Reports

Paleoseismic Evidence for Recurrence of Earthquakes near Charleston, South Carolina

Abstract. *A destructive earthquake that occurred in 1886 near Charleston, South Carolina, was associated with widespread liquefaction of shallow sand structures and their extravasation to the surface. Several seismically induced paleoliquefaction structures preserved within the shallow sediments in the meizoseismal area of the 1886 event were identified. Field evidence and radiocarbon dates suggest that at least two earthquakes of magnitudes greater than 6.2 preceded the 1886 event in the past 3000 to 3700 years. The evidence yielded an initial estimate of about 1500 to 1800 years for the maximum recurrence of destructive, intraplate earthquakes in the Charleston region.*

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One of the largest earthquakes (Modified Mercalli intensity X; estimated magnitude, 6.6 to 6.9) in the eastern United States occurred near Charleston, South Carolina, in August 1886 (*1*). During and immediately after this event, liquefaction of shallow sediments was observed throughout the meizoseismal area in the form of sandblows and accompanying small craters (*2*). In the past decade an intensive effort has been made to determine the cause of this earthquake and the ongoing seismicity in this region (*3*). However, there is considerable debate over the cause of this seismicity and the recurrence rates of large events (*4*).

One of the important elements in assessing the seismic hazard at any location is the determination of the recurrence rates of large events. Charleston lies in an intraplate region, where large earthquakes have been infrequent in terms of the relatively short (300 years) historical record and apparently are not associated with surface faulting. However, each significant earthquake leaves its imprint in the stratigraphic record. A new technique, paleoseismology or the study of prehistoric earthquakes (*5*), is being used to estimate recurrence rates. We now report estimates of recurrence rates in the eastern United States based on paleoseismological investigations in the Charleston area. While many geologic and geomorphic features can provide paleoseismological information, our ongoing work has focused on the identification, interpretation, and analysis of seismically induced liquefaction (*6*) structures that have been preserved within the shallow stratigraphy.

In view of the historical accounts of liquefaction in 1886 and laboratory and other field data suggesting that liquefaction can recur at a site (*7, 8*), we began a search in 1982 for sandblows and other liquefaction features within the meizoseismal area. Our progress was impeded by heavy vegetation and new housing and business developments. During the summer of 1983, a sandblow associated with the 1886 earthquake was excavated and analyzed (*9*). Those results served as a calibration for recently completed field studies in 1984.

Of the different locations where evidence of seismically induced liquefaction features was discovered (Fig. 1), the best results were obtained from several outcrops in a drainage ditch (3 km in length) near Hollywood, South Carolina. Two of these outcrops are herein referred to as sites 1 and 2 (*10*).

Evidence suggesting that at least two temporally distinct earthquakes comparable to the 1886 event occurred during recent prehistoric time was found at site 2 (Fig. 2). The undisturbed stratigraphic sequence comprised of the A, Bh (humate-enriched), and C soil horizons was seen on the northeast and southwest edges of the trench log. Mapping and analysis of the central portion of the trench suggested that liquefaction occurred in the following sequence of events (see Fig. 2). First, a feeder dike of liquefied sand (**1**) expressed as a crosscutting conduit was emplaced across the C horizon. The liquefaction-induced cratering appears to have violently ruptured the existing land surface, expelling the underlying sands and removing most of the Bh-horizon material. Some Bh-horizon material slumped or fell back into the then open crater as blocks (**4**). This crater existed at the site of sand expulsion and was eventually infilled, as evidenced by stratification and grading of sand within the crater (**2**). This structure is similar to an infilled expulsion crater

