Appalachian State University
Boone, North Carolina

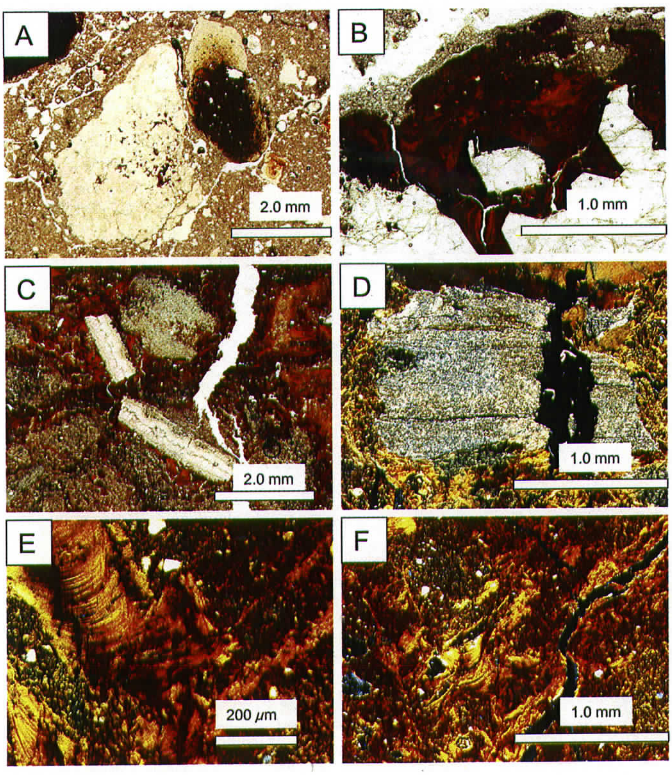
Southeastern Geology: Volume 48, No. 1
February 2011

Editor in Chief: S. Duncan Heron, Jr.

Abstract

Academic journal published quarterly by the Department of Geology, Duke University.

SOUTHEASTERN GEOLOGY



Vol. 48, No. 1 February 2011

SOUTHEASTERN GEOLOGY

Published

at

Duke University

Duncan Heron

Editor-in-Chief

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ISSN 0038-3678

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GENESIS OF CLAY-RICH SOILS FROM CARBONATE BEDROCK ON UPLAND SURFACES IN THE VALLEY AND RIDGE PROVINCE, EASTERN TENNESSEE, USA

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ABSTRACT

Clay-rich soils (Typic Paleudults) developed on an upland landscape underlain by Cambrian-Ordovician carbonate bedrock in eastern Tennessee, USA, were examined using both excavated soil pits and deep boreholes (to 11 m depth). Two hypotheses for soil formation were tested using field relationships, micromorphology, mass-balance of whole-soil geochemistry, and x-ray analyses of clay mineralogy. The simpler single-parent-material (*in situ*, top-down pedogenesis) hypothesis of formation is not supported; instead, a polygenetic origin that involved repeated inputs of colluvial and alluvial materials is indicated. Buried paleosurfaces, evidenced by increases in grain size, changes in clay mineralogy, preservation of organic matter and rooting, and concentrations of chert and alluvially derived metaquartzite grains indicate that episodes of landscape instability affected this mature landscape, which may have formed over as much as several million years, based upon dolostone insoluble residue contents and assumed dissolution rates of 10-30 mm/1000 yr. Field and micromorphologic study indicates fluvial and colluvial influxes of detrital quartz and metaquartzite grains not present in the underlying carbonate bedrock. Mass-balance analyses show that *in situ* dissolution of carbonate bedrock alone would have required > 100 m thickness of bedrock to develop the thickest soil profiles present at these sites. Clay mineralogical analysis supports formation of some pedogenic kaolinite, halloysite and hydroxy-interlayer minerals by weathering, but with significant inheritance of illites from underlying Paleozoic carbonate bedrock. The results of this study indicate that inputs of colluvial and alluvial materials can play an important role in formation of Ultisols on clay-poor carbonate bedrock parent materials in warm-temperate and humid climates such as the southeastern US.

INTRODUCTION AND PURPOSE

This study concerns the weathering of carbonate bedrock in a warm temperate, humid climate and subsequent soil development from carbonate-derived residual materials comprising colluvium, alluvium and *in situ* residuum. In this paper we use "residual materials" to denote deeply weathered clay-rich material that is present beneath surface soils beyond the typical depths (circa 2 m) typically assigned to the active soil zone (cf. Richter and Markewiz, 1995). Traditionally, two major soil groups develop on carbonate-derived residual materials, namely, the dark "Rendzina-like" soils, which generally occur in areas with relatively shallow depths to bedrock, and "Terra Rossa-like" soils, which are characterized by red and yellow colors in the clay-rich B horizons and commonly extend to depths exceeding several meters (Olson et al., 1980; Merino and Banerjee, 2008). Terra Rossa-like soils are common in the southeastern United States (US), including large areas in Tennessee, and many of these soils are USDA Ultisols, among the deepest and most clay-rich soils in the US (Soil Survey Staff, 2006).

Ultisols generally form in temperate to tropical regions and have both a well-developed argillic (or kandic) horizon and low base saturation (Buol et al., 1997; Birkeland, 1999; Soil Survey Staff, 2006). Additional characteristics of Ultisols include formation on geologically old, mature landscapes and in moisture regimes where precipitation exceeds potential evaporation during a portion of most years (Buol et al., 1997; Birkeland, 1999). Ultisols commonly have a horizonation dominated by multiple Bt horizons.

Pioneering research by Ciolkosz et al. (1989, 1990) on Ultisol genesis in central Pennsylvania and in the northeastern US established that Ultisols formed in the Valley and Ridge Physiographic Province of the US Appalachian Mountains and developed from limestone bedrock are thick, with deeply developed argillic horizons that result from a greater period of time for clay to move down the soil profile, as well as sufficient time for clay to be stripped from the upper part of the argillic and translocated downward; such soils were termed "genetic" Ultisols by these authors, and genetic Ultisols were further distinguished from "parent material" Ultisols, those which during their development never had a base status high enough to be classified as an Alfisol due to insufficient base cation content of the parent materials. Many of the limestone-derived soils in Pennsylvania are actually Alfisols (e.g., Hagerstown and Duffield soils) because of their generally higher base status (Ciolkosz et al., 1995).

Despite the widespread occurrence of carbonate-derived residual materials throughout the southeastern US (Soil Survey Staff, 1999), published literature concerning Ultisol genesis on carbonate bedrock in this region is relatively scarce, and weathering relationships between the residual materials and underlying carbonate rock are poorly understood. One of the few examples of previously published soil genesis research in this type of setting is a pair of papers (Crownover et al., 1994a, b) that examined Ultisols formed on carbonate bedrock at the Oak Ridge National Laboratory (ORNL), Tennessee, about 35 km from the sites discussed in this report. At Crownover et al.'s (1994a, b) ORNL field site, polygenetic contributions of parent materials were interpreted for soils formed in proximity to an active sinkhole (doline) system, with ages of soil morphostratigraphic units ranging from late Pleistocene to Holocene.

The primary objectives of this study are to: (1) document the genesis of Ultisols from Paleozoic carbonate bedrock at a site in humid eastern Tennessee, (2) determine possible origins of the deeper residual materials (to depths of up to 11 m), and (3) develop a conceptual pedological and geomorphological model for genesis of carbonate-derived residual materials and surface soils for this site that might possibly be applicable to other areas with similar climate and geology in this region. Two hypotheses considered for the genesis of Ultisols in this study are: (1) an *in situ* formation of residuum (sensu stricto) from carbonate bedrock, in which weathering occurs from the top down along a sharply defined weathering front (e.g., Merino and Banerjee, 2008), and (2) a polygenetic origin, in which the soil developed from a combination of *in situ* weathering of the subjacent Mascot Fm. dolostone (Upper Cambrian to Lower Ordovician), colluvial reworking of Mascot-derived residuum, and inputs of alluvial materials derived from the ancestral Holston River. The second hypothesis implies weathering on a dynamic geomorphic surface, and raises the possibility that such clay-rich soils represent archives of past climate and landscapes. We specifically chose this site for study because: (1) soils are mapped as Dewey series (among the thickest most highly-developed Ultisols in this region), (2) the site was not associated with any known, mapped fluvial terraces (though 0.5 km from the modern Holston River), and (3) the site is associated with many active sinkholes, which are common, dynamic features on karst landscapes such as this in eastern Tennessee. Individual sampling sites (shown in Fig. 1) were selected to maximize the range of soil geomorphic conditions on the landscape.

