Sand boils induced by the 1993 Mississippi River flood: Could they one day be misinterpreted as earthquake-induced liquefaction?

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ABSTRACT

In areas that are seismically active but lacking clear surficial faulting, many paleoearthquake studies depend on the interpretation of ancient liquefaction features (sand blows) as indicators of prehistoric seismicity. Sand blows, however, can be mimicked by nonseismic sand boils formed by water seeping beneath levees during floods. We examined sand boils induced by the Mississippi River flood of 1993 in order to compare their characteristics with sand blows of the New Madrid earthquakes of 1811–1812. We found a number of criteria that allow a distinction between the two types of deposits. (1) Earthquake-induced liquefaction deposits are broadly distributed about an epicentral area, whereas flood-induced sand boils are limited to a narrow band along a river's levee. (2) The conduits of most earthquake-induced sand blows are planar dikes, whereas the conduits of flood-induced sand boils are most commonly tubular. (3) Depression of the preearthquake ground surface is usual for sand blows, not for sand boils. (4) Flood-induced sand boils tend to be better sorted and much finer than sand-blow deposits. (5) Source beds for earthquake-induced deposits occur at a wide range of depths, whereas the source bed for sand boils is always near surface. (6) Materials removed from the walls surrounding the vent of a sand blow are seen inside sand blows, but are rarely seen inside sand boils. In general, flood-induced sand boils examined are interpreted to represent a less-energetic genesis than earthquake-induced liquefaction.

INTRODUCTION

The process of soil liquefaction during earthquakes is well understood. When strong ground shaking occurs, seismic waves—in particular, shear waves—propagate through the saturated granular layers. These waves cause a collapse in the granular structure, which can significantly elevate the intergranular pore pressure if drainage is impeded (Greene et al., 1994). When pore-water pressure approximates the weight of the overlying impermeable sediments, the granular layer liquefies, or behaves as a viscous liquid rather than as a solid. The mixture of sand and water then may vent through fractures to the surface, often violently, where it forms "sand blow" deposits. Sand blows are considered diagnostic evidence of severe liquefaction at depth. Liquefaction has been observed and documented during many large earthquakes worldwide (e.g., Committee on Earthquake Engineering, 1985; Obermeier, 1995; Seed and Idriss, 1967).

Paleoseismological studies form a crucial part of seismic hazard evaluations. A basic premise of paleoseismological studies is that liquefaction-induced deposits are evidence of strong prehistoric earthquakes that, if accurately dated, can be used to estimate the recurrence rates of large earthquakes. Paleoliquefaction features have been used to infer prehistoric strong earthquakes worldwide—in California, South Carolina, the Wabash Valley of Indiana and Illinois (Obermeier et al., 1993), the New Madrid seismic zone of the lower Mississippi Valley (e.g., Saucier, 1991; Tuttle and Schweig, 1995), China, Canada, and Japan. In the lower Mississippi Valley, the great New Madrid earthquakes of 1811 and 1812 bear testimony to the fact that very strong earthquakes occur there. In the Wabash Valley region, however, the size of the inferred prehistoric earthquakes greatly exceeds any earthquake recorded in historical time (Obermeier et al., 1993).

Features similar to earthquake-induced sand blows, but caused by other driving mechanisms, are well documented (e.g., Holzer and Clark, 1993). In particular, seepage caused by water head differences along artificial levees during high floods can carry sand to the surface, forming conical sand mounds, often referred to as sand boils (Kolb, 1976). Because both severe floods and seismicity are common in the Mississippi Valley, sand boils and sand blows may coexist. The questions then arise, Can these deposits with different origins be distinguished in the geological record? and Have we misinterpreted flood-induced sand boils as earthquake-induced sand blows, or vice versa? The answers are critical to paleoseismological research in regions where faults are not observed at the surface and, in particular, where the time interval between strong earthquakes is longer than the historical record. Misinterpretation of flood-induced deposition as earthquake-induced liquefaction introduces a misapprehension of extraearthquake events, which in turn leads to a hypothesis of shorter recurrence intervals and thus an overestimate of the seismic hazard. The magnitudes of paleoearthquakes may also be misestimated because the spatial coverage affected by an earthquake may be overrepresented if some sand boils are correlated with sand blows. Therefore, successfully distinguishing between the two mechanisms is essential to paleoseismic studies for a region.

