USGS
science for a changing world

Paleoliquefaction Field Reconnaissance in Eastern North Carolina—Is There Evidence for Large Magnitude Earthquakes Between the Central Virginia Seismic Zone and Charleston Seismic Zone?

Scientific Investigations Report 2019–5057

U.S. Department of the Interior
U.S. Geological Survey

Cover. Brett McLaurin, Bloomberg University, inspects an exposure of well-bedded Holocene alluvium, consisting of alternating beds of sand, silt, clay, and organic leaf litter, along the Neuse River east of Goldsboro, North Carolina. Photograph by Mark Carter, U.S. Geological Survey..

Paleoliquefaction Field Reconnaissance in Eastern North Carolina—Is There Evidence for Large Magnitude Earthquakes Between the Central Virginia Seismic Zone and Charleston Seismic Zone?

By Mark W. Carter and Brett T. McLaurin

Scientific Investigations Report 2019–5057

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2019

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Although this information product, for the most part, is in the public domain, it also may contain copyrighted materials as noted in the text. Permission to reproduce copyrighted items must be secured from the copyright owner.

Suggested citation:
Carter, M.W., and McLaurin, B.T., 2019, Paleoliquefaction field reconnaissance in eastern North Carolina—Is there evidence for large magnitude earthquakes between the Central Virginia Seismic Zone and Charleston Seismic Zone?: U.S. Geological Survey Scientific Investigations Report 2019–5057, 54 p., https://doi.org/10.3133/sir20195057.

ISSN 2328-0328 (online)

Acknowledgments

We wish to thank Jacob Glassbrenner, University of Tennessee, for assistance in the field. Dr. Thomas Pratt, U.S. Geological Survey, Central and Eastern U.S. Coordinator, USGS Earthquake Hazards Program, and Dr. Kenneth Taylor, State Geologist of North Carolina, provided valuable reviews that greatly improved the manuscript.

Contents

Acknowledgments iii
Abstract 1
Introduction 1
Geographic and Geologic Setting 4
    Stratigraphy 4
    Coastal Plain Faults 5
    Geomorphic Evidence for Holocene Deformation 7
    Methodology 7
Results 10
Discussion 15
Conclusions 21
References Cited 21
Appendix 1. Data for paleoliquefaction survey along the Tar and Neuse Rivers in central-eastern North Carolina, June 21–25, 2016. 28
Appendix 2. Radiocarbon data for a sample of organic matter from an alluvial bar deposit at the mouth of an abandoned river meander bend on the Neuse River, central-eastern North Carolina 54

Figures

1. Illustration of paleoliquefaction exploration in the southeastern United States, 1980s to present 2
2. Geologic map of central-eastern North Carolina in the vicinity of Tarboro, Goldsboro, and Kinston, North Carolina 3
3. Coastal Plain stratigraphy in central-eastern North Carolina 4
4. Photographs of representative map units in central-eastern North Carolina 6
5. Light detection and ranging-derived 3-meter digital elevation model of the Kinston, North Carolina, area 8
6. Diagram showing a few of the key field criteria for liquefaction to occur in an unconsolidated stratified sequence of sediment 9
7. Graphs showing U.S. Geological Survey stream gage data for the Tar and Neuse Rivers in the study area, for the days each river was traversed 10
8. Photographs of three stratigraphic conditions suitable for liquefaction recorded along the Tar and Neuse Rivers 14
9. Photographs showing features of likely syndepositional, bioturbation, or pedogenic origin documented during this study 16
10. Diagram showing location of station NS-38.3 on an alluvial bar deposit at the mouth of an abandoned river meander 17
11. Photographs showing paleoliquefaction dikes and polygonal cracks in alluvial sediments, Virginia and North Carolina 18
12. Map and graphs showing distribution and statistical significance of paleoliquefaction features in the Central Virginia Seismic Zone 19

Table

1. Compilation of outcrops along the Tar and Neuse Rivers in central-eastern North Carolina and their liquefaction susceptibility classification based on field criteria 11

Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the World Geodetic System (WGS 84).

Altitude, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations

CSZ	Charleston Seismic Zone
CVSZ	Central Virginia Seismic Zone
M	magnitude
NEHRP	National Earthquake Hazard Reduction Program
USGS	U.S. Geological Survey

Paleoliquefaction Field Reconnaissance in Eastern North Carolina—Is There Evidence for Large Magnitude Earthquakes Between the Central Virginia Seismic Zone and Charleston Seismic Zone?

By Mark W. Carter[1] and Brett T. McLaurin[2]

Abstract

In June 2016, approximately 64 kilometers (km) of riverbank were examined along the Tar and Neuse Rivers near Tarboro and Kinston, North Carolina, for evidence of liquefaction-forming earthquakes. The study area is in the vicinity of the Grainger's fault zone in eastern North Carolina. The Grainger's fault zone is a fault zone in the inner Coastal Plain Province that has well-documented Paleogene and younger deformation of Cretaceous to Eocene strata. Low-magnitude earthquakes near the fault zone (for example, magnitude [M] 2.1 in 2013, 13 km south-southwest of Kinston) suggest larger earthquakes may have struck this region in the past. The study area is about equidistant from newly documented Holocene paleoliquefaction sites in the Central Virginia Seismic Zone (CVSZ) and liquefaction sites formed during the 1886 M7.1 Charleston, South Carolina earthquake. The northernmost Holocene paleoliquefaction features associated with the Charleston Seismic Zone (CSZ) are in Southport, North Carolina.

Conditions suitable for liquefaction were identified at 38 sites on both rivers, but only one site was classified as highly susceptible. Stratigraphy consists of Paleozoic gneiss; Cretaceous sandstone/shale; Paleocene mudstone/claystone to Eocene fossiliferous limestone; Quaternary unconsolidated, crossbedded sand and gravel; and Holocene alluvium. Three sets of stratigraphic conditions suitable for liquefaction—unconsolidated source sand beneath capping strata—were identified in detailed examinations at 105 sites: (1) Holocene alluvial sand beneath alluvial silt and clay beds; (2) Quaternary terrace sand beneath beds of silt and clay; and (3) Holocene alluvial sand or Quaternary terrace sand capped by clay-rich Bt soil horizons. Weathered and unconsolidated Cretaceous sand capped by a Bt soil horizon was identified at one site, but the weathered sand is likely too compacted to liquefy readily. One outcrop containing three small sand dikes, and four outcrops of soft-sediment deformation features—mostly load casts—were observed, but none of these features could be conclusively established as seismogenic. A few examples of pseudo-sand-dikes were also identified: sand-filled cypress root casts and pedogenic weathering fronts created the appearance of sand dikes and sills.

A comparable survey in 2015 of 119 km of riverbank exposures in the CVSZ yielded 19 paleoliquefaction sites of probable earthquake origin; these features formed from at least one M~6 earthquake in the past 6,000 years (6 ka). This survey in eastern North Carolina revealed no definitive paleoliquefaction features; earthquakes of sufficient magnitude to produce liquefaction likely have not affected this region during the Holocene.

Introduction

The magnitude (M)5.8 Mineral, Virginia, earthquake on August 23, 2011, created renewed interest in seismic research in the Central Virginia Seismic Zone (CVSZ) (for example, Horton and others, 2015), including new exploration for paleoliquefaction features and paleoseismic recurrence based on that research (Tuttle and others, 2015; Carter and others, 2016). One ongoing direction of that research focuses on establishing the boundaries of CVSZ paleoliquefaction field(s); this report summarizes the first post-2011 attempt to document the presence or absence of paleoliquefaction features south of the CVSZ in an area of eastern North Carolina generally considered to be aseismic (Tarr and Wheeler, 2006), despite historical low-magnitude and infrequent earthquakes (fig. 1). The study area is about equidistant from Holocene paleoliquefaction sites in the CVSZ and liquefaction sites formed during the 1886 M~7 Charleston, South Carolina,

[1]U.S. Geological Survey.

[2]Bloomsburg University.

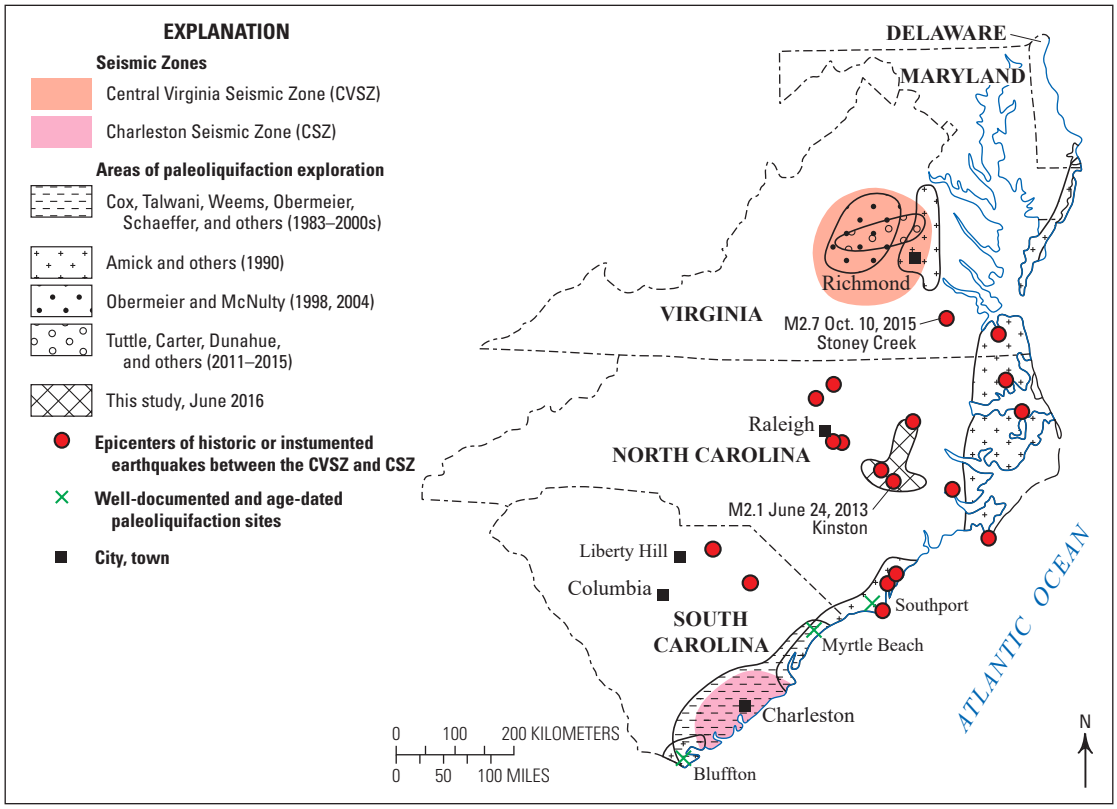

Figure 1. Paleoliquefaction exploration in the southeastern United States, 1980s to present. Epicenters of historical or instrumented earthquakes between the Central Virginia Seismic Zone and Charleston Seismic Zone, and well-documented and age-dated paleoliquefaction sites associated with the Charleston Seismic Zone at Bluffton and Myrtle Beach, South Carolina, and Southport, North Carolina, are shown. Liquefaction from the 1886 magnitude (M)~7 Charleston earthquake was also reported at Liberty Hill, South Carolina (see Talwani and Schaeffer, 2001). Map modified from Amick and others (1990).

earthquake (for example, Obermeier and others, 1990; Talwani and Schaeffer, 2001). The northernmost Holocene paleoliquefaction features associated with the Charleston Seismic Zone (CSZ) are in Southport, North Carolina (Weems and others, 1986; 1988; Weems and Obermeier, 1990).

Amick and others (1990) and Amick and Gelinas (1991) conducted the first exploration for paleoliquefaction features in the CVSZ, but mostly in the easternmost portion of the seismic zone (fig. 1). This work stemmed from earlier investigations in the CSZ in the Coastal Plain Province of South Carolina by Cox and Talwani (1983) and Cox (1984); the goal of Amick and his colleagues was to extend the search for paleoliquefaction features northward along the eastern seaboard, with focus mostly on gravel pit exposures. A more thorough and comprehensive investigation by Obermeier and McNulty (1998) resulted in the identification of two sites that preserved Holocene features of probable and possible seismic-induced liquefaction origin in the CVSZ. Obermeier later added a third locality to the list of sites in the CVSZ that preserve possible paleoliquefaction features (Dominion Nuclear North Anna, LLC, 2004); the features documented were several thin sand dikes exposed in riverbank alluvium.

The M5.8 earthquake of August 23, 2011, produced several small liquefaction features at two sites near the epicenter (Carter and others, 2012; Lasley and others, 2013; Green and others, 2015). Discovery of these features renewed interest in paleoliquefaction research in the CVSZ. In November 2011, Martitia Tuttle and Taylor Bush of M. Tuttle and Associates found possible paleoliquefaction features in the epicentral area and near one of the three original CVSZ paleoliquefaction sites (M. Tuttle, oral commun., 2011). Concerted local and regional exploration in 2012, 2014, and 2015 led to the discovery and documentation of 19 additional sites in the CVSZ that preserve probable paleoliquefaction features in Holocene riverbank alluvium, including sand dikes, sand sills, and soft-sediment deformation features (Tuttle and others, 2015; Carter and others, 2016). These data hint that at least one M6+ earthquake has struck the CVSZ in the past 6,000 years (6 ka) (Tuttle and others, 2015).

Although cutbank exposures along 119 kilometers (km) of six rivers were systematically surveyed in 2015, this constituted approximately one-third, and only the central portion, of the total area of the CVSZ (fig. 2). The southern extent of distribution of CVSZ paleoliquefaction features remained (and

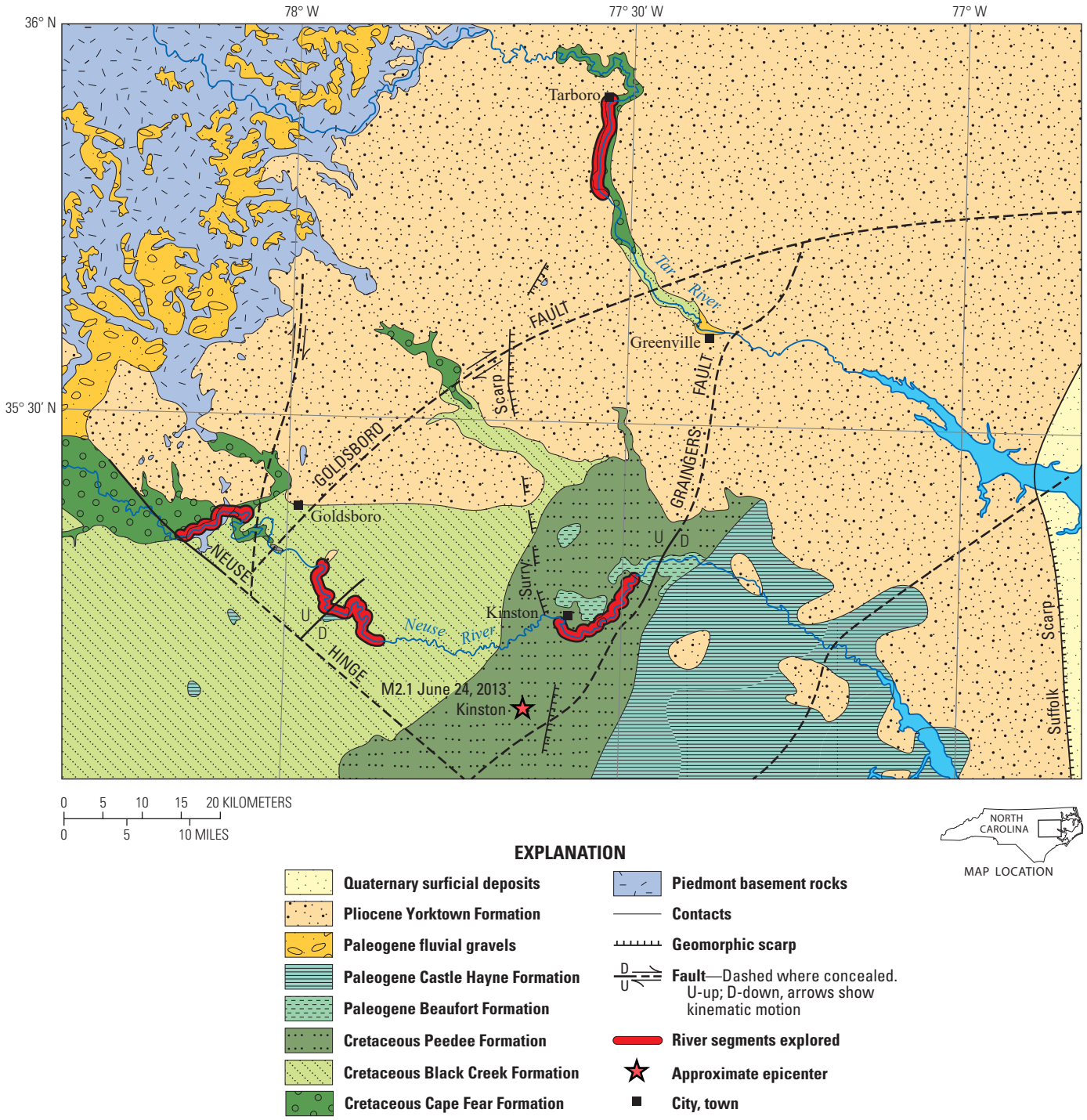

Figure 2. Geologic map of central-eastern North Carolina in the vicinity of Tarboro, Goldsboro, and Kinston, North Carolina. The map shows major map units, contacts, faults, geomorphic scarps, and the approximate epicenter of the 2013 magnitude (M)2.1 earthquake southwest of Kinston. Segments of the Tar and Neuse Rivers explored for paleoliquefaction features for this study are highlighted. Map modified from the geologic map of North Carolina (North Carolina Geological Survey, 1985), Lawrence and Hoffman (1993), and McLaurin and Harris (2001).

still is) unresolved. At about the same time as the 2015 paleoliquefaction survey in the CVSZ, another collaborator—Dr. Frank Pazzaglia and students of Lehigh University in Bethlehem, Pennsylvania—began a U.S. Geological Survey (USGS) National Earthquake Hazard Reduction Program (NEHRP)-funded comparative study of possible neotectonic controls on the geomorphic expression of rivers in the CVSZ, CSZ, and an aseismic area in the eastern Piedmont and inner Coastal Plain Provinces of North Carolina (Pazzaglia, 2017). The aseismic region in central-eastern North Carolina (fig. 2) was chosen as a study site because faults of demonstrable Cretaceous to Paleogene age cut regional stratigraphy, with speculative Holocene deformation based on regional river sinuosity patterns and well-preserved fault scarp-like topographic features (McLaurin and Harris, 2001). To complement the Lehigh University NEHRP research, the USGS embarked on an expedition to search for paleoliquefaction features in this area in June 2016. In addition to the known faults and anomalous fluvial and topographic features, low-magnitude and infrequent earthquakes in the vicinity (most recently an M2.1 on June 24, 2013, approximately 15 km southwest of Kinston, North Carolina) suggest larger magnitude earthquakes capable of producing liquefaction fields may have struck this region in the past. The 2016 USGS paleoliquefaction survey was the first to be undertaken in this heretofore unexplored region of the southeastern United States.

Geographic and Geologic Setting

The study area is located in central-eastern North Carolina, approximately 100 km (60 miles [mi]) east and southeast of Raleigh, North Carolina, and includes the cities of Tarboro, Goldsboro, and Kinston, North Carolina (fig. 2). The region is drained by the east-flowing Tar and Neuse Rivers, and major tributaries of those river systems. These rivers flow from the crystalline Piedmont Province into and across the North Carolina Coastal Plain before discharging into Pamlico Sound, a distance of approximately 400 km (250 mi) from headwater sources. Both river drainage basins are entirely contained within North Carolina.

Stratigraphy

The Fall Zone region, at the boundary between the Piedmont and Coastal Plain Provinces, consists of both crystalline and sedimentary strata. Neoproterozoic to Paleozoic phyllite; metavolcanic rocks of mafic, intermediate and felsic composition; and granitoid intrusions of the eastern Piedmont Province (Parker, 1968, Sampair, 1979) compose the basement beneath Coastal Plain and fluvial strata of Cretaceous to Holocene age (fig. 3). Lithified to semilithified Upper Cretaceous rocks unconformably overly basement (fig. 4). The oldest Cretaceous unit is the Cape Fear Formation of Stephenson (1907) and Sohl (1976) that consists of feldspathic, micaceous, crossbedded sandstone with clay rip-ups, and sandy mudstone. The Cretaceous Black Creek Formation (Cooke, 1936; Black Creek Group of Sohl and Owens, 1991) consists of lignitic black clay, interbedded with micaceous, crossbedded organic-rich sand. The youngest Cretaceous unit is the Peedee Formation of Stephenson (1923), which consists of glauconitic and fossiliferous sand. The Cape Fear Formation is well exposed in steep riverbank exposures on the Tar River, and all Cretaceous formations are well exposed on the Neuse River (figs. 4*B*–*G*).

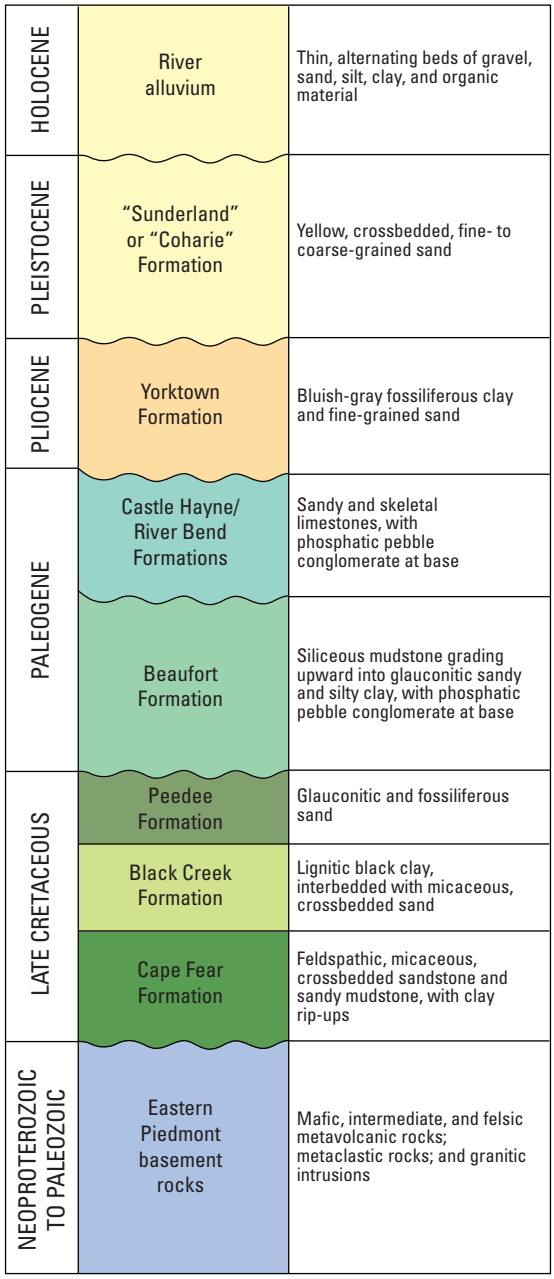

Figure 3. Coastal Plain stratigraphy in central-eastern North Carolina. Wavy line, unconformity.

Locally exposed in riverbank outcrops along the Neuse River are rocks of the Paleocene Beaufort Formation, either unconformable above, or in fault contact with underlying Cretaceous rocks. The Beaufort Formation (Brown, 1959; Harris and others, 1993) consists of a lower package of siliceous mudstone (fig. 4*H*) containing sandstone lenses, above a basal phosphatic pebble conglomerate (Jericho Run Member), and an upper member of glauconitic, fossiliferous, and locally calcareous sand and silty clay (Moseley Creek Member). Rocks of the Eocene Castle Hayne Formation (fig. 4*I*) and Oligocene River Bend Formation (Ward and others, 1978)—sandy, molluscan-mold and bryozoan-echinoid skeletal limestones—unconformably overlie the Beaufort Formation along a basal micritic phosphate pebble conglomerate. Locally, these rocks are also in fault contact with Cretaceous formations. Pliocene fossiliferous clayey sand assigned to the Yorktown Formation (Clark and Miller, 1906; LeGrand and Brown, 1955; Ward and Blackwelder, 1980) north of the Neuse River and Duplin Formation (Clark and others, 1912; Ward and others, 1991) south of the Neuse River occupy the high interfluvial regional topography and only crop out locally along the Tar River (fig. 4*J*).

Unconsolidated sand and gravel of Pleistocene age unconformably overlies older stratigraphic units in many riverbank exposures. The terms “Sunderland” in Maryland (Shattuck, 1901) and “Coharie” in North Carolina (Stephenson, 1912) were applied to these widespread fluvial terrace deposits (Cooke, 1931), but Huddlestun (1988) formally abandoned usage as formational units. Still, fluvial deposits of well-bedded, crossbedded, and graded, fine- to coarse-grained sand and quartz granule- to cobble-sized gravels are well exposed as terraces inset into the higher riverbank bluffs (for example, Cliffs of Neuse State Park, see Carpenter, 1989) along both the Tar and Neuse Rivers (fig. 4*K*). The distinction between Pleistocene terrace deposits and Holocene river alluvium is simple: (1) alluvium is typically thinner-bedded (decimeters [dm] to about 0.5-meter [m] thick) and consists of alternating beds of sand, silt, clay, and organic leaf layers (fig. 4*L*), whereas Pleistocene terraces consist of coarser-grained sand and gravel and thicker-bedded (0.5- to about 1-m thick); (2) terrace deposits are locally floored by a layer (centimeters [cm] to decimeters thick) of ferricrete or ironstone (created by iron and manganese precipitated from percolating shallow groundwater at the interface of permeable and impermeable materials) at the unconformable contact with underlying stratigraphy (this phenomenon is absent in younger alluvial deposits); and (3) alluvial deposits tend to be inset lower into the topography and on the modern river floodplain, whereas Pleistocene terraces occupy positions higher on the land surface.

Coastal Plain Faults

Evidence for Mesozoic to Cenozoic faulting in the Coastal Plain of central-eastern North Carolina is well established (Ferenczi, 1959; Brown and others, 1977; Harris and others, 1979; Sampair, 1979). Faults originate in the Piedmont basement and extend into the overlying Cretaceous to Paleogene strata (Sampair, 1979; Lawrence and Hoffman, 1993). The Graingers fault zone (Harris and others, 1979) east of Kinston, North Carolina, is one of the more well-studied structures (fig. 2). Ferenczi (1959) interpreted the northeast-southwest linear segment of the Neuse River floodplain east of Graingers, North Carolina, as a fault. Baum and others (1978) named this structure the Carolina fault. Brown and others (1977) recognized a system of northeast-southwest-trending sinistral wrench faults in this area that bound a series of northeast-plunging grabens, half-grabens and a central horst, which they named the Graingers fault zone. Lawrence and Hoffman (1993) interpreted the Graingers fault zone to be a splay of the dextral strike-slip Goldsboro fault; Harris and Laws (1997) merged the fault zone into the northwest-southeast-oriented Neuse hinge, a monoclinal zone of basement flexure. Based on the sharply defined east-west distribution of Paleocene strata in the region, McLaurin and Harris (2001) revised the model of Brown and others (1977) to include a series of east-west-trending syndepositional faults. In their model, these Paleocene faults overprinted earlier-formed northeast-southwest-trending Paleozoic to Mesozoic faults, which reactivated post-Paleocene to impart the strong northeast-oriented structural grain to the regional geomorphology.

