iments with a garnet peridotite composition containing anhydrous phlogopite at 3.8 to 10 GPa and 1350° to 1400°C, the K content of diopside increased with increasing pressure up to 0.26% K_2O by weight at 10 GPa (*20*). Extrapolation to K contents as high as that in diopside K18a yields a high pressure, >20 GPa, which is probably beyond the stability field of diopside, but there is great uncertainty in the estimated temperatures for this inclusion and Koffiefontein xenoliths. Garnet-cpx assemblages give temperatures from 1000° to 1550°C (*21*), whereas the two K18 chromium diopside inclusions are in disequilibrium, yielding olivine-cpx temperatures of 1033° and 1233°C (*15*). Two-pyroxene geothermometry gives temperatures from 1000° to 1350°C at ~5 GPa (uncorrected for K content, of course) (*22–25*). Certainly, further experiments on the solubility of K in cpx are required to interpret the pressure conditions under which substantial K can enter pyroxenes. In any case, the K content of cpx cannot be used as a geobarometer in the absence of other K-bearing phases. This limitation is a particular problem with diamond inclusions. Alone, the implication of the presence of high K contents in cpx is that formation under high pressure is required, but K contents of cpx will vary with the total amount of K in the rock and the other phases present.

The high levels of K in these clinopyroxenes suggest that the host diamonds formed in unusually K-rich environments. Navon *et al.* (*26*) have described inclusions from morphologically cubic diamonds containing high levels of K, CO_2, and H_2O and suggested that potassic melts or metasomatic fluids in the mantle were responsible for the enrichments. As already noted, K in omphacite has been used as a marker for Group I eclogites (*2*), which are the eclogites that contain diamond. This relation reinforces the connection between these K-rich melts or fluids, diamonds, and K-rich cpx.

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The Search for Evidence of Large Prehistoric Earthquakes Along the Atlantic Seaboard

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The spacial distribution of seismically induced liquefaction features discovered along the Atlantic seaboard suggests that during the last 2000 to 5000 years, large earthquakes (body wave magnitude, $m_b \geq 5.8 \pm 0.4$) in this region may have been restricted exclusively to South Carolina. Paleoliquefaction evidence for six large prehistoric earthquakes was discovered there. At least five of these past events originated in the Charleston, South Carolina, area, the locale of a magnitude 7+ event in 1886. During the past two millennia, large events may have occurred about every 500 to 600 years.

THE LARGEST HISTORICAL EARTHquake in the eastern United States occurred near Charleston, South Carolina, in August 1886. The proximity of this magnitude 7+ event to populated areas made it the most destructive U.S. earthquake of the 19th century (*1*). Today a similar earthquake could result in several thousand deaths and property damage in excess of $400 million (*2*). Clearly, the potential for another large earthquake near Charleston or elsewhere along the Atlantic seaboard must be assessed. This task is especially difficult because Charleston lies far from an active plate boundary in a region where no comparable historical earthquakes have occurred and where there is no clear paleoseismic evidence of surface faulting associated with large prehistoric events (*3*).

Although the bedrock faulting responsible for the Charleston earthquakes has not reached the ground surface, strong ground shaking associated with the 1886 and earlier events resulted in the formation of numerous seismically induced liquefaction (*4–6*) features in surficial sediments (Fig. 1). The results of past studies suggest that the return period between large ($m_b \geq 5.8 \pm 0.4$) earthquakes is about 1500 years (*7–9*). In this report, we synthesize published and newly acquired paleoliquefaction data and show that the frequency of large (*10*) earthquakes occurring near Charleston is greater than previously established. We also report