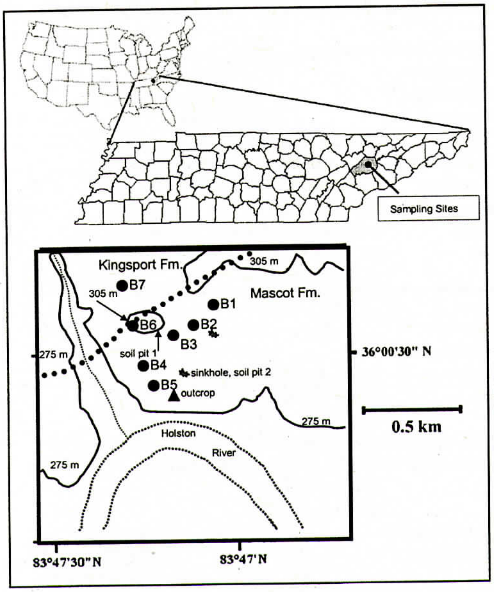

Figure 1. Map showing location of soil boreholes and soil pits used for this study. Note dotted geological overlay showing contact between Kingsport and Mascot Formations, as well as major topographical features. One transect comprises boreholes 1 through 4 (B1-B4); second transect comprises boreholes 5 through 7 (B5-B7) and surface rock outcrop. Note that location of soil pit 1 is approximately 50 m south-southeast of borehole 6 (ridge-top), and that soil pit 2 corresponds to borehole 2 (adjacent to sinkhole).

LOCATION AND SETTING

Clay-rich soils and residuum derived from the Mascot and Kingsport Dolomite (Upper Cambrian to Lower Ordovician) are present at the Strong Farm site at N 36°03'02" latitude and W 83°47'13" longitude, in northeastern Knox County, Tennessee, USA (Fig. 1). The site is an upland landscape with well-drained, moderate (5 to 12%) slopes, with common sinkholes (dolines), and surface drainages that empty into the nearby Holston River. Arcuate headwall scarps on slump blocks with up to 1 m of displacement bound the areas proximal to sinkholes and are evidence of active subsidence of soil material into sinkholes. The land cover is mostly pasture with a mixture of cool-season fescue grasses and shrubs, but would have been dominated by hardwood (oak-hickory) forests prior to European settlement. Soils at this site are mapped as Dewey Series, and are characteristically well drained and very deep, > 1.5 m (Roberts et al., 1955; Schultz, 2005). The taxonomic class of Dewey soils is fine, kaolinitic, thermic Typic Paleudults (Soil Survey Staff, 2006). Below approximately 50 cm depth, soil horizons characteristically exhibit very high clay content and gradational boundaries between soil horizons. Other important features include distinct clay films (illuviated clays) as pore linings and on ped faces at variable depths. The presumed parent material for residuum at the study site includes the underlying Mascot and Kingsport Formations (Uppermost Knox Group), a 75-203 m thick stratigraphic succession that consists of light-gray to grayish-brown, massively bedded fine-grained dolostone, with occasional thin interbeds of chert, shale, siltstone and sandstone (Oder and Miller, 1945; Harris, 1969). The bedrock at this site strikes (trends) northeast-southwest and dips at angles ranging from near-horizontal to generally less than 25° to the southeast; hence the geology of this site is fairly typical for the Valley and Ridge Physiographic Province in eastern Tennessee.

METHODS

Field Studies

Field sampling involved 7 boreholes along two transects, sampled at various slope positions (Fig. 1). Coring was conducted using a hydraulically driven direct-push technology (DPT) rig that provided continuous 5 cm diameter samples in 1.2 m long acetate liners. The boreholes were advanced to refusal, which was generally assumed to be the top of carbonate bedrock. Excavation of two shallow soil pits (~4 m wide x ~2.5 m depth) with a backhoe allowed for additional observations of larger-scale pedological features and for collection of

Table 1. Selected morphological properties and ages for residual materials at two soil pit locations. Ages are for bulk soil humates analyzed using AMS^{14}C method. (See Fig. 1 for soil pit locations).

Horizon	Depth (cm)	[1]Color; [2]Mottle Color	Texture	Ped Structure	Buried Surface	Thin-Section Sample	AMS ^{14}C age
Soil pit 1 (ridge top)							
Ap	0-16	10YR 4/2	gravelly loam	f. granular		none	
BE	16-33	10YR 5/4	sandy loam	f. granular		P1-BE-25 cm	
Bt1	33-46	7.5YR 5/6; 7.5YR 6/4 (25%)	silty clay	m granular		P1-BE-Bt1-35 cm	
Bt2	46-84	2.5YR 4/6; 7.5YR 5/6 (10%)	silty clay	m subang. bky		P1-Bt2-65 cm	
Bt3	84-128	10YR 6/8; 2.5YR 4/6 (50%)	silty clay	m ang. bky	[3]redox depl.	P1-Bt3-Bt4-90 cm	
Bt4	123-162	10YR 6/8; 2.5YR 4/6 (25%)	silty clay	m subang. bky	saprorelicts @150-200 cm	P1-Bt4-145 cm	
Bt5	162-220+	2.5YR 5/8; 10YR 5/8 (25%) 10YR 6/4 (5%)	silty clay	c ang. bky	indicative of colluvium/ residuum mixing	P1-Bt5-200 cm	7370 ± 50 ^{14}C yr BP @ 200 cm
Soil pit 2 (edge of sinkhole)							
Ap	0-11	10YR3/4	gravelly loam	f. granular		none	
Bt1	11-48	2.5YR 4/6; 10YR 6/6 (10%)	sandy clay	f subang. bky		none	
Bt2	48-117	2.5YR 4/6; 10YR 5/6 (40%)	silty clay	f subang. bky	[3]redox depl., mottle boundary @ 117 cm	P2-Bt2-55 cm	
Bt3	117-200	10YR 6/6; 2.5YR 4/6 (30%)	gravelly clay	weak prismatic to columnar	metaquartzite cobbles @182 -200 cm marking buried surface	P2-Bt2-Bt3-117 cm P2-Bt3-150 cm	
Bt4	200-260+	2.5YR 4/6; 10YR 5/6 (20%)	silty clay	weak prismatic to columnar		P2-Bt4-240 cm	11,030 ± 60 ^{14}C yr BP @ 220 cm

[1]Colors are based on examination of moist samples
[2]The % value in parentheses represents the relative proportion of mottling on soil surface
[3]Redox depletions present in Bt3, Bt4 and Bt5 horizons of soil pit 1, and Bt2 and Bt3 horizons of soil pit 2

samples for radiocarbon age-dating, bulk density, geochemical, and micromorphological analyses. Pit locations were determined from previous borehole observations, and were chosen to provide profiles at different geomorphic locations in an effort to identify topographic influences on residuum development (soil pit 1 = ridge-top; soil pit 2 = edge of active sinkhole; see Fig. 1). Soil in pits and in cores was described using current Soil Survey Staff (2006) methods and Munsell soil color charts, with sub-sampling for thin-section preparation, bulk density, particle-size analysis, elemental chemistry of whole soil material, and clay mineralogy.

