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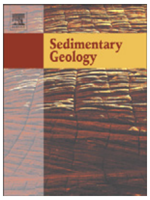

The environmental significance of soft-sediment deformation structures: key signatures for sedimentary and tectonic processes

Soft-sediment deformation occurs in unconsolidated sediment during or shortly after deposition, and before significant diagenesis (Allen, 1982): soft-sediment deformation structures (SSDSs) are strongly influenced by the sedimentary environment since they usually occur at surface or close to it, where sedimentary processes physically interact with unconsolidated sediments (currents, waves, mass movements, etc.).

For these reasons, physical deformation of soft-sediments is a reference chapter in many books on sedimentology. The pioneer works of Shrock (1948), Potter and Pettijohn (1963), Pettijohn and Potter (1964), Dzulynski and Walton (1965) and Selley (1969) already recognize the SSDSs as an important class of sedimentary structures. Later, Allen (1970), Picard and High (1973), Reineck and Singh (1980), Leeder (1982), Allen (1982) and Lindholm (1987) establish useful classifications and discuss the mechanisms of deformation in depth. More recently, Demicco and Hardie (1994), Miall (2000), Tucker (2003), Bridge and Demicco (2008), Collinson et al. (2006), as well as Stow (2010) compile interesting chapters of their sedimentology books summarizing the extensive specific literature and offering an overview of the processes of soft-sediment deformation. On the other hand, the relevance of the SSDSs is underlined by the publication of several special issues and books that are focused on this only topic (Jones and Preston, 1987; Maltman, 1994; Maltman et al., 2000; Shiki et al., 2000; Ettensohn et al., 2002; Van Rensbergen et al., 2003; Storti and Vannucchi, 2007; Owen et al., 2011; Festa et al., 2014; van Loon, 2014).

Moreover, the specific literature contains some fundamental papers that set the scientific basis for the modern knowledge on SSDSs and in particular: - the compilation of rational classifications made up by Nagtegaal (1965), Lowe (1975), Allen (1982), Owen (1987), van Loon (2009), Owen et al. (2011); - the analogic models and experiments of Rettger (1935), Kuenen (1958), McKee et al. (1962a, b), McKee and Goldberg (1969), Anketell et al. (1970), Tsuji and Miyata (1987), Nichols et al. (1994), Owen (1996), Moretti et al. (1999), Frey et al. (2009) and Ross et al. (2011); - the procedures to establish the mechanisms of deformation (Allen, 1982; Nichols, 1995; Owen and Moretti, 2011) and the driving force systems (Owen, 1987); - the methods to correctly interpret the trigger agents, following multiple stage approaches (Jones and Omoto, 2000; Owen et al., 2011).

This Special Issue is intended to fill the knowledge gap related with the lack of studies focused on the complex relationships between the soft-sediment deformation occurrence and the sedimentary environments in which the deformation develops. The water-saturated soft-sediments are able to record the frequent, ordinary authigenic sedimentary processes that are very interesting for sedimentological purposes: overloading, unequal loading, cyclic or impulsive effect of storm-waves, sudden variations of the groundwater table, slump and slide along more or less steep slopes, etc. The sedimentary environments are also fundamental for the occurrence of SSDSs with an allogenic trigger (as for the seismically-induced SSDSs - seismites). In fact the sedimentary environments can be considered as the place in which liquefaction and fluidization take place during the seismic shocks and which deeply influence their local effects. SSDSs can be considered as a virtually continuous record of the sedimentary and tectonic processes that occur in the poorly-known time interval between deposition and diagenesis.

Influence of the sedimentary environment on soft-sediment deformation

Soft-sediment deformation occurs when geological processes are able to trigger certain deformation mechanisms (mostly liquefaction and/or fluidization). In this case, deformation can be recognized in the geological record when a driving force system is active after the loss of shear strength of the water-saturated sediments (Owen, 1987). The occurrence of SSDSs is thus limited by the (almost) simultaneous presence of the following conditions: 1) soft-sediments; 2) a fluid (water-gas) saturation condition; 3) a high susceptibility to liquefaction/fluidization (which is a function of grain-size, relative density, porosity, matrix content, etc.); 4) presence of a driving force system (like an unstable density gradient, an unequal loading, etc.); 5) a trigger mechanism with magnitude and duration thatare able to induce liquefaction/fluidization. Despite this need of a large number of (almost) coexisting conditions, the SSDSs seem to be ubiquitous, being widespread in every sedimentary environment.

