Shaking Loose: Sand volcanoes and Jurassic earthquakes

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Seismology has provided records of earthquake shaking dating back centuries, but even the longest historical records cannot sufficient to demonstrate the long-term patterns, as we learned from the 2011 Tohoku Earthquake (Liu and Zhou, 2012). A major challenge for the study of past earthquakes is that events on such time scales—seconds to minutes—are rarely preserved in the rock record. When they are, the records represent isolated moments, not the days to years before and after the event that would place them in context. "Earthquake geology" includes the study of rupture itself (on the fault surface), ground shaking and its effects, and stress and fluid pressure changes both on- and off-fault, on geologic to human time scales (Sibson, 2011). Loope et al. (2013, p. 1131 in this issue of *Geology*) document an exceptionally well-preserved array of sand volcanoes in the Navajo Sandstone (southwest United States), capturing an ~1-yr-long Jurassic earthquake swarm.

Radiating seismic waves cause transient changes in pressure conditions that may result in permanent damage. Examples include slope failure, intrusion, injection and extrusion of fluidized sediments (liquefaction), folding and slumping, and autobrecciation (Montenat et al., 2007). Such deformed sediments, sometimes called "seismites," record energetic disturbance of material at the earth's surface. If the sediments are rapidly buried, they may be preserved and identifiable in the rock record. Earthquakes, however, are not the only source of energy that might deform soft sediments. Storms, landslides and rockfalls, currents, far-traveled tsunami waves, and impacts may also cause liquefaction and deformation. The stress perturbation caused by such a transient event might be required for liquefaction and deformation, even when the main driving forces develop slowly, such as increasing pore pressure due to burial loading and diagenesis (Obermeier [1996], Owen et al. [2011], and Owen and Moretti [2011]).

Geological examples of soft-sediment deformation features (Fig. 1) potentially triggered by earthquakes record the temporary local loss of sediment cohesion during acceleration. Convolute beds between intact planar layers (Fig. 1A) may be caused by storms (or other events) so they are not always uniquely interpretable as ancient earthquakes. Injected sands (Figs. 1B and 1C), in contrast, may be more strongly linked to seismic shaking. In both examples, a layer of coarse sediment buried under lower permeability beds was temporarily fluidized simultaneous with fracturing of the overlying sediment. The sand-water slurries injected upward, filling the cracks, then compacted into homogenous sand dikes. Conditions (permeability stratification, probable complete saturation, and the unconsolidated, low-cohesion state of the sand layer) were favorable to liquefaction and injection. The sand dikes in fluvial mudstone adjacent to the Upheaval Dome impact structure (Fig. 1B) were likely triggered by seismic waves from this impact (Kenkmann, 2003). The isolated sand dike cutting coal beds (Fig. 1C) may have been triggered by regional seismicity, but is less easy to interpret, because no obvious local trigger has been identified. Similar dikes were not found in the underlying mudstone strata, and the local scarcity of such features could reflect the rarity of earthquakes. Or perhaps earthquakes were common during this period of deposition, but the lithologic transition to coarse sand and coal beds at the top of this formation resulted in depositional environments favorable to preservation of the structures caused by earthquakes. We cannot be certain, but by comparing lateral extent, frequency, and sedimentary and tectonic conditions, it is often possible to make a reasonable judgment of the likely causes. In many cases, there may be nothing morphologically unique about the sedimentary structures themselves that indicates the nature of the triggering event. So how to distinguish true seismites? How can these features be used to identify past earthquakes and their characteristics?

Figure 1. A: Convolute bedding in siltstone/shale from the Malmsbury Formation, Robben Island, South Africa (Rowe et al., 2010). B: Numerous small wavy sand dikes cutting fluvial silt, displaying branching and anastomosing geometry. Upheaval Dome Impact Structure, Canyonlands National Park, Utah. C: Fluidized sandstone dike penetrating coal beds of the Cretaceous Castle Sandstone, Blackhawk Formation, Book Cliffs, Utah. D: Dewatering structures formed following sand mobilization in the Miocene Yellow Bank Beach Injectite, Santa Cruz, California (Sherry et al., 2012).