Two previously unknown faults were identified during this study; one is on the Neuse River, approximately 14 km (8.7 mi) southeast of Goldsboro (35.2642°, −77.9321°). Here, in a steep cliff-face on the south bank of the river, near-flat-lying Cretaceous Black Creek Group, lignitic sands and beds of woody debris crop out in a 4-m-high exposure at the same elevation as flat-lying Eocene limestone interbedded with calcareous sand and clay beds in a 10-m-high exposure downstream and across a covered interval (a small ravine filled with colluvium) of about 10 m (32 feet). Displacement is unknown across the structure, as Eocene beds do not cap the exposure of Black Creek Group rocks west of the fault, nor do Cretaceous sands underlie Eocene limestone in outcrop east of the fault. The trend of the structure is northeast-southwest to north-south. A fault of much smaller displacement occurs in a road cut along the west side of State Route 1701 at Wheat Swamp, approximately 13 km (8 mi) north of Kinston (35.3777°, −77.5854°). A reverse fault with about 1 dm of displacement offsets beds of Jericho Run siliceous mudstone (fig. 4*H*). The fault trends generally east-west, with a steep northward dip.

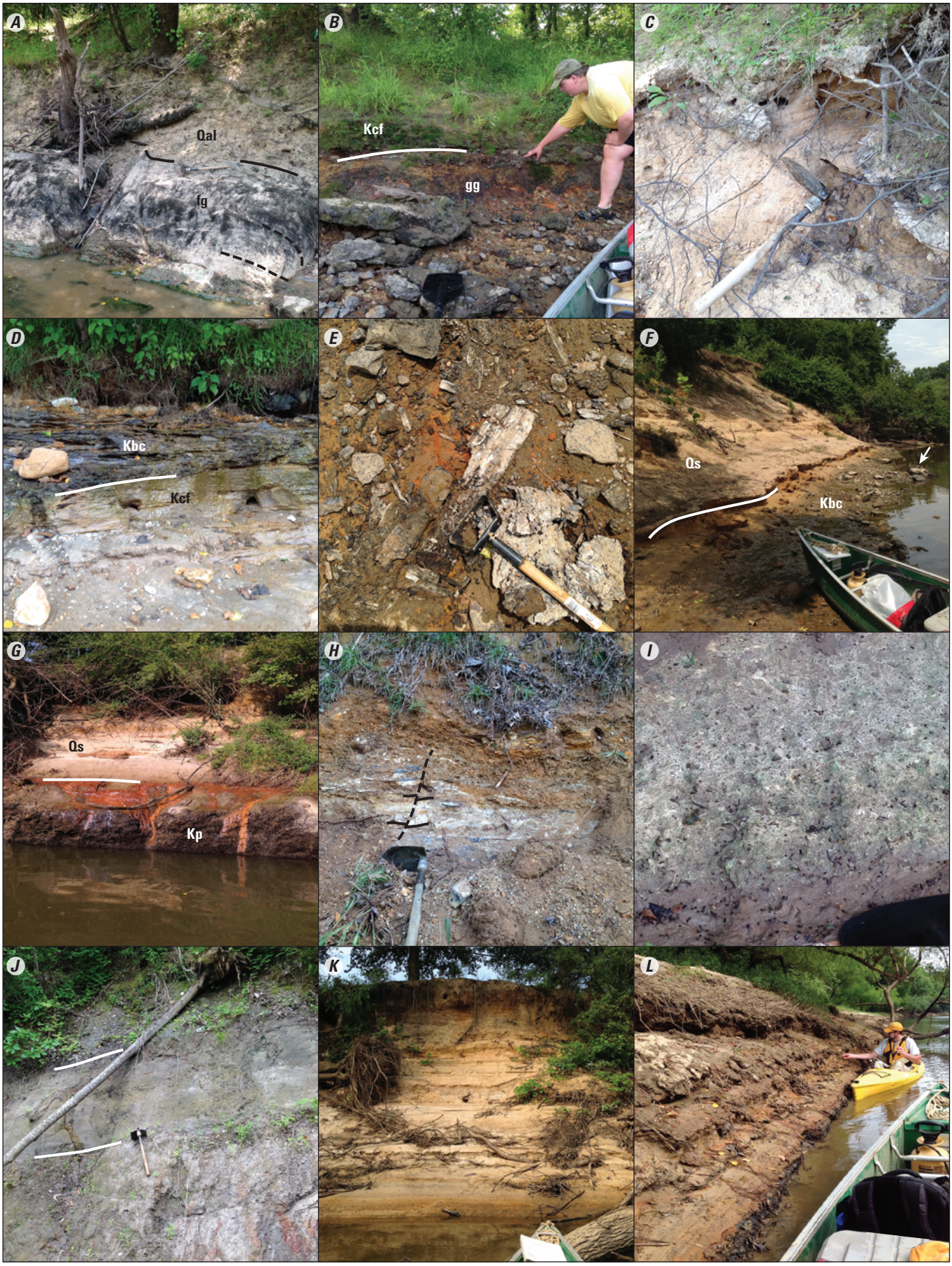
A
Qal
fg
B
Kcf
gg
C
D
Kbc
Kcf
E
F
Qs
Kbc
G
Qs
Kp
H
I
J
K
L

Figure 4 (page 6). Photographs of representative map units in central-eastern North Carolina. *A*, Felsic gneiss (fg) of the Piedmont basement beneath Quaternary alluvial sand (Qal). Shovel rests on contact (solid black line). Foliation in the gneiss (dashed black line) strikes 044° and steeply dips to the southeast (NS-22.2: 35.3672°, –78.1043°). *B*, Contact between granitic gneiss (gg) of the Piedmont basement and basal Cretaceous Cape Fear Formation (Kcf); Jake Glassbrenner rests his hand on the contact (also marked by solid white line). Cape Fear Formation conglomerate, consisting mostly of vein quartz clasts, occurs at the contact here (NS-17.2: 35.3552°, –78.1327°). *C*, Crossbedded coarse-grained to gravelly sand of the Cape Fear Formation (note crossbeds above shovel, for scale). Cape Fear Formation sand and gravel is also typically arkosic to feldspathic (NS-21.2: 35.3640°, –78.1087°). *D*, Feldspathic sand of the Cape Fear Formation (Kcf) beneath dark, lignitic and organic, thin-bedded sand of the Cretaceous Black Creek Formation (Kbc). Contact is marked by solid white line. Field of view in photograph is about 2-meters (m) wide (NS-30.2: 35.3661°, –78.0682°). *E*, Carbonized wood weathers out of an outcrop of the Black Creek Formation. Head of the hula hoe is ~2-decimeters (dm) (NS-57.4: 35.2796°, –77.9365°). *F*, Black Creek Formation (Kbc) crops out beneath Pleistocene Coharie crossbedded sand and gravel (Qs). Contact is marked by white line in foreground. Pleistocene sand and gravel is easily distinguished from Cretaceous sand and gravel because it is unconsolidated, contains less clay and feldspar, and contains more quartz than Cretaceous units. Note the large carbonized tree trunk in the Black Creek Formation (white arrow in background). Bow of canoe for scale (NS-57.4: 35.2796°, –77.9365°). *G*, Shelly and glauconitic clayey sand of the Cretaceous Peedee Formation (Kp) crops out beneath unconsolidated graded-bedded and crossbedded sand of a Coharie terrace deposit (Qs). Sharp contact is marked by white line. Field of view in photograph is about 2-m wide (NS-75.5: 35.2566°, –77.5905°). *H*, Siliceous mudstone of the Paleocene Beaufort Formation is exposed in a road cut outcrop along State Route 1701 north of Kinston. An outcrop-scale fault (marked by black dashed line), with about 1-dm of displacement, offsets a light-colored mudstone bed (top and bottom of beds adjacent to the fault marked by solid black lines). Shovel for scale (35.3777°, –77.5854°). *I*, Shell-hash and skeletal limestone of the Eocene Castle Hayne Formation. Field of view in photograph is about 0.5-m wide (NS-73.4: 35.2611°, –77.9130°). *J*, Beds of fossiliferous sand and silt alternate with nonfossiliferous sand in an exposure of Pliocene Yorktown Formation. Beds are about 1-m thick. Contacts between beds marked by white lines. Shovel for scale (Tar-15.1: 35.7850°, –77.5491°). *K*, Outcrop of well bedded but unconsolidated Pleistocene Coharie terrace sand and gravel. Bow of canoe for scale (NS-78.5: 35.2439°, –77.5808°). *L*, Exposure of well-bedded Holocene alluvium, consisting of alternating beds of sand, silt, clay, and organic leaf litter (NS-33.3: 35.2688°, –77.8992°).

Geomorphic Evidence for Holocene Deformation

Brown and others (1977) identified the Jericho Run fault scarp, a topographic lineament just a few kilometers east and northeast of Kinston, North Carolina (fig. 5). The feature is a northeast-southwest-trending, southeast-facing topographic rise with relief as high as 13 m, that generally parallels the trend of the Neuse River and the lower portion of Jericho Run and Stonyton Creek, tributaries of the Neuse River. McLaurin and Harris (2001) interpreted extensive ravinement normal to the scarp trend and triangular faceting to possibly indicate recent (Holocene) deformation, although the feature is not precisely coincident with underlying mapped fault traces. Prior to this study, Brown and others (1982) recorded the only known exposure of an outcrop-scale fault in the Graingers fault zone (Prowell, 1983) and along the Jericho Run fault scarp. The fault, of unspecified displacement, deforms beds of Paleocene strata; however, the orientation of the fault, N63°E, is oblique to the trend of the scarp, which is approximately N40°E.

A close inspection of the light detection and ranging (lidar)-derived 3-m digital elevation model (DEM) shows another linear topographic feature approximately 25 km (16 mi) south-southeast of Kinston and between the Surry scarp to the west (fig. 5) and the Suffolk scarp to the east (fig. 2). The lineament is about 9-km long and 1.5-m high, and trends approximately N10°E, toward the northeast-trending segment of the Neuse River first identified by Ferenczi (1959) as fault controlled. The lineament may mark the surface expression of the contact between the Cretaceous Peedee and Eocene Castle Hayne Formations, it may represent a geomorphic scarp younger than the early Pleistocene Surry scarp (Cronin and others, 1984; Hobbs, 2004) approximately 10 km (6 mi) to the west and older than the late Pleistocene Suffolk scarp 60 km (37 mi) to the east (Mixon and others, 1982), or it may be an erosionally degraded fault scarp; remote sensing of the 3-m DEM is inconclusive.

Methodology

Liquefaction is the process by which cohesionless sediment transforms from a solid state into a viscous liquefied state (Youd, 1973); earthquake-induced liquefaction occurs as cyclic shear waves pass through and compact water-saturated sediment, increasing pore-water pressure (Seed and Idriss, 1982). When pore-water pressure equals or exceeds overburden pressure, shear-strength of the sediment drops to zero, and sediment and water covert to a slurry that flows upward as a result of the hydraulic gradient (Obermeier and others, 2005). Liquefaction features created by this process include sand dikes and sills, and vented-sand volcanoes (in other words, sand blows or sand boils) that reach the surface (Obermeier, 1989). Soft-sediment deformation features such as load casts, ball-and-pillow structures, and pseudonodules form from seismic-induced liquefaction (Wheeler, 2002), but

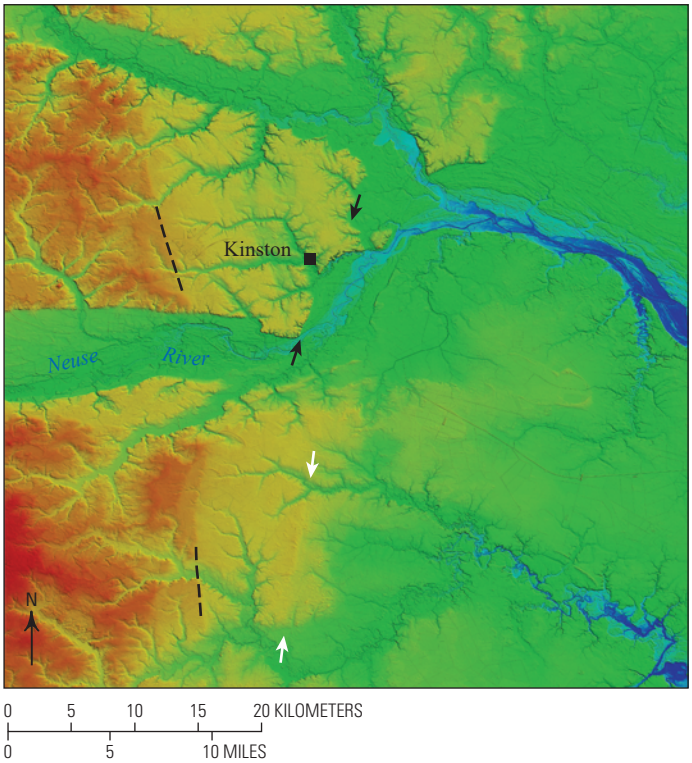

Figure 5. Light detection and ranging (lidar)-derived 3-meter digital elevation model of the Kinston, North Carolina, area. The steep, high-relief topographic feature north and south of the town and the Neuse River is the prominent Surry scarp (marked in part by a black dashed line). The Jericho Run fault scarp of Brown and others (1977) is marked at either end by black arrows. A distinct linear feature, marked by white arrows, occurs southeast of Kinston and south of the Neuse River. It may be the topographic expression of the exposed weathered contact between rocks of the Cretaceous Peedee Formation and the Eocene Castle Hayne Formation, or it may be an erosionally degraded fault scarp. Original elevation data from the National Elevation Dataset available at http://earthexplorer.usgs.gov. Image constructed from these data using Global Mapper ver. 18.1.0.

these features are also generated syndepositionally in many fluvial and marine environments that facilitate high sedimentation rates (Allen, 1982). Likewise, sand dikes, sills, and boils can be formed in unconsolidated sediments through nonseismogenic mechanisms; for example, by artesian groundwater flow, rapid changes in surface hydrology (in other words, rapid release of impounded water by breached dams), and nonseismic mass-wasting events (for example, Kolb, 1976; Lade, 1992; Holzer and Clark, 1993). Lateral spreads and landslides are larger-scale features produced by sediment fluidization during earthquakes (for example, Youd, 1984), but these may be difficult to conclusively attribute to seismicity. However, liquefaction features unequivocally produced by large prehistoric earthquakes in central and eastern United States coastal and floodplain settings are well documented (for example, Talwani and Cox, 1985; Tuttle and Seeber, 1991; Obermeier and others, 1990; Tuttle, 2001). These studies and others establish field criteria for the identification of such features, with excellent discussions presented in Obermeier (1996, 2009).

For a sedimentary sequence to be field classified as susceptible to liquefaction, a stringent list of criteria must be met (fig. 6). Strata must include a nonpermeable base, a liquefiable layer, and a capping layer of lower permeability, to allow for a sufficient increase in pore pressure before reconsolidation and densification (in other words, compaction during packing; for example, Scott, 1986; Kokusho, 2003) or dissipation. The cap is generally thin (<1- to 2-m thick); liquefaction is severely restricted for cap thicknesses greater than 5 m (Obermeier, 2009) owing to overburden pressure. A nonpermeable base is typically required to allow pore-pressure to build in the overlying liquefiable layer without dissipation though the base between cyclic shearing (Castro, 1987; Dobry, 1989). Liquefiable beds are typically 0.3- to 1.0-m thick, and consist of clean, loose sand; fine sand, even containing as much as 30 percent silt (Andrus and Youd, 1987; Obermeier, 1996), will liquefy readily if not already densely packed (Tsuchida and Hayashi, 1971). Clay content above 15 percent severely limits liquefaction potential (Seed and others, 1983). The degree of weathering is also important: oxidation impedes liquefaction in most field settings (Obermeier and others, 2005). As weathering is related to age, susceptible sediments are typically middle- to late-Holocene in age (Youd and Perkins, 1978), but sediments as old as 200 ka have been documented to have liquefied (for example, Obermeier and others, 1990). The depth to water table is critical. In humid subtropical environments, sand beds must be saturated to liquefy. For source sands more than 10 meters above the water table, susceptibility to liquefaction is nil (Obermeier, 2009). Liquefied sand can penetrate unsaturated capping strata above the water table. An M4.6 aftershock of the 1989 Loma Prieta, California, earthquake is the minimum magnitude earthquake reported to have triggered liquefaction (Sims and Garvin [1995] as cited in Kavazanjian and others [2018]), with ejecta vented through existing dikes formed during the main shock and an earlier aftershock (Kavazanjian and others, 2018).

Once features suspected of being produced by liquefaction are identified in susceptible outcrops, another detailed list of criteria come into play (see Obermeier, 2009). Sand dikes

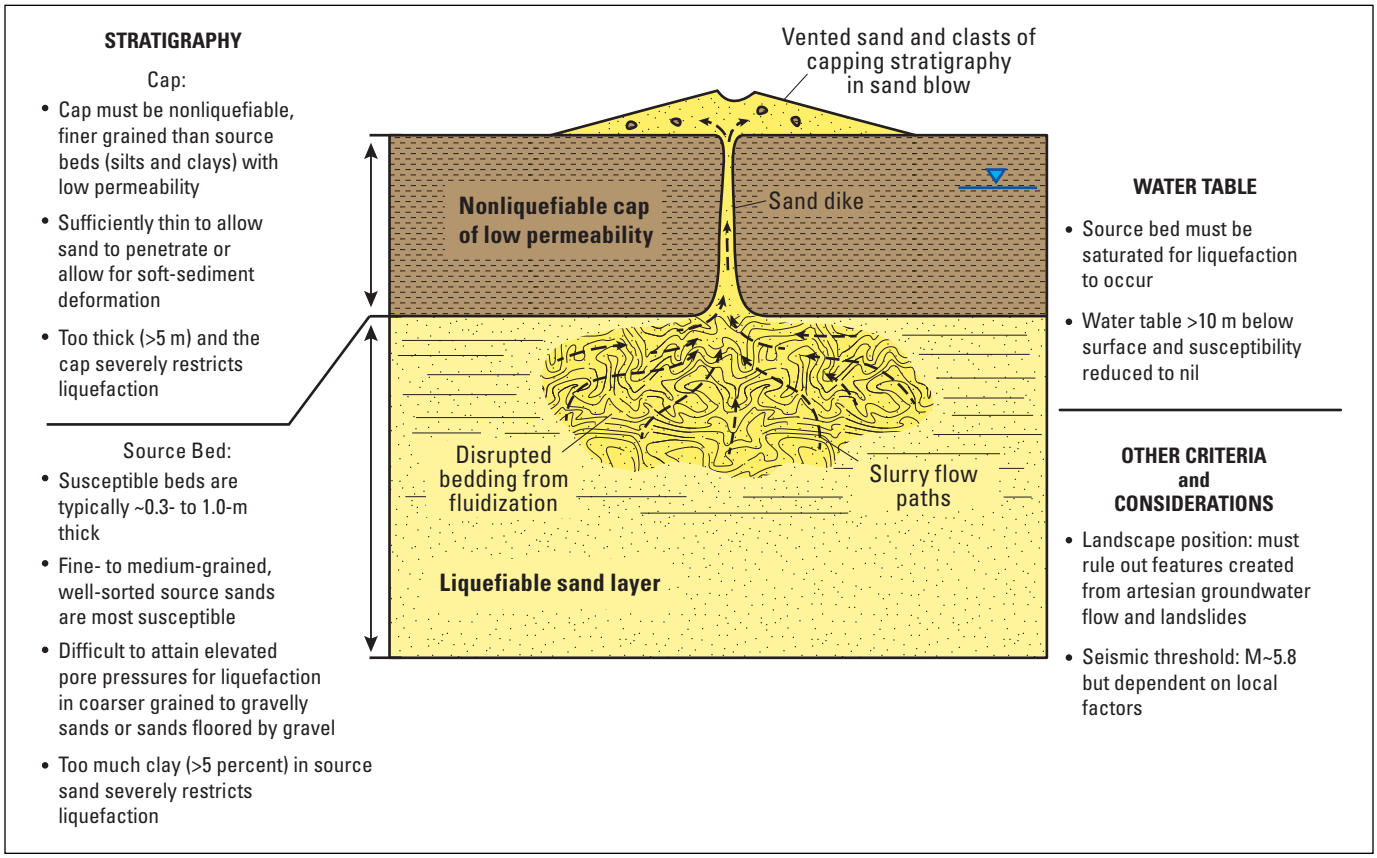

Figure 6. A few of the key field criteria for liquefaction to occur in an unconsolidated stratified sequence of sediment. Liquefaction occurs when cyclic earthquake shear waves pass through and compact water-saturated sediment, increasing pore-water pressure in the sediment and decreasing its shear-strength to zero, so that sediment and water covert to a slurry that flows upward as a result of the hydraulic gradient (Seed and Idriss, 1982; Obermeier and others, 2005). Diagram and criteria modified mostly from Obermeier (2009), with additional sources referenced in text. M, magnitude; >, greater than; m, meters.

that cut through capping strata into higher riverbank stratigraphy must be younger than the youngest intruded bed (or for sand blows, the surface onto which the sand is vented), and cannot be syndepositional in origin. Dikes can be millimeters to meters thick, several meters in height, and tens of meters in length, depending on the characteristics of the sediments and strata from which they were created (for example, Ishihara, 1985) and their mode of formation (for example, lateral spreads). Dikes tend to widen downward toward the source bed, pinch together or branch upward, and may bifurcate into sills beneath root mats near the surface (for example, Obermeier, 1994). Tracing dikes down to the source bed is key (M. Tuttle, oral commun., 2015). Clasts of host strata may also be incorporated into the dike, sill, or sand blow (for example, Obermeier and others, 1990), and disturbed bedding indicative of upward flow into the neck of the dike may be apparent in the source bed. Topographic position and geomorphic setting establish yet another key criterion: sand dikes, sills, and blows preserved in outcrops adjacent or near the base of floodplain bluffs or similar geomorphic settings may be the product of nonseismic artesian flow or landslides; awareness of surroundings is critical.

To aid in the proper categorization of paleoliquefaction features during a regional field survey, Obermeier (1996) provides a detailed set of conditions that must be met to satisfy that those features are of potentially seismic origin. These include (adopted from Tuttle, 2001) (1) the features have sedimentary characteristics consistent with quick, earthquake-induced liquefaction, including evidence for a suddenly applied, upward-directed hydraulic force of short duration; (2) sedimentary characteristics are also consistent with case histories of earthquake-induced liquefaction; (3) occurrence of more than one type of feature (including soft-sediment structures), and of similar features at multiple locations; (4) occurrence in geomorphic settings where hydraulic conditions would not develop features under nonseismic conditions; and (5) age data to support both contemporaneous and episodic formation of features over a large area.

For this study, approximately 64 km (40 mi) of the Tar and Neuse Rivers were traversed (fig. 2) by canoe and kayak, during a period when river water levels were extremely low (fig. 7). River segments targeted for exploration included linear segments that may be fault-, joint-, or contact-controlled (for example, Ferenczi, 1959); changes in sinuosity, which may reflect the geomorphic response to changes in river gradient owing to neotectonic uplift (for example, Holbrook and Schumm, 1999); and proximity to regional faults and historical and instrumented seismicity (for example, Ferguson and Stewart, 1975; Best and Cavanaugh, 1977). Actively eroding riverbank exposures along these river segments were examined for paleoliquefaction features, following the field methods of Obermeier (1998). Based on field criteria, 105 sites (or one outcrop per 0.6 km of river length) were documented and described for stratigraphy and susceptibility to liquefaction. Data were recorded on an iPad 3rd Gen (Model A1403) using Gaia GPS v. 10.9.13 for locational control and GISKey Field Assets version 4.0 for data collection and management, before export to Microsoft Excel. Outcrop data (table 1; appendix 1) included attributes such as exposure description (length, height, quality, and so forth), stratigraphic description (including liquefiable host and capping strata), bedding thickness, lithologic composition, field-estimated grain-size, and degree of weathering (including mottling or the formation of ferricrete or ironstone crusts). Sediment characteristics below river water-level (in other words, below the water-level at the time of the survey) were also described using both a 1-m soil probe and a 1.5-m auger. From these data, outcrops were categorized for liquefaction susceptibility, using qualifiers of “nil”, “low”, “marginal”, and “high” (after Youd and Perkins, 1978). Potential liquefaction features or features of sedimentary or pedogenic origin that were observed in outcrop were described in detail (appendix 1).

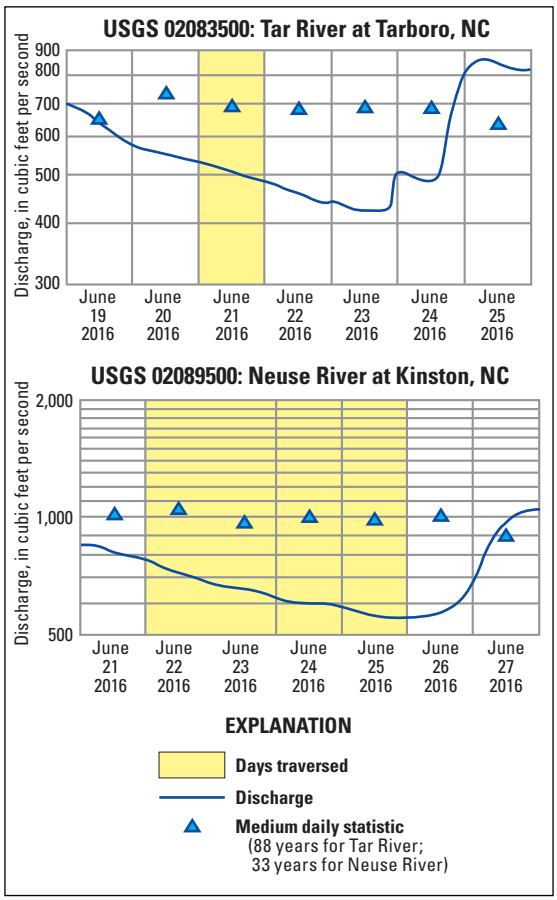

Figure 7. U.S. Geological Survey stream gage data for the Tar and Neuse Rivers in the study area, for the days each river was traversed (highlighted in yellow). Note that river levels were falling, or at their lowest, on the days traversed. Surface water data available at https://waterdata.usgs.gov/.