Every sedimentary environment has typical sedimentary features and different conditions of fluid saturation, leading to a great variability in the morphologies of the soft-sediment deformation structures. For example, cross-laminated eolian dunes, after deformation, can result in sedimentary bodies with contorted lamination, recumbent-folds, etc., while sandy-silty alternations in proximal lacustrine facies are related to load-structures.

Every sedimentary environment is subject to a particular kind of trigger mechanism: for example, turbiditic deposits can show load-structures related to overloading processes, while shallow-water sediments are subject to ordinary liquefaction effects related to the action of storm waves. Another typical example comes from the lacustrine basins that have the ideal conditions to record the allogenic processes (like seismic shocks) being characterized almost by low sedimentation rates and weak hydrodynamic processes; nevertheless, wave action (Martel and Gibling, 1993) and overloading processes (Ezquerro et al., 2015) are often not negligible. Since every trigger mechanism has a different

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magnitude and frequency, the possibility that a trigger mechanism will leave a recognizable trace in the geological record is a question very similar to the problem of the potential of preservation of other sedimentary structures. In other words, seismic shocks can induce liquefaction in beach environments, but it is very probable that wave-action (Dalrymple, 1979), tidal processes (Greb and Archer, 2007) and, more rarely, synsedimentary karstic action (Moretti et al., 2011) will easily obliterate the seismic liquefaction effects; conversely, foredune and lagoonal (Alfaro et al., 1999; Moretti et al., 2002) and inner platform carbonate areas (Mastrogiacomo et al., 2012) are coastal sectors that are more prone to record seismic trigger agents.

Contributions of the Special Issue

The authors of the 26 papers of this Special Issue have been asked to focus their interpretations on the relationships between the occurrence of soft-sediment deformation and the processes that were active in the surrounding sedimentary environments. This Special Issue contains a large variety of examples of soft-sediment deformation covering almost the all the sedimentary environments. We have placed the twenty-six scientific contributions in an order based on their environmental occurrence: that is, we will summarize them starting with continental and finishing with marine environments.

Some papers describe the occurrence of SSDSs in a variety of continental environments.

The paleoseismicity of a southern Siberia area is evaluated by Lunina and Gladkov (2016) taking into account the seismically-induced SSDSs recognized in different Quaternary continental deposits. Criteria to distinguish seismic from not seismic liquefaction features are suggested. Weathley et al. (2016) describe the occurrence of seismically-induced clastic pipes in the Colorado Plateau (SW USA) in Phanerozoic successions deposited in eolian (especially interdune), sabkha, and fluvial environments tracing the tectonic evolution of this area.

A single contribution is devoted to the description of SSDSs in an “anthropic” continental environment. Rodríguez-Pascua et al. (2016) describe the effects of earthquakes on some anthropic structures (foundations, cisterns, graves, etc.) of the Roman city of Complutum (Alcalá de Henares, central Spain). This kind of Earthquake Archaeological Effects (EAEs) is special liquefaction structures with an important historical seismic significance.

Two contributions are devoted to the SSDSs that characterize glacial and sub-glacial environments.

Gruszka et al. (2016) describe some spectacular giant-load-casts in glacial and periglacial deposits. These SSDSs are interpreted as the result of differential overburden conditions during the retreating and re-advancing ice processes. The role of the seismic activity related with the glacial isostatic adjustment is also discussed. Menzies et al. (2016) report different microstructures in subglacial tills. They are described as a continuum of morphologies and interpreted as the result of variable strain stages. The role of clay content and pore water conditions is discussed as well.

The largest number of contributions is related to the lacustrine environments.

