Finding Faults in the Charleston Area, South Carolina: 2. Complementary Data

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ABSTRACT

The seismotectonic framework associated with the Middleton Place–Summerville seismic zone (MPSSZ) inferred from seismicity data consists of the ~50-km-long, ~N30°E-striking, NW-dipping, Woodstock fault associated with right-lateral oblique strike-slip motion, with a ~6-km-long antidilatational left step near Middleton Place, dividing it into the Woodstock north and south faults. Three ~NW-SE striking reverse faults, two NE dipping and one SW dipping, were recognized within this step. The Woodstock (N) fault lies along the southeast boundary of a buried Triassic basin, and the current seismicity is due to its reactivation. A comparison of this seismotectonic framework using a Geographic Information System shows that it is consistent with available geomorphological, geodetic, shallow stratigraphic (<150 m), seismic reflection and refraction, and potential field data, some of which were used in Durá-Gómez and Talwani (2009) to develop it. It further suggests that ongoing tectonic activity on the faults comprising this framework has resulted in breaking the overlying basalt along the Woodstock fault and in warping of the overlying sediments. Continuous vertical movements along the NW-SE stepover faults has resulted in uplift on the NE and SW bounding faults with the formation of the Mount Holly and Fort Bull domes. We found that these interpretations of complex faulting on multiple faults in the MPSSZ agreed with and explained the observed macroscopic data gathered after the 1886 Charleston earthquake.

INTRODUCTION

The destructive Charleston earthquake of 1886 and the current seismicity near Summerville, South Carolina, are associated with the Middleton–Place Summerville seismic zone (MPSSZ) (Tarr *et al.* 1981; Tarr and Rhea 1983). This instrumentally located seismicity occurs below a depth of ~3 km, and there are no surface expressions of the causative faults. In a companion paper by Durá-Gómez and Talwani (2009; hereinafter referred to as Paper 1), we presented a seismotectonic framework of MPSSZ inferred from the analysis of instrumentally recorded seismicity (1974–2004) with constraints from geological and other data. This revised seismotectonic framework is described in the next section of this paper. In this paper we compare detailed data gathered over the past three decades (some of which had been used earlier to constrain the seismotectonic framework) to test the plausibility of our framework and infer the tectonic history.

Earlier models to explain the seismicity in the MPSSZ were based on limited seismicity data (Talwani 1982; Madabhushi and Talwani 1993; Garner 1998; Talwani 2001) or on the macroscopic effects of the 1886 Charleston earthquake (Taber 1914; Bartholomew and Rich 2007), river morphology (Marple and Talwani 1993), biostratigraphic correlations of shallow auger and boreholes (z < 25 m) (Weems and Lewis 2002), shallow stratigraphic data (z < 150 m) (Colquhoun *et al.* 1983; Lennon 1985; Muthanna 1988), and inferred offsets on top of the basalt flows obtained from seismic refraction and reflection profiles (Ackermann 1983; Hamilton *et al.* 1983; Schilt *et al.* 1983; Behrendt 1985, 1986; Marple 1994; Talwani and Marple 1997; Marple and Miller 2007). In general, these studies showing deformational features in the pre-Cretaceous sediments and on the ground surface lacked any systematic integration with the seismicity data.

In addition to the studies described above, there are additional data sets that help clarify our understanding of the local seismotectonics. Collected by various investigators over the past four decades in the vicinity of the MPSSZ, these studies include coastal plain stratigraphy by Prof. Donald Colquhoun and his students at the University of South Carolina (summarized in Colquhoun *et al.* 1983), detailed stratigraphic mapping and biostratigraphic correlations by the U.S. Geological Survey (summarized in Weems and Lewis 2002), detailed gravity and aeromagnetic investigations (see Wildermuth 2003 for a review), geodetic investigations (Poley and Talwani 1986; Talwani *et al.* 1997; Trenkamp *et al.* 2003), and seismic reflection and refraction surveys carried out by the USGS, the Consortium for Continental Reflection Profiling (COCORP), and Virginia Polytechnic Institute & State University (VPI&SU) (see, *e.g.*, USGS Professional Paper 1313, cited in the references as Gohn 1983). These studies provide a plethora

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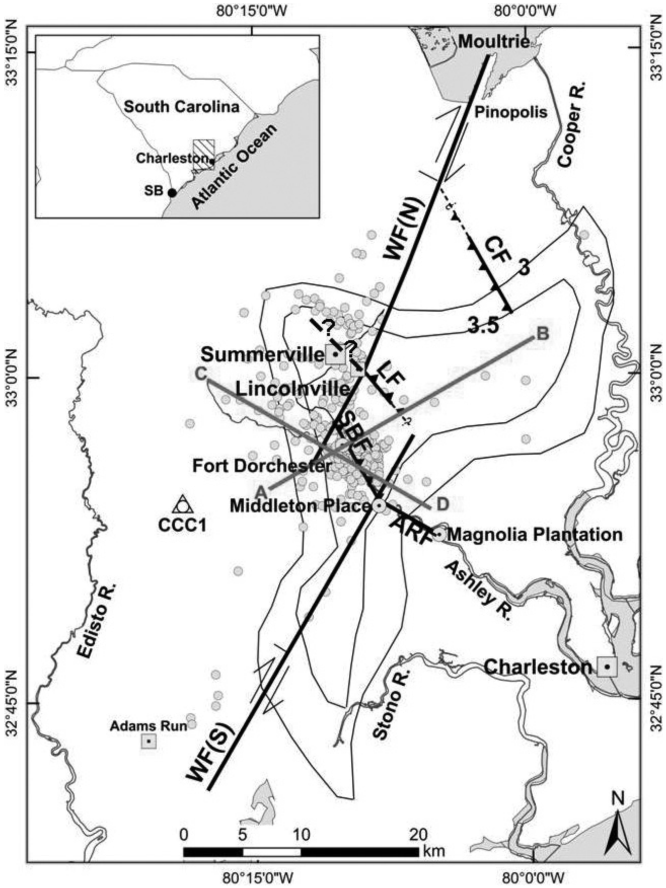


▲ **Figure 1.** Instrumentally located seismicity in the Middleton Place– Summerville seismic zone (MPSSZ), gray dots, for the period 1974–2004 (quality A and B), superposed on the seismotectonic framework, and Sloan's isoseismals of the 1886 earthquake (Dutton 1890). Inset shows the location of the MPSSZ in South Carolina along with Savannah Beach, Georgia (SB). ARF, CF, LF, SBF, WF(N), and WF(S) are the Ashley River, Charleston, Lincolnville, Sawmill Branch, Woodstock (north) and Woodstock (south) faults, respectively. The MPSSZ consists of the main cluster of seismicity in the vicinity of Summerville and Middleton Place (Tarr and Rhea 1983). A small cluster of seismicity occurs near Adams Run defined as the Adams Run seismic zone. A, B, C, and D show locations of cross-sections shown in Paper 1 (AB and CD) and Figures 12 and 13. CCC1 shows the location of Clubhouse Crossroads well #1. The figure shows the most prominent styles of faulting.

of additional data that can help to examine and constrain the crustal structure of the MPSSZ area at various depths, both above and within the seismogenic zone.

We compiled and compared the wide variety of data described above in a Geographic Information System (GIS) (Durá-Gómez 2004) for easy comparison. In this paper we compare the seismotectonic framework defined by the seismicity at depths of 3 to 13 km (Paper 1) with mapped features related to faulting on the subsurface basalt flows and with the sedimentary and surface features overlying the MPSSZ. Also, we use constraints from various geomorphic, geological, geodetic, and geophysical data to infer the current and past tectonic activity on the faults we have interpreted in our model of the MPSSZ area.

In the next section we describe the seismotectonic framework obtained from the seismicity data (Paper 1). In subsequent sections we compare this model with progressively deeper data, starting with the surface features (river geomorphology and digital elevation model), the configuration of pre-Cretaceous sediments (depth ~<700 m), faults that offset the top of the basalt horizon (depth ~700 m) and top of the igneous basement (depth 1–3 km), and the potential field data. We then compare our seismotectonic framework with the macroscopic effects of the 1886 Charleston earthquake and find that it successfully explains them.

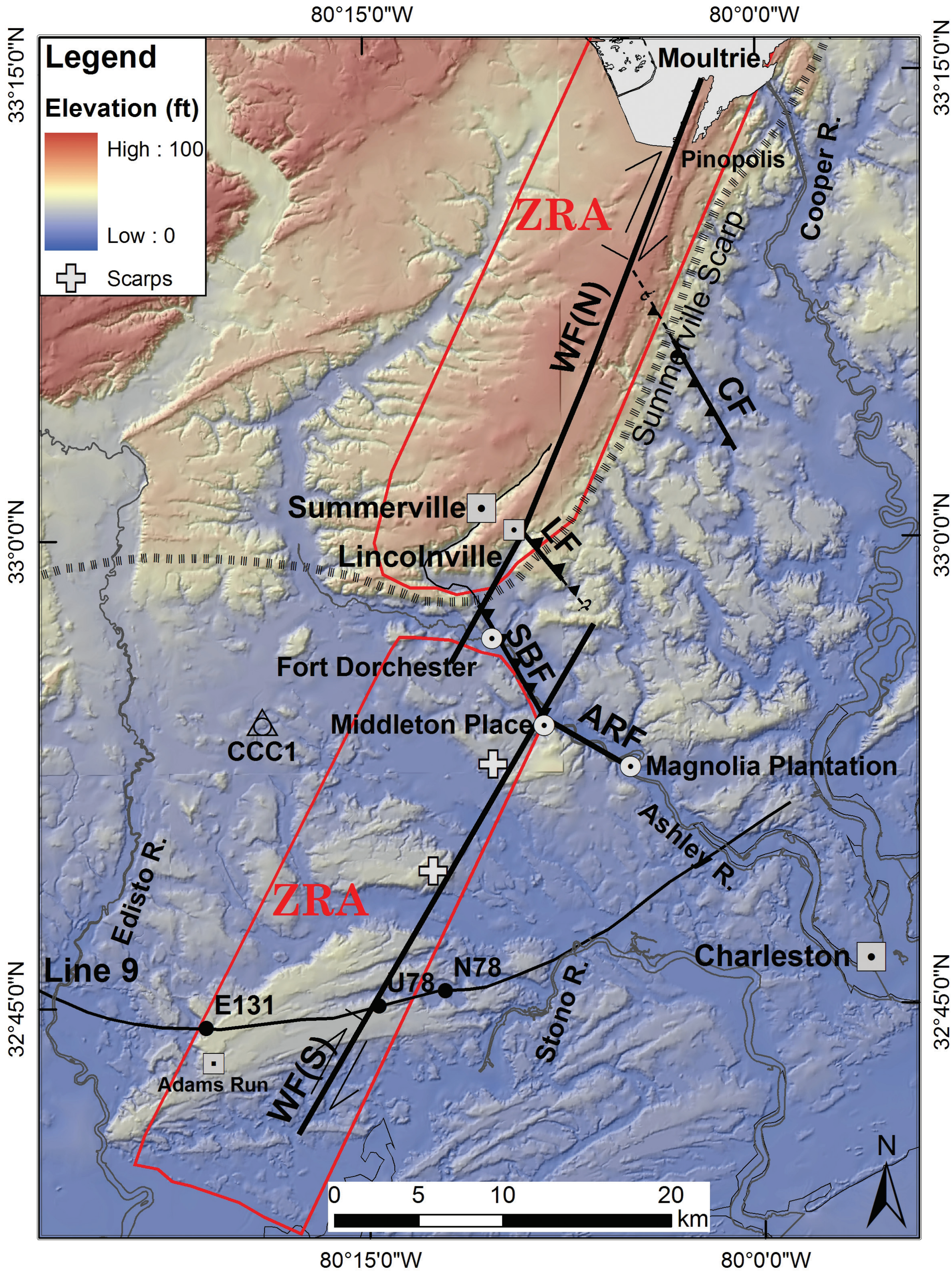
SEISMOTECTONIC FRAMEWORK

From our seismological study (Paper 1) we concluded that the seismotectonic framework in the MPSSZ is composed of the ~N30°E-oriented Woodstock fault, which is associated with oblique right-lateral strike-slip motion (Figure 1). The fault has a ~6-km-long compressional anti-dilatational left step near Middleton Place that divides it into the north and south Woodstock faults—WF(N) and WF(S)—both of which dip steeply (≥50°) to the northwest. The N30°W to N40°W striking Sawmill Branch, Lincolnville, and Charleston faults are located within the left step and are associated with oblique left-lateral strike-slip and reverse faulting. The ~3 to 4-km-wide N30°W Sawmill Branch fault zone (SBFZ) is the most active of these faults. It extends from Middleton Place to about 3.5 km northwest of Fort Dorchester. The N40°W striking Lincolnville fault (LF) is located about 5 km northeast of the SBFZ, near the towns of Lincolnville and Summerville, and dips steeply to the northeast. The N30°W striking Charleston fault (CF) is located about 18 km to the northeast of the SBF; its dip is not constrained by the seismicity data alone. A dip of about 40° to the southwest was inferred from the presence of the Oligocene-age Mount Holly dome (see the section on stratigraphic studies below). The aseismic ~N55°W-striking Ashley River fault (ARF) is located between Middleton Place and Magnolia Plantation in the MPSSZ. The tectonic deformation occurs in response to an in situ stress field with the direction of the maximum horizontal stress oriented ~N 60° E (Talwani 1982; Talwani *et al.* 1997)

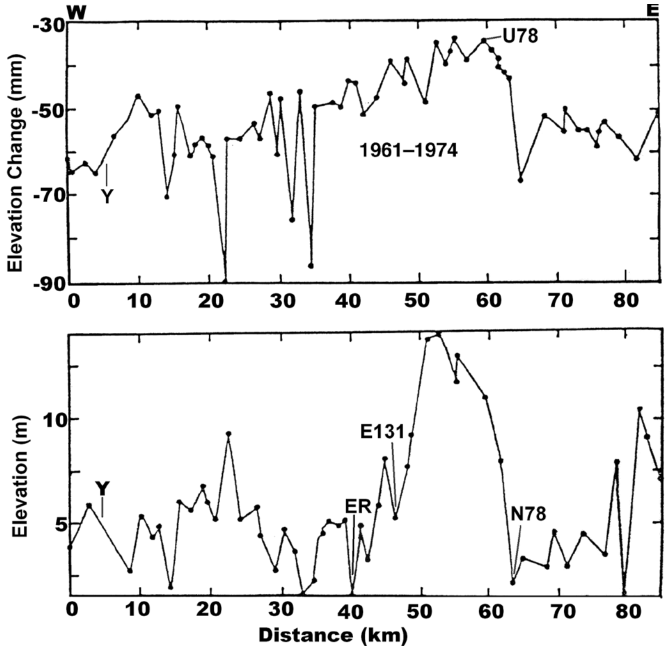
SURFACE FEATURES

Various studies describe the surface features in the area and their possible tectonic significance. In this section we examine them with reference to the seismotectonic framework outlined in the previous section.

