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Recurrence rates of large earthquakes in the South Carolina Coastal Plain based on paleoliquefaction data

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Abstract. We present a reanalysis of results of 15 years of paleoliquefaction investigations in the South Carolina Coastal Plain. All earlier radiocarbon age data and locations of organic material collected by various investigators were reviewed and recalibrated to obtain a uniform data set. The calibrated dates and the spatial extent of the sandblows having similar dates were used to estimate ages and magnitudes of prehistoric earthquake episodes. The results of this analysis suggest seven episodes (episodes A–G) of prehistoric liquefaction in the past 6000 years and two possible scenarios for their occurrence. In the first scenario, three seismic sources exist within the Coastal Plain of South Carolina; at Charleston (A, B, E, and G) with magnitudes M 7+, Georgetown (C and F), and Bluffton (D) with magnitudes $M \sim 6$. In the second scenario, episodes C and D are combined into one episode, episode C′. In this scenario all earthquakes occurred at Charleston and with M 7+. Episodes A and B seem to be more representative of the earthquake cycle and suggest a recurrence time of 500–600 years for M 7+ earthquakes at Charleston. The recurrence times and magnitudes for episodes C and D are estimated at ≥2000 years and ~6.0, respectively. The older episodes are less frequent, a fact that may be attributable to times of low ground water table. Before ~6000 years B.P., the ground water table was too low to permit observable liquefaction features to develop at the surface.

1. Introduction

Historical records, including over 2000 accounts, of felt earthquakes in South Carolina go back as far as 1698 [*Bollinger and Visvanathan*, 1977; *Visvanathan*, 1980]. To extend the historical record further back in time, paleoseismological investigations, started more than a decade ago, identified and dated paleoliquefaction features preserved in the shallow Coastal Plain sediments (Figure 1). Sand expulsion features known as sandblows, which result from seismically induced liquefaction, are preserved in the shallow sediments of the South Carolina Coastal Plain (SCCP) and provide information that can be used to construct the prehistoric earthquake record. Since the discovery of the first prehistoric sandblow in South Carolina [*Cox and Talwani*, 1983], there have been concerted efforts to document the extent of these sandblows in South Carolina (section 2). The information from these investigations helps to assess the potential seismic hazard in South Carolina. In this study we present an analysis of the spatial and temporal extent of these liquefaction data, in order to obtain the recurrence times and estimate magnitudes of prehistoric earthquakes that formed the sandblows.

2. Early Studies

The first systematic search of a paleoliquefaction feature in South Carolina was conducted by *Cox* [1984] and led to the discovery of a sandblow at Warrens Crossroads located ~40 km west of Charleston, South Carolina, which was caused by the 1886 earthquake (Figure 1). Detailed mapping and soil sampling showed the source sand to be a clean, white, mica-rich sand layer approximately 2.7 m thick and located ~2.3 m below the surface [*Cox and Talwani*, 1983]. Shallow trenching at this site showed that the sandblow formed by the upward movement of sand toward the surface along a feeder dike that widened from 20 cm at the base of the trench to approximately 0.6 m at the ground surface. Clasts of surface soil had slumped into the sandblow shortly after it developed. Even though this study did not uncover any pre-1886 features, it suggested that sandblows and other structures can be preserved in the soils of the SCCP and that areas which experienced liquefaction during the 1886 earthquake might contain sandblows that developed in prehistoric earthquakes of magnitude similar to that of the 1886 earthquake [*Cox*, 1984].

This discovery was followed by intensive studies by the U.S. Geological Survey in the mid-1980s, by Ebasco Services in the early 1990s, and by the University of South Carolina sporadically since 1983. These studies were primarily aimed at discovering the spatial extent of paleoliquefaction features and developing criteria for their identification. S. F. Obermeier and R. E. Weems of the U.S. Geological Survey and their coworkers were the first to discover sandblows that predated 1886. Following their initial discovery of a prehistoric sandblow at Hollywood, they discovered several additional sandblows in other parts of the SCCP [*Obermeier et al*., 1987]. D. C. Amick, R. Gelinas, and their coworkers from Ebasco Services discovered other sandblows in the SCCP and extended the search for

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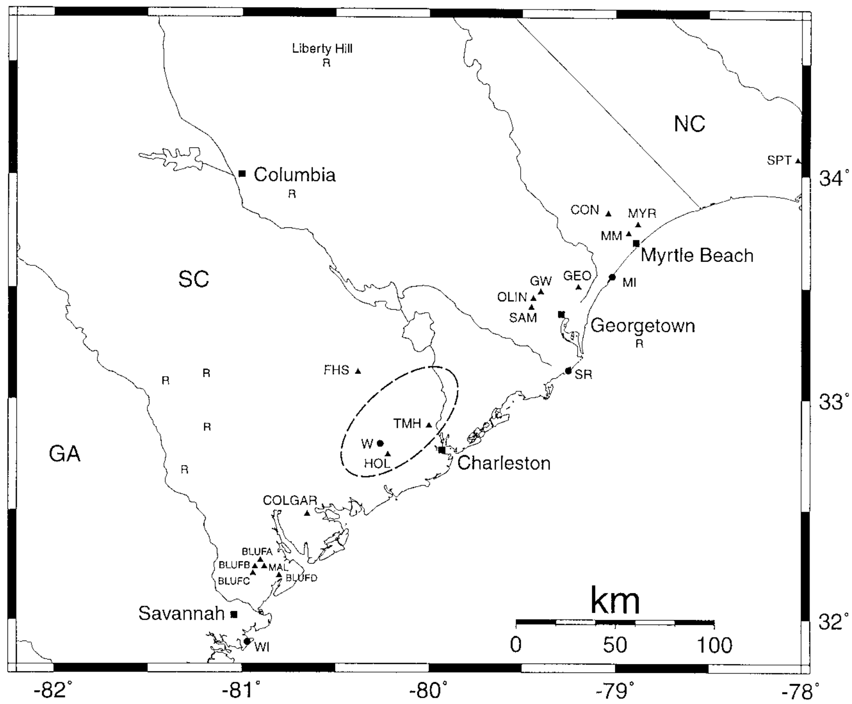

Figure 1. Dashed line encloses area of pronounced craterlet activity associated with the 1886 earthquake [from *Dutton*, 1889]. Reports (R) of liquefaction features extend to Columbia and Georgetown [*Seeber and Armbruster*, 1981] and to Sand Hills near Liberty Hill [*Floyd*, 1969]. Liquefaction features associated with the 1886 earthquake were discovered at Warren's Crossroads (W) and at Bluffton (BLUF-A). Triangles show the location of paleoliquefaction sites in the North Carolina and South Carolina Coastal Plain from which datable material associated with prehistoric earthquakes was obtained. Abbreviations are as follows: Bluffton, BLUF; Colony Gardens, COLGAR; Conway, CON; Four Hole Swamp, FHS; Gapway, GW; Georgetown, GEO; Hollywood, HOL; Malpherous, MAL; Martin Marietta, MM; Myrtle Beach, MYR; Sampit, SAM; South Port, North Carolina, SPT; and Ten Mile Hill, TMH. Holocene ground water table data obtained from Murrell's Inlet (MI), Santee River Delta (SR), and Wilmington Island, Georgia (WI), are described in the text.

paleoliquefaction to other locations along the Atlantic seaboard [*Amick*, 1990; *Amick et al.*, 1990]. C. P. and K. Rajendran of the University of South Carolina discovered new sandblows near Bluffton and the Four Hole Swamp [*Rajendran and Talwani*, 1993; *Talwani et al.*, 1993], while *Schaeffer* [1996] discovered four at Gapway.

To use the liquefaction features for seismic hazard assessment, they must be dated. Abundant vegetation in the SCCP commonly makes it possible to collect organic material for radiocarbon dating. Most of the early dates came from a drainage ditch near Hollywood, South Carolina (*Talwani and Cox* [1985], *Weems et al.* [1986]; Table 1). Subsequently, *Weems et al.* [1988] and *Weems and Obermeier* [1990] obtained dates from sandblows covering an areal extent of ~25,000 km^2 in the SCCP. These data provided loose constraints on the ages and number of prehistoric earthquakes. To tighten the age constraints, *Amick et al.* [1990] obtained multiple dates at new sites discovered by them and of features originally discovered by *Obermeier et al.* [1990]. Additional dates at four locations in the Bluffton area were obtained by *Talwani et al.* [1993]. More recently, additional data were obtained in the Georgetown and Charleston areas, including the newly discovered sites at Gapway and Four Hole Swamp [*Schaeffer*, 1996] (Figure 1).

At each location one or more sandblows were encountered and as many as six datable samples were recovered from a single sandblow. In Tables 1 and 2, various locations of sandblows are referred to as "sites" (treating the four Bluffton locations as one site), and the sandblows are referred to as "features." The original names of sandblows assigned by the author(s) have been preserved. A total of 121 radiocarbon ages including 35 accelerator mass spectrometer (AMS) ages (Table 1) were obtained from 54 sandblows at 14 sites (Figure 1).

3. Methodology

The radiocarbon age of a sample can provide a minimum, contemporary, or maximum age estimate of the earthquake that caused the liquefaction, depending on the stratigraphic position of the sample and its cross-cutting relationship with elements of the sandblow. Radiocarbon dates reported by earlier workers had not been calibrated to account for fluctuations in atmospheric ^{14}C over time. In order to merge all of the age data collected by various workers the stratigraphic positions of the samples within the sandblows were reexamined, and conventional radiocarbon ages were recalibrated.

3.1. Dating Paleoliquefaction Features

Two methods discussed by *Amick et al.* [1990] were used to determine the age of the sandblows. The first method determines the relative age of the sandblow using weathering criteria, and the second determines its absolute age by radiometric dating of organic-rich samples. The relative age of a sandblow can usually be determined by examining the location of the sandblow and the thickness of the overlying soil profile, the

Table 1. Sources of Radiocarbon Dates[a]

Site	Number of Features	Data Source[b] 1	2	3	4	5	6	Total
SPT	1			1				1
CON	1			1				1
MYR	3			1	2			3
MM	1				2			2
GEO	3			1	6			7
GW	2						7	7
OLIN	2			1	5			6
SAM	9				11		10	21
FHS	1						1	1
TMH	6			1	10		2	13
HOL	8	7	11	2				20
COLGAR	1				2			2
MAL	1				6			6
BLUF	15			1	7	23		31

[a]The numbers of radiocarbon dates are shown under each data source. The sites are shown in Figure 1: Southport, North Carolina (SPT), Conway (CON), Myrtle Beach (MYR), Martin Marietta (MM), Georgetown (GEO), Gapway (GW), Olin, Sampit (SAM), Four Hole Swamp (FHS), Ten Mile Hill (TMH), Hollywood (HOL), Colony Gardens (COLGAR), Malpherous (MAL), and Bluffton (BLUF).

[b]References: 1, *Talwani and Cox* [1985]; 2, *Weems et al.* [1986]; 3, *Weems and Obermeier* [1990]; 4, *Amick et al.* [1990]; 5, *Talwani et al.* [1993]; 6, *Talwani et al.* [1999].

degree of staining, and the amount of weathering of the materials within the sandblow. In general, older sandblows have thicker overlying soil profiles, and the sediments in them are usually more heavily stained compared to the younger sandblows. Cross-cutting relationships can also be used to establish the relative age of one feature with respect to another.

The absolute age of a sandblow is obtained by ^{14}C dating of organic material recovered from within it. The absence of organics in borehole samples of sediments from below and near the sandblows (*Cox* [1984] and other unpublished data) allows us to conclude that all organics found in the sandblow came from above and were not a part of the ejected sand from below. Figure 2, modified from *Amick* [1990], illustrates how the stratigraphic position of samples in and around the sandblow can be used to infer its age and establish the minimum age and maximum age constraints. In Table 2 the sample location is described with respect to the stratigraphic setting in the sandblow. (For an excellent discussion of the morphology of a sandblow, see *Obermeier et al.* [1990].) "Contemporary" is used to describe the date of formation of the sandblow. The dates of pieces of leaves, bark, and wood that have been washed or blown into the sandblow shortly after its formation (item 1 in Figure 2) are interpreted as the best contemporary age estimates. For every sandblow, using the criteria described in Figure 2, we decided if the dates of organic samples were indicative of maximum, minimum, or contemporary age estimates of the ages of the earthquakes. These data gave broad ranges for the date of the earthquake. Then the contemporary ages were used in the calculations of dates of earthquake episodes (section 5).

3.2. Calibration of Radiocarbon Ages

In this study the ^{14}C dates determined from samples recovered during this study and previous studies were calibrated to obtain their calendar ages. The necessity for the calibration arises because the conventional ^{14}C date is determined assuming that the amount of atmospheric ^{14}C has remained constant over time. However, studies of tree ring samples have shown that the atmospheric ^{14}C has fluctuated over timescales of hundreds to thousands of years [*Geyh and Schleicher*, 1990]. In the calibration process the radiocarbon date is compared with the calibrated timescale curve. This was accomplished using the computer program CALIB v3.0.3c developed by *Stuiver and Reimer* [1993]. In the calibration program, intercept values of $\pm 1\sigma$ and $\pm 2\sigma$ are obtained for each calibrated age. When determining the interpreted age for the calibrated ^{14}C age dates, the 1σ range was used. In paleoseismological literature both 2σ ages [e.g., *Tuttle and Schweig*, 1996] and 1σ ages [e.g., *Bell et al.*, 1999] have been used to estimate the ages of prehistoric earthquakes. The 2σ ages have wider ranges, and those for two distinct events hundreds of years apart may overlap. Since the main objective of our analyses was to identify different prehistoric earthquakes and establish their ages, we chose a shorter range for correlation and used 1σ ages. The 1σ ranges provide a more rigorous test for correlation and are less likely to lead to spurious correlations.

4. Results

We examined the descriptions and figures and other relevant data for all the sandblows from which samples of organic material had been collected. Using the criteria given in section 3.1, each date was interpreted to be associated with the minimum, maximum, or contemporary age estimate of the causative earthquake. Each radiocarbon age date was calibrated (section 3.2). All the age relationships (Table 2) are the same as given by the original authors, except for those used by *Rajendran and Talwani* [1993] for Bluffton. Their field notes and figures were reanalyzed, and the revised age relationships are used in this study.