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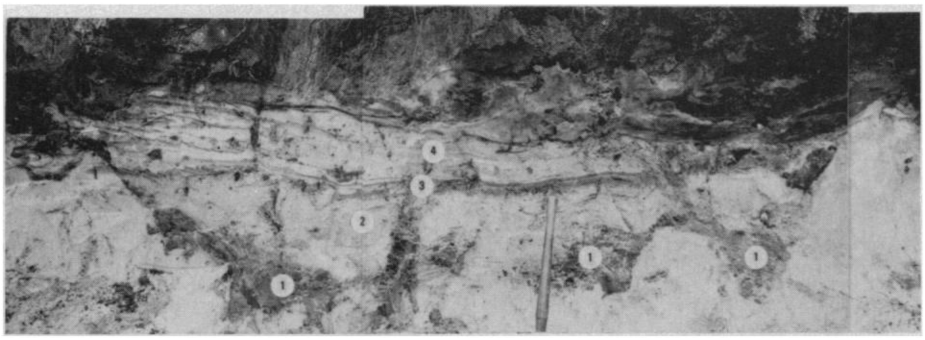

Fig. 1. Cross section of large paleoliquefaction feature in the Charleston area. This feature illustrates how evidence of large prehistoric earthquakes can be preserved in the geologic record. Three vents or feeder dikes are at the base of this feature. They are filled with large clasts of Bh soil. The large clast zones are overlain by a sequence of homogeneous sand containing scattered clasts and no distinctive flow structure. Above this massive zone is a dark subhorizontal layer, approximately 15 cm thick that contains numerous small clasts of Bh material. Above the fine clast zone is a bedded infill sequence consisting of inclined, thin layers of sand, Bh horizon material, and organic debris deposited subsequent to crater formation (handle of trenching shovel in right center for scale). Numbers 1 through 4 identify the large clast zone, homogeneous sands, smell clast zone, and bedded infilling, respectively.

on our search for paleoliquefaction (*11*) evidence of large prehistoric earthquakes outside the Charleston area, along a 1000-km stretch of the Atlantic seaboard extending from the Georgia-Florida state line to southern New Jersey.

We compiled earlier radiocarbon dates of organic samples (*8, 9, 12, 13*) and obtained radiometric data for more than 50 new samples (Fig. 2). These data suggest that at least six liquefaction episodes occurred near Charleston during the past 5000 to 6000 years. Including the 1886 episode, we refer to them from youngest to oldest as CH-1 through CH-6. As shown in Fig. 2, pre-1886 liquefaction episodes occurred approximately 580 ± 104 (CH-2), 1311 ± 114 (CH-3), 3250 ± 180 (CH-4), and 5125 ± 700 (CH-5) years before the present (*14*). An even older episode (CH-6) is cut by a CH-5 feature. Liquefaction episodes CH-1, CH-3, and CH-4 are defined by a larger number of liquefaction features and organic samples, whereas episodes CH-2, CH-5, and CH-6 are represented by fewer dated features.

With the exception of the 1886 event, no moderate to large historical earthquakes have occurred along the Atlantic seaboard (*15*). However, in many coastal areas extending from New Jersey to Florida, local geologic and hydrologic conditions are suitable for the generation and preservation of paleoliquefaction features. We conducted a systematic search for evidence of prehistoric earthquake activity outside the Charleston area in upper Quaternary beach and near-shore marine deposits in Virginia, North Carolina, South Carolina, and Georgia. These units are most similar to the deposits where most of the liquefaction features have been identified in the Charleston area (*16*). The presence of extensive drainage ditches, borrow pits, and sand and gravel quarries allowed for a relatively uniform search throughout this region. In addition, limited reconnaissance studies were conducted in similar deposits located on the Delmarva peninsula of Virginia and Maryland and the Cape May peninsula of New Jersey. In all, we examined more than 1000 potential liquefaction sites. Except for one site located just north of the South Carolina–North Carolina state line, liquefaction features were found exclusively in South Carolina (*17*).