In the Mississippi River Valley, the great flood of 1993 inundated more than 20 million acres in nine states (Zimmerman, 1994). This hundred-year flood induced many sand boils along the Mississippi River levee system. It provided an ideal opportunity to observe, first-hand, numerous flood-induced sand boils and to compare them with earthquake-induced sand blows. We located active sand boils at the time of the flooding and later excavated some of them (Fig. 1).

LIQUEFACTION FEATURES INDUCED BY 1811–1812 NEW MADRID EARTHQUAKES

Both Fuller (1912) and Penick (1981) quoted an observer of the great New Madrid earthquakes: "Great amounts of liquid spurted into the air, it rushed out in all quarters . . . ejected to the height from ten to fifteen feet, and [falling] in a black shower, mixed with the sand. . . . The whole surface of the country remained covered with holes, which resembled so many craters of volcanoes. . . ." After nearly 200 yr of erosion and agricultural modification, the wide-

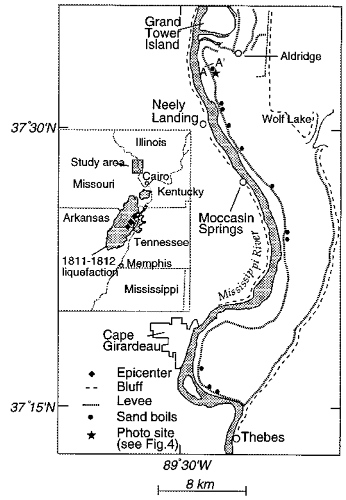

Figure 1. Distribution of flood-induced sand boils in Mississippi River Valley. Black dots represent sites where sand boils were found. Inset shows study area in relation to liquefaction from 1811–1812 New Madrid earthquakes (after Obermeier, 1995). Dots indicate presumed epicenters of 1811–1812 earthquakes (after Johnston, 1996). Star marks site of Figure 4. A to A′ marks profile position in Figure 3.

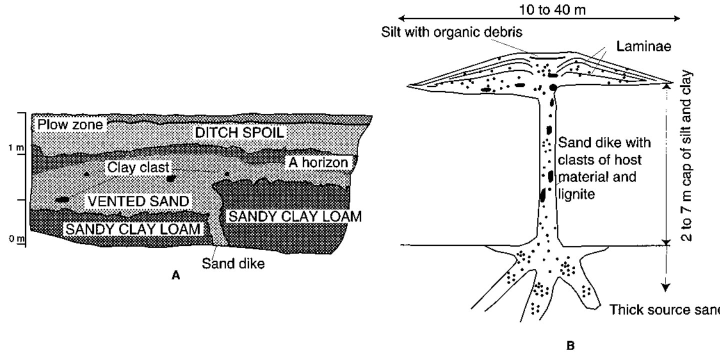

Figure 2. Typical sand blows in New Madrid seismic zone. A: Log of sand blow probably formed during 1811–1812 earthquakes (no vertical exaggeration; from Li et al., 1994). Note vertical separation of top of sand clay loam. B: Ideal sand blow and its structure (modified from Obermeier, 1995).

spread evidence of liquefaction left by the 1811 and 1812 New Madrid earthquakes remains clear and abundant over thousands of square kilometres. Fuller (1912) described widespread sand-filled fissures induced by 1811–1812 earthquakes when he visited the site about 100 yr later. Previously, investigators (Wesnousky et al., 1989; Obermeier, 1989) attributed the widespread abundance of the vented deposits in the Mississippi alluvial lowlands to the great size of the earthquakes (estimated moment magnitudes, **M** ~8.1; Johnston, 1996), as well as to the susceptibility of the Mississippi Valley deposits to liquefaction during strong shaking. Worldwide data show that, regionally, the distal extent and the concentration of liquefaction-induced features are proportionally related to the energy released by an earthquake (Youd et al., 1989)—e.g., the 1811–1812 sand blows are broadly distributed about the assumed epicenters of the New Madrid earthquakes (inset in Fig. 1). The location of individual sand blows is controlled by the distribution and age of potential source of sand deposits (Youd et al., 1989; Obermeier, 1989), the presence of an overlying impermeable layer above the liquefied source sand (Fear and McRoberts, 1995), the thickness of the impermeable layer (Obermeier, 1989; Youd and Garris, 1995), and the morphology of the contact between the source and impermeable layers (Tuttle and Barstow, 1996).