We discuss the data for the sites from northeast to southwest (Figure 1 and Table 2). Data from Sampit (Figure 3) are used to illustrate our approach. We discuss the age of the sandblow associated with each earthquake from the relative dates of the sample(s). For example, at some locations several samples were recovered from one sandblow, thus providing tighter age constraints (e.g., SAM-2A, SAM-2B, SAM-2C, and SAM-2D are four samples with contemporary ages from the sandblow Sampit Middle Right (SPMR) at the Sampit site).

4.1. Northern Sites

4.1.1. Southport, North Carolina, and Conway, South Carolina. These two are the northernmost sites (Figure 1) where datable material was recovered [*Weems et al.*, 1988; *Weems and Obermeier*, 1990]. Pieces of charcoal embedded deeply in intensely deformed soil profiles at Southport, North Carolina, and Conway yielded maximum ages of 9743 +167/−208 years B.P. and 6530 +204/−172 years B.P., respectively (Table 2).

4.1.2. Myrtle Beach. The Myrtle Beach site, ~10 km north of Myrtle Beach, South Carolina (MYR in Figure 1), is the northernmost site having a contemporary date of a sandblow in the SCCP. This site was investigated by *Amick et al.* [1990] and *Weems and Obermeier* [1990]. They identified three different sandblows at this site, and depending on the degree of staining and the thickness of the overlying soil profile, they were interpreted as not being associated with the 1886 Charleston earthquake. This interpretation is supported by ^{14}C age dates (Table 2). The calibrated dates suggest that at least two episodes of liquefaction occurred at this site. A stem recovered

Table 2. Calibrated Ages[a]

Name	Source[b]	Lab Sample and ^{14}C Test	Sample I.D.	Sample Kind and Stratigraphic Setting	^{14}C Age, years B.P.	Calibrated Age $\pm1\sigma$, years B.P.	Min, Max, or Con
				Southport, North Carolina, and Conway, South Carolina, Sites			
Southport	3	Beta-22089	SPT-1	charcoal in features with much more deeply and intensely deformed soil profiles	8770 ± 120	9743 +167/−208	max
Conway	3	USGS W5836	CON-1	charcoal in features with much more deeply and intensely deformed soil profiles	5750 ± 150	6530 +204/−172	max
				Myrtle Beach Site			
Feature 1	4	GX14996, AMS	MYR-1	humate clast from base of large clast zone	1565 ± 290	1414 +393/−234	max
Feature 2	4	GX15575, beta	MYR-2	charcoal in overlying soil profile "new burn"	4575 ± 350	5297 +353/−469	min
Feature 3	3	USGS W5799	MYR-3	stem/wood in crater	1700 ± 250	1568 +310/−246	con
				Martin Marietta Site			
Feature 1	4	GX14994	MM-1A	tree bark from the matrix of the large clast zone	1860 ± 180	1809 +177/−257	con
	4	GX15004	MM-1B	organic-rich clast from the top of the small clast zone	1880 ± 200	1820 +188/−267	max
				Georgetown Site			
Feature A	4	GX15192, beta	GEO-1A	root grown into the feature	210 ± 170	151 +317/−151	min
	4	GX14995, beta	GEO-1B	charcoal within the overlying soil profile "recent burn"	1200 ± 110	1078 +187/−107	min
	4	GX15003, beta	GEO-1C	charcoal within the overlying soil profile "recent burn"	1360 ± 110	1285 +56/−114	min
	4	GX15587/AMS	GEO-1D	wood from within the feature	1050 ± 190	945 +223/−209	con
Feature B	4	GX15198, AMS	GEO-2A	root grown into the feature	modern	modern	min
	4	GX15577, beta	GEO-2B	tap root cutting the right-side margin of the feature	2820 ± 220	2908 +337/−161	min
Feature C	3	USGS W5830	GEO-3	charcoal in the crater	2570 ± 100	2739 +25/−257	max
				Gapway Site			
Gapway A	6	CAMS15939, AMS	GW-1A	charcoal within bedded sequence	4570 ± 60	5295 +23/−235	max
	6	CAMS16539, AMS	GW-1B	root cutting south side of feature	2040 ± 60	1985 +68/−88	min
	6	CAMS16540, AMS	GW-1C	charcoal within bedded sequence	3370 ± 70	3623 +67/−146	max
	6	CAMS16541, AMS	GW-1D	root cutting north side of feature	1610 ± 50	1518 +21/−106	min
Gapway D	6	CAMS19473, AMS	GW-2A	root cutting north side of feature	310 ± 60	312 +151/−19	min
	6	CAMS19472, AMS	GW-2B	bulk detrital charcoal	3880 ± 60	4321 +88/−164	max
	6	CAMS19471, AMS	GW-2C	small twig in bedded sequence	4420 ± 50	4985 +218/−113	con
				Olin Site			
Feature A	4	GX14992, beta	OLIN-1A	tap root cutting the right side of the feature	1360 ± 110	1285 +56/−114	min
	4	GX15006, beta	OLIN-1B	tap root cutting the right side of the feature (split of GX14992)	1150 ± 190	1059 +220/−146	min
	4	GX15199, beta	OLIN-1C	bark from central vent of feature	1647 ± 390	1533 +452/−360	con
	4	GX15005, beta	OLIN-1D	humate clast from the base of the large-clast zone	2635 ± 200	2753 +188/−379	max
	4	GX14993, AMS	OLIN-1E	humate clast from the base of the large-clast zone	2197 ± 84	2236 +91/−170	max
Feature B	3	USGS W5827	OLIN-2	charcoal	1600 ± 100	1511 +58/−157	max

Table 2. (continued)

Name	Source[b]	Lab Sample and ^{14}C Test	Sample I.D.	Sample Kind and Stratigraphic Setting	^{14}C Age, years B.P.	Calibrated Age $\pm 1\sigma$, years B.P.	Min, Max, or Con
				Sampit Site			
SPN	4	GX15206, AMS	SAM-1	bark from within the large-clast zone	504 ± 97	521 +102/−39	con
SPMR	4	GX15589, beta	SAM-2A	bark within the clast zone	969 ± 80	918 +27/−136	con
	4	GX15202, AMS	SAM-2B	bark within the clast zone	940 ± 80	834 +100/−98	con
SPMR	4	GX15200, AMS	SAM-2C	bark within the bedded sequence	907 ± 79	787 +137/−63	con
	4	GX15579, beta	SAM-2D	bark within the clast zone	1380 ± 175	1290 +121/−206	con
SPML	4	GX15191, AMS	SAM-3A	root cut by the feature; max for feature SPMR, min for feature SPML	1232 ± 77	1165 +100/−105	max min
Cinnamon feature	6	CAMS20425, AMS	SAM-3B	wood from top of the feature	250 ± 60	293 +19/−293	min
SPS	4	GX15189, beta	SAM-4A	root grown into the feature	1955 ± 75	1881 +101/−61	min
	4	GX14997, beta	SAM-4B	carbonized wood from the bedded sequence	1690 ± 220	1561 +302/−221	con
	4	GX14998, beta	SAM-4C	charcoal from the bedded sequence	2385 ± 170	2353 +379/−197	possible max
	4	GX15001, beta	SAM-4D	charcoal from the bedded sequence	2455 ± 250	2471 +308/−315	possible max
BWL	6	CAMS18562, AMS	SAM-5A	bark from older feature	980 ± 60	922 +17/−131	con
	6	CAMS18563, AMS	SAM-5B	root from the younger feature; thought to be wood when it was collected; very young, so it must be a root sample	161 ± 2	158 +110/−158	min
BWR	6	CAMS20426, AMS	SAM-6A	root grown into feature	990 ± 60	925 +21/−131	min
	6	BETA81787, beta	SAM-6B	root grown into feature	2770 ± 90	2855 +99/−87	min
	6	CAMS19944, AMS	SAM-6C	charcoal recovered in the feature	1350 ± 60	1282 +17/−88	max
Stump M	4	GX15135, ?	SAM-7	wood from a stump near the middle of the ditch	4655 ± 90	5394 +171/−100	general stratigraphic control
Stump H1	6	BETA78432, beta	SAM-8	wood from a stump located high in the stratigraphic section	1400 ± 60	1296 +37/−18	general stratigraphic control
Stump H2	6	BETA78433, beta	SAM-9	wood from a stump located high in the stratigraphic section; BWL flowed around this stump; therefore this is also a max BWL	1930 ± 60	1870 +62/−56	general stratigraphic control and max for BWL
Stump L1	6	BETA78434, beta	SAM-10	wood from a stump located low in the stratigraphic section	5830 ± 70	6665 +69/−123	general stratigraphic control
Stump L2	6	BETA78435, beta	SAM-11	wood from a stump located low in the stratigraphic section	6510 ± 70	7386 +12/−96	general stratigraphic control
				Four Hole Swamp Site			
Feature 1	6	GX19011	FHS-1	organic matter, bark	1755 ± 75	1659 +70/−107	con
				Ten Mile Hill Site			
Feature A	4	GX15201, AMS	TMH-1A	tree bark from horizontal layer within bedded sequence	3438 ± 87	3688 +139/−112	con
	4	GX15182, beta	TMH-1B	tree bark from horizontal layer within bedded sequence	3405 ± 255	3634 +342/−270	con
	4	GX15187, beta	TMH-1C	tree bark within the organic layer of bedded sequence at top of bedding may be in overlying profile	2165 ± 260	2140 +282/−307	min
	4	GX15196, beta	TMH-1D	carbonized wood from bedded sequence	2675 ± 310	2765 +437/−415	con
Feature B	4	GX15186, beta	TMH-2A	large tree root cutting central portion of crater	2865 ± 90	2965 +150/−98	min
	4	GX15188, beta	TMH-2B	vertical root cutting right margin of feature	155 ± 150	127 +184/−127	min
Feature C	4	GX15185, AMS	TMH-3	tree bark from organic layer of bedded sequence	3450 ± 120	3691 +152/−129	con

Table 2. (continued)

Name	Source[b]	Lab Sample and ^{14}C Test	Sample I.D.	Sample Kind and Stratigraphic Setting	^{14}C Age, years B.P.	Calibrated Age $\pm 1\sigma$, years B.P.	Min, Max, or Con
				Ten Mile Hill Site (continued)			
Feature D	4	GX15194, beta	TMH-4A	tree root grown into right portion of clast zone	4730 ± 265	5425 +305/−379	min
	4	GX15184, beta	TMH-4B	charcoal from bedded sequence	5790 ± 710	6596 +789/−828	max
	4	GX15578, beta	TMH-4C	tree root grown into clast zone	1165 ± 125	1063 +176/−124	min
ARP	3	—	TMH-5	tree bark from bedded sequence	3280 ± 130	3471 +210/−107	con
Ten-Trench 01	6	116793, beta	TMH-6A	pieces of wood from trench	1410 ± 70	1299 +47/−21	con (?)
Ten-Trench 02	6	116794, beta, and AMS6	TMH-6B	piece of charcoal taken from trench (may or may not be a part of wood sample in Ten-Trench 01)	3690 ± 40	4038 +46/−109	max
				Hollywood Site			
Site 1	1	Cox 1	HOL-1A	root cut by fault associated with feature	3740 ± 110	4086 +153/−164	max
Feature 1	1, sample 6	Cox 2	HOL-1B	root cross-cutting feature	530 ± 150	535 +118/−68	min
	1, sample 7	Cox 3	HOL-1C	root cross-cutting feature	1270 ± 90	1206 +79/−139	min
	1, sample 1	Cox 4	HOL-1D	root cross-cutting feature	380 ± 220	467 +156/−467	min
	2	B-11836	HOL-1E	root grown in feature	1660 ± 100	1538 +156/−126	min
Site 1	1	Cox 5	HOL-2A	root cut by feature	3060 ± 110	3261 +113/−182	max
Feature 2	1	Cox 6	HOL-2B	root?	3820 ± 100	4185 +220/−187	max
	1	Cox 7	HOL	root outside sandblow; not useful in dating	1930 ± 90		
Hollywood XIII	2	B-11824	HOL-3A	humate clast in base of feature; poor age constraint	7086 ± 110	7851 +98/−100	max
	2	B-11825	HOL-3B	root grown into feature	4160 ± 100	4690 +146/−163	min
Hollywood VII	2	B-11820	HOL-4	humate clast in base of feature; poor age constraint	9780 ± 80	10,982 +18/−31	max
Hollywood VIII	2	B-11830	HOL-5A	root cut by feature	4220 ± 140	4768 +104/−232	max
	2	B-15396	HOL-5B	root grown in feature	1780 ± 90	1701 +114/−141	min
Hollywood 125	3	B-20186, beta	HOL-6A	wood: one end round and broken side branch (detrital)	640 ± 60	601 +57/−51	con
	3	B-27733, beta	HOL-6B	root grown into stratified zone	435 ± 60	503 +16/−39	min
Site 2 Hollywood XVII	2	USGS W5664	HOL-7A	stick with rounded ends in feature	1230 ± 90	1164 +106/−107	con
	2	B-12886, beta	HOL-7B	stick with rounded ends in feature	1230 ± 85	1164 +104/−106	con
	2	USGS W-5668	HOL-7C	stump in feature	1070 ± 200	961 +262/−208	con
	2	B-15661, beta	HOL-7D	stump in feature	1290 ± 80	1213 +75/−124	con
Hollywood XIV	2	B-12885, beta	HOL-8	wood in neck of sandblow	1230 ± 75	1164 +100/−102	con
				Colony Gardens Site			
Feature 1	4, CGARDS	GX15136, AMS	COLGAR-1A	wood in Bh clast; tight maximum age constraint; could be younger ~100 years	1305 ± 87	1263 +31/−124	max
	4, CGARDS	GX15586, AMS	COLGAR-1B	wood from bedded sequence	1066 ± 78	958 +100/−34	con
				Malpherous Site			
Feature 1	4, MCR	GX15131, beta	MAL-1A	root cutting massive zone and soil clast	4620 ± 195	5312 +273/−324	min
	4, MAL-2	GX15190, AMS	MAL-1B	charcoal in massive zone	5520 ± 370	6300 +429/−385	max
	4, Mc Root	GX15133, AMS	MAL-1C	roots in feature (not useful)	547 ± 87	542 +99/−33	min
	4, MCC-1	GX15134H, AMS	MAL-1D	split of one humate clast for age control	7435 ± 345	8169 +336/−321	max
	4, MCC-1	GX15134, AMS	MAL-1E	split of one humate clast for age control	6870 ± 440	7647 +459/−361	max
	4, MCC-2	GX15137, AMS	MAL-1F	split of one humate clast for age control	7710 ± 240	8419 +522/−22	max