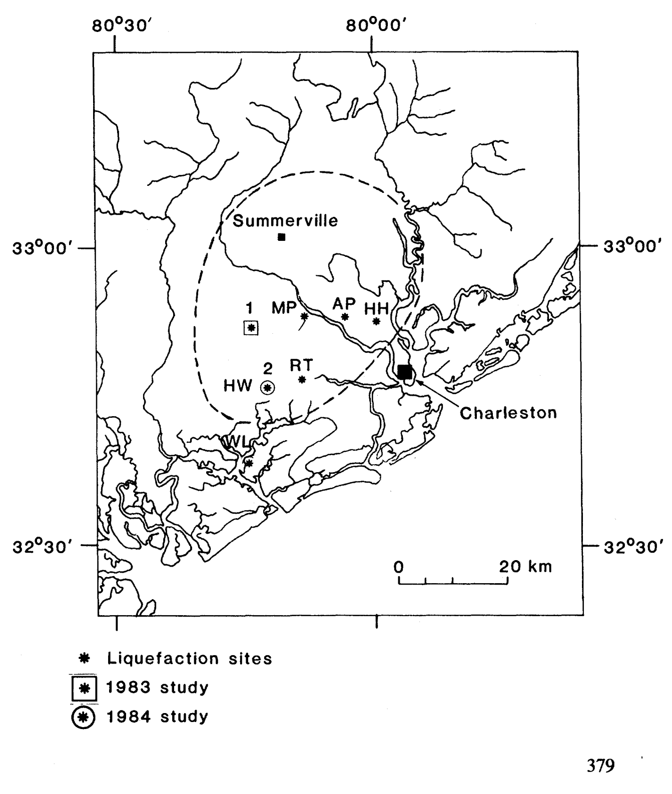

Fig. 1. Map showing the location of both the 1983 study area (**1**) and the 1984 site (**2**), which is located near Hollywood, South Carolina (HW). The dashed outline represents the meizoseismal area of the 1886 earthquake (*2*). Other locations with potential paleoliquefaction features are located at Middleton Place (MP), Rantowles (RT), Wadmalaw Island (WL), a burrow pit near Ashley Phosphate Road (AP), and Hanahan (HH, a probable 1886-age sandblow).

studied in 1983 (*9*) and to craters reported by Dutton (*2*) and Meisling (*11*).

We infer that, because of a subsequent earthquake, liquefied sand was ejected in a conduit (**3**) crosscutting not only the existing soil stratigraphic sequence but also the layered stratigraphy within the earlier crater (**6**); this conduit must therefore postdate the earlier crater. Further, the layered sand (**2**) must have been drained and reasonably consolidated to preserve the crosscutting relations (**6**). Also the sand in the conduit is homogeneous, massive, and lighter in color than the layered sand infilling the crater, suggesting that two different sources of injected sand were involved. Radiocarbon dating of charcoal obtained from material overlying these structures yielded modern (post-1950) ages.

These observations suggest the occurrence of two different episodes of sand intrusion, separated by enough time to allow filling and consolidation in the first crater. The two episodes of sand intrusion should not be considered as contemporaneous—that is, having taken place in response to a main shock and aftershock—but as temporally distinct events. However, no diagnostically located material that could be radiometrically dated was found at site 2; hence only relative ages could be inferred. Although we cannot exclude the possibility that the younger liquefaction event was associated with the 1886 earthquake, the presence of a thick overlying Bh horizon (which takes hundreds of years to form) argues strongly against that possibility.

Site 1, 50 m southwest of site 2, is composed of a preserved crater (**1**) infilled by backwashed sand and humate material (**2**) (Fig. 3). A conduit (**3**) located northeast of the crater is composed of clean, well-sorted, nonbedded sand. The infilled crater is similar to that at site 2. The crater has well-defined lateral boundaries, with the largest clasts of Bh material deposited at the bottom of the structure (**4**). Immediately above the lowermost zone of clasts there is a structureless zone, over which finer grained materials lie in distinct depositional beds.

Field evidence of crosscutting relationships between extruded sands and datable, decomposed roots allowed time constraints to be established for causative seismic events at this site (Fig. 3). Radiocarbon dates obtained from two roots that were crosscut by the conduit at **5** indicated that the conduit (**3**) was emplaced later than 3060 ± 110 years before present. Dating of a root (**7**) that crosscut the infilled crater yielded an age of 1270 ± 90 years, indicating that a large earthquake occurred before this time. Two roots dated at 530 ± 150 (**6**) and 380 ± 220 years before present crosscut the infilled crater, indicating that this structure was in place before 1886. Two small faults (F) along the northeast margin of site 1 may have been generated by slumping of relatively large blocks of C-horizon material toward the crater, offsetting a root dated at 3740 ± 110 years before present. Thus we conclude that the event associated with the formation of the crater (**1**) occurred between 3740 and 1270 years ago.

