Extent and Character of Soil Liquefaction during the 1811–12 New Madrid Earthquakes

STEVEN G. WESNOUSKY, EUGENE S. SCHWEIG, AND SILVIO K. PEZZOPANE

Center for Earthquake Research and Information
Memphis State University
Memphis, Tennessee 38152

INTRODUCTION

The great 1811–12 New Madrid earthquakes produced extensive liquefaction which is still very much in evidence today. Visible as a myriad of light-colored and often irregular shapes against the dark brown soils of the Mississippi embayment, sands liquefied and extruded during the 1811–12 earthquakes are still readily recognized both in the field and on aerial photographs. No systematic studies of the geological effects of the earthquake were undertaken immediately after the earthquakes. Consequently, the extent, magnitude, and style of liquefaction produced by the earthquakes can be assessed from compilations of graphic accounts of contemporaries who witnessed the events and from later studies of evidence registered in the geologic record. Our intent here is not to duplicate those efforts. Rather, we will limit ourselves to a brief synopsis of work bearing on liquefaction which took place during 1811–12 as a basis for discussing the potential that still exists to advance our understanding of liquefaction processes and seismic hazard in the Mississippi embayment through further study of the geologic record.

THE NEW MADRID SEISMIC ZONE

Seismological Characteristics

The New Madrid Seismic Zone strikes about 175 km in a northeasterly direction through the Mississippi embayment, from near Memphis, Tennessee in the south to Cairo, Illinois in the north[1] (FIG. 1). The seismic zone is not expressed on the ground surface by an active and mappable fault zone, though subtle evidence of tectonic warping and faulting of recent sediments have been reported in a limited region overlying the seismic zone.[2–6] Nonetheless, reviews of isoseismal data and secondary ground deformations resulting from the New Madrid earthquakes lend strong support to assertions that the New Madrid Seismic Zone was indeed the source of the displacements that produced the 1811–12 New Madrid earthquakes.[7] Isoseismal data show that the 1811–12 sequence of earthquakes was arguably the largest seismic disturbance in the conterminous United States during historical time (FIG. 2). The magnitude and extent of observed ground deformations are consistent with such an argument.

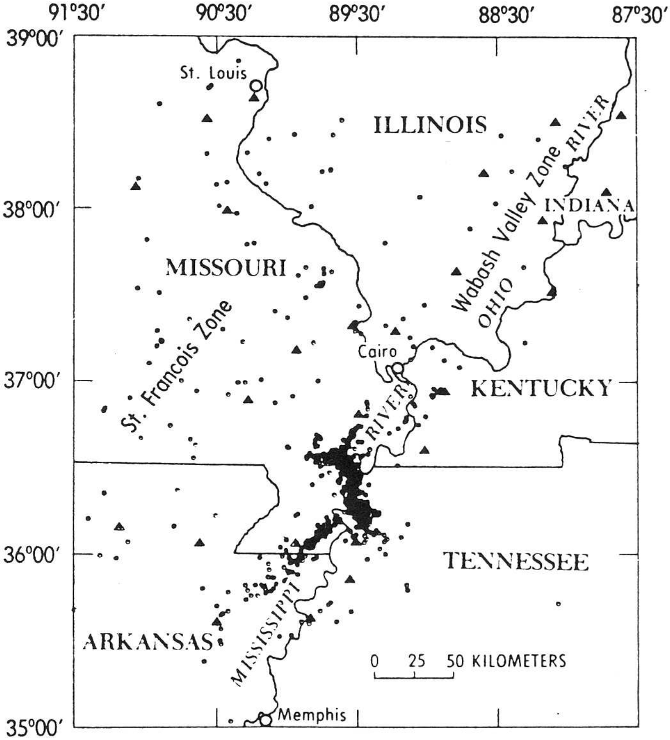

FIGURE 1. The location of the New Madrid Seismic Zone is clearly delineated by this plot of earthquake epicenters and extends from south of Cairo, Illinois to northwest of Memphis, Tennessee. (Adapted directly from Stauder.[1])