Laboratory

A total of 28 oriented samples were selected from the pits and boreholes for micromorphological observations; mid-points of each horizon were sampled in the soil pits (Table 1), whereas sampling in cores emphasized locating possible buried surfaces and other discontinuities in the deeper subsurface (Schultz, 2005). Micromorphological study included a qualitative description of pedological features, macropore structure, texture, composition, cementation and alteration of grains using an Olympus BX51 research microscope equipped with a 12.5 MPx camera. Micromorphological terminology primarily follows Fitzpatrick (1993) and Stoops (2003). Particle-size analysis was carried out on 23 subsamples, 15 grams each, from boreholes 1 and 4 using a Brookhaven Instruments X-ray disk centrifuge (XDC) system (details of methodology are reported in Schultz, 2005). Bulk geochemical analysis was performed on 25 subsamples (including Mascot Fm. bedrock) from the borehole material, using X-ray fluorescence (XRF) of powdered material (Singer and Janitzky, 1986) analyzed at the University of Tennessee using a Philips Magic-Pro wavelength-dispersive XRF and appropriate clay soil standards. An additional 13 subsamples from the excavated test

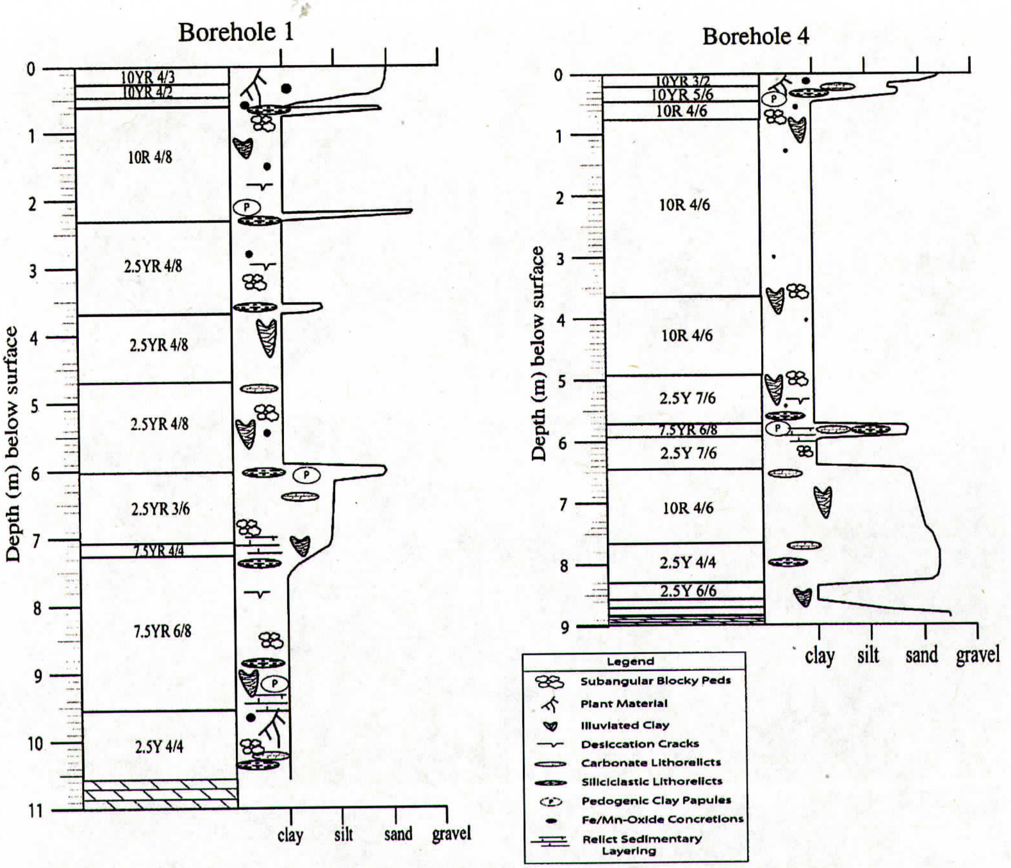

Figure 2. Descriptions of variations in morphological features and particle size-distributions of soil and residual materials in boreholes 1 and 4 versus depth. Particle size shown is an average of sand-silt-clay (combined) and is presented in stratigraphical log-type format for ease of visual presentation. Note presence of pedogenic features at substantial depths below soil surfaces, grain-size discontinuity at 6 m depth, as well as possible buried soil, as evidenced by plant material at 9.5 m depth in borehole 1. See text for discussion of important features.

pits (mid-points of each horizon) were analyzed commercially by ALS Chemex Mineral Laboratory (Reno, NV) using inductively-coupled plasma mass-spectrometry (ICP MS) on soil digests prepared by "near-total" dissolution in strong acids (aqua regia comprised of concentrated nitric and hydrochloric, plus hydrofluoric acid). All soil pit geochemical data are reported in Appendix 1; additional data for soil cores are in Schultz (2005). Bulk densities of soil pit samples were determined using the wax clod method (Blake and Hartge, 1986). Whole-soil geochemical data for the soil pit samples were evaluated using a mass-balance approach to characterize chemical variations in the soils due, in part, to closed-system effects of volumetric changes (strain), residual enrichment of soil matrix, and open-system transport of material into or out of various horizons (translocation or transport function, τ); these methods are described in detail in Brimhall et al. (1991a, b), Chadwick et al. (1990), and in Driese et al. (2000). Clay mineral analysis of the <2, <0.5, and <0.1 μm size fractions was performed on 5 soil samples selected from boreholes 1 and 4 using an automated Phillips XRG 3100 X-ray generator by Willamette Geological Service on both glycolated and heat-treated mounts as described in Moore and Reynolds (1997); semi-quantitative estimates of clay minerals were

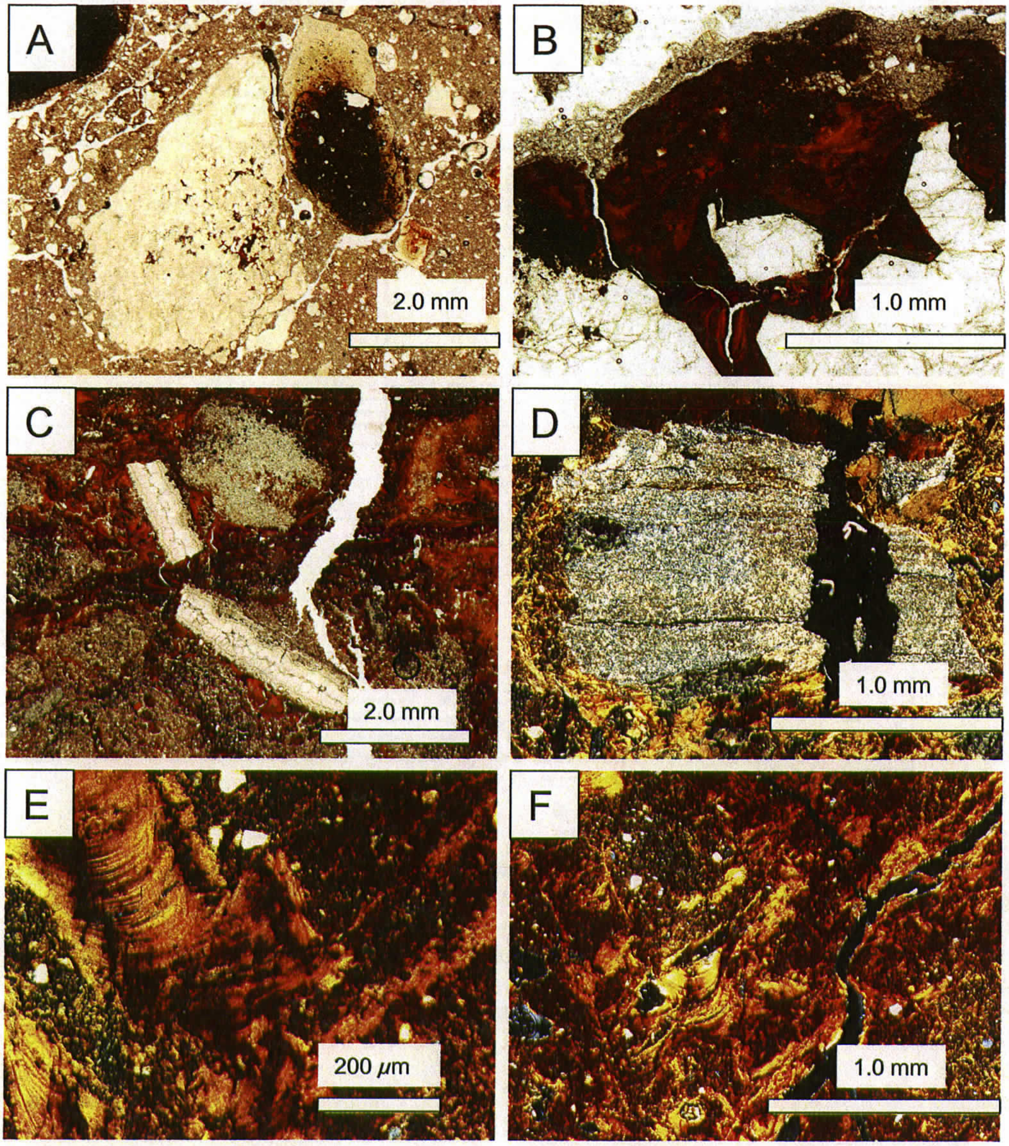

Figure 3. Photomicrographs of micromorphological features in soil pit 1. (A) Chert grains and Fe/Mn nodule, BE horizon at 25 cm depth, in plane-polarized light (PPL); (B) Pedogenic Fe oxide impregnation of chert grain, BE-Bt1 horizons at 35 cm depth (PPL); (C) Fragmented and broken saprorelict grain derived from parent bedrock, Bt2 horizon at 90 cm depth (PPL); (D) Saprorelict grain with laminations, Bt3-Bt4 horizons at 128 cm depth, in cross-polarized light (XPL); (E) Pedogenic clays with high birefringence and meniscate fine banding, Bt4 horizon at 145 cm depth (XPL); (F) Pedogenic clays and redox-related redistributions of Fe/Mn, Bt5 horizon at 200 cm depth (XPL).

