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Soft-sediment deformation structures induced by strong earthquakes in southern Siberia and their paleoseismic significance

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ABSTRACT

Liquefaction-induced soft-sediment deformation structures (SSDS) formed by earthquakes in southern Siberia, that were historically mentioned or monitored by instruments, are described and analyzed. Clastic dikes are the most common among all SSDS in the epicentral areas of the investigated seismic events. They are also the most reliable paleoseismic indicators in regions where cryogenic processes are intense. We suggest seven criteria that may be useful to distinguish the seismogenic clastic dikes from non-seismogenic SSDS in a single outcrop: (1) pushed up sedimentary blocks within the dike body; (2) regular distorted contacts of a dike with host sediments, reflecting cyclic loading during propagation of seismic waves; (3) turned up layers of host deposits on contacts with a dike; (4) displacement along dike contacts usually in the form of a normal fault caused by subsidence that compensates for the removed sediment; (5) a dike structure similar to a diapir; (6) filling of a clasic dike with coarser materials than the host sediments; and (7) a sediment layer extruded on the surface or between strata, similar in composition to the dike. In the extruded sandy-gravel-pebble layer, rock fragments show normal grading (from large to small clasts). In addition to these indicators, fractures may indirectly indicate the seismogenic genesis of liquefaction-induced SSDS. Due to the close spatial relationship of dikes with the fault structures of the investigated areas, they can be used to identify seismogenic fault, and the characteristics of dikes (lateral gradual changes in the frequency, size, and type of the deformations) can help to determine the epicenter, magnitude and the local intensity of the associated earthquakes.

1. Introduction

Southern Siberia is a mountainous area with alternating ridges and basins in which the Altai–Sayan and the Sayan–Baikal fold belts have the highest present-day seismic activity (Fig. 1). During 1950–2014, this area experienced more than a hundred earthquakes with magnitudes $M \geq 5$. The maximum value north-east of Lake Baikal is $M = 7.6$ and $M = 8.1$ in neighboring Mongolia. Regardless of their focal mechanisms illustrating mainly tension and transtension in the Baikal region and strike-slip and transpression in the Altai–Sayan fold belt, a significant portion of the seismic events caused ground liquefaction (Andreev and Lunina, 2013). In this sense, the territory of southern Siberia is a huge natural laboratory where there is potential to study the liquefaction-induced soft-sediment deformation structures (SSDS) triggered by recent earthquakes.

Until recently, paleoseismic studies in southern Siberia were solely based on rupture mapping (e.g., Smekalin et al., 2010). Despite the widespread development of unconsolidated deposits in the intermountain basins that are favourable for seismic liquefaction, as well as numerous worldwide publications on the research topic (Anand and Jain, 1987; Mohidra and Bagati, 1996; Obermeier, 1996, 1998, 2009; Blanc et al., 1998; Alfaro et al., 2001; Tuttle et al., 2002; Mazumder et al., 2006; Chunga et al., 2007; Moretti and Sabato, 2007; Pandey et al., 2009; Berra and Felletti, 2011; Gibert et al., 2011; Moretti and Ronchi, 2011; Moretti et al., 2011; Suter et al., 2011; Van Loon and Maulik, 2011), investigations of seismogenic SSDS in southern Siberia began relatively recently (Gladkov et al., 2005; Deev et al., 2009, 2013; Lunina et al., 2009, 2012a, 2012b; Gladkov and Lunina, 2010). Hitherto, all seismogenic SSDS were attributed to cryogenic deformation structures.

Since 2002, when studying the active faults in the Baikal region, we constantly observed SSDS, some of which were associated with paleoearthquakes (Gladkov et al., 2005). However, further investigations have shown that the existing criteria to identify the seismogenic genesis of the structures (Seilacher, 1969, 1984, 1991; Obermeier, 1996; Rossetti, 1999; Ettensohn et al., 2002; Greb and Dever, 2002; Montenat et al., 2007) are not always applicable to southern Siberia (Gladkov and Lunina, 2010), which is characterized by seasonal freezing and thawing of the ground. In addition, the region underwent climate warming 3600–2600 years ago (Alexeev et al., 2014). As a result, pseudomorphs, cryoturbation, wedge structures, involutions, drop- and mushroom-shaped sinkages, and domes formed. Some of them resemble the seismogenic deformation structures that have been described in

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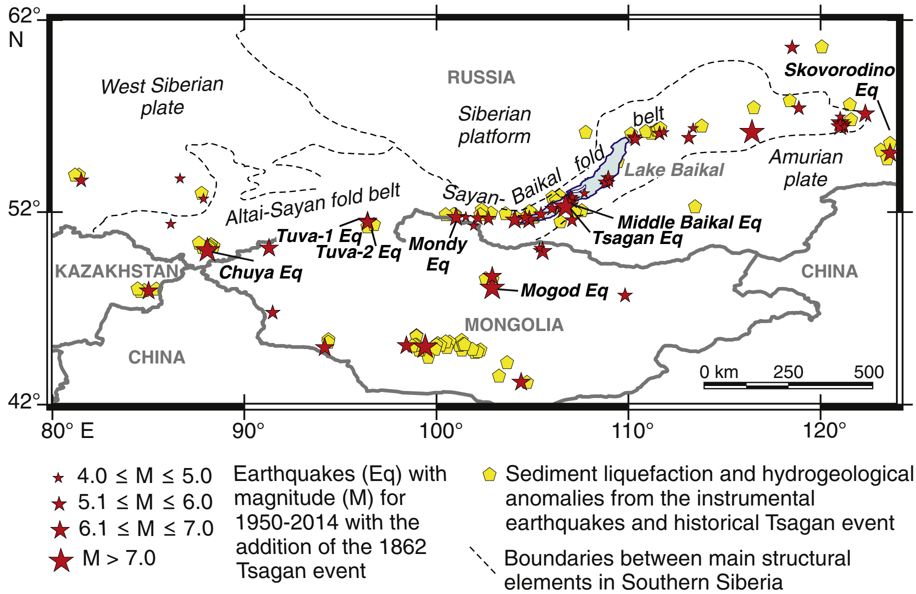