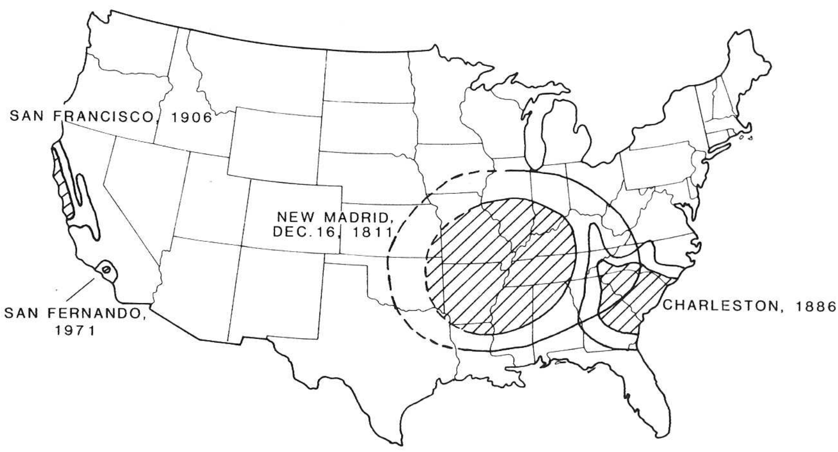

FIGURE 2. Isoseismals of Modified Mercalli (MM) VI and VII for four major United States earthquakes. Regions sustaining MM VII shaking or greater are *hachured*.

Contemporary Accounts of Liquefaction Phenomena during 1811–12

Initial reports of ground deformations and damage during the earthquakes are primarily the result of eyewitness accounts of local inhabitants. Several compilations of such material have been published since 1811–12.[8–11] Although personal accounts of the earthquakes are often and understandably biased toward the sensational, compilations of those accounts leave no doubt regarding the extensive nature of liquefaction during 1811–12. Perusal of the accounts provides evidence of major liquefaction phenomena, including extensive ground fissuring, the ejection of sand, water, and other debris through fissure systems, the settling of extensive tracts of land below the water table, and numerous landslides along the bluffs that border the Mississippi River. Evidence of the style, magnitude, and extent of liquefaction that took place in 1811–12 is also provided by geologic studies subsequent to the earthquakes.

Geologic Accounts of Liquefaction Phenomena

Sir Charles Lyell was among the first geologists to visit and provide a graphic description of liquefaction phenomena as recorded in the geologic record.[12] Lyell recorded the still relatively fresh evidence of fissuring, sand blows, landslides, and "sunken" lands. A number of other descriptions of geologic deformations that occurred during the 1811–12 earthquake were reported during the century after the earthquake. Among them, Usher[2] and McGee[3] cited evidence for doming and uplift of young alluvial sediments in the New Madrid region. The first work to systematically document the style, extent, and magnitude of deformations resulting from the New Madrid earthquakes is Fuller's[9] synthesis of prior accounts of the earthquakes, and report of his own geological traverses across the region nearly 100 years after the event. Fuller's work shows that liquefaction during 1811–12 was pervasive within a zone ranging from 20 to 50 km wide extending northeasterly for a distance of about 150 km from near Memphis, Tennessee in the south to New Madrid, Missouri in the north (FIG. 3). Fuller concluded that fissuring of the ground surface was the most common and widespread form of liquefaction phenomena within this zone. He cited contemporary accounts indicating fissures reaching to 5 miles in length and 600–700 feet in width. His study of landforms showed that the fissures commonly produced the down-faulting of narrow blocks to 5 or 6 feet or more, and were generally limited to the portion of the zone south of New Madrid, within the broad flat alluvial bottoms of the Mississippi and St. Francis drainage basins. The creation of fissures was often accompanied by the ejection of water, sand, mud, and gas. Ejecta commonly were produced through sandblows, leaving distinct patches of sand reaching diameters of 100 feet or more for circular varieties, or lengths of 200 feet and breadths of 25–50 feet for the linear varieties. In other cases, the amount of ejecta was sufficient to cover tracts of land many miles in extent by sand and water 3 to 4 feet in thickness and depth, respectively. Local settling or warping of alluvial deposits due to ground shaking also resulted in flooding of tracts of land miles in extent and, in turn, the widespread destruction of forest lands. Fuller[9] also corroborated eyewitness accounts of extensive landslide failures by observing the scars of landslides still well preserved and concentrated along the set of bluffs that border the eastern edge of the Mississippi River between New Madrid, Missouri and Cairo, Illinois. Contemporary and geologic accounts thus show that essentially every type of liquefaction failure that has been observed during recent earth-