Using surface elevation data and the convex upward pattern of several river courses, Rhea (1989) discovered a ~400 km^2 uplift in the Summerville area, roughly north of 33.05° N and between 80.05° and 80.45° W. Figure 2 shows the digital elevation model (DEM) for the study area extracted from the Statewide DEM data for South Carolina developed by



▲ **Figure 2.** Digital elevation model for the study area. Notice the two zones of relative high elevation in the MPSSZ and ARSZ, which approximately coincide with the zone of river anomalies (ZRA) described by Marple and Talwani (1993). The Summerville scarp (dashed line) is roughly parallel (until ~33° N latitude) to the topographic high and the WF(N). The location of the bench mark U78 on line 9 (from Yemassee to Charleston) (Poley and Talwani 1986) has been assumed to represent the surface expression of WF(S) and is used to define the ~N30°E strike of the WF(S). E131 and N78 represent the western and eastern boundaries of the higher topography in the ARSZ. The two scarps used to delineate the WF(S) are shown as open gray crosses.



▲ **Figure 3.** Elevation (bottom) and elevation changes (top) between 1961 and 1974 along line 9 between Yemassee and Charleston. The ~15-km-wide topographic high between bench marks E131 and N78 is associated with relative uplift southwest of Summerville between the Ashley and Edisto rivers (ER). See Figure 2 for the locations of benchmarks E131, U78, and N78 (modified from Poley and Talwani 1986).

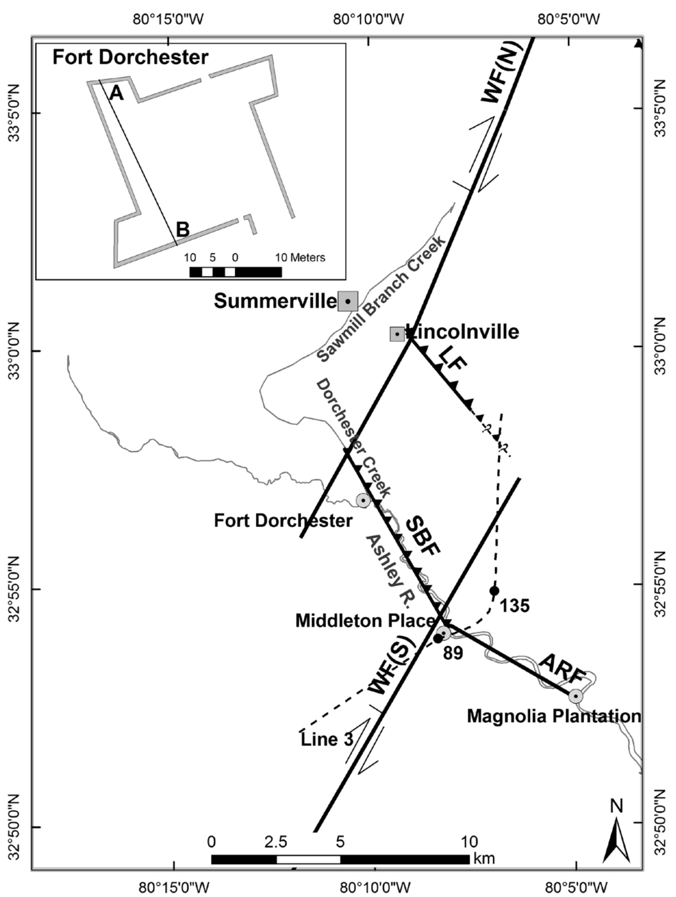
the South Carolina Geological Survey (SCGS) and South Carolina Department of Natural Resources (see Data and Resources Section). It shows two zones of relatively higher elevation (as much as 15m [45 ft] higher than the surrounding Coastal Plain), one north of the Ashley River that was originally recognized by Rhea (1989) and trends northeastward and the other about 25 km to the southwest, near Adams Run. The region between these high grounds was covered by swamps and cut by tributaries of the Stono River. In the 19th century before the draining of the swamps, Charlestonians used to adjourn to the high grounds at Summerville and Adams Run during summer. The two locations were accessible from Charleston by railroad and supplied some of the macroseismic data after the 1886 earthquake. We have compared the DEM with the results of (river) geomorphological investigations (Marple and Talwani 1992; 1993), releveling data (Poley and Talwani 1986), and geological investigations (Colquhoun *et al.* 1983; McCartan *et al.* 1984) and some surface features.

Marple and Talwani (1992) examined a multispectral image from SPOT (the French space agency's first Earth resources satellite) to reveal the possible expression of a buried fault at least 65 km long and trending N10°–15°E roughly along WF(N) and to its northeast. It was a part of the "zone of river anomalies" (ZRA) defined by Marple and Talwani (1993) based on the correlative northeast deflection of southeast flowing rivers. The ZRA was found to extend for ~200 km along a N10-15° E trend with a width of ~15 km. It occupies elevated ground, and these authors suggested that it was the probable result of continuous upwarping along the buried Woodstock fault. In Figure 2 we have outlined that section of the ZRA that coincides with the elevated regions in the DEM. The ZRA north of the Ashley River shows an excellent spatial correlation with the northern leg of the Woodstock fault, supporting the causal association suggested by Marple and Talwani (1993). Recall that the WF(N) defined by vertical offsets in the basalt is narrow compared to the warped surface sediments that define the ZRA. To the south, parts of the ZRA appear to have been eroded away by the streams in the swamp, leaving behind some scarps and isolated high grounds (Figure 2).

Lyttle *et al.* (1979) examined leveling data for two first-order surveys conducted in 1955 and 1974 between Charleston and Savannah Beach (see the location on Figure 1 inset). They concluded that the entire profile between Charleston and Yemassee located ~85 km to its west showed subsidence, although they did find a small region of relative uplift 35 km west of Charleston (near Adams Run shown in Figure 2). Poley and Talwani (1986) compared first-order leveling data for two surveys conducted in 1961 and 1974 along a part of the same profile, line 9 between Yemassee and Charleston (Figures 2 and 3). They confirmed the overall subsidence of the Coastal Plain between these two locations, and they also confirmed the relative uplift southwest of Summerville between the Ashley and Edisto rivers. Figure 3 shows elevation changes between 1961 and 1974 and the topography along a part of Line 9 between Yemassee and Charleston. We note the presence of a ~15-km-wide topographic high near Adams Run, between benchmarks E131 and N78. Although the change in elevation along this line shows general subsidence toward the coast, we notice a relative uplift along this high, the eastern edge of which is near bench mark U78 (Figure 3). Additionally, uplift is also suggested by a couple of southeast-facing scarps between Middleton Place and Adams Run (Figure 2). The locations of U78 and these scarps were inferred to be related to, and to define the eastern edge of, the WF(S), in agreement with its location and its ~N30° E strike based on the seismicity data (Paper 1).

The elevated area north of the Ashley River is bounded to its east and south by the Summerville scarp (Figure 2). Colquhoun (1962, 1965) defined the Summerville scarp as the contact between the ~1.5 Ma Pleistocene Penholoway formation with upper elevation at 70 to 75 ft (21 to 23 m) to the west and the ~450 ka Talbot terrace at 40 to 42 ft (12 to 13 m) to the east. More recent geologic mapping (McCartan *et al.* 1984) also indicated that the Summerville scarp lies along the contact between the 700 ka and 450 ka formations. We interpret the northeastern part of the Summerville scarp to be tectonic in origin and related to the WF(N). Gravity data (see the Potential Field Data section below) provide a possible explanation for the abrupt change in the strike of the Summerville scarp from northeast to east-west.

We note that the ~6-km-long stretch of the Ashley River between Middleton Place and Fort Dorchester and the ~3-km-long Dorchester Creek north of it run in a ~N30°W direction; this is the same as the inferred orientation of the SBF in this area (Paper 1, Figure 4). About 0.5 km to the west, the 1886



▲ **Figure 4.** Inset shows the ground plan of Fort Dorchester. Two parallel tabby walls broke left-laterally during the 1886 Charleston earthquake. Horizontal offsets of 7 cm and 10 cm were measured in the northern (A) and southern (B) walls respectively (Talwani 2001). The map shows the location of Fort Dorchester, Dorchester Creek, the ~N30°W Sawmill Branch fault (SBF), and seismic reflection line 3 (dashed line going through Middleton Place). The presence of a fault between stations 89 and 135 in line 3 (where no data were obtained) was suggested by the discontinuity of the J and B reflectors on the two sides of the Ashley River (Schilt *et al.* 1983).

Charleston earthquake (Talwani 2000a; 2001) caused the 1-m-thick north and south walls of Fort Dorchester to rupture and be displaced 7 cm and 10 cm in a left-lateral sense. The ruptures in the two walls lie along a ~N20°W azimuth, roughly parallel to and possibly related to one of the faults comprising the SBFZ (Figure 4). These observations are in agreement with the inferred oblique left-lateral reverse faulting on the Sawmill Branch fault zone based on the seismicity data (Paper 1). Note that the course of Sawmill Branch Creek north of Dorchester Creek was manmade for drainage purposes in the 19th century and did not exist in earlier maps.

The 1886 earthquake also cracked the northwest and southeast walls of the 3-m × 3-m × 3-m Drayton family tomb located on the south bank of the Ashley River in the Magnolia Plantation (Figure 4; Talwani 2000a). Talwani 2000a interpreted the cracking to be associated with movement on the ARF, with a ~northwest strike along a line joining these cracks and is parallel to the Ashley River between Magnolia Plantation and Middleton Place (Figure 4).

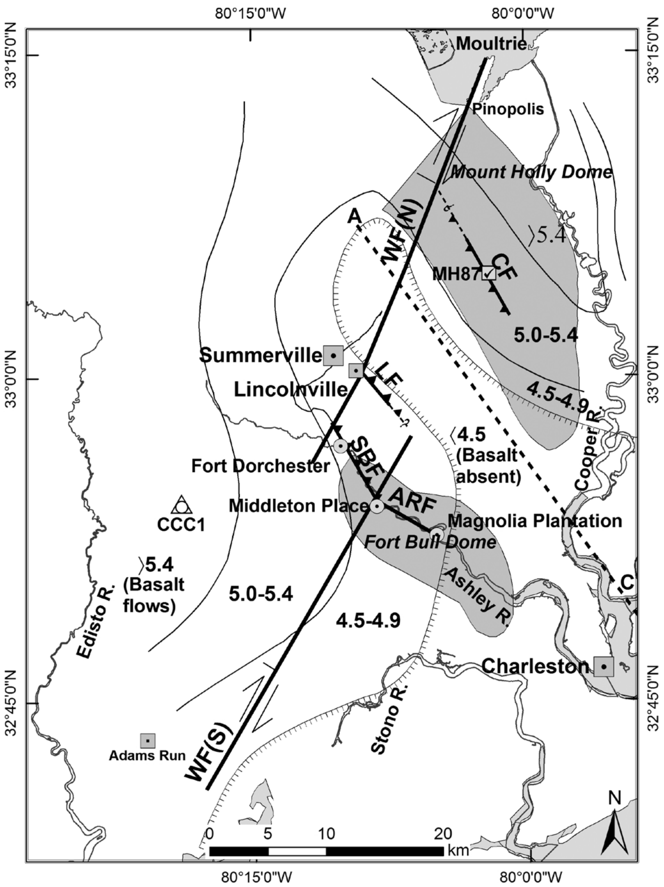
To summarize, the DEM, releveling data, river geomorphology, and physiographic features observed in the vicinity of the MPSSZ are consistent with the inferred seismotectonic framework of Paper 1 and Figure 2.