Results

Nearly 3.8 km of riverbank outcrop were surveyed at some level of detail for this study (table 1). Most outcrops consisted of Coastal Plain stratigraphy that was too old, too lithified, or not of the proper lithology to liquefy during an earthquake. Detailed study at other sites highlighted three working models for stratigraphic conditions that are suitable for liquefaction in this region: (1) beds of Holocene alluvial sand, decimeters thick, capped by lower permeability beds of alluvial silt and clay; (2) Quaternary Coharie terrace sand beds, decimeters to about a meter thick, capped by several decimeters- to meter-thick clay beds; and (3) C soil horizon (parent material) Holocene alluvium or Quaternary terrace sand, capped by a Bt soil horizon (a soil horizon containing illuvial clay) as much as or more than a meter thick (fig. 8). Amick and others (1990) described similar soil profiles conducive to liquefaction in the Coastal Plain of South Carolina. However, of the 38 outcrops identified as susceptible to liquefaction, only conditions at 17 of these sites warranted a susceptibility classification of “low” (table 1; appendix 1). With the exception of one outcrop classified as highly susceptible to liquefaction, most sites were marginally liquefiable for several reasons: (1) some sand beds were floored by gravel, which would likely dissipate pore-pressure during an earthquake; (2) sand beds may be too coarse-grained to liquefy, although even coarse-grained sand and gravel will liquefy under certain conditions (for example, Andrus and others, 1991; Valera and others, 1994; Bezerra and others, 2005); (3) some of the most susceptible sands in the Quaternary Coharie terrace deposits were many meters above water level, and would be saturated only during river flood stage; and (4) capping units of a meter or more may be too thick, which would severely restrict or impede liquefaction (Ishihara, 1985). At several outcrops, weathered and unconsolidated sand of Cretaceous age was observed to be capped by a suitable Bt soil horizon, but the

Table 1. Compilation of outcrops along the Tar and Neuse Rivers in central-eastern North Carolina and their liquefaction susceptibility classification based on field criteria.

[cm, centimeters; m, meters; dd, decimal degrees; B.P., before present; horizontal datum is the World Geodetic System (WGS 84)]

Station	Cut length (m)	Stratigraphy	Liquefaction susceptibility	Features	Latitude (dd)	Longitude (dd)
Tar-3.1	100	Coharie sand and gravel over Cape Fear Formation sand and gravel	Low - unconsolidated weathered sand is well-packed	None	35.8865	−77.5387
Tar-4.1	50	Coharie sand and gravel over Cape Fear Formation sand and gravel	Low - unconsolidated weathered sand is not saturated	None	35.8781	−77.5386
Tar-5.1	50	Coharie sand and gravel over Cape Fear Formation sand and gravel	Low - unconsolidated weathered sand is well-packed	None	35.8750	−77.5357
Tar-9.1	50	Coharie sand and gravel over Cape Fear Formation sand and gravel	Low - unconsolidated weathered sand is well-packed	None	35.8572	−77.5348
Tar-11.1	5	Soil profile on weathered Cape Fear Formation sand and gravel	Low - unconsolidated weathered sand is well-packed	Three small features along root casts are filled from above	35.8372	−77.5460
Tar-13.1	50	Soil profile on Coharie sand and gravel above Cape Fear Formation	Low - unconsolidated weathered sand is well-packed	None	35.8032	−77.5489
NS-20.2	15	Alluvial sand	Marginal - capping sand not significantly less permeable than potential source beds	Load casts and pseudonodules of likely syndepositional origin	35.3630	−77.1211
NS-24.2	10	Alluvial sand and silt	Marginal to high - 10+ cm-thick saturated sand capped by silt	None	35.3812	−77.0625
NS-25.2	10	Alluvial sand and silt	Marginal to high - 10+ cm-thick saturated sand capped by silt	Polygonal cracks likely desiccation features	35.3783	−77.0557
NS-33.3	20	Alluvial sand and silt	Low to marginal	None	35.2688	−77.8992
NS-34.3	20	Soil profile on weathered Black Creek Formation sand	Low - well-packed C horizon beneath clay-rich Bt horizon	None	35.2752	−77.8960
NS-36.3	300	Soil profile on weathered Black Creek Formation sand	Low - well-packed C horizon beneath clay-rich Bt horizon	None	35.2693	−77.8861
NS-37.3	75	Coharie terrace sand	Low - no capping stratigraphy	None	35.2677	−77.8886

Table 1. Compilation of outcrops along the Tar and Neuse Rivers in central-eastern North Carolina and their liquefaction susceptibility classification based on field criteria.—Continued

[cm, centimeters; m, meters; dd, decimal degrees; B.P., before present; horizontal datum is the World Geodetic System (WGS 84)]

Station	Cut length (m)	Stratigraphy	Liquefaction susceptibility	Features	Latitude (dd)	Longitude (dd)
NS-38.3	15	Alluvial sand, silt, and organic matter at mouth of abandoned meander	Marginal to high - liquefiable saturated sand beneath silty cap	Load casts and pseudonodules in historic (120±25 years B.P.) deposit	35.2640	−77.8874
NS-39.3	100	Coharie terrace sand over Black Creek Formation lignitic sand	Low - terrace sand not saturated and no cap; Cretaceous sand too old	None	35.2603	−77.8892
NS-40.3	75	Coharie terrace sand over Black Creek Formation lignitic sand	Low - terrace sand not saturated and no cap; Cretaceous sand too old	None	35.2544	−77.8846
NS-41.3	10	Soil profile on Coharie terrace sand	Marginal - C horizon very fine silty sand may liquefy	None	35.2581	−77.8821
NS-43.3	30	Coharie terrace sand over Black Creek Formation lignitic sand	Low - terrace sand not saturated and no cap; Cretaceous sand too old	None	35.2483	−77.8807
NS-44.3	50	Coharie terrace sand over Black Creek Formation lignitic sand	Low - terrace sand not saturated and no cap; Cretaceous sand too old	None	35.2423	−77.8806
NS-48.4	2	Alluvial sand and silt	Marginal to high - unconsolidated and saturated sand beneath thick cap	None	35.3089	−77.9477
NS-52.4	10	Alluvial sand and silt	Marginal to high - unconsolidated and saturated sand beneath thick cap	Lens of fine-silty sand in cap but no connectivity to source bed	35.2966	−77.9489
NS-53.4	20	Soil profile on Coharie terrace sand	Marginal - unconsolidated and saturated C horizon sand beneath thick Bt horizon cap	None	35.2851	−77.9428
NS-55.4	10	Soil profile on Coharie terrace sand	Marginal - unconsolidated and saturated C horizon sand beneath thick Bt horizon cap	Sand contains thin (millimeters-thick) argillic horizons modified by manganese precipitation	35.2818	−77.9325
NS-59.4	10	Soil profile on Coharie terrace sand	Marginal to high - unconsolidated and saturated C horizon sand beneath thick Bt horizon cap	None	35.2775	−77.9404
NS-60.4	20	Soil profile on alluvial sand	Marginal to high - unconsolidated and saturated C horizon sand beneath thick Bt horizon cap	Indistinct sand-filled root casts likely filled from above (no connectivity to source sand)	35.2767	−77.9392
NS-64.4	75	Coharie terrace sand	Low - unconsolidated sand and gravel to coarse to liquefy and not saturated (silty clay cap is present at top of cut)	None	35.2693	−77.9415

Table 1. Compilation of outcrops along the Tar and Neuse Rivers in central-eastern North Carolina and their liquefaction susceptibility classification based on field criteria.—Continued

[cm, centimeters; m, meters; dd, decimal degrees; B.P., before present; horizontal datum is the World Geodetic System (WGS 84)]

Station	Cut length (m)	Stratigraphy	Liquefaction susceptibility	Features	Latitude (dd)	Longitude (dd)
NS-65.4	5	Soil profile on Coharie terrace sand	High - unconsolidated saturated C horizon sand beneath Bt horizon clay cap	None	35.2666	−77.9377
NS-83.5	15	Soil profile on Coharie terrace sand	Low to marginal - ironstone layers in C horizon sand would impede liquefaction beneath Bt horizon cap	None	35.2491	−77.5509
NS-84.5	15	Coharie terrace gravel, sand, and clay	Marginal to high - gravel base may allow pore-pressure to dissipate	Geochemical weathering front give appearance of liquefaction dikes and sills	35.2480	−77.5488
NS-86.5	30	Coharie terrace gravel, sand, and clay	Marginal to high	None	35.2475	−77.5396
NS-89.5	20	Alluvial sand and clay	Marginal - silty clay cap may be too thick	None	35.2563	−77.5315
NS-91.5	10	Alluvial sand and clay	Marginal - gravel base may allow pore-pressure to dissipate; silty clay cap may be too thick	Soft sediment deformation features at base of clay likely syndepositional	35.2630	−77.5179
NS-92.5	10	Alluvial sand and clay	Low - gravelly sand may not liquefy; silty clay cap may be too thick	Soft sediment deformation features at base of clay likely syndepositional	35.2635	−77.5172
NS-93.5	100+	Alluvial sand and clay	Low - coarse-grained sand may not liquefy; silty clay cap may be too thick	None	35.2667	−77.5136
NS-94.5	200	Alluvial sand and clay	Marginal to high - coarse-grained sand may not liquefy; silty clay cap may be too thick; liquefiable strata high in riverbank cut	None	35.2654	−77.5103
NS-96.5	50	Alluvial sand and clay	Marginal - coarse-grained sand may not liquefy; silty clay cap may be too thick	None	35.2721	−77.5086
NS-103.5	10	Alluvial sand and clay	Low - gravelly sand may not liquefy; silty clay cap may be too thick	None	35.2855	−77.4979
NS-105.5	6	Alluvial sand and clay	Low to marginal - iron precipitation in sand may hinder liquefaction	None	35.2928	−77.4984

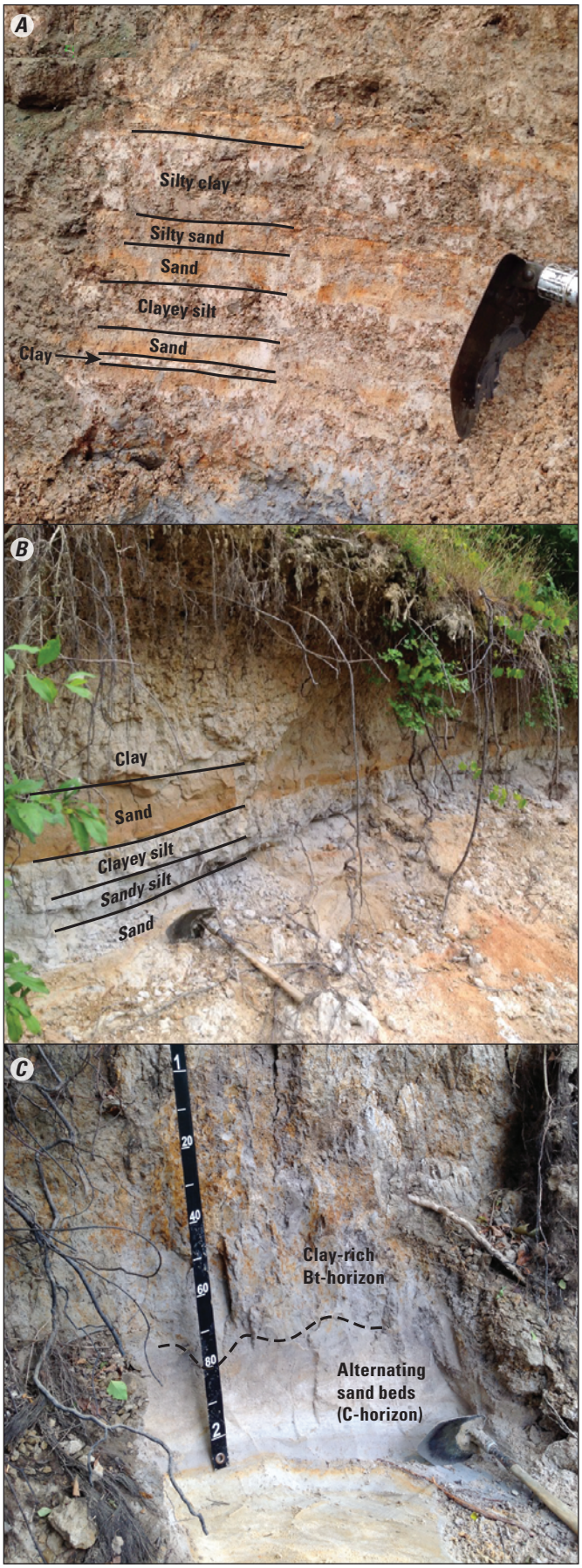

Figure 8. Photographs of three stratigraphic conditions suitable for liquefaction recorded along the Tar and Neuse Rivers. *A*, Interbedded Holocene alluvial sand, silt, and clay. Sand beds typically consist of fine- to medium-grained sand and are both floored and capped by finer-grained units, resulting from fining-upwards deposition. Alluvial deposits are also typically exposed at or near water-level. Shovel-head for scale (NS-38.3: 35.2640°, –77.8874°). *B*, Interbedded sand, silt, and clay in Pleistocene Coharie terrace deposits. Coharie terrace sand is typically coarser-grained to gravelly than alluvial sand, few outcrops preserve capping stratigraphy, and the units are typically exposed high in the riverbank cuts, so saturation only occurs at flood stage. Shovel for scale (NS-64.4: 35.2693°, –77.9415°). *C*, Soil profile developed on Coharie (or alluvial) sand. Clay-rich Bt soil horizons can serve as a suitable cap, and typically contain root casts and animal burrows that would act as conduits to channel fluidized sand upward. However, these horizons are typically thick, which may impede liquefaction, and some are exposed well above the water-line. Soil tape and shovel for scale (NS-59.3: 35.2775°, –77.9404°).

weathered sand is likely too compacted to liquefy readily, and thus received a classification of "low" (table 1; appendix 1).

Ten outcrops classified as having some susceptibility to liquefaction contained features of syndepositional, bioturbation, or pedogenic origin (fig. 9). An outcrop along the Tar River (Tar-11.1: 35.8372°, −77.5460°) preserved three small sand-filled features within heavily mottled sandy silt (table 1; appendix 1). Near water level, one feature of about a centimeter in width (fig. 9*A*) extended vertically nearly 0.5 meters (m) through the host unit and appeared to branch into several thinner dikes as it neared the top of the outcrop. Two other silty, fine-sand-filled features were oblong in plan-view (~1 dm × 3 cm; fig. 9*B*). The vertical feature was discontinuously mantled by a thin precipitated film of iron oxide as much as a millimeter thick, which allowed the feature to be traced with difficulty upward through the cut. All three features tapered and disappeared within several centimeters of the vertical surface of the river cutbank. Weathered unconsolidated sand of Cretaceous age occurs to at least 110 cm below water level, but none of the features could be definitively traced to the underlying sand. The heavily mottled sandy silt serves as a cap and is likely a Bt soil horizon developed above the sand. The oblong features are interpreted to be cypress root casts within the soil profile and were likely filled with sand from above. The vertical feature may also be a root cast, or a deep-rooted fissure, and was likely also filled with sand from above. Iron precipitation along its margin suggests it acted as a conduit for meteroric water to percolate downward through the soil column. Similar sand-filled root casts were observed in another outcrop along the Neuse River (NS-60.4: 35.2767°, −77.9392°). At NS-52.4 (35.2966°, −77.9489°) a lens of fine silty sand occurs within a cap of mottled silty clay, but no connectivity was established between sand in the lens and decimeter-thick beds of fine- to medium-grained sand at depth and is likely a channel deposit (fig. 9*C*). None of these features are interpreted to be evidence of paleoliquefaction.

Four outcrops on the Neuse River preserved soft-sediment deformation features in Holocene alluvium; mostly load casts and a few pseudonodules at the base of clay or silty clay above coarse-grained sand beds (fig. 9*D*). Radiocarbon analysis of leaf material at one outcrop (NS-38.3: 35.2640°, −77.8874°) yields a modern age of 120±25 years before present (B.P.) (J. McGeehin, USGS, written commun., November 2016; appendix 2). The alluvial deposit is at the mouth of an abandoned river meander (fig. 10), but it is likely a modern point bar attached to the riverbank rather than abandoned channel-fill material. This modern deposit is probably syndepositional rather than coseismic, although its age does fall within error of the 1886 M~7 Charleston, South Carolina earthquake. Liquefaction associated with the Charleston temblor was reported 200 km (124 mi) north of the epicentral area near Liberty Hill, South Carolina, (fig. 1) and 1886 sand blows are known from Bluffton, South Carolina, ~110 km (68 mi) southwest of Charleston (Rajendran and Talwani, 1993; Talwani and Schaeffer, 2001, and references therein), but most liquefaction associated with that event occurred within 40 km west of the city (Dutton, 1889). The Neuse River site is approximately 340 km (212 mi) northeast of Charleston. Other examples of soft-sediment deformation features in outcrops along the Neuse River are also likely of syndepositional origin rather than coseismic, but lack age controls. However, Suther and others (2011) report optically stimulated luminescence (OSL) Holocene (1.3±0.3 ka) to historical ages for floodplain deposits, and Quaternary (94.0±15.9 ka to 9.9±2.0 ka) ages for terraces along the Little River (a tributary of the Cape Fear River) 112 km (70 mi) to the west, in the upper Coastal Plain near Fayetteville, North Carolina. Similar ages for alluvium and terraces along the Tar and Neuse Rivers in central-eastern North Carolina are likely.

One outcrop on the Neuse River (NS-84.5: 35.2480°, −77.5488°) preserved a pseudoliquefaction feature (fig. 9*E*). Here, white sand appears to swell up and intrude into reddish sand, beneath a clay cap. The feature is 7 cm at its widest point and 15-cm high, splits in two branches, then runs along the base of the clay like a thin sand sill. Close inspection, however, shows that crossbeds extend from the reddish sand into the white sand; the sharp transition in sand color is a geochemical weathering front produced from fluctuating shallow ground water and iron precipitation beneath the clay, creating the appearance of load casts and liquefaction sand dikes and sills. Another outcrop on the Neuse River (NS-55.4: 35.2818°, −77.93247°) preserved thin (<1-millimeter-thick) argillic horizons (fig. 9*F*), modified slightly by black manganese precipitation, in unconsolidated fine- to medium-grained, crossbedded sand.

Discussion

Despite an intensive search under optimal river conditions, no evidence of demonstrable seismogenic paleoliquefaction was documented during this study. Comparatively, numerous paleoliquefaction sand dikes, sills, and soft-sediment deformation features were discovered at 19 sites within 55 km of the epicenter of the 2011 moment magnitude M5.8 Mineral, Virginia, earthquake during systematic surveys of cutbank exposures along 119 km of six rivers in the Central Virginia Seismic Zone in 2015 (Tuttle and others, 2015). Several dikes and sills are well exposed at one site on the South Anna River near Louisa, Virginia (Horseshoe Farm: 37.9709°, −78.0311°). Here, one 4-cm-wide dike filled with fine sand extends nearly 1 m above its source bed of unconsolidated fine- to medium-grained sand through iron oxide-stained silty loam and is truncated by younger sediment near the top of the exposure (Carter and others, 2016; fig. 11*A*, *B*). Another dike at the site bifurcates into several sills before pinching out in the cap. OSL data constrain the age of the source sand at Horseshoe Farm to about 28 ka, but the dikes and sills are likely Holocene (Pazzaglia and others, 2015). Throughout the CVSZ, paleoliquefaction dikes and sills utilize pre-existing structures in the marginally liquefiable alluvial sediments, including bioturbation (for example, root casts and animal burrows)

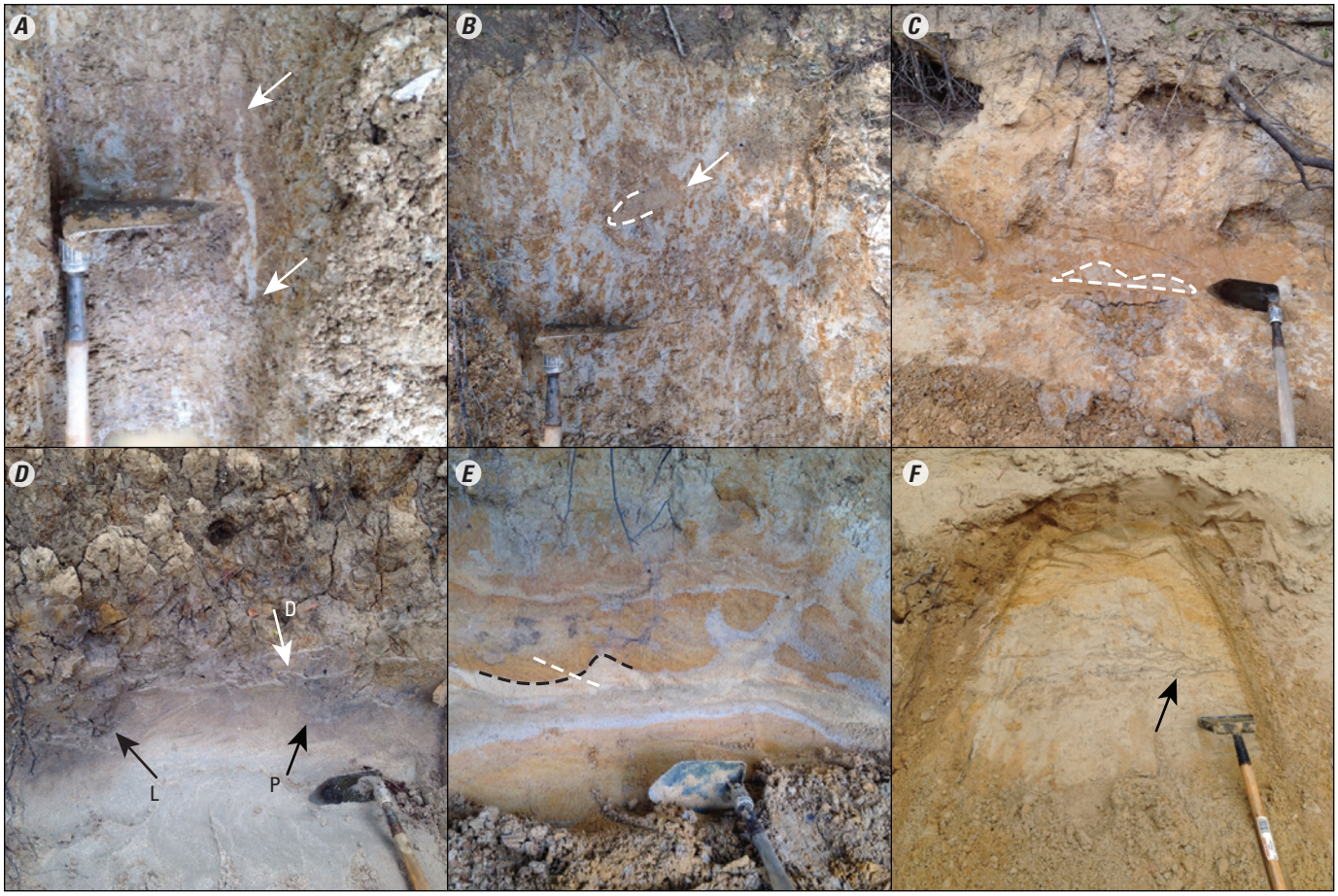

Figure 9. Features of likely syndepositional, bioturbation, or pedogenic origin documented during this study. None of the features are conclusively seismogenic in origin, but some are considered to be pseudoliquefaction features. *A*, Portion of a fine silty sand-filled feature within heavily mottled sandy silt, marked by white arrows. Although the feature extended vertically nearly 0.5 meters to near the top of the cutbank, it extended laterally into the cut only a few centimeters, and could not be traced to a source sand bed at depth. Despite appearing to branch into several thinner features near the top of the cut, the tubular (rather than tabular) shape of the feature suggests it is a preserved sand-filled root cast rather than a paleoliquefaction sand dike. Shovel for scale (Tar-11.1: 35.8372°, –77.5460°). *B*, An oblong, fine silty sand-filled feature, marked by a white arrow and partly outlined with a dashed white line. Two of these features were documented in the same outcrop as the sand-filled dike shown in photograph A (Tar-11.1: 35.8372°, –77.5460°). The two features tapered both vertically and laterally within centimeters of the surface and could not be traced to a source sand bed at depth. The shape of both features suggests sand-filled root casts of cypress knees. Shovel for scale. *C*, A lens of fine silty sand occurs within a cap of mottled silty clay, outlined by dashed white line. No connectivity was established between sand in the lens and decimeter-thick beds of fine- to medium-grained sand at depth and is likely a channel deposit. Shovel for scale (NS-52.4: 35.2966°, –77.9489°). *D*, A load cast (L), sand diapir (D), and pseudonodule (P) along the base of a clay bed within Holocene alluvium. Soft sediment deformation features such as these were documented at several outcrops during this study but are likely syndepositional rather than seismogenic because features like sand dikes and sills were not documented in the same or nearby outcrops. Shovel for scale (NS-91.5: 35.2630°, –77.5179°). *E*, Geochemical weathering front in sand (partly marked by black dashed line), produced from fluctuating shallow ground water and iron precipitation beneath an overlying clay bed, creates the appearance of load casts and liquefaction sand dikes and sills in the sand. Crossbeds in the sand (one marked by dashed white line) extend across the sharp transition in sand color. Shovel for scale (NS-84.5: 35.2480°, –77.5488°). *F*, Thin argillic horizons (one marked by black arrow), modified slightly by black manganese precipitation, created from surface water percolating downwards through permeable sand. Head of hula hoe for scale (NS-84.5: 35.2818°, –77.9325°).

