Jurassic earthquake sequence recorded by multiple generations of sand blows, Zion National Park, Utah

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ABSTRACT

Earthquakes along convergent plate boundaries commonly occur in sequences that are complete within 1 yr, and may include 8–10 events strong enough to generate sand blows. Dune crossbeds within the Jurassic Navajo Sandstone of Utah (western United States) enclose intact and truncated sand blows, and the intrusive structures that fed them. We mapped the distribution of more than 800 soft-sediment dikes and pipes at two small sites. All water-escape structures intersect a single paleo-surface, and are limited to the upper portion of the underlying set of cross-strata and the lower portion of the overlying set. A small portion of one set of crossbeds that represents ~1 yr of dune migration encloses eight generations of eruptive events. We interpret these superimposed depositional and deformational structures as the record of a single shock-aftershock earthquake sequence. The completeness and temporal detail of this paleoseismic record are unique, and were made possible when sand blows repeatedly erupted onto lee slopes of migrating dunes. Similar records should be sought in modern dunefields with shallow water tables.

INTRODUCTION

The Navajo Sandstone (Utah, western United States) accumulated in a giant sand desert near the convergent plate boundary along Pangaea's western margin. Numerous studies of the Navajo and correlative Aztec Sandstones have attributed dramatic, large-scale deformation of cross-strata to liquefaction and fluidization of shallow-subsurface, water-saturated sand during paleoseismic events (Doe and Dott, 1980; Horowitz, 1982; Bryant and Miall, 2010). This deformation may be the result of dune collapse (mass flow) when underlying sand liquefied (Horowitz, 1982; Bryant and Miall, 2010). The complexity of these soft-sediment structures hinders determination of the position of the land surface prior to the event, and assessment of the number of seismic events involved. Our study, which confirms the previous observation of Marzolf (1983) that large-scale deformation is nearly completely absent at Zion National Park, Utah, instead focuses on small pipes and dikes that formed when fluidized sand repeatedly intruded individual migrating dunes and vented onto their lower slopes (Fig. 1).

Earthquakes along plate boundaries commonly occur as sequences that are complete within 1 yr, and can include 8–10 events of sufficient strength (M_w 5) to trigger liquefaction (Ambraseys and Sarma, 1969; Galli, 2000; Stein and Liu, 2009). During a 15-mo-long portion of the mainshock-aftershock earthquake sequence that struck New Zealand's South Island in 2010, Quigley et al. (2013) recorded seven distinct sand-blow episodes with photos, videos, trenches, and maps.

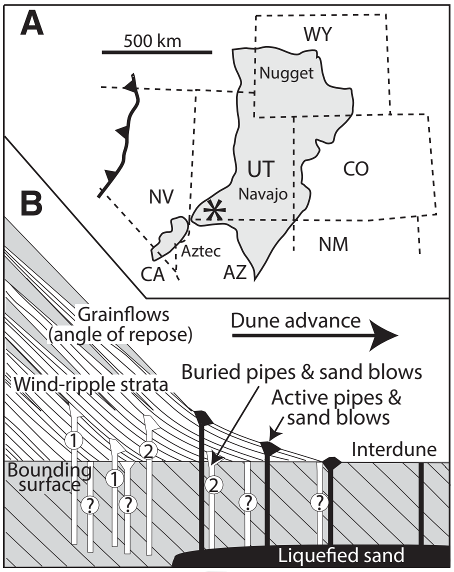

Figure 1. Paleogeographic (A) and sedimentologic (B) setting of water-escape structures buried by migrating dunes. Asterisk is position of Zion National Park (Utah, western United States). Buried sand blows record at least three paleo-liquefaction events, but timing of only two of them can be tied directly to rate of dune migration. Position of Early Jurassic thrust front is from Allen et al. (2000). WY—Wyoming; NV—Nevada; UT—Utah; CO—Colorado; CA—California; AZ—Arizona; NM—New Mexico.

The completeness of a geologic record of earthquake activity depends, in part, on erosion rates, but also on the relative frequency of burial events versus seismic events. If no sediment buries the injected/vented sand from a first seismic-triggered event before arrival of a second event, the two events are difficult to discern. For example, from the wall of a 20-m-long trench excavated in thick-bedded floodplain deposits in the southern Mississippi Embayment (southern United States), Cox et al. (2007, p. 283 and their figure 5) carefully located scores of water-escape structures "showing at least two sand-venting episodes." Working in the same region, Saucier (1989, his figure 3) provided a notable exception to the limitation imposed by infrequent sedimentation events: one excavation in the New Madrid fault zone revealed three distinct episodes of seismic activity, all recorded within a single cluster of superimposed sand blows, each delineated by a silt-rich cap. Similarly, during their investigation following a swarm of 2000 weak, shallow earthquakes along the northwest coast of Venezuela, Audemard and de Santis (1991) recognized an oxidation surface separating two distinct generations of sand blows. They correlated these deposits to the two most powerful shocks in the cluster—an M_w 5.5 and an M_w 5.0, which occurred three days apart.