STRUCTURAL FEATURES ABOVE ~3 KM DEPTH

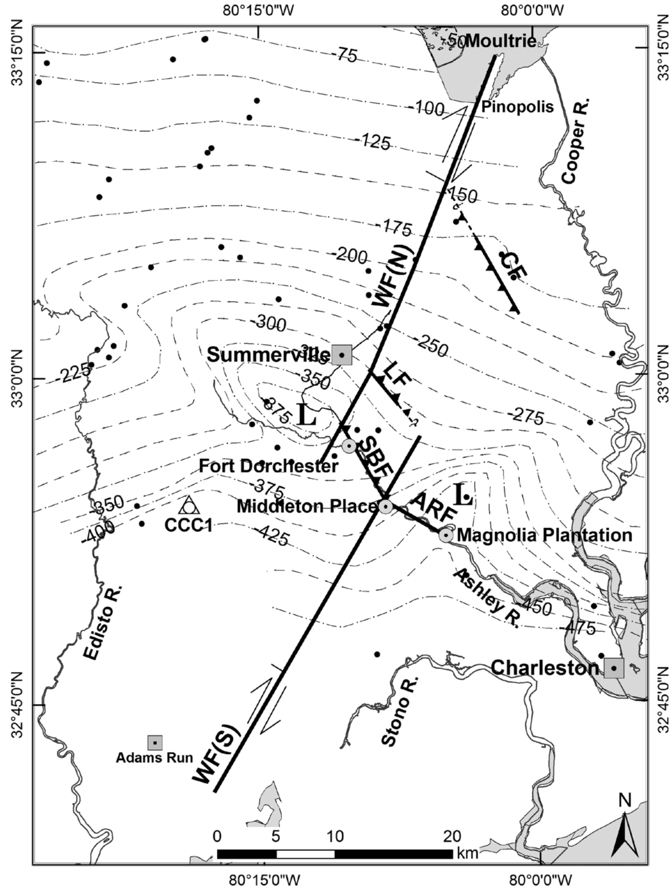
Although the seismicity in the MPSSZ is located at depths of 3 km and greater, several shallower features attest to geologically recent tectonic activity in the area. In this section we describe those features and their possible relationship with the faults defined in the seismotectonic framework of Paper 1.

Stratigraphic Studies

The South Carolina Coastal Plain is a gently sloping surface underlain by a thickening wedge of late Cretaceous and younger sediments. These sediments, which overlie the deformed sedimentary and crystalline rocks, extend southeast from the fall line, where they pinch out to a thickness exceeding 1 km near Charleston (Colquhoun *et al.* 1983). Earlier stratigraphic studies in the 1960s and 1970s were synthesized by Colquhoun *et al.* (1983), who discussed the existence of a northwest-trending fault located north and northwest of Charleston, which they named the Charleston fault. Using auger-hole data, Lennon (1985) confirmed the presence of the Charleston fault by mapping it at the base of three Tertiary units. He considered this fault to be extensional, with the hanging wall to the southwest. In the 1980s and 1990s the USGS carried out an extensive program of auger drilling to determine the shallow subsurface stratigraphy (to depths ~100 ft (31 m)) in the meizoseismal and surrounding regions of the 1886 Charleston earthquake (Weems and Lewis 2002). Based on lithologic, biostratigraphic, and other data from more than 1,000 auger holes and nine coreholes, they identified 16 Tertiary stratigraphic units, an absence of "layer-cake" stratigraphy, and evidence of persistent, repetitive vertical deformation over the past 34 Ma. These included seven ~28 Ma age (Oligocene) domes. The axis of the northwest trending, ~20-km × 6-km Fort Bull dome lies along the Sawmill Branch and Ashley River faults, whereas the southwestern side of the ~25-km × 12-km Mount Holly dome was interpreted to be the surface projection of the southwest dipping Charleston fault (AC in Figure 5). The location of the Charleston fault given by Weems and Lewis (2002) (Figure 5) is roughly the same as that given by Lennon (1985). A review of the original data (Weems and Lemon 1984) and its interpretation (Weems and Obermeier 1989) suggest a much smaller spatial extent for the Mount Holly dome. However, Weems and Lewis (2002) interpreted the Charleston fault to be a high-angle compressional fault with the northeast side upthrown. In support of the presence of reverse faulting, they cite Weems and Obermeier (1989), who reported that in the core from the center of Mount Holly dome (MH87, located at 33°04.75′N, 80°02′W) "the middle Eocene Santee Limestone



▲ **Figure 5.** Location of the buried Mt. Holly and Fort Bull domes (from Weems and Lewis 2002), which are associated with movements along the CF and along the SBFZ and ARF, respectively. The thin lines delineate different seismic refraction velocities (in km/s) and their inferred geological sources (from Ackermann 1983). MH87 shows the location of auger hole MH-87 where a reverse fault was encountered (from Weems and Obermeier 1989). AC shows the location of the Charleston fault according to Weems and Lewis (2002).



▲ **Figure 6.** Elevation to the base of the Santee formation (from Muthanna 1988), contour interval 25 feet. Well control shown by dots. L shows a center of low elevation. The inferred sense of fault movements is described in the text.

is thrust onto upper Eocene Cooper sediments along a shear surface with about one foot of observable displacement." The interpretation by Weems and Lewis (2002), a NW striking, SW dipping compressional fault lying ~7 km to the southwest of AC with the northeast side upthrown (Figure 5), is inconsistent with our understanding of fault kinematics. A more plausible explanation is that the CF is not a steeply dipping fault, and its surface projection is along the northwest axis of the Mount Holly dome with the southwest side upthrown (Figure 5). The location of the CF chosen by Lennon (1985) and by Weems and Lewis (2002) appears to be the southwest edge of the Mount Holly dome, whereas we interpret the axis of the SW-dipping uplift to suggest that the location of the CF is further to the northeast as shown in Figure 5. The hypocentral data (Figure 12) are inadequate to constrain the dip of the CF, but do not rule out a shallow dip. A southwest dip of ~40° was estimated based on the inferred geometry (see the section on seismicity data below).

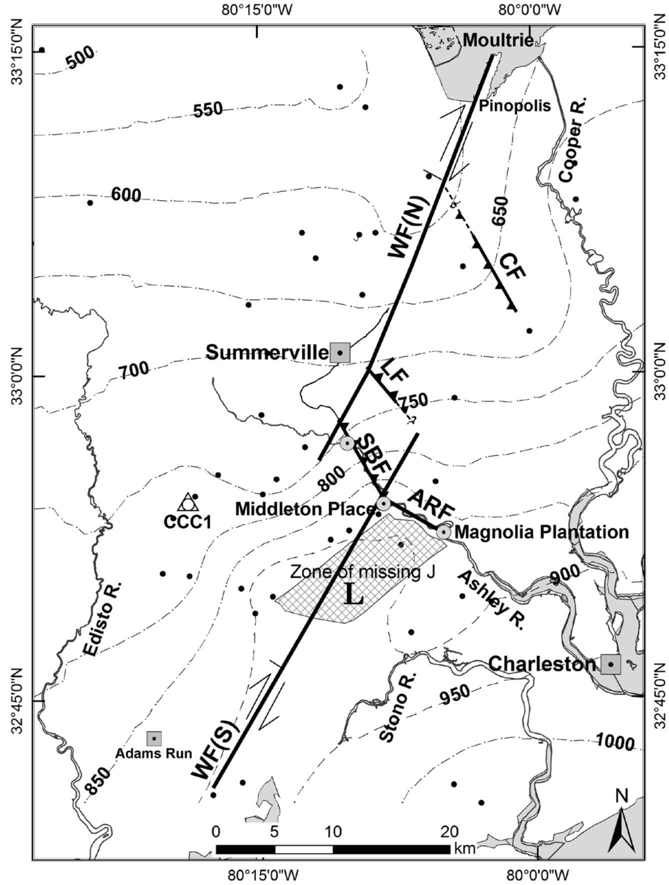
Muthanna (1988) found that the contact between the Cooper formation and the Santee limestone mapped by Lennon (1985) was irregular and did not extend throughout the study area. Muthanna (1988) mapped the underlying hard basal phosphate layer that occurs between the middle Eocene Santee limestone and the Paleocene–early Eocene Black Mingo group (48 Ma, Unconformity 8) to map the geometry of the tectonically deformed sediments. Using additional auger drilling data from strategically located sites, he obtained the depth to Unconformity 8 at more than 100 locations (Figure 6). The regional pattern of deepening of Unconformity 8 from north to south is interrupted in the vicinity of the MPSSZ. Two anomalous lows (shown by L in Figure 6) are observed, the first northwest of Fort Dorchester with a maximum depth >375 ft (114 m) and the second to the north of the Magnolia Plantation at a maximum depth ~430 ft (131 m). Between these two lows and along the Sawmill Branch fault, the depth to Unconformity 8 is ~330 ft (101 m). This pattern of relative lows to the northwest of the intersection between SBF and WF(N) and east of its intersection with WF(S), with an uplifted high between them, is accordant with right–lateral oblique slip on the two Woodstock faults (the lows outside the left step associated with extensional deformation, and the high within the left step a result of compression).

The Extensive Basalt Flows

The USGS drilled three deep test holes at Clubhouse Crossroads (CC#1, CC#2, and CC#3 to depths of 792, 907, and 1,152 m, respectively) to study the nature of the rocks underlying the sediments (Gohn *et al.* 1983). These holes were sited to coincide with gravity and magnetic highs in the MPSSZ (Popenoe and Zeitz 1977). The drill holes encountered basalt flows at depths of 750 to 776 m but did not penetrate the entire sequence. These basalts are a part of an extensive 200-million-year–old Central Atlantic Magmatic Province (Marzoli *et al.* 1999) that locally underlies the South Carolina Coastal Plain. Using the 40Ar/39Ar incremental heating ages method, Hames *et al.* (2000) dated three dike samples from the South Carolina Piedmont at about 199.5 ± 2.0 Ma. They assert that dikes in the southeastern United States were emplaced throughout a brief episode of magmatism that lasted ~0.5–1 Ma around 200 Ma ago. A wildcat well (in search of oil and gas) drilled at Lodge (33° 00′ 54″ north, 80° 55′ 44″ west) encountered basalt at depth of 1.4 km. The well encountered four sequences of basalt flows and red beds before it reached a total depth of 3.8 km, where it bottomed out in basalt (Talwani,2000b). The thicknesses of the layers of basalts and intercalated sediments, which overlie the crystalline basement, vary under the Coastal Plain. The depth of the crystalline basement in the MPSSZ was estimated by seismic refraction surveys and is described in a later section.

Geophysical Investigations

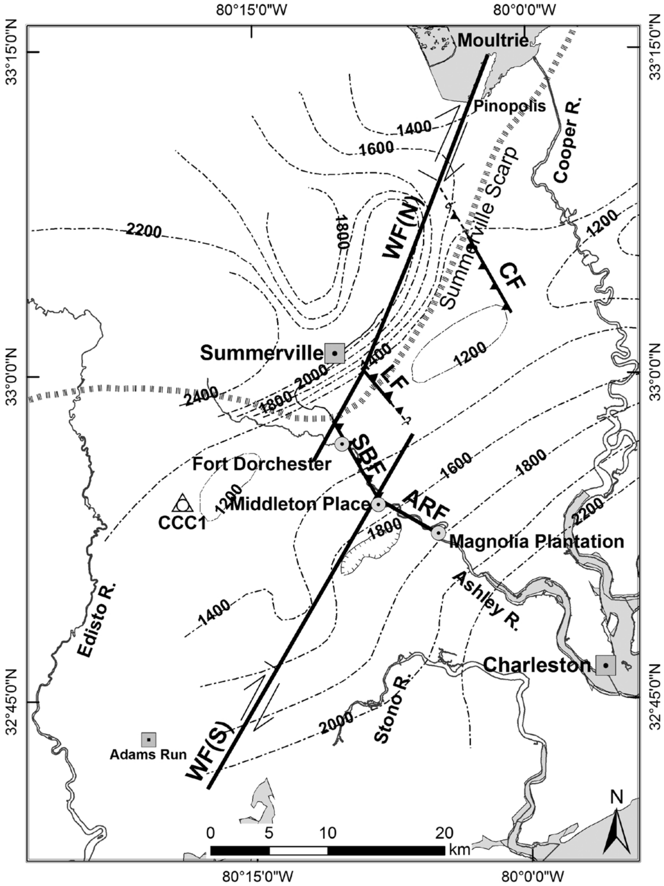
In the mid-to-late 1970s, the USGS carried out several seismic refraction surveys in the MPSSZ and surrounding areas to determine the depth to, and the nature of, the major seismic reflectors (Ackermann 1977, 1983). A moderate effort by the University of South Carolina in the epicentral area complemented these efforts (Amick 1979). Two unconformities were discovered. The shallower one, lying at depths of ~500 m to 1,000 m (with a *P*-wave velocity range from 4.2 to 5.7 km/s associated with lateral variations in lithology; Ackermann 1983) and gently dipping seaward, was the contact between the Upper Cretaceous sediments and the Jurassic basalts encountered in the deep wells at Clubhouse Crossroads (Figure 7). This contact was identified as the "J" (for Jurassic) reflector in subsequent seismic reflection surveys (Hamilton *et al.* 1983; Schilt *et al.* 1983). Reflection data (discussed below) show faults and flexures having tens of meters of displacement. However, the resolution of the seismic refraction data with depth estimates good to ~50 m is inadequate to delineate small structural features, although a steeper gradient of this contact is noticeable in the vicinity of the SBF (Figure 7). The *P*-wave seismic velocities describe a northwest trending tongue of lower values, which define a graben-like feature between the SBF and ARF to the southwest and the Charleston fault to the northeast (Figure 5). Ackermann (1983) interpreted the 4.4 km/s velocity in the northwest trending low at a depth of ~700 m to be associated with Triassic rocks, which lie between the crystalline rocks northeast of Mount Holly dome and basalt flows southwest of Fort Dorchester. This spatial correlation among



