsolidated to semi-consolidated sediment during deposition, or shortly after burial (Lowe, 1975; Mills, 1983; Owen, 1992; Van Loon, 2009). For soft-sediment deformation to occur, two requisite conditions must be satisfied (Allen, 1986; Rodríguez-López et al., 2007; Owen and Moretti, 2011; Owen et al., 2011): (1) sediment must be susceptible to deformation, and (2) a triggering mechanism initiates deformation. Sediment conditions (e.g., porosity, permeability, and cohesion), which are dependent on sediment composition and texture, sedimentation rate, compaction, and early cementation, determine rheological behavior and thus deformation mechanisms (e.g., liquefaction of granular non-cohesive sediment vs. thixotropy of fine-grained cohesive sediment) (e.g., Obermeier, 1996; Jones and Omoto, 2000; Rodríguez-López et al., 2007). In addition, early-diagenetic processes are fundamental to induce different kinds of SSDS in siliciclastic and carbonate sediment. For example, load structures (e.g., ball-and-pillow features) occur frequently in siliciclastic deposits (e.g., Mills, 1983; Molina et al., 1998; Moretti et al., 2001; Alfaro et al., 2002; Owen and Moretti, 2008; Ghosh et al., 2012), whereas the presence of breccia can be the main sedimentary record of deformation processes in carbonate susceptible to rapid cementation (Spalletta and Vai, 1984; Bouchette et al., 2001; Chough et al., 2001; Kahle, 2002; Kwon et al., 2002; Myrow et al., 2004; Chen et al., 2009a,b, 2011; Ettensohn et al., 2011).

There are in nature a number of triggers, either endogenic (e.g., rapid deposition, storm waves, tsunamis, and tides) or exogenic (e.g., earthquakes, impacts, and sea-level fluctuations) in origin (Owen, 1996; Spence and Tucker, 1997; Rossetti, 1999; Bouchette et al., 2001; Kullberg et al., 2001; Alfaro et al., 2002; Moretti and Sabato, 2007; Singh and Jain, 2007; Chen et al., 2009a,b; Van Loon, 2009; Chen et al., 2011; Owen et al., 2011). Among these, earthquakes have been the popular trigger for most of the reported SSDS, in spite of the fact that the criteria and evidence are not diagnostic (Sims, 1975; Wheeler, 2002; Owen et al., 2011). Other potential triggers are difficult to interpret, and may be misidentified due to the lack of specific diagnostic sedimentary features and inconclusive evidence (cf. Li et al.,

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1996; Alfaro et al., 2002; Greb and Archer, 2007; Moretti and Sabato, 2007).

We report herein the common and exclusive occurrence of various SSDS from both siliciclastic and carbonate storm deposits (e.g., hummocky cross-stratified fine sandstone and peloidal grainstone) of the Cambrian Mantou and Chaomidian formations, Shandong Province, China. The Chaomidian limestone breccias that show similar features to those described herein have been the subject of several previous publications (Chen et al., 2009a,b, 2010; Van Loon et al., in press). Chen et al. (2009a, 2010) first described limestone breccias with vertically oriented clasts and ascribed their origin to intrastratal soft-sediment deformation (brecciation and mobilization) of fine-grained ribbon rocks. Van Loon et al. (in press) revisited some of these breccias and concluded that the vertically oriented clasts formed by upward escape of underlying liquefied sediments despite a lack of evidence of liquefaction in the bed below the breccias. Chen et al. (2009b) also reported some unique funnel-shaped, breccia-filled sedimentary dykes, which can be a common phenomenon of carbonate SSDS. All of the previously published papers failed, however, to demonstrate a direct relationship between the deformation structures and a specific trigger mechanism. In this paper, we illustrate a clear example of SSDS for which storm waves as a trigger can be interpreted in a reliable way, and also demonstrate different deformation mechanisms and resultant SSDS in both siliciclastic and carbonate sediment induced by a single trigger. This paper provides a potential test for the standard procedure of SSDS studies recently suggested by Owen et al. (2011), i.e., “combining the assessment of facies, potential triggers, and available criteria”.

2. Geological setting

The North China Block (i.e., Sino–Korean Block) was tectonically stable and drifted northward near the equator during the Paleozoic. The block is bound to the south by the Qinling–Dabieshan fold belt, and to the east by the Tanlu fault, which formed during collision with the South China Block in the Early Triassic (Chough et al., 2000) (Fig. 1). A vast epeiric sea (North China Platform, ca. 1000 km north–south and 1500 km west–east) formed on the North China Block during the Early Paleozoic in subtropical regions as a result of a second order sea-level rise (Scotese and McKerrow, 1990; Meng et al., 1997; Kwon et al., 2006; Chough et al., 2010; McKenzie et al., 2011). Mixed siliciclastic and carbonate, shallow-marine environments formed within the epeiric sea by initial flooding over the irregular basement, and later evolved into a carbonate-dominant setting (Chen et al., 2011, 2012; Lee and Chough, 2011).