The dunes that deposited the cross-strata within the Navajo Sandstone at Zion National Park were large (averaging >10 m in height), and migrated ~1.0–1.5 m/yr (Rubin and Hunter, 1982; Hunter and Rubin, 1983). Grain flows, generated by dry avalanches, are centimeters thick and composed of well-sorted medium to coarse sand. Wind-ripple laminae, which accumulate beyond the toe of the slipface, are thin, poorly sorted, and dip at a lower angle than grain flows. The same Navajo cross-strata that provide detailed information of wind variability and dune dynamics have the potential to be paleoseismic archives: cross-strata that progressively accumulate within the approximate time span of a single shock-aftershock earthquake sequence could enclose many distinct generations of sand blows (Fig. 1).

SOFT-SEDIMENT DEFORMATION STRUCTURES AT ZION

Small dikes and pipes are abundant in eolian cross-strata along at least three different bounding surfaces within Zion National Park. With differential GPS, we mapped more than 800 of these structures at two favorably exposed sites (Fig. 2). At each site, all deformation structures lie within two sets of cross-strata, and are restricted to a 4-m-thick zone just above and below the bounding surface that separates them. Many deformation structures at the eastern site

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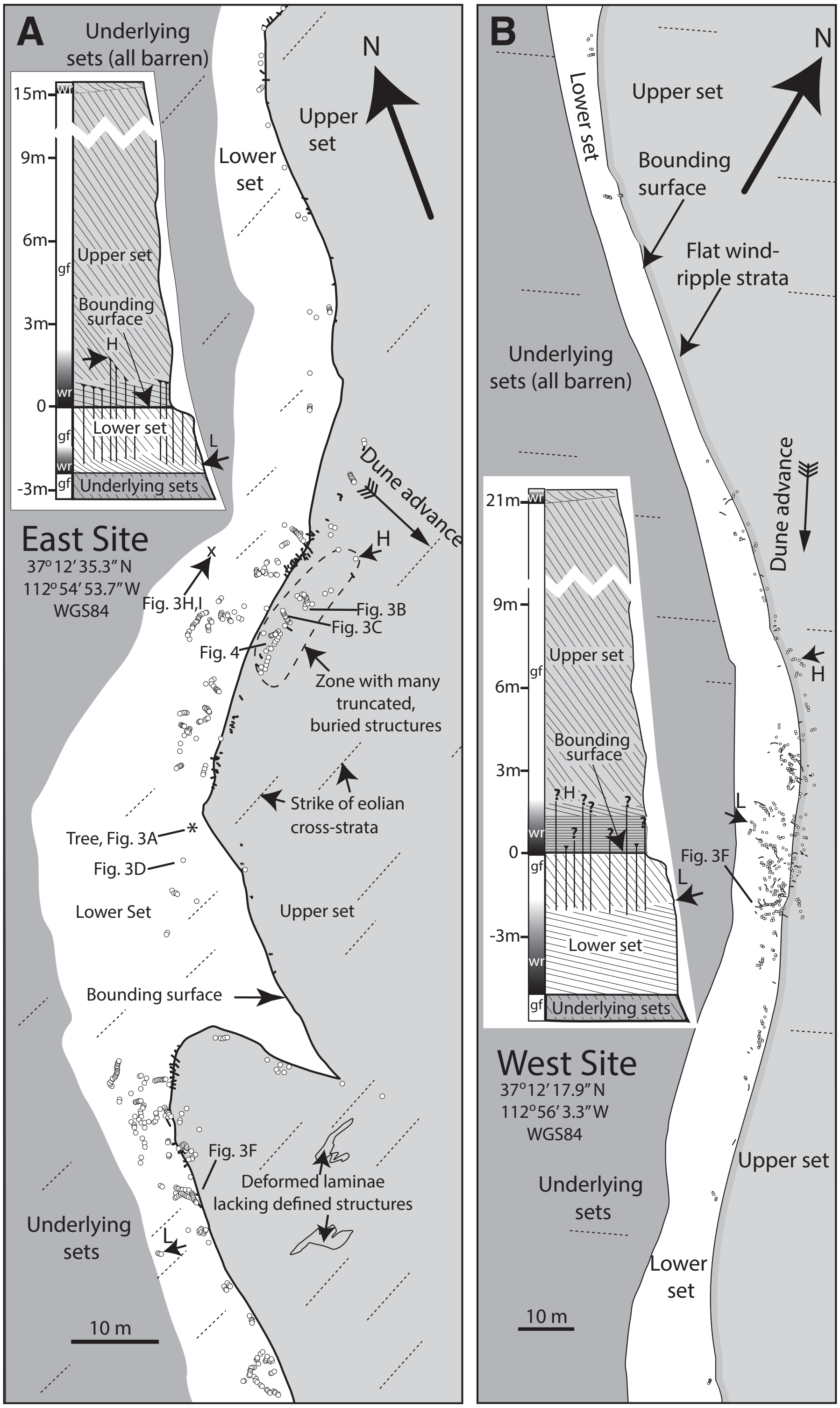