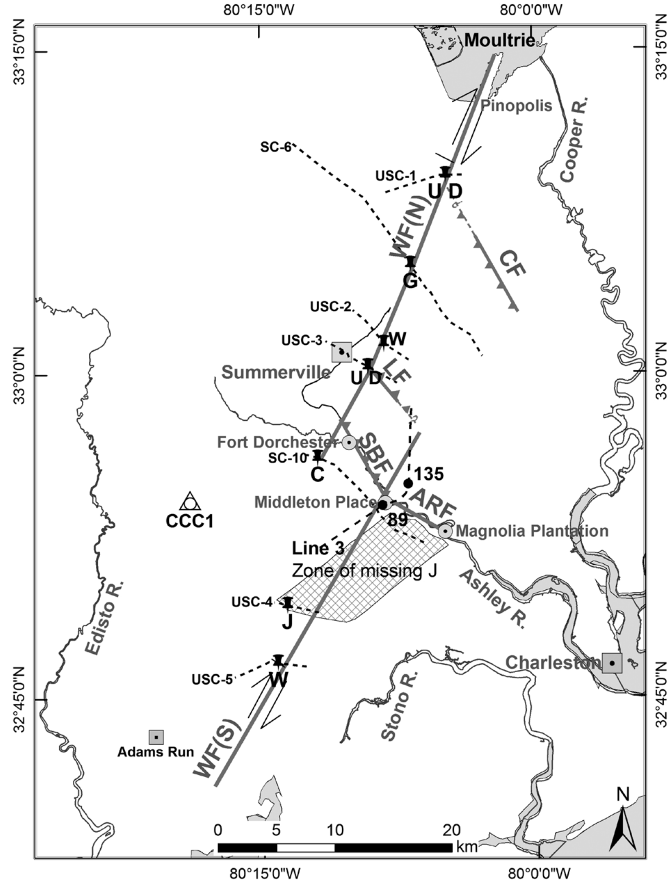
▲ **Figure 7.** Compilation of data points from Ackermann (1983) and Amick (1979) to obtain the 50 m depth contour map to the pre-Cretaceous unconformity whose depth is shown in meters. The location of the zone of missing J coincides with the low to the southeast of WF(S); both support the presence of WF(S) and right-lateral oblique motion along this fault.

the pre-Cretaceous velocity structure, the northwest trending Sawmill Branch and Charleston faults (from seismicity data), the Fort Bull and Mount Holly domes, and the absence of "layer-cake" stratigraphy of the Tertiary beds (from shallow stratigraphic data, Weems and Lewis 2002), suggests ongoing tectonic activity with vertical deformation along these faults.

The top of a pre-Mesozoic crystalline basement complex (with *P*-wave velocity values 6.0 to 6.4 km/s), identified as the "B" reflector in seismic-reflection surveys, was discovered at depths of 700 m to 2,400 m (Ackermann 1983). Centered beneath Fort Dorchester, it included a 6-km-wide and >20-km-long ridge-like feature at a depth of ~1,200 to 1,400 m (Ackermann 1983; Figure 8). This ridge is bounded to the northwest by a ~900-m escarpment, which was subsequently interpreted as the edge of the Triassic Jedberg basin by Behrendt (1985, 1986). The Jedberg basin is a Triassic-age extensional feature, whose geometry does not reflect the current tectonic activity related to a northeast-oriented compressional stress regime. The southeast boundary of this ridge is poorly defined. However, Ackermann (1983) discovered, based on two closely spaced seismic spreads (his numbers 18 and 19),



▲ **Figure 8.** Contours show depths in meters of the 6.0–6.4 km/s B reflector, which is interpreted to represent the crystalline basement (from Ackermann 1983). The WF(N) affected the basement as well as the Earth's surface as indicated by the higher elevation and the Summerville scarp.



▲ **Figure 9.** Seismic reflection profiles (dashed lines) and faults that offset the basalt layer at about 700 m depth. G and C show the location of the Gants and Cooke faults (Hamilton *et al.* 1983). COCORP line 3 is indicated with a dashed line going through Middleton Place. The presence of a fault between stations 89 and 135 was suggested by the discontinuity of the J and B reflectors (Schilt *et al.* 1983). W shows the location of warped sediments in the USC lines 2 and 5. J on USC line 4 shows the location of a fault with the northeast side up (Marple and Talwani 2000). The zone of missing J (shaded area) is located to the southeast of WF(S).

that 2 to 3 km south of Middleton Place the gently dipping southeast surface is broken by a 200-m to 300-m fault-like displacement (defined by the closed 1,800 m contour, Figure 8).

Comparing these features with the seismotectonic framework, we note that the center of the northeast-trending ridge lies within the left step-over between the WF(N) and the WF(S). We correlate the northwest boundary of the ridge with the WF(N), whose surface projection is coincident with the Summerville scarp (Figure 8). According to our proposed seismotectonic framework (Figure 1), oblique right–lateral strike-slip faulting on the WF(S) would result in uplift on the northwest side relative to the southeast side of the fault, consistent with the observed drop in depth to the basement south of Middleton Place (Ackermann 1983; Figure 8).

The Jurassic basalt layer was exposed for ~100 Ma before the deposition of late Cretaceous sediments, accounting for its relatively smooth surface. The refraction data do not have the resolution to detect small (~ < 5 m) offsets in the basalt and shallower horizons. Those were detected by using seismic reflection data, which are described next.

In the late 1970s and early 1980s, extensive seismic reflection surveys were carried out in the study area by the USGS (lines SC 1–10, 140 km), COCORP (lines C 1–4, 72 km), and VPI&SU (three lines, 7.0 km) (Figure 9). In addition to the J and B reflectors described above, an additional reflector, labeled K, was detected corresponding to a facies change in the Black Creek formation of late Cretaceous age (Hamilton *et al.* 1983) Analysis of the COCORP reflection data by Schilt *et al.* (1983) and of the cumulative data by Hamilton *et al.* (1983) led to the discovery of four faults and various structural features. On USGS line SC-10 (coincident with COCORP line C-2), both Schilt *et al.* (1983) and Hamilton *et al.* (1983) identified the Cooke fault offsetting by 50 m the J reflector (C in Figure 9) at a depth of ~750 m, down to the southeast. It was associated with a zone of flexures in the Upper Cretaceous and Cenozoic sediments, which Hamilton *et al.* (1983) interpreted to suggest continuing Cenozoic movement of a post-basalt-flow, pre–late Cretaceous reverse Cooke fault, which may have formed during Triassic rifting (Figure 9). Behrendt (1985, 1986) reprocessed an industry Seisdata line S4 and identified the Triassic Jedberg basin west of Summerville, in the meizoseismal area of the 1886 Charleston earthquake.

Another reverse fault, named the Gants fault, was discovered on SC-6 (G on Figure 9) by Hamilton *et al.* (1983). These authors suggested that the Cooke and Gants faults were parts of a northeast trending fault system associated with the observed seismicity in the MPSSZ.

The Gants and Cooke faults were within the zone of river anomalies of Marple and Talwani (1993), who had earlier linked them to the Woodstock fault. To confirm its existence, the University of South Carolina carried out six additional Mini-Sosie reflection surveys aimed at mapping offsets in the J reflector (Talwani and Marple 1997; Marple and Talwani 2000; labeled "USC" in Figure 9). The results of these investigations (southeast side down displacement on USC lines 1 and 3 and warped sediments on USC line 2), combined with earlier reflection surveys, confirmed the existence of the WF(N) offsetting the J reflector and the northeasterly strike of the Woodstock fault, with the southeast side down displacement, consistent with the ~N15°E strike at the surface suggested by the ZRA (Marple and Talwani 2000). The inlet in Lake Moultrie was assumed to be a surface expression of the WF(N). Our redefined strike of the WF(N) varies from ~N20°E north of Summerville to ~N30°E in the southern part, near its intersection with SBF (Figure 9).

In addition to indications for the existence of the WF(S) as described by the seismotectonic framework and from the seismic refraction data just described, subtle support for its presence and continued activity in the Cenozoic comes from seismic reflection data.

The northwestern edge of a zone where there is an absence of reflections from the J reflector on SC 4 and 10, called "the zone of missing J" by Hamilton *et al.* (1983), was roughly coincident with, and was interpreted to be associated with, the Woodstock fault (Marple and Talwani 1993). Schilt *et al.* (1983) noted that reflections from the J reflector southeast of station 230 (about 2 to 3 km south of Middleton Place) on the NW-SE line C-2 (coincident with SC line 10) were absent, whereas the basement reflectors were shallower to the southeast and dipped to the northwest (toward the basement low found by Ackermann 1983; Figure 8). We interpret these observations to be manifestations of WF(S).

Furthermore, along a 4.3-km-long, N60°E oriented line (not shown in Figure 9) that starts from about 3 km southeast of Middleton Place, Yantis *et al.* (1983) noted that the reflections from the basalt were 40 ms later at its southwest end, suggesting the presence of a fault between that end and Middleton Place, consistent with the results of Ackerman (1983).

These observations from seismic reflection data, together with the inferred faulting south of Middleton Place from geomorphic data, all support the presence of basement uplift to the northwest side of WF(S) (resulting from oblique right-lateral strike-slip faulting suggested by focal mechanisms) and subsidence to the southeast. This basement pattern persists to the shallow sediments (Section 3, Figure 6), suggesting that the WF(S) has been active during Cenozoic times.

Potential Field Data

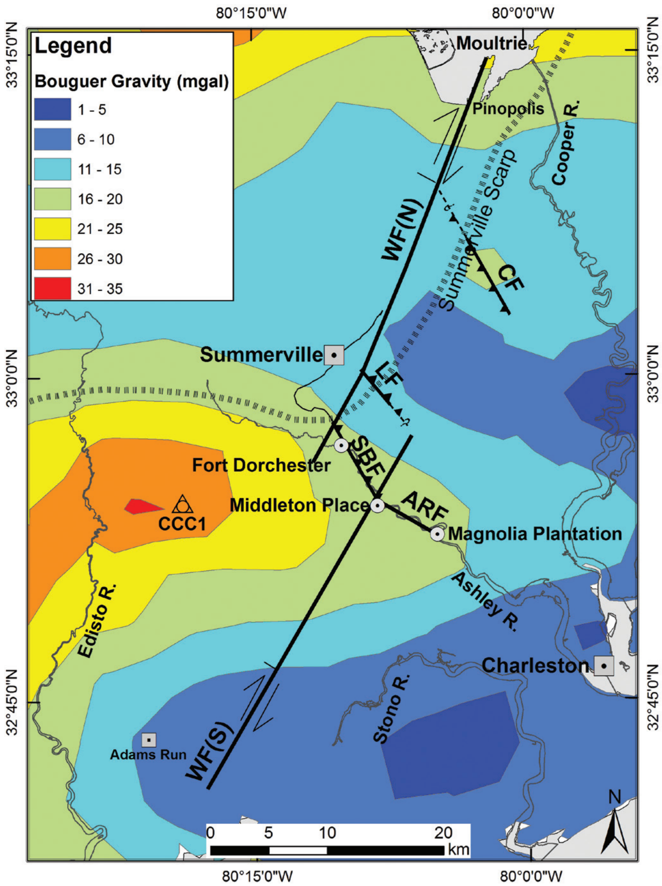
The earlier Bouguer gravity and aeromagnetic anomaly maps of the area (Long and Champion 1977; Popenoe and Zeitz 1977) show coincident highs near Clubhouse Crossroads, which were interpreted by those authors to be associated with a deep buried mafic pluton and which accounted for the extensive basalt flows encountered in the deep wells. An improved gravity map (with a contour interval of 1 mgal) based on detailed gravity surveys by students at the University of South Carolina has been more recently compiled and analyzed together with the aeromagnetic data (Wildermuth 2003). A comparison of the new Bouguer anomaly map (Figure 10) with the seismotectonic framework does not show any obvious correlation of the gravity features with underlying buried faults. However, we note that the eastern edge of the 31-mgal gravity high, interpreted by Wildermuth (2003) to be associated with a buried pluton, roughly coincides with SBFZ. The northeast trending Summerville scarp changes strike to east-west (Figure 2) near Fort Dorchester. Intriguingly, the scarp borders and runs parallel to the northern boundary of the gravity high, suggesting that the east-west trend of the basalt flows to the north of the pluton influenced the subsequent depositional pattern of sediments.

A ~10.5-km × 3.0-km magnetic high located to the north of Middleton Place lies north of a similarly shaped magnetic low (Figure 11). Analysis of this bipolar anomaly suggests a shallow cause, possibly the northern edge of the basalt flow (Wildermuth 2003), an interpretation consistent with the speculative interpretation of the gravity data and the pre-Cretaceous velocity data in the area (Figure 5).