Table 2. (continued)

Name	Source[b]	Lab Sample and ^{14}C Test	Sample I.D.	Sample Kind and Stratigraphic Setting	^{14}C Age, years B.P.	Calibrated Age $\pm 1\sigma$, years B.P.	Min, Max, or Con
				Bluffton Site			
Feature A-1	4, AA	GX15581, AMS	BLUF-1	leaves in bedding sequence	100 ± 1	35 +91/−35	con
Feature A-2	4, AB	GX15183, AMS	BLUF-2	leaves in bedding sequence	200 ± 1	121 +158/−121	con
Feature A-3	4, AC	GX15582, AMS	BLUF-3	tree bark in bedding sequence	107 ± 61	70 +199/−70	con
Feature A-4	4	GX15132, beta	BLUF-4A	new burn charcoal	275 ± 105	301 +167/−301	min
	4, AD	GX15130, beta	BLUF-4B	tap root with bedding deposited down against it	605 ± 160	598 +74/−93	con
	3	USGS W5804	BLUF-4C	same as BLUF-4B	570 ± 100	547 +103/−36	con
	5, A-6	GX17547, beta	BLUF-4D	new burn charcoal in overlying feature	345 ± 110	376 +132/−87	min
	5, A-6	GX1713, beta	BLUF-4E	charcoal in feature	695 ± 110	656 +47/−105	max
Feature A-5	4, BD	GX15584, AMS	BLUF-5A	charcoal embedded in sequence	2164 ± 68	2140 +168/−94	max
	4, BD	GX15585, AMS	BLUF-5B	new burn charcoal from tap root penetrating feature	1850 ± 80	1782 +89/−146	min
	5, B-9	GX17137, beta	BLUF-5C	charcoal in feature	2415 ± 130	2359 +366/−31	max
	5, B-9	GX17546, beta	BLUF-5D	new burn charcoal above feature	1805 ± 120	1713 +156/−157	min
Feature A-6	5, A-5	GX17545, beta	BLUF-6A	roots in clasts in the feature	1290 ± 115	1213 +85/−148	min
	5, A-5	GX17139, beta	BLUF-6B	aggregate of charcoals from two locations within feature	1195 ± 110	1072 +191/−103	max
Feature A-7	5	GX17542, beta	BLUF-7	"fresh" charcoal in feature	525 ± 105	532 +108/−36	con
Feature B-8	5, B-10	GX1136, beta	BLUF-8A	new burn charcoal	195 ± 110	121 +190/−121	min
	5, B-10	GX17550, beta	BLUF-8B	bark in bedding sequence	515 ± 60	527 +22/−20	con
Feature B-9	5, B-11	GX17544, beta	BLUF-9A	charcoal in feature	1455 ± 115	1327 +89/−49	max
Feature B-10	5, B-12	GX17549, beta	BLUF-10A	charcoal in soil profile cut by feature	1940 ± 125	1874 +123/−157	max
	5, B12	GX17551, beta	BLUF-10B	charcoal within feature	800 ± 110	697 +91/−42	max
Feature C-11	5	GX17705, beta	BLUF-11	wood recovered from feature	525 ± 110	532 +110/−40	con
Feature C-12	5, C-2	GX17135, beta	BLUF-12A	charcoal in feature	2275 ± 125	2323 +34/−192	max
	5, C-2	GX17548, beta	BLUF-12B	new burn charcoal in redeveloped soil profile	775 ± 125	674 +111/−97	min
Feature D-13	5	GX17707, beta	BLUF-13	charcoal in bedding sequence	3815 ± 145	4190 +224/−251	max
Feature D-14	5, D-15	GX17700, beta	BLUF-14A	wood sample from bedding sequence	3160 ± 190	3368 +208/−279	con
	5, D-15	GX17757, beta	BLUF-14B	charcoal in clast in feature	5070 ± 350	5821 +448/−484	max
Feature D-15	5, D-16	GX17701, beta	BLUF-15A	sample from root in feature	1520 ± 190	1397 +206/−123	min
	5, D-16	GX17702, beta	BLUF-15B	charcoal location?	3860 ± 235	4264 +299/−344	max
	5, D-16	GX17703, beta	BLUF-15C	brownish charcoal (wood?) in feature	3130 ± 135	3354 +115/−188	con
	5, D-16	GX17706, beta	BLUF-15D	charcoal in host sand	4205 ± 180	4766 +203/−318	max
	5, D-16	GX17758, beta	BLUF-15E	charcoal in host sands	4085 ± 150	4538 +293/−130	max

[a]For each sample the first two columns identify the feature and its investigator(s). The second column also lists additional sample names used by the author. The third column indicates the laboratory identification number and the technique used to date the sample (conventional or AMS). The fourth column is the sample identification number (this study). The fifth column indicates the type of organic material used for dating and its location in the feature to establish a relative age. In the sixth column is the conventional radiocarbon age reported by the testing facility. The calibrated age and the 1σ range determined during this study using the computer program CALIB v3.0.3c [*Stuiver and Reimer*, 1993] are given in the seventh column. The last column indicates the interpreted relative age relationship of the sample (minimum, maximum, contemporary (con)), based on field observations and its location in the feature.

[b]References: 1, *Talwani and Cox* [1985]; 2, *Weems et al.* [1986]; 3, *Weems and Obermeier* [1990]; 4, *Amick et al.* [1990]; 5, *Talwani et al.* [1993]; 6, *Talwani et al.* [1999].

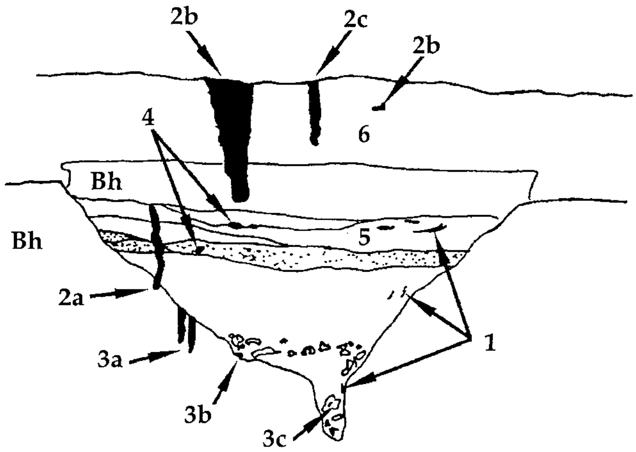

Figure 2. Schematic cross section of a sandblow crater that has intruded the soil profile and location of organic material used for radiocarbon dating. Bh is an organic-rich soil horizon. Clasts of Bh soil fall and are trapped with extruded clean sand within the crater. These are overlain by a bedded sequence of backfilled sand and organic material (item 5). The age of liquefaction episodes can be estimated by radiometric dating of organic materials that can be stratigraphically related to the liquefaction features. The most accurate age estimates are from radiometric dating of organic debris such as leaves, pine needles, bark, or small branches that were washed or blown into the liquefaction crater shortly after its formation (item 1). These are labeled "contemporary" ages. The ^{14}C ages of roots that have grown into the sandblow (item 2a) or the overlying soil profile (items 2b and 2c) provide minimum ages for the liquefaction episode. Minimum ages are also derived from forest-fire-derived charcoal from the shallow soil profile (item 6) overlying the feature. To be useful, this "new burn" charcoal must clearly be within the overlying soils that postdate feature formation. Maximum ages can be obtained from roots cut by the feature (item 3a), humate organic-rich soil (Bh) clasts that are isolated from contamination because of their depth in the feature (item 3b), or by organic material from soil clasts that predate liquefaction and collapsed into the deeper part of the crater during liquefaction (item 3c). Maximum age constraints can also be obtained by dating forest-fire-derived charcoal which was washed or blown into the crater after its formation (item 4). While wood from within the feature, especially the bedded sequence, can provide an accurate age constraint for the feature, charcoal is biologically inert, and before being washed into the bedded sequence, it can reside at or near the ground surface for hundreds or even thousands of years following a forest fire. Consequently, this type of sample only provides a maximum age constraint on the time of liquefaction. Modified from *Amick* [1990].

from the washed-in sand in the crater of feature 3 suggests that the earthquake causing liquefaction occurred ~1568 +310/−246 years B.P. (MYR-3, Table 2). Features 1 and 3 lie adjacent to each other with the same A horizon profile. The maximum age of an earthquake inferred from a humate clast in feature 1 overlaps the inferred contemporary age of MYR-3 and could possibly be associated with that episode, and not be representative of a younger one. A piece of "new burn" charcoal recovered from the overlying soil profile in feature 2 (MYR-2) suggests a liquefaction episode older than 5297 +353/−469 years B.P., and this is certainly different from the 1568 +310/−246 years B.P. liquefaction episode.

4.1.3. Martin Marietta. The Martin Marietta site (MM in Figure 1) is approximately 5 km south of the Myrtle Beach site. Here *Amick et al.* [1990] discovered three sandblows, but only one yielded organic material suitable for ^{14}C dating. One sample was a piece of tree bark from the lower portion of the central vent, which yielded a contemporary age for the liquefaction event. A sample of a humate-rich soil clast from the upper part of the sandblow, above the small clast zone, yielded a maximum age for the earthquake causing the liquefaction.

The calibrated dates indicate that at least one liquefaction episode occurred ~1809 +177/−257 years B.P. (MM-1A, Table 2). Field observations suggest that the tree bark associated with the contemporary age and the overlapping organic-rich soil clast are associated with the same episode.

4.1.4. Georgetown. The Georgetown site (GEO in Figure 1) is located approximately 35 km southwest of the Martin Marietta site and ~15 km north of the city of Georgetown. *Amick et al.* [1990] identified four sandblows at this site, all having similar staining and overlying soil profiles, which indicates that they developed about the same time. Features A, B, and C yielded four, two, and one organic samples, respectively, suitable for ^{14}C dating (Table 2). A root sample (GEO-2A) which had grown into feature B yielded a modern ^{14}C age, and it was interpreted as new growth and not used for age determination.

Interpreted calibrated ^{14}C age dates indicate two or possibly three episodes of liquefaction at this site. One episode occurred ~945 +223/−209 years B.P., on the basis of the contemporary date of a piece of wood recovered from within feature A (GEO-1D, Table 2). Field relations of the samples suggest that the overlapping minimum ages for GEO-1B and GEO-1C are associated with the same earthquake. Stratigraphic relationships indicate the occurrence of one or two other liquefaction episodes at this site. A minimum age constraint from sample GEO-2B indicates a liquefaction episode older than 2908 +337/−161 years B.P., and a maximum age constraint from sample GEO-3 indicates a liquefaction episode younger than 2739 +25/−257 years B.P. It is possible that GEO-3 represents the same episode indicated by GEO-1D.

4.1.5. Gapway. The Gapway site, discovered by *Schaeffer* [1996], is located ~60 km southwest of Myrtle Beach and approximately 20 km northwest of Georgetown (Figure 1). It contains four sandblows, two of which yielded datable samples (Figure 4). Four samples were recovered from Gapway A: A root that cuts the south boundary of the sandblow yielded a minimum ^{14}C age, (GW-1B, Table 2), and a second root that cuts the north boundary provided a minimum age (GW-1D). Two charcoal samples from the bedded sequence in the sandblow provided maximum ages (GW-1A and GW-1C). These ages indicate that this sandblow developed during a liquefaction episode that occurred between 1985 +68/−88 years B.P. (GW-1B) and 3623 +67/−146 years B.P. (GW-1C, Table 2).

Three samples from Gapway D indicate that one episode of liquefaction occurred at this site ~4985 +218/−113 years B.P. A twig from the bedded sequence yielded a contemporary ^{14}C age date (GW-2C), and a root which cut the north boundary of the feature yielded a minimum ^{14}C age which is considered a poor minimum age constraint. Small pieces of detrital charcoal from the bedded sequence of this sandblow were individually too small for age dating, so the pieces were combined to form a bulk detrital charcoal sample that yielded a maximum age of 4321 +88/−164 years B.P. (GW-2B). Normally, a maximum age would be older than the corresponding contemporary age.

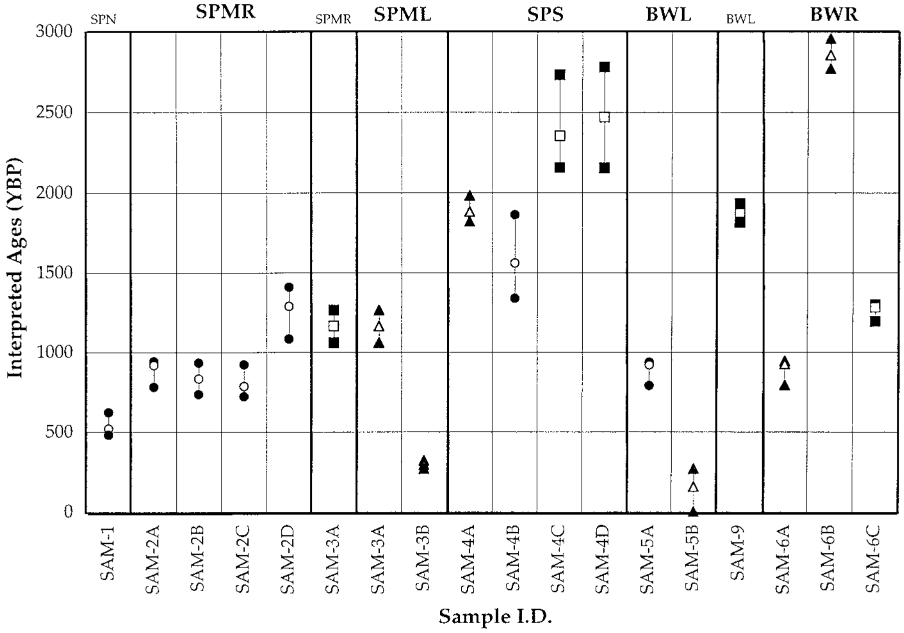

Figure 3. Plot of calibrated ages for Sampit site. Triangles, minimum ages; circles, contemporary ages; squares, maximum ages; short vertical lines, 1σ ranges. The features (Sampit North (SPN), Sampit Middle Right (SPMR), Sampit Middle Left (SPML), Sampit South (SPS), Big White Left (BWL), and Big White Right (BWR)) are separated by bold vertical lines, and multiple samples from a single feature are designated by the letters A, B, . . . (see also Table 2). Data from SAM-3A provide a maximum age constraint for SPMR and a minimum age constraint for SPML.