Fig. 1. Present-day earthquakes that produced sediment liquefaction and hydrogeological anomalies in southern Siberia and the surrounding area.

the literature (Alfaro et al., 1997; Montenat et al., 2007) and/or can involve them. Other researchers have also noted that most criteria for a seismic trigger are not diagnostic or are unreliable (Owen et al., 2011). Owen and Moretti (2011) showed that just a few of them applied to seismic triggers are indicative and several are not applicable on the scale of single outcrops.

Nevertheless, the research of seismically induced SSDS is very important for both southern Siberia and other regions characterized by a wide assortment of unconsolidated sediments and a short record of earthquakes. For example, the duration of the historical period in the seismic studies of east Siberia lasted from the late 17th century to the early 20th century (Radziminovich and Shchetnikov, 2013). In the meantime, some investigations have demonstrated that soft-sediment deformation indicates not only a seismic area but can also apply to the estimation of earthquake parameters such as the epicenter location, magnitude, and macroseismic intensity (Green et al., 2005; Obermeier et al., 2005; Rodríguez-Pascua et al., 2010; Lunina et al., 2011, 2012a, 2012b; Lunina and Gladkov, 2015). Using specialist approaches together with dating of deformed sediments significantly extends the timeframe for our knowledge of seismicity compared to historical records (the list of earthquakes occurring before routine instrumental recording) and instrumental records (since 1950 in southern Siberia). However, the unambiguous discerning of the seismogenic genesis of SSDS is the first important task for a paleoseismic investigation. Study of deformations seismically induced by instrumental and historical earthquakes makes a significant contribution to the solution of the problems discussed above (Audemard and de Santis, 1991; Clague et al., 1992; Nakajima and Kanai, 2000; Sims and Garvin, 1995; Obermeier, 1996, 2009), but such works are rare.

Here we describe liquefaction-induced soft-sediment deformation structures, mainly clastic dikes, formed during recent earthquakes in southern Siberia in order to define criteria for identification of seismogenic deformation developed under cryogenic conditions in seismically active regions with poor exposure. Then we give a short review of the approaches that can be useful to locate and evaluate parameters of the seismogenic source based on study of clastic dikes.

2. Earthquake-triggered liquefaction in southern Siberia and surroundings

We compiled a geohazard database, operated within the GIS MapInfo Professional 10.0 system "Active Tectonics," which is a module for storage, visualization, and analysis of information on earthquakes and related coseismic effects, including hydrogeological anomalies, soil liquefaction, surface rupture, slope instability, soil subsidence, and other phenomena (Andreev and Lunina, 2013; Lunina et al., 2014). The database has been populated with our own data, as well as data reported in earthquake catalogs and with published evidence. According to the database, 57 earthquakes, producing different environmental effects, occurred in the period of 1950–2014 in southern Siberia and adjacent areas of Mongolia and Kazakhstan (Fig. 1). Thirty of these earthquakes are known to have caused soil liquefaction and hydrogeological anomalies. Unfortunately, macroseismic descriptions of the effects of the majority of these seismic events only point to liquefaction in epicentral areas. Just a few clastic dikes associated with the January 5, 1967, Mogod (Ms = 7.8) earthquake and the August 29, 1959, Middle Baikal (Ms = 6.8) earthquake were exposed in the sections. Cracks, from which the sand erupted in the river valleys, were documented for three more events: the October 16, 2011, Skovorodino (Ms = 6.1), the December 27, 2011, Tuva-1 (Ms = 6.7) and the February 26, 2012, Tuva-2 (Ms = 6.8) earthquakes.

The September 27, 2003, Chuya earthquake (Ms = 7.5) that affected the Gorny Altai is one of the remarkable seismic events (Figs. 1, 2A) during which widespread outpouring of sand and sandy-boulder-pebble sediments took place in the valleys (Rogozhin et al., 2007). The epicentral intensity of the earthquake was valued at IX–X degrees on the MSK-64 macroseismic intensity scale, the depth was 18 km, and the focal mechanism was strike-slip due to the movement along the North-Chuya fault (Shitov, 2004). Liquefaction marks were visible on the surface (Fig. 2B–E) after the seismic event, and for this reason, we selected the epicentral area as one of the testing sites for the study of soft-sediment deformation structures, which will be the focus of this article.

The April 4, 1950, Mondy earthquake (Ms = 7.0), with an intensity of IX at the epicenter, 14 km depth and strike-slip focal mechanism (Delouis et al., 2002; Baikal Branch of the Geophysical Survey), happened in the Mondy fault zone and was also a perceptible event in southern East Siberia (Fig. 1), but a macroseismic survey in 1950 did not reveal ground liquefaction (Treskov and Florensov, 1952). Nevertheless, when studying the seismogenic deformation of this event (Lunina et al., 2015), we found evidence for SSDS, which will be presented below.

The January 12, 1862, Thagan earthquakes (M ~ 7.4–7.5) that occurred on the Delta normal fault on the eastern shore of Lake Baikal