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Seismically induced soft-sediment deformation structures in the Eocene lacustrine Green River Formation (Wyoming, Utah, Colorado, USA) – a preliminary study

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Summary

Pervasive horizons of various kinds of soft-sediment deformation structures were identified in the lacustrine sediments of the Eocene Green River Formation, USA. These features are present in a variety of sediments deposited in paludal (coal, sand) to profundal (oil shale) environments. Deformation is represented by brittle and plastic behavior, as well as sediment injection, and the deformed layers are confined by undeformed beds with similar thickness and lithology to the deformed ones. Based on the (1) tectonic setting of the subbasins; (2) the sedimentary environment and sedimentological characteristics of the successions in which the deformed layers occur; (3) their lateral extent; (4) their recurrence at different stratigraphic levels; and (5) their similarity to those described as seismically induced deformation structures in other areas and reproduced experimentally, we interpret these features as having developed as a result of increased pore pressure and vertical or horizontal stresses induced by seismic activity.

Introduction

Soft-sediment deformation features occur in unconsolidated sediments with low or zero shear resistance reached by thixotropic behaviour, liquefaction and/or fluidization (liquidization) (Allen, 1982). Liquidization can be triggered by several processes (e.g. overloading, storm waves, earthquakes) (Owen, 1987, 1996). However the final morphology and size of the deformed structure depends on the driving force system (e.g. density contrast, unequal loading, tangential stress) and the areal extent and thickness of the rheologically susceptible sediment. Accordingly, the determination of the trigger mechanism relies on criteria that are not yet well established (Sims, 1975; Seilacher, 1984; Jones & Omoto, 2000; Montenat et al., 2007, Owen et al. 2011). Sediments deposited in lacustrine environments offer a great possibility to study seismically induced soft-sediment deformation structures (seismites, *sensu* Seilacher, 1969) (Sims, 1973, 1975; Rodríguez-Pasqua et al., 2000; Moretti & Sabato, 2007). The deposition in a low-gradient, quiet-water environment eliminates other triggering mechanisms of synsedimentary deformation, and increases the potential for preservation.

Lacustrine sediments of the Green River Formation were deposited in interconnected foreland basins along the Front Range of the Rocky Mountains during the middle Eocene (53 Ma – 45 Ma) and comprise of siliciclastic, evaporitic and carbonate sediments almost 2 km thick, in Wyoming, Utah and Colorado (Bradley, 1964; Dickinson et al.,1988; Roehler, 1992, 1993; Smith et al., 2008). Despite the known syndepositional tectonic activity along the structures in and around these basins, and the large number of geological studies devoted to the stratigraphy, deformation features definitely related to seismic events have not previously been identified.

Theory and/or Method

Soft-sediment deformation features induced by earthquakes (seismites) are indicative of synsedimentary tectonism. The geographic and stratigraphic distribution of these features can provide information about the location, timing, and intensity of the movements of structural elements in the study area (e.g. El Taki & Pratt, 2012). Deformation structures identified on outcrops of the Green River Formation were described in detail on the field and in thin sections, and classified based on their descriptive geometric characteristics. Their stratigraphic and geographic distribution was plotted to provide data on their temporal and spatial occurrence.