In this case the maximum age sample GW-2B is younger than the corresponding contemporary age sample GW-2C. Since this sandblow shows no signs of a second episode of liquefaction, and since sample GW-2B is a bulk soil sample, it could possibly have been contaminated with young material.

4.1.6. Olin. The Olin site is located ~50 km southwest of the Myrtle Beach site and approximately 20 km northwest of the city of Georgetown (Figure 1). *Amick et al*. [1990] discussed two sandblows identified by them and by *Weems and Obermeier* [1990] (Table 2). The degree of staining and the thickness of the overlying soil profile suggest that the sandblows at this site predated the 1886 Charleston earthquake. Five samples from feature A were dated by *Amick et al*. [1990], and one from feature B was dated by *Weems and Obermeier* [1990]. Analysis of the calibrated ^{14}C ages indicates that one liquefaction episode occurred ~1533 +452/−360 years B.P. This age was obtained from a sample of tree bark from within the sandblow, which yielded a contemporary ^{14}C age (OLIN-1C). Two tap root samples that cut the right boundary of the feature yielded bracketing minimum ^{14}C ages (OLIN-1A and OLIN-1B). Two charcoal samples from feature A yielded bracketing maximum ^{14}C age dates (OLIN-1E and OLIN-1D). Sample OLIN-2 indicates only the occurrence of a liquefaction event younger than 1511 +58/−157 years B.P., which does not distinguish its age from the age of the earthquake associated with feature A.

4.1.7. Sampit. *Amick et al*. [1990] and *Talwani et al*. [1999] studied six sandblows at the Sampit site, which is located ~1 km south of Olin, and analyzed 21 samples of organic material (Figures 1, 3, and 4 and Table 2). In the northern portion of this site a bark sample from the large clast zone in Sampit North (SPN; *Amick et al*. [1990]), yielded a contemporary ^{14}C age (SAM-1). Restudy of this site by *Talwani et al*. [1999] did not discover any additional datable samples. We interpret the contemporary calibrated age date to indicate that this sandblow was formed ~521 +102/−39 years B.P. (SAM-1).

Two sandblows in the middle part of the drainage ditch at Sampit were identified as Sampit Middle Right (SPMR) and Sampit Middle Left (SPML) by *Amick et al*. [1990]. Sampit Middle Right (SPMR) is located adjacent and to the south of SPML (Figure 4). They recovered four samples for ^{14}C dating: Two bark samples (SAM-2A and SAM-2B, Table 2) from the clast zone yielded contemporary ^{14}C age dates, and a bark sample (SAM-2C) from the bedded sequence in SPMR yielded a contemporary ^{14}C age date. *Amick et al*. [1990] identified a small crater-shaped sandblow within the main one, and on the basis of staining, they interpreted the smaller sandblow to have formed about the same time as the main feature. A bark sample (SAM-2D) from the smaller sandblow yielded a contemporary age.

The four contemporary ages define the approximate time that SPMR developed. The 1σ age range of SAM-2D does not overlap those of the other three samples, possibly because SAM-2D was recovered from a smaller feature that was located within the main sandblow and that probably predates it.

Sampit Middle Left (SPML) is adjacent to and north of SPMR (Figure 4). A sample of a root that had grown into the feature was analyzed by *Amick et al*. [1990] and yielded a minimum ^{14}C age date (SAM-3A). *Amick et al*. [1990] also found evidence of a younger, small sand dike that had intruded SPML and cut the root (SAM-3A). This indicates the root was in place prior to the sand dike intrusion. The degree of staining of the sand dike and SPMR are similar, which was interpreted as showing that both developed about the same time. Therefore this sample represents not only a minimum age for SPML but also a maximum age for SPMR. *Talwani et al*. [1999]

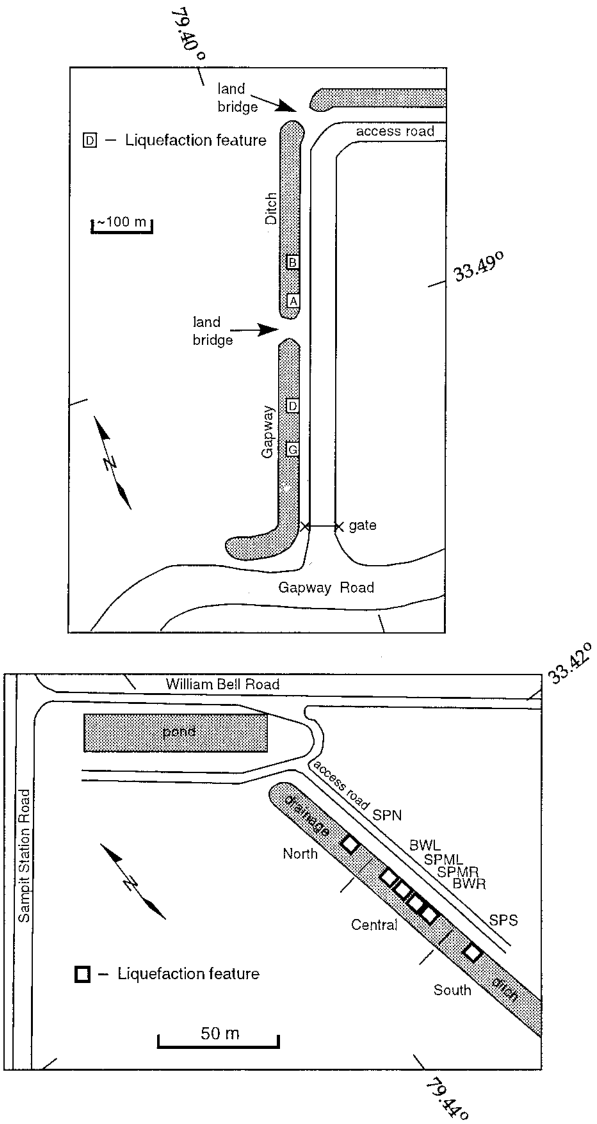

Figure 4. Schematic maps of the (top) Gapway and (bottom) Sampit sites showing locations of features in the drainage ditches.

recovered a sample of wood from the top of SPML, which is believed to have been deposited in the crater sometime after it formed. This sample provides a minimum ^{14}C age (SAM-3B). The clear cross-cutting relations that were observed between BWL (discussed later) and SPML were interpreted to show that SPML is older than SAM-5A. The young age of SAM-3B suggests that it was derived from spoil that fell onto the surface of the sandblow and therefore does not reflect an age constraint for it. The minimum age SPML indicates that it developed during a liquefaction episode older than 1165 +100/−105 years B.P. (SAM-3A). Since the upper portion of the south boundary of BWL (described below) cuts the upper portion of the north boundary of SPML, this cross-cutting relationship indicates that SPML existed prior to the formation of BWL.

Sampit South (SPS) is in the southern portion of the Sampit site (Figure 4). *Amick et al.* [1990] recovered four samples from it. Two charcoal samples (SAM-4C and SAM-4D) from the bedded sequence yielded maximum ages, a carbonized wood sample from the bedded sequence (SAM-4B) yielded a contemporary ^{14}C age date, and a root sample that had grown into SPS (SAM-4A) yielded a minimum age. Field observations of the location of this sample (SAM-4A) suggest that it is associated with the same episode. Analysis of the calibrated age dates indicate that SPS developed during a liquefaction episode that occurred around 1561 +302/−221 years B.P. (SAM-4B, Figure 3). This episode is bracketed by two maximum ages, SAM-4C and SAM-4D.

In a later study, *Schaeffer* [1996] discovered two more sandblows in the central portion of the Sampit site (Big White Left and Big White Right). Big White Left (BWL) is located north of and adjacent to SPML. *Schaeffer* [1996] recovered three samples for ^{14}C dating: A bark sample yielded a contemporary ^{14}C age (SAM-5A), a root (SAM-5B) recovered from BWL yielded a minimum ^{14}C age, and a third sample was a piece of wood from stump H2 (SAM-9), around which BWL developed. Since the stump predates development of this feature, the wood sample is a maximum age constraint for BWL (SAM-9).

Big White Right (BWR) is located ~3 m to the south of SPMR and yielded three datable samples. A root that had grown into BWR yielded a minimum ^{14}C age (SAM-6A), a second root recovered from another part of this feature yielded a minimum ^{14}C age (SAM-6B), and charcoal recovered from within it yielded a maximum ^{14}C age date (SAM-6C). Upon inspection of the calibrated ages from BWR it was found that the minimum age sample, SAM-6B, has an older age than the maximum age sample, SAM-6C. The exact cause of this discrepancy is not known, but it is suspected that a labeling error occurred either at the testing laboratory or during the field preparation of these two samples. Since a reliable maximum age is not available, the analysis of the calibrated ages indicates that BWL is older than 925 +21/−131 years B.P. (SAM-6A, Table 2).

Summarizing, dates of the paleoliquefaction features and their cross-cutting relations at Sampit suggest at least three episodes of earthquake activity (Figure 3). SAM-1, collected from the northern part of the drainage ditch, is associated with an earthquake that occurred around 500 years B.P. The four samples from SPMR (SAM-2A to SAM-2D) and one from BWL (SAM-5A) and bracketing ages at BWR (SAM-6A and SAM-6C) argue for an event that occurred ~1000 years B.P. The cross-cutting relationship of BWL with SPML suggests that SPML (SAM-3) is associated with an earthquake older than BWL (SAM-5) and SPMR (SAM-2). The minimum age of SPML (SAM-3A) and the maximum age of BWL (SAM-9) could be associated with the earthquake that yielded a contemporary age at SPS (SAM-4B), 1561 +302/−221 years B.P.

4.2. An Inland Sandblow

The Four Hole Swamp (FHS) site is located approximately 23 km northwest of Summerville (Figure 1) near the intersection of highways 78 and 178. This site is situated on a Pleistocene age beach ridge composed of clean, fine-to-medium-grained sand. A sandblow at this site was discovered by C. P. Rajendran (unpublished data, 1993). A bark sample collected from within it (FHS-1, Table 2) yielded a contemporary age of 1659 +70/−107 years B.P., which was taken to be the age of the paleoliquefaction event [*Talwani et al.*, 1999]. *Schaeffer* [1996] found no new datable samples.

4.3. Central (Charleston) Sites

4.3.1. Ten Mile Hill. In the Charleston area many sandblows formed near Ten Mile Hill in 1886 (Figure 1), but because of extensive urbanization and thick vegetation, direct evidence of the sandblows is obscured. *Amick et al*. [1990] discovered four sandblows in a drainage ditch ~1.6 km north of the Charleston Air Force Base (CAFB). Another feature near CAFB was studied by *Weems and Obermeier* [1990]. During a recent study by *Talwani et al*. [1999], anomalous sand was encountered in a hole drilled for standard penetration tests ~0.8 km north of the CAFB. A shallow trench (~1.5 m deep) at this location provided two datable samples.

Four contemporary ages for features A and C of *Amick et al*. [1990] and Airport (ARP) of *Weems and Obermeier* [1990] (TMH-1A, TMH-1B, TMH-3, and TMH-5, Table 2) all suggest that an episode of liquefaction occurred between 3400 and 3700 years B.P. TMH-1D gave an anomalously younger contemporary age, whereas TMH-4A and TMH-4B bracket an older event between ~5400 and 6600 years B.P., and TMH-2A and TMH-2B provide minimum ages.

TMH-6A, collected from the shallow trench, consisted of pieces of wood sieved from clayey sand and is possibly contaminated. It gave a contemporary (?) age of 1299 +47/−21 years B.P. (TMH-6A). The second sample consisted of pieces of charcoal sieved from a few pounds of silty clay, yielded an age of 4038 +46/−109 years B.P. (TMH-6B), and is interpreted as a maximum age. It possibly represents the age of the enclosing clay layer.

4.3.2. Hollywood. Several sandblows in a drainage ditch just north of Hollywood (HOL in Figure 1) and located ~30 km to the west of Charleston provided samples at seven locations (*Talwani and Cox* [1985], *Weems et al*. [1986, 1988], and *Weems and Obermeier* [1990]; Table 2). Contemporary ages were obtained from HOL-6A with a strong minimum age constraint for an earthquake at ~600 years B.P. (HOL-6B). Four samples from site 2 (HOL-7A to HOL-7D) and one from Hollywood XIV (HOL-8) gave contemporary age dates for an earthquake between ~1000 and 1200 years B.P. The other sandblows provided broad minimum or maximum age constraints. For example, HOL-1A to HOL-1E support the occurrence of one or more earthquakes between ~1500 and 4000 years B.P. At another site the dates obtained for HOL-2A and HOL-2B suggest an earthquake that occurred before 3200 years B.P.

At the Hollywood XIII site the ages of samples HOL-3A and HOL-3B argue for an earthquake between ~4700 and 7900 years B.P.; elsewhere, the sample HOL-4 did not provide any age constraint. HOL-5A and HOL-5B provide weak constraints for an event (events) between 1700 and 4768 years B.P.

Thus the data from Hollywood suggest at least four prehistoric earthquakes. Well-constrained ages identify an earthquake between ~500 and 600 years B.P. (HOL-6A and HOL-6B) and another one between ~1000 and 1200 years B.P. (HOL-7A to HOL-7D and HOL-8). Weak constraints suggest an event between ~1500 and 4100 years B.P. (HOL-1A and HOL-1E) and between ~1700 and 4800 years B.P. (HOL-5B and HOL-5A). Finally, an earthquake with poorly constrained age may have occurred between ~4700 and 7900 years B.P. (HOL-3B and HOL-3A).

