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Multi-origin of soft-sediment deformation structures and seismites

The seismite problem

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Abstract During a period of 82 years (1931—2013), 39 genetic terms were introduced for various deposits. Of the 39 terms, only ten are meaningful in understanding the true depositional origin (*e.g.*, turbidites), the remaining 29 are just jargons (*e.g.*, seismites, tsunamites, *etc.*). The genetic term "seismites", introduced by Seilacher (1969) for recognizing palaeoearthquakes in the sedimentary record, is a misnomer. The term was introduced in haste, based on an examination of a single exposure of the Miocene Monterey Formation (10 m) in California, without a rigorous scientific analysis. The fundamental problem is that earthquake is a triggering mechanism, not a depositional process. Type of triggers cannot be recognized in the ancient sedimentary record because evidence for triggers is not preserved by nature. Soft-sediment deformation structures (SSDS), commonly used as the criteria for interpreting seismites, are a product of liquefaction. However, liquefaction can be induced by any one of 21 triggers, which include earthquakes, meteorite impacts, tsunamis, sediment loading, among others. Brecciated clasts, typically associated with earthquake-induced deposits in the Dead Sea Basin, are also common depositional products of debris flows (*i.e.*, synsedimentary product unrelated to earthquakes). Also, various types of SSDS, such as duplex-like structures and clastic injections, can be explained by synsedimentary processes unrelated to earthquakes. Case studies of sandstone petroleum reservoirs worldwide, which include Gulf of Mexico, North Sea, Norwegian Sea, Nigeria, Equatorial Guinea, Gabon, and Bay of Bengal, reveal that there is compelling empirical evidence for sediment loading being the primary cause of SSDS. The Krishna—Godavari Basin, located on the eastern continental margin of India, is ideal for sediment failures by multiple triggering mechanisms where overpressure and liquefaction have led to multi-origin SSDS. Because tsunamis and meteorite impacts are important phenomena in developing extensive deposits, lateral extent of SSDS cannot be used as a unique distinguishing attribute of earthquakes. For these reasons, the genetic term "seismites", which has no redeemable scientific value, is obsolete.

Keywords Soft-sediment deformation structures (SSDS), Seismites, Earthquakes, Meteorite impacts, Liquefaction, Clastic injections

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1. Introduction

Logan (1863) was one of the early workers who accurately sketched the complexity of soft-sediment deformation structures (SSDS), which include slump folds in Devonian limestones exposed in the Gaspé Peninsula of Quebec, Canada. The significance of his observation is that localized deformed beds occur within otherwise undeformed beds (Fig. 1). This sandwiched occurrence of folded layers between undeformed layers is the underpinning principle of SSDS. In a detailed study of slump folds in the Upper Ordovician flysch of Newfoundland Appalachians, Canada, Helwig (1970, p.172) attributed the origin of slump folds to early deformation, but cautions that "*A strict distinction between sedimentary and tectonic structures seems unrealistic because the close relationship of tectonics and sedimentation in mobile belts assures widespread prelithification deformation*". Perhaps for this reason, the origin of soft-sediment deformation has long been a point of contention (Maltman, 1984, 1994a, 1994b).

Kirkland and Anderson (1970) were the first to describe some spectacular microfolds in the anhydrite—calcite layers of the Castile Formation of Permian Age in the Delaware Basin, New Mexico and Texas. The significance of their study is that they utilized not only outcrops but also subsurface cores (Fig. 2), taken specifically for research purposes, funded by the National Science Foundation (USA). Kirkland and Anderson (1970) attributed the origin of microfolds to tectonism. The meter-scale folds on each side of the basin intermittently slumped. In the process, the millimeter-scale microfolds formed in the interior of the larger folds. As the folds formed there was a room problem in the center of the larger folds, which caused the microfolding to occur (Fig. 2). It is worth noting that anhydrite layers may behave differently than those of clastic rocks due to differences in their plasticity during deformation. In further explaining the origin of Castile microfolds, Alexander and Watkinson (1989, p. 750) state that "*In conclusion, we envisage the tectonic scenario for the Castile folds as multilayer buckling with stress concentrations in the hinge zones of the larger-scale folds causing increased strain rates and initiation of buckle-folded layers between stabilized layers, both thicker and thinner than the folded layers*". These authors dealt with the origin of microfolds strictly as a structural geology problem.

On the other hand, the Castile microfolds are attractive candidates for classifying them as "seismites" for two reasons. First, the Castile microfolds are sandwiched between undeformed layers (Fig. 2), which is a major criterion for recognizing seismites (Seilacher, 1969). Second, discrete units of Castile microfolds were correlated over a distance of 113 km (Kirkland and Anderson, 1970; Kirkland *et al.*, 2000), which is another criterion for recognizing seismites (Sims, 1975). The seismic origin, however, suffers because it is difficult to explain as to why seismic

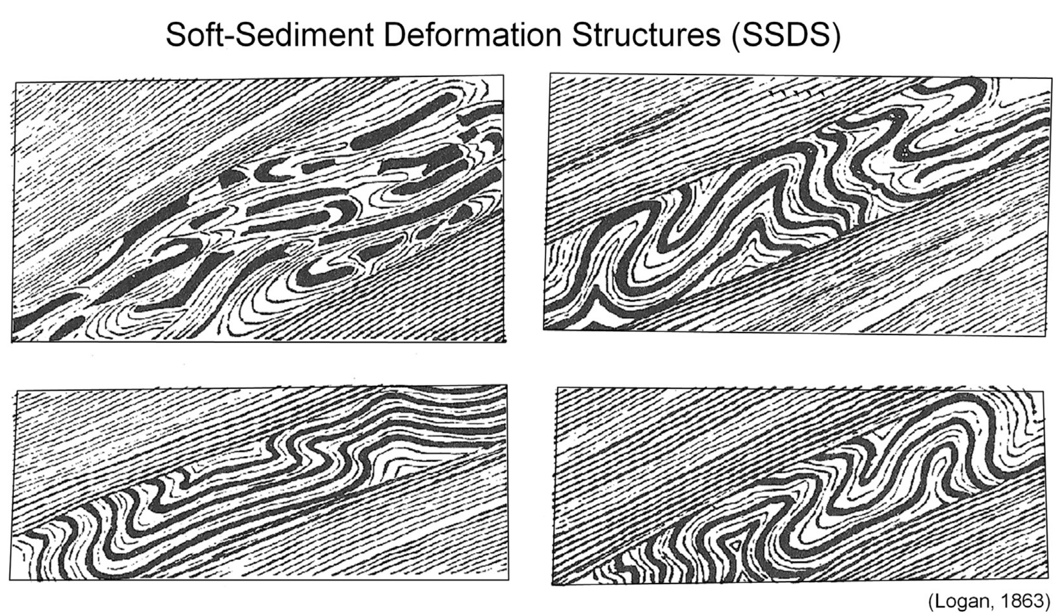

Fig. 1 Detailed sketches by Sir William Edmond Logan of localized deformed beds within otherwise undeformed Devonian limestones, Gaspé Peninsula, Quebec, Canada (Logan, 1863). Such deformed beds are commonly called "Soft-sediment deformation structures" (SSDS). Diagram reproduced from Maltman (1994a).