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Evidence of Strong Earthquake Shaking in the Lower Wabash Valley from Prehistoric Liquefaction Features

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Earthquake-induced liquefaction features in Holocene sediments provide evidence of strong prehistoric shaking, magnitude m_b 6.2 to 6.7, in the Wabash Valley bordering Indiana and Illinois. The source of the one or more earthquakes responsible was almost certainly in or near the Wabash Valley. The largest event is interpreted to have occurred between 7500 and 1500 years ago on the basis of archeological, pedological, and stratigraphic relations.

Five slightly damaging earthquakes having body-wave magnitudes (m_b) of 5.0 to 5.8 and many smaller events have taken place in and near the lower Wabash River Valley of Indiana and Illinois during the 200 years of historic record (*1*). Because of this continuing seismicity and the numerous faults in the Wabash Valley seismic zone [as defined by Nuttli (*2*)] the tectonic setting (*3*) has long been suspected of having the capability to produce shaking much stronger than observed. Some of the faults may be related to faults associated with the great earthquakes of 1811 to 1812 near New Madrid, Missouri (Fig. 1). The northern limit of the 150-km-long causative fault of the four largest of these earthquakes (m_b 7.0 to 7.4) (*4*) lies just south of Illinois and strikes northeastward toward the Wabash Valley seismic zone.

To determine whether the lower Wabash Valley has sustained strong earthquake shaking in the recent geologic past, we undertook a field search for earthquake-induced liquefaction-flowage features. Liquefaction results from strong shaking of loose, water-saturated, subsurface sediment. Once liquefaction occurs, water and sediment can flow toward the ground surface along fissures opened through overlying finer grained sediments. Common evidence of liquefaction and flowage includes sand-filled dikes and small mounds of sand (sand volcanoes) ejected to the surface, called "sand blows" (*5*). The 1811–1812 earthquakes produced many large sand blows and sand-filled dikes in and near their epicentral region (*6, 7*), and small sand blows were reported in the southernmost 30 km of the Wabash Valley (*8*). As a result of our search in the lower Wabash Valley, we identified several tens of liquefaction features (Fig. 1) similar to but predating those produced by the 1811–1812 earthquakes. These features occur in Holocene meander-belt deposits along the Wabash and White rivers and in Upper Pleistocene glacial outwash and lake deposits.

The liquefaction features in the Wabash Valley are planar sand-filled dikes that are vertical to steeply dipping and that widen downward and connect to a sediment source at depth. The dikes cut through a low-permeability cap, generally rich in silt and clay, that overlies the source strata of silty to gravelly sand. Dikes are as long as 3.5 m and as wide as 0.6 m at depths near the source. Sediment in various dikes ranges from silty fine sand to fine and medium sand to silty gravelly sand; grain size tends to fine upward where gravel occurs. At two exceptionally large dikes (Sites BR and PB), sediment that vented onto an ancient ground surface is still visible in vertical section as a buried sand-rich zone beneath younger alluvium (Fig. 2).

In addition to the similarities with dikes near the epicenter of the 1811–1812 earthquakes, other evidence also shows that the features in the Wabash Valley were created by earthquake-induced liquefaction. Syndepositional processes can be eliminated as the origin because the dikes cut across sediment much younger than the source sands, or else the dikes cut across thick, highly plastic clay that accumulated slowly in a swamp environment; the possibility of rapid build-up of pore pressure due to sudden deposition of overlying sediments is therefore eliminated. Other non-earthquake origins that could have produced superficially similar features are permafrost, artesian springs, and landslides. These are rejected because of the following aspects of the dikes: (i) they widen downward; (ii) they are strongly aligned in local areas; (iii) they vented to the surface; (iv) material in the dikes fines upward and was transported upward; (v) bedding in the source beds is homogenized and contacts with overlying fine-grained material are highly convoluted in some cases; (vi) dikes occur in flat and topographically elevated landforms; and (vii) the size of the dikes generally decreases with increasing distance from a central area of large dikes (see Fig. 1).