4.4. Southern Sites

Samples from six sites south of Charleston (Figure 1) provide ages of liquefaction episodes similar to those near Charleston and the northern sites. From north to south they are Colony Gardens (COLGAR), Malpherous (MAL), and Bluffton A–D (Figure 1).

4.4.1. Colony Gardens. Colony Gardens (COLGAR in Figure 1) is the closest of the southern liquefaction sites to Charleston. *Amick et al*. [1990] identified several sandblows, the largest approximately 3 m in width, comparable to some of the larger features discovered at Ten Mile Hill. A piece of wood recovered from a unit of interbedded sand and organics gave a contemporary age of 958 +100/−34 years B.P. (Table 2). A second piece of wood recovered from a soil clast provided a tight maximum age constraint of 1263 +31/−124 years B.P. Thus the data from Colony Gardens support a prehistoric earthquake occurring around 1000 years B.P.

4.4.2. Malpherous. Six samples from one heavily stained sandblow provided age constraints, but no contemporary age data [*Amick et al*., 1990] at Malpherous (MAL in Figure 1). The inferred age of one earthquake, between ~5300 and 6300 years B.P., is constrained by a large root that had grown into the sandblow and provided a minimum age constraint (MAL-1A) (Table 2) and a small charcoal sample from within a soil clast that had collapsed into the same feature, which provided a maximum age constraint (MAL-1B). Three splits of a humate clast gave redundant maximum ages (MAL-1D to MAL-1F). Younger roots from MAL-1C provided minimum age constraints that were not useful.

4.4.3. Bluffton. Four liquefaction sites near Bluffton were named BLUF-A to BLUF-D. BLUF-A and BLUF-B were originally discovered by *Obermeier et al*. [1987]. *Amick et al*. [1990] reinvestigated BLUF-A and BLUF-B and discovered BLUF-C. *Talwani et al*. [1993] reinvestigated BLUF-A to BLUF-C and discovered BLUF-D, ~6 km east of the earlier sites. Thus, for the various sites, samples analyzed by one or more investigators provide redundancy and better age constraints. The age relation used by *Rajendran and Talwani* [1993] were reanalyzed using the criteria in section 3.1, and the revised relationships are given in Table 2.

Amick et al. [1990] dated organic material in four sandblows at site BLUF-A (features A-1, A-2, A-3, and A-4) and, for the first three, obtained contemporary ages corresponding to the 1886 Charleston earthquake (Table 2). At the fourth location (feature A-4) they obtained a minimum calibrated age of 301 +167/−301 years B.P. (BLUF-4A) and a contemporary calibrated age of 598 +741/−93 years B.P. (BLUF-4B). These ages are close to the contemporary age of *Weems and Obermeier* [1990] for the same feature, 547 +103/−36 years B.P. (BLUF-4C). *Talwani et al*. [1993] discovered seven sandblows at BLUF-A, four of which provided no datable samples and one of which (identified in Table 2 as BLUF-4E was the same as that studied earlier by *Weems and Obermeier* [1990] and *Amick et al*. [1990] (feature A-4). In feature A-4, *Talwani et al*. [1993] also found a new burn charcoal in the sands overlying the feature that yielded a minimum calibrated age of 376 +132/−87 years B.P. (BLUF-4D). A piece of charcoal within the sandblow yielded a maximum radiocarbon age of 656 +471/−105 years B.P. (BLUF-4E). These dates further constrain the ages obtained by *Amick et al*. [1990] (BLUF-4A and BLUF-4B) and *Weems and Obermeier* [1990] (BLUF-4C). Thus, at BLUF-A, feature A-4 yielded contemporary ages of 550–600 years B.P. (BLUF-4B and BLUF-4C), and these ages were bracketed by minimum ages of 301 years B.P. (BLUF-4A) and 376 years B.P. (BLUF-4D) and a maximum age of 656 years B.P. (BLUF-4E). Roots in clasts in another sandblow at

BLUF-A, feature A-6, provided a minimum age of 1213 +85/−148 years B.P. (BLUF-6A), and an aggregate of charcoals from two locations within the sandblow gave a maximum age of 1072 +191/−103 years B.P. (BLUF-6B). Because of the aggregation the age of BLUF-6B does not provide a tight constraint. The age of the sample from BLUF-6A suggests an earthquake older than ~1200 years B.P. At feature A-7 a "fresh" piece of charcoal within the sandblow yielded a probable contemporary age of 532 +108/−36 years B.P. (BLUF-7).

At BLUF-B, *Talwani et al*. [1993] investigated five sandblows; four yielded datable samples. Sandblow feature B-9 had been earlier investigated by *Amick et al*. [1990] and was identified as their site BD. In this study, that sandblow is identified as feature B-5 and provided four calibrated ages. The two studies provided two minimum ages (BLUF-5B and BLUF-5D) and two maximum ages (BLUF-5A and BLUF-5C), bracketing the age of the liquefaction episode between ~1780 and 2140 years B.P. One of the three organic samples at feature B-8 yielded a modern date. Of the other two, a piece of bark in the bedding sequence yielded a contemporary age of 527 +22/−20 years B.P. (BLUF-8B) whereas a new burn piece of charcoal (BLUF-8A) gave a minimum radiocarbon age of 121 +190/−121 years B.P. Charcoal in feature B-9 gave a maximum age of 1327 +89/−49 years B.P. At site B-10, charcoal in the soil profile cut by the sandblow (BLUF-10A) gave a maximum age of 1874 +123/−157 years B.P., whereas charcoal within it (BLUF-10B) gave a maximum age of 697 +91/−42 years B.P. Summarizing, at BLUF-B we have evidence of two or possibly three prehistoric earthquakes: an earthquake that occurred between ~500 and 600 years B.P. (BLUF-8B, and bracketing maximum age, BLUF-10B), loose constraint for an event younger than ~1300 years B.P. (BLUF-9), and an older earthquake between ~1800 and 2150 years B.P. (BLUF-5B and BLUF-5A).

At BLUF-C, wood from feature C-11 yielded a contemporary age of 532 +110/−40 years B.P. (BLUF-11), and charcoal in the sandblows and a new burn charcoal in the redeveloped soil profile in feature C-12 provided bracketing ages between ~2300 and 700 years B.P. (BLUF-12A and BLUF-12B). These loosely constrain the timing of one or more earthquakes.

At BLUF-D, four sandblows were discovered by *Talwani et al*. [1993], from which a piece of charcoal within the bedding sequence provided a maximum age of 4190 +224/−251 years B.P. (BLUF-13), and no datable material was obtained from the second feature. Two radiocarbon samples from feature D-14 indicate that an earthquake occurred ~3400 years B.P. on the basis of a contemporary date of a piece of wood from within the bedding sequence (BLUF-14A) and of a piece of charcoal in a clast in the sandblow (BLUF-14B).

Five samples were recovered from feature D-15. Three charcoal samples (BLUF-15B, BLUF-15D, and BLUF-15E) provide maximum ages ranging from ~4264 to 4766 years B.P. BLUF-15A was a sample from a root in the feature and provided a minimum age of ~1400 years B.P. BLUF-15C consisted of a sample of brownish charcoal or wood in the sandblow. It provided a contemporary age of 3354 +115/−188 years B.P. Thus data from all three sandblows at BLUF-D (features D-13 to D-15) suggest the occurrence of an earthquake ~3400 years B.P. Next all the calibrated ages given in Table 2 were analyzed for recurrence rates and seismogenic sources (section 5).

5. Dates and Magnitudes of Prehistoric Earthquakes

To determine the dates and estimate the magnitudes of prehistoric earthquakes, we examined the calibrated ages and stratigraphic positions of samples from the various sandblows throughout the Coastal Plain of South Carolina. For each sandblow we obtained an estimate of its age from the radiocarbon data and stratigraphic setting. When contemporary ages were available, they were interpreted to be the age of the causative paleoearthquake. Ages of other sandblows were based on maximum and minimum age constraints discussed in section 4. Once all the age data for all the sandblows were in hand, they were compared with each other and used to obtain the dates of earthquake episodes that caused them. Contemporary ages and corroborative age constraints, where available, were binned together according to the following criteria. Overlapping 1σ ranges of contemporary dates were interpreted to indicate a single earthquake episode. The estimated age of the episode is calculated from the weighted averages of the overlapping contemporary ages. An absence of overlapping 2σ ranges of contemporary dates was interpreted to indicate different earthquake episodes. The maximum and minimum ages were used to provide constraints. If a particular sandblow had both maximum and minimum age ranges that overlapped the range of contemporary 1σ ages, they are referred to as tight-bracketing age constraints. If the range of 1σ maximum and minimum ages did not overlap the range of 1σ contemporary ages, they are referred to as loose-bracketing age constraints. If only a maximum or a minimum age was available for a particular sandblow, it was referred to as a tight or loose age constraint depending on if the corresponding range of 1σ ages overlapped the contemporary age ranges or not.

We use earthquake episodes because it is not possible to determine if a specific liquefaction feature is associated with only one mainshock or with the mainshock and its aftershocks. The analysis identified seven prehistoric episodes (episodes A–G), which are discussed below. The dates of formation of sandblows at various sites were compared with each other to infer the date of the earthquake episode. The data for each episode are presented in Figures 5a–5g, wherein samples from a site are identified in accordance with Table 2. For each episode the contemporary dates and tight-bracketing constraints are plotted once and were used to define its age. In some cases, loose-bracketing constraints and the loose constraints could apply to more than one episode, and they are included in figures for more than one episode. For example, the ages of BLUF-12A and BLUF-12B provide loose constraints for the dates of episodes B, C, and D. Here they are included with data for episode D (Figure 5d). However, only locations that provided contemporary or tight-bracketing dates for each episode are shown in Figure 6.

Various empirical methods have been suggested to estimate the magnitude of an earthquake from paleoliquefaction data [see, e.g., *Ambraseys*, 1988; *Tuttle*, 1994; *Obermeier and Pond*, 1999]. We chose a simple method that is probably more applicable to the SCCP and compared our results with the empirical method of *Ambraseys* [1988].

The areal extent of liquefaction features associated with a particular prehistoric episode was compared with the areal distribution of sandblows associated with the 1886 earthquake to estimate the size of the prehistoric earthquake. For contemporary sandblows occurring in the northern, central, and south-

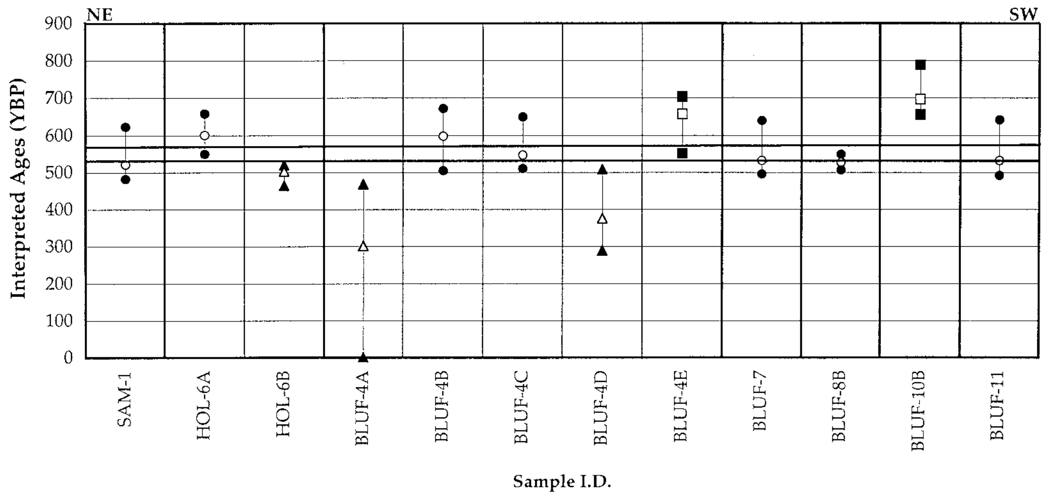

Figure 5a. Age data used to obtain the age of episode A (546 ± 17 years B.P.). Symbols are defined in Figure 3. Locations of samples providing contemporary ages and tight-bracketing ages are shown in Figure 6. BLUF-4A to BLUF-4D and BLUF-7; BLUF-8B and BLUF-10B; and BLUF-11 are samples from BLUF-A, BLUF-B, and BLUF-C, respectively. The thick horizontal lines bracket the interpreted age of the episode.

ern parts of the SCCP the assigned magnitude is M 7+ (comparable with the 1886 earthquake). Smaller magnitudes were assigned to episodes with smaller areal distribution of sandblows. *Obermeier et al.* [1990] argue that the sandblows discovered by them were caused by earthquakes stronger than m_b 5.5 (based on their estimate of the threshold magnitude for liquefaction in the SCCP). When we encountered liquefaction features of a particular age at more than one site, but with smaller areal extent than the 1886 Charleston earthquake, we have assigned a minimum magnitude M 6.0.

On the basis of over 100 data points, *Ambraseys* [1988] found that moment magnitude M for any earthquake was related to the maximum epicentral distance R_e, measured from the adopted epicenter to the most distant site where there was clear evidence of liquefaction-induced ground failure. He found that the equation

$$M = -0.31 + 2.65 \times 10^{-8}R_e + 0.99(\log R_e),$$

where R_e (in centimeters), represented the upper limit for R_e as a function of M.