made using a NEWMOD® computer simulation for mixtures of illite, disordered kaolinite, disordered Fe-Al chlorite, and randomly interstratified chlorite/vermiculite/smectite (chloritic intergrade or hydroxy interlayered smectite simulation). Halloysite contents could not be modeled with NEWMOD®, therefore the behavior of the patterns upon heating was used to

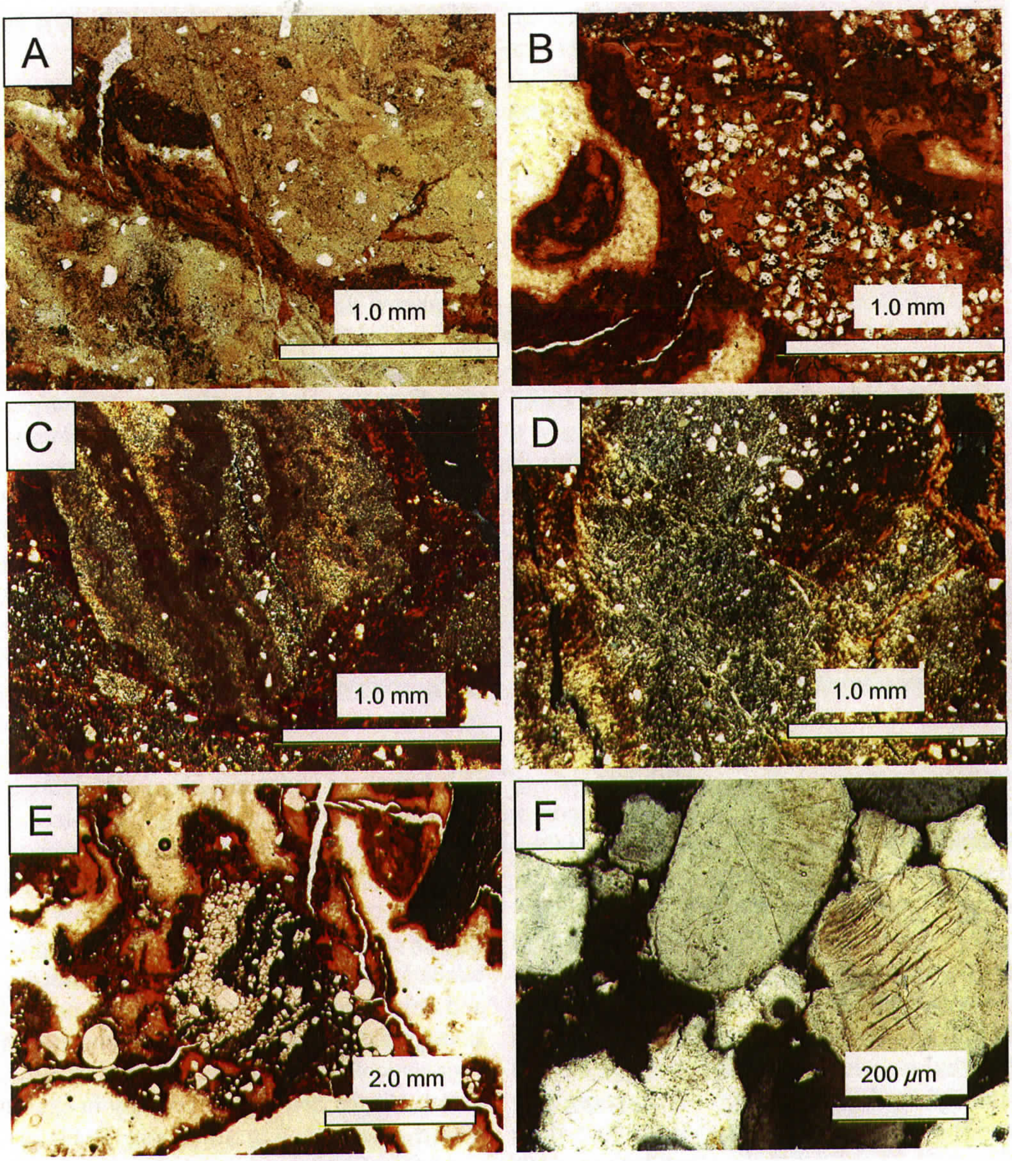

Figure 4. Photomicrographs of micromorphological features in soil pit 2. (A) Redox-related redistributions of Fe/Mn, Bt2 horizon at 55 cm depth (PPL); (B) Biopore channel infilled with clay and silt, Bt2-Bt3 horizons at 117 cm depth (PPL); (C) Layered silts deformed by mass flowage, Bt3 horizon at 150 cm depth (XPL); (D) Redox-related redistributions of Fe/Mn showing prominent depletion, Bt3 horizon at 150 cm depth (XPL); (E) Sand-sized sandstone lithorelict grain, Bt4 horizon at 240 cm depth (PPL); (F) Monocrystalline quartz sand grains and quartz cement comprising metaquartzite cobble in prominent stone line, Bt4 horizon at 240 cm depth (XPL).

estimate halloysite.

Two additional samples were analyzed for non-carbonate materials: (1) bulk dolostone bedrock and (2) isolated chert material obtained from 10% HCl-acid reacted bedrock; this strong acid was necessary for complete carbonate rock dissolution due to the low solubility of the dominant dolomite mineralogy.

Radiocarbon ages of bulk soil humates from two subsoil Bt horizon samples were determined by Beta Analytic, Inc., using the AMS method suitable for materials with very low organic content, and are reported here as raw (uncalibrated) ^{14}C dates in ^{14}C years before present (BP).

RESULTS AND INTERPRETATION

Soil Morphology

Selected morphological properties of the two soil pits are summarized in Table 1. After reconnaissance field mapping we were unable to distinguish mappable bodies of alluvium (terraces) or colluvium (colluvial lobes). Two prominent sinkholes were present within 50-200 m of all of the test pits and boreholes, except soil pit 2, which was located within a few meters of one of the sinkholes in order to establish possible effects of sinkhole processes on soil genesis (Fig. 1). Sparse bedrock outcrop exposures along the back-slope (facing the Holston River) and along a nearby roadcut revealed sub-horizontal bedding in dolostone containing rare chert-rich intervals. In general, the regolith consists of strongly oxidized, dense clay that becomes heavily mottled and darker, with higher concentrations of angular to subangular dolostone, chert, and quartz sand and metaquartzite lithorelicts with increasing depth. The thickness of the regolith ranges from 3.7 to 10.6 m and varies with landscape position and with proximity to active sinkholes, which is discussed in greater detail in Schultz (2005). Boreholes 1 and 4 were selected for discussion here because they had the thickest regolith, located on toe-slope (borehole 1) and cross-dip shoulder (borehole 4) landscape positions. Sharp contacts are present between dolostone bedrock and the residual materials, with the notable absence of a saprolitic (Cr horizon) transition such as characterizes saprolites formed from clastic or mixed lithology sedimentary bedrock (shale-sandstone-carbonate) in this same region and in similar geomorphic settings (Driese et al., 2001; McKay et al., 2005) (Fig. 2).