Although in general the larger liquefac-

Episode	Site	Age	Data
CH-1 104	Many	104	(*5*)
S-1	4	100	(*23*)
		≤200	
		107 ± 61	
CH-2 580±104	1	640 ± 60	(*12*)
S-2	4	≥275 ± 105	(*23*)
		605 ± 160	
		570 ± 100	(*12*)
N-1	6	504 ± 97	(*23*)
CH-3 1131±114	1	1230 ± 75	(*9*)
		1230 ± 85	
		1070 ± 200	
		1290 ± 200	
		1230 ± 90	
S-3	3	1066 ± 75	(*23*)
		≤1305 ± 87	
N-2	6	940 ± 80	(*23*)
		907 ± 79	
		1380 ± 175	
		969 ± 80	

Episode	Site	Age	Data
N-3 1722±273	6	≥1232 ± 77	(*23*)
		≥1955 ± 75	
		≥1690 ± 220	
		≤2385 ± 170	
		≤2355 ± 250	
	7	≥1360 ± 110	(*23*)
		≥1150 ± 190	
		1647 ± 390	
		≤2197 ± 200	
		≤2697 ± 84	
		≤1600 ± 100	(*12*)
	8	≥210 ± 170	(*23*)
		≥1200 ± 110	
		≥1360 ± 110	
		≥1050 ± 190	
		≤2570 ± 100	(*12*)
	9	1820 ± 180	(*23*)
		≤1860 ± 200	
	10	≤1465 ± 290	(*23*)
		1700 ± 250	(*12*)

Episode	Site	Age	Data
CH-4 3250±180	1	≥380 ± 220	(*8*)
		≥530 ± 150	
		≥1270 ± 90	
		≤3740 ± 110	
		≥1660 ± 100	(*9*)
	2	3438 ± 87	(*23*)
		3405 ± 255	
		≥2865 ± 260	
		2675 ± 310	
		3450 ± 120	
		3280 ± 130	(*13*)
CH-5 5125±700	1	≥4160 ± 100	(*9*)
		≤7060 ± 110	
	2	≥4730 ± 265	(*23*)
		≤5790 ± 710	
S-4	5	≥4620 ± 195	(*23*)
		≤5520 ± 370	
N-4	10	≥4575 ± 350	(*23*)
CH-6 >CH-5	2	≥5790 ± 710	(*23*)
		≤27,000	

Fig. 2. Radiocarbon dates on several types of organic materials contained within or cut by liquefaction features [see (*23*)]. The most accurate age estimates are obtained from the radiocarbon age of organic debris that was washed or blown into the liquefaction feature shortly after its formation. Dates for these types of samples are reported without leading signs. The ages of roots that grew into a feature or into the overlying soil profile and forest fire–derived charcoal recovered from the shallow soil profiles overlying features provide minimum ages. These ages are noted with a ≥. Roots cut by features and charcoal which was washed or blown into a feature shortly after its formation provide maximum ages. A few maximum ages were also obtained from humate materials recovered from soil clasts that were isolated from surface recharge because of their isolation at depth in a feature, and from organic materials recovered from within soil clasts that collapsed into the deeper part of a feature during the liquefaction episode. Maximum ages are noted with a ≤. Preferred ages for each episode are given on the left.

tion features are at sites near Charleston, some liquefaction features are at sites far from Charleston (Fig. 3). Their presence can be accounted for by three possible models: (i) they could be outlying liquefaction features resulting from the 1886 or earlier prehistoric Charleston earthquakes; (ii) they could be a result of a large earthquake originating near Charleston that generated liquefaction features over a broader area; or (iii) they could be the result of liquefaction associated with an earthquake originating elsewhere. The first two models predict the ages of these paleoliquefaction liquefaction features would be the same as those of Charleston earthquakes. Conversely, model 3 predicts that their ages may not be the same.