The 1886 Charleston earthquake caused widespread liquefaction, and sandblows formed hundreds of kilometers from Charleston [*Dutton*, 1889; *Seeber and Armbruster*, 1981]. Besides the meizoseismal area, liquefaction features described as "sinkholes" were found at four locations over a hundred kilometers west of Charleston, along the coast near Georgetown, and inland near Columbia [*Dutton*, 1889; *Seeber and Armbruster*, 1981] and in Sand Hills near Liberty Hill [*Floyd*, 1992] (Figure 1). After the discovery of a sandblow associated with the 1886 earthquake near Warren's Crossroads (*Cox* [1984]; Figure 1), intensive search over the SCCP for other 1886 sandblows was not very successful. Only three other sandblows associated with the 1886 earthquake were discovered near Bluffton (BLUF-1, BLUF-2, and BLUF-3, Table 2). Comparing the felt area and the areal extent of various intensity values

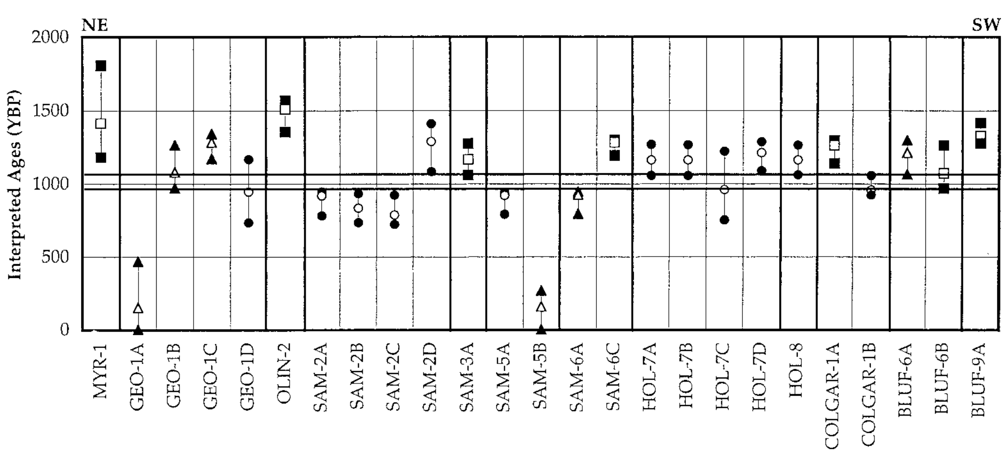

Figure 5b. Age data used to obtain the age of episode B (1021 ± 30 years B.P.). Symbols are defined in Figure 3. Locations of samples providing contemporary ages and tight-bracketing ages are shown in Figure 6. BLUF-6A, BLUF-6B, and BLUF-9A are samples from BLUF-A and BLUF-B, respectively. The thick horizontal lines bracket the interpreted age of the episode.

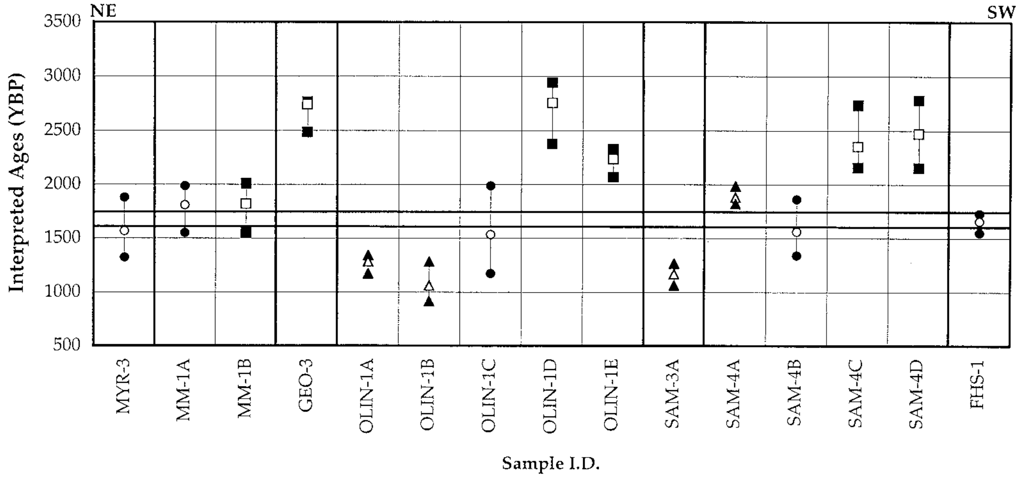

Figure 5c. Age data used to obtain the age of episode C (1648 ± 74 years B.P.). Symbols are defined in Figure 3. Locations of samples providing contemporary ages and tight-bracketing ages are shown in Figure 6.

for the 1886 Charleston earthquake with those of other earthquakes in stable continental regions, *Johnston* [1996] assigned it a magnitude M 7.3 ± 0.26. Assuming that the current seismicity defines the source of the 1886 Charleston earthquake and considering reports of liquefaction near Columbia (160 km) and Liberty Hill (180 km), application of *Ambraseys*' [1988] formula yields estimates of 7.3 and 7.4, respectively, values comparable to *Johnston*'s [1996] estimates. The estimated magnitudes and dates of prehistoric earthquakes that caused liquefaction were combined to estimate the recurrence times of large earthquakes in the South Carolina Coastal Plain.

5.1. Episode A

Seven contemporary ages between ~500 and 600 years B.P. with overlapping 1σ ranges were obtained from samples at Sampit in the north (SAM-1), Hollywood near Charleston (HOL-6A), and BLUF-A (BLUF-4B, BLUF-4C, and BLUF-7), BLUF-B (BLUF-8B), and BLUF-C (BLUF-11) in the south (Figures 5a and 6). The weighted average of the seven dates (including uncertainties) is 546 ± 17 years B.P., which is the age we assign episode A. Tight-bracketing constraint to this age was obtained from three samples from BLUF-B (BLUF-4A (minimum), BLUF-4D (minimum), and BLUF-4E (maximum)). Tight constraints were also obtained from Hollywood (HOL-6B (minimum)) and BLUF-B (BLUF-10B (maximum)). Loose constraints were obtained from Myrtle Beach and Olin (MYR-1 and OLIN-2). As contemporary ages were obtained from locations in the north, the middle, and the south (Figure 6) we interpret the earthquake(s) associated with episode A to be at least as large as the 1886 episode and centered near Charleston and assign it a magnitude M 7+. On the basis of the epicentral distance (110 km) to the most distant sandblow (BLUF-C, Figure 6a), *Ambraseys*' [1988] formula gives M 7.0.

5.2. Episode B

Twelve contemporary ages between ~900 and 1200 years B.P. with overlapping 1σ ranges were obtained from Georgetown (GEO-1D), Sampit (SAM-2A to SAM-2D and SAM-5A) in the northern part of the SCCP, Hollywood (HOL-7A to

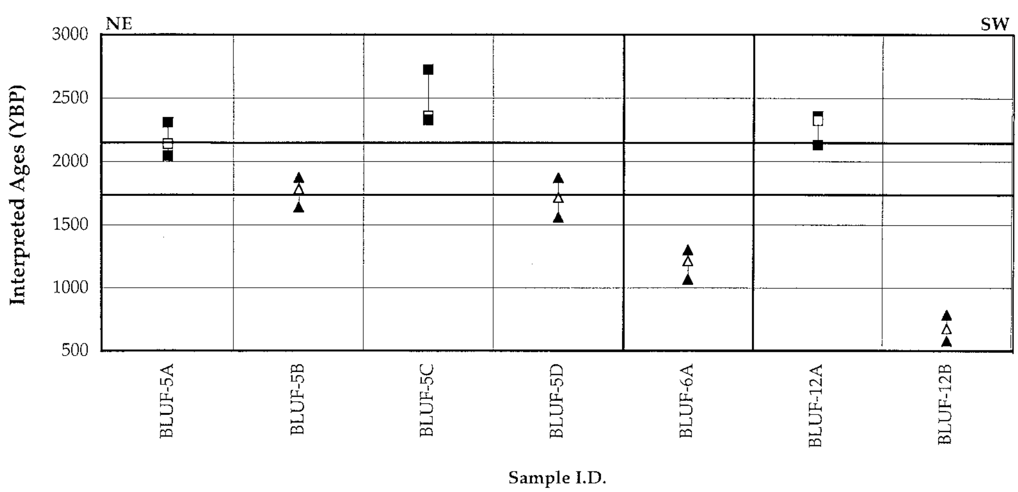

Figure 5d. Age data used to obtain the age of episode D (1754–2177 years B.P.). Symbols are defined in Figure 3. Locations of samples providing contemporary ages and tight-bracketing ages are shown in Figure 6. BLUF-5A to BLUF-5D and BLUF-6A; and BLUF-12A, and BLUF-12B are samples from BLUF-B and BLUF-C, respectively. The thick horizontal lines bracket the interpreted age of the episode.

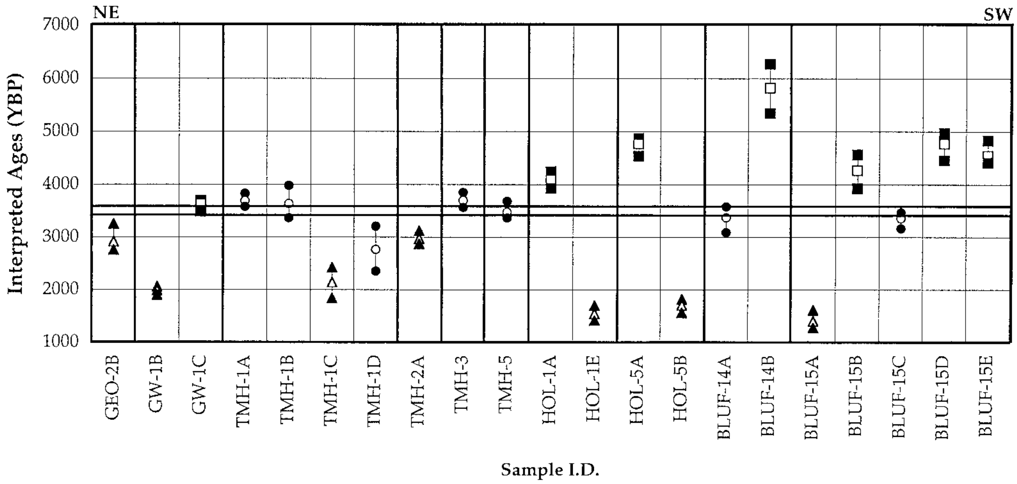

Figure 5e. Age data used to obtain the age of episode E (3548 ± 66 years B.P.). Symbols are defined in Figure 3. Locations of samples providing contemporary ages and tight-bracketing ages are shown in Figure 6. BLUF-14A, BLUF-14B, and BLUF-15A to BLUF-15E are samples from BLUF-D. The thick horizontal lines bracket the interpreted age of the episode.

HOL-7D and HOL-8) near Charleston, and Colony Gardens (COLGAR-1B) in the southern part of SCCP (Figures 5b and 6). The weighted average of the 12 dates was 1021 ± 30 years B.P., which is the age we assign to episode B. The interpreted age of episode B is tightly constrained by bracketing ages at Georgetown (GEO-1B and GEO-1C), Sampit (SAM-6A and SAM-6C), Colony Gardens (COLGAR-1A), and BLUF-A (BLUF-6A and 6B), by another three maximum ages (Figures 5b and 6), and, loosely, by one maximum and two minimum ages.

In view of the occurrence of contemporary ages from locations in the northern, the middle, and the southern sites along the coast (Figure 6) we interpret episode B to be as large as the Charleston 1886 episode and to be dated 1021 ± 30 years B.P. and also located near Charleston and assign it a magnitude M 7+. Application of *Ambraseys*' [1988] formula, with an epicentral distance of 110 km to Georgetown (GEO in Figure 6b), gives M 7.0.

5.3. Episode C

Five contemporary ages between ~1500 and 1800 years B.P. with overlapping 1σ ranges were obtained from samples at Myrtle Beach (MYR-3), Martin Marietta (MM-1A), Olin (OLIN-1C), and Sampit (SAM-4B) sites in the north and from Four Hole Swamp (FHS-1), ~50 km northwest of the Charleston area (Figures 5c and 6). The weighted average of the five contemporary dates was 1648 ± 74 years B.P., which is the age we assign to episode C. The interpreted age of episode C is tightly constrained by bracketing ages at Olin (OLIN-1A, OLIN-1B, and OLIN-1E) and Sampit (SAM-4A, SAM-4C, and SAM-4D) and by a maximum value at Martin Marietta (MM-1B) and a minimum value at Sampit (SAM-3A). In view of the absence of any contemporary or tightly bracketing age near Charleston, or at southern sites, we interpret episode C to be associated with a seismic source in the north. Because of the smaller areal extent of sandblows associated with episode C

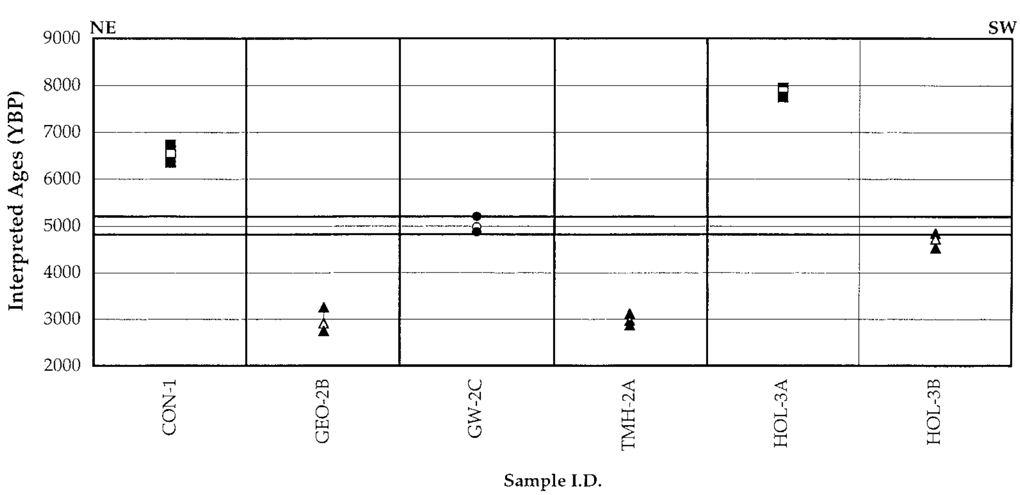

Figure 5f. Age data used to obtain the age of episode F (5038 ± 166 years B.P.). Symbols are defined in Figure 3. Locations of samples providing contemporary ages and tight-bracketing ages are shown in Figure 6. The thick horizontal lines bracket the interpreted age of the episode.

