

# **Seismically Induced Soft-Sediment Deformation Structures in the Eocene Lacustrine Green River Formation (Wyoming, Utah, Colorado, USA) – A Preliminary Study\***

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## **Abstract**

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 and 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 and 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 (53-45 Ma) and are comprised 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.

### **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 and Pratt, 2012). Deformation structures identified in outcrops of the Green River Formation were described in detail in 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.

### **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 bounded 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, over-steepening of depositional slopes, wave-induced cyclical shear stresses, and 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 episodic syndepositional fault activity, the paleo-tectonic history of the lake basin can be refined.

## References Cited

- Allen, J.R.L., 1982, *Sedimentary Structures: their Character and Physical Basis*, v. II, *Developments in Sedimentology*, 30, Elsevier, Amsterdam, 663 p.
- Bradley, W.H., 1964, The geology of the Green River Formation and associated Eocene rocks in southwestern Wyoming and adjacent parts of Colorado and Utah: U.S. Geological Survey Professional Paper, 496-A, 86 p.
- Dickinson, W.R., M.A. Klute, M.J. Hayes, S.U. Janecke, E.R. Lundin, M.A. Mckittrick, and M.D. Olivares, 1988, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region: *Geological Society of America Bulletin*, v. 100, p. 1023-1039.
- Pratt, B., 2012, Syndepositional tectonic activity in an epicontinental basin revealed by deformation of subaqueous carbonate laminites and evaporites: Seismites in Red River strata (Upper Ordovician) of southern Saskatchewan, Canada: *Bulletin of Canadian Petroleum Geology*, v. 60, p. 37-58.
- Jones, A.P., and K. Omoto, 2000, Towards establishing criteria for identifying trigger mechanisms for soft-sediment deformation: a case study of Late Pleistocene lacustrine sands and clays, Onikobe and Nakayamadaira Basins, northeastern Japan: *Sedimentology*, v. 47, p. 1211-1226.
- Montenat, C., P. Barrier, P. Ott d'Estevou, and C. Hibschi, 2007, Seismites: an attempt at critical analysis and classification: *Sedimentary Geology*, v. 196, p. 5-30.
- Moretti, M., and L. Sabato, 2007, Recognition of trigger mechanisms for soft-sediment deformation in the Pleistocene lacustrine deposits of the Sant' Arcangelo Basin (Southern Italy): seismic shocks vs. overloading: *Sedimentary Geology*, v. 196, p. 31-45.
- Owen, G., 1987, Deformation processes in unconsolidated sands, *in* M.E. Jones and R.M.F. Preston, eds., *Deformation of Sediments and Sedimentary Rocks*: Geological Society of London, Special Publications 29, p. 11-24.
- Owen, G., 1996, Experimental soft-sediment deformation structures formed by the liquefaction of unconsolidated sands and some ancient examples: *Sedimentology*, v. 43, p. 279-293.
- Owen, G., M. Moretti, and P. Alfaro, 2011, Recognising triggers for soft-sediment deformation: current understanding and future directions, *in* G. Owen, M. Moretti, and P. Alfaro, eds., *Recognising Triggers for Soft-Sediment Deformation: Current Understanding and Future Directions*: *Sedimentary Geology*, v. 235, p. 133-140.
- Roehler, H.W., 1992, Correlation, composition, areal distribution, and thickness of Eocene stratigraphic units, Greater Green River Basin, Wyoming, Utah, and Colorado: U.S. Geological Survey Professional Paper, 1506E, 49 p.

Roehler, H.W., 1993, Eocene climates, depositional environments, and geography, greater Green River basin, Wyoming, Utah, and Colorado: U.S. Geological Survey Professional Paper, 1506F, 74 p.

Rodríguez-Pasqua, M.A., J.P. Calvo, G. De Vicente, and D. Gomez-Gras, 2000, Soft-sediment deformation structures interpreted as seismites in lacustrine sediments of the Prebetic Zone, SE Spain, and their potential use as indicators of earthquake magnitudes during the Late Miocene: *Sedimentary Geology*, v. 135, p. 117-135.

Seilacher, A., 1969, Fault-graded beds interpreted as seismites: *Sedimentology*, v. 13, p. 155-159.

Seilacher, A., 1984, Sedimentary structures tentatively attributed to seismic events: *Marine Geology*, v. 55, p. 1-12.