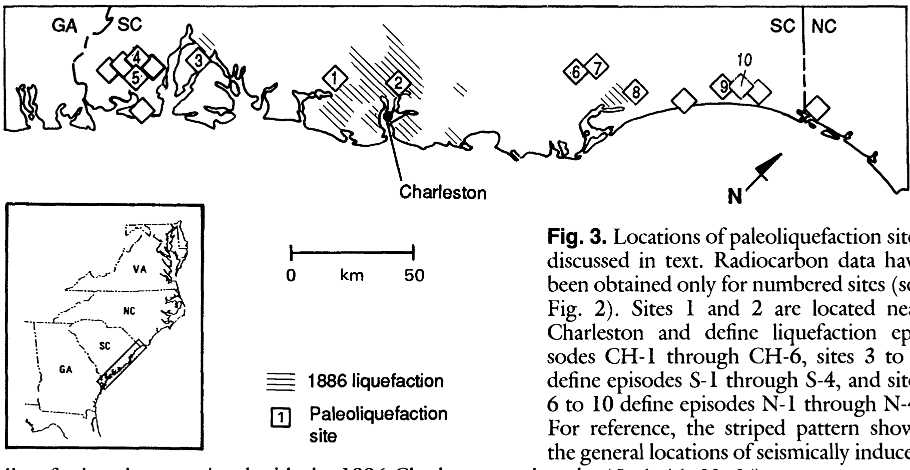

Fig. 3. Locations of paleoliquefaction sites discussed in text. Radiocarbon data have been obtained only for numbered sites (see Fig. 2). Sites 1 and 2 are located near Charleston and define liquefaction episodes CH-1 through CH-6, sites 3 to 5 define episodes S-1 through S-4, and sites 6 to 10 define episodes N-1 through N-4. For reference, the striped pattern shows the general locations of seismically induced liquefaction sites associated with the 1886 Charleston earthquake (*5, 6, 16, 23, 24*).

To address this issue, we obtained radiometric ages of samples from paleoliquefaction sites located 75 to 125 km south of Charleston and sites located 75 to 150 km to the north (see Figs. 2 and 3). The ages of organic samples collected at the southern liquefaction sites suggest that four liquefaction episodes occurred in this area. They are referred to from youngest to oldest as episodes S-1 through S-4. All four episodes correlate to Charleston liquefaction episodes, and we interpret each to be the result of an earthquake originating in the established Charleston source area. These ages also provide independent confirmation of Charleston liquefaction episodes CH-1, CH-2, CH-3, and either CH-5 or CH-6. The ages of samples collected from the northern sites suggest that four liquefaction episodes have occurred in this area (N-1 through N-4). The ages of liquefaction episodes N-1 and N-2 correlate with and provide independent confirmation of Charleston episodes CH-2 and CH-3. The age of N-4 is generally consistent with episodes CH-5 or CH-6 but is poorly constrained.

Although all the southern liquefaction episodes and northern episodes N-1, N-2, and N-4 probably resulted from earthquakes occurring in the established Charleston source area, episode N-3 has no clear relation to a Charleston episode. This episode was identified at five northern sites and may have been caused by a local earthquake. Additional studies are needed to confirm the presence of this postulated second earthquake source.

Our search for evidence of past large earthquakes targeted areas where present geologic and hydrologic conditions are conducive for the generation of seismically induced liquefaction features. However, because of variability in climatic conditions and fluctuations in sea level, ground-water levels over much of the study area may have been much lower in the past (*18–21*). Because saturated conditions are required for liquefaction to occur, changes in ground-water levels would be expected to play a significant role in determining the spatial and temporal distribution of paleoliquefaction features. On the basis of climatic data (*21*) and sea level curves (*18–20*) for the southeastern United States, ground-water levels are thought to have been at or near present levels for only the past 2000 years. Consequently, the paleoliquefaction record is probably most complete for this period. During the period from 2000 to about 5000 years ago, ground-water levels fluctuated over a range of about 1 to 4 m below present level. The paleoseismic record for this interval probably includes only those earthquakes that occurred during periodic transgressive seas or wetter climatic periods. Before about 5000 years ago these studies suggest that the climate in the region was drier and sea level was even lower. Such conditions would severely reduce or eliminate the potential for seismically induced liquefaction in many of the deposits that we studied and may account for the absence of older paleoliquefaction features in the Charleston area.