Properties of sand blows from the 1811–1812 earthquakes are well documented (Fig. 2). Typically, a thin A horizon (≤10 cm) has developed on the sand blows, although agriculture has sometimes replaced the natural A horizon with a plow zone. A planar dike typically cuts through a 2–7-m-thick surficial cap of silt and clay-rich sediment (the top stratum). The top stratum overlies about 30–60 m of unconsolidated sand (the substratum) (Obermeier, 1995). These substratum sands are the source for the liquefied and vented deposits. Clasts torn from the walls of the top stratum are commonly found within the dike and within the surface vented sand deposits (Wesnousky et al., 1989). Dikes normally widen downward or have walls that are parallel (Obermeier, 1995). Sand blows fed by dikes that have developed in surface fractures caused by lateral spreading during earthquakes are often parallel to stream channels. These dikes normally show a narrow distribution of strikes within a given area. The widths of dikes vary from millimetres to more than 2 m. The original ground surface underlying the sand blows is commonly depressed, owing to displacement of sand and water from the subsurface onto the surface. Bedding may be found both in the sand blows and in the dikes themselves, marking the flow direction of the vented sand. Grain sizes can range from gravel to silt in a single sand blow.

SAND BOILS INDUCED BY 1993 MISSISSIPPI RIVER FLOOD

Flooding along a river can produce hydraulic head differences on opposite sides of a river levee, thereby generating seepage forces capable of causing piping beneath and adjacent to the levee. The resultant seepage force can transport to the surface sand, deposited in the form of conical mounds or sand boils, generally immediately adjacent to the landward side of the artificial levee system (Fig. 3). The origin and geologic control factors of such sand boils have been studied along the lower reaches of the river by the U.S. Army Corps of Engineers and others (Mansur et al., 1956; Kolb, 1976) because of the threat that seepage poses to levee stability. During the floods of 1937, 1957, and 1973, these studies showed that, as expected, the severity of underseepage below the levees corresponds to the overbank flood height. As the flood occurs, the sand boils commonly start as small "pin boils," which are springs or upwellings of water on the landward side of the levee; these carry no material to the surface. As the flood height increases, the pin boils may enlarge into sand boils that pipe material to the surface. The distribution of the sand boils is controlled by several factors, including the thickness and permeability of the top stratum on both sides of the levee system (Kolb, 1976). Regardless of the geologic conditions, however, sand boils have been generally observed within about 100 m of the artificial levees (Kolb, 1976).

The sand boils caused by the 1993 Mississippi River flooding were similar to those described in the earlier studies. The 8-m-high, artificially constructed levee represents the tallest of any kind in the region (Robert Keller, U.S. Army Corps of Engineers, 1993, oral commun.). Flood-induced sand boils were widely reported north of Cairo, Illinois, where 4 m of head was available between the river and the landward ground surface. Farther south, greater channel dimensions reduced the flood water height and head differential, and no sand boils were observed.

We examined 12 sites where the flood-induced sand boils occurred along the Mississippi River levee west of Ware, Illinois

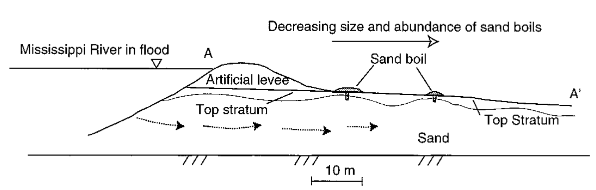

Figure 3. Generalized sand boil formation in study area. Topography profile and water level measured at Ware, Illinois (A to A′ in Fig. 1).

Figure 4. Sand boil induced by 1993 flood with levee in background (van on top of levee). See Figure 1 for location of this site.

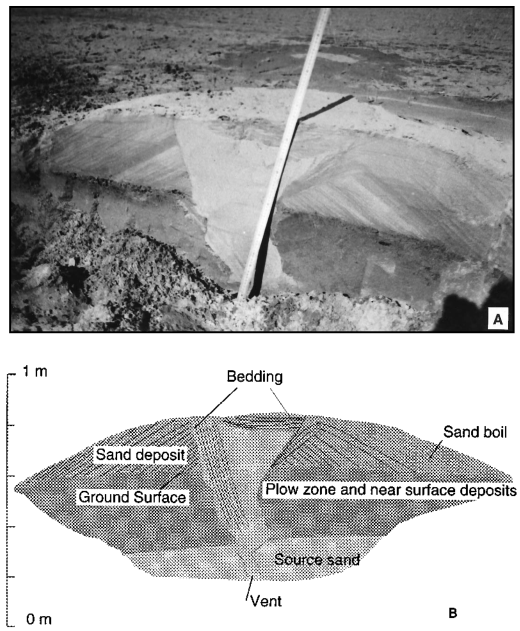

Figure 5. A: Cross section of sand boil shown in Figure 4; stick is 1 m long. B: Log of section shown in A (no vertical exaggeration). Conical sand deposit has alternating bands of dark silty sands and light clean sands that dip steeply away from central vent; filling of irregularly tubular conduit is composed of medium size, clean sand that cuts through original ground surface of silty sand, steep bedding planes within conduit filling represent final ejection of material; plow zone and near-surface sediments; conduit merges downward into shallow layer of source sand.