These stratigraphic relations and dates at site 1 suggest the following possibilities for the timing and number of events. First, the injection of sands in the crater (**1**) is time-correlative with the formation of the conduit (**3**), implying the occurrence of only one pre-1886 event between 1270 and 3060 years ago. Second, the sands in conduit **3** are associated with the 1886 event. The presence of a

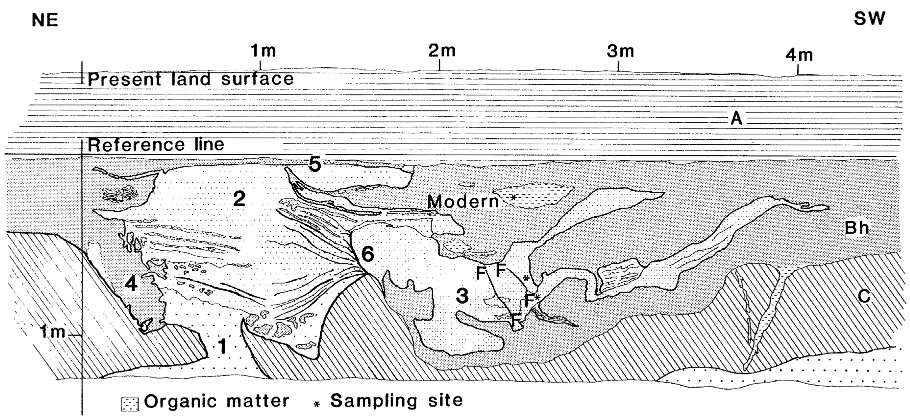

Fig. 2. Trench log showing structures at site 2. The soil profile consisting of A, Bh, and C horizons has been disturbed by two liquefaction events. The structure to the northeast has been interpreted as an infilled crater. A preserved feeder dike (**1**) just below the crater differs markedly from the internal bedding present within the crater (**2**). A large block of Bh material (**4**) slumped along the northeast margin of the crater. A Bh horizon (**5**) that has developed since the emplacement of the crater overlies the crater and attains a maximum thickness of 10 to 15 cm. The undisturbed Bh horizon at this locale typically attains a thickness of 60 cm. Southwest of the crater is another preserved conduit (**3**). We interpret this conduit as being associated with a later event because it truncates the internal bedding of the crater along its southwest margin (**6**). Two small faults (F) are present within this conduit.

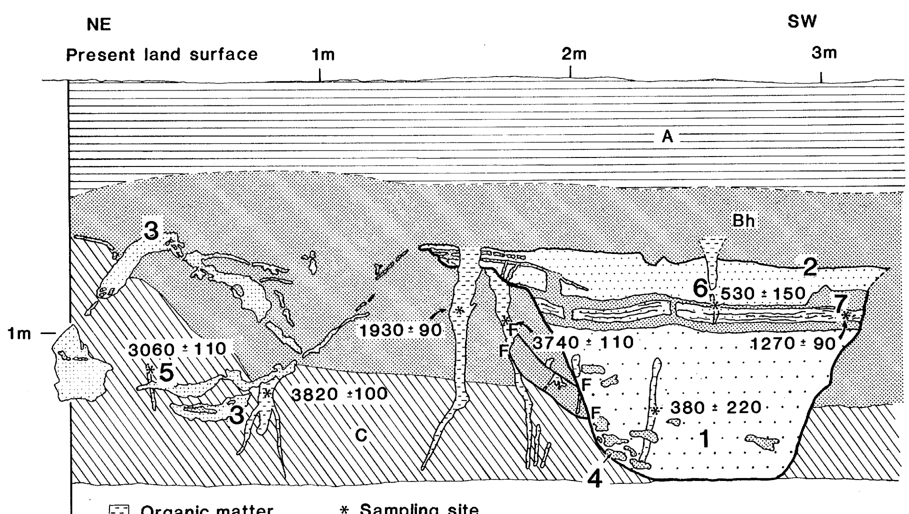

Fig. 3. Cross-sectional trench log at site 1, located approximately 50 m southwest of site 2, where seven samples were radiometrically dated by ^{14}C analysis. The preserved crater (**1**) has the same internal grading and bedding (**2**) and slumped clasts of Bh material (**4**) as were observed at site 2 and at the sandblow studied in 1983. A preserved conduit or sandblow (**3**) is northeast of the crater. Faulting (F) associated with formation of the crater offsets roots dated at 3740 ± 110 years before present. Dates obtained from roots crosscutting the infilled crater yielded ages of 530 ± 150 years (**6**), 380 ±220 years, and 1270 ± 90 years (**7**). The oldest root is not shown because it was covered at the time the outcrop was mapped. Dates from the infilled crater indicate that it was emplaced after 3740 ± 110 but before 1270 ± 90 years before present. An age of 1930 ± 90 years for a root provided no useful data on the timing of events.