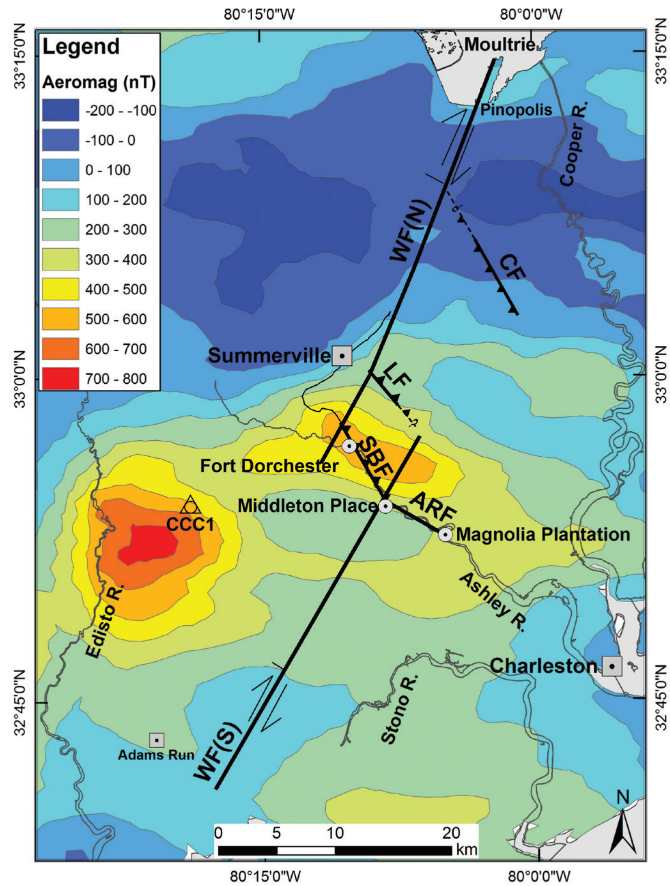
COMPARISON WITH SEISMICITY DATA

The faults inferred from seismicity data are deeper than 3 km, whereas, except for potential field data, the various geophysical, geological, and geodetic data presented above are for shallower features. To better determine the validity of our seismotectonic framework, we compare the hypocentral locations and the inferred faults with the complementary data in the top 3 km along cross-sections perpendicular to the faults (Figures 12 and 13A–B).

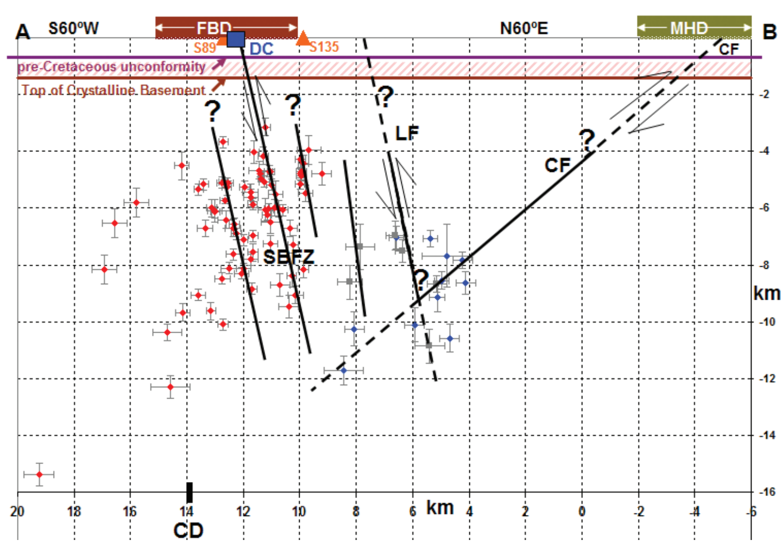
Figure 12 shows hypocentral locations and complementary data along a cross-section perpendicular to the SBFZ, LF, and CF. The NE dipping SBFZ is consistent with the location of the inferred fault by Schilt *et al.* (1983) along seismic reflection line 3 between stations 89 and 135 (Figure 4). These points bracket the Ashley River, which in this area is collinear to the ~N30°W Dorchester Creek (DC) and whose location has been inferred to be fault controlled (Figure 4). Additionally, reverse slip on SBFZ is in agreement with the location of the buried Oligocene-age Fort Bull dome (FBD) detected by shallow drilling (Figure 5; Weems and Lewis 2002). Focal mechanisms of earthquakes associated with the SBFZ (Figure 3 of Paper 1) sug-



▲ **Figure 10.** Bouguer gravity anomaly map shows a 31 mgal high west of the MPSSZ. The SBFZ follows the eastern edge of the gravity high while the WF(S) lies to its southeast side. The Summerville scarp changes to an E-W strike along the northern margin of the gravity high centered on CCC1.



▲ **Figure 11.** Aeromagnetic data (color) shows a large magnetic high centered around the CCC1 well. The paired aeromagnetic high and low near Middleton Place has been interpreted to be associated with the edge of the basalt flows (Wildermuth 2003).



▲ **Figure 12.** The cross-section along AB (Figure 1), roughly perpendicular to the SBFZ, LF, and CF. Earthquakes associated with SBFZ, LF, and CF are shown in red, gray, and blue, respectively (Paper 1). The shaded area in red shows the interpreted location of basalt flows. The presence of a series of parallel faults in the SBFZ dipping steeply to the northeast is corroborated by the location and orientation of Dorchester Creek (DC), the Fort Bull dome (FBD), and faulting between S89 and S135. Uplift on the southwest dipping CF is associated with the Mt. Holly dome (MHD.

gest both reverse and left-lateral strike-slip motion. We suggest that one or more of the faults comprising the SBFZ were associated with the left-lateral motion observed at Fort Dorchester in 1886 (Figure 4), ~0.5 km southwest of Dorchester Creek. The available hypocentral data are inadequate to accurately define the lower extent of the LF and CF.

The hypocenters associated with the CF are inadequate to accurately determine its dip. The presence of the Mount Holly dome to the northeast of the hypocenters suggests a shallow dip and reverse faulting on CF (Figures 5 and 12). The surface location of the CF by Colquhoun *et al.* (1983) and Weems and Lewis (2002) was based on it being associated with the southwest edge of the Mount Holly dome, *i.e.*, uplift to the northeast on a fault dipping to the southwest (Figure 14 in Weems and Lewis 2002). However, that location is inconsistent with up-throw to the southwest of the CF as would be expected on a southwest dipping fault in response to NE-SW oriented direction of maximum horizontal compression. This suggests that the CF is associated with a shallow southwest dip and its surface projection lies along the axis of the Mount Holly dome (MHD in Figure 12). The fault geometry in Figure 12 suggests that there should be a topographic rise between the SBFZ and CF. Due to a slope in the Coastal Plain from north to south and to surface erosion, no significant topographic expression of such an uplift is visible. However, a subtle suggestion of one appears in the DEM between CF and SBF (Figure 2).

The epicenters of the earthquakes associated with the WF(N) are mainly located to the north of the Ashley River, whereas those defining the WF(S) are along it, or to its southwest. (Figure 13 of Paper 1). The inferred sense of movement on both the WF(N) and the WF(S) is oblique right-lateral strike-slip. That results in the observed up-to-the-northwest movement on top of the basalt flows on the seismic reflection data and on the observed topographic highs to the northwest of the WF(N) and the WF(S) (Figure 2). The boundaries of the topographic high to the northwest of the WF(N) are easily seen, whereas only a few scarps are visible between Middleton Place and Adams Run (Figures 2 and 13A–B). Near Adams Run, the topographic uplift lies between benchmarks E131 and N78 (Figure 3). The southeast edge of the topographic high associated with WF(N) is the Summerville scarp, which is located to its southeast (Figures 2 and 13A–B). The apparent opposite sense of movement of the crystalline basement into the Jedberg basin (dashed arrows in Figure 13B and Behrendt 1985, 1986) is because that Triassic basin was formed during an extensional stress regime. Its spatial correlation with WF(N) suggests that the WF(N) was probably associated with the southeast margin fault of an existing Triassic basin, as was originally suggested by Hamilton *et al.* (1983). Additionally, the downwarping of the Santee formation to the southeast of the WF(S) and to the northwest of the WF(N) (Figure 6) is consistent with oblique right-lateral movement on these faults. In summary, Figures 13A and 13B show both a spatial and causal association between the inferred oblique right-lateral strike-slip faulting on the WF(N and S), the Jedberg basin, the up-to-the-northwest displacement of the basalt flows, and the topographic highs and scarps observed at the ground surface.

COMPARISON OF THE SEISMOTECTONIC FRAMEWORK WITH THE MACROSCOPIC EFFECTS OF THE 1886 CHARLESTON EARTHQUAKE

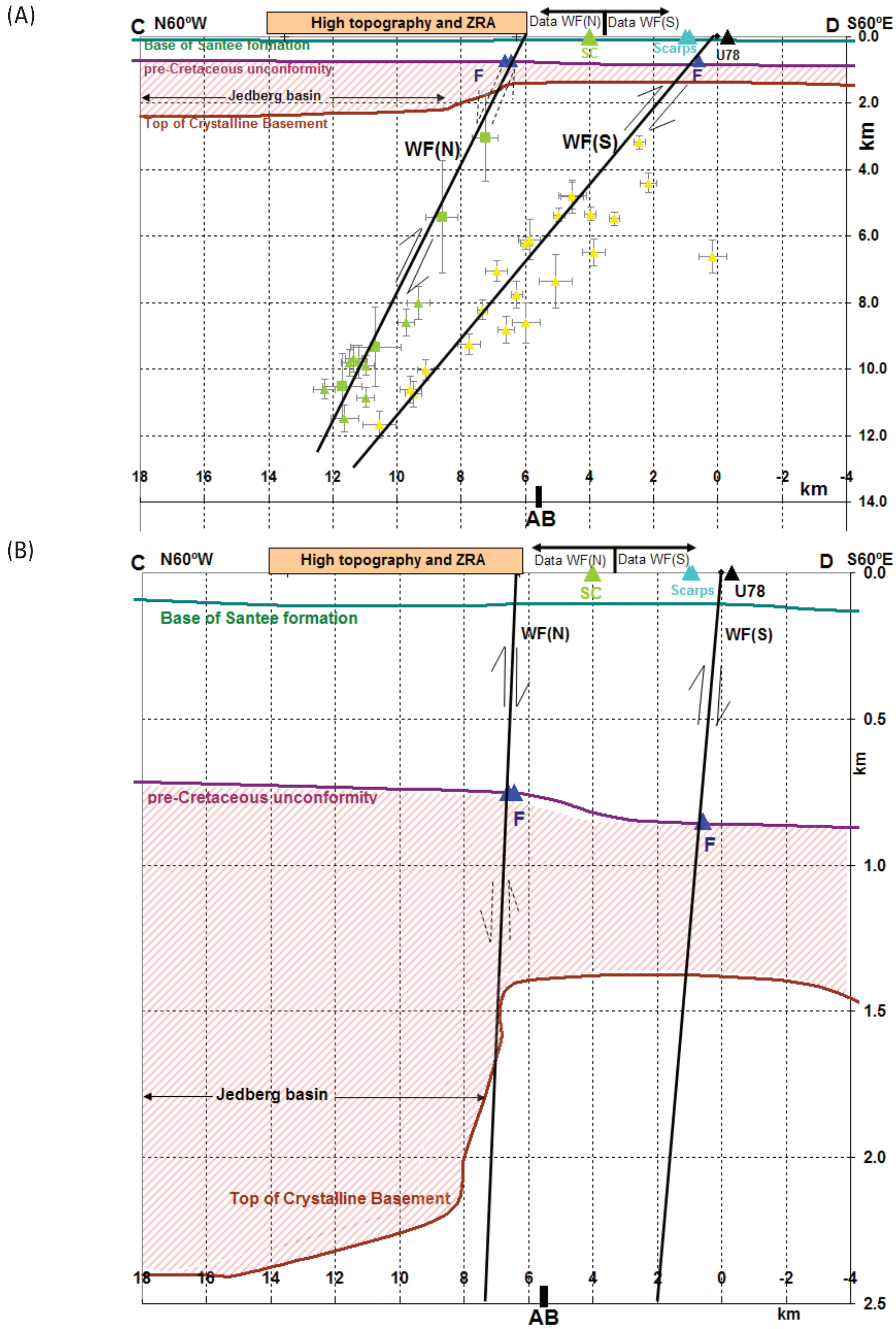
In 1886 the region underlying the MPSSZ and the surrounding areas was largely covered by forests and swamps. Charleston, located about 30 km southeast of the MPSSZ, was connected to the outside world by three major railroad tracks. The South Carolina Railroad (SCRR) connected Charleston with Columbia to its northwest via Summerville. The North Eastern Railroad (NERR) and the Charleston and Savannah Railroad (C&SRR) connected Charleston to the north and west and shared the tracks for the first seven miles out of Charleston. In addition to these major railroad routes, there were a few short railroad spurs to locations of phosphate mining near Summerville and Lambs.

Macroscopic effects and firsthand reports of the earthquakes that began on 31 August 1886 were obtained from observations of these railroad tracks and from Summerville, Charleston, a few isolated thinly populated hamlets, and the phosphate works.

Soon after the earthquake, William McGee of the USGS was dispatched to Charleston from Washington, DC. He spent about five days in South Carolina, half of them in the epicentral area. While in Charleston, he hired a young local geologist and mining engineer, Earle Sloan, who made a comprehensive study of the effects of the earthquake in the following two months. Sloan's detailed report, together with those of McGee and other local observers, was collected and compiled into the official USGS report by Dutton (1890). For comparison with the seismotectonic framework, we note that in the MPSSZ and surrounding area most of the reports are based on the original observations by Sloan and McGee, which were compiled by Peters and Hermann (1986) and form the main source of the information presented below. We present the observed static and dynamic motions in a series of maps (Figures 14 A–C) and the original quotes in the appendix.