(Fig. 1). Some sites have only one sand boil, but most have tens of them. Whether widely dispersed or clustered, sand boils formed a beltlike distribution parallel to the levee, the largest and greatest abundance being within 5 m of the levee toe. The size of the sand boils was found to range from about 0.5 m to 10 m in diameter, and their heights were commonly 0.3 m above the ground surface. At a distance of 100 m from the levee, typically only small pin boils were observed. Beyond 100 m, no significant evidence of surface seepage was observed in our study area.

A typical sand boil is a cone-shaped sand deposit overlying and surrounding a vent (Fig. 4). In cross section (Fig. 5), the sand boil can be divided into two parts, sand deposits vented to the surface and a sediment-filled conduit connecting the source to the sand deposits. The deposits consist of alternating bands of dark and light silt dipping 35° to 45° away from the central vent. Individual bands vary in thickness from 0.5 to 10 cm. A grain-size analysis on one sand boil showed that 98% by weight of the grains are smaller than 0.125 mm in diameter. The conduits are tubular, irregularly narrowing with depth until they merge into the source bed. In those sand boils examined, the distance from the ground surface to the source bed averages about 0.3 m, indicating that the underseepage occurs at shallow depths; as the sand deposits gradually accumulated near the conduit, the vent migrated upward into the vented sand deposits.

Subhorizontal lamination can be found in the vent above the surface, which is probably associated with episodic readjustment of pore pressure in the source bed (Fig. 5B). In some sand boils, steeply dipping (60°–65°) bedding is observed inside the conduit (probably representing the last ejection of the mixed water and sediments), but these features are subtle on fresh surfaces. Clasts of host material were not found either inside the conduit or in the surface deposits.

DISCUSSION AND CONCLUSIONS

Distinguishing between flood-induced sand boils and earthquake-induced sand blows is complicated by the fact that geomorphic and pedologic modification will blur initial differences over time. In this study we compare flood-induced sand boils of 1993 and earthquake-induced sand blows produced nearly two centuries earlier. Natural erosion and farming activities have modified many of the 1811–1812 sand blows. If allowed to undergo natural and artificial modification, the cone-shaped sand boils of 1993 would erode, leaving little more than the sand-filled conduit and a thin veneer of sand. However, clear and definable criteria remain that should allow distinction between the two types of deposits (Table 1).

First, the distribution pattern is a diagnostic criterion. Earthquake-induced liquefaction deposits generally will be widely distributed about an epicenter or a presumed epicentral zone. Earthquake features should also be bigger and more abundant about an epicentral region. The density of earthquake features is generally proportional to the magnitude of earthquakes. The 1993 flood-induced sand boils, however, were limited to a 100-m-wide zone near the toe of the levees. Thus, we would expect sand boils induced in a paleoflood to exhibit a narrow, beltlike distribution tightly following a paleochannel.

Second, there is a distinct difference between conduit morphology of earthquake- and flood-induced deposits. The conduits of earthquake-induced sand blows are most commonly planar dikes, which developed in fissures that formed due to lateral spreading above a subsurface liquefied sand layer. The width of the dikes can be more than 2 m. They are sublinear in plan view. In contrast, the conduits of flood-induced sand boils are most commonly circular in plan view and have a tubular, pipelike geometry. The pipes are isolated three dimensionally, and are probably controlled by preexisting holes from decaying tree roots and crayfish burrows within the fine-grained host (Kolb, 1976). The widest conduit we observed was 50 cm in diameter near the ground surface. Some sand boils are reported to have diameters of more than 1 m (Obermeier, 1995).

Third, a depression of the pre-sand-blow ground surface as much as 1 m (sometimes more) is common in the New Madrid region, owing to removal of large amounts of sand and water from below during the eruption of a sand blow. Vertical offset was also observed in the sand blows induced by the Loma Prieta earthquake and its aftershocks (Sims and Garvin, 1995). In contrast, such surface depression was not seen with the flood-induced sand-boil formation, perhaps because the sand source is not concentrated under the sand boil itself but is removed from along the entire path of water flow that runs along the base of the semipervious sedimentary cap (Fig. 3).