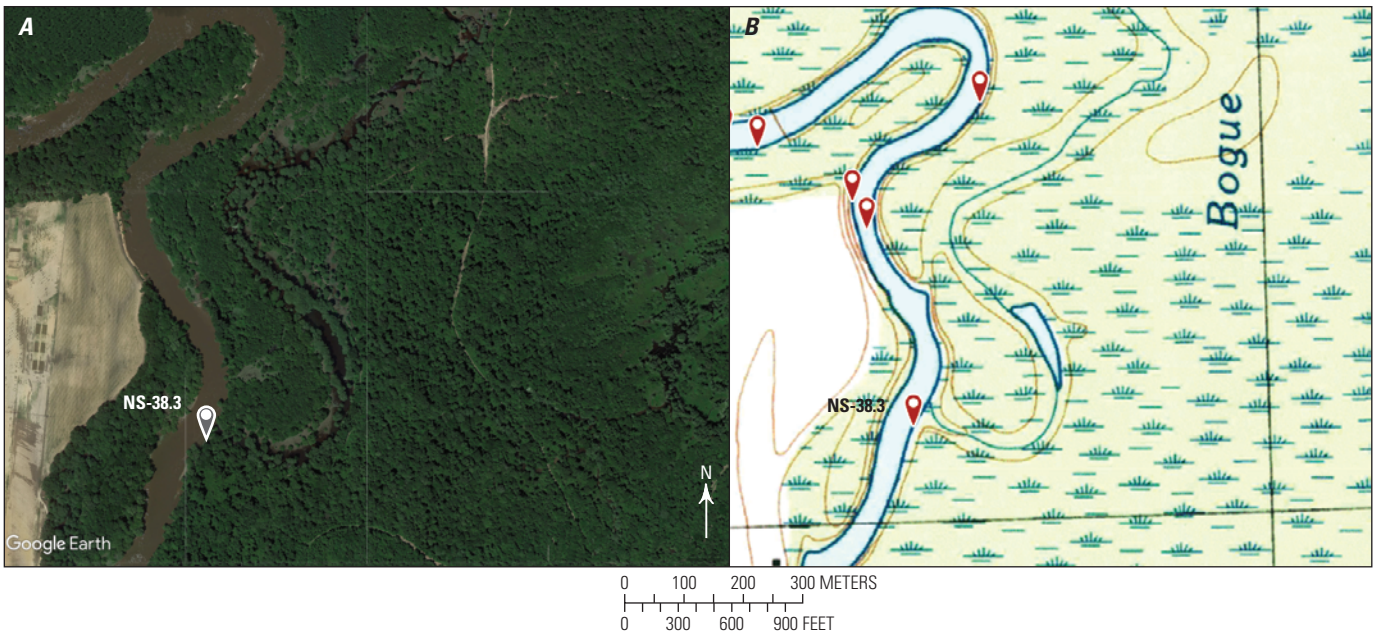

Figure 10. Location of station NS-38.3 (35.2640°, –77.8874°) on an alluvial bar deposit at the mouth of an abandoned river meander (the meander is now occupied by a modern stream that drains the swampy floodplain). Radiocarbon analysis of interbedded leaf material at this outcrop yielded a modern age of 120±25 years before present (J. McGeehin, U.S. Geological Survey, written commun., November 2016; appendix 2). *A*, Google Earth™ image of the Neuse River and abandoned meander. Base map data from Google, 2019 DigitalGlobe, imagery date May 14, 2016. *B*, Gaia GPS™ image of the same area as in *A*. Note that there are other locational symbols (inverted red teardrops with white circles) north of the location of NS-38.3 at the mouth of the meander cut-off in *B*. Also note scale and north arrow is the same for both images.

and at Horseshoe Farm, a network of meter-scale polygonal cracks developed in the silty loam cap (fig. 11*C*, *D*). Amick and others (1990) describe similar polygonal soil fracturing in the Coastal Plain of South Carolina that they attribute to seismic shaking. Polygonal cracks in mottled clayey silt were also observed at one outcrop along the Neuse River (NS-25.2: 35.3783°, −78.0557°) during this study (fig. 11*E*, *F*), but a more plausible explanation is that they are desiccation, rather than seismogenic, features. Regardless, radiocarbon dating of organic samples in host sediment provide maximum age constraints of mid-Holocene (5,595–4,290 years B.P.) at two paleoliquefaction sites in the CVSZ; cross-cutting relations and the degree of weathering of the sand dikes suggest two generations of features across 3,100 km^2 within the northeastern CVSZ (Tuttle and others, 2015). All of these data from the CVSZ satisfy requirements of Obermeier (1996) to conclude a paleoseismic origin for the documented features.

Very few riverbank outcrops along the two rivers traversed during this study preserved strata even marginally susceptible to liquefaction (table 1; appendix 1). Obermeier (1996) reports that for regions struck by an earthquake of Modified Mercalli Intensity (MMI) of ≥IX (equivalent to Richter magnitude scale of at least M6 to M6.5), "liquefaction features should abound even where liquefaction susceptibility is moderate, and that any reasonable effort to locate numerous liquefaction features should be successful; for MMI VII–VIII, small features may be sparse, but still should be numerous enough that some features would be discovered during a widespread search of stream banks, even where susceptible deposits occur only very locally." In the Central Virginia Seismic Zone, this assessment proved to be true—marginally liquefiable Pleistocene to Holocene sediments preserve numerous paleoliquefaction features across a broad meizoseismal area (Tuttle and others, 2015, Carter and others, 2016). Statistical analyses using the breadth of the paleoliquefaction field (assuming all features were produced by one large-magnitude event) indicate a minimum magnitude prehistoric event of at least M6–6.5 to have struck the CVSZ (Ambraseys, 1988; fig. 12–slide 13, Castilla and Audemard, 2007). Although this traverse in central-eastern North Carolina covered little more than half the river length searched in the 2015 CVSZ explorations, and less than the minimum of fresh exposure (more than 10 km) suggested by Obermeier (2009) to find effects from earthquake accelerations as low as 0.1–0.2g (acceleration due to gravity), field conditions at the time were optimal, and at least marginally liquefiable strata were documented at some locations across the region. Thus, at least a few convincing features of probable paleoliquefaction should have been found had this region been struck by a large-magnitude event in the past. However, absence of evidence is not evidence

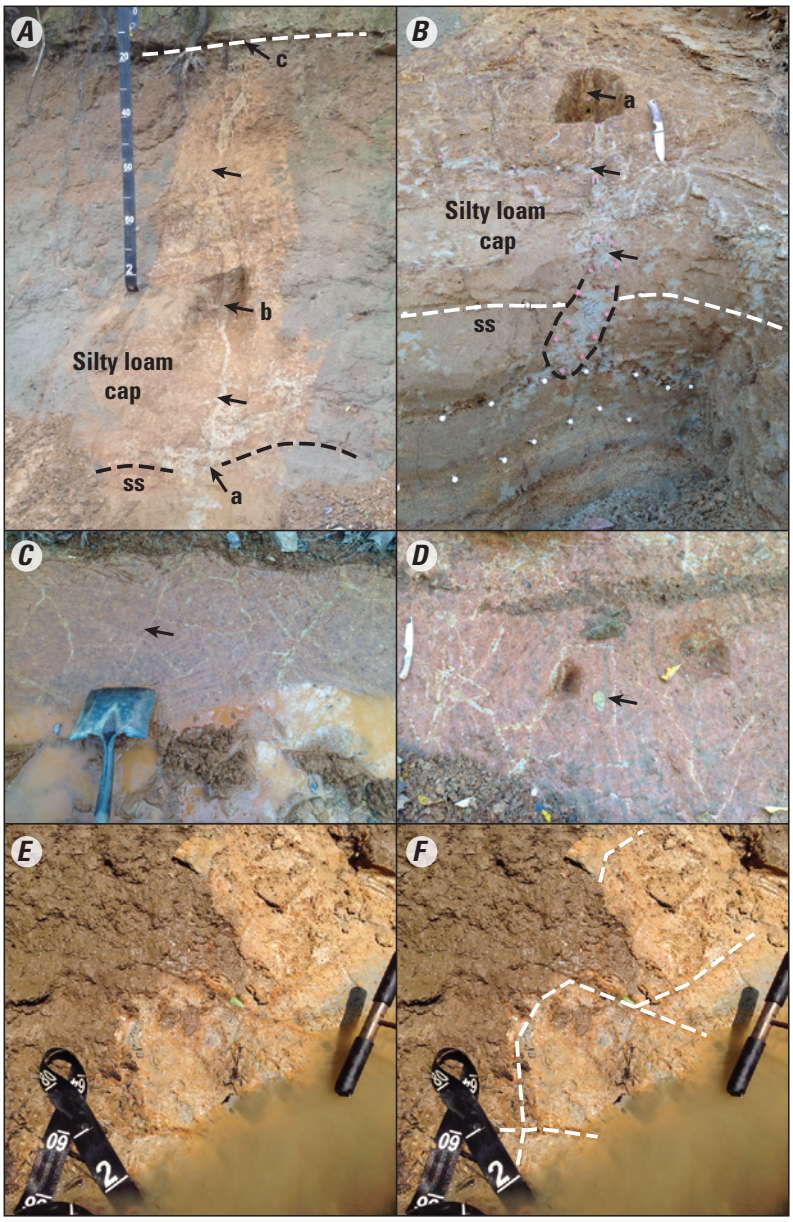

Figure 11. Paleoliquefaction dikes and polygonal cracks in alluvial sediments, Virginia and North Carolina. *A*, Paleoliquefaction dike at Horseshoe Farm in the Central Virginia Seismic Zone (37.9709°, –78.0311°). The dike (marked by black arrows) rises from a source bed (ss) of fine- to medium-grained sand (the contact between the source sand and silty loam cap is marked by dashed black line) at black arrow "a", rises vertically through the cap (the excavation at black arrow "b" demonstrates the tabular, not tubular geometry of the dike, and its lateral continuity), and is truncated at the top of the cut (at white arrow "c") by younger Holocene alluvial (legacy) sediments. An optically stimulated luminescence age of the source sand yields an age of ~28,000 years ago (28 ka) (Pazzaglia and others, 2015) but the dike is likely much younger. Soil tape for scale. *B*, An adjacent dike (marked by black arrows) rises from source sand bed (ss) into the silty loam cap (the contact between the source sand and silty loam cap is marked by dashed white line). Bedding in the source sand is disrupted within the region marked by black dashed line, indicating that fluidized sand flowed into the neck of the dike. The excavation at black arrow "a" demonstrates the tabular, not tubular geometry of the dike, and its lateral continuity. Soil knife for scale. *C*, An array of meter-scale polygonal cracks (one thin light-colored crack is marked by a black arrow) in iron-indurated silty loam at Horseshoe Farm. These cracks may be desiccation features, but the age of the underlying sand (58–28 ka; Pazzaglia and others, 2015) lends support for a cryogenic origin; Amick and others (1990) suggested a seismogenic origin for similar cracking in soils of the South Carolina Coastal Plain. Photograph is a plan view of the cracks, with shovel for scale. Carter (2015) and Pazzalgia and others (2015) proposed a model in which these cracks were jarred open during a paleoearthquake in the CVSZ, allowing fluidized sand to intrude along the opened crack to form the sand-filled dike. *D*, Oblique to vertical riverbank cut through the polygonal cracks (one thin light-colored crack is marked by a black arrow) shown in photograph *C*. If not intruded by sand from below, the cracks are filled by light-gray silty clay. Soil knife for scale. *E*, Polygonal cracking in clayey silt at NS-25.2 (35.3783°, –78.0557°) on the Neuse River in central-eastern North Carolina. *F*, Same view as in photograph *E*, with the polygonal cracks marked with dashed white lines. These cracks are also filled with light-gray silty clay, but none were observed to be filled with sand, as those in the CVSZ, despite a bed of unconsolidated sand at depth and beneath polygonally cracked silty clay.

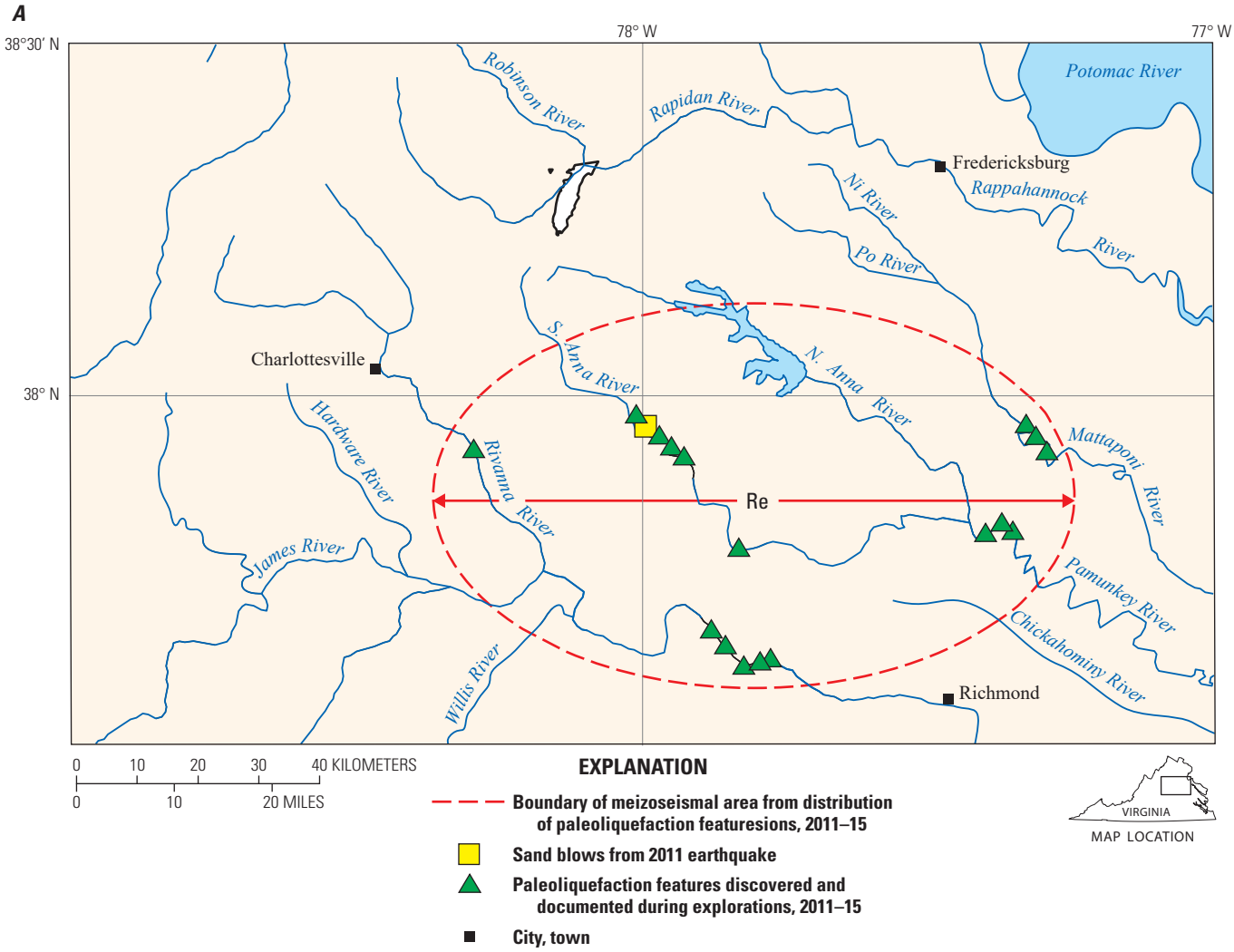

Figure 12. Distribution and statistical significance of paleoliquefaction features in the Central Virginia Seismic Zone (CVSZ). *A*, Map of the paleoseismic meizoseismal field (Re) based on the distribution of documented paleoliquefaction in the CVSZ. Data compiled from Obermeier and McNulty (1998), Dominion Nuclear North Anna, LLC (2004), Carter and others (2012), Carter (2015), Green and others (2015), Tuttle and others (2015), and Carter and others (2016). *B*, Ambraseys (1988) statistical curve for the maximum magnitude earthquake from the paleoseismic meizoseismal field (Re). *C*, Castilla and Audemard (2007) generated a curve for the same dataset as in *B*. Maximum magnitude (M~6.8) for both curves assumes the paleoseismic meizoseimal field was created from one paleoearthquake, and the distribution of features does not reflect multiple overlapping meizoseismal fields. However, the liquefaction field from the 2011 M5.8 earthquake covered an area of just several kilometers in the immediate epicentral area of the temblor, far smaller than the fields both curves suggest should have been created.

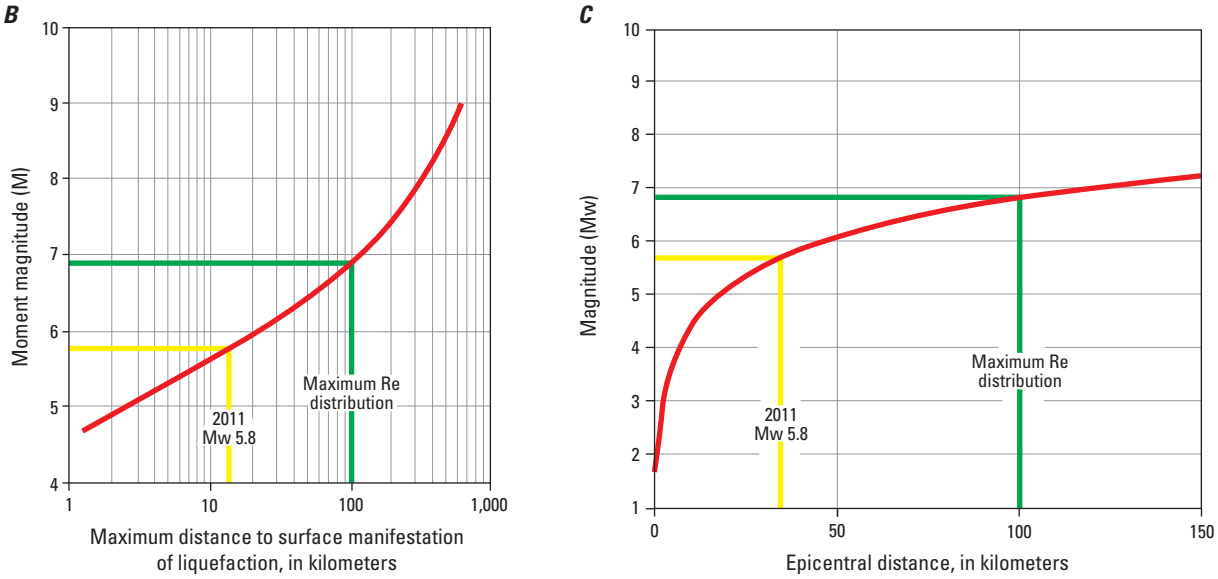

Figure 12. Distribution and statistical significance of paleoliquefaction features in the Central Virginia Seismic Zone (CVSZ). *A*, Map of the paleoseismic meizoseismal field (Re) based on the distribution of documented paleoliquefaction in the CVSZ. Data compiled from Obermeier and McNulty (1998), Dominion Nuclear North Anna, LLC (2004), Carter and others (2012), Carter (2015), Green and others (2015), Tuttle and others (2015), and Carter and others (2016). *B*, Ambraseys (1988) statistical curve for the maximum magnitude earthquake from the paleoseismic meizoseismal field (Re). *C*, Castilla and Audemard (2007) generated a curve for the same dataset as in *B*. Maximum magnitude (M~6.8) for both curves assumes the paleoseismic meizoseimal field was created from one paleoearthquake, and the distribution of features does not reflect multiple overlapping meizoseismal fields. However, the liquefaction field from the 2011 M5.8 earthquake covered an area of just several kilometers in the immediate epicentral area of the temblor, far smaller than the fields both curves suggest should have been created.—Continued

of absence, and additional work in this region may uncover previously unrecognized features (just as the 2015 CVSZ traverses documented many additional sites from the few originally discovered in the 1990s). It is also important to note that this was a field study only—outcrop classification for liquefaction susceptibility was based on field-deduced criteria (for example, grain size); Youd and others (2001) provides an excellent discussion of geotechnical methods to precisely determine the liquefaction potential of sediments.

In his comparative geomorphic study of the CVSZ, CSZ, and this aseismic region of central-eastern North Carolina, Pazzaglia (2017) found equivocal evidence for crustal deformation recorded by topographic and stream channel metrics: several measured parameters simply reflect underlying changes in rock type, but sinuosity variations along both the Neuse and Tar Rivers are strongly associated with mapped faults of the Graingers fault zone. Faulting at least as young as Paleogene here is on a par with well documented faulting in the Coastal Plain of Virginia (for example, Dischinger, 1987; Berquist and Bailey, 1999; Powars and others, 2015), but deformation on those faults is as young as Pliocene. New zircon fission-track, apatite fission-track U-Th/He thermochronologic, and OSL data (for example, Roden-Tice and others, 2012; McKeon and others, 2014; Pazzaglia and others, 2015; McGavick and others, 2016; Naeser and others, 2016) indicate eastern United States landscapes from New Hampshire to North Carolina are far more stable than once thought—much of the topographic form today could be only slightly modified from the Miocene and has been essentially stable in the upper Coastal Plain since the late Pliocene (Weems and Edwards, 2007). Fault scarps near Kinston (Brown and others, 1977; this study) could well be the erosionally degraded remnants of Pliocene surface rupture from large magnitude quakes in this region, but riverbank outcrops only preserve the fault roots in Cretaceous to Paleogene strata, and Pleistocene to Holocene fluvial sediments are too young to record Neogene deformation. Data from this study suggest that despite well-documented Cenozoic faults and continued low-magnitude and low-frequency regional seismicity, large magnitude earthquakes capable of producing widespread liquefaction fields have not struck this region of North Carolina in the last several million years. However, the role of aseismic creep (for example, Kaduri and others, 2017) and cumulative Pleistocene to Holocene surface deformation along faults of the Graingers fault zone from low-magnitude seismic events (with millimeter-scale deformations) should not be dismissed; data to compare local denudation rates with regional crustal uplift presently do not exist.

Conclusions

Despite historical and recent low-magnitude and infrequent regional seismicity, a search for paleoliquefaction features along 64 kilometers of the Tar and Neuse Rivers in the heart of the Paleogene Graingers fault zone in central-eastern North Carolina yielded no features of probable or certain seismogenic origin. Most of the riverbank exposures consisted of Cretaceous to Paleogene stratigraphy that is too old and compacted to liquefy during an earthquake. Younger Pleistocene to Holocene alluvial stratigraphy is too young to preserve evidence for Neogene-age quakes that may have affected this region, but degraded fault scarps in the vicinity of Kinston, North Carolina, may be the preserved remnants of such seismic activity. Radiocarbon age analysis indicates that soft-sediment deformation preserved in one riverbank exposure dates to within error of the 1886 Charleston M~7 earthquake, but it is unlikely that the soft-sediment features are associated with that event this far to the north. Probable syndepositional soft-sediment deformation was documented at several other outcrops in the study area, as were examples of pseudoliquefaction, including sand-filled root casts and pedogenic geochemical weathering fronts.

References Cited

Allen, J.R.L., ed., 1982, Chapter 9 Soft-sediment deformation structures: Developments in Sedimentology, v. 30, Part B, p. 343–393, accessed April 2019 at https://doi.org/10.1016/S0070-4571(08)71019-7.

Ambraseys, N.N., 1988, Engineering seismology: Earthquake Engineering and Structural Dynamics, v. 17, no. 1, p. 1–50, accessed April 2019 at https://doi.org/10.1002/eqe.4290170101.

Amick, D.C., and Gelinas, R., 1991, The search for evidence of large prehistoric earthquakes along the Atlantic seaboard: Science, v. 251, no. 4994, p. 655–658, accessed April 2019 at https://doi.org/10.1126/science.251.4994.655.

Amick, D.C., Gelinas, R., Maurath, G., Cannon, R., Moore, D., Billington, E., and Kemppinen, H., 1990, Paleoliquefaction features along the Atlantic seaboard: Nuclear Regulatory Commission, Technical Report NUREG/CR-5613, 146 p.

Andrus, R.D., Stokoe, K.H., and Roesset, J.M., 1991, Liquefaction of gravelly soil at Pence Ranch during the 1983 Borah Peak, Idaho earthquake: Proceedings of the 5th International Conference on Soil Dynamics and Earthquake Engineering, Karlsruhe, Germany, p. 251–262.

Andrus, R.D., and Youd, T.L., 1987, Subsurface investigation of a liquefaction-induced lateral spread, Thousand Springs Valley: Idaho, U.S. Army Corps of Engineers, Engineer Waterways Experiment Station Miscellaneous Paper GL-87-8, 132 p.

Baum, G.R., Harris, W.B., and Zullo, V.A., 1978, Stratigraphic revision of the exposed middle Eocene to lower Miocene formations of North Carolina: Southeastern Geology, v. 20, p. 1–19.

Berquist, C.R., Jr., and Bailey, C.M., 1999, Late Cenozoic faulting in the Fall Zone, southeastern Virginia: The Journal of Geology, v. 107, p. 727–732, accessed April 2019 at https://doi.org/10.1086/314374.

Best, D.M., and Cavanaugh, T.D., 1977, A catalogue of seismic events recorded at seismograph station CHC, Chapel Hill, North Carolina, January 1, 1955 through December 31, 1970: North Carolina Division of Mineral Resources Special Publication 6, 72 p.

Bezerra, F.H.R., da Fonseca, V.P., Vita-Finzi, C., Lima-Filho, F.P., and Saadi, A., 2005, Liquefaction-induced structures in Quaternary alluvial gravels and gravelly sediments, NE Brazil: Engineering Geology, v. 76, no. 3–4, p. 191–208, accessed April 2019 at https://doi.org/10.1016/j.enggeo.2004.07.007.

Brown, P.M., 1959, Geology and ground water resources in the Greenville area, North Carolina: North Carolina Division of Mineral Resources Bulletin 73, 87 p.

Brown, P.M., Brown, D.L., Shufflebarger, T.E., Jr., and Sampair, J.L., 1977, Wrench-style deformation in rocks of Cretaceous and Paleocene age, North Carolina Coastal Plain: North Carolina Department of Natural and Economic Resources Special Publication 5, 47 p.

Brown, P.M., Shufflebarger, T.E., Jr., and Smith, S.R., 1982, Structural-stratigraphic framework and geomorphic signature of the Graingers wrench zone, North Carolina Coastal Plain: Atlantic Coastal Plain Geological Association, 1982 Field Trip Guidebook, 34 p.

Carpenter, P.A., III, 1989, A geologic guide to North Carolina's state parks: North Carolina Geological Survey Bulletin 91, 69 p.

Carter, M.W., 2015, Characterizing pedogenic and potential paleoseismic features in South Anna River alluvium; epicentral region of the 2011 earthquake Central Virginia Seismic Zone: Presentation at the 2015 Virginia Geological Research Symposium, April 13, 2015, Charlottesville, Va.

Carter, M.W., Blanpied, M.L., Leeds, A.L., Harp, E.L., McNamara, D.E., Harrison, R.W., and Schindler, J.S., 2012, USGS response to the Mineral, Virginia Mw5.8 earthquake of 23 August 2011 [abs.]: Geological Society of America Abstracts with Programs, v. 44, no. 4, p. 13.

Carter, M.W., Tuttle, M., and Dunahue, J., 2016, Characteristics of paleoliquefaction features in the Central Virginia Seismic Zone (CVSZ) [abs.]: Geological Society of America Abstracts with Programs, v. 48, no. 3, accessed April 2019 at https://doi.org/10.1130/abs/2016SE-273045.

Castilla, R.A., and Audemard, F.A., 2007, Sand blows as a potential tool for magnitude estimation of pre-instrumental earthquakes: Journal of Seismology, v. 11, no. 4, p. 473–487, accessed April 2019 at https://doi.org/10.1007/s10950-007-9065-z.

Castro, G., 1987, On the behavior of soils during earthquakes—Liquefaction, *in* Cakmak, A.S., ed., Soil dynamics and liquefaction: Developments in Geotechnical Engineering v. 42, p. 169–204.

Clark, W.B., and Miller, B.L., 1906, The geology of the Virginia Coastal Plain, *in* Ries, H., The clay deposits of the Virginia Coastal Plain: Virginia Geological Survey Bulletin 2, p. 11–24.

Clark, W.B., Miller, B.L., and Stephenson, L.W., 1912, The stratigraphy of the coastal plain of North Carolina; the geological history of the coastal plain of North Carolina, *in* Clark, W.B., Miller, B.L., Stephenson, L.W., Johnson, B.L., and Parker, H.N., The coastal plain of North Carolina; Part 1, The physiography and geology of the coastal plain of North Carolina: North Carolina Geological and Economic Survey, v. 3, 552 p.

Cooke, C.W., 1931, Seven coastal terraces in the southeastern states: Washington Academy of Science Journal, v. 21, p. 503–513.

Cooke, C.W., 1936, Geology of the coastal plain of South Carolina: U.S. Geological Survey Bulletin 867, 196 p.

Cox, J.H.M., 1984, Paleoseismology studies in South Carolina: Columbia, University of South Carolina, M.S. thesis, 75 p.

Cox, J., and Talwani, P., 1983, Paleoseismic studies in the 1886 Charleston earthquake meizoseismal area [abs.]: Geological Society of America Abstracts with Programs, v. 16, no. 130.