thick Bh horizon that was penetrated by the conduit and comparison of the conduit sand with other outcrops suggests that it is associated with a pre-1886 event. The third possibility is that the conduit sand is associated with an event that took place before 1886 but later than 3060 years ago and that is distinct from the event that produced the crater (**1**). This suggests the occurrence of two events between 3740 and 1270 years ago. Comparison of site 1 with site 2 revealed similarities in the stratigraphy, composition, and nature of the liquefied sands. Comparison of the texture, color, and compaction of these sands supports the assumption of two temporally distinct events at site 1 and suggests that they are the same as those seen at site 2.

Although the number of earthquakes inferred at these sites is uncertain, definite field evidence indicates that one event occurred before 1886 with a strong possibility that at least two moderate to large earthquakes occurred near Charleston before 1886 but later than 3740 years ago (possibly between about 3000 and 1200 years ago). When the 1886 event is included, an initial average for a maximum recurrence interval of about 1500 to 1800 years is suggested for the Charleston seismogenic zone. Our results show that, with additional trenches and radiocarbon dating, tighter constraints can be developed for the number and timing of past events.

References and Notes

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2. C. E. Dutton, *U.S. Geol. Surv. Annu. Rep.* **9**, 203 (1889).
3. D. W. Rankin, Ed., *Geol. Surv. Prof. Pap. 1028* (1977); G. S. Gohn, Ed., *Geol. Surv. Prof. Pap. 1313* (1983).
4. L. Seeber and J. G. Armbruster, *J. Geophys. Res.* **86**, 7874 (1981); P. Talwani, *Geology* **10**, 654 (1982); C. M. Wentworth and M. Mergner-Keefer, *Geol. Surv. Prof. Pap. 1313* (1983), p. S1; J. C. Behrendt *et al.*, *ibid.*, p. J1.
5. Paleoseismology was a term first used in the United States by R. E. Wallace [in *Earthquake Prediction: An International Review*, D. W. Simpson and P. G. Richards, Eds. (American Geophysical Union, Washington, D.C., 1982), pp. 290–216; for a review see K. E. Sieh, in *ibid.*, pp. 181–207]. In this field we seek evidence of prehistoric earthquakes as they are preserved in shallow sediments. By dating suitably located organic materials on exposed trench faces, the historical record can be extended back in time and the recurrence rate estimated. Paleoseismic methods have been used extensively in the western United States [see K. E. Sieh, *J. Geophys. Res.* **83**, 3907 (1978); F. H. Swan, D. P. Schwartz, L. S. Cluff, *Bull. Seis. Soc. Am.* **70**, 1431 (1980)]. The first use of this technique in the central United States was by D. P. Russ [*Bull. Geol. Soc. Am.* **90**, 1013 (1979)].
6. Seismically induced liquefaction is usually associated with moderate to large earthquakes and is accompanied by forceful ejection of sand and water and the formation of sandblows and small craters. Liquefaction is caused by an increase in pore-water pressure during passage of seismically generated shear waves. If the pore-water pressure increases to a point equal to that of the confining pressure, the effective stress drops to 0 and the soil will enter a liquefied state (*8*). Well-sorted, cohesionless, water-saturated sands are most prone to liquefaction. For a detailed description of the mechanics of the liquefaction process see, for example, H. B. Seed and I. M. Idriss [in *Ground Motions and Soil Liquefaction During Earthquakes* (Earthquake Engineering Research Institute, Berkeley, Calif., 1982)]. D. P. Russ [*U.S. Geol. Surv. Prof. Pap. 1236* (1982), p. 95] argues that the approximate threshold of liquefaction in the New Madrid region is $m_b \geq 6.2$ (m_b, body wave magnitude). We assume a similar threshold for the Charleston region.
7. R. F. Scott and K. A. Zuckerman, in *The Great Alaska Earthquake of 1964* (National Academy of Sciences, Washington, D.C., 1973), vol. 7, pp. 179–189.
8. T. L. Youd, in *Proceedings of the World Conference on Earthquake Engineering 8*, San Francisco, 21–28 July 1984. In this study, field evidence of recurrence of liquefaction at locations in Japan and the United States is described.
9. J. M. Cox, thesis, University of South Carolina, Columbia (1984).
10. Site 1 is also being investigated by S. F. Obermeier *et al.* [*Science* **227**, 408 (1985)]. The outcrop studied by us is about 30 cm further into the plane of the wall. These are two of four sites where our detailed studies are under way.
11. K. E. Meisling, in *Geological Excursions in Southern California*, P. L. Abbott, Ed. (San Diego State University, San Diego, 1980), pp. 63–66.
12. Funded by a grant from the Nuclear Regulatory Commission following an initial effort funded by the U.S. Geological Survey (contract 14-08-001-21334). We thank several colleagues who visited the trenches and made valuable suggestions, in particular K. Sieh, K. Coppersmith, B. Voight, B. Ehrlich, L. Gardner, and D. Colquhoun. We thank D. Schwartz, K. Coppersmith, and B. Ehrlich for constructive reviews of the manuscript.