Fourth, earthquake-induced liquefaction deposits in the New Madrid seismic zone are commonly poorly sorted, reflecting the grain-size distribution of the source beds, whereas flood-induced sand-boil deposits are well sorted, probably due to less-energetic extrusion during flood-induced piping. The grains in flood-induced

TABLE 1. COMPARISON OF EARTHQUAKE-INDUCED SAND BLOWS AND FLOOD-INDUCED SAND BOILS IN THE MISSISSIPPI RIVER VALLEY

	Earthquake-induced sand blows	Flood-induced sand boils
Distribution	Widely distributed; largest and most abundant near epicenter	Limited to a narrow band close to levee system, commonly within 100 m
Conduit morphology	Planar dikes along fractures even for small sand blows; vent width and length may be large but variable	Generally relatively small tubular pipes
Preexisting ground surface	Commonly depressed because of collapse into void from which material removed	Commonly unwarped
Particle size, texture, and bedding features	Grain size varies greatly; gravel and silt may appear as structureless mass; some flow structures	Very fine grained silt, well sorted, homogeneously distributed; commonly laminar horizontal bedding in sand boil deposit
Material source	Below impermeable capping clay or silt; clasts of side-wall material commonly included	Shallow-source sand; clasts of other materials rare

sand boils are significantly finer than those in earthquake-induced sand blows.

Finally, the source layer of sand boils is always observed to be near surface, in contrast to the long dikes of earthquake-induced deposits that commonly penetrate to a depth of 2–7 m. In addition, the near absence of clasts of material removed from the surrounding deposits in the flood-induced deposits is attributed to a shallow source layer and a low-energy driving mechanism.

The Wabash Valley region, where dikes and vented deposits have been discovered recently, has provided a good field area to apply these criteria. Obermeier et al. (1993) used criteria similar to those listed above to infer that the features around the Wabash Valley were the result of earthquake-induced liquefaction, rather than flood-induced piping. First, the planar dikes and vented deposits in the Wabash Valley are distributed regionally. Although exposure is best along the Wabash River and its tributaries, many dikes occur in flat-lying regions hundreds to thousands of metres away from any breaks in topographic slopes. Second, the maximum width of the dikes generally decreases radially with increasing distance from a central area of large dikes. Third, the grain sizes of liquefaction deposits vary even more greatly than in the New Madrid seismic zone, and coarse gravels are common. Finally, the dike fillings (large gravels and large clasts of upward-transported side-wall material) indicate a high-energy environment. Obermeier et al. (1993) argued that these features in Holocene sediments were induced by strong prehistoric earthquakes (moment magnitude **M** ~7.5). The earthquake source was located in the vicinity of the Wabash Valley.

Thus, in cases where dating techniques are sufficient to demonstrate that a suite of sand blows or sand boils is contemporaneous, the first criterion, the distribution pattern, may satisfactorily distinguish the two types of deposits. However, it may be necessary to bring all the criteria to bear on the problem.

There remains the question of whether, in the absence of artificial levees, extensive sand boils would form by the mechanism of hydraulic-head difference; we expect not. We know of no natural levees anywhere that are as tall, narrow, and long as the artificial levees in the modern flood plain (Stanley Schumm, 1995, oral commun.). The height of natural levee ridges along the Mississippi River is normally between 3.0 and 4.6 m, and they are interrupted by many breaks along their length (Kolb, 1976). Even during the great 1993 flood, when the water level was 4 m above the surrounding flood plain, sand boils were observed only within 100 m of the artificial levees. That deposition of overbank sediments was common before the building of the artificial levees and occurs rarely now provides further testimony that natural levees generally are lower than modern artificial levees. In addition, the artificial levees commonly are constructed of impermeable materials, forcing water flow to concentrate beneath the levee fill, whereas natural levees are largely formed from semipervious silt deposits (Kolb, 1976). Floods occur frequently along the Mississippi River and its tributaries (much more frequently than earthquakes capable of inducing liquefaction), and both modern and abandoned natural levees are abundant in the Mississippi River flood plain; if natural levees led to development of sand boils, it might be expected that flood-induced sand boils would be commonplace, yet in our paleoearthquake studies we have not encountered any sand features that would meet the criteria we have listed above for sand boils.

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