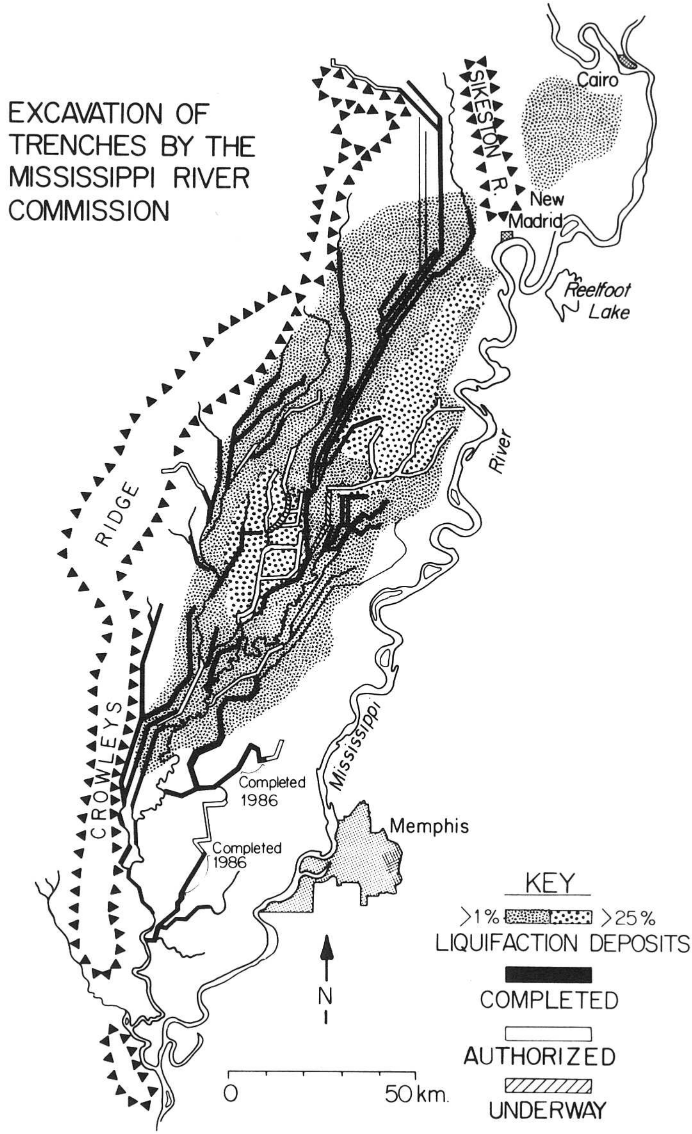

FIGURE 3. Aerial photography and field studies[9,13,14] show that liquefaction phenomena were pervasive during 1811–12 in the region extending from near Cairo, Illinois to northwest of Memphis, Tennessee. Areas in which liquefaction deposits still comprise ≥1% and ≥25% of the ground cover are *shaded* and *stippled,* respectively. The region of liquefaction south of New Madrid encompasses the St. Francis drainage basin, which empties into the Mississippi River south of Memphis. It is this region that Fuller[9] referred to as the "St. Francis Sunk Lands." For purposes of flood control and land reclamation, the U.S. Army Corps of Engineers has excavated an extensive network of drainage channels. The channels, which range from completed (*black*) through under way (*hachured*) to authorized (*open*) for excavation in the near future, total hundreds of kilometers in length, are generally several or more meters in depth, and are tens of meters wide. Excavation of these channels provides kilometers of new exposure each year, which is ideal for examining the geologic record of liquefaction within the St. Francis Sunk Lands.

quakes was pervasive over a region measured in thousands of square kilometers during 1811–12. Indeed, liquefaction phenomena reported for other large earthquakes within the conterminous United States during historical time pale in comparison to those registered during the New Madrid earthquakes.

During the last decade, investigators have used aerial photography to reexamine the extent of liquefaction during the 1811–12 earthquakes. Jibson and Keefer[15] examined landslide deposits along the bluffs that run along the eastern edge of the Mississippi River between about New Madrid, Missouri and Memphis, Tennessee. They concluded that the majority of landslides in evidence were produced by shaking during 1811–12, and that the entire extent of bluffs remains extremely susceptible to landsliding during earthquakes. Heyl and McKeown's[13] and Obermeier's[14] recent use of aerial photography generally confirmed Fuller's conclusions regarding the extent of liquefaction in 1811–12 (FIG. 3). Of considerable interest, the above zone of concentrated liquefaction deposits overlies the zone of microearthquakes which define the New Madrid Seismic Zone (FIGS. 1 and 3).