Shake table–sediment tank experiments by Moretti et al. (1999) revealed the short time scales of soft sediment deformation in simulated earthquakes. Using shaking patterns of real earthquakes as a trigger, they observed that pore pressure increased to a peak *just after* peak shaking, initiating sediment liquefaction, and the liquefied beds were internally mixed (e.g., Fig. 1A). After liquefaction, the sand collapsed and began to compact, so that pore pressure increased, causing vigorous eruption of sand volcanoes. These eruptions lasted up to tens of minutes longer than the earthquake shaking. The feeder conduits to the sand volcanoes formed sharp-edged pipes of homogenous sand, easily distinguished from the bedded sand penetrated by the pipes (similar to Figures 1B and 1C). In

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some experiments, bubbles of pore water appeared in the sediments during liquefaction. After the expulsion of sand dikes and volcanoes, compaction of the previously liquified sand and venting water from the bubbles generated a pillar structures over tens of minutes. These structures are formed by localized upward deflections of sand, sometimes with internal homogenization, but have gradual contacts (a geological example is shown in Figure 1D). So, shaking itself causes loss of strength, and if differential loading or sediment fracturing creates a force to push the weakened material to deform, it may dilate and then compact, creating structures at each stage (Owen and Moretti, 2011).

Quigley et al. (2013) observed the development of a sequence of sand volcanoes during the Christchurch, New Zealand, earthquake swarm of 2010–2012. The presence of floodplain sediments and the shallow groundwater table contributed to fluidization of a sand layer a few meters below the surface, which flowed into dikes (possibly similar to Figures 1B and C), supplying linear arrays of vents (sand volcanoes) on the surface. These vents were reactivated during aftershocks, erupting only during M >5 earthquakes, within ~30–40 km of the site. The size and scale of these sand volcanoes, and the time for the development of the array, is comparable to the conditions inferred by Loope et al. for the sand volcano pipes in the Navajo Sandstone, Zion National Park, Utah. Their discovery offers a rare opportunity to constrain events occurring on a time scale not often preserved in the rock record, due to the position within a fast migrating dune field.

Previous studies of the Navajo Sandstone and equivalents indicated that saturated conditions were common, with interdune ponds forming even during dune field migration (e.g., Bryant and Miall, 2010). The porous, uncemented, and well-sorted sands typical of the Navajo Sandstone are particularly sensitive to liquefaction due to their lack of cohesion and the ease with which changes in fluid pressure can separate grain contacts and reduce shear strength (Owen and Moretti, 2011). In bedded sediments, soft sediment deformation may be caused by differences in porosity and compaction between beds contributing to fluid overpressure (e.g., Oliveira et al., 2009). In contrast, in a pure sand environment with uniformly high permeability, it is more difficult to generate overpressures without outside forcing. During the Navajo sand deposition, the groundwater table may have been within a few meters of the surface, creating an interface for differential fluidization even where the sand itself is uniform.

The geometry, velocity, and overpressure conditions required to trigger injections and sand volcano eruptions are increasingly better constrained by recent experiments and numerical models (e.g., Levi et al., 2008, 2011; Rodrigues et al., 2009). Historical compilations of liquefaction around earthquake source areas have shown that earthquakes must be very large or very close in order to trigger sand injection (Fig. 2). Therefore, Loope et al. imply that the Jurassic dune field of present-day Zion National Park was vigorously shaken by repeated earthquake swarms. The interdune pond setting may have been quite transient (in space and time), but more than 800 individual pipes are present, representing an unknown number of earthquake-aftershock sequences. Records like this give an indication of proximal faulting during the middle Jurassic, providing clues to the foreland basin tectonics. In most cases, the forces required are similar to those expected during earthquakes. Loope et al.'s observations, and particularly the quantification of time scale for the development of sand volcano swarms, are a step forward in our ability to read the ancient earthquake record from deformed soft sediments.

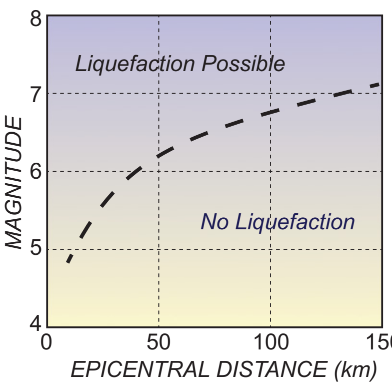

Figure 2. Approximate limit for liquefaction structures in magnitude-distance space. Modified from Galli (2000).

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