Micromorphology of Ridge-Top Site

A 16 cm thick Ap horizon is present at the ridgetop location of soil pit 1. The underlying BE horizon shows characteristic clay eluviation, and is enriched in silt- and sand-sized grains dominated by 0.05-0.5 mm diameter monocrystalline quartz, which may reflect alluvial and eolian inputs (Fig. 3A). Chert rock fragments derived from the local Mascot Formation (0.5-2 mm diameter) resemble so-called "cauliflower chert", characterized by coarse radial-fibrous aggregates of megaquartz crystals, which is also present in the parent dolostone as diagenetic silica replacement of former gypsum or anhydrite crystal masses (Chowns and Elkins, 1974). Relict fragments of birefringent pedogenic clay coatings are disseminated in the soil matrix. Fe-Mn glaebules are present, but are not as common as in the underlying Bt1 horizon. Fe-oxides fill rhomb-shaped "dolomoldic" porosity (i.e., formed after leaching of dolomite rhombs) in chert-replaced dolostone.

The Bt1 horizon exhibits a marked increase in birefringent pedogenic clays, which are evidence for clay illuviation (Fig. 3B). Hard, Fe-Mn nodules 2-4 mm in diameter are common, and contain engulfed quartz silt/sand and chert sand grains. Many pore spaces within cauliflower chert grains are filled with complexly banded pedogenic clays and Fe oxides. Root and animal biopores are filled with normally size-graded "vadose" silt and pedogenic clay. Pedogenic clay and Fe/Mn precipitates also fill rhomb-shaped dolomoldic porosity in chert-replaced dolostone. The underlying Bt2 horizon has fewer Fe/Mn nodules and more abundant pedogenic clays than the Bt1 horizon, with multiple generations (i.e., expressed as many different colors) of coats on ped faces and as pore-fillings within root and other macropores. There are relict quartz veins or fracture-fills, apparently inherited from the bedrock, and these are disrupted by pedoturbation (Fig. 3C). The illuviated clays are finely micro-banded and the pedogenic clays occur on floors of voids and macropores.

Based on both field and petrographic observations, the Bt3 horizon is marked by a prominent change to more yellow coloration. Relict saprolitized Mascot Fm. fragments with fine quartz silt laminations are common. Pedogenic clay is present as biopore coats, along ped faces, and former tectonic fractures in saprorelict grains (Table 1; Fig. 3D). A gradational transition into the Bt4 horizon is evident, although the Bt4 horizon is also characterized by very high pedogenic clay content. The illuviated clay is finely micro-banded, with some very dark layers rich in organic matter or Mn oxides (Fig. 3E). Pedogenic clay deposits occur on the floors of voids and macropores characterized by meniscus-like microbanding. These clays also have complex red-orange color patterns, and commonly exhibit quartz silt dispersed within a yellow-brown silty-clay matrix. Redox depletions and enrichments of Fe oxides suggest that this may be a low conductivity horizon that promoted water-table perching (episaturation) during wetter seasons. This material diffusely grades into the Bt5 horizon, which also has complex patterns of redox depletions and enrichments similar to those of the Bt4 horizon (Fig. 3F). Biopores up to 1 mm in diameter are common, and are lightly coated with pedogenic clays; other biopores are completely infilled with finely micro-banded pedogenic clay with meniscus-like structures. Monocrystalline very fine silt-sized quartz is locally abundant however, clay-sized material dominates.

Micromorphology of Site at Edge of Sinkhole

Similar to soil pit 1, a friable, thin, and loamy Ap horizon occurs at the surface down to 11 cm depth (Table 1). However, in contrast to soil pit 1 there is no BE horizon present in soil pit 2, instead, the Ap horizon has an abrupt contact with the underlying Bt1 horizon. Although the Bt1 horizon in soil pit 2 resembles the Bt1 horizon in soil pit 1, the transition into the Bt2 horizon is characterized by pronounced redox depletions in which there has been wholesale Fe stripping from the fine matrix. In addition to abundant, multi-generation pedogenic clay coats on ped faces and as pore-fillings within root channels and macropores, there are soil fractures and soft-sediment deformation, possibly associated with soil creep into the sinkhole (22A). Fragments of chert derived from the underlying dolostone bedrock and rounded monocrystalline quartz grains up to 0.25 mm in diameter are present.

The boundary between the Bt2 and Bt3 horizons at 117 cm depth was identified in the field as a possible buried surface (Table 1). This boundary exhibits relict redox mottling cross-cut by younger, brighter-red pedogenic clays, and there are relict very fine, 1 mm-diameter quartz sand-filled biopores that also contain aggregated pelleted features (possible wormcasts; Fig. 4B). Saprorelicts of bedded quartzose dolomitic siltstone are present up to 5 cm in diameter, many with Fe-oxide staining and impregnation (Fig. 4C). Redox-depletion channels are prominent at 150 cm depth (Fig. 4D).

The top of the Bt4 horizon is marked by a prominent "stone line" that was identified in the field (Table 1), which is indicative of another possible buried surface. Sandstone rock fragments are highly weathered and rounded, ranging from 2 mm to several cm in diameter (Fig. 4E). The pebbles are comprised of monocrystalline quartz sand grains ranging from 0.06 to 0.5 mm in diameter, and averaging around 0.25 mm. The sand grains exhibit undulose extinction, some with wavy crystal dislocation tangles (termed Boehm lamellae) indicative of strain associated with penetrative structural deformation, and many have syntaxial (in optical continuity with host quartz grain) quartz overgrowth cements (Fig. 4F). These metaquartzite pebbles with distinctive quartz sand grains were apparently derived from the Chilhowee Group (Lower Cambrian), which crops out in the foothills of the Blue Ridge outside the Great Smoky Mountains National Park, and thus the pebbles are of alluvial origin. Fe oxides and pedogenic clays infill intergranular pore spaces within the weathered sandstone pebbles. Locally derived chert-replaced dolostone clasts are also present, as are dark-colored, organic-rich grains of uncertain origin.

Table 2: Micromorphological features of borehole 1. (See Fig. 1 for location of borehole and Fig. 2 for depth log).

Horizon	Depth (cm)	Texture	Pore Structure	Concretions/Nodules	Coatings
BE + Bt1	43-51	sandy loam > clay	planar-dendritic	10-12% multigen. Fe-oxide (< 4 mm)	red illuviated clay lining grains, Fe-oxide concretions, and as aureoles
Bt2 interbed	233-239	sandy clay	planar-sinuous	5-8% Fe-Mn oxide (< 3 mm), 10% in organic-rich zone, red pedogenic clay nodules	Fe-Mn cements lining grains and pore faces; pervasive multigen. pedogenic clays
Bt3 interbed	367-373	silty clay	dendritic-sinuous	12-14% Fe-oxide masses (< 3 mm), 2-5% Mn-oxides disseminated	Pervasive multigen. pedogenic clay coats and vadose pendants
Bt4	554-562	gravelly clay	dendritic-sinuous	5% Fe-Mn oxide masses (< 1 mm)	8% Fe-oxide coatings on peds, pore faces, and between dolomite silt grains; well-developed multi-gen. pedogenic clay + Fe-oxide coats
Bt4 + Bt5	595-602	silt loam	dendritic	8% red pedogenic clay papules (< 1 mm), <5% Fe-Mn oxide nodules (< 1 mm)	pervasive multi-gen. pedogenic clay, often completely occluding pores; Fe-Mn oxide coats + hypocoats
Bt5	671-678	gravelly sandy clay	wavy-planar	3% Fe-Mn oxide masses (< 1 mm)	pervasive multi-gen. pedogenic clay, 5% Fe-Mn oxide coats
Bt/Cr (as an inclusion) + Bt6	707-714	gravelly sandy clay	discontinuous -dendritic	3% Fe-Mn oxide masses (< 1 mm)	pervasive multi-gen. pedogenic clay, 5-7% Fe-Mn oxide coats
Bt6	796-803	gravelly silty clay	sinuous-dendritic	5-7% Fe-oxide masses and glaebules (< 2 mm)	pervasive Fe-oxide + pedogenic clay coats, often with convoluted wavy bands (Fe-oxide ~8%)
BC	979-986	gravelly silty clay	dendritic-planar	common Fe-rich pedogenic clay papules (< 0.5 mm); 3% Fe-oxide nodules	extensive pedogenic clay coats; 8% Fe-oxide coats
BC	1023-1030	clay	discontinuous -dendritic-planar	3% pedogenic clay papules near top	pervasive multi-gen. pedogenic clay coats; few kaolinite/dickite cement coats along sandstone/siltstone lithorelicts; extensive Fe-rich coats + hypocoats

Micromorphology of Boreholes 1 and 4, and Mascot Dolostone

Micromorphological observations for boreholes 1 and 4 are summarized in Tables 2 and 3, respectively. The micromorphological features present in the borehole samples resemble those observed in samples from the two soil pits. However, the greater abundance of sepic-plasmic fabrics observed in core samples, and reported in Schultz (2005), is anomalous and generally uncharacteristic of Ultisols. Ultisols

Table 3: Micromorphological features of borehole 4. (See Fig. 1 for location of borehole and Fig. 2 for depth log).