Figure 2. Maps of structures at two sites in Zion National Park and their stratigraphic context. Small circles are pipes, short lines are dikes (both larger than true scale). gf—grain flows; wr—wind ripples. "L"s and "H" s mark lowest and highest exposed deformation structures.

can be traced upward to where they flare against truncation surfaces; others flare and terminate as domed deposits that were onlapped by wind-ripple laminae (Fig. 3B). Close examination shows multiple, superimposed generations of flared structures, each separated by low-angle wind-ripple strata (Fig. 4).

Pipes are vertical and 2–6 cm in diameter. Dikes are also vertical, and are ~6 cm wide. Although individual structures rarely are exposed more than 50 cm vertically, their mapped distribution indicates that the entire population extends as far as 4 m vertically. Most exposed deformation structures in the lower sets have been truncated by modern erosion, but many can be observed to cross the bounding surface into the deposits of the higher sets. Many pipes are arranged in rows (Figs. 2 and 3C); some rows include more than 20 pipes, and are interrupted by dikes of the same orientation (Fig. 3E). Brittle-deformation fractures bound dikes lying >2 m below bounding surfaces (Fig. 3E). Some pipes and dikes contain brecciated wind-ripple laminae (Fig. 3F). Pipes and some dikes retain primary (dune) lamination in their down-dropped (1–2 mm) cores (Figs. 3C–3E). Many pipe cores are surrounded by vertically laminated annuli (Fig. 3D), and in some pipes, the outer edges of inner laminae are upturned.

Within otherwise-undeformed, wind-ripple strata that lie below pipes and dikes, some laminae are broken, distended, and upwarped into closely spaced antiforms (Figs. 3H and 3I).

PALEOSEISMIC INTERPRETATION

Sedimentary structures at our study sites record the interplay of (1) relatively steady dune migration, and (2) intermittent, co-seismic sediment fluidization and eruption (Fig. 1). Within one sequence of Jurassic crossbeds representing ~1 yr (1 m of dune advance; Hunter and Rubin, 1983), we recognize eight distinct generations of water-escape features (Fig. 4) that we interpret as the record of a shock-aftershock earthquake sequence.

Cyclic sediment shearing during each of many seismic events apparently triggered liquefaction in zones ~2.5 m below interdunes (Figs. 1 and 2). Water escaping upward from these zones entrained a small portion of overlying sand, and vented onto gently sloping dune surfaces. Wind erosion later truncated some vented sediment, but other sand blows were buried intact (Figs. 3B and 4). Lateral spreading of material lying above liquefied zones likely controlled orientations of dikes and aligned pipes (Figs. 3C, 3E, and 3G; cf. Audemard and de Santis, 1991; Quigley et al., 2013).

Obermeier (2009) developed criteria for recognizing seismic-triggered, soft-sediment deformation features that include their morphology, texture, temporal and geographic distribution, as well as their geomorphic and hydrogeologic context. The texture (clay-free, fine to medium sand) and high initial porosity (~40%) of the Jurassic dune deposits below the bounding surfaces place them in Obermeier's "most liquefiable" category of sedimentary deposits. Tabular dikes, cylindrical pipes, and sand blows are abundant at our two study sites, but, in our experience, are uncommon in most outcrops of the Navajo Sandstone at Zion National Park and elsewhere on the Colorado Plateau. Our two Zion sites (Fig. 2) lie ~2 km apart, at a similar elevation, but several intervening, deep canyons make correlation of the