Evidence of Compression

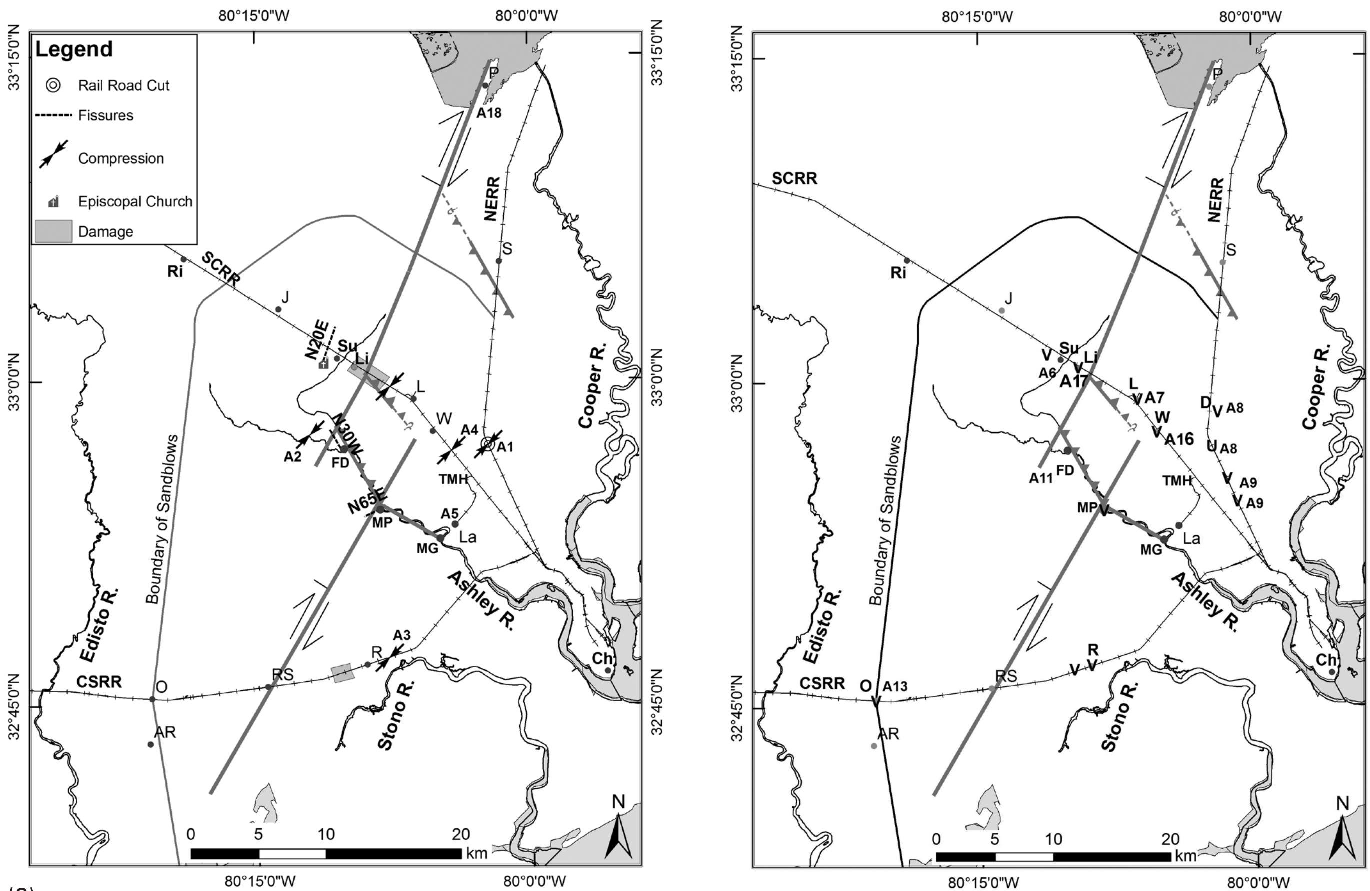
There was widespread evidence of horizontal compression in the meizoseismal region of the 1886 earthquake. Many portions of the railroad tracks were bent into S-shaped curves and had to be cut and straightened for further use. Estimates of the total length that the tracks had to be cut range from 4 to 5 m, although details of individual portions that were cut are limited to a few locations. On the NERR 0.6 m of track had to be cut (Appendix 1, first item in the Appendix, hereafter, A1, Figure 14A). On Bacons Bridge across the Ashley River, 3 km west of Fort Dorchester, the earthquake caused "one plank to overlap another seven inches" and jammed the joints (A.2., Figure 14A). Other indications of shortening were observed on the C&SRR where it crossed the Rantowles creek (A.3, Figure 14A). Sloan also reported evidence of northerly stress along



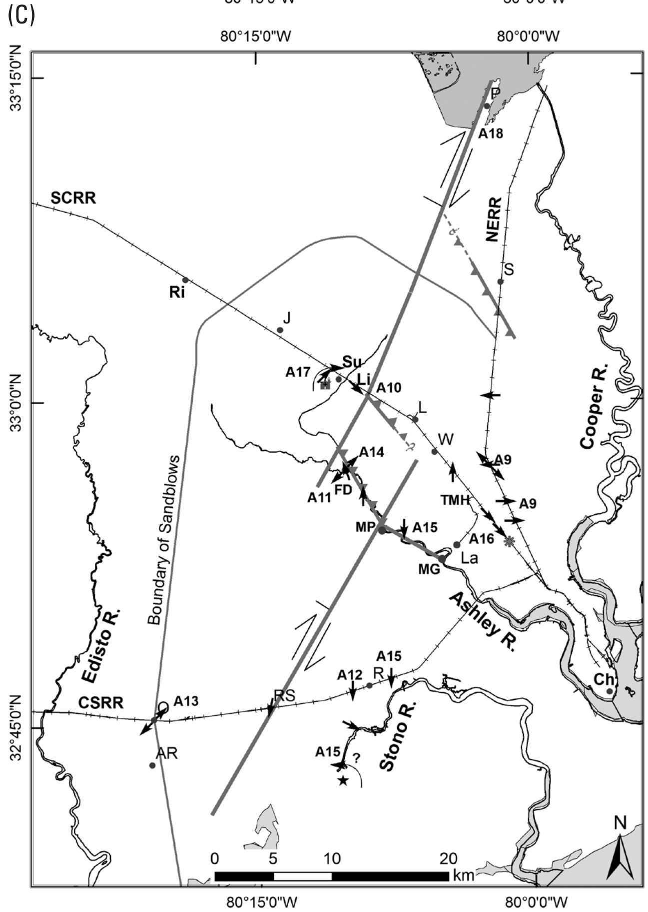
▲ **Figure 13.** (A) Cross-section along CD (Figure 1), perpendicular to the WF. Earthquakes related to the WF(N) and WF(S) are shown in green and yellow, respectively (see Paper 1). The shaded area shows the inferred location of basalt flows. The inferred locations of both WF(S) and WF(N) at the surface are in agreement with faults mapped in the basalt (F) (~700 m depth), surface geology, and topographic data. Data to the northwest of the Summerville scarp are associated with the WF(N) and those to its southeast with the WF(S). The northwest dipping normal fault in the crystalline basement (dashed arrows) is an ancient feature associated with Triassic extension that developed the Jedberg basin. Current movement on the WF(N), oblique right-lateral strike-slip, is associated with northwest-up displacement in the basalt and with the topographic high associated with the ZRA. The Summerville scarp is the southeast edge of this topographic high. The scarps shown to the southeast of the Summerville scarp are associated with the WF(S) (see also Figure 2). U78 shows the southeast edge of the topographic high associated with the WF(S). (B) Shallow data from (A) are presented on an enlarged vertical scale (vertical exaggeration ~8).

(A)

(B`)



(C)



▲ **Figure 14.** (A) Felt effects of the 1886 Charleston earthquake, showing the direction of compression (converging arrows), fissures (dashed lines), and the location where a portion of the NERR was cut superposed on the seismotectonic framework and the railroad. The location names have been abbreviated. Along the SCRR, J, Su, Li, L, W, and TMH stand for Jedberg, Summerville, Lincolnville, Ladson, Woodstock, and Ten Mile Hill, respectively. O, RS, and R on the C&SRR are for Osborn, Ravenel Station, and Rantowles, respectively, and AR is for Adams Run. S on the NERR is the location of Strawberry. FD, MP, and MG along the Ashley River are for Fort Dorchester, Middleton Place, and Magnolia Plantation, respectively. (B) Same as Figure 14A but showing the location of vertical shaking (V), uplift (U), and downdrop (D) reported in the 1886 earthquake. P and Ri show the locations of Pinopolis and Ridgeville, respectively. All other locations are the same as on Figure 14A. (C) Same as Figure 14B but showing the locations and directions of horizontal displacement (single arrows) and ground shaking (divergent arrows).

the SCRR north of Ten Mile Hill and between Ladson and Lincolnville (A.4, Figure 14A). These observations all suggest that the damage was associated with a northerly oriented compression.

In Figure 14A, the direction of tectonic compression has been plotted along N60°E-S60°W, in accordance with our current understanding. Support for this orientation is also obtained from the observation that along the southwest-trending railroad spur from Ten Mile Hill to Lambs, no damage was observed to the railroad track (A.5).

Comparison with the Seismotectonic Framework

Various accounts of the 1886 earthquake document both vertical and horizontal static displacements and ground shaking, often at the same location. Although the observed effects of an earthquake depend on many factors such as its focal mechanism, its rupture direction, the site conditions of the observed effects, etc., we show that the observations of vertical and horizontal movements are generally consistent with oblique right-lateral strike-slip motion on the Woodstock fault and with the (primarily) reverse faulting accompanied by left-lateral strike-slip motion on the SBF and LF.

The initial shock on 31 August 1886 caused a downward movement in the home of Thomas Turner in Summerville (A.6, Figure 14B). Intense vertical movements were reported from Summerville, Lincolnville, Ladson, and Woodstock along the SCRR (A.7, Figure 14B). Vertical motion was also observed along the NERR. Sloan identified permanent vertical offsets across a northwest-southeast trending Goose Creek, down to the north and up to the south (A.8, Figure 14B). He also reported both vertical motion and eastward displacement to the south of Goose Creek toward Charleston. (A.9, Figure 14C) and westward displacements to the north of the NW-SE direction of shaking. These observations of both horizontal and vertical displacement along the NERR and associated shaking in a NW-SE direction lead us to suggest that there was primarily reverse faulting with a strong left-lateral strike-slip component on the inferred southwest dipping Charleston fault in response to NE-SW compression. Along the SCRR horizontal displacements of several feet to the southeast were observed at Lincolnville and Ten Mile Hill (A.10, Figure 14C). The left-lateral displacement to N20°W of the tabby (roasted oyster shell) walls of Fort Dorchester was also documented by Sloan (A.11, Figure 14C).

We associate the vertical motions at Summerville and other locations along the SCRR, together with horizontal southeast displacements at Lincolnville and near Ten Mile Hill and northwest displacement at Fort Dorchester, with primarily reverse faulting with a strong component of left-lateral strike-slip motion on the Lincolnville and Sawmill Branch faults (A.12, Figure 14C). The inference of primarily reverse faulting on the NW-SE faults with associated left-lateral horizontal movement is consistent with the seismotectonic framework inferred from the seismicity data. Next we address the observed ground movements (both static and dynamic) associated with the Woodstock fault.

An account from Osborn (Adams Run Station in some maps) documents both the strong NE-SW horizontal and vertical movements observed in the vicinity of the Woodstock faults (A.13, Figures 14B and 14C). Additional evidence of strong NE-SW ground shaking was observed ~200 m north of Fort Dorchester, where large pieces of brick from the top of the old church were thrown >11 m N25°E from the base of the church tower (A.14, Figure 14C). South and southeastward ground displacement was observed at locations on or east of the Woodstock fault(s) along the Ashley and Stono rivers at various points along the C&SRR (Figure 14C). About 3 km northwest of Middleton Place at Greggs Landing northward ground displacement was observed. A long southwest trending fissure opened up at Middleton Place (A.15, Figures 14A, C). A house in Wadmalaw Island to the south of the Stono River rotated on its axis. The direction of rotation was not given in Sloan's report, and the inferred sense of rotation has been plotted (A.15, Figure 14C,). These observations suggest strong NE-SW shaking and oblique right-lateral strike-slip faulting along the Woodstock faults. McGee noted that it was the second mainshock, about 10 minutes (eight in other accounts) after the first shock that derailed the locomotive about a mile east of Ten Mile Hill on August 31, 1886 (A.16, Figure 14C). We suggest that this shock occurred on WF(S).

Several observations at Summerville suggested movements on the WF(N). Evidence of horizontal movement in Summerville includes the ~33-cm (13-in) displacement to the northeast of Mr. Turner's house and the evidence of clockwise rotation of the Episcopal Church and a tombstone in its cemetery in the southwest part of town (A.17, Figure 14A and C). A northeast oriented, ~30-m-long fissure opened up about 100 m north of the Episcopal Church. The fissure was along the northeast trend of elevated ground parallel and northwest of the Sawmill Branch Creek. These observations and the earthquakes that were felt in June 1887 at Pinopolis along the peninsula in Lake Marion to the northeast all suggest continuous seismicity on the Woodstock fault (N) (A.18, Figure 14A).