Consideration of dike sizes and distribution in the Wabash Valley, in conjunction with the regional geological setting and seismic record, shows that the tectonic source area was near the lower Wabash Valley. The decreasing size of dikes with increasing distance from a central area probably reflects variations in the shaking of the underlying bedrock, because liquefaction susceptibility at the sites (Fig. 1) is relatively

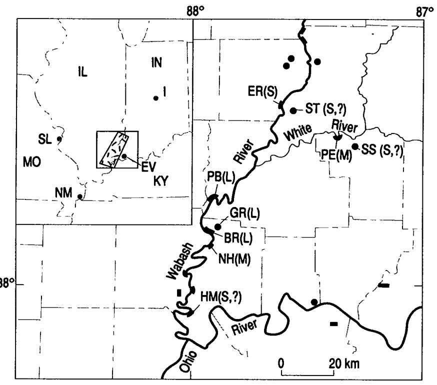

Fig. 1. Localities searched having sediments susceptible to liquefaction; dots are sand pits and heavy lines are stream banks. Sites having dikes are shown in capital letters. Maximum width of dikes shown as L (large, >15 cm), M (medium, >6 cm), or S (small, <6 cm); question mark indicates uncertain earthquake origin. County boundaries are shown as dashed fine lines. Patterned area on regional map shows Wabash Valley seismic zone; box indicates the study area. SL, St. Louis; I, Indianapolis; EV, Evansville; NM, New Madrid.

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uniform regionally, in that the depth of the water table and thickness and properties of alluvium are similar. In addition, historical data on earthquakes, and especially data showing the distribution of liquefaction features induced by the 1811–1812 earthquakes (*6*), do not indicate that earthquakes originating elsewhere could have caused the anomalously high degree of bedrock shaking required to account for the features we observed in the Wabash Valley. Thus, a local tectonic source almost certainly induced the features.

We have not discovered organic matter directly associated with the liquefaction features that is suitable for radiocarbon dating. Constraints on the time of liquefaction can be placed only at sites in the cluster of large dikes and nearby medium dikes (Sites GR, PB, BR, and NH) if stratigraphic, pedological, and archeological relations are used. At Site GR, the dike source materials are braided-stream, low-terrace deposits from the last large discharges down the Wabash River from Glacial Lake Maumee, dated shortly after 14,000 years ago (*9*). The dikes penetrate fine-grained materials largely deposited during late Pleistocene to early Holocene floods, on the basis of archeological data; Paleo-Indian (12,000 to 10,500 years ago) and Early Archaic (10,500 to 8,000 years ago) artifacts are common on the Maumee terrace surface, and one habitation site (12-Po-889) has also been found 200 m from the dikes at Site GR. Comparison of soil development in dike fillings and in undisturbed adjacent soil shows that the dikes postdate terrace formation, all overbank deposition, and most Holocene soil development. Because the dikes cut across a relatively well-developed modern B horizon, yet contain beta-B development (iron oxide films and clay enrichment at the base of the B horizon), some antiquity for the liquefaction event is indicated. Possibly more than one liquefaction event is shown by cross-cutting of coarse and fine material within dikes at Site GR.

Other sites in the cluster of large dikes and nearby medium dikes are in Holocene meander-belt deposits. At Site NH, a leaf-litter mat lying upon point-bar sand and gravel (dike source material) has a ^{14}C age of 9040 ± 150 years ago, which provides a maximum age for the dikes. Dikes at Sites PB, BR, and NH, like those at Site GR, also contain beta-B development.

At Site PB, dikes vented onto a paleosol (3Bwb) that is now buried by more recent overbank deposits (Fig. 2). The buried soil overlies a still older buried soil (4Bwb). Dikes intersect both paleosols. An archeological site (11-W-113) on the lowest paleosol contains hearth features. Wood and nut charcoal from the hearth shown in Fig. 2 has been ^{14}C-dated at 7570 ± 130 years ago. A minimum age for the earthquake at Site PB is determined by archeological Site 11-W-68, where artifacts of the Middle Woodland Period (1500 to 2000 years ago) lie on sediments that cap the vented material.

Relatively minor, although variable, modern pedogenesis has penetrated sediments capping the large dikes and the now buried vented sediments. The degree of soil development in materials capping vented sediments and in beta-B extensions into dike fillings shows that all the liquefaction features must be at least several hundred years old but much younger than the early and middle Holocene sediments cut by the large dikes. The grouping of large dikes in a restricted area, all with limited yet easily recognizable soil development (*10*), suggests that at least most of these dikes were formed from a single earthquake; various lines of evidence yield an age sometime between 7500 and 1500 years ago. Smaller liquefaction features, far from the group of large dikes (>40 km), cannot yet be assigned ages other than Holocene. Probably the only features we discovered in our study area that might have been induced by the 1811–1812 earthquakes are the southernmost small dikes at Site HM.