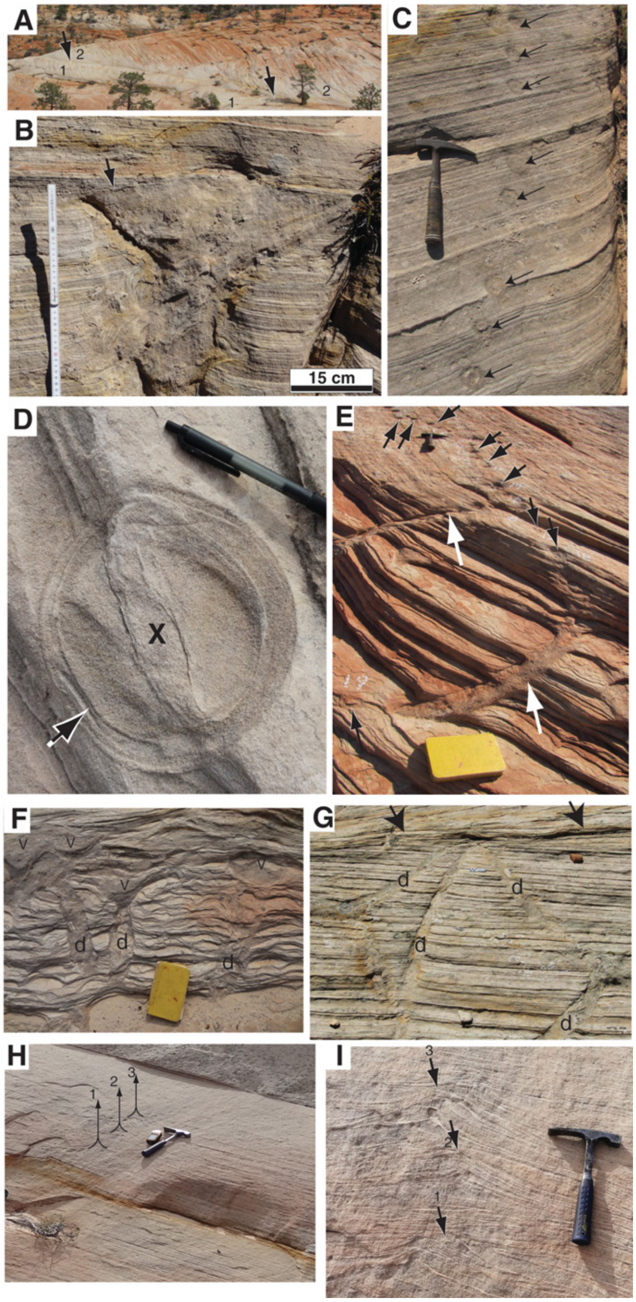

Figure 3. Deformation features in outcrop. In all photos except D, outcrops slope 10°–30° toward viewer. A: East study site. Bounding surface (arrows) separates deposits of older (1) and younger (2) dune deposits. Tree near right arrow is ~8 m tall. B: Sand blow onlapped by wind-ripple laminae of younger dune, 1.5 m above bounding surface (at surface 6 of Fig. 4). Arrow marks upper surface of erupted sand. C: Eight vertical pipes intruding wind-ripple laminae of younger dune. Hammer is 29 cm long. D: Horizontal cross-section of cylindrical pipe. Inner part (x) retains dune bedding; outer part (arrow) is vertically laminated. E: Tabular dikes (white arrows) and cylindrical pipes (black arrows) in lower set of cross-strata. Lower dike lies along curving trend of 19 pipes. F: Vented sediment (v) and broken blocks of wind-ripple laminae within dikes (d). Field notebook (12 × 18 cm) straddles bounding surface. G: Dikes (d) cut cross-strata and terminate at bounding surface (arrows). 15 cm scale. H: Tabular wind-ripple laminae surrounding three structures interpreted as the bases (burst-outs) of three aligned, vertical pipes (arrows). I: Close-up view of H.

Figure 4. Portions of eight superimposed erosion surfaces defined by truncated, flared tops of dikes and pipes (see Figure 2 for location). Surface 5 truncates 16 intrusions; surface 6 truncates 8 intrusions, and onlaps the sand blow in Figure 3B. Wind-ripple laminae dip 10° to left. See Item DR2 (see footnote 1) for photo without annotation.

two bounding surfaces difficult. Linkage of pipes and dikes to single bounding surfaces demonstrates that structures formed at shallow depth (<2.5 m)—a position where the potential for liquefaction is great. Brittle-deformation fractures near the base of the older dune deposits suggest that sand above the main zone of liquefaction was cohesive or lightly cemented and did not liquefy.