The rupture of the north and south walls of the Drayton family tomb on the grounds of the Magnolia Plantation along a northwest trend suggest movement on the Ashley River fault. In conclusion, the macroscopic observations following the 1886 earthquake, although limited in their spatial extent to the three railroad tracks out of Charleston, Summerville, and a few isolated hamlets, are generally consistent with primarily vertical motions on the NW-SE trending reverse faults and horizontal movements on the Woodstock faults (N and S), consistent with the seismotectonic model obtained from current seismicity data.

Discussion of Macroscopic Effects

The macroseismic effects of the 1886 Charleston earthquake indicate that both legs of the Woodstock fault as well as the Lincolnville and Charleston faults were active during that earthquake sequence. Intense NE-SW shaking with a strong vertical component was observed at Osborn about 25 km southwest of Middleton Place (A.13). This observation is in accord with our earlier interpretation (Talwani 1982) that the seismicity observed in the Adams Run seismic zone was associated with the Woodstock fault. Reports of intense shaking at Osborn seem to have been missed by Sloan and consequently by Dutton, who did describe the intense shaking at Walterboro, ~35 km northwest of Osborn.

Continuous activity on the Woodstock fault is evident from felt earthquakes near Pinopolis in June 1887 (McKinley 1887), ~30 km northeast of Summerville along the WF(N).

Turner's observation of downward motion in Summerville when the first shock hit on August 31, 1886 suggests that it was likely associated with the Lincolnville fault. Dutton noted that the shaking at Lincolnville was more severe than in Summerville (A.7) but discounted its significance because of its low population. The southeast displacement of houses in Lincolnville (A.10) and the railroad tracks of SCRR near mileposts 11 and 10 (Figure 14C) and uplift at Woodstock further supports the inference of major severe motion on the Lincolnville fault with a strong left-lateral component.

Sloan's observations on the NERR strongly suggest intense activity on the Charleston fault. There was evidence of vertical displacement on either side of Goose Creek (Figure 14B) approximately along the southeast extension of the Charleston fault, with the fault movements up to the south and down to the north. This observation is consistent with NE-SW compression on a southwest dipping Charleston fault. This (primarily) vertical offset was accompanied by intense NE-SW shaking at the 12 mi 450 ft mark on the NERR. This shaking was also accompanied by displacement to the east, between 8 mi +5,100 ft and 10 mi +350 ft from Charleston and to the west, 12 mi from Charleston (A.9). This observation supports our interpretation of reverse faulting in the Charleston fault with a strong left-lateral strike-slip component.

Sloan and later Dutton attributed the intense shaking at Woodstock and damage to the rails near Rantowles to be because they were located at the epicentral location. We suggest another possible explanation for these observations in light of our tectonic framework. In Figure 14A we note that Woodstock lies near the intersection of the northeast extension of the WF(S) with the southeast extension of the Lincolnville fault. Fault intersections are known to be stress concentrators (see, *e.g.*, Gangopadhyay *et al.* 2004). So the observed vertical movements at Woodstock together with an extensive belt of craterlets west of Woodstock along a S80°W oriented ridge could be manifestations of the release of stress building at the intersection of these faults that resulted in vertical movements along the Lincolnville fault and southwesterly horizontal motion along the WF(S). Intriguingly, Turner's observation of vertical motion with the first shock (A.6) and the derailment of the locomotive on the SCRR (A.16, Figure 14C) 10 minutes later suggests that the first shock was on the Lincolnville fault and the next main shock was on the WF(S).

Sloan located an epicenter at Rantowles based on the ground shaking observed near Rantowles where the C&SRR crossing over Rantowles Creek had resulted in large flexures of the rails. However we note that this part of the C&SRR overlies extensive swamps, and we suggest that the observed damage was more an artifact of site conditions rather than the location being an epicenter.

CONCLUSIONS

The seismotectonic framework for the MPSSZ was inferred from very diffuse instrumentally recorded seismicity that occurs at depths of 3 km and greater in the crystalline basement below the widespread basalt flows. To test its validity we compared and integrated it with a variety of geophysical, geologic, and geomorphic data to examine if they are consistent with the geometry and tectonic activity of the inferred faults comprising the framework and with the observed macroscopic effects of the 1886 Charleston earthquake and its aftershocks. Our results suggest a plausible scenario to explain the past and current seismicity. We conclude that the MPSSZ has undergone tectonic activity, and these tectonic movements have affected sediments as old as ~48 Ma. The ~N30°E trending, >50-km-long Woodstock fault is associated with oblique right-lateral strike-slip motion. It is offset along a ~6 km antidilatational left step along the NW trending Sawmill Branch, Lincolnville, and Charleston faults in the Middleton Place–Summerville area. The current seismicity is (almost) exclusively in the vicinity of this left step, with the SBF being the most active of the faults and forming a ~3-km-wide zone. Post-1974 very little seismicity has been recorded on the north and south legs of the Woodstock fault outside the Summerville–Middleton Place area or on the Charleston and Lincolnville faults.

Finally, integrating the seismotectonic framework with the observed effects of the 1886 earthquake, we note that the most intense shaking occurred on the Woodstock fault (north and south) and on the NW-SE trending Charleston and Lincolnville faults and comparatively less on the Sawmill Branch fault.

DATA AND RESOURCES

The digital elevation model (DEM) used in this study can be obtained from the South Carolina Department of Natural Resources at http://www.dnr.sc.gov/GIS/descdem.html (last accessed June 2009). All the other data used in this paper came from published sources listed in the references. Figures were made using ArcGIS version 9.1 (http://www.esri.com/arcgis).

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REFERENCES

Ackermann, H. D. (1977). Exploring the Charleston, South Carolina earthquake area with seismic refraction—a preliminary study. In Rankin 1977, 167–175.

Ackermann, H. D. (1983). Seismic-refraction study in the area of the Charleston, South Carolina, 1886 earthquake. In Gohn 1983, F1–F20.

Amick, D. C. (1979). Crustal structure studies in the South Carolina Coastal Plain, MS thesis, University of South Carolina, Columbia, 81 pps.

Bartholomew, M. J., and F. J. Rich (2007). The walls of colonial Fort Dorchester: A record of structures caused by the August 31, 1886 Charleston, South Carolina earthquake and its subsequent earthquake history. *Southeastern Geology* **44**, 147–169.

Behrendt, J. C. (1985). *Interpretations from Multichannel Seismic-reflection Profiles of the Deep Crust Crossing South Carolina and Georgia from the Appalachian Mountains to the Atlantic Coast*. Miscellaneous Field Studies Map. USGS Report MF-1656, 3 sheets.

Behrendt, J. C. (1986). Structural interpretation of multichannel seismic-reflection profiles crossing the southeastern United States and the adjacent continental margin decollements, faults, Triassic (?) basins and moho reflections. *Geodynamics Series* **14**, 201–213.

Colquhoun, D. J. (1962). On surficial sediments in central South Carolina—a progress report. *South Carolina Development Board, Division of Geology Geol. Notes* **6**, 63–80.

Colquhoun, D. J. (1965). Terrace sediment complexes in central South Carolina: Atlantic Coastal Plain. Geological Association, Field Conference, 1965, University of South Carolina, Columbia, 62 pps.

Colquhoun, D. J., I. D. Woollen, D. S. Van Nieuwenhuise, G. G. Padgett, R. W. Oldham, D. C. Boylan, P. D. Howell, and J. W. Bishop (1983). *Surface and Subsurface Stratigraphy, Structure, and Aquifers of the South Carolina Coastal Plain*. Ground Water Protection Division, Report for Department of Health and Environmental Control. Columbia, SC: Office of the Governor, 78 pps.

Durá-Gómez, I. (2004). Seismotectonic framework of the Middleton Place Summerville seismic zone near Charleston, South Carolina. MS thesis, University of South Carolina, Columbia, 180 pps.

Durá-Gómez, I., and P. Talwani (2009). Finding faults in the Charleston Area, South Carolina: 1. Seismicity data. *Seismological Research Letters* **80**, 883–900.

Dutton, C. E. (1890). *The Charleston Earthquake of August 31, 1886*. USGS Annual Report, no. 9, 203–528 (republished in 1975).

Gangopadhyay, A., J. Dickerson, and P. Talwani (2004). A two-dimensional numerical model for the current seismicity in New Madrid seismic zone. *Seismological Research Letters* **75,** 406–418.

Garner, J. T. (1998). Re-evaluation of the Seismotectonics of the Charleston, South Carolina Area. MS thesis, University of South Carolina, Columbia, 250 pps.

Gohn, G. S., ed. (1983). *Studies Related to the Charleston, South Carolina, Earthquake of 1886—Tectonics and Seismicity*. USGS Professional Paper 1313.

Gohn G. S., B. Houser, and R. R. Schneider (1983). Geology of the lower Mesozoic(?) sedimentary rocks in Clubhouse Crossroads test hole #3, near Charleston, South Carolina. In Gohn 1983, D1–D17.

Hames, W. E., P. R. Renne, and C. Ruppel (2000). New evidence for geologically instantaneous emplacement of earliest Jurassic Central Atlantic magmatic province basalts on the North American margin. *Geology* **28**, 859–862.

Hamilton, R. M, J. C. Behrendt, and H. D. Ackermann (1983). Land multichannel seismic reflection evidence for tectonic features near Charleston, South Carolina. In Gohn 1983, I1–I18.

Lennon, G. (1985). Identification of a northwest trending seismogenic graben near Charleston. MS thesis, University of South Carolina, Columbia, 84 pps.

Long, L. T., and J. W. Champion (1977). Bouguer gravity map of the Summerville-Charleston, South Carolina, epicentral zone and tectonic implications. In Rankin 1977, 151–166.

Lyttle, P. T., G. S. Gohn, B. B. Higgins, and D. S. Wright (1979). Vertical crustal movements in the Charleston, South Carolina-Savannah, Georgia area. *Tectonophysics* **52**, 183–189.

Madabhushi, S., and P. Talwani (1993). Fault plane solutions and relocations of recent earthquakes in Middleton Place Summerville Seismic Zone near Charleston, South Carolina. *Bulletin of the Seismological Society of America* **83**, 1,442–1,466.

Marple, R. T. (1994). Discovery of a possible seismogenic fault system beneath the Coastal Plain of South and North Carolina from integration of river morphology and geological and geophysical data. PhD diss., University of South Carolina, Columbia, 354 pps.

Marple, R. T., and R. Miller (2006). Association of the 1886 Charleston, South Carolina, earthquake and seismicity near Summerville with a 12 degrees bend in the East Coast fault system and triple-fault junctions. *Southeastern Geology* **44**, 101–127.

Marple, R. T., and P. Talwani (1992). The Woodstock lineament: A possible surface expression of the seismogenic fault of the 1886 Charleston, South Carolina, earthquake. *Seismological Research Letters* **63**, 153–160.

Marple, R. T., and P. Talwani (1993). Evidence of possible tectonic upwarping along the South Carolina Coastal Plain from an examination of river morphology and elevation data. *Geology* **21**, 651–654.

Marple, R. T., and P. Talwani (2000). Evidence for a buried fault system in the Coastal Plain of the Carolinas and Virginia—implications for neotectonics in the southeastern United States. *GSA Bulletin* **112**, 200–220.

Marzoli, A., P. R. Renne, E. M. Piccirillo, M. Ernesto, G. Bellieni, and A. De Min (1999). Extensive 200-million-year-old continental flood basalts of the Central Atlantic magmatic province. *Science* **284**, 616–618.

McKinley, C. (1887). A descriptive narrative of the earthquake of August 31, 1886. In *Appendix for the City (of Charleston) Year Book, 1886,* Charleston S.C.: Walker, Evans, and Cogswell, Co. 345–441.

McCartan, L., E. M. Lemon Jr., and R. E. Weems (1984). *Geologic Map of the Area between Charleston and Orangeburg, South Carolina*. Miscellaneous investigations series, USGS Report I-1472, 2 sheets.

Muthanna, A. (1988). An integrated geological and geophysical study of the Central South Carolina Coastal Plain. MS thesis, University of South Carolina, Columbia, 107 pps.

Peters, K., and R. B. Herrmann, eds. (1986). *A Collection of Historical Documents Pertaining to the 1886 Charleston, South Carolina Earthquake*. South Carolina Geological Survey Bulletin 41, 116 pps.

Poley, C. M., and P. Talwani (1986). Recent vertical crustal movements near Charleston, South Carolina. *Journal of Geophysical Research* **91**, 9,056–9,066.

Popenoe, P., and I. Zietz (1977). The nature of the geophysical basement beneath the Coastal Plain of South Carolina and northeastern Georgia. In Rankin 1977, 119–137.

Rankin, D. W., ed. (1977). *Studies Related to the Charleston, South Carolina, Earthquake of 1886—A Preliminary Report*. USGS Professional Paper 1028.

Rhea, S. (1989). Evidence of uplift near Charleston, South Carolina. *Geology* **17**, 311–315.

Schilt, F. S., L. D. Brown, J. E. Oliver, and S. Kaufman (1983). Subsurface structure near Charleston, South Carolina—results of COCORP reflection profiling in the Atlantic Coastal Plain. In Gohn 1983, H1–H19.

Taber, S. (1914). Seismic activity in the Atlantic Coastal Plain near Charleston, South Carolina. *Bulletin of the Seismological Society of America* **4**, 108–160.

Talwani, P. (1982). Internally consistent pattern of seismicity near Charleston, South Carolina. *Geology* **10**, 654–658.