Horizon	Depth (cm)	Texture	Pore Structure	Concretions/ Nodules	Coatings
A	3-10	sandy loam	sinuous-dendritic	5-8% multigen. Fe oxide (< 5 mm)	few pedogenic clays near base; some diffuse Fe-oxide hypocoats
BE + Bt1	44-52	silty clay	sinuous-dendritic	some red pedogenic clay papules; 3% Fe-oxide (< 4 mm)	extensive multigen. pedogenic clay coats; some macropores coated with Fe-oxide cements + weak hypocoatings
Bt5	572-580	gravelly sandy clay	dendritic-sinuous	4% Fe-oxide (< 1.5 mm); common pedogenic clay papules (< 1 mm)	convoluted and criss-crossing network of multi-gen. pedogenic clays + Fe-oxide coats
Bt6	598-606	very fine-grained sandy clay	discontinuous -dendritic	3% Fe-oxide masses (< 1 mm); sparse pedogenic clay papules	10-15% Fe-Mn oxide seams (< 3 mm); extensive multigen. pedogenic clay coats
Bt8	813-820	gravelly clay	discontinuous -dendritic	none	some pores/grains + shale lithorelicts coated with kaolinite cement; common pedogenic clay coats; thick Fe-oxide coats
Bt10 + Bt11	873-880	sandy loam	discontinuous -planar	few fine Fe-oxide masses	common pedogenic clay coats; Fe-oxide coats (6%)

are typically kaolinitic (i.e., not composed of highly expandable clays such as smectite) and leached of base cations, and kaolinite clay mineralogy is atypical for sepic-plasmic fabric development in soil matrices. Because no sepic-plasmic microfabrics were observed in samples collected from the two soil pits, we postulate that the clay reorientation in the matrices of soil borehole samples was induced by directed stress imposed on the soil by the DPT coring process; thus apparent sepic-plasmic microfabrics in the cores are not primary soil matrix features. Indeed, core recovery during sampling was often >100% and in some cases the soil flowed out of the core liner, confirming that the coring process caused physical disturbance of the soil.

Representative micromorphological features present in borehole samples are shown in Figure 5. Important features include pedogenic Fe-Mn concretions (Fig. 5A), illuviated clay coatings and infillings and concentrations of chert (locally derived from dolostone bedrock; Figs. 5B, D, E), quartz sand-rich layers (transported alluvial material; Fig. 5C), relict bedrock (saprorelict) features (Figs. 5D, E), and possible buried soil surfaces with darkening and increased rooting at great depths (Fig. 5F); all of these observations point to a persistence of pedogenic features throughout the soil, even to depths of 11 m, and also indicate that genesis of the residual materials was complex. The transition between residual materials and Mascot Dolostone bedrock is very abrupt.

The Mascot Fm. bedrock is composed of fine- to medium-grained, tan-brown dolostone, with some coarse dolomite spar-fill cements. Few small fractures (< 500 μm thick) have a planar-sinuous structure and extend sub-horizontally along bedding planes and chert layers. Fe-oxide cements and fine Fe masses (< 100-200 μm) commonly fill these fractures, as well

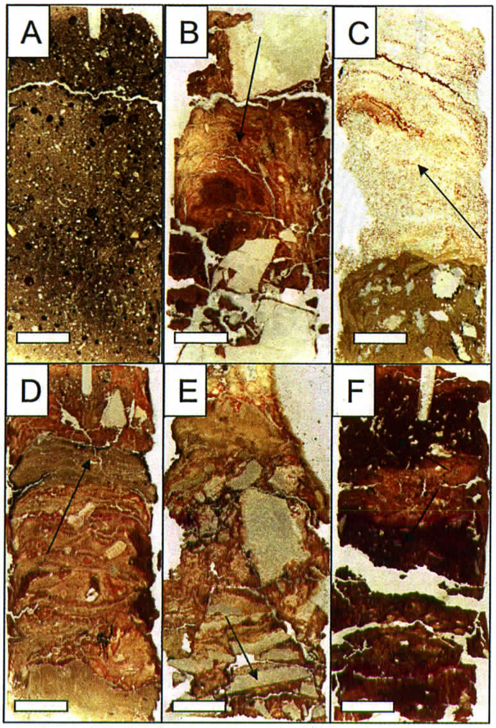

Figure 5. Photographs of 5 x 7 cm thin-sections from borehole samples. A) Surface loamy Ap horizon with abundant Fe-Mn concretions (borehole 2, 29-37 cm depth); B) Mosaic of pedogenic clays (arrow) (borehole 1; 796-803 cm); C) Layer of quartz sand (arrow) (borehole 4; 873-880 cm); D) Rare saprolitic interbed (arrow) (borehole 1; 979-986 cm); E) Very deeply weathered dolostone rock fragments (arrow) with pedogenic clay and Fe/Mn-oxide rinds (borehole 4; 813-820 cm); F) Basal paleosol sample with few burrows and presence of fecal material (arrows) (borehole 1; 1023-1030 cm). 1 cm scale bar on each photo.

as intergranular pores. Minor amounts of oxidized, pedogenic clay are observed near the top of the bedrock surface.

Texture and Particle-Size Distribution

Particle-size analyses obtained from boreholes 1 and 4 are summarized in Figure 6. Samples were selected to include the major soil horizons, as well as sandy or silty interbeds identified visually in the cores. The uppermost 50 cm in both boreholes (both A and BE horizons) is composed of sandy loam, with common gravel-size chert and dolostone rock fragments. A marked increase in clay content extends to depths greater than 8 meters (Fig. 6). The clay fraction generally attains a maximum at depths of 1 to 5 meters. Much of what constituted the very fine sand fraction in this clay-rich zone was actually fragmented and disaggregated chert rather than detrital quartz grains. Clay content decreases markedly at 6 m in both boreholes, suggesting a discontinuity. Below 8 m, the core material at both borehole locations is increasingly silty, and gravel-size rock fragments are more common. Although residual materials from both boreholes exhibit similar particle-size distribution trends with depth, borehole 1 contained the greater overall clay content. Detailed particle-size analysis results for the < 2 μm size fractions are reported in Schultz (2005) and are not discussed here.