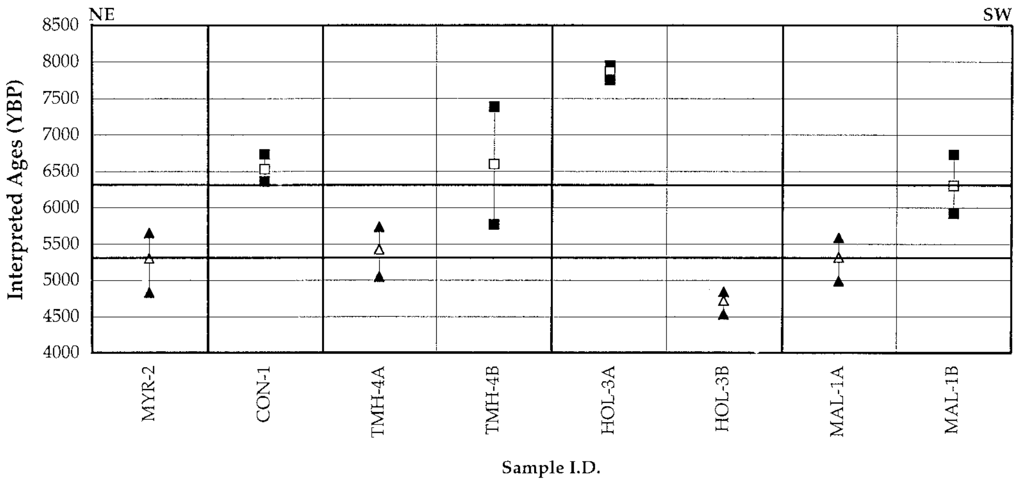

Figure 5g. Age data used to obtain the age of episode G (5300–6300 years B.P.). Symbols are defined in Figure 3. Locations of samples providing contemporary ages and tight-bracketing ages are shown in Figure 6. The thick horizontal lines bracket the interpreted age of the episode.

(Figure 6) we interpret the magnitude to be smaller than that of the 1886 episode and assign it a magnitude of M 6.0. Assuming a northern source midway between the Sampit and Myrtle Beach sites (SAM and MYR in Figure 6), an epicentral distance of 35 km, suggests M 6.3 using *Ambraseys*' [1988] formula. If we estimate the source to be midway between Four Hole Swamp and Myrtle Beach (FHS and MYR), we get M 6.8.

5.4. Episode D

We do not have convincing evidence for episode D lying between ~1700 and 2200 years B.P. Evidence of episode D is inferred primarily from tight-bracketing ages from four samples from BLUF-B (BLUF-5A to BLUF-5D), a maximum value at BLUF-C (BLUF-12A), and a minimum value at BLUF-A (BLUF-6A) (Figures 5d and 6). Because evidence of episode D is limited to the southern sites (Figure 6), we interpret it to be associated with a southern source near Bluffton, and because of the limited areal extent of the sandblows we assign it a magnitude M 6.0. The age is inferred to lie between ~1754 and 2177 years B.P. Application of *Ambraseys*' [1988] formula, and assuming an epicentral distance of 10 km yields M 5.7.

Although no evidence of episode C or episode D was found near Charleston, we cannot rule out the alternative scenario that episode C (the evidence for which was found at northern sites and near Four Hole Swamp) (Figure 6) and episode D (the evidence for which was found near Bluffton) (Figure 6) were associated with one (or two) larger earthquake(s), centered near Charleston. If the age of episode C is 1648 ± 74 years B.P. and the age of episode D is 1966 ± 212 years B.P., then they are statistically different at 1σ level but the same at 2σ level. Alternatively, if we assume that they were in fact associated with a single large episode C′, the weighted mean of their ages is 1683 ± 70 years B.P. Because episode C′ incorporates ages of sandblows to the north (near Georgetown), the northwest (near Four Hole Swamp), and the south (near Bluffton) of Charleston, we ascribe the episode to the Charleston source. We attribute the absence of contemporary sandblows near Charleston to their being obliterated by successive earthquakes or to our having just not found them. We assign episode C′ a magnitude M 7+ on the basis of the spatial extent of contemporary sandblows. Assuming the epicenter to lie near Charleston, and epicentral distance to MYR, using *Ambraseys*' [1988] formula suggests M 7.2. We retain the episodes C and D scenario and the episode C′ scenario as likely interpretations of the data.

5.5. Episode E

Six contemporary ages between ~3300 and 3700 years B.P. with overlapping 1σ ranges were obtained from three locations near Ten Mile Hill (TMH-1, TMH-3, and TMH-5), located near Charleston, and from BLUF-D (BLUF-14A and BLUF-15C). These dates were constrained by a minimum age near Georgetown (GEO-2B) and a maximum age near Gapway (GW-1C) in the north; a minimum age near Ten Mile Hill (TMH-2A), a maximum age near Hollywood (HOL-1A) near Charleston; and a maximum age at BLUF-D (BLUF-15B) in the south (Figures 5e and 6). The weighted average of these contemporary ages is 3548 ± 66 years B.P., which is the age we assign to episode E.

Because evidence for episode E was found at sites in the north, middle, and south, we interpret the size of this (these) earthquake(s) to be at least as big as the 1886 Charleston earthquake and its location to be near Charleston, and we assign it a magnitude M 7+. Using *Ambraseys*' [1988] formula and a distance of 100 km (distance to BLUF-D), we get M 7.0.

5.6. Episode F

Episode F has been inferred from one contemporary age for a sample at Gapway (GW-2C) and tight-bracketing constraint from Hollywood (HOL-3B) and from loose maximum constraints from Hollywood (HOL-3A) and Conway (CON-1) and loose minimum constraints from Georgetown (GEO-2B) and Ten Mile Hill (TMH-2A) (Figures 5f and 6). The two ages obtained from HOL-3A and HOL-3B do not provide a tight age constraint for episode F and could be evidence for a later earthquake (episode G). The age of episode F is 5038 ± 166 years B.P., based on one contemporary age with possibly a northern source. We ascribe it a magnitude M ~6.0.

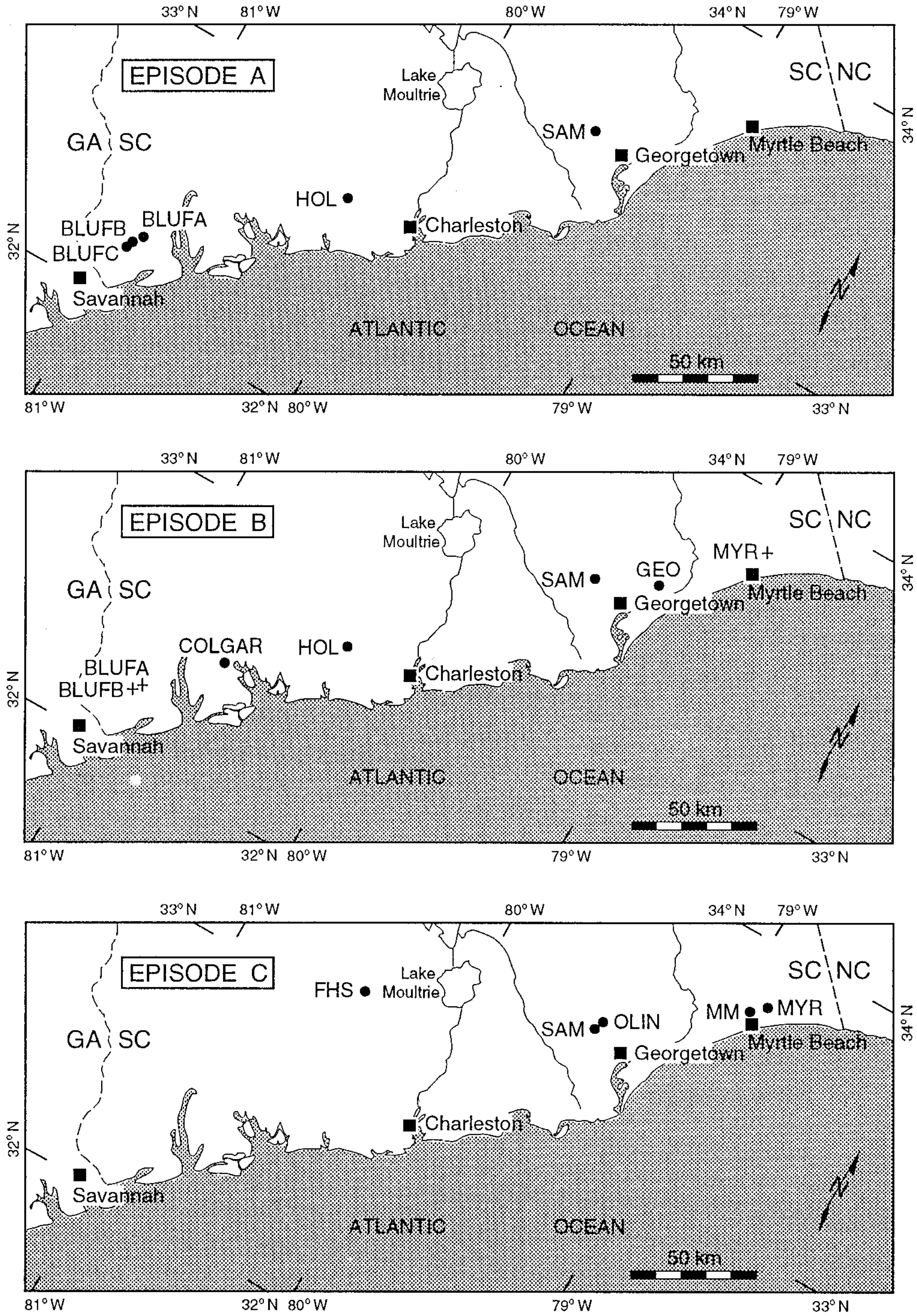

Figure 6. Locations of sites where contemporary (solid circles) and tight-bracketing age (crosses) data were obtained for episodes A–G.

5.7. Episode G

The age of this liquefaction episode is not defined by any contemporary ages. It is determined from tight-bracketing age constraints at Ten Mile Hill (TMH-4A and TMH-4B) near Charleston and at Malpherous (MAL-1A and MAL-1B) to the south (Figures 5g and 6). Tight maximum age is provided by a sample from Conway (CON-1), and tight minimum age constraint is provided by a sample from Myrtle Beach (MYR-2). Loose age constraints are provided by samples from Hollywood (HOL-3A and HOL-3B); their ages could also be evidence of episode F. Other samples from Malpherous (MAL-1E and MAL-1F) and Southport, North Carolina, provide loose constraints. The assigned age of episode G (5300–6300 years B.P.) is estimated from the tight constraint provided by MAL-1A and MAL-1B and slightly looser constraint provided by TMH-4A and TMH-4B. We assign it a magnitude M 7+ and place it near Charleston because evidence of this episode was found in northern, middle, and southern sites. Application of *Ambraseys*' [1988] formula and a distance of 140 km to MYR give M 7.2.

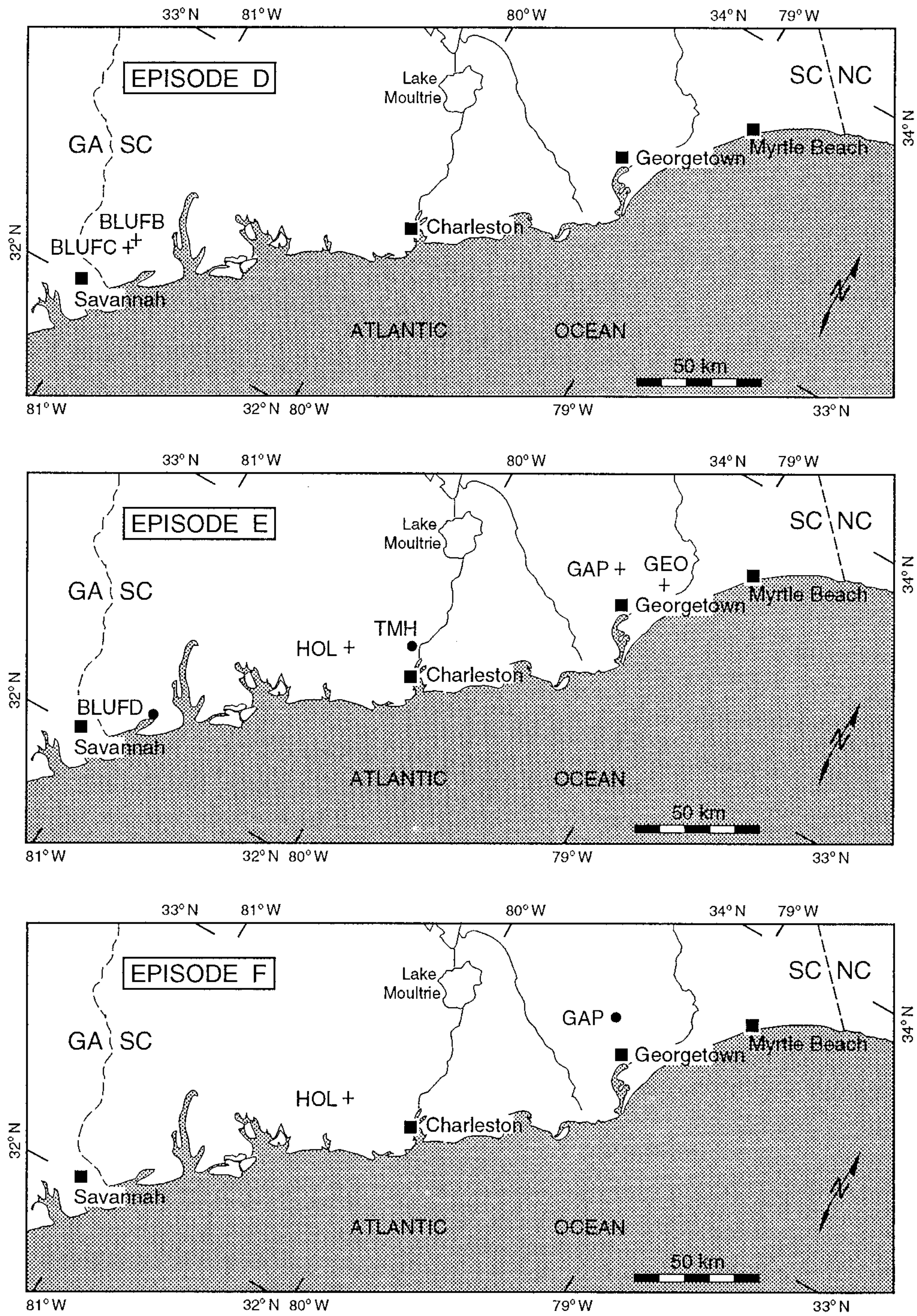

Figure 6. (continued)

6. Discussion

Calibrated ages of radiocarbon samples from sandblows at multiple sites in South Carolina suggest the occurrence of seven prehistoric earthquakes, large enough to cause liquefaction. The inferred ages of these episodes are 546 ± 17, 1021 ± 30, 1648 ± 74, 1754–2177, 3548 ± 66, 5038 ± 166, and 5300–6300 years B.P. Age ranges are used when the age is based primarily on bracketing ages.