Potential for Further Study

It is thus evident from reports of the 1811–12 earthquakes that deposits of the Mississippi embayment are extremely prone to liquefaction. The New Madrid region is a vastly different place than it was in 1811–12. Characterized by a population measured in the thousands in 1811–12, the number of people living within the zone marked by strong ground motions in 1811–12 now measures in the millions. In that regard, we may be certain that the recurrence of earthquakes similar to those in 1811–12 would produce equally extensive liquefaction and, in turn, immense losses to property and life. However, there are few data that bear upon how often events similar to those of 1811–12 occur, or whether such earthquakes can be expected to occur elsewhere in the Central United States. For example, Johnston and Nava[16] recently estimated the average repeat time of New Madrid-type earthquakes to equal about 600 years, but their estimate was based on the extrapolation of instrumentally recorded data reaching back only 10 years and historical records for the period after 1811. A similar value of repeat time for large earthquakes in the region was also put forth by Russ[4] primarily on the basis of geomorphic study if displaced and deformed near-surface sediments exposed along Reelfoot Fault. That estimate, however, was limited because it is not certain that the discrete displacements registered in the trench were due to earthquakes equivalent in size and origin to the New Madrid earthquakes.[4] The widespread liquefaction phenomena recorded so well in the stratigraphy of the Mississippi embayment represent an excellent opportunity to further address the question of seismic potential in the Mississippi embayment.

Recent studies in Charleston, South Carolina have shown the potential value that geological study of liquefaction effects may play in understanding the prehistoric record of large earthquakes in a region.[17,18] As yet, a systematic study of liquefaction phenomena to identify deformation due to prehistoric earthquakes within the Mississippi embayment has not been done. Ongoing flood control efforts by the U.S. Army Corps of Engineers have resulted in an extensive system of major drainage channels throughout the New Madrid Seismic Zone (FIG. 3). The most recently excavated channels provide an excellent opportunity to search for liquefaction features that possibly predate the 1811–12 sequence and to examine the mechanics of liquefaction in cross-section as well. Thus far, we have examined several sites along these channels on a reconnaissance basis. Although evidence of earthquakes prior to 1811–12 has not been observed, the resulting logs of exposed sediments show the excellent exposure of liquefaction phenomena afforded by the Corps' channels.

Logs of two exposures examined near Big Lake, Arkansas are shown in FIGURES 4 and 5. At site No. 1 (FIG. 4) the exposed strata consist of thick soil horizons underlain by fine- to medium-grained alluvial sands alternating with clay beds. The logs clearly show that impermeable clay layers play a controlling role in the liquefaction process by limiting the vertical flow of sands, as evidenced by sills