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Periodicity in Tree Rings from the Corn Belt

Abstract. *Previous tree-ring studies indicated that the total area affected by drought in the western United States has rhythmically expanded and contracted over the past 300 years, with a period near the 18.6-year lunar nodal and 22-year double-sunspot cycles. Recently collected tree-ring data from the U.S. Corn Belt for the years 1680 to 1980 were examined for evidence of either of these cycles on a regional scale. Spectral analysis indicated no periodicity in the eastern part of the Corn Belt, but a significant 18.33-year period in the western part. The period length changed from 17.60 to 20.95 years between the first 150 years and the last 151. High-resolution frequency analysis showed that the structure of the 18.33-year spectral peak was complex, with contributions from several frequencies near both the lunar nodal and double-sunspot periods. A* t-*test of difference of means in reconstructed annual precipitation weakly corroborated a previous finding of an association between drought area and the phase of the double-sunspot cycle. Both the high-resolution frequency analysis and the* t-*test results indicate that the periodic component of drought near 20 years is too weak and irregular to be of use in drought forecasting for the Corn Belt.*

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Evidence from tree rings of a 20-year rhythm in the total area of drought in the western United States (*1*) has been used to support the hypothesis that drought is linked to the 22-year Hale double-sunspot cycle, the 18.6-year lunar nodal cycle, or both (*2–5*). A convincing explanation of the physical mechanisms linking these solar and lunar cycles to climate is lacking, however, and the sparseness of tree-ring data for some parts of the western United States makes any assessment of the total area of drought conjectural. The largest gaps in coverage are in the grain-producing regions of the U.S. Great Plains, where droughts have been particularly devastating. In a previous study of tree growth in four regions on the fringes of the Great Plains, a period near 20 years was found only for central Iowa (*6*). Tree-ring data from other parts of the Corn Belt have since been collected and used to reconstruct a regional series of annual precipi-

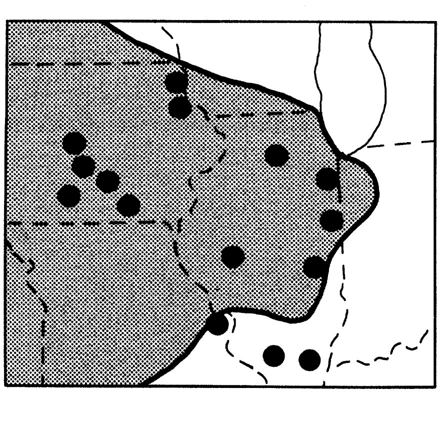

Fig. 1. Site locations of trees and boundaries of the grassland of central North America. Total number of trees for the 15 sites ranged from 37 in 1680 to more than 500 in the 20th century. All sites have at least one tree dating back to 1686, and all but two sites have trees dating to 1680. All samples were white oak (*Quercus alba*). Indices of annual ring width from these sites are highly correlated ($r > 0.80$) with annual (August to July) precipitation (*7*). Grassland boundaries are redrawn from Borchert (*8*).