Mineralogy and Geochemistry

Clay mineral % compositions were estimated based on NEWMOD® computer simulation mixtures of illite, disordered kaolinite, disordered Fe-Al chlorite, and randomly interstratified mixtures of chlorite, vermiculite, and smectite (Table 4). Halloysite cannot be modeled with NEWMOD, but the behavior of the patterns upon heating and the presence of a 4.5Å peak common to halloysite strongly suggest that dehydrated halloysite occurs in mixture with disordered kaolinite and thus could also be approximated. Some randomly interstratified kaolinite/smectite might be present in the clay fraction based upon the low-angle broadening of the disordered kaolinite 7.2Å peak, but other portions of the K/S pattern were usually absent, which suggests that the peak broadening was due to halloysite. The collapse of the 7.2Å peak with mild heating was also characteristic of halloysite. In all five clay-rich samples examined, the matrix is primarily composed of illite and kaolinite (Table 4). Lesser quantities of dehydrated halloysite, Fe-Mg chlorite, and hydroxy-interlayered (HIM) min-

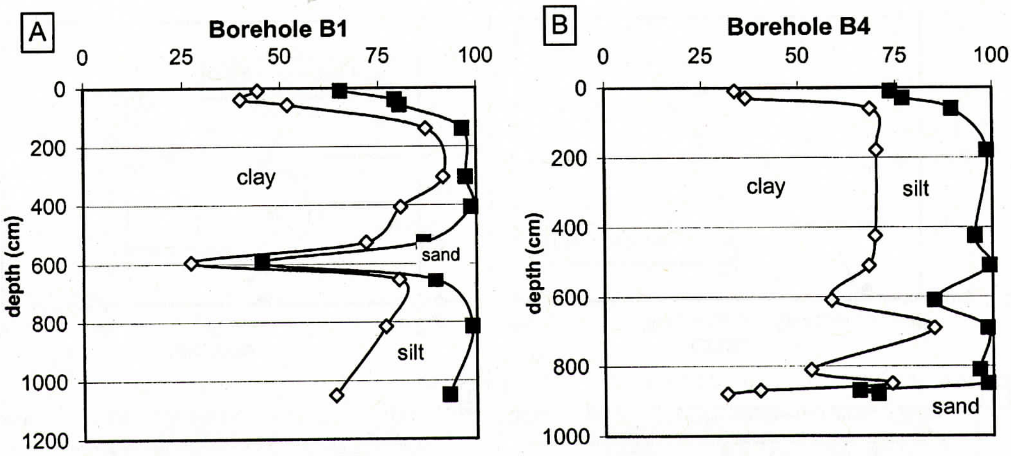

Figure 6. Cumulative particle-size distributions (%) plotted versus depth for boreholes 1 (A) and 4 (B). Each particle-size fraction (clay-silt-sand) is labeled. Note prominent clay bulge with increasing depth in each borehole, but with increased sand and silt localized at 600 cm depth in both borehole 1 and 4, as well as at bases of each borehole, which suggests a parent material discontinuity at 6 m depth.

Table 4: Summary of semi-quantitative clay mineralogy estimated for different size fractions of samples from selected depths from boreholes 1 and 4. See Fig. 1 for locations.

Borehole Sample I.D. #	Depth (cm)	Size Fraction (μm)	Hydroxy-Interlayered Minerals %	Smectite %	Illite %	Chlorite %	Kaolinite %	Halloysite %	Total %
4	30	2-0.5	21	0	35	18	26	0	100
4	30	0.5-0.1	11	0	25	15	43	6	100
4	30	<0.1	16	0	17	11	51	6	100
1	305	2-0.5	0	0	72	0	22	6	100
1	305	0.5-0.1	3	0	22	0	72	3	100
1	305	<0.1	5	0	24	0	60	12	100
4	610	2-0.5	5	0	59	2	20	14	100
4	610	0.5-0.1	3	0	52	3	29	12	100
4	610	<0.1	5	0	54	0	24	18	100
4	810	2-0.5	4	0	96	0	0	0	100
4	810	0.5-0.1	1	0	81	0	14	4	100
4	810	<0.1	1	0	85	0	11	3	100
1	1050	2-0.5	3	0	63	0	27	8	100
1	1050	0.5-0.1	6	0	34	2	53	6	100
1	1050	<0.1	2	0	28	2	62	6	100

erals comprise the other clay species. Illite becomes increasingly disordered in the finer fractions, which is exemplified by increasing peak width and slight shifts in d-spacings. The kaolinite component appears to be highly disordered and, in some cases, demonstrates peak character associated with dehydrated halloysite. The most significant trends revealed by clay mineralogical analysis include marked increases in illite with increasing depth, decreases in kaolinite with increasing depth, an increase in halloysite near the 6 m depth discontinuity, and increases in hydroxyl-interlayer minerals and chlorite at the soil surface (Table 4).

Non-calcareous material derived by HCL reaction of two 100 g samples of Mascot Fm. bed-

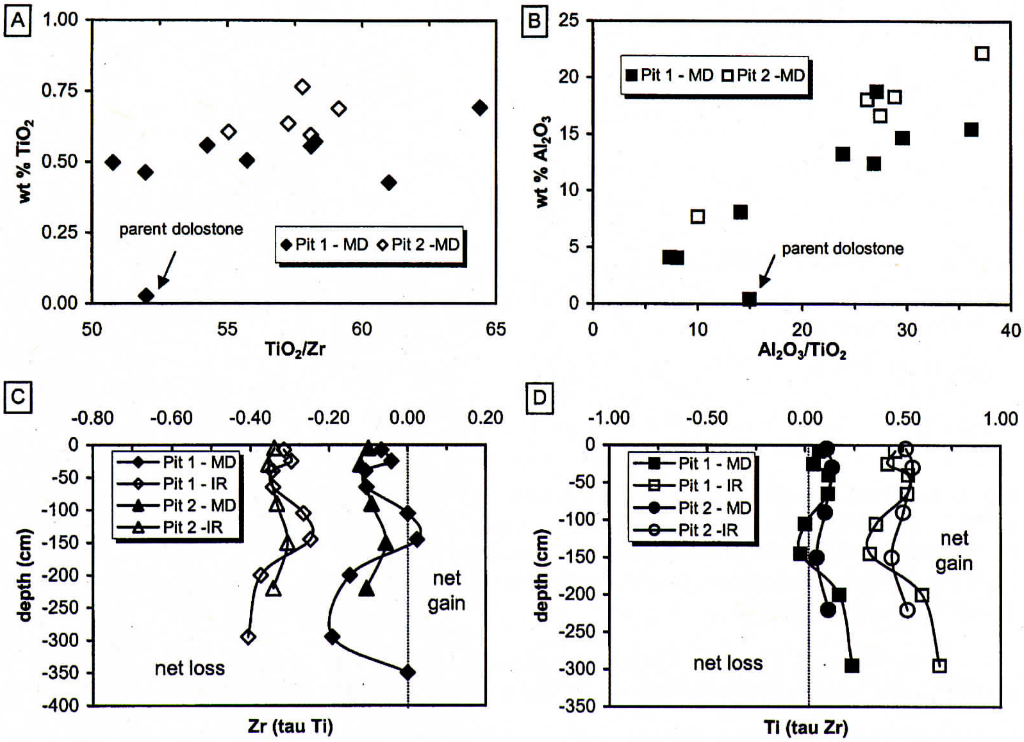

Figure 7. (A and B) Plots of TiO_2 vs. TiO_2/Zr, and of Al_2O_3 vs. Al_2O_3/TiO_2 used to assess parent material uniformity and immobile index element selection for soil pits 1 and 2. (C and D) Translocation plots calculated for Ti and Zr, assuming that the other respective element was immobile, and using both bulk Mascot Fm. dolostone (MD) and Mascot Fm. dolostone insoluble residue (IR) as the parent materials. To convert (C) and (D) to percentage increases or decreases, multiply values by 100. See text for discussion.

rock ranged from 7 to 15%, and consisted of mainly brown-colored silts and cherty residue. The samples analyzed included both typical Mascot Fm. dolostone bedrock (mainly dolomite mineralogy) and a subsample of chert-rich bedrock. XRD mineralogical data indicate that the rock is almost entirely dolomite with subordinate quartz, calcite, microcline, and albite. The chert sample contained mostly quartz, with minor dolomite and traces of calcite, microcline, and albite.