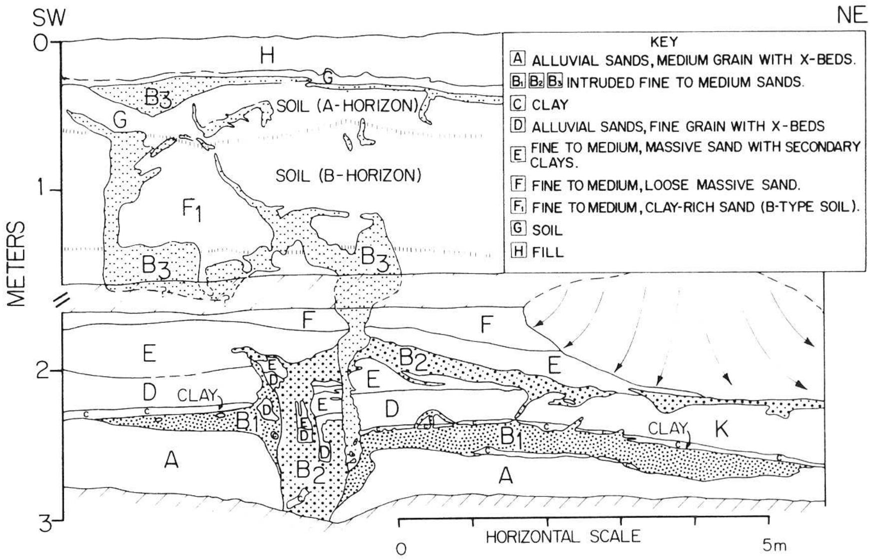

FIGURE 4. Trench log demonstrates excellent exposure of liquefaction phenomena afforded by channels recently excavated by the Army Corps of Engineers. At this site (No. 1), near Big Lake, Arkansas, cross-cutting relations show evidence of three episodes or phases of sand injection (*stippled units* B_1, B_2, and B_3). The competent clay (unit C) and clay-rich (unit E) layers inhibited the upward propagation of liquefied sand, as evidenced by the intruded sills of liquefied sand which underlie the respective units. The horizontal extent of these sills reaches to near 10 m in this exposure.

of sand (stippled) that extend from the central pipe to a distance of approximately 5 meters horizontally beneath impermeable clay layers. Cross-cutting relationships further indicate several phases of sand injection (FIG. 4). In this case, the liquefied sand was primarily limited to injection into dikes and sills in the subsurface. Site No. 2 (FIG. 5) shows the cross section of a sandblow or fissure that shows apparent extension of about 50 cm and from which extruded sands reached to about 1 meter in thickness. The exposures are limited to between 2–3 meters in depth by the water table at both sites Nos. 1 and 2, and the source of liquefied sands is below this level in each case. Although evidence of any liquefaction prior to the 1811–12 earthquakes has not been observed in this brief reconnaissance, our work shows that the preexisting and growing network of drainage channels provides perhaps the most viable and economic opportunity to systematically examine the mechanics of liquefaction and to search for evidence of large earthquakes prior to 1811–12 within the Mississippi embayment. This resource currently remains untapped.

SUMMARY

The great 1811–12 New Madrid earthquakes produced extensive liquefaction which is still very much in evidence today. Visible as a myriad of light-colored and irregular shapes against the dark brown soils of the Mississippi embayment, sands liquefied and extruded during the 1811–12 earthquakes are readily recognized

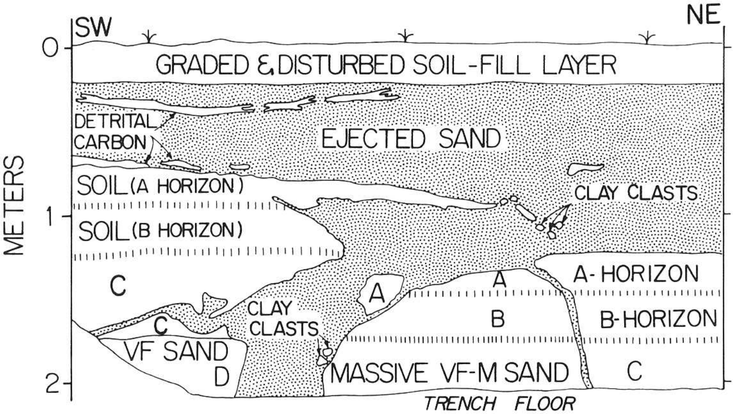

FIGURE 5. A second example of liquefaction exposed near Big Lake, Arkansas (site No. 2) shows the extrusion of sand through soil horizons, resulting in an overlying deposit of sand up to 1 m thick.

both in the field and on aerial photographs. The extent of surficial liquefaction deposits produced by the 1811–12 earthquakes has been well established by both field studies and airphoto analyses. Liquefaction deposits are most concentrated in a zone approximately 20–50 km wide that strikes southwestward about 150 km along the western edge of the Mississippi River from near New Madrid, Missouri to Marked Tree, Arkansas. Extruded sands account for more than 25% of the surface deposits in much of this area, and excavations show the sand deposits reaching to more than a meter in thickness. It is certain that the occurrence today of similar sized earthquakes in the New Madrid region would produce equally destructive liquefaction. However, few data exist to bear upon how often events similar to those of 1811–12 recur, or whether such earthquakes can be expected elsewhere in the Central United States. Statistical analysis of historical seismicity cannot confidently address these questions because of the relative brevity of recorded history. But clues to the past occurrence of large earthquakes may be recorded in the geology, and application of paleoseismologic techniques may be the key to determining the expected location and occurrence rate of large earthquakes in the area. Ongoing flood control efforts by the Army Corps of Engineers have resulted in an extensive system of major drainage ditches throughout the New Madrid Seismic Zone. The most recently excavated drainage ditches provide an opportunity to look for liquefaction features that possibly predate the 1811–12 sequence and to examine the mechanics of liquefaction in the vertical dimension. Several drainage areas have thus far been examined. Exposed strata are generally composed of fine- to medium-grained alluvial sands alternating with clay beds. Exposures are limited to a depth of about 3 meters by the water table, and the source of liquefied sands is below this level in each case. Exposures examined show that impermeable clay layers play a controlling role in the liquefaction process by limiting the vertical flow of sands, as evidenced by sills of sand extending more than 5 meters from the central pipe beneath impermeable clay layers. Cross-cutting relationships indicate at least several phases of sand injection, but evidence of liquefaction prior to the 1811–12 earthquakes has not been observed. This preliminary work shows that the preexisting and growing network of drainage ditches might provide a good opportunity to examine the mechanics of liquefaction and to search for paleoseismic evidence of large pre-1811 earthquakes within the Mississippi embayment.