Alsop et al. (2016) describe the occurrence of various kinds of seismically-induced slump sheets in (Late Pleistocene) lacustrine deposits. The role of the lateral changes of the lacustrine facies (from detrital alluvial to the depocentral units) for the final morphology of the slumped bodies is discussed in detail. Ezquerro et al. (2016) calculate an apparent period of recurrence for the earthquakes related with a single fault zone using deformed beds in Plio-Pleistocene palustrine and lacustrine deposits. In Gladkov et al. (2016), the occurrence of deformed beds in late Pleistocene lacustrine deposits is used to evaluate the seismicity of the Tien Shan Range, an active intracontinental mountain belt in Central Asia. Jiang et al. (2016) describe several deformed beds in late Pleistocene lacustrine deposits (eastern Tibetan Plateau) improving the paleoseismic record of the eastern Tibetan Plateau area. Different morphologies of the seismically-induced SSDSs are associated with variable paleomagnitude of the earthquakes. Seismically-induced SSDSs in Holocene lacustrine deposits are described by Onorato et al. (2016) in order to assess the paleoseismic record of the activity of the Magallanes–Fagnano Fault System (southern Argentina). Snyder and Waldron (2016) report SSDSs with some unusual morphological features in a fluvio-lacustrine succession suggesting a possible seismic origin. Sherrod et al. (2016) describe the subsurface morphology of fluid-escape structures in the Lake Powell delta using electrical resistivity tomography (ERT) and ground-penetrating radar (GPR) methods. Finally, the occurrence of seismically-induced SSDSs in an Eocene lacustrine succession (Wyoming) is described by Törő and Pratt (2016). The deformed intervals seem to record distinct stages in the sedimentary evolution of this continental basin in response to syndepositional tectonic activity.

The SSDSs in eolian environments are described in three papers.

Bryant et al. (2016) delineate the deformational history of the spectacular contorted beds of the (Lower Jurassic) Navajo Sandstone in terms of different phases of hydrological setting and water-saturation conditions of these eolianites. In the same Formation, the unusual geometry of some slump features in the lee-side of an eolian dune is interpreted by Ford et al. (2016) in terms of lateral facies changes in dune and interdune sub-environments. Finally, a large variety of seismically-induced SSDSs is described in Pliocene continental deposits of the Teruel Basin (SE Spain) by Liesa et al. (2016). The morphological variability of the seismites is interpreted in terms of lateral facies changes (eolian to alluvial environments).

Two contributions are focused on fluvial environments.

Hilbert-Wolf et al. (2016) describe SSDSs in Cretaceous braided deposits (SW Tanzania) interpreting them as gas-escape structures which are genetically related with seismic-shocks. Rana et al. (2016) report SSDSs in Late Pleistocene – Holocene fluvial deposits. They show reliable relationships between every type of SSDSs, the facies involved in the deformation and the overloading processes.

The SSDSs in marine deposits are depicted in eight papers related with shallow to deep-sea environments.

Chiarella et al. (2016) interpret recumbent folds and deformed cross-laminations in tidally dominated sandy deposits (Early Pleistocene) as the result of overloading processes during the migration of 2D and 3D dunes. A marine geology approach is used by Kopf et al. (2016) to study the submarine Nice slope (NW Mediterranean Sea). Data derived from the geotechnical characterization of the sediments involved in the 1979 slope failure are used to establish the vulnerability of the submarine area close to Nice airport. Basilone et al. (2016) describe rotational (slump) and translational (glide) slides in (Upper Triassic) carbonate pelagic deposits interpreting the SSDSs as the record of a paleoslope affected by synsedimentary tectonics and seismic shocks. A large variety of SSDSs is described in a Mio-Pliocene deep-sea succession by Mazumder et al. (2016). The supposed trigger mechanism is related with seismic shocks. The occurrence of coarse-grained extrudites and injectites in upper Pliocene fine-grained deep-water sedimentary succession is interpreted by Ito et al. (2016) as the result of two combined trigger mechanisms: seepage of coal methane-bearing water and seismic shaking. Ortner and Kilian (2016) describe the