The analysis presented in section 5 leads to two scenarios for the inferred prehistoric seismicity. In the first, there are three possible seismic source zones: One is located near Charleston, another is located near Georgetown (northern source), and the third is located near Bluffton (southern source). The second scenario involves all earthquakes occurring in the Charleston seismic zone. The timing of the earthquakes in the two scenarios is summarized in Table 3.

The possibility of a source zone outside of the Charleston area has been suggested earlier. For example, *Weems and Obermeier* [1990] suggested that the older ages (>5750 years B.P.) at Conway and (>8770 years B.P.) at Southport, North Carolina, might be evidence of a northern source. *Amick and Gelinas* [1991] attributed (our) episode C to a northern source.

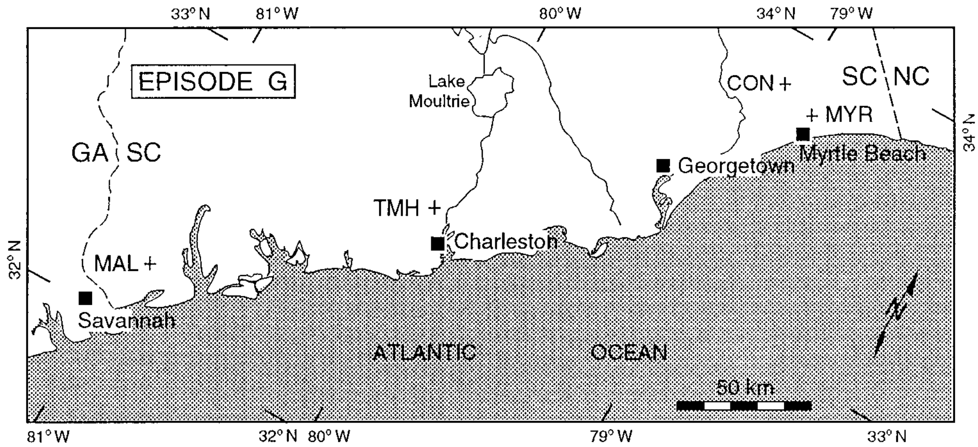

Figure 6. (continued)

Rajendran and Talwani [1993] attributed (our) episode D to a southern source.

Historical accounts clearly show that the 1886 earthquake occurred near Charleston. Evidence of episodes A (546 ± 17 years B.P.), B (1021 ± 30 years B.P.), C′ (1683 ± 70 years B.P.), E (3548 ± 66 years B.P.), and G (5300–6300 years B.P.) is present in the northern, middle, and southern sites (Figure 6). These are also interpreted to be Charleston events, and we assign them magnitudes comparable to the Charleston 1886 earthquake, i.e., M 7+.

Evidence of episode C comes primarily from northern sites and one inland site (FHS) with no corroborative ages from southern or Charleston sandblows. In scenario 1 we assign it a northern source, with $M \sim 6.0$. Episode D is based primarily on bracketing ages for sandblows at BLUF-B and BLUF-C. We assign it a southern source with $M \sim 6.0$. If episode C and D are associated with one episode C′, then its magnitude is also $M \sim 7+$. Episode F is based primarily on a contemporary age at Gapway (GW-2C), 4985 +218/−113 years B.P., which is statistically different from the inferred age of episode G, 5800 ± 500 years B.P. at the 1σ level and the same at the 2σ level. Two samples from Hollywood (HOL-3A and HOL-3B) provide loose age constraints, for both episodes F and G. If they are associated with episode G, then episode F is inferred only from data from Gapway and Conway, i.e., only the northern sites. In this scenario (scenario 1) we assign a magnitude $M \sim 6.0$ to the northern source. If HOL-3A and HOL-3B are associated with episode F, then we assign a larger magnitude to episode F, M 7+ (scenario 2). Clearly, more data are needed to resolve between the two scenarios presented above.

6.1. Ages of Prehistoric Earthquakes and Sea Levels

In the South Carolina Coastal Plain all evidence of prehistoric earthquakes is based on studies of seismically induced liquefaction features. An essential requirement for the development of the sandblows is the presence of a saturated unconsolidated source sand horizon and a shallow ground water table (about <3–4 m deep for the various sandblows investigated in this study). A priori, we have no way of knowing the depth of the ground water table at the time of the prehistoric earthquakes. Except for the inland site at Four Hole Swamp the other sandblows are in beach ridges within ~20–30 km from the present coast line. So we make a simple assumption that the prehistoric ground water table levels were directly related to the corresponding age sea levels, data for which are available.

Prehistoric sea levels have been studied by several workers. *Fairbanks* [1989] provided a continuous and detailed record of the sea level offshore of Barbados over the past 17,000 years. Sea level was ~10 m lower than present sea level at ~6000 years B.P. and considerably lower before that. If the ground water table at liquefaction sites was correspondingly deeper than today, it would be difficult for liquefaction to occur and reach the surface, because the water table would be too deep. Therefore the "clock" started at ~6000 years B.P., possibly

Table 3. Two Scenarios for Paleoearthquake Ages and Source Zones

Liquefaction Episode	Age, years B.P.	Scenario 1		Scenario 2	
		Source	Magnitude[a]	Source	Magnitude[a]
1886 AD	113	Charleston	7.3	Charleston	7.3
A	546 ± 17	Charleston	7+	Charleston	7+
B	1021 ± 30	Charleston	7+	Charleston	7+
C	1648 ± 74	northern part	~6.0	···	—
C′	1683 ± 70	···	···	Charleston	7+
D	1966 ± 212	southern part	~6.0	···	—
E	3548 ± 66	Charleston	7+	Charleston	7+
F	5038 ± 166	northern part	~6.0	Charleston	7+
G	5800 ± 500	Charleston	7+	Charleston	7+

[a]Magnitude is M_w; 1886 magnitude is from *Johnston* [1996].

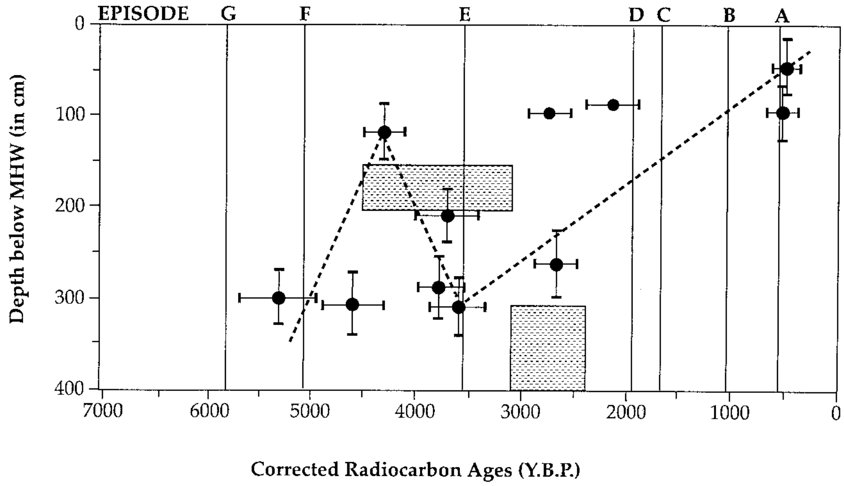

Figure 7. Depths below mean high water (MHW) level inferred to represent late Holocene sea levels for the SCCP, from *Scott et al.* [1995] (solid circles) and from *DePratter and Howard* [1981] (stippled pattern). Age data from *DePratter and Howard* [1981] were calibrated before plotting. The times of episodes A–G are shown by solid vertical lines for comparison.

explaining the age of the oldest liquefaction episode indicated by all of the studies conducted to date.

Evidence of late Holocene sea level fluctuations have been identified in the South Carolina and Georgia Coastal Plains [*DePratter and Howard*, 1981; *Colquhoun and Brooks*, 1986; *Gayes et al.*, 1993; *Scott et al.*, 1995]. These studies identified a highstand during the past 6000 years of relative sea level between ~4500 and 3100 years B.P. *DePratter and Howard* [1981] used historical data together with dated archaeological artifacts, submerged in-place tree stumps, and numerous buried trees in northeast Georgia near Wilmington Island and neighboring South Carolina (Figure 1). They found that the sea level reached −1.5 to −2 m mean sea level (msl) by ~4500 years B.P., began to lower ~3100 years B.P., was −3 to −4 m for ~500–600 years, and then rose to its present levels around 2400 years B.P. *Gayes et al.* [1993] obtained a relative sea level curve from tidal wetland deposits of Murrell's Inlet, South Carolina, 30 km northeast of Georgetown (Figure 1). They also found a sea level highstand between ~5300 and 3600 years B.P. [*Gayes et al.*, 1993, Figure 6, p. 159] wherein water oscillated from −3 m about 5300 years B.P. to −1 m msl by 4280 years B.P. and then fell to −3 m by 3600 years B.P. before rising again to its present position. At the Santee River delta (25 km south of Georgetown) they present evidence for deepening of sea level to about −5–6 m msl during the period from 3200 to 2000 years B.P. They attribute the lower differential Holocene submergence to sediment loading by the Santee delta. *Scott et al.* [1995] added micropaleontologic constraints to the results of *Gayes et al.* [1993] and confirmed their conclusions. *Colquhoun and Brooks* [1986] developed a Holocene sea level curve for the southeastern United States through a study of marsh stratigraphy and archeological sites in marsh and interriverine areas from near Georgetown to Savannah, Georgia. They also found a sea level rise from about −4 m about 5000 years B.P. with a highstand (−1 m msl) ~4000 years B.P. Their data showed several fluctuations in sea level and were not well constrained.

The effect of ground water level on the formation of sandblows is examined by comparing prehistoric sea level curves with the times of episodes A–G (Figure 7). Both at Murrell's Inlet [*Scott et al.*, 1995] and near Savannah, Georgia [*DePratter and Howard*, 1981], there was a highstand higher than about −2 m msl of relative sea level from ~4500 to 3100 years B.P., a lowstand lower than about −3 to 4 m msl from 3000 to 2400 years B.P., and shallower water levels, higher than −2 m msl for the past 2000 years. We note that at the time of occurrence of episodes A, B, C, and D (and C′) the water levels were shallower than −2 m msl, thus making widespread liquefaction possible for Charleston-type events (episodes A and B) or smaller local earthquakes (episodes C and D). If the groundwater levels between 3000 and 2000 years B.P. in other parts of the SCCP were also low, as at Santee (−5 to 6 m msl), we would not expect liquefaction features to reach the surface, providing a possible explanation for the absence of sandblows of that age. The absence of sandblows older than episode G could be due to water levels being too low to cause liquefied sands to reach the surface and not due to an absence of earthquakes.

The inferred occurrence of only one earthquake (episode E) in the 3000 year period between episodes A–D and episodes F and G could be due to temporal clustering of seismicity, fluctuation water levels, or their evidence having been obliterated. Our data do not allow us to distinguish between these alternatives. Thus, for estimating recurrence rates of prehistoric earthquakes based on paleoliquefaction events we consider the paleoliquefaction record to be complete for the past 2000 years. Because the paleoliquefaction record may not be complete for the period between ~5800 and 2000 years B.P., the recurrence intervals between older paleoliquefaction events may not be representative of the paleoliquefaction rates in the SCCP. Thus, in estimating the recurrence rates of earthquakes in the SCCP we place greater emphasis on the data for the past 2000 years B.P., i.e., up to episode D.

6.2. Recurrence Rates

In estimating the recurrence rate for scenario 1 we assume that the liquefaction observed near Georgetown and dated at ~1650 years B.P. (episode C) resulted from an earthquake on a northern source. We further assume that episode D, which occurred ~2000 years B.P., was associated with a southern source near Bluffton. In this scenario no earthquakes occurred in the Charleston source at 1650 or 2000 years B.P. Thus, in the past 2000 years we have three earthquakes located near Charleston; 1886 A.D., 546 years B.P., and 1021 years B.P. with an average recurrence rate of 454 ± 21 years. The next known (older) earthquake associated with liquefaction occurred ~3550 years B.P. (Table 3). Evidence for any (?) earthquake(s) between ~2000 and 3550 years B.P. could be missing. If we assume that we have one missing earthquake midway between 2000 and 3550 years B.P. (for which there is no record of a liquefaction feature), the mean recurrence rate for the Charleston source is ~859 ± 532 years. If we assume two equally spaced missing earthquakes between 2000 and 3550 years B.P., the mean recurrence rate for the Charleston source zone is 687 ± 405 years. For the northern and southern sources, on the basis of one event each in the past 2000 years, we assign a recurrence rate of 2000 years for M 6.0 earthquakes.

For scenario 2 (Table 3) we assume that there was only one earthquake associated with liquefaction between ~1000 and 2000 years B.P. and that it occurred at the Charleston source at 1683 years B.P. (episode C′). In this scenario there are four Charleston earthquakes before 2000 years B.P. (1886 A.D., 546 years B.P., 1021 years B.P., and 1683 years B.P.), with a mean recurrence interval of 523 ± 100 years B.P. In anticipation of additional data we suggest a recurrence rate between 500 and 600 years for M 7+ earthquakes at Charleston and ~2000 years for M 6.0 events at the northern and southern sources in the SCCP.

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