Cronin, T.M., Bybell, L.M., Poore, R.Z., Blackwelder, B.W., Liddicoat, J.C., and Hazel, J.E., 1984, Age and correlation of emerged Pliocene and Pleistocene deposits, U.S. Atlantic Coastal Plain: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 47, no. 1–2, p. 21–51, accessed April 2019 at https://doi.org/10.1016/0031-0182(84)90079-8.

Dischinger, J.B., Jr., 1987, Late Mesozoic and Cenozoic stratigraphy and structural framework near Hopewell, Virginia: U.S. Geological Survey Bulletin 1567, 45 p.

Dobry, R., 1989, Some basic aspects of soil liquefaction during earthquakes: Annals of the New York Academy of Sciences, v. 558, no. 1, p. 172–182, accessed April 2019 at https://doi.org/10.1111/j.1749-6632.1989.tb22567.x.

Dominion Nuclear North Anna, L.L.C., 2004, North Anna early site permit application; Response to [Nuclear Regulatory Commission (NRC)] request for additional information (RAI) letter no. 3 of April 15, 2004: Glen Allen, Va., Dominion Nuclear North Anna, LLC, Serial No. 04-270, Docket No. 52-008, 110 p.

Dutton, C.E., 1889, The Charleston earthquake of August 31, 1886: U.S. Geological Survey, Ninth Annual Report 1887–88, p. 203–528.

Ferenczi, I., 1959, Structural control of the North Carolina Coastal Plain: Southeastern Geology, v. 1, p. 105–116.

Ferguson, J.F., and Stewart, D.M., 1975, Summary of North Carolina seismicity in the 18th and 19th centuries: Seismological Research Letters, v. 46, no. 1–2, p. 27–36, accessed April 2019 at https://doi.org/10.1785/gssrl.46.1-2.27.

Green, R.A., Lasley, S., Carter, M.W., Munsey, J.W., and Tuttle, M.P., 2015, Geotechnical aspects in the epicentral region of the 2011, Mw5.8 Mineral, Virginia earthquake, *in* Horton, J.W., Jr., Chapman, M.C., and Green, R.A., eds., The 2011 Mineral, Virginia, earthquake and its significance for seismic hazards in eastern North America: Geological Society of America Special Paper 509, p. 151–172, doi: 10.1130/2014.2509(09).

Harris, W.B., and Laws, R.A., 1997, Paleogene stratigraphy and sea-level history of the North Carolina Coastal Plain—Global coastal onlap and tectonics: Sedimentary Geology, v. 108, no. 1–4, p. 91–120, accessed April 2019 at https://doi.org/10.1016/S0037-0738(96)00049-8.

Harris, W.B., Zullo, V.A., and Baum, G.R., 1979, Tectonic effects on Cretaceous, Paleogene, and early Neogene sedimentation, North Carolina, *in* Baum, G.R., and others, eds., Structural and stratigraphic framework for the coastal plain of North Carolina: Carolina Geological Society and the Atlantic Coastal Plain Association, Field Trip Guidebook, p. 17–29.

Harris, W.B., Zullo, V.A., and Laws, R.A., 1993, Sequence stratigraphy of the onshore Paleogene, southeastern Atlantic Coastal Plain, USA, *in* Posamentier, H.W., Summerhayes, C.P., Haq, B.U., and Allen, G.P., eds., Sequence stratigraphy and facies associations: International Association of Sedimentologists Special Publication 18, p. 537–561.

Hobbs, C.H., III, 2004, Geological history of Chesapeake Bay: Quaternary Science Reviews, v. 23, no. 5–6, p. 641–661, accessed May 2019 at https://doi.org/10.1016/j.quascirev.2003.08.003.

Holbrook, J., and Schumm, S.A., 1999, Geomorphic and sedimentary response of rivers to tectonic deformation—A brief review and critique of a tool for recognizing subtle epeirogenic deformation in modern and ancient settings: Tectonophysics, v. 305, no. 1–3, p. 287–306, accessed May 2019 at https://doi.org/10.1016/S0040-1951(99)00011-6.

Holzer, T.L., and Clark, M.M., 1993, Sand boils without earthquakes: Geology, v. 21, no. 10, p. 873–876, accessed May 2019 at https://doi.org/10.1130/0091-7613(1993)021<0873:SBWE>2.3.CO;2.

Horton, J.W., Jr., Chapman, M.C., and Green, R.A., eds., 2015, The 2011 Mineral, Virginia, earthquake, and its significance for seismic hazards in eastern North America: Geological Society of America Special Paper 509, 431 p.

Huddlestun, P.F., 1988, A revision of the lithostratigraphic units of the coastal plain of Georgia; the Miocene through the Holocene: Georgia Geologic Survey Bulletin 104, 162 p.

Ishihara, K., 1985, Stability of natural soil deposits during earthquakes: Proceedings of the 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, Calif., v. 1, p. 321–376.

Kaduri, M., Gratier, J.-P., Renard, F., Çakir, Z., and Lasserre, C., 2017, The implications of fault zone transformation on aseismic creep—Example of the North Anatolian Fault, Turkey: Journal of Geophysical Research, v. 122, no. 6, p. 4208–4236, accessed May 2019 at https://doi.org/10.1002/2016JB013803.

Kavazanjian, E., Jr., Andrade, J.E., Arulmoli, K., Atwater, B.F., Christian, J.T., Green, R., Kramer, S.L., Aecom, L.M., Mitchell, J.K., Rathje, E., Rice, J.R., and Wang, Y., 2018, State of the art and practice in the assessment of earthquake-induced soil liquefaction and its consequences: Report of the National Academies of Science, Engineering, and Medicine, Washington, DC, National Academies Press, 350 p., accessed May 2019 at https://doi.org/10.17226/23474.

Kokusho, T., 2003, Current state of research on flow failure considering void redistribution in liquefied deposits: Soil Dynamics and Earthquake Engineering, v. 23, no. 7, p. 585–603, accessed May 2019 at https://doi.org/10.1016/S0267-7261(03)00067-8.

Kolb, C.R., 1976, Geologic control of sand boils along Mississippi River levees, *in* Coats, D.R., ed., Geomorphology and engineering: New York, Halsted Press, p. 99–114.

Lade, P.V., 1992, Static instability and liquefaction of loose fine sandy slopes: Journal of Geotechnical Engineering, v. 118, no. 1, p. 51–71, accessed May 2019 at https://doi.org/10.1061/(ASCE)0733-9410(1992)118:1(51).

Lasley, S., Green, R.A., Carter, M.W., Munsey, J., and Martin, J.R., 2013, Geotechnical effects in the epicentral region of the 23 August 2011 central Virginia earthquake [abs.], *in* Eastern section-SSA 2011 meeting report: Seismological Research Letters, v. 84, no. 1, p. 155.

Lawrence, D.P., and Hoffman, C.W., 1993, Geology of basement rocks beneath the North Carolina Coastal Plain: North Carolina Geological Survey Bulletin 95, 60 p.

LeGrand, H.E., and Brown, P.M., 1955, Guidebook of excursions in the coastal plain of North Carolina: Carolina Geological Society Field Trip Guidebook, October 8–9, 1955, 43 p.

McGavick, M., Pazzaglia, F.J., Carter, M.W., Mahan, S.A., Counts, R., Rittenour, T., and Nelson, M.S., 2016, Landscape evolution on the Virginia piedmont—A new soil chronosequence, luminescence (OSL and IRSL) and cosmogenic (TCN) dating, and intraplate seismicity-driven river incision [abs.]: Geological Society of America Abstracts with Programs, v. 48, no. 7, accessed May 2019 at https://doi.org/10.1130/abs/2016AM-285877.

McKeon, R., Zeitler, P.K., Pazzaglia, F.J., Idleman, B., and Enkelmann, E., 2014, Decay of an old orogen—Inferences about Appalachian landscape evolution from low-temperature thermochronology: Geological Society of America Bulletin, v. 126, no. 1–2, p. 31–46, accessed May 2019 at https://doi.org/10.1130/B30808.1.

McLaurin, B.T., and Harris, W.B., 2001, Paleocene faulting within the Beaufort Group, Atlantic Coastal Plain, North Carolina: Geological Society of America Bulletin, v. 113, no. 5, p. 591–603, accessed May 2019 at https://doi.org/10.1130/0016-7606(2001)113<0591:PFWTBG>2.0.CO;2.

Mixon, R.B., Szabo, B.J., and Owens, J.P., 1982, Uranium-series dating of mollusks and corals, and age of Pleistocene deposits, Chesapeake Bay area, Virginia and Maryland: U.S. Geological Survey Professional Paper 1067-E, 18 p.

Naeser, C.W., Naeser, N.D., Newell, W.L., Southworth, S., Edwards, L.E., and Weems, R.E., 2016, Erosional and depositional history of the Atlantic passive margin as recorded in detrital zircon fission-track ages and lithic detritus in Atlantic Coastal Plain sediments: American Journal of Science, v. 316, p. 110–168, accessed May 2019 at https://doi.org/10.2475/02.2016.02.

North Carolina Geological Survey, 1985, Geologic map of North Carolina: North Carolina Geological Survey, General Geologic Map, scale 1:500,000.

Obermeier, S.F., 1989, The New Madrid earthquakes—An engineering-geologic interpretation of relict liquefaction features: U.S. Geological Survey Professional Paper 1336-B, 114 p.

Obermeier, S.F., 1994, Using liquefaction-induced features for paleoseismic analysis, chap. A *of* Obermeier, S.F., and Jibson, R.W., eds., Using ground-failure features for paleoseismic analysis: U.S. Geological Survey Open File Report 94-663, p. 1–58.

Obermeier, S.F., 1996, Use of liquefaction-induced features for paleoseismic analysis – An overview of how seismic liquefaction features can be distinguished from other features and how their regional distribution and properties of source sediment can be used to infer the location and strength of Holocene paleo-earthquakes: Engineering Geology, v. 44, no. 1–4, p. 1–76, accessed May 2019 at https://doi.org/10.1016/S0013-7952(96)00040-3.

Obermeier, S.F., 1998, Liquefaction evidence for strong earthquakes of Holocene and latest Pleistocene ages in the states of Indiana and Illinois, USA: Engineering Geology, v. 50, no. 3–4, p. 227–254, accessed May 2019 at https://doi.org/10.1016/S0013-7952(98)00032-5.

Obermeier, S.F., 2009, Using liquefaction-induced and other soft-sediment features for paleoseismic analysis, chap. 7 *of* McCalpin, J.P., ed., Paleoseismology: International Geophysics, v. 95, p. 497–564, accessed May 2019 at https://doi.org/10.1016/S0074-6142(09)95007-0.

Obermeier, S.F., Jacobson, R.B., Smoot, J.P., Weems, R.E., Gohn, G.S., Monroe, J.E., and Powars, D.S., 1990, Earthquake-induced liquefaction features in the coastal setting of South Carolina and in the fluvial setting of the New Madrid Seismic Zone: U.S. Geological Survey Professional Paper 1504, 44 p., accessed May 2019 at https://doi.org/10.3133/pp1504.

Obermeier, S., and McNulty, W., 1998, Paleoliquefaction evidence for seismic quiescence in central Virginia during the late and middle Holocene time: Eos, v. 79, no. 17, p. S342.

Obermeier, S.F., Olson, S.M., and Green, R.A., 2005, Field occurrences of liquefaction-induced features—A primer for engineering geologic analysis of paleoseismic shaking: Engineering Geology, v. 76, no. 3–4, p. 209–234, accessed May 2019 at https://doi.org/10.1016/j.enggeo.2004.07.009.

Parker, J.P., III, 1968, Structure of easternmost North Carolina piedmont: Southeastern Geology, v. 9, no. 3, p. 117–132.

Pazzaglia, F.J., 2017, Geomorphic expression of the seismotectonics and seismic potential of source zones in CEUS—CVSZ and Charleston: Technical Report in fulfillment of U.S. Geological Survey NEHRP Award G15AP00092, Bethlehem, Pa., Lehigh University, 80 p.

Pazzaglia, F.J., Carter, M., Berti, C., Counts, R., Hancock, G., Harbor, D., Harrison, R., Heller, M., Mahan, S., Malenda, H., McKeon, R., Nelson, M., Prince, P., Rittenour, T., Spotilla, J., and Whittecar, R., 2015, Geomorphology, active tectonics, and landscape evolution in the mid-Atlantic region, *in* Brezinski, D.K., Halka, J.P., and Ortt, R.A., Jr., eds., Tripping from the Fall Line—Field excursions for the GSA Annual Meeting, Baltimore, 2015: Geological Society of America Field Guide 40, p. 109–169, doi: 10.1130/2015.0040(06).

Powars, D.S., Catchings, R.D., Horton, J.W., Jr., Schindler, J.S., and Pavich, M.J., 2015, Stafford fault system—120 million year fault movement history of northern Virginia, *in* Horton, J.W., Jr., Chapman, M.C., and Green, R.A., eds., The 2011 Mineral, Virginia, earthquake, and its significance for seismic hazards in eastern North America: Geological Society of America Special Paper 509, p. 407–431, accessed May 2019 at https://doi.org/10.1130/2015.2509(23).

Prowell, D.C., 1983, Index of faults of Cretaceous and Cenozoic age in the eastern United States: U.S. Geological Survey Miscellaneous Field Studies Map MF-1269, scale 1:2,500,000.

Rajendran, C.P., and Talwani, P., 1993, Paleoseismic indicators near Bluffton, South Carolina—An appraisal of their tectonic implications: Geology, v. 21, no. 11, p. 987–990, accessed May 2019 at https://doi.org/10.1130/0091-7613(1993)021<0987:PINBSC>2.3.CO;2.

Roden-Tice, M.K., Eusden, J.D., Jr., and Wintsch, R.P., 2012, Apatite fission-track evidence for the Cretaceous development of kilometer-scale relief and steady-state Tertiary topography in New England: Geomorphology, v. 141–142, p. 114–120, accessed May 2019 at https://doi.org/10.1016/j.geomorph.2011.12.029.

Sampair, J.L., 1979, Geological and geophysical evaluation of the Graingers basin for Triassic sediments: North Carolina Geological Survey Open File Report 79–1, 37 p.

Scott, R.F., 1986, Solidification and consolidation of a liquefied sand column: Soil and Foundation, v. 26, no. 4, p. 23–31, accessed May 2019 at https://doi.org/10.3208/sandf1972.26.4_23.

Seed, H.B., and Idriss, L.M., 1982, Ground motions and soil liquefaction during earthquakes: Berkeley, Earthquake Engineering Research Institute, University of California, 134 p.

Seed, H.B., Idriss, I.M., and Arango, I., 1983, Evaluation of liquefaction potential using field performance data: Journal of Geotechnical Engineering, v. 109, no. 3, p. 458–482, accessed May 2019 at https://doi.org/10.1061/(ASCE)0733-9410(1983)109:3(458).

Shattuck, G.B., 1901, The Pleistocene problem of the north Atlantic Coastal Plain: Johns Hopkins University Circular, v. 20, no. 152, p. 69–75.

Sims, J.D., and Garvin, C.D., 1995, Recurrent liquefaction induced by the 1989 Loma Prieta earthquake and 1990 and the 1991 aftershocks—Implications for paleoseismicity studies: Bulletin of the Seismological Society of America, v. 85, no. 1, p. 51–65.

Sohl, N.F., 1976, Reinstatement of the name Cape Fear Formation in North and South Carolina, *in* Cohee, G.V., and Wright, W.B., eds., Changes in stratigraphic nomenclature by the U.S. Geological Survey, 1975: U.S. Geological Survey Bulletin 1422-A, p. A68.

Sohl, N.F., and Owens, J.P., 1991, Cretaceous stratigraphy of the Carolina Coastal Plain, *in* Horton, J.W., Jr., and Zullo, V.A., eds., The geology of the Carolinas: Carolina Geological Society, 50th Anniversary Volume, p. 191–220.

Stephenson, L.W., 1907, Some facts relating to the Mesozoic deposits of the coastal plain of North Carolina, *in* Notes from the Geological Laboratory, 1906–1907: Johns Hopkins University Circular, no. 7, p. 93–99.

Stephenson, L.W., 1912, The Cretaceous, Lafayette, and Quaternary formations, *in* The coastal plain of North Carolina; Part 1, The physiography and geology of the coastal plain of North Carolina: North Carolina Geological and Economic Survey, v. 3, p. 73–171, 258–290.

Stephenson, L.W., 1923, The Cretaceous formations of North Carolina; Part 1, Invertebrate fossils of the Upper Cretaceous formations, with a supplemental chapter on the decapod crustaceans of the Upper Cretaceous formations by M.J. Rathbun: North Carolina Geological and Economic Survey, v. 5, 604 p.

Stuiver, M., and Polach, H.A., 1977, Discussion reporting of ^{14}C data: Radiocarbon, v. 19, no. 3, p. 355–363.

Suther, B.E., Leigh, D.S., and Brook, G.A., 2011, Fluvial terraces of the Little River valley, Atlantic Coastal Plain, North Carolina: Southeastern Geology, v. 48, p. 73–93.

Talwani, P., and Cox, J., 1985, Paleoseismic evidence for recurrence of earthquakes near Charleston, South Carolina: Science, v. 229, no. 4711, p. 379–381, accessed May 2019 at https://doi.org/10.1126/science.229.4711.379.

Talwani, P., and Schaeffer, W.T., 2001, Recurrence rates of large earthquakes in the South Carolina Coastal Plain based on paleoliquefaction data: Journal of Geophysical Research, v. 106, no. B4, p. 6621–6642, accessed May 2019 at https://doi.org/10.1029/2000JB900398.

Tarr, A., and Wheeler, R., 2006, Earthquakes in Virginia and vicinity 1774–2004: U.S. Geological Survey Open-File Report 2006–1017, 1 sheet, scale 1:1,000,000.

Tsuchida, H., and Hayashi, S., 1971, Estimation of liquefaction potential of sandy soils, *in* Proceedings of the 3rd Joint Meeting, U.S.–Japan Panel on Wind and Seismic Effects: Cooperative Program in Natural Resources (UJNR), Tokyo, May 1971, p. 91–109.

Tuttle, M., and Seeber, L., 1991, Historic and prehistoric earthquake-induced liquefaction in Newberry, Massachusetts: Geology, v. 19, no. 6, p. 594–597, accessed May 2019 at https://doi.org/10.1130/0091-7613(1991)019<0594:HAPEIL>2.3.CO;2.

Tuttle, M.P., 2001, The use of liquefaction features in paleoseismology—Lessons learned in the New Madrid Seismic Zone, central United States: Journal of Seismology, v. 5, no. 3, p. 361–380, accessed May 2019 at https://doi.org/10.1023/A:1011423525258.

Tuttle, M.P., Carter, M.W., and Dunahue, J., 2015, Paleoliquefaction study of the earthquake potential of the Central Virginia Seismic Zone (CVSZ) [abs.]: Geological Society of America Abstracts with Programs, v. 47, no. 7, p. 466.

Valera, J.E., Traubenik, M.L., Egan, J.A., and Kaneshiro, J.Y., 1994, A practical perspective on liquefaction of gravels, *in* Prakash, S., and Dakoulas, P., eds., Ground failures under seismic conditions: American Society of Civil Engineers Geotechnical Special Publication 44, p. 241–257.

Ward, L.W., Bailey, R.H., and Carter, J.G., 1991, Pliocene and early Pleistocene stratigraphy, depositional history, and molluscan paleobiogeography of the coastal plain, *in* Horton, J.W., Jr., and Zullo, V.A., eds., The geology of the Carolinas: Carolina Geological Society, 50th Anniversary Volume, p. 274–289.

Ward, L.W., and Blackwelder, B.W., 1980, Stratigraphic revision of upper Miocene and lower Pliocene beds of the Chesapeake Group, middle Atlantic Coastal Plain: U.S. Geological Survey Bulletin 1482-D, 61 p.

Ward, L.W., Lawrence, D.R., and Blackwelder, B.W., 1978, Stratigraphic revision of the middle Eocene, Oligocene, and lower Miocene; Atlantic Coastal Plain of North Carolina: U.S. Geological Survey Bulletin 1457-F, 23 p.

Weems, R.E., and Edwards, L.E., 2007, Post-middle Miocene origin of modern landforms in the eastern piedmont of Virginia: Stratigraphy, v. 4, no. 1, p. 35–48.

Weems, R.E., Jacobson, R.B., Obermeier, S.F., Gohn, G.S., and Meyer, R., 1988, New radiocarbon ages from earthquake-induced liquefaction features in the lower coastal plain of the Carolinas [abs.]: Geological Society of America Abstracts with Programs, v. 20, no. 322.

Weems, R.E., and Obermeier, S.F., 1990, The 1886 Charleston earthquake—An overview of geological studies, *in* Proceedings of the 17th Water Reactor Safety Information Meeting: Nuclear Regulatory Commission, NUREG/CP-0105, v. 2, p. 289–313.

Weems, R.E., Obermeier, S.F., Pavich, M.J., Gohn, G.S., and Rubin, M., 1986, Evidence for three moderate to large prehistoric Holocene earthquakes near Charleston, South Carolina, *in* Proceedings of the 3rd U.S. National Conference on Earthquake Engineering, Charleston, South Carolina: Earthquake Engineering Research Institute, Oakland, Calif., v. 1, p. 3–13.

Wheeler, R.L., 2002, Distinguishing seismic from nonseismic soft-sediment features—Criteria from seismic hazard analysis, *in* Ettensohn, F.R., Rast, N., and Brett, C.E., eds., Ancient seismites: Geological Society of America Special Paper 359, p. 1–11, accessed May 2019 at https://doi.org/10.1130/0-8137-2359-0.1.

Youd, T.L., 1973, Liquefaction, flow and associated ground failure: U.S. Geological Survey Circular 688, 12 p.

Youd, T.L., 1984, Geologic effects—Liquefaction and associated ground failure, *in* Williams, M.E., Proceedings of the geologic and hydrologic hazards training program: U.S. Geological Survey Open File Report 84-760, p. 210–232.

Youd, T.L., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian, J.T., Dobry, R., Finn, W.D.L., Harder, L.F., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.S.C., Marcuson, W.F., III, Martin, G.R., Mitchell, J.K., Moriwaki, Y., Power, M.S., Robertson, P.K., Seed, R.B., and Stokoe, K.H., II, 2001, (reprinted 2003), Liquefaction resistance of soils—Summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils: Journal of Geotechnical and Geoenvironmental Engineering, v. 127, no. 10, p. 817–833, accessed May 2019 at https://doi.org/10.1061/(ASCE)1090-0241(2001)127:10(817).

Youd, T.L., and Perkins, D.M., 1978, Mapping liquefaction-induced ground failure potential: Journal of Geotechnical Engineering, v. 104, p. 433–446.

Appendixes

Appendix 1. Data for paleoliquefaction survey along the Tar and Neuse Rivers in central-eastern North Carolina, June 21–25, 2016.

Appendix 2. Radiocarbon data for a sample of organic matter from an alluvial bar deposit at the mouth of an abandoned river meander bend on the Neuse River, central-eastern North Carolina (NS-38.3: 35.2640°, –77.8874°).

Appendix 1. Data for paleoliquefaction survey along the Tar and Neuse Rivers in central-eastern North Carolina, June 21–25, 2016.