Sims, J.D., 1973, Earthquake-induced structures in sediments of Van Norman Lake, San Fernando, California: *Science*, v. 182, p. 161-163.

Sims, J.D., 1975, Determining earthquake recurrence intervals from deformational structures in young lacustrine sediments: *Tectonophysics*, v. 29, p. 141-152.

Smith, M.E., A.R. Carroll, and B.S. Singer, 2008, Synoptic reconstruction of a major ancient lake system: Eocene Green River Formation, western United States: *Geological Society of America Bulletin*, v. 120, p. 54-84.

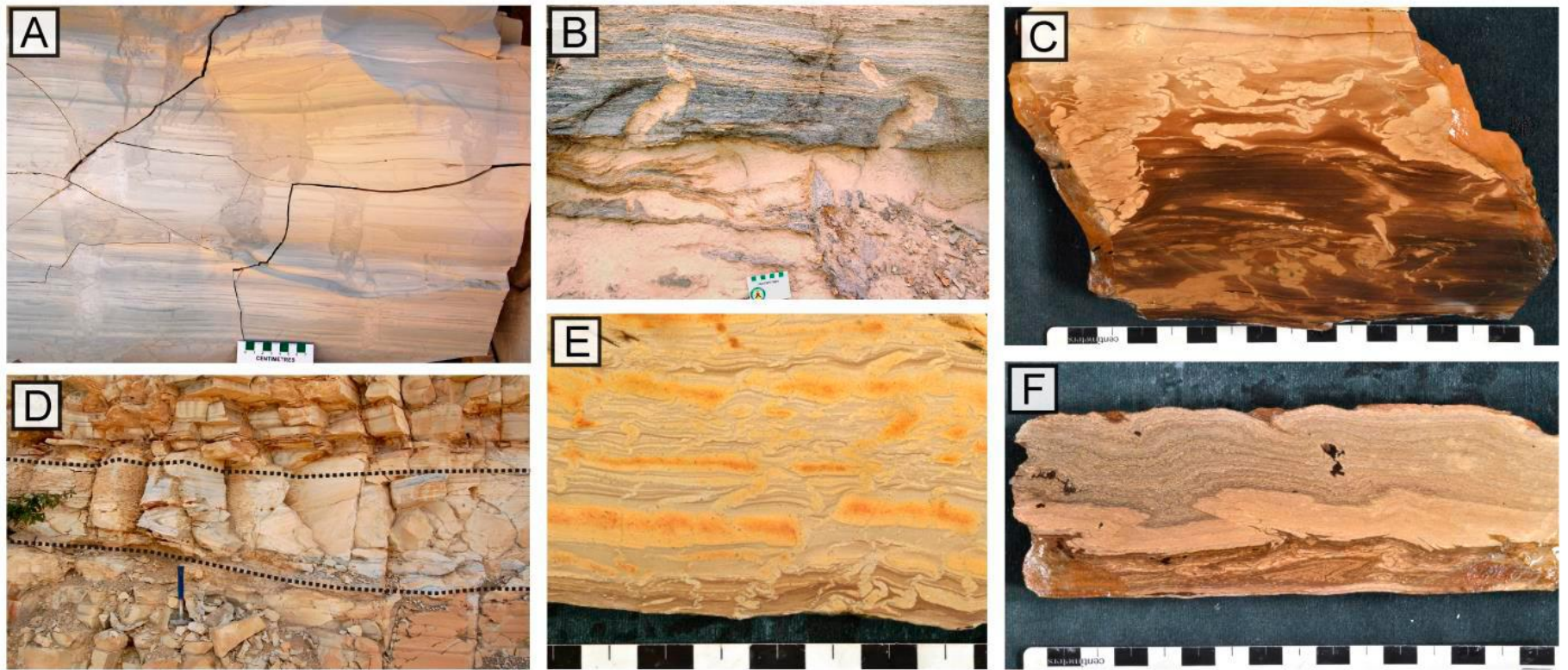


Figure 1. Examples of soft-sediment deformation structures in the Green River Formation (scale in centimeters). (A) Sedimentary injection features in sublittoral silty carbonate mudstones showing multiple fluidization events (Utah). Injections filled with mixed silty sediment with fragments of the laminated 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).