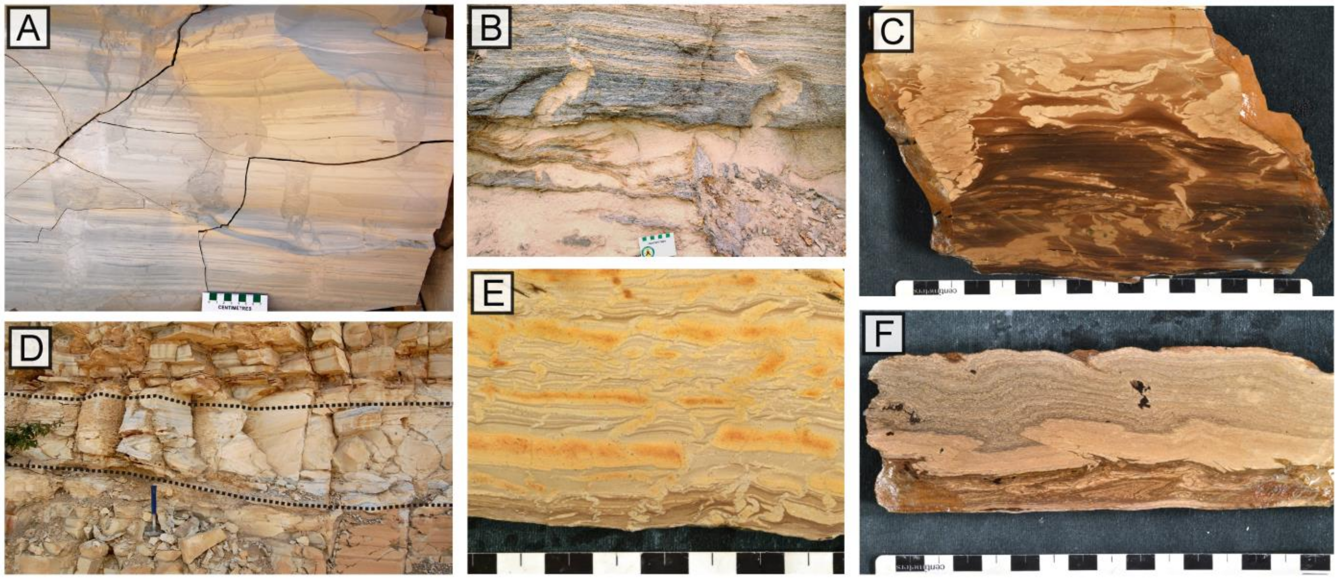

Figure 1: Examples of soft-sediment deformation structures in the Green River Formation (scale in centimeter). A. Sedimentary injection features in sublittoral silty carbonate mudstones showing multiple fluidization events (Utah). Injections filled with mixed, silty sediment with fragments of the laminated carbonate mudstone; B. Sand injections in coal bearing paludal deposits (Wyoming); C. Sedimentary injections, filled with carbonate mud, in profundal rich oil shales (Utah); D. Large-scale recumbent fold in rich oil shale deposit, confined by undeformed, laminated oil shales (hammer for scale) (Colorado); E. Small-scale injection features ('syneresis cracks') in sublittoral, laminated, silty carbonate mudstone deposit (Colorado); F. Folds and microfaults in profundal organic-rich laminated carbonate mudstone, with a convoluted lower part (Wyoming)

Examples

Deformed layers have been found in deposits ranging from paludal (coal and sand) to profundal (oil shale) lacustrine environments. In most cases, these layers are bound above and below by undeformed beds of similar facies with horizontal bedding plane surfaces, which imply short-lived, recurring events that effected only sediments with a susceptible rheological state at the time. Deformation typically occurred intrastratally, i.e. under the sediment-water interface. These isolated horizons demonstrate plastic and brittle deformation, such as folds, convolution, load and flame features, dislocated, fractured and/or fragmented laminites, small sedimentary dikes, and synsedimentary faults exhibiting a wide range of morphology and size. The variation in size, morphology and areal extent of the deformations can be explained by the thickness changes and/or lateral facies variations and by the nature of the driving force. Some of the sedimentary injection features show multiple deformations, indicating more than one event that induced failure of the sediments. Other potential trigger mechanisms, such as overloading, oversteepening of depositional slopes, wave-induced cyclical shear stresses, sudden changes in groundwater level or bioturbation, can be discarded based on the depositional setting of these deposits and the characteristics of these features.

Conclusions

Soft-sedimentary deformation structures observed in the Green River Formation are interpreted as seismites, developed as a result of increased pore pressure and vertical or horizontal stresses induced by seismic activity. Their wide variety and proximity to known active fault systems during the time of deposition further indicate an external, seismic origin. By combining the stratigraphy of the area and the deformation features as indicators of episodical syndepositional fault activity, the paleotectonic history of the lake basin can be refined.

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