[Horizontal datum is the World Geodetic System (WGS 84); dd, decimal degrees; m, meters; cm, centimeters; dm, decimeters; mm, millimeters; nil, none; >, greater than; USGS, U.S. Geological Survey]

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
Tar-1.1	Exposure length	5 m	35.8939	−77.5292	June 21, 2016, at 10:47 AM
	Exposure height	3 m			
	Exposure quality	Excellent			
	Exposure setting	Riverbank outcrop on outside bend of river cutbank			
	General exposure description	Exposure of Cretaceous Cape Fear Formation semilithified sand and gravel; bedding from 1 dm- to ~0.5 m-thick; crossbedding sedimentary structures; top of cut covered			
	Liquefaction susceptibility of outcrop	Nil - sediment is too old, compacted, and semilithified			
Tar-2.1	Exposure length	5 m	35.8901	−77.5380	June 21, 2016, at 11:17 AM
	Exposure height	4 m			
	Exposure quality	Excellent			
	Exposure setting	Riverbank outcrop on outside bend of river cutbank			
	Photograph	Tar-2.1 Cretaceous sand and gravel.jpg			
	General exposure description	Exposure of Cretaceous Cape Fear Formation semilithified sand and gravel; bedding from 1 dm- to ~0.5 m-thick; crossbedding sedimentary structures; top of cut covered			
	Detailed stratigraphic description	Uppermost unit: clayey sand, about 2-m thick, top not exposed; middle unit: homogenous silty sand, about 1.5-m thick; lower unit: crossbedded sand, about 0.5 m exposed above waterline			
	Sedimentary structures	Crossbedding, on the order of decimeter-thick sets, mostly in the bottom-exposed unit (see photograph)			
	Liquefaction susceptibility of outcrop	Nil - sediment is too old, compacted, and semilithified			
Tar-3.1	Exposure length	100 m	35.8865	−77.5387	June 21, 2016, at 12:03 PM
	Exposure height	3 m			
	Exposure quality	Poor (vegetated)			
	Exposure setting	Inside bend of river; wedge of modern alluvium is a point bar deposit, but plastered onto an older flood-stage cutbank			
	General exposure description	Coharie terrace deposit, about 3-m thick, above what looks to be weathered Cretaceous Cape Fear Formation sand. There is a wedge of modern alluvium, floored by leaves and capped by silt, on a bench 2.5 m in width between the terrace sand and Cretaceous sand, about 80 cm in maximum thickness next to water level. Weathered Cretaceous sand is completely below water level.			
	Lowest unit thickness	Unknown, at least 1 m in auger hole and soil probe			
	Lowest unit grain size	Fine to medium sand			
	Lowest unit color	25YR 5/1			
	Lowest unit properties	Unconsolidated sand, likely weathered Cretaceous			
	Capping unit thickness	3 m			
	Capping unit grain-size	Silty sand			
	Capping unit color	25YR 5/3			
	Capping unit properties	Indurated when dry; mottled, with mottling several millimeters in diameter and 2.5YR 4/6 color, modern bioturbation.			
	Liquefaction susceptibility of outcrop	Low to nil - weathered Cretaceous sand is unconsolidated, completely saturated, and capped by finer-grained material, but the thickness of the unconsolidated Cretaceous sand is unknown, lithology beneath the sand layer is unknown, and the interpreted age of the sand (Cretaceous) would suggest it is already well packed, despite being unconsolidated			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
Tar-4.1	Exposure length	50 m	35.8781	−77.5386	June 21, 2016, at 12:21 PM
	Exposure height	3 m			
	Exposure quality	Poor (vegetated)			
	Exposure setting	Flood-stage cutbank			
	General exposure description	Coharie terrace deposit, about 2.5-m thick, above what looks to be weathered Cretaceous Cape Fear Formation sand. Weathered Cretaceous sand is partly above waterline by a few decimeters			
	Liquefaction susceptibility of outcrop	Low to nil - weathered Cretaceous sand is unconsolidated, but not completely saturated; and terrace material is slightly sandier than at last station.			
Tar-5.1	Exposure length	50 m	35.8750	−77.5357	June 21, 2016, at 12:45 PM
	Exposure height	3 m			
	Exposure quality	Poor			
	Exposure setting	Flood-stage cutbank			
	Photograph	Tar-5.1 mottled Coharie terrace.jpg			
	General exposure description	Mottled Coharie terrace deposit over likely weathered Cretaceous Cape Fear Formation sand, here medium to coarse grained. Still a wedge of modern alluvium, 90 cm at thickest near water			
	Lowest unit thickness	At least 50+ cm; base not exposed; sand is interpreted to be weathered Cretaceous-age material			
	Lowest unit grain size	Medium to coarse sand, from soil probe.			
	Lowest unit properties	Unconsolidated			
	Lowest unit sedimentary structures	Soil probe suggests sand is bedded, on scale of several centimeters per bed.			
	Capping unit thickness	3 m			
	Capping unit color	Yellowish mottles are 25YR 5/6; gray mottles are 25YR 7/2; all mottles are several centimeters in diameter			
	Capping unit grain-size	Silty fine sand			
	Capping unit properties	Homogenously mottled			
	Liquefaction susceptibility of outcrop	Low to nil - weathered Cretaceous sand is unconsolidated, completely saturated, and capped by finer-grained material, but the thickness of the unconsolidated Cretaceous sand is unknown, lithology beneath the sand layer is unknown, and the interpreted age of the sand (Cretaceous) would suggest it is already well packed, despite being unconsolidated			
Tar-6.1	Exposure length	5 m	35.8724	−77.5358	June 21, 2016, at 12:53 PM
	Exposure height	3 m			
	Exposure quality	Excellent			
	Exposure setting	Riverbank outcrop on outside bend of river cutbank			
	General exposure description	Exposure of Cretaceous Cape Fear Formation sand and gravel; highly indurated; top of cut covered			
	Liquefaction susceptibility of outcrop	Nil - sediment is too old, compacted, and indurated			
Tar-7.1	Exposure length	10 m	35.8683	−77.5346	June 21, 2016, at 1:02 PM
	Exposure height	3 m			
	Exposure quality	Excellent			
	Exposure setting	Riverbank outcrop on outside bend of river cutbank			
	General exposure description	Exposure of Cretaceous Cape Fear Formation sand and gravel; top of cut covered			
	Liquefaction susceptibility of outcrop	Nil - sediment is too old, compacted, and indurated			
Tar-8.1	Exposure length	50 m	35.8698	−77.5332	June 21, 2016, at 1:25 PM
	Exposure height	5 m			
	Exposure quality	Excellent			
	Exposure setting	Riverbank outcrop on outside bend of river cutbank			
	General exposure description	Exposure of Cretaceous Cape Fear Formation sand and gravel; sand beds are several meters thick, but iron-cemented and indurated; top of cut covered			
	Liquefaction susceptibility of outcrop	Nil - sediment is too old, compacted, and iron-cemented and indurated			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
Tar-9.1	Exposure length	50 m	35.8572	−77.5348	June 21, 2016, at 1:42 PM
	Exposure height	3 m			
	Exposure quality	Poor; vegetated and wedge of modern alluvium and colluvium at base			
	Exposure setting	Outside bend of river in an actively eroding cutbank (becomes colluviated between higher-flow events)			
	General exposure description	Coharie terrace-like deposit above Cretaceous Cape Fear Formation sand (which is beneath wedge of modern alluvium/colluvium - contact is not exposed). Wedge of modern alluvium/colluvium is 1.15-m thick			
	Lowest unit thickness	Unknown but at least 50-cm thick			
	Lowest unit grain size	Medium to coarse sand, from soil probe			
	Lowest unit sedimentary structures	Soil probe suggests sand is not bedded, or thick-bedded			
	Capping unit thickness	3+ m (top not exposed)			
	Capping unit grain-size	Silty fine sand			
	Capping unit color	10 YR 6/4			
	Capping unit properties	Very faint mottling			
	Liquefaction susceptibility of outcrop	Low to nil - weathered Cretaceous sand is unconsolidated, completely saturated, and capped by finer-grained material, but the thickness of the unconsolidated Cretaceous sand is unknown, lithology beneath the sand layer is unknown, and the interpreted age of the sand (Cretaceous) would suggest it is already well-packed, despite being unconsolidated			
Tar-10.1	Exposure length	30 m	35.8419	−77.5443	June 21, 2016, at 2:27 PM
	Exposure height	5 m			
	Exposure quality	Excellent			
	Exposure setting	Riverbank outcrop on inside bend of river flood-stage cutbank			
	General exposure description	Exposure of Cretaceous Cape Fear Formation sand and gravel			
	General stratigraphic description	Beds of Cretaceous sand are 1 to 2-m thick; uppermost sand bed, just below covered root mass at surface, has well-developed soil profile with mottles in the B horizon (soil is developed in Cretaceous sand bed, not younger Coharie terrace as in previous outcrops)			
	Liquefaction susceptibility of outcrop	Nil - sediment is too old and compacted			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
Tar-11.1	Exposure length	5 m	35.8372	−77.5460	June 21, 2016, at 3:14 PM
	Exposure height	4 m (upper 2 m colluviated and slumped)			
	Exposure quality	Fair (sediments are extremely mottled)			
	Exposure setting	Actively eroding cutbank on outside river bend			
	Photographs	Tar-11.1.1 possible sand dike along root cast.jpg; Tar-11.1.2 possible sand dikes in cypress knee casts.jpg			
	General exposure description	Mottled sandy silt, weathered Cretaceous sand down to at least 110 cm below water level			
	Lowest unit thickness	Unconsolidated to at least 110 cm			
	Lowest unit grain size	Medium sand			
	Lowest unit properties	Consolidated at depth (about 1.5 m below water level)			
	Host unit thickness	2.5 meters, but upper part of this unit is colluviated and slumped			
	Host unit grain-size	Sandy silt			
	Host unit color	Mottles are 10YR 5/4 and the gray reduced zones, including the thin dikes are 10YR 7/1			
	Host unit properties	Mottled and somewhat stiff			
	Liquefaction susceptibility of outcrop	Low - weathered Cretaceous sand is unconsolidated, completely saturated, and capped by finer- grained material, thickness of the unconsolidated Cretaceous sand is known, lithology beneath the sand layer is unknown but consolidated, but the interpreted age of the sand (Cretaceous) would suggest it is already well-packed, despite being unconsolidated			
	Liquefaction features	Three small possible dikes, one is vertical and looks to be intruded along a cypress root cast; the other two are far less distinct, and may be filling cypress root casts (oblong in shape)			
	General description of features	Three thin features along cypress root casts and branching up from them			
	Type of feature (and number)	Three - one is clear, other two are in indistinct within mottling			
	Strike/dip of dikes	283/85 for clearest and most vertical of three features			
	Width and height of dikes	1-cm thick × ~0.5-m high for vertical feature; 1-dm × 3 cm in plan view for oblong features - scraping the cut shows all three taper away within centimeters of the surface			
	Termination of dikes	Single vertical feature appears to branch upward toward surface after about 0.5 m			
	Depth of termination or deformation below surface	At least 5 m (estimation to top of cut)			
	Penetration height into host strata	0.5 m from water level up, but if sourced from weathered Cretaceous sand below, 160 cm total			
	Grain-size of dike or sill	Silty fine sand			
	Soil development or chemical weathering	Discontinuous iron oxide rind on margin, about 1-mm thick at thickest point			
	Distance between similar features	1.5 m between vertical dike in photo #1 and sand-filled cypress knee casts; about 30 cm between the sand-filled cypress knee casts			
	Interpretation of features	Although it's possible that these are liquefaction features, the low potential for the sediment in the outcrop to liquefy, and the fact that the sand in the dikes can't be definitively traced to a source bed (that's interpreted from the soil probe and auger), suggests these features (particularly the sand-filled cypress knee casts) may be filled in from above, or are geochemical/pedogenic features (vertical dike-like feature)			
Tar-12.1	Exposure length	50 m	35.8283	−77.5477	June 21, 2016, at 3:49 PM
	Exposure height	5 m			
	Exposure quality	Excellent			
	Exposure setting	Riverbank outcrop on inside bend of river flood-stage cutbank			
	General exposure description	Exposure of Cretaceous Cape Fear Formation sand and gravel; sand and gravel are completely lithified here			
	Liquefaction susceptibility of outcrop	Nil - sediment is too old and lithified			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
Tar-13.1	Exposure length	50 m	35.8032	−77.5489	June 21, 2016, at 4:48 PM
	Exposure height	5 m (upper 2 m colluviated and slumped)			
	Exposure quality	Fair			
	Exposure setting	Actively eroding cutbank on outside river bend			
	General exposure description	Mottled Coharie terrace sediment above Cretaceous sand, but contact is under water and below colluvial wedge at base of crop; wedge of colluvium is 1.2-m thick at water line			
	Lowest unit thickness	1.2+ m below water level; total thickness unknown			
	Lowest unit grain size	Generally medium sand in coarser-grained units, from soil probe			
	Lowest unit sedimentary structures	Soil probe suggests sand is bedded, on the order of ~decimeter-thick beds, and separated by centimeter-thick finer-grained beds			
	Capping unit thickness	>3 m			
	Capping unit grain size	Silty very fine sand			
	Capping unit color	25YR 6/4, but weakly mottled			
	Capping unit properties	Stiff (semilithified when dry) and weakly mottled			
	Liquefaction susceptibility of outcrop	Low to nil - weathered Cretaceous sand is unconsolidated, completely saturated, and capped by finer-grained material, but the thickness of the unconsolidated Cretaceous sand is unknown and (from soil probe) alternates between sand and finer-grained beds; the interpreted age of the sand (Cretaceous) would suggest it is already well-packed, despite being unconsolidated			
Tar-14.1	Exposure length	25 m	35.7955	−77.5512	June 21, 2016, at 5:04 PM
	Exposure height	4 m			
	Exposure quality	Excellent			
	Exposure setting	Riverbank outcrop on inside bend of river flood-stage cutbank			
	General exposure description	Exposure of Cretaceous Cape Fear Formation sand and gravel; sand and gravel are well indurated			
	Liquefaction susceptibility of outcrop	Nil - sediment is too old and indurated			
Tar-15.1	Exposure length	50 m	35.7850	−77.5491	June 21, 2016, at 5:32 PM
	Exposure height	7+ m			
	Exposure quality	Excellent			
	Exposure setting	Actively eroding cutbank outcrop on outside bend of river			
	Photograph	Tar-15.1 Yorktown Formation fossiliferous sand.jpg			
	General exposure description	Exposure of Pliocene Yorktown Formation fossiliferous sand			
	Detailed stratigraphic description	Uppermost unit: clayey silt, about 1.5- m thick, with abundant *Chesapecten*, *Turritella*, and *Ostrea* fossils and phosphate pebbles, top not exposed; middle unit: grayish crossbedded sand, about 1.5-m thick (but only lower 0.5 m is crossbedded); lower unit: olive gray to light gray clayey silt, about 3 m exposed; base of section at waterline is covered by colluvium from above			
	Liquefaction susceptibility of outcrop	Nil - fossiliferous sediment is nonliquefiable; sand is too old and compacted			
NS-16.2	Exposure length	50 m	35.3568	−78.1356	June 22, 2016, at 10:00 AM
	Exposure height	2.5 m			
	Exposure quality	Good			
	Exposure setting	Actively eroding outside bend of river			
	General exposure description	Riverbank outcrop of Cretaceous Cape Fear Formation exposed alternating layers of clay and ferricrete, with more ferricrete below water level, and sand at 120 cm below water level			
	Lowest unit thickness	Sand at base may just be an interbed within this package			
	Lowest unit grain size	Lowest unit at 120 cm below water level is medium sand; ferricrete units exposed are silty fine sand, unsorted, with some medium sand.			
	Lowest unit sedimentary structures	Bedding for sandy units is ~1 dm thick			
	Lowest unit color	Clay is 10YR 6/1; ferricrete sand is 7.5YR 6/4			
	Liquefaction susceptibility of outcrop	Nil - ferricrete and iron cementation should severely restrict liquefaction; age would suggest sand is too compacted to liquefy			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-17.2	Exposure length	5 m	35.3552	−78.1327	June 22, 2016, at 10:12 AM
	Exposure height	1 m			
	Exposure quality	Good			
	Exposure setting	Actively eroding cutbank outcrop on outside bend of river			
	Photograph	NS-17.2 basal Cape Fear Fm contact with Piedmont basement.jpg			
	General exposure description	Basal contact between the Cape Fear Formation and underlying eastern Piedmont rocks			
	Detailed stratigraphic description	Uppermost unit: subangular quartz gravel; middle unit: iron-stained and clayey, with rounded pebbles; lower unit: weathered granitoid-like rock			
	Liquefaction susceptibility of outcrop	Nil - no units here capable of liquefaction			
NS-18.2	Exposure length	20 m	35.3581	−78.1305	June 22, 2016, at 10:41 AM
	Exposure height	2.5 m			
	Exposure quality	Good			
	Exposure setting	Actively eroding cutbank outcrop on outside bend of river			
	General exposure description	Terrace sand above granitic basement, which is 45 cm below water level			
	Detailed stratigraphic description	~3 m of fine to medium sand, with color of 10YR 4/3; unconsolidated and mottled throughout, and bioturbated			
	Liquefaction susceptibility of outcrop	Nil - grain size is correct, but no capping strata to contain pore-pressure			
NS-19.2	Exposure length	15 m	35.3500	−78.1263	June 22, 2016, at 11:07 AM
	Exposure height	2 m			
	Exposure quality	Good			
	Exposure setting	Flood-stage river cutbank			
	General exposure description	Terrace above granitoid basement; bed of sand at base of terrace (or weathered granite at top of granite - soil probe data only)			
	Detailed stratigraphic description	Upper unit: 2.5 m of fine sand; unconsolidated and mottled; mottles are ~5 mm in diameter; red mottles are 10R 4/3; color for reduced gray is 7.5YR 7/1; lower unit: at 1.2 m below water level, medium to coarse sand (soil probe only); sand layer is about 1-dm thick, then probe refusal. Sand likely weathered granite on top of less weathered granite but could be basal sand unit at contact.			
	Liquefaction susceptibility of outcrop	Nil - no capping strata to contain pore-pressure in fine sand, and intense mottling (iron precipitation reduces susceptibility			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-20.2	Exposure length	15 m	35.3630	−78.1211	June 22, 2016, at 11:42 AM
	Exposure height	2 m			
	Exposure quality	Good			
	Exposure setting	Point bar accumulation of modern alluvium on inside bend of river			
	General exposure description	Three units in outcrop: upper fine sand; middle medium sand (crossbedded and soft-sediment deformed) and lower gray silt. Soil probe suggests similar packages of thin interbedded sand at depth within lower silt, to 1.2 cm			
	Capping unit grain size	Fine sand			
	Capping unit color	Gray reduced zones of 10YR 10/1 with reddish brown mottles of 5YR 4/4			
	Capping unit thickness	2 m			
	Capping unit properties	Unconsolidated and mottled			
	Host unit thickness	15 cm			
	Host unit grain size	Fine to medium sand			
	Host unit sedimentary structures	Crossbedding and soft sediment deformation features			
	Lowest unit thickness	1.7 m			
	Host unit color	25YR 7/4			
	Lowest unit grain size	Silt			
	Lowest unit properties	Unconsolidated, with mottles			
	Liquefaction susceptibility of outcrop	Marginal - stratigraphy is generally correct, but basal silt likely too permeable, and permeability of capping fine sand is likely not much different than that of the host fine- to medium sand			
	Liquefaction features	Soft sediment deformation features, but likely from deposition and not coseismic			
	Type of feature (and number)	Few pseudonodules, but mostly load casts			
	Description of soft-sediment features	Load casts are at the base and a few pseudonodules are along the top of thin, 15-cm-thick sand unit within the middle sand layer			
	Distance between similar features	10 cm			
	Liquefiable unit grain size	Silty fine sand			
	Liquefiable unit color	7.5YR 5/1 for predominantly gray sand; mottles are 2.5YR 4/6			
	Interpretation of features	Depositional setting in an alluvial point bar of likely Holocene age suggests these soft sediment deformation features are likely of syndepositional sedimentary origin rather than coseismic			
NS-21.2	Exposure length	10 m	35.3640	−78.1089	June 22, 2016, at 12:29AM
	Exposure height	2 m			
	Exposure quality	Poor (vegetated)			
	Exposure setting	River cutbank on outside bend of river			
	Photograph	NS-21.2 Cape Fear Fm x-bedded sand.jpg			
	General exposure description	Cape Fear Formation sand and gravel			
	Detailed stratigraphic description	~1.8 m of crossbedded sand and fine gravel, very arkosic (thus Cape Fear-like rather than younger terrace sand and gravel unit) and semilithified from clay content from the weathering of feldspars; ~2 dm of coarser-grained gravel beneath water level, then soil probe refusal (likely Piedmont basement)			
	Liquefaction susceptibility of outcrop	Nil - stratigraphy is incorrect (no capping strata) and sand-and-gravel unit is semilithified			
NS-22.2	Exposure length	10 m	35.3671	−78.1043	June 22, 2016, at 1:02 PM
	Exposure height	3 m			
	Exposure quality	Poor (vegetated)			
	Exposure setting	River cutbank on outside bend of river			
	Photograph	NS-22.2 alluvium above Piedmont felsic rock.jpg			
	General exposure description	Modern alluvium above quartz-rich felsite Piedmont basement rock			
	Detailed stratigraphic description	~1.5+ m of alluvial sand and fine gravel, above ~1.5 m of felsite; 044°/80° southeast for foliation in felsite (with joints parallel to foliation) and 123°/66° southwest, 272°/50° north, and 130°/88° southwest for dominant joint sets.			
	Liquefaction susceptibility of outcrop	Nil - alluvial sand ~1.5 m above river level (in other words, not saturated at normal river flow), and no capping layer			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-23.2	Exposure length	15 m	35.3778	−78.1021	June 22, 2016, at 1:38 PM
	Exposure height	3 m			
	Exposure quality	Good			
	Exposure setting	Actively eroding cutbank on outside bend of river			
	General exposure description	Monotonous section of mottled silty fine alluvial sand above foliated gneiss (bedrock) at 50 cm below water level			
	Detailed stratigraphic description	~3.5 m of unconsolidated, silty fine sand, mottled, with reduced gray sand 5Y 7/1 and mottles 7.5YR 5/6; likely bioturbated too; soil probe refusal at 50 cm below water level (likely Piedmont basement)			
	Liquefaction susceptibility of outcrop	Nil - alluvial sand has no capping stratigraphy			
NS-24.2	Exposure length	10 m	35.3812	−78.0625	June 22, 2016, at 3:19 PM
	Exposure height	2+ m exposed above water level, but upper part of outcrop is slumped			
	Exposure quality	Fair			
	Exposure setting	Outside bend of river			
	General exposure description	Silty mottled sand over a thin bed of sand at base (below water level, about 10 cm thick, 65 cm below water level			
	Detailed stratigraphic description	~2.75 m of silty, very fine sand, unconsolidated and mottled (25YR 7/2; mottles are 5YR 5/4) above a more than 10-cm-thick bed of fine- to medium sand			
	Liquefaction susceptibility of outcrop	Marginal to high – Greater than 10-cm-thick bed of alluvial sand at depth is saturated, and capped by a finer-grained and lower permeability unit			
	Liquefaction features	None observed			
NS-25.2	Exposure length	10 m	35.3783	−78.0557	June 22, 2016, at 3:42 PM
	Exposure height	3+ m			
	Exposure quality	Fair			
	Exposure setting	Actively eroding outside bend of river			
	Photograph	NS-25.2 polygonal cracks in clayey silt.jpg			
	General exposure description	Silty clay alluvium with network of polygonal cracks			
	Detailed stratigraphic description	~2.8 m of unconsolidated and mottled silty clay (fresh is 5Y 7/1; mottles are 7.5 YR 5/6), above 10 dm of fine to medium sand ~70 cm below water level and above soil probe refusal. This outcrop may be capped by a younger stratigraphic unit consisting of yellowish-brown mottled sand (Coharie-like deposit), but the interpretation here is that this is a cutbank of Holocene alluvium			
	Liquefaction susceptibility of outcrop	Marginal to high – Greater than 10-cm-thick bed of alluvial sand at depth is saturated, and capped by a finer-grained and lower permeability unit			
	Liquefaction features	None observed			
	Other structures observed	Network of polygonal cracks, decimeter- to meter-scale, filled with mottled clayey silt; these are interpreted to be a product of desiccation or shrink-swell pedogenesis			
NS-26.2	Exposure length	50 m	35.3769	−78.0556	June 22, 2016, at 3:55 PM
	Exposure height	5+ m			
	Exposure quality	Excellent			
	Exposure setting	Actively eroding outside bend of river			
	General exposure description	Outcrop of Cape Fear Formation indurated sand and gravel			
	Liquefaction susceptibility of outcrop	Nil - sand is too old and lithified			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-27.2	Exposure length	50 m	35.3752	−78.0530	June 22, 2016, at 3:55 PM
	Exposure height	5+ m			
	Exposure quality	Excellent			
	Exposure setting	Actively eroding outside bend of river			
	Photograph	NS-27.2 Black Creek Fm thin bedded sand.jpg			
	General exposure description	Outcrop of Cretaceous bedded sand; darker gray color, finer-grain size and thinner bedding suggest this is part of the Black Creek Formation rather than the coarser-grained, more arkosic, and thicker-bedded (and crossbedded) Cape Fear Formation			
	Detailed stratigraphic description	Bedding is 087°/12° southeast; beds range from several decimeters to about 0.5-m thick; very indurated and lithified			
	Liquefaction susceptibility of outcrop	Nil - sand is too old and lithified			
NS-28.2	Exposure length	20 m	35.3701	−78.0651	June 22, 2016, at 4:30 PM
	Exposure height	1.5 m			
	Exposure quality	Excellent			
	Exposure setting	Actively eroding outside bend of river			
	Photograph	NS-28.2 Black Creek Fm laminated to thin-bedded sand.jpg			
	General exposure description	Outcrop of Cretaceous laminated to thin-bedded lithified sand of the Black Creek Formation			
	Detailed stratigraphic description	Laminated to thin-bedded sand is sulfidic and lithified			
	Liquefaction susceptibility of outcrop	Nil - sand is too old and lithified			
NS-29.2	Exposure length	10 m	35.3705	−78.0659	June 22, 2016, at 4:41 PM
	Exposure height	1.5 m			
	Exposure quality	Excellent			
	Exposure setting	Actively eroding outside bend of river			
	General exposure description	Outcrop of Cretaceous crossbedded sand			
	Detailed stratigraphic description	Crossbeds are 064°/27° southeast; crossbedding, lighter-colored, and coarser-grained sand suggest this is Cape Fear Formation again (contact between this and last outcrop)			
	Liquefaction susceptibility of outcrop	Nil - sand is too old and lithified			
NS-30.2	Exposure length	15 m	35.3661	−78.0682	June 22, 2016, at 4:59 PM
	Exposure height	3.5 m			
	Exposure quality	Fair			
	Exposure setting	Actively eroding outside bend of river			
	Photographs	NS-30.2.1 Black Creek Fm laminated lignitic sand.jpg; NS-30.2.2 Black Creek Fm laminated lignitic sand over x-bedded Cape Fear Fm.jpg; NS-30.2.3 channel of Coharie terrace sand cutting Cape Fear and Black Creek Fm.jpg			
	General exposure description	Outcrop of Cretaceous Cape Fear Formation at base, overlain by Black Creek Formation, with a cap of likely Coharie terrace deposit			
	Detailed stratigraphic description	~2 m of white, crossbedded sand (Cape Fear Formation), overlain by ~0.5 m of thin-bedded, darker gray sand (Black Creek Formation); upper unit: pebble line with Piedmont-derived clasts at base (at contact with Black Creek Formation), with ~1.5+ m of light brown sand above the gravel.			
	Liquefaction susceptibility of outcrop	Nil - Cretaceous sand is too old and lithified; terrace sand is not saturated, and not capped by finer-grained unit			
NS-31.3	Exposure length	300 m	35.2620	−77.9041	June 23, 2016, at 9:21 AM
	Exposure height	2 m			
	Exposure quality	Excellent			
	Exposure setting	Actively eroding outside bend of river			
	General exposure description	Wall of Cretaceous sand; darker gray color suggests Black Creek Formation			
	Liquefaction susceptibility of outcrop	Nil - Cretaceous sand is too old and lithified			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-32.3	Exposure length	50 m (but continuation of wall of outcrop from last station)	35.2642	−77.8994	June 23, 2016, at 9:32 AM
	Exposure height	2+ m			
	Exposure quality	Excellent			
	Exposure setting	Outside bend of river, near mouth of tributary stream			
	Photograph	NS-32.3 Holocene alluvium plastered to Cretaceous outcrop.jpg			
	General exposure description	Wall of gray Cretaceous sand, with a deposit of modern (Holocene) alluvial sand plastered to outcrop, likely derived from nearby creek discharge			
	Liquefaction susceptibility of outcrop	Nil - Cretaceous sand is too old and lithified; alluvial sand is too thin (<0.5 m thick)			
NS-33.3	Exposure length	20 m	35.2688	−77.8992	June 23, 2016, at 9:55 AM
	Exposure height	1 m exposed below top-of-cut slumping			
	Exposure quality	Excellent			
	Exposure setting	Inside bend of river, active deposition of alluvial bar deposit			
	Photograph	NS-33.3 bedded point bar deposit.jpg			
	General exposure description	Modern point bar deposit; Cretaceous outcrop on other side of river			
	Detailed stratigraphic description	Modern point bar composed of essentially all sand, with organic interbeds; pile is approximately 1-m thick, with about 5-cm thick for individual sand beds; sand is very fine- to fine-grained, fresh 2.5 GY 8/1; red stained is 2.5YR 7/6; micaceous, medium sand bed at 80 cm below water level; organic zone, ~3-cm thick, at water line, soil probe suggests a few more below waterline and at depth			
	Sedimentary structures observed	Low-angle cross-laminations, with bioturbated root casts throughout; millimeter-thick organic mud drapes on cross beds			
	Liquefaction susceptibility of outcrop	Low to marginal - saturated medium sand at depth may be sufficiently capped by finer-grained sand and organic beds above water level; this deposit is likely too young to have experienced a large-magnitude earthquake			
NS-34.3	Exposure length	20 m	35.2752	−77.8960	June 23, 2016, at 10:45 AM
	Exposure height	3 m			
	Exposure quality	Excellent			
	Exposure setting	Actively eroding outside bend of river			
	Photograph	NS-34.3 Soil profile developed in Cretaceous sand.jpg			
	General exposure description	Soil profile developed in light gray Cretaceous sand			
	Detailed stratigraphic description	Basal unit of Cretaceous sand is gravelly coarse sand, >50-cm thick (base covered), with color of 10YR 7/6; pebbles in basal unit are subrounded to well rounded, about a centimeter in diameter, and consist mostly of quartz; middle unit consists of about 15 cm of medium to coarse sand, with color of 10YR 8/1; upper unit consists of 15 cm of medium to coarse sand, color N/7, with rounded pebbles about 5 mm in diameter; angular transition from B soil horizon to C soil horizon is top of this upper unit			
	Pedogenic description	B soil profile developed in Cretaceous sand is >2.5-m thick, consists of sandy silty clay with color of N/6 (mottling is 2.5 YR 7/6), indurated when dry, appears to contain small precipitations of calcareous material			
	Liquefaction susceptibility of outcrop	Low to nil - clay-rich B soil horizon could act as a capping unit to less indurated sands beneath, but these are well packed already because of their age			
NS-35.3	Exposure length	50 m	35.2686	−77.8905	June 23, 2016, at 11:22 AM
	Exposure height	5 m			
	Exposure quality	Very good			
	Exposure setting	Actively eroding outside bend of river			
	Photograph	NS-35.3 Section of Cretaceous sand and gravel.jpg			
	General exposure description	Exposure of Cretaceous sand, with climbing ripples within sand beds			
	Liquefaction susceptibility of outcrop	Nil - age and packing of Cretaceous sand negates liquefaction susceptibility			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-36.3	Exposure length	300 m	35.2693	−77.8861	June 23, 2016, at 11:51 AM
	Exposure height	4+ m (upper 2 m may be a B1 horizon)			
	Exposure quality	Good			
	Exposure setting	Actively eroding outside bend of river			
	General exposure description	Thick section of weathered B horizon above Cretaceous sand, which is ~75 cm below water level, and is >10-cm thick			
	Pedogenic description	B soil horizon developed above Cretaceous sand is a gray silty clay (7.5 Y 8/1), mottled (2.5 YR 6/8) and indurated when dry; uppermost part of exposure could be a B1 horizon, as it is less mottled and more massive than the lower (B2?) Horizon			
	Liquefaction susceptibility of outcrop	Low to nil - clay-rich B soil horizon could act as a capping unit to less indurated sands beneath, but these are well packed already because of their age			
NS-37.3	Exposure length	75 m	35.2677	−77.8886	June 23, 2016, at 12:00 PM
	Exposure height	3 m			
	Exposure quality	Excellent			
	Exposure setting	Actively eroding outside bend of river			
	Photograph	NS-37.3 Coharie terrace sand.jpg			
	General exposure description	Terrace medium to coarse sand; bedded, with bedding decimeters thick			
	Liquefaction susceptibility of outcrop	Low to nil - no capping stratigraphy to contain elevated pore pressure during an earthquake			
NS-38.3	Exposure length	15 m	35.2640	−77.8874	June 23, 2016, at 12:20 PM
	Exposure height	2.5 m			
	Exposure quality	Very good			
	Exposure setting	Inside bend of river at mouth of abandoned river meander, now occupied by a modern stream			
	Photographs	NS-38.3.1 bedding in alluvium.jpg; NS-38.3.2 outcrop of alluvium at mouth of abandoned river meander bend.jpg			
	Samples	Leaf litter from an organic layer within gray silty clay for radiocarbon analysis; age is 120±25 years B.P. (historical); Jack McGeehan, USGS Radiocarbon lab			
	General exposure description	Silty clay with thin organic layers throughout, above a medium-grained sand layer at 20 cm below water level; sand (may be Cretaceous) continues for another 20 cm; above silty clay is alternating several centimeters- to decimeter-thick beds of sand and silty clay			
	Liquefiable unit thickness	>20 cm, but 20 cm below water level			
	Liquefiable unit grain size	Medium sand			
	Host unit thickness	40 cm (20 cm is below water level)			
	Host unit grain-size	Silty clay			
	Host unit color	N 6/0			
	Host unit properties	Seams of thin organic leaf litter throughout			
	Capping unit thickness	2 m, with upper 1 m of developed soil.			
	Capping unit grain size	Sandy beds are micaceous very fine sand; interbedded silty clay is slightly micaceous			
	Capping unit color	Sand beds are 2.5YR 7/3 silty clay beds are 2.5 Y 7/1			
	Capping unit properties	Slightly mottled, unconsolidated			
	Capping unit sedimentary structures	Bedding is several centimeters- to decimeters-thick and alternating between sand and silty clay			
	Liquefaction susceptibility of outcrop	Marginal to high - saturated and liquefiable sand beneath silty clay			
	Liquefaction features	Soft sediment deformation features within silty clay			
	Type of feature (and number)	Few pseudonodules, but mostly load casts			
	Interpretation of features	Age (historical) and depositional setting in an alluvial bar at the mouth of an abandoned river meander indicates soft sediment deformation features are of syndepositional sedimentary origin rather than coseismic			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-39.3	Exposure length	100 m	35.2603	−77.8892	June 23, 2016, at 12:55 PM
	Exposure height	5 m			
	Exposure quality	Fair (vegetated at top of cut)			
	Exposure setting	Actively eroding outside bend of river			
	Photograph	NS-39.3 Coharie terrace sand above dark Black Creek Fm sand.jpg			
	General exposure description	~1.5 m of very dark gray to brownish black, organic-rich, lignitic, thin-bedded sand (Cretaceous Black Creek Formation) beneath 3.5+ m of light-yellow gravelly sand (Coharie terrace deposit)			
	Liquefaction susceptibility of outcrop	Low to nil - terrace sand above Cretaceous lithified lignitic sand is not saturated, and no capping stratigraphy to contain elevated pore pressure during an earthquake			
NS-40.3	Exposure length	75 m	35.2544	−77.8846	June 23, 2016, at 1:30 PM
	Exposure height	5 m			
	Exposure quality	Fair (vegetated at top of cut)			
	Exposure setting	Actively eroding outside bend of river			
	General exposure description	Very dark gray clay, interbedded with brownish black, organic-rich, lignitic, thin-bedded sandstone (Cretaceous Black Creek Formation) beneath light yellow, crossbedded gravelly sand (Coharie terrace deposit)			
	Liquefaction susceptibility of outcrop	Low to nil - terrace sand above Cretaceous is not saturated, and no capping stratigraphy to contain elevated pore pressure during an earthquake			
NS-41.3	Exposure length	10 m	35.2581	−77.8821	June 23, 2016, at 1:58 PM
	Exposure height	2 m			
	Exposure quality	Good (mottled)			
	Exposure setting	Actively eroding outcrop on outside bend of river			
	Photograph	NS-41.3 section from silty sand into mottled b horizon.jpg			
	General exposure description	Terrace sand at base, and sand extends least 1 m below water level; mottled B horizon caps unconsolidated sand; upper 50 cm of scraped cut is heavily mottled; mottles decrease with depth			
	Liquefiable unit thickness	At least 1 m			
	Liquefiable unit grain size	Very fine silty sand, micaceous			
	Liquefiable unit color	5 bp 7/1			
	Capping unit grain size	Silty clay, slightly micaceous, mica content decreases upwards			
	Capping unit thickness	1 m scraped, and at least 1 m above			
	Capping unit color	Gray is 5R 7/1; mottles are 2.5 YR 7/6			
	Capping unit properties	Indurated when dry; mottles decrease with depth			
	Pedogenic description	May be two B horizon profiles here (B1 and B2 - in other words, buried soil horizon)			
	Liquefaction susceptibility of outcrop	Marginal - very fine silty sand may liquefy; capping unit is essentially the B soil horizon			
NS-42.3	Exposure length	10 m	35.2518	−77.8789	June 23, 2016, at 2:27 PM
	Exposure height	2 m to top of cut			
	Exposure quality	Good			
	Exposure setting	Flood-stage river cutbank			
	Photograph	NS-42.3 brown legacy sediments above older alluvium.jpg			
	General exposure description	Mottled gray clayey silt, beneath a brown legacy unit			
	Detailed stratigraphic description	Upper unit: 60 cm of 7.5 YR 7/6 clayey silt; lower unit: 1.5 m (to waterline) of mottled silty clay (2.5 Y 7/2; mottles are 2.5 Y 6/8); indurated when dry			
	Liquefaction susceptibility of outcrop	Nil - silty clay not susceptible to liquefaction			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-43.3	Exposure length	30 m	35.2483	−77.8807	June 23, 2016, at 2:39 PM
	Exposure height	2.5 m to top of cut			
	Exposure quality	Good			
	Exposure setting	Flood-stage river cutbank			
	Photographs	NS-43.3.1 terrace sand above Cretaceous Black Creek Fm.jpg; NS-43.3.2 terrace sand above Cretaceous Black Creek Fm.jpg			
	General exposure description	~0.5 m of dark brownish-gray thin- bedded sand (Cretaceous Black Creek Formation) beneath 2 m of yellowish thicker-bedded sand			
	Liquefaction susceptibility of outcrop	Low to nil - terrace sand above Cretaceous material has no capping stratigraphy			
NS-44.3	Exposure length	50 m	35.2425	−77.8803	June 23, 2016, at 2:57 PM
	Exposure height	5 m to top of cut, but upper 3 m vegetated and slumped			
	Exposure quality	Good			
	Exposure setting	Actively eroding cutbank on outside bend of river			
	Photograph	NS-44.3 terrace sand above Cretaceous Black Creek Fm.jpg			
	General exposure description	~2 m of thin-bedded dark gray lignitic sand (Black Creek Formation) beneath 3+ m of yellow sand (Coharie terrace deposit)			
	Liquefaction susceptibility of outcrop	Low to nil - terrace sand above Cretaceous material has no capping stratigraphy			
NS-45.3	Exposure length	100 m	35.2402	−77.8837	June 23, 2016, at 3:02 PM
	Exposure height	15 m to top of cliff, much slumping and vegetation			
	Exposure quality	Good			
	Exposure setting	Actively eroding cutbank on outside bend of river			