Modern sand blows commonly reach the surface through fractures in mud-rich "capping beds" (Obermeier, 2009), but no such deposits are present at our study sites. Nichols et al. (1994), however, showed that water-escape structures develop whenever the fluidization of subsurface sand is delayed either by overlying cohesive material or by coarser sands (which require higher flow velocities to fluidize). Build-up of pressure causes water-filled voids to grow just a few centimeters below the contact between the two sediment masses; voids eventually rupture and water escapes upward.

Many Navajo Sandstone outcrops in other parts of the region contain carbonate lenses that accumulated in interdune ponds (Eisenberg, 2003; Parrish and Falcon-Lang, 2007), but interdune carbonates are virtually absent at Zion National Park (Marzolf, 1983). The Navajo Sandstone accumulated within a low-lying, subsiding basin. Much of the rain that fell on active dunes recharged groundwater (Loope and Rowe, 2003), and it is likely that the water table remained at a shallow depth during most of the Navajo deposition. Artesian conditions can generate water-escape structures that, when buried, could be misinterpreted as evidence for earthquake-induced liquefaction (Holzer and Clark, 1993). Under steady-state conditions, groundwater within narrow zones at interdune margins can flow upward at velocities approaching 0.01 mm/s. This flow rate, however, is no more than 10% of that required to fluidize fine to medium sand (Item DR1 in the GSA Data Repository[1]). Such groundwater flow could have, nonetheless, reduced effective stress and sediment strength, making sand beneath Jurassic dune toes especially sensitive to liquefaction by a seismic trigger. Manga and Brodsky (2006) noted that earthquakes commonly enhance other processes that produce high fluid pressures. Landslides down dune slopes (Loope et al., 2001) did not trigger liquefaction because the dune slopes are exposed at both sites, and show no evidence of mass movements other than thin, dry grain flows.

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[1] GSA Data Repository item 2013313, Item DR1 (outlining steady-state groundwater flow in dunefields) and Item DR2 (Figure 4 with and without annotation), is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

DISCUSSION

Laboratory studies have enhanced understanding of conditions and processes leading to coseismic emplacement of pipes, dikes, and sand blows (Allen, 1982; Owen, 1996; Nichols et al., 1994; Ross et al., 2011). If shearing in the saturated zone causes liquefaction, water expelled upward during consolidation can cause distinct, conical voids to form within finer-grained strata that are overlain by coarser sediment (Nichols et al., 1994). The rows of vertical pipes in the Navajo Sandstone (Figs. 2, 3C, and 3E) likely were produced by burst-outs of such water-filled voids, and spacing of the pipes may reflect Rayleigh-Taylor instability (Nichols et al., 1994). Lab experiments produce “pillar structures with splayed ends” (Nichols et al., 1994, p. 252). We interpret the structures in Figures 3H and 3I as the splayed bases of a row of three (now-eroded) pipes that formed in wind-ripple strata that are overlain by coarser, better-sorted grain-flow strata.

Convex-up sand blows in the Navajo cross-strata (Fig. 3B) were preserved where sand erupted onto cohesive sediment. Transported sediment erupting onto a non-cohesive substrate progressively depresses the surface, generating a flat-topped, bowl-shaped fill (Fig. 3F; Nichols et al., 1994). Although some Navajo sand blows were eroded, leaving only truncated, flaring conduits as evidence for their former presence (Fig. 4), others are nearly fully preserved (Fig. 3B).

Brittle-deformation fractures near the base of older dune deposits at the western site (Fig. 3E) indicate that sand there was either moist or lightly cemented during liquefaction events. The unusual interior structure of the pipes at our study sites indicates that upward-moving water and fluidized sand were restricted to an annulus surrounding undisturbed bedding in the cylindrical cores of pipes (Fig. 3D). Pipes with similar structure and context have been described previously. Pipes in Precambrian eolian sandstones of Mali are, as here, attributed to upward flow of fluidized sand around a plug of cohesive sediment (type 2 structures of Deynoux et al. [1990]). The inner portion of a Navajo pipe in northern Arizona illustrated by Bryant and Miall (2010, their figure 9) retains undisturbed dune bedding, and, like upper parts of many of the pipes at Zion National Park, this pipe is interpreted as an earthquake-triggered, water-escape structure that intruded cohesive sand.

Dunes are present today in many areas of high seismic activity, and may contain structures that would be helpful for seismic risk assessment. The Jurassic seismic record at Zion National Park is sufficiently detailed that directed searches for analogs on and within modern dune fields with shallow water tables should be considered. The eruptive features described here were never prominent features on the Jurassic landscape; they were truncated and buried within days or weeks. Unfortunately, finding preserved structures within lithified cross-strata is likely much easier than finding them buried within unconsolidated dunes.

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