The magnitude of the prehistoric earthquake or earthquakes that induced the Wabash Valley liquefaction features probably exceeded m_b 6.2. Historic Wabash Valley earthquakes having magnitudes up to m_b 5.8 have not induced liquefaction (that was reported). The smallest regional, historic earthquake that induced liquefaction was the m_b 6.2 event within the New Madrid seismic zone at Charleston, Missouri (*11*), 40 km north of New Madrid. That event produced only small sand blows scattered over a 16-km-diameter area near Charleston. The Wabash Valley prehistoric examples consist of large dikes within at least a 14-km-wide zone, north to south, and smaller dikes beyond (Fig. 1). Thus, in the Wabash Valley, at least one local event probably exceeded m_b 6.2 (*12*) as suggested by the formation of larger features than the m_b = 6.2 Charleston event and by the translocation of gravelly sands, which are difficult to liquefy and vent. If a single event produced the dikes extending from Sites ER and PE to NH, spanning more than 60 km, the strength of this earthquake could have approached that of another intraplate earthquake, the 1886 earthquake of Charleston, South Carolina ($m_b \simeq 6.7$), as suggested by comparison of sizes and areal distribution of liquefaction features in South Carolina (7) with those in the Wabash Valley. Whatever earthquake magnitude produced the Wabash Valley features, the ground shaking far exceeded that which has taken place in the 200-year historical record.

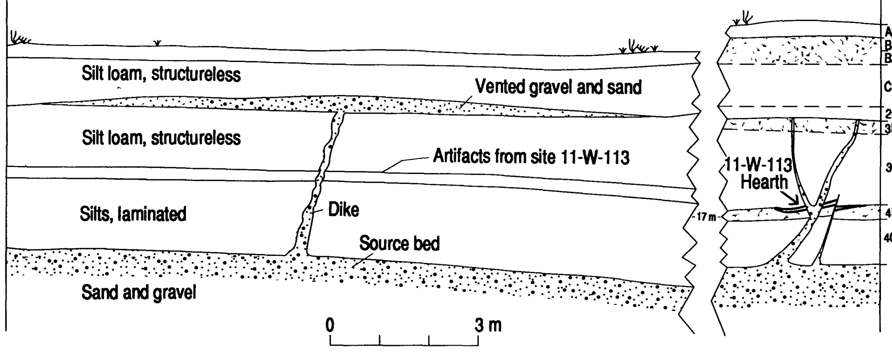

Fig. 2. Vertical section of Site PB showing relation of dikes and vented sand to archeological sites, modern soil, and paleosols. Soil horizons are shown in detail at right. Archeological site 11-W-68 is located on the surface 500 m to the north. No vertical exaggeration.

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response to the 1811–1812 New Madrid earthquakes. Such vented sediments are extensive south of the town of New Madrid (Fig. 1), in the epicentral region of the 1811–1812 earthquakes.
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13. Research by the U.S. Geological Survey in the Wabash Valley is supported through the National Earthquakes Hazard Reduction Program in cooperation with the U.S. Nuclear Regulatory Commission.

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New Fossil Evidence on the Sister-Group of Mammals and Early Mesozoic Faunal Distributions

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Newly discovered remains of highly advanced mammal-like reptiles (Cynodontia: Tritheledontidae) from the Early Jurassic of Nova Scotia, Canada, have revealed that aspects of the characteristic mammalian occlusal pattern are primitive. Mammals and tritheledontids share an homologous pattern of occlusion that is not seen in other cynodonts. The new tritheledontids represent the first definite record of this family from North America. The extreme similarity of North American and African tritheledontids supports the hypothesis that the global distribution of terrestrial tetrapods was homogeneous in the Early Jurassic. This Early Jurassic cosmopolitanism represents the continuation of a trend toward increased global homogeneity among terrestrial tetrapod communities that began in the late Paleozoic.

CURRENT VIEWS OF THE PHYLOGENY and biogeography of early mammals have been hampered by a poor understanding of their sister group. Recently, the tritheledontid synapsids have been hypothesized to be the sister-group of mammals (*1*). Relatively little material has been described, and consequently the early evolution of characteristic mammalian features remains poorly understood.