REFERENCES

1. Stauder, W. 1982. Present-day seismicity and identification of active faults in the New Madrid seismic zone. U.S. Geol. Surv. Prof. Pap. **1236:** 20–30.
2. Usher, F. C. 1837. On the elevation of the banks of the Mississippi in 1811. Silliman's J. (Am. J. Sci., first series) **31:** 291–294
3. McGee, W. J. 1892. A fossil earthquake [abstract]. Geol. Soc. Am. Bull. **4:** 411–415.
4. Russ, D. P. 1979. Late Holocene faulting and earthquake recurrence in the Reelfoot Lake area, northwestern Tennessee. Geol. Soc. Am. Bull. **90:** 1013–1018.
5. Russ, D. P. 1982. Style and significance of surface deformation in the vicinity of New Madrid, Missouri. U.S. Geol. Surv. Prof. Pap. **1236-H:** 94–114.
6. Stearns, R. G. 1979. Recent vertical movement of the land surface in the Lake County uplift and Reelfoot Lake basin areas, Tennessee, Missouri, and Kentucky. *NUREG/CR-0874*. U.S. Nuclear Regulatory Commission. Washington, DC.
7. Nuttli, O. W. 1973. The Mississippi Valley earthquakes of 1811 and 1812 intensities, ground motion and magnitudes. Seismol. Soc. Am. Bull. **63:** 227–248.
8. Mitchell, S. L. 1815. A detailed narrative of the earthquakes which occurred on the 16th day of December, 1811. Trans. Lit. Philos. Soc. New York **1:** 281–307.
9. Fuller, M. L. 1912. The New Madrid Earthquake. U.S. Geol. Surv. Bull. **494.**
10. Penick, J. 1981. The New Madrid earthquakes of 1811–12. The University of Missouri Press. Columbia, MO.
11. Rankin, D. W. 1977. Studies related to the Charleston, South Carolina, earthquake of 1886—introduction and discussion. U.S. Geol. Surv. Prof. Pap. **1028:** 1–16.
12. Lyell, C. 1849. A second visit to the United States, Vol. 2. Harper and Brothers. New York.
13. Heyl, A. & F. McKeown. 1978. Preliminary seismotectonic map of central Mississippi valley and environs. U.S. Geological Survey Miscellaneous Field Studies Map MF-1011.
14. Obermeier, S. 1984. Liquefaction potential for the central Mississippi Valley. U.S. Geol. Surv. Open File Rep. **84-770:** 391–446.

15. JIBSON, R. & D. KEEFER. 1984. Earthquake-induced landslide potential for the central Mississippi Valley, Tennessee and Kentucky. U.S. Geol. Surv. Open File Rep. **84-770:** 353–390.
16. JOHNSTON, A. C. & S. NAVA. 1985. Recurrence rates and probability estimates for the New Madrid seismic zone. J. Geophys. Res. **90**(B7).
17. OBERMEIER, S., G. GOHN, R. WEEMS, R. GELINAS & M. RUBIN. 1985. Geologic evidence for recurrent moderate to large earthquakes near Charleston, South Carolina. Science **227:** 408–411.
18. TALWANI, P. & J. COX. 1985. Paleoseismic evidence for recurrence of earthquakes near Charleston, South Carolina. Science **229:** 379–381.