	Photograph	NS-45.3 Cretaceous Black Creek Fm at Cliffs of the Neuse State Park.jpg			
	General exposure description	At Cliffs of the Neuse State Park, Cretaceous Black Creek Formation from water level to possibly 13 m, ~2 m of Coharie terrace deposit at top of cut; other units may be between, but not accessible			
	Liquefaction susceptibility of outcrop	Nil - Cretaceous Black Creek Formation is well lithified; stratigraphy above Cretaceous Black Creek Formation is well above waterline and zone of saturation, even in flood stage			
NS-46.3	Exposure length	10 m	35.2325	−77.8752	June 23, 2016, at 3:34 PM
	Exposure height	3+ m			
	Exposure quality	Good			
	Exposure setting	Flood-stage river cutbank			
	General exposure description	Alluvial (terrace?) sediment; Cretaceous material is across river (south side)			
	Detailed stratigraphic description	Sandy clayey silt is 3-m thick, color 10YR 7/6, unconsolidated, mottled, but not indurated like Cretaceous units and B horizon soil profiles			
	Liquefaction susceptibility of outcrop	Nil - too fine-grained, too clayey, no capping stratigraphy			
NS-47.3	Exposure length	100 m	35.2291	−77.8669	June 23, 2016, at 3:49 PM
	Exposure height	15 m			
	Exposure quality	Excellent			
	Exposure setting	Actively eroding river cutbank			
	Photographs	NS-47.3.1 outcrop of Cretaceous Black Creek Fm.jpg; NS-47.3.2 contact between Black Creek Fm and Yorktown Fm.jpg			
	General exposure description	15-m high cliff, with Cretaceous Black Creek Formation lithified thin-bedded sandstone at the base, and light brown sandy unit above, which may be western facies of Yorktown Formation rather than a terrace deposit			
	Detailed stratigraphic description	At least 6 m of Cretaceous material in cliff, lower 4 m is lithified; upper 3 to 9 m may be sandy facies of Yorktown Formation; may be Coharie terrace deposit at very top of cut			
	Sedimentary structures observed	Soft sediment deformation features (primarily load casts) in beds of Cretaceous age			
	Liquefaction susceptibility of outcrop	Nil - sandy units too high above water level, and capping stratigraphy is absent			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-48.4	Exposure length	2 m	35.3089	−77.9477	June 24, 2016, at 8:30 AM
	Exposure height	Bank is 2.5-m high, but only about 1 m of sediment exposed; an additional 1.4 m of stratigraphy determined with auger			
	Exposure quality	Fair			
	Exposure setting	Alluvial point-bar bank on inside bend of river			
	General exposure description	Alluvial stratigraphy with liquefiable sediments at depth (no features)			
	Liquefiable unit thickness	>20 cm			
	Liquefiable unit grain size	Fine to medium sand, beneath ~1.4 cm of silty very fine sand of 10YR 7/2 color			
	Capping unit thickness	30 cm exposed, but another 2 m covered to top of bank			
	Capping unit grain size	Sandy silty clay			
	Capping unit color	Clay is N7/0; mottles are 2.5YR 6/8			
	Capping unit properties	Unconsolidated and mottled			
	Capping unit sedimentary structures	May be bedded, but too mottled to demonstrate			
	Liquefaction susceptibility of outcrop	Marginal to high - sand of proper consistency and saturation beneath cap of lower permeability; cap may be too thick (impede liquefaction)			
NS-49.4	Exposure length	50 m	35.3067	−77.9504	June 24, 2016, at 8:42 AM
	Exposure height	5 m			
	Exposure quality	Good			
	Exposure setting	Flood-stage cutbank on inside bend of river			
	General exposure description	Cretaceous sand at water level, beneath alluvium or more likely terrace deposit of sand; large sand and gravel operation on flat above			
	Liquefaction susceptibility of outcrop	Nil - sandy units too high above water level, and capping stratigraphy is absent			
NS-50.4	Exposure length	7 m	35.3059	−77.9524	June 24, 2016, at 9:06 AM
	Exposure height	2.5 m but lower 1.5 m is rubble/colluvium			
	Exposure quality	Good			
	Exposure setting	Actively eroding (and colluviating) outside bend of river			
	Photograph	NS-50.4 cross bedded sand and gravel.jpg			
	General exposure description	Crossbedded sand and gravel may be Quaternary Coharie Formation of Stevenson (1912)			
	Detailed stratigraphic description	3 m total (including 1.4 m with soil probe below water level) of fine to medium sand, color 2.5 YR 7/8, with coarse sand to pebble zones or pods within crossbeds			
	Sedimentary structures observed	Well crossbedded; basal gravel has clasts of sericitic quartz schist within it, so it is locally sourced			
	Liquefaction susceptibility of outcrop	Nil - all sand, and much of it too coarse for liquefaction; no cap			
NS-51.4	Exposure length	30 m	35.2978	−77.9508	June 24, 2016, at 9:36 AM
	Exposure height	6 m			
	Exposure quality	Excellent			
	Exposure setting	Flood-stage cutbank on inside bend of river			
	Photographs	NS-51.4.1 outcrop of Coharie terrace over Black Creek Fm.jpg; NS-51.4.2 contact between Coharie terrace and Black Creek Fm.jpg; NS-51.4.3 contact between Coharie terrace and Black Creek Fm.jpg			
	General exposure description	Cretaceous Black Creek Formation at water level to about 2.5 m, terrace deposit (Coharie Formation of Stevenson, 1912) above to top of cut			
	Liquefaction susceptibility of outcrop	Nil - sandy units too high above water level, and capping stratigraphy is absent			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-52.4	Exposure length	10 m	35.2966	−77.9489	June 24, 2016, at 10:12 AM
	Exposure height	2 m exposed above colluvial fan at base. Colluvial wedge is about 50-cm thick at cliff face			
	Exposure quality	Good			
	Exposure setting	Actively eroding and colluviating river cutbank on outside bend of river			
	Photograph	NS-52.4 mottled silty fine sand.jpg			
	General exposure description	Uppermost part of outcrop mottled silty fine sand, with a 20-cm-thick sand lens			
	Detailed stratigraphic description	From augering, at 130 cm below surface (base of slope, 50 cm above waterline) is gray silty clay N 5/0 at least 10-cm thick; above is 130 cm of silty clayey very fine sand, interbedded with fine to medium sand, at decimeter scale, with color of 10YR 6/6; exposed above waterline is mottled silty clay (2.5 GY 8/1, with red mottles 10YR 7/8); all units are micaceous; within mottled silty clay is a fine silty sand lens, about 1.5-dm thick and 30-cm long; no connectivity to sand in lens to interbedded fine to medium sand at depth; most likely a channel			
	Liquefaction susceptibility of outcrop	Marginal to high - fine- to medium-grained sand beds at depth are saturated, with capping stratigraphy (although cap may be too thick and impede liquefaction)			
	Observed features	Fine silty sand lens, about 1.5-dm thick and 30-cm long, within mottled silty fine sand; no connectivity to sand in lens to interbedded fine to medium sand at depth; most likely a channel			
NS-53.4	Exposure length	20 m	35.2851	−77.9428	June 24, 2016, at 10:53 AM
	Exposure height	2 m exposed, but 1.5 m above to surface is covered in vegetation, and ~1 m of colluvium at base of cut			
	Exposure quality	Fair			
	Exposure setting	Actively eroding and colluviating river cutbank on outside bend of river			
	Photographs	NS-53.4.1 Coharie with developed soil profile.jpg; NS-53.4.2 Coharie with developed soil profile.jpg; NS-53.4.3 Coharie with developed soil profile.jpg; NS-53.4.4 Coharie with developed soil profile.jpg			
	General exposure description	Upper unit is mottled, and likely B horizon to soil profile; middle unit composed of sand and gravel of Coharie terrace deposit; at 1 m below water level is soil probe refusal - likely hard Cretaceous beds			
	Detailed stratigraphic description	Lower unit: 2 m of crossbedded sand and gravel, medium to coarse sand, pebbly, containing muscovite, color 7.5 YR 6/6 well crossbedded, with grading from gravel to medium sand along crossbeds; upper unit: 1 m exposed (but upper 1+ m is rooted and slumped) of 7.5 Y 8/3 silty clay (mottles are 2.5YR 6/8), indurated when dry			
	Liquefaction susceptibility of outcrop	Marginal - sand beneath silty clay is susceptible to liquefaction, and saturated, but may be too much iron (reddish color); B horizon clay cap may be too thick (impedes liquefaction)			
NS-54.4	Exposure length	10 m	35.2818	−77.9346	June 24, 2016, at 11:26 AM
	Exposure height	4 m			
	Exposure quality	Good			
	Exposure setting	Flood-stage cutbank			
	General exposure description	Crossbedded sand and gravel likely be Coharie deposit			
	Liquefaction susceptibility of outcrop	Nil - sandy units too high above water level, and capping stratigraphy is absent			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-55.4	Exposure length	10 m	35.2818	−77.9325	June 24, 2016, at 11:26 AM
	Exposure height	4 m			
	Exposure quality	Good			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	Photograph	NS-55.4 manganese precipitation lines in sand.jpg			
	General exposure description	Crossbedded sand and gravel likely be Coharie deposit			
	Detailed stratigraphic description	Unconsolidated fine- to medium-grained, crossbedded sand with gravel lenses, capped by mottled clayey silt (likely B horizon)			
	Pedogenic features observed	Sand contains thin (less than millimeter-thick) argillic horizons, modified by manganese/iron precipitation, from surface water percolating downwards through permeable sand			
	Liquefaction susceptibility of outcrop	Marginal - sand beneath silty clay is susceptible to liquefaction and is saturated, but may contain too much iron (reddish color); B horizon clay cap may be too thick (impedes liquefaction)			
NS-56.4	Exposure length	10 m	35.2798	−77.9330	June 24, 2016, at 11:57 AM
	Exposure height	~1.5 m			
	Exposure quality	Good			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	Photograph	NS-56.4 shelf of dark gray silty clay.jpg			
	General exposure description	Cretaceous fine-grained sand with shell molds (start of Peedee Formation?) Beneath Coharie sand			
	Detailed stratigraphic description	Cretaceous dark gray silty clay (approximately 50 cm exposed above water line) contains shell molds; crossbedded sand and gravel (Coharie) caps Cretaceous material, but is less than a meter thick			
	Liquefaction susceptibility of outcrop	Nil - sandy units too high above water level, and capping stratigraphy is absent			
NS-57.4	Exposure length	60 m	35.2796	−77.9365	June 24, 2016, at 12:16 PM
	Exposure height	5+ m			
	Exposure quality	Good			
	Exposure setting	Flood-stage cutbank			
	Photographs	NS-57.4.1 outcrop of Coharie sand over Black Creek Fm.jpg; NS-57.4.2 wood fragments in Black Creek Fm.jpg; NS-57.4.3 Coharie sand and gravel.jpg; NS-57.4.4 contact between Coharie and Black Creek.jpg; NS-57.4.5 wood fragments in Black Creek Fm.jpg			
	General exposure description	Cretaceous fine-grained sand with wood fragments and debris beneath well-preserved section of Coharie sand			
	Detailed stratigraphic description	~50 cm of Cretaceous medium- to coarse-grained sand, color 10YR 7/8, in beds about a decimeter thick, interbedded with layers of carbonized wood fragments; above is at least 5 m of yellow (10YR 7/4) medium- to coarse-grained sand, pebbly, with few metamorphic clasts within the gravel component, trough crossbedding throughout			
	Liquefaction susceptibility of outcrop	Nil - sandy unit is too coarse-grained and capping stratigraphy is absent			
NS-58.4	Exposure length	50 m	35.2797	−77.9407	June 24, 2016, at 12:37 PM
	Exposure height	5+ m			
	Exposure quality	Excellent			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	General exposure description	Crossbedded sand and gravel			
	Liquefaction susceptibility of outcrop	Nil - sandy unit is too coarse-grained and capping stratigraphy is absent			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-59.4	Exposure length	10 m	35.2775	−77.9404	June 24, 2016, at 12:54 PM
	Exposure height	3 m			
	Exposure quality	Good			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	Photographs	NS-59.4.1 soil profile developed on Coharie sand.jpg; NS-59.4.2 outcrop of soil profile developed on Coharie sand.jpg; NS-59.4.3 soil profile developed on Coharie sand.jpg			
	General exposure description	2 m of mottled silty clay above 50+ cm of fine to medium sand.			
	Detailed stratigraphic description	50 cm (from waterline upwards) of fine to medium sand, color 2.5 YR 7/4, crossbedded, with some specks of organic material (reworked Cretaceous material?); capped by 2+ m of mottled silty clay, color N 8/0 (mottles are 7.5YR 6/8), indurated when dry, likely B horizon to soil profile developed on Coharie terrace deposit			
	Liquefaction susceptibility of outcrop	Marginal to high - sand beneath silty clay is susceptible to liquefaction and is saturated; B horizon clay cap, however, may be too thick (impedes liquefaction)			
NS-60.4	Exposure length	20 m	35.2767	−77.9392	June 24, 2016, at 1:10 PM
	Exposure height	3 m			
	Exposure quality	Good			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	Photograph	NS-60.4 mottled silty clay with indistinct root casts.jpg			
	General exposure description	1+ m of mottled silty clay above 50+ cm of fine to medium sand.			
	Pedogenic features observed	Root casts are common in mottled silty clay, but all are filled with clayey silt or very fine-grained sand, and none are filled with sand that can be demonstrably linked to sand beds at depth			
	Liquefaction susceptibility of outcrop	Marginal to high - sand beneath silty clay is susceptible to liquefaction and is saturated; B horizon clay cap, however, may be too thick (impedes liquefaction)			
NS-61.4	Exposure length	50 m	35.2761	−77.9376	June 24, 2016, at 1:16 PM
	Exposure height	4+ m			
	Exposure quality	Good			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	General exposure description	Yellowish-orange crossbedded sand and gravel			
	Liquefaction susceptibility of outcrop	Nil - sandy unit is too coarse-grained and capping stratigraphy is absent			
NS-62.4	Exposure length	100 m	35.2710	−77.9355	June 24, 2016, at 1:38 PM
	Exposure height	5+ m			
	Exposure quality	Excellent			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	Photographs	NS-62.4.1 outcrop of K beneath yellow sand.jpg; NS-62.4.2 contact between K below and yellow sand above.jpg			
	General exposure description	Cretaceous organic silty sand beds beneath a thick section of yellowish-orange crossbedded sand and gravel			
	Liquefaction susceptibility of outcrop	Nil - sandy unit is too coarse-grained and capping stratigraphy is absent			
NS-63.4	Exposure length	30 m	35.2689	−77.9391	June 24, 2016, at 1:49 PM
	Exposure height	3+ m			
	Exposure quality	Good			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	General exposure description	Yellowish-orange crossbedded sand and gravel to river level			
	Liquefaction susceptibility of outcrop	Nil - sandy unit is too coarse-grained and capping stratigraphy is absent			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-64.4	Exposure length	75 m	35.2693	−77.9415	June 24, 2016, at 2:07 PM
	Exposure height	3+ m			
	Exposure quality	Good			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	Photographs	NS-64.4.1 outcrop of Coharie sand and gravel above K.jpg; NS-64.4.2 outcrop of Coharie sand and gravel above K.jpg; NS-64.4.3 K bedded organic silty sand.jpg; NS-64.4.4 crossbeds in organic K beds.jpg; NS-64.4.5 clay beds at top of cut.jpg			
	General exposure description	~1.5 m of very dark gray to brownish-black organic-rich, lignitic, thin-bedded sand (Cretaceous Black Creek Formation) beneath 1.5+ m of light-yellow gravelly sand (Coharie terrace deposit); upper portion of Coharie (uppermost 0.5 m of outcrop) consists of alternating several decimeter-thick beds of sand/gravel and silty clay			
	Liquefaction susceptibility of outcrop	Low - sand/gravel beds at top of cut are likely too coarse-grained to liquefy readily, and too high above water level, but caps (silty clay beds) are present			
NS-65.4	Exposure length	5 m	35.2666	−77.9377	June 24, 2016, at 2:38 PM
	Exposure height	~3 m before vegetated top of cut (another 2 m of soil and vegetation to top of cut)			
	Exposure quality	Good			
	Exposure setting	Flood-stage cutbank			
	Photographs	NS-65.4.1 pedogenic Bt horizon over x-bedded sand.jpg; NS-65.4.2 pedogenic Bt horizon over x-bedded sand.jpg			
	General exposure description	Mottled silty clay capping crossbedded yellow sand			
	Detailed stratigraphic description	1.8 m (50 cm exposed above waterline, 1.3 m below water line) of medium to coarse sand, 7.5YR 6/8, below 1 m of well-exposed - hard material (top of Cretaceous stratigraphy) at 130 cm below waterline.			
	Liquefaction susceptibility of outcrop	High - saturated sand is beneath clay cap (clay cap may be too thick); this outcrop should respond to lateral spreading during a quake, as sand would liquefy and the clay cap would begin to spread; no evidence for any type of liquefaction in cut, however			
NS-66.4	Exposure length	10 m	35.2652	−77.9342	June 24, 2016, at 2:46 PM
	Exposure height	3+ m			
	Exposure quality	Good			
	Exposure setting	Flood-stage cutbank			
	Photograph	NS-66.4 x-bedded sand and gravel.jpg			
	General exposure description	Yellowish-orange crossbedded sand and gravel to river level			
	Liquefaction susceptibility of outcrop	Nil - sandy unit is too coarse-grained and capping stratigraphy is absent			
NS-67.4	Exposure length	50 m	35.2642	−77.9332	June 24, 2016, at 3:02 PM
	Exposure height	4 m			
	Exposure quality	Excellent			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	General exposure description	Outcrop of Cretaceous Black Creek Formation			
	Detailed stratigraphic description	At least 4 m of lignitic sand and beds of woody fragments, no yellow crossbedded sand, nor Paleocene-Eocene stratigraphy above Cretaceous stratigraphy			
	Liquefaction susceptibility of outcrop	Nil – Cretaceous material is semilithified			
NS-68.4	Exposure length	10 m	35.2642	−77.9329	June 24, 2016, at 3:13 PM
	Exposure height	4 m			
	Exposure quality	Good			
	Exposure setting	Actively eroding river cutbank along steep cliff face			
	General exposure description	Outcrop of Cretaceous Black Creek Formation with yellow sand and gravel above			
	Liquefaction susceptibility of outcrop	Nil - Cretaceous material is semilithified; sand and gravel above is too coarse-grained, not saturated, and capping stratigraphy is absent			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-69.4	Exposure length	5 m	35.2642	−77.9321	June 24, 2016, at 3:33 PM
	Exposure height	1 m			
	Exposure quality	Poor (vegetated and colluviated)			
	Exposure setting	Actively eroding river cutbank along steep cliff face			
	Photograph	NS-69.4 location of fault separating K from Eo.jpg			
	General exposure description	Fault separating Cretaceous stratigraphy to west from Eocene stratigraphy to east located in this colluviated drainage			
	Liquefaction susceptibility of outcrop	Nil - colluviated riverbank			
NS-70.4	Exposure length	50 m	35.2642	−77.931	June 24, 2016, at 3:30 PM
	Exposure height	10 m			
	Exposure quality	Excellent			
	Exposure setting	Actively eroding river cutbank along steep cliff face			
	Photograph	NS-70.4 Eocene limestone.jpg			
	General exposure description	At least 10 m of medium-grained to finely crystalline limestone, alternating with decimeter- to meter-thick beds of glauconitic-bearing sand and gray clay			
	Liquefaction susceptibility of outcrop	Nil - limestone is crystalline			
NS-71.4	Exposure length	40 m	35.2642	−77.9307	June 24, 2016, at 3:44 PM
	Exposure height	3+ m			
	Exposure quality	Excellent			
	Exposure setting	Actively eroding river cutbank along steep cliff face			
	Photographs	NS-71.4.1 K at water level beneath lower T.jpg; NS-71.4.2 K at water level beneath lower T.jpg			
	General exposure description	~3 m of glauconitic-bearing sand and gray clay above lignitic Cretaceous beds at water level; phosphate pebbles along unconformity between Cretaceous and lower Tertiary unit			
	Liquefaction susceptibility of outcrop	Nil - Tertiary sediments are too old and well-compacted to liquefy			
NS-72.4	Exposure length	10 m	35.2632	−77.923	June 24, 2016, at 4:16 PM
	Exposure height	2+ m			
	Exposure quality	Poor (colluviated)			
	Exposure setting	Flood-stage cutbank			
		Lignitic Cretaceous beds at water level; colluviated blocks of phosphate pebble conglomerate from higher on slope; may be yellow sand unit at very top of cut			
	General exposure description	Nil - Cretaceous and Tertiary sediments are too old, lithified, and well compacted to liquefy; yellow			
	Liquefaction susceptibility of outcrop	Sand too high in cut (if present), not saturated, and no capping strata			
NS-73.4	Exposure length	10 m	35.2611	−77.913	June 24, 2016, at 4:35 PM
	Exposure height	2+ m			
	Exposure quality	Excellent			
	Exposure setting	River cutbank on slight outside bend of river			
	Photographs	NS-73.4.1 Eo Castle Hayne limestone.jpg; NS-73.4.2 Eo Castle Hayne limestone.jpg			
	General exposure description	Exposure of Eocene Castle Hayne Formation limestone			
	Liquefaction susceptibility of outcrop	Nil - limestone is crystalline			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-74.4	Exposure length	30 m	35.2610	−77.9103	June 24, 2016, at 4:48 PM
	Exposure height	3+ m			
	Exposure quality	Poor (colluviated)			
	Exposure setting	Flood-stage cutbank			
	Photographs	NS-74.4.1 outcrop of T beneath Coharie terrace.jpg; NS-74.4.2 lower T glauconitic sand.jpg			
	General exposure description	Glauconitic sand at water-level; slump blocks of reddish-yellow sand and gravel above			
	Liquefaction susceptibility of outcrop	Nil - lower Tertiary sand is too compacted to liquefy; yellow sand above is not saturated, and not capped by lower permeability unit			
NS-75.5	Exposure length	20 m	35.2564	−77.5905	June 25, 2016, at 8:18 AM
	Exposure height	3+ m			
	Exposure quality	Good			
	Exposure setting	Actively eroding river cutbank along steep cliff face			
	Photograph	NS-75.5 K Peedee beneath Coharie.jpg			
	General exposure description	~1 m of dark brownish-gray clayey sand with shell fragments (Cretaceous Peedee Formation) beneath 2+ m of yellow crossbedded sand and gravel			
	Liquefaction susceptibility of outcrop	Nil - Cretaceous sand is too compacted to liquefy; yellow sand above is not saturated, and not capped by lower permeability unit			
NS-76.5	Exposure length	10 m	35.2533	−77.5871	June 25, 2016, at 8:35 AM
	Exposure height	2.5 m			
	Exposure quality	Poor			
	Exposure setting	Flood-stage cutbank			
	Photographs	NS-76.5.1 silty fine mottled sand beneath x-bedded yellow fine to medium sand.jpg; NS-76.5.2 silty fine mottled sand beneath x-bedded yellow fine to medium sand.jpg			
	General exposure description	50 cm of crossbedded sand above mottled silty fine sand, 50 cm exposed above waterline, and another 1.4 m below (from soil probe)			
	Liquefaction susceptibility of outcrop	Nil - silty fine sand is saturated, but cap above (crossbedded sand) is of higher permeability; no cap above crossbedded sand			
NS-77.5	Exposure length	10 m	35.2510	−77.5858	June 25, 2016, at 8:45 AM
	Exposure height	2.5 m			
	Exposure quality	Poor			
	Exposure setting	Flood-stage cutbank			
	General exposure description	Crossbedded sand above mottled silty fine sand			
	Liquefaction susceptibility of outcrop	Nil - silty fine sand is saturated, but cap above (crossbedded sand) is of higher permeability; no cap above crossbedded sand			
NS-78.5	Exposure length	20 m	35.2439	−77.5808	June 25, 2016, at 8:56 AM
	Exposure height	5 m			
	Exposure quality	Poor			
	Exposure setting	Actively eroding river cutbank			
	Photograph	NS-78.5 Coharie yellow x-bedded sand and gravel.jpg			
	General exposure description	Yellow crossbedded sand and gravel at water-level; Cretaceous Peedee Formation is not exposed			
	Liquefaction susceptibility of outcrop	Nil - sandy unit is too coarse-grained and capping stratigraphy is absent			
NS-79.5	Exposure length	100 m	35.2401	−77.5682	June 25, 2016, at 9:22 AM
	Exposure height	5 m			
	Exposure quality	Excellent			
	Exposure setting	River cutbank on slight outside bend of river			
	Photograph	NS-79.5 long wall of K Peedee Fm.jpg			
	General exposure description	~2.5 m of dark brownish-gray clayey sand with shell fragments (Cretaceous Peedee Formation) beneath 2+ m of yellow crossbedded sand and gravel			
	Liquefaction susceptibility of outcrop	Nil - Cretaceous sand is too compacted to liquefy; yellow sand above is not saturated, and not capped by lower permeability unit			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-80.5	Exposure length	30 m	35.2403	−77.5623	June 25, 2016, at 9:35 AM
	Exposure height	8+ m			
	Exposure quality	Excellent			
	Exposure setting	River cutbank on slight outside bend of river			
	Photographs	NS-80.5.1 outcrop of K Peedee Fm beneath Coharie.jpg; NS-80.5.2 outcrop of K Peedee Fm beneath Coharie.jpg; NS-80.5.3 contact between K Peedee Fm beneath Coharie sand and gravel.jpg			
	General exposure description	4 m of dark brownish-gray clayey sand with shell fragments (Cretaceous Peedee Formation) beneath 4+ m of yellow and reddish-brown crossbedded sand and gravel			
	Liquefaction susceptibility of outcrop	Nil - Cretaceous sand is too compacted to liquefy; yellow sand and gravel above is too coarse-grained, not saturated, and not capped by lower permeability unit			
NS-81.5	Exposure length	10 m	35.2411	−77.5604	June 25, 2016, at 9:44 AM
	Exposure height	3 m			
	Exposure quality	Excellent			
	Exposure setting	River cutbank on slight outside bend of river			
	Photograph	NS-81.5 contact between K Peedee Fm beneath Coharie sand and gravel.jpg			
	General exposure description	1.5 m of dark brownish-gray clayey sand with shell fragments (Cretaceous Peedee Formation) beneath 1.5 m of yellow and reddish brown crossbedded sand and gravel			
	Liquefaction susceptibility of outcrop	Nil - Cretaceous sand is too compacted to liquefy; yellow sand and gravel above is too coarse-grained, not saturated, and not capped by lower permeability unit			
NS-82.5	Exposure length	10 m	35.2484	−77.5552	June 25, 2016, at 10:02 AM
	Exposure height	2 m			
	Exposure quality	Fair			
	Exposure setting	River cutbank on outside bend of river			
	General exposure description	Yellow crossbedded sand and gravel above a gray clay			
	Detailed stratigraphic description	Alluvial clay typically has beds of leaf litter; this clay contains no leaf litter, and is likely part of the Peedee Formation			
	Liquefaction susceptibility of outcrop	Nil - Cretaceous clay is nonliquefiable; yellow sand and gravel above is too coarse-grained, not saturated, and not capped by lower permeability unit			
NS-83.5	Exposure length	15 m	35.2491	−77.5509	June 25, 2016, at 10:29 AM
	Exposure height	4+ m			
	Exposure quality	Good			
	Exposure setting	River cutbank on outside bend of river			
	Photograph	NS-83.5 mottled silty sand b horizon above bedded sand.jpg			
	General exposure description	Mottled silty sand above a medium to coarse sand, bedded, with ferricrete layers at base of beds			
	Detailed stratigraphic description	2 m (from water line up) of medium-grained sand (2.5Y 6/8), bedded and crossbedded (decimeter-thick beds), beneath 2 m of gray (7.5YR 6/2) silty sand, mottled (mottles are 7.5YR 7/8), indurated when dry (B soil horizon to C horizon sand beneath)			
	Liquefaction susceptibility of outcrop	Low to marginal - unconsolidated sand beneath silty sand is of the proper grain-size and consistency to liquefy, and is capped by a lower permeability unit; ferricrete layers would impede liquefaction, and cap may be too thick			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-84.5	Exposure length	15 m	35.2480	−77.5488	June 25, 2016, at 11:09 AM
	Exposure height	2 m exposed above colluvium at base			
	Exposure quality	Good			
	Exposure setting	River cutbank at downstream end of an outside bend of river			
	Photographs	NS-84.5.1 geochemical weathering front in x-bedded sand.jpg; NS-84.5.2 geochemical weathering front in x-bedded sand.jpg; NS-84.5.3 geochemical weathering front in x-bedded sand.jpg; NS-84.5.4 geochemical weathering front in x-bedded sand.jpg			
	General exposure description	Clay cap is 1.5-m thick, sand beneath includes 50 cm exposed above water line and another 40 cm below water line, with gravel base (gravel base determined by augering)			
	Detailed stratigraphic description	Gravel layer at base; 70 cm of white (5Y 8/2), unconsolidated, coarse- to medium-grained sand, grading upward into a more reddish (7.5YR 8/6) medium sand (medium-grained sand is slightly indurated owing to iron precipitation; bedding in sand about 1-dm thick, and beds are crossbedded; upper unit is 1.5-m thick, gray (5Y 7/1) sandy clay, and mottled (mottles are 7.5YR 7/6), indurated when dry; sandy clay is likely part of the Coharie package, but also may be B horizon to C horizon sand below			
	Pedogenic features observed	Geochemical weathering front gives the appearance of liquefaction (pseudoliquefaction: coarse white sand appears to swell up or intrude into reddish sand, beneath the clay cap); transition is a weathering front: 7 cm at widest point, 15-cm high, splits in two branches, then runs along base of clay, like a thin sand sill; crossbeds extend from reddish silty sand into white sand, across the weathering front			
	Liquefaction susceptibility of outcrop	Marginal to high - unconsolidated sand beneath sandy clay cap is liquefiable: of the proper grain size and consistency to liquefy, and is capped by a lower permeability unit; gravel at base may allow pore-pressure to dissipate, and cap may be too thick			
NS-85.5	Exposure length	10 m	35.2466	−77.5403	June 25, 2016 at 11:26 AM
	Exposure height	2 m			
	Exposure quality	Fair			
	Exposure setting	River cutbank on outside bend of river			
	General exposure description	Outcrop of Cretaceous Peedee Formation			
	Liquefaction susceptibility of outcrop	Nil - Cretaceous sediments are nonliquefiable			
NS-86.5	Exposure length	30 m	35.2475	−77.5396	June 25, 2016, at 11:32 AM
	Exposure height	8+ m			
	Exposure quality	Excellent			
	Exposure setting	River cutbank on outside bend of river			
	Photograph	NS-86.5 outcrop of Coharie clay, sand, and gravel.jpg			
	General exposure description	Outcrop of Coharie clay, sand, and gravel			
	Detailed stratigraphic description	8 m of bedded sand; beds are decimeters-thick, crossbedded, and graded-bedded with gravel lenses; about 2 m above water line is a 30-cm-thick bed of stiff gray clay; no soft sediment deformation features at the base of the clay, or liquefaction dikes observed cutting through the clay			
	Liquefaction susceptibility of outcrop	Marginal to high - stiff gray clay within sand sequence caps sand of proper consistency and grain size to liquefy, but no features observed			
NS-87.5	Exposure length	20 m	35.2535	−77.5381	June 25, 2016, at 11:47 AM
	Exposure height	2 m			
	Exposure quality	Fair			
	Exposure setting	River cutbank on outside bend of river			
	General exposure description	Mottled gray clay over gravel bed at 90 cm below water line			
	Detailed stratigraphic description	2.9 m of 7.5Y 8/1 gray clay, mottled (mottles are 2.5 YR 6/8) above a gravel bed, 90 cm below water line			
	Liquefaction susceptibility of outcrop	Nil - clay above gravel will not liquefy			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-88.5	Exposure length	10 m	35.2546	−77.5325	June 25, 2016, at 12:02 PM
	Exposure height	2 m			
	Exposure quality	Good			
	Exposure setting	River cutbank on outside bend of river			
	Photographs	NS-88.5.1 contact between K Peedee and Pe Jerico Run.jpg; NS-88.5 outcrop of K Peedee and Pe Jericho Run.jpg			
	General exposure description	Paleocene Jerico Run silicified mudstone over Cretaceous Peedee Formation			
	Liquefaction susceptibility of outcrop	Nil - units too old and lithified to liquefy			
NS-89.5	Exposure length	20 m	35.2563	−77.5315	June 25, 2016, at 12:29 PM
	Exposure height	2 m			
	Exposure quality	Fair			
	Exposure setting	Flood-stage cutbank			
	General exposure description	Mottled gray clay above medium sand, 110 cm below waterline			
	Detailed stratigraphic description	Medium-grained sand (from soil probe), more than 5-cm thick, underlies 3.1 m (1.1 m below water line, from soil probe) of silty clay; exposed gray (5Y 7/1) silty clay above water line is mottled (mottles are 7.5 YR 6/4)			
	Liquefaction susceptibility of outcrop	Marginal - medium-grained sand at depth is saturated, but silty clay cap may be too thick; contact between the two units is not exposed, and no liquefaction dikes were observed in the cap above the water line			
NS-90.5	Exposure length	5 m	35.2634	−77.5232	June 25, 2016, at 12:57 PM
	Exposure height	2.5 m			
	Exposure quality	Fair			
	Exposure setting	River cutbank on outside bend of river			
	General exposure description	Mottled gray clay			
	Detailed stratigraphic description	At least 1 m of clay below water line; no sand beds at depth			
	Liquefaction susceptibility of outcrop	Nil - clay is nonliquefiable, and no sand beds at depth to liquefy			
NS-91.5	Exposure length	10 m	35.2630	−77.5179	June 25, 2016, at 1:21 PM
	Exposure height	2 m			
	Exposure quality	Good			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	Photographs	NS-91.5.1 load casts at base of clay over sand.jpg; NS-91.5.2 load casts at base of clay over sand.jpg			
	General exposure description	Mottled clay over crossbedded sand			
	Detailed stratigraphic description	Gravel base (soil probe refusal); above gravel is 0.5 m (30 cm below waterline) of 2.5 YR 6/1 coarse sand; above coarse sand is 2 m (to top of cut) of 10YR 6/1 mottled silty clay (mottles are 10YR 6/6), well indurated when dry			
	Sedimentary structures observed	Load casts at base of clay into sand below, penetrating about 10 cm into sand at deepest point; likely depositional rather than coseismic; load casts demonstrate that clay is part of depositional package rather than a clay-rich B soil horizon			
	Liquefaction susceptibility of outcrop	Marginal - coarse-grained sand at depth is partly saturated (and fully saturated at normal river flow), but silty clay cap may be too thick; gravel base may allow pore-pressure dissipation			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-92.5	Exposure length	10 m	35.2635	−77.5172	June 25, 2016, at 1:26 PM
	Exposure height	1.5 m			
	Exposure quality	Good			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	Photographs	NS-92.5.1 load casts at base of clay over sand.jpg; NS-92.5.2 load casts at base of clay over sand.jpg			
	General exposure description	Mottled clay over crossbedded coarse sand and gravel			
	Detailed stratigraphic description	30 cm of coarse-grained gravelly sand, crossbedded, beneath 1+ m of well indurated mottled silty clay			
	Sedimentary structures observed	Load casts at base of clay into sand below, penetrating about 5 cm into sand at deepest point; likely depositional rather than coseismic; load casts demonstrate that clay is part of depositional package rather than a clay-rich B soil horizon			
	Liquefaction susceptibility of outcrop	Low - sand is partly saturated (and fully saturated at normal river flow), but coarser-grained and pebbly; silty clay cap may be too thick			
NS-93.5	Exposure length	100+ m	35.2667	−77.5136	June 25, 2016, at 2:01 PM
	Exposure height	2 m			
	Exposure quality	Good			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	General exposure description	Clay over coarse sand (soil probe) at 140 cm below water level; total thickness of sand bed is unknown			
	Detailed stratigraphic description	3 m of gray (5B 6/1) and mottled (2.5 YR 6/6) silty clay, with decimeter-scale nodules of manganese, caps coarse sand at 140 cm below water level			
	Liquefaction susceptibility of outcrop	Low - sand is saturated, but may be too coarse-grained to liquefy; silty clay cap may be too thick; contact between the two units is not exposed, and no liquefaction dikes were observed in the cap above the water line			
NS-94.5	Exposure length	200 m	35.2654	−77.5103	June 2, 2016, at 2:13 PM
	Exposure height	1.5 m			
	Exposure quality	Good			
	Photograph	NS-94.5 outcrop of interbedded sand and clay.jpg			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	General exposure description	Interbedded sand and clay			
	Detailed stratigraphic description	Sand at 1.3 m below water level; mottled gray silty clay above sand, and is 3.2-m thick; at top of clay is thin-bedded sand and clay, ~1-dm-thick (beds are centimeter-scale); sand bed, ~1-dm-thick, at top of cutbank; manganese nodules in fine-grained units			
	Liquefaction susceptibility of outcrop	Marginal to high - sand is saturated, but may be too coarse-grained to liquefy; silty clay cap may be too thick; thin-bedded alternating sand and clay beds at top of cut are not saturated, but may be at normal flow; no liquefaction dikes or soft-sediment structures were observed			
NS-95.5	Exposure length	50 m	35.2710	−77.5075	June 25, 2016, at 2:27 PM
	Exposure height	2.5 m			
	Exposure quality	Good			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	General exposure description	Clay and sand			
	Detailed stratigraphic description	Clay is 2.7-m thick (1.2 m below water level to hard pan at depth - likely lithified Cretaceous or Paleocene sediments); 60 cm of bedded and crossbedded sand caps clay at top of cut			
	Liquefaction susceptibility of outcrop	Nil - clay is not liquefiable; no sand at depth; sand at top of cut is not saturated, and is not capped by lower permeability unit			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-96.5	Exposure length	50 m	35.2721	−77.5086	June 25, 2016, at 2:36 PM
	Exposure height	2 m			
	Exposure quality	Good			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	General exposure description	Clay above sand at depth (and below water line)			
	Detailed stratigraphic description	2 m of mottled clay above waterline, but extends to 90 cm below waterline; below clay is medium to coarse sand and gravel of unknown thickness			
	Liquefaction susceptibility of outcrop	Marginal - sand is saturated, but may be too coarse-grained to liquefy; silty clay cap may be too thick; contact between the two units is not exposed, and no liquefaction dikes were observed in the cap above the water line			
NS-97.5	Exposure length	10 m	35.2740	−77.5109	June 25, 2016, at 2:44 PM
	Exposure height	2.5 m			
	Exposure quality	Poor			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	General exposure description	Clay			
	Liquefaction susceptibility of outcrop	Nil - all clay			
NS-98.5	Exposure length	20 m	35.2764	−77.5109	June 25, 2016, at 2:53 PM
	Exposure height	2 m			
	Exposure quality	Fair (partly colluviated)			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	Photograph	NS-98.5 gravel contact between K Peedee and Q Coharie.jpg			
	General exposure description	Cretaceous Peedee Formation clay beneath yellow sand and gravel; gravel at base of sand unit			
	Liquefaction susceptibility of outcrop	Nil - Cretaceous clay won’t liquefy; sand and gravel too coarse, and not capped			
NS-99.5	Exposure length	20 m	35.2778	−77.5076	June 25, 2016, at 3:12 PM
	Exposure height	2 m			
	Exposure quality	Fair			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	General exposure description	Mottled silty very fine sand			
	Detailed stratigraphic description	3.2 m (2 m above water line, 1.2 m below water line) of silty very fine sand that is gray (5Y 8/1) with brown manganese mottles (5Y 4/2);			
	Liquefaction susceptibility of outcrop	Nil - all silty very fine sand			
NS-100.5	Exposure length	30 m	35.2791	−77.5075	June 25, 2016, at 3:17 PM
	Exposure height	2 m			
	Exposure quality	Fair			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	General exposure description	Cretaceous Peedee Formation clay beneath yellow sand and gravel			
	Liquefaction susceptibility of outcrop	Nil - Cretaceous clay won’t liquefy; sand and gravel too coarse, and not capped			
NS-101.5	Exposure length	50 m	35.2790	−77.5057	June 25, 2016, at 3:24 PM
	Exposure height	1.5 m			
	Exposure quality	Fair			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	General exposure description	2.5 m (1.3 m below water level) of mottled silty very fine sand			
	Liquefaction susceptibility of outcrop	Nil - all silty very fine sand			