Fluctuations in prehistoric ground-water levels may also control how far from Charleston paleoliquefaction features occur. For example, the recognition of episode CH-4 only in the Charleston area suggests that it may have been caused by an earthquake smaller than the 1886 event. However, at the time of the CH-4 liquefaction episode, sea level was 3 m lower than at present. This would most likely have resulted in lower ground-water levels and an associated decrease in the liquefaction potential of shallow sediments along the South Carolina coast. Similarly, about 1800 years ago, sea level may have been slightly higher than at the present (*19*). If this resulted in higher regional ground-water tables, then the liquefaction potential of shallow sediments along the coast would have been increased. This postulated episode of high sea level may thus explain the observed distribution of N-3 features. This hypothesis could be confirmed if paleoliquefaction features of similar ages are subsequently found in the Charleston area.

This study confirms that the frequency of large earthquakes in the Charleston area is greater than previously established and suggests that a seismic source approximately 100 km northeast of the known Charleston source area may have been active during the past several thousand years. The mean return period between liquefaction episodes identified in the geologic record (including both those originating in the Charleston area and the single postulated event to the north) is about 1000 years; however, the time between episodes has varied from about 2000 years to about 500 years in more recent times. The apparently longer return periods may be related to gaps in the earlier record because some earthquakes may have occurred during times of greatly decreased liquefaction potential. The timing of the past four large liquefaction-associated earthquakes has behaved in a time-predictable manner, and events have occurred about every 500 to 600 years. Because only about 100 years have elapsed since the 1886 event, the probability of a similar earthquake occurring within the Charleston area over the next several decades is inferred to be low. Although the potential for an earthquake large enough to produce significant liquefaction features is low, the hazard presented by smaller earthquakes should not be overlooked (*22*).

The absence of paleoliquefaction features elsewhere within about 50 to 100 km of the southeastern coast of the United States must also be viewed in the context of prehistoric climatic conditions and sea levels. In consideration of the impact of these factors on ground-water tables, the paleoliquefaction record along the present coast is probably complete only for the last 2000 years, intermittent for the period 2000 to 5000 years ago, and may be extremely limited for earlier times.

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A Water Storage Adaptation in the Maya Lowlands

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Prehispanic water management in the Maya Lowlands emphasized collection and storage rather than the canalization and diversion accentuated in highland Mexico. Reexamination of site maps of the ancient Maya city of Tikal, Guatemala, has revealed an important, overlooked factor in Maya centralization and urban settlement organization. In a geographical zone affected by an extended dry season and away from permanent water sources, large, well-planned reservoirs provided resource control as well as political leverage.

The settlement pattern of the ancient Maya, a civilization identified with a dispersed support population, continues to perplex Mesoamericanists (*1, 2*). Occupying central and northern Guatemala and adjacent areas of Mexico, Belize, and Honduras (Fig. 1), southern Maya Lowland cities contrast with other great experiments in Mesoamerican urban statecraft—Monte Albán (*3*), Teotihuacán (*4, 5*), Tenochtitlán (*5, 6*). Although as advanced as these more nucleated and ordered ancient settlements of highland Mexico, the lowland Maya urban aggregate differed in population density and spatial organization. One condition separating these two settlement adaptations is the availability of water.

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Water availability limits the location of permanent populations. In highland Mexico, rainfall is less annually abundant than in the southern Maya Lowlands, but perennial drainages and year-round springs allow the deliberate diversion of water to nearby settlements (*5, 7*). Although more precipitation may fall in the Maya area, little permanent external drainage exists (*8*). Water management in the Maya Lowlands emphasized collection over diversion, source over allocation.

Most studies of water management in preindustrial states emphasize water allocation rather than water sources and their abundance (*9*). With the use of previously published contour maps, a study of large Classic Period Maya cities (A.D. 250 to 900) was initiated, focusing on water sources (*10*). Examination of the ancient reservoir