The Cambrian succession in Shandong (eastern China) consists of six lithostratigraphic units (i.e., Liguan, Zhushadong, Mantou, Zhangxia, Gushan, and Chaomidian formations in ascending order) (Fig. 2). The Cambrian strata unconformably overlie Precambrian granitic gneiss and metasedimentary rocks and, are conformably overlain by the Ordovician Sanshanzi Formation (Zhang et al., 1994; Chough et al., 2010). The basal Cambrian unit, the Liguan Formation (laterally discontinuous, 0–30 m thick), consists mainly of quartzose sandstone and mudstone. The Zhushadong Formation (15–40 m thick) is dominated by stromatolitic and dolomitic lime mudstone, and locally also contains bioturbated wackestone. The Mantou Formation (ca. 250 m thick) consists of mixed siliciclastic and carbonate strata including purple mudstone, sandstone, and various carbonate lithologies. The Zhangxia Formation (ca. 180 m thick) is characterized by a variety of microbialites and carbonate lithologies, as well as shale in the middle of the formation. The Gushan Formation (52–105 m thick) is dominated by shale facies, and the overlying Chaomidian Formation (190–260 m thick) by various carbonate facies.

3. Sedimentary facies

The SSDS are well exposed in four sections in Shandong (Jiulongshan, Dacangshan, Liangcheng, and Wanglaoding sections) (Fig. 1). Sedimentary logs were made in detail (scale of 1:50) for illustration of SSDS and associated sedimentary facies (Fig. 3). The SSDS occur exclusively in the storm deposits from the upper part of the Mantou Formation (Cambrian Series 3) and the middle part of the Chaomidian Formation (Furongian) (Figs. 2 and 3).

3.1. Upper part of the Mantou Formation

The upper part of the Mantou Formation consists dominantly of interbedded dark purple mudstone and sandstone (facies M–S),

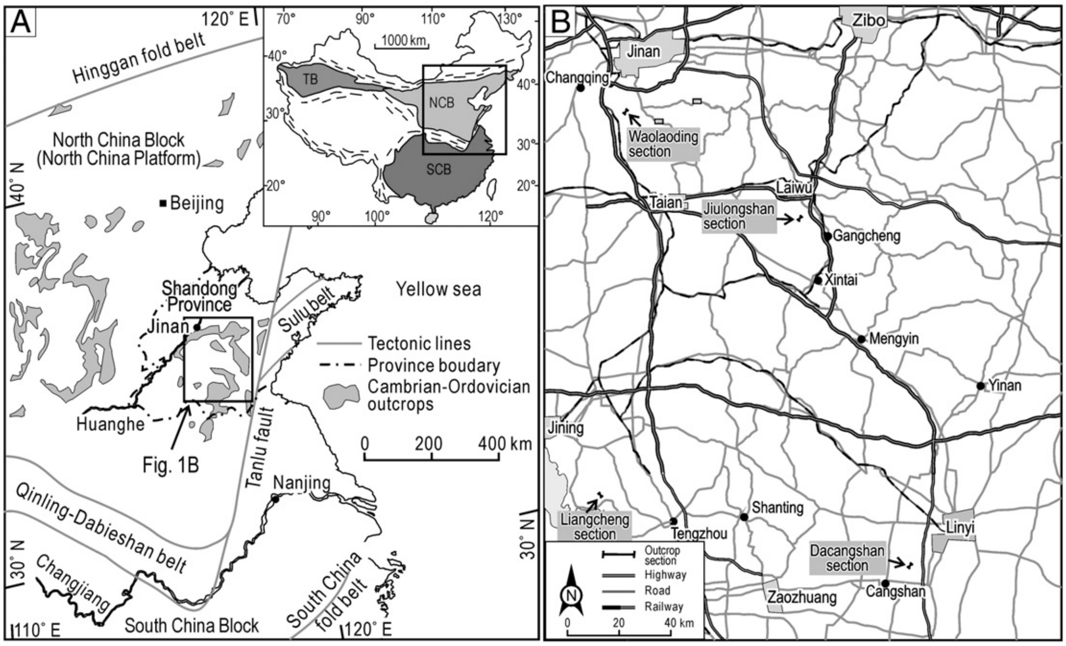

Fig. 1. A. Major tectonic boundaries of the North China Platform and distribution of the Cambrian–Ordovician outcrops. NCB: North China Block, SCB: South China Block, TB: Tarim Block. B. Location map of the studied outcrop sections. For detailed geological maps of the outcrop sections, see Chough et al. (2010) and Lee and Chough (2011).