Talwani, P. (2000a). Macroscopic effects of the 1886 Charleston earthquake (field trip guide). In *A Compendium of Field Trips of South Carolina Geology*, 1–6. Produced in association with the Geological Society of America Southeastern Section Meeting March 23–24, 2000, Charleston, SC. Charleston, SC: South Carolina Department of Natural Resources Geological Survey.
Talwani, P. (2000b). *Velocity Structure Inferred from an Exploratory Oil Well in Colleton County, South Carolina*. Unpublished report, 4pps.
Talwani, P. (2001). Macroseismic effects of the Charleston earthquake. In *73rd Annual Meeting of the Eastern Section of the Seismological Society of America*, Field Trip Guide, 14 October 2001.
Talwani, P., J. N. Kellogg, and R. Trenkamp (1997). *Validation of Tectonic Models for an Intraplate Seismic Zone, Charleston, South Carolina, with GPS Geodetic Data*. U.S. Nuclear Regulatory Commission NUREG/CR-6529, 41pps.
Talwani, P., and R. T. Marple (1997). *Use of Seismic Reflection to Confirm a Major Buried Fault System beneath the Coastal Plain of South Carolina*. Final (unpublished) report for National Science Foundation Grant No. EAR-9508229. Columbia, SC, University of South Carolina, 9 pps.
Tarr, C., P. Talwani, S. Rhea, D. Carver, and D. Amick (1981). Results of recent South Carolina seismological studies. *Bulletin of the Seismological Society of America* **71**, 1,883–1,902.
Tarr, C., and S. Rhea (1983). Seismicity near Charleston, South Carolina, March 1973 to December 1979. In Gohn 1983, R1–R17.
Trenkamp, R., P. Talwani, and L. Lapine (2003). *Seismotectonics of the Charleston South Carolina Region*. Final Technical Report to the U.S. Geological Survey Award No. 99HQGR0013.
Weems, R. E., and E. M. Lemon Jr. (1984). *Geologic Map of the Mount Holly Quadrangle, Berkeley and Charleston Counties, South Carolina*. USGS Geologic Quadrangle Map GQ-1579.
Weems, R. E., and W. C. Lewis (2002). Structural and tectonic setting of the Charleston, South Carolina, region: Evidence from the Tertiary stratigraphy record. *GSA Bulletin* **114**, 24–42.
Weems, R. E., and S. F. Obermeier (1989). The 1886 Charleston earthquake—an overview of geological studies. In *Proceedings of the U.S. Nuclear Regulatory Commission, Seventeenth Water Reactor Safety Information Meeting, Rockville, Maryland*, vol. 2, 289–313.
Wildermuth, E. (2003). Potential field studies in northeast South Carolina. MS thesis, University of South Carolina, Columbia, 153 pps.
Yantis, B. R., J. K. Costain, and H. D. Ackermann (1983). A reflection seismic study near Charleston, South Carolina. In Gohn 1983, G1–G20.

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APPENDIX

Sloan's report (SR), McGee's report, and Turner's report have been taken from Peters and Hermann (1986) (PH). The page number in PH is given. In Sloan's report the location is described as the distance from Charleston along the different railroads. Other sources include Dutton's report (1890), McKinley's account in the *Charleston Year Book* for 1886, and the Charleston *News and Courier*. These verbatim descriptions of damage are shown on Figures 14A–C as A1, A2 etc.

A1. Sloan's report. Peters and Hermann (1986) (SR, PH), p.53. North Eastern Rail Road 12 miles 700 ft.
Found necessary to cut 22 inch section of stringer before tangent could be restored.

A2. SR, PH, p. 60, Bacons Bridge—Ashley River
Affords evidence of tendency of banks to approach centre of channel. Here expressed by compression of bridge causing one plank to overlap another seven inches & jamming joints.

A3. SR, PH, pps. 51 and 63, Charleston and Savannah R.R. Rantowles bridge spanning Rantowles Creek
… bents indicate approach of banks towards the channel of stream 13 inches from W & 5 inches from E.

A4. SR, PH, pps. 44 and 67, SCRR
… from point beyond Ten Mile Hill Nor′ward the superstructure has suffered strain of thrust in Northerly direction rather than Southerly shearing… For at 19 mile post & 4500 feet… is a 30 foot trestle 14 ft high, just South of which superstructure was found flexured… & indicates a northerly stress of entire superstructure…

A5. SR PH, p. 67, Spur Line to Lambs
A short branch line from Ten Mile Hill to Lambs, on Ashley River has been insignificantly disturbed (2 ½ miles, S41°W).

A6. From "Experiences of Mr. Thomas Turner, President Charleston Gas-Light Company" PH, p. 106
The house raised about four feet from the ground and set on pine logs set into the earth in lieu of brick piers…and was entering the door of the Hall when, without any rumble or premonitory symptoms, just as I was stepping in at the door, for a single instant the floor seemed to sink from under me … the floor seemed to go down in front of me at an angle of about 25 to 30 degrees.

A7. McGee's report, PH, p. 26
… the structure, like all others in Summerville, suggests violent vertical movements…
in Lincolnville the injury to buildings is similar in kind and degree to that of Summerville, …

Dutton, pps. 276–277
(At) Lincolnville… The violence of the shocks here was apparently a little greater than at Summerville, though the difference is so small that its existence may seem doubtful

SR, PH, p. 56, SCRR
Ladsons – Houses strained Northerly. Chimneys collapsed. Furniture moved S10°W – Vertical effects pronounced

SR, PH, p. 59, SCRR
Woodstock – Vertical component finds expression in collapse of large sheds & neighboring chimneys.

A8. SR, PH, p. 67

The NERR 12 miles N26°W from Charleston at the 14 mile post crosses a broad U depression with valley line slightly above sea level, and ascends on both sides pronounced ridges constituting water shed of Goose Creek. About this locality various evidences of Vertical force find expression – as in rupturing backs & wing walls of culverts downward ...

Proceeding Southerly we find northerly slope of ridge near 12 mile post violently disturbed with expressions near crest of Vertical Component which has sufficiently raised the stringers of short trestle to admit overturning of bents…

A9. SR, PH, pps. 52 and 53 NERR

8 mi + 5100 ft: Superstructure shifted 4 ins to E
9 mi + 4000 ft: Superstructure deflected to E
10 mi + 350 ft: 15 ft embankment forced 4 ft 6 ins E along 150 chorts (*sic*) ... 12 mi: Inception of flexure to W increasing till at 12 + 450
12 + 450: Side of hill has evidently vibrated SE & NW with an energy rupturing it from body of hill towards adjacent valley line…

A10. McGee's report, PH, p. 26

"… in Lincolnville… the building has been moved 10 feet to the southward and 3 feet to the eastward. ... Two or three hundred yards northeast of the building… has been thrown also to the southeastward. Its movement was 4 or 5 feet to the south and 2 or 3 feet to the east…"

A11. SR, PH, p. 59

Dorchester N20°W Old Fort walls of shell concrete 8 ft high with thickness battered from 3 ft at base to 2 ft at top cracked thro E (?) wall at SE (?) corner also badly cracked in two places at N.W. corner.

A12. Dutton, p. 284

The distortions of the track and its dislocations appeared to have nearly attained their maximum between the 10-mile and 11-mile posts. It was often displaced laterally and sometimes alternatively depressed and elevated. Occasionally several lateral flexures of double curvature and of great amount were exhibited. Many hundreds of yards of track had been shoved bodily to the southeastward.

On the Charleston side of the epicentrum (Woodstock) the shove is always toward Charleston, on the opposite side of the epicentrum it is in the opposite direction.

A13. From *Charleston News and Courier* 9 September 1886, p. 8

OBSERVATIONS OF A SURVEYOR

Facts Noted During the Earthquake at Osborn, Colleton County.

(Correspondence of the News and Courier)

OSBORN, COLLETON COUNTY, S.C., August 31, 12 P.M.

The shock of an earthquake was first felt at this place of 9:40 P.M. by the writer's clock. My house, a small framed building of four rooms, was first raised several inches and came down with a heavy thump. I sat on the edge of the bed alone in my room. I comprehended the situation at once, and thinking that the shock was quite as local as the shocks had been at Summerville three days previously, I carefully noted all movements, which I found undulating north and south – or rather northeast and southwest – an oscillation of movement, which seemed to move the house (earth and all) quite three feet on a plane. It seemed to gyrate a little. During these movements there was an awful quivering of the earth and a rising and falling, with a thump, as if a solid strata of the earth had been raised by a supernatural power and allowed to drop on another solid strata. The movements did not stop for quite three minutes, and almost immediately another lesser shaking occurred. Others followed at greater intervals of time for about one hour. Then a rest of about an hour. (My clock had been destroyed). The thirteenth shock was quite severe.

After the third shock I sat up my surveyor's compass in the yard and watched it closely. The needle kept steadily N, but constantly quivered until when the first faint murmur of the sound which always preceded the shock by a few seconds, the needle appearing to dip showed that there was a movement of the staff N and S. There was not a breath of air moving - ... by two lamps which I used in taking my notes, I watched the thermometer. The mercury fell gradually from 79 to 74. At this writing twenty shocks, each proceeded by the awful, ominous, warning sound have occurred.

8:56 A.M. September 1. Twenty three shocks have occurred at this writing. Craters from a fraction of an inch to several feet which threw up water, mud and sand, also fissures in the earth some of them as much 10 feet long by one foot wide. Many of these craters and cracks are found from Edisto River to Rantowles, from Salt Water to Caw Caw swamp.

1 o'clock PM. September 1. Twenty six shocks up to this time. The writer starts for Charleston, which is said to be destroyed.

This place is on the Charleston and Savannah Railway, twenty two miles from Charleston air line.

A14. SR, PH, p. 59–60. Dorchester N48E

Old Church tower of massive brick work SE & NW walls being 3 ft 10 ins thick the other two feet thick the whole occupying plan 18 ft square. Violently cracked & ruptured dismembered massed of 15 to 20 cubic feet of cemented brick have been thrown to every point of compass one mass of 20 cubic feet having been found 35 ft from base of tower in direction N25°E some having been dislodged from point 35 ft above ground. Corresponding mass of almost equal volume found almost equally far to S.W.

A15. SR, PH, p. 63. Rantowles Station C&SRR

Railway office—Old fashioned heavy school desk in S.W. corner, with back against the wall, running N20°W, has been operated on at same instant by horizontal force jamming desk to south

SR, PH, p. 60. Ravenels Station on C&SRR

Bowl of soft butter found on shelf of small dairy with much of viscid mass overhanging rim S12°W

SR, PH, p. 61. New Cut Landing, Wadmalaw Island

Square frame building of three floors – and two interior chimneys, the West one broken off 6 ft from top & thrown clear of eaves S70°W to ground. The Easterly one was sheaved off & twisted in situ - … positions of overturned furniture movement indicate NE & SW strain of approx. 50°.

SR, PH, p. 64. North bank of Stono River.

Large two story frame building of square plan has suffered severe strain in direction N65°E.

McGee's account, PH, pps. 21–22

At phosphate works (at Greggs Landing, south of Ashley River and ~3 km NW of Middleton Place - P.T.)

… The viaducts through which the sand and mud are carried from the washer to the waste heap have both been shifted northward 2 to 4 feet…

SR, PH, p. 60. Ashley River Middleton Hall

Numerous strains NW & SE 58°.… Violence great.… Cracks in earth N65°E

A16. McGee Report, PH, p. 22

Something less than a mile east of Ten Mile Hill lies the derailed locomotive, … So far as can be ascertained from the condition of the rails, ties, and low embankment, and the testimony of the watchman and other, the train was thrown from the track by the tremor and not derailed in consequence of bending or breaking of the track by preceding tremors. The derailment, however, occurred during the second shock of Tuesday (August 31, 1886 – PT) evening, ten minutes after the great quake.

A17. Turner's report, PH, p. 106

In an examination of the house, we found that … House was moved and the piles carried over 13 inches on a N.E.ly direction.

McGee's report, PH, p. 19.

The Episcopal Church in the south-western part of town, a wooden structure 30x50 feet resting on 36 piers of brick each 2 ½ feet square and 4 feet high, fronting N70°E, has been displaced northward 2 ½ inches at west end, 1 ¾ inches in the middle, an 1 inch at the east end. … Several of the pillars … a few have oblique fissures extending from south obliquely downward & little north.

A monument (tombstone) 20 feet north of church … The effect of the shock was to break the cross from its socket and throw it directly westward… The base is torsionally displaced with the sun 2 ½ inches (clockwise rotation P.T.). The 200 lb block twisted in the same direction. 3/4 of an inch and moved slightly northward, and the 150 lb block was turned in the same direction ½ inch and also shifted northward slightly while the 300 lb base is undisturbed.

McGee's account, PH, p. 21

Perhaps the most noteworthy of the Summerville fissures is one in the south-western part of town, 300 yards north of the Episcopal Church, which is perhaps 1 inch in width, 100 feet in length, extending S20°W … although this one is of the very highest points in that part of the country, water flowed from it continuously from the time of the great shock of Tuesday evening until Sunday morning the 5th inst. The water was somewhat colder than that of the wells and when examined by me on the 4th or 5th was pure, clear, and free from odor.

A18. County of Charleston, yearbook 1886. McKinley's account, p. 439

The latest disturbance at Charleston, prior to the publication of the Year Book, occurred on 5 June (1887 PT), about 7 o'clock P.M., but was detected by very few persons. A number of tremors were reported the same day from Pinopolis.