Station	Attribute	Information	Latitude (dd)	Longitude (dd)	Created
NS-102.5	Exposure length	10 m	35.2815	−77.5024	June 25, 2016, at 3:36 PM
	Exposure height	2.6 m			
	Exposure quality	Fair			
	Exposure setting	River cutbank on slight outside bend of river			
	General exposure description	1 m of reddish-brown, structureless silty fine sand over 2.5 m of red mottled silty clay			
	Liquefaction susceptibility of outcrop	Nil - silty fine sand over silty clay			
NS-103.5	Exposure length	10 m	35.2855	−77.4979	June 25, 2016, at 3:52 PM
	Exposure height	2 m			
	Exposure quality	Fair (partly colluviated)			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	General exposure description	White gravelly sand at water level, beneath silty very fine sand			
	Liquefaction susceptibility of outcrop	Low - white gravelly sand likely too coarse-grained to liquefy; silty very fine sand cap may be too thick; no soft sediment deformation features observed along the contact, and no sand dikes within silty very fine sand			
NS-104.5	Exposure length	10 m	35.2870	−77.5016	June 25, 2016, at 4:05 PM
	Exposure height	2 m			
	Exposure quality	Good			
	Exposure setting	Actively eroding river cutbank on outside bend of river			
	General exposure description	Exposure of mottled silty clay			
	Detailed stratigraphic description	3.5 m of mottled silty clay (2 m above water line, and 1.5 m below water line from soil probe and augering)			
	Liquefaction susceptibility of outcrop	Nil - all silty clay (nothing to liquefy)			
NS-105.5	Exposure length	6 m	35.2928	−77.4984	June 25, 2016, at 4:21 pm
	Exposure height	2 m			
	Exposure quality	Fair			
	Exposure setting	Flood-stage cutbank			
	General exposure description	Interbedded silty fine sand and silty clayey sand			
	Detailed stratigraphic description	Lowest unit: 1 m of crossbedded silty fine sand; above is 1 m of silty fine sand with mottles (soil development?), with iron-staining along the contact; uppermost unit (top not exposed) is homogenous, mottled silty clayey sand			
	Liquefaction susceptibility of outcrop	Low to marginal - silty fine sands at depth (saturated at normal river flow) capped by silty clayey sand; iron-staining (precipitation) will hinder liquefaction; no soft sediment features observed along the contact between fine sand and clayey sand, and no sand dikes within clayey sand cap			

Appendix 2. Radiocarbon data for a sample of organic matter from an alluvial bar deposit at the mouth of an abandoned river meander bend on the Neuse River, central-eastern North Carolina (NS-38.3: 35.2640°, −77.8874°).

U.S. GEOLOGICAL SURVEY
FLORENCE BASCOM GEOSCIENCE CENTER
(formerly EASTERN GEOLOGY AND PALECLIMATE SCIENCE CENTER)

^{14}C LABORATORY

^{14}C Results for: Mark Carter

WW	CAMS	SAMPLE ID	MATERIAL	REGION	δ^{13}C	^{14}C AGE	±	DATED ON
10979	175342	NS-11.2	Plant material	Neuse River	-25.5	120	25	09/06/16

Notes:

- Samples were processed at the ^{14}C laboratory of the U.S. Geological Survey in Reston, Virginia.
- ^{14}C ages were determined at the Center for Accelerator Mass Spectrometry (CAMS), Lawrence Livermore National Laboratory, Livermore, California.
- The quoted age is in radiocarbon years (BP) using the Libby half-life of 5,568 years.
- The WW number is the identification assigned to a sample by the USGS ^{14}C laboratory.
- Values reported for δ^{13}C are the assumed values according to Stuiver and Polach (Radiocarbon, v. 19, p. 355, 1977) when given without decimal places. Values measured for the material itself are given with a single decimal place.

Comments or questions may be referred to:
Jack McGeehin
U. S. Geological Survey
MS 926A National Center
Reston, VA 20192

Comments or questions may be referred to:
Florence Bascom Geoscience Center, Director
U.S. Geological Survey
12201 Sunrise Valley Dr
Reston, VA 20192

or visit our website at:
https://www.usgs.gov/centers/fbgc

Publishing support provided by the
Reston and West Trenton Publishing Service Centers

Carter and McLaurin—**Paleoliquefaction Field Reconnaissance in Eastern North Carolina**—Scientific Investigations Report 2019–5057

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20195057