The family Tritheledontidae was initially proposed to include the genera *Pachygenelus, Diarthrognathus,* and *Tritheledon,* all from the Lower Jurassic upper Stormberg Group of South Africa (*1, 2*). Subsequently, *Therioherpeton* (Upper Triassic Santa Maria Formation, Brazil) (*3*), *Chaliminia* (Upper Triassic Los Colorados Formation, Argentina) (*4*), and a fragmentary jaw referred to *Pachygenelus* (Upper Triassic Dockum Formation, Texas) (*5*) were referred to the family Tritheledontidae. The single record of *Pachygenelus* from Texas is doubtful and lacks any diagnostic cynodont characters because all the teeth are fused to the jaw and there are no cingula on the postcanine teeth (*6*). The Nova Scotian tritheledontid, described below, thus constitutes the first definite record of this family from North America.

Tritheledontidae is considered the sister-group of mammals on the basis of the following synapomorphies (*1*): (i) basicranium foreshortened anteroposteriorly; (ii) prismatic tooth enamel (*7*); (iii) buccal (external) cingulum on the upper postcanine teeth; (iv) absence of postorbital (and postorbital bar); (v) absence of postfrontal; and (vi) secondary pony palate that extends to the level of the posteriormost postcanine. Another synapomorphy with mammals is the presence of a jaw joint between the dentary and squamosal (*8*).

The new tritheledontid material was found in the Lower Jurassic sedimentary rocks of the McCoy Brook Formation of the Fundy Group (Newark Supergroup) in Nova Scotia, Canada. The Fundy Group is a >1000-m-thick sequence of predominantly red clastic rocks and extrusive tholeiitic basalts (*9*). Five formations ranging in age from Middle Triassic to Early Jurassic are recognized, of which the McCoy Brook is the youngest. Tritheledontid remains occur in two distinct facies within the McCoy Brook Formation: a brown, fluvio-lacustrine sandstone and a basalt talus agglomerate. Palynological, footprint, and radiometric data suggest an Hettangian (earliest Jurassic) age for both facies (*9*). The talus cones contain sandstone-filled fissures with abundant, fragmentary tetrapod remains. The McCoy Brook assemblages are exceptional in the number of different stratigraphic controls that support an Early Jurassic age. In contrast, the ages of the tritheledontid-bearing upper Elliot and Clarens formations (upper Stormberg Group) of South Africa are poorly constrained (*10*).

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To date, excellently preserved fragments of two premaxillae, ten maxillae, and six dentaries have been discovered. The coronal configuration of the postcanine teeth and the structure of the dentary and maxilla of these specimens are indistinguishable from those of *Pachygenelus monus* from the upper Stormberg Group of southern Africa (*11*), and hence the Nova Scotia material is here referred to *Pachygenelus* cf. *P. monus*. The excellent preservation of the dentition allows a detailed analysis of several important aspects of tritheledont dental anatomy, including tooth replacement, enamel structure, and occlusal patterns.

Pachygenelus cf. *P. monus* possesses patterns of tooth implantation and replacement similar to those of more generalized cynodonts such as *Thrinaxodon* (*12*). Tooth replacement is alternating (Fig. 1, A, B, and C). The dental lamina is housed in a small fossa that contains small pits for replacing teeth. The mode of tooth implantation is correlated with the pattern of tooth replacement. Older, well-worn postcanines are fused to the alveoli by a small ring of attachment bone. This feature is highly variable along the tooth row; newly replacing teeth are implanted in the alveoli without any bony attachment.

The molariform teeth of early mammals are distinguished by bifurcated roots that are oriented longitudinally in the jaw (*13*). The roots of the postcanine teeth of *Pachygenelus* cf. *P. monus* are intermediate in this condition in that they incipiently divided longitudinally (Fig. 1D).

Several aspects of the dentition of *Pachygenelus* are similar to primitive mammals (*1*) such as *Morganucodon* and *Megazostrodon* and are therefore derived with respect to other nonmammalian cynodonts. In both *Pachygenelus* cf. *P. monus* and the Morganucodontidae (*Megazostradon* and *Morganucodon*) the enamel consists of closely packed crystallites with a small difference in orientation between prismatic and interprismatic enamel. No clear prismatic sheath is present. A herringbone arrangement of crystallites is present within each prismatic domain (*14*). This pattern is not seen in any other nonmammalian cynodont.

Mammals have long been thought to be distinguished by consistent patterns of occlusal wear that suggest stereotyped patterns of jaw movement (*13*). *Pachygenelus* cf. *P. monus* provides the first evidence that several aspects of this pattern are primitive. A char-