Immobile Element Selection

Simple immobile element plots (e.g., Zr, Ti, Nb, Y) versus soil depth for samples from the 2.5 m deep soil pits had insufficient variation to detect parent material discontinuities (Appendix 1). However, elemental data from the soil cores (presented in Schultz, 2005) showed large excursions with depth that coincided with discontinuities identified using particle-size data, especially the major discontinuity at 6 m depth in borehole 1 and also present at 6 m in borehole 4 (Fig. 6). Plots of TiO_2 vs. TiO_2/Zr, and of Al_2O_3 vs. Al_2O_3/TiO_2 for samples from the two soil pits were used to assess parent material uniformity and immobile element selection (Fig. 7). TiO_2 and Zr have horizontal plots indicating that they do not change with respect to each other (Fig. 7A). The Al_2O_3 vs. Al_2O_3/TiO_2 plot, in contrast, has a significant positive slope, indicating that Al_2O_3 is not uniform with respect to TiO_2 ; in addition, the low Al_2O_3 (and low clay content) samples (e.g., Ap and BE horizons) are clearly separated from subjacent Bt horizons and reflect clay (Al-silicates) eluviation from Ap and BE, to Bt horizons (Fig. 7B). In order to

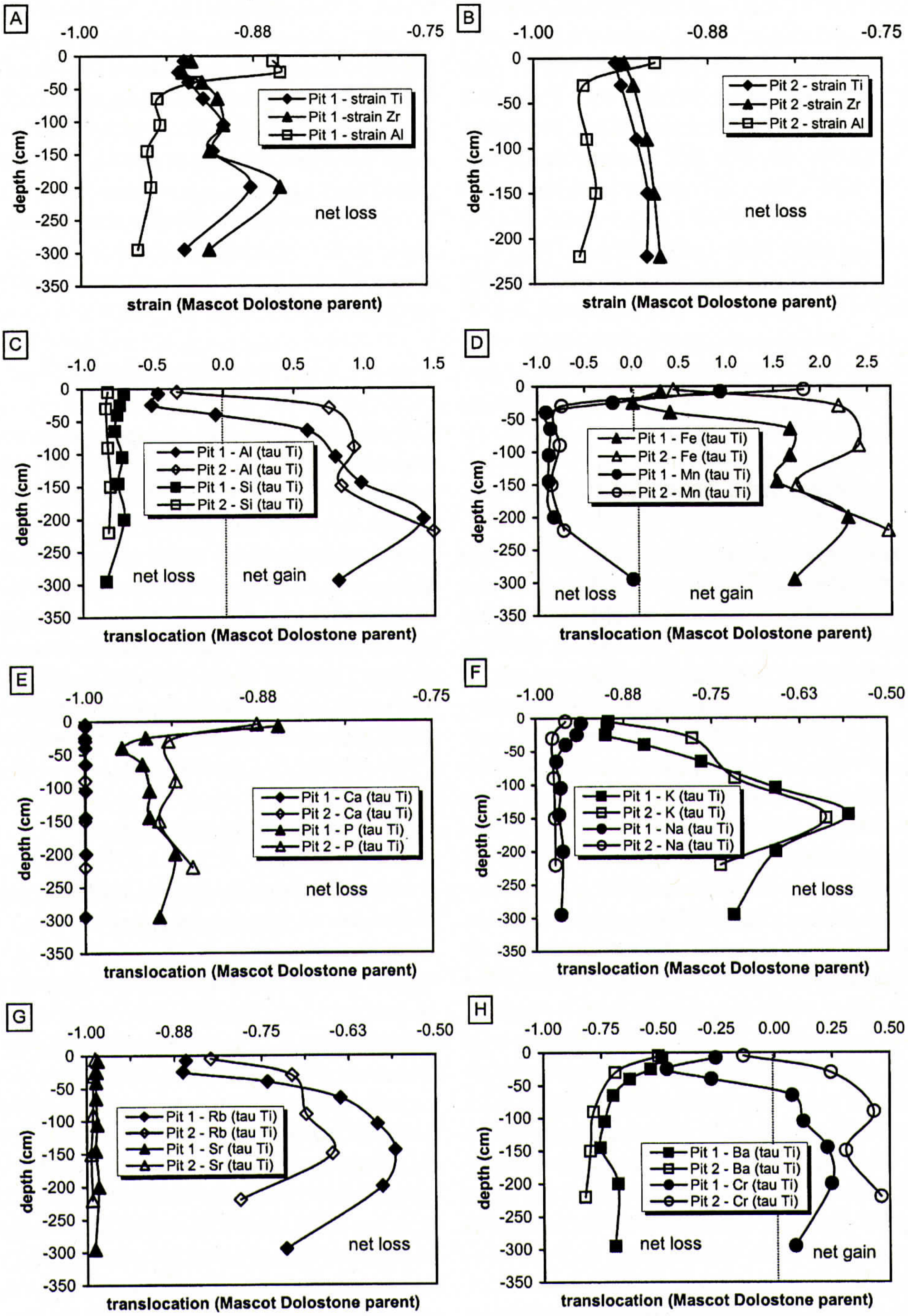

Figure 8. (A, B) Strain (volume change) and (C-H) translocation (tau) calculated for soil pits 1 and 2, assuming immobile Ti during weathering. Note that wholesale volume loss during weathering is indicated by strain plots; wholesale losses of Si, Mn, Ca, P, K, Na, Rb, Sr, and Ba are indicated based upon translocation calculations, whereas Al, Fe, and Cr gains are indicated. To convert to percentage increases or decreases, multiply values by 100. See text for discussion.

further test element immobility, translocations (tau) were calculated for Ti and Zr (assuming that the other respective element was immobile), and using both Mascot Fm. dolostone (MD) and insoluble residue (IR) as the parent materials (Figs. 7C, D). Mascot dolostone shows conservation of both TiO_2 and Zr, whereas TiO_2 was gained but Zr was lost in the IR. Based on these observed behaviors, TiO_2 was chosen as the immobile index element because of its higher abundance and least evidence for mobility during pedogenesis, and Mascot Fm. dolostone (MD) was chosen for the model parent material because TiO_2 is present in the same proportions in the soil as in the dolostone.

Strain and Translocation

Strain (volume change) calculated with depth and assuming immobile TiO_2, Zr and Al_2O_3, and Mascot dolostone (MD) as parent material, indicates major collapse of 88-95% for both soil pits (Figs. 8A, B). These results indicate there were major losses of constituents and mass during weathering of carbonate rock. Results with Mascot dolostone insoluble residue (IR) as the parent material (not shown) are similar to those with MD, but with slightly reduced estimates of volume losses.

Translocation is calculated for Al_2O_3 as 0-150% net gains, increasing with depth in the profile and attributed to clay concentration by illuviation, with 50% losses in the A and BE horizons due to clay losses (eluviation) (Fig. 8C). SiO_2 losses are a uniform 75-90% with no variation with depth (Fig. 8C). Fe_2O_3 shows 25-250% net gains that increase with depth attributable to oxidation of Fe in Fe-bearing minerals and fixation as Fe oxides and oxyhydroxides (Fig. 8D). MnO, in contrast, shows net gains only in A horizons that are highly oxidizing, but substantial 50-99% losses deeper in the profiles (Fig. 8D).

CaO, MgO (not shown), and Na_2O all show 95-99% net losses that exhibit little variation with depth, attributed to wholesale leaching of carbonate bedrock and hydrolysis of minor detrital feldspars (Figs. 8E, F). P_2O_5 shows lesser, but still very significant losses, with some evidence of biocycling in the A horizon (Fig. 8E). K_2O losses are 90% in the A horizon, decreasing to 50% in the deep Bt horizons because of decreasing K-feldspar leaching and clay production by pedogenesis (Fig. 8F). Rb and Cr show very similar patterns to that of K_2O with depth, tracking similar processes (Figs. 8G, H). Sr shows complete 99% uniform losses with depth, reflecting carbonate bedrock dissolution (Fig. 8G). Ba losses decrease towards the soil surface in each soil pit (Fig. 8H).

Radiocarbon Ages

Two bulk soil humate sample ages were determined using the AMS ^{14}C method (Table 1). Sample Beta - 223027 has an age of 7,370 $\pm$ 50 ^{14}C yr BP, and was sampled from soil pit 1 (ridge top) from the Bt5 horizon at 200 cm depth, with a soil organic matter $\delta^{13}C$ value of -24.4 ‰ PDB (relative to PeeDee Belemnite standard). Sample Beta – 223028 has an age of 11,030 $\pm$ 60 ^{14}C yr BP and was sampled from soil pit 2 (edge of sinkhole) from the Bt4 horizon at 220 cm depth, with a soil organic matter $\delta^{13}C$ value of -23.6 ‰ PDB.

DISCUSSION

Soil Genesis and Landscape Development

This research addresses Ultisol genesis from carbonate (dolostone) bedrock in the humid southeastern US. The combined morphological, micromorphological, geochemical and clay mineralogical data indicate that the Ultisols at the field site in eastern Tennessee are "genetic Ultisols", *sensu* Ciolkosz et al. (1989, 1990), formed from primarily dolostone bedrock but with probable inputs of colluvial and alluvial materials; thick, deeply developed argillic horizons resulted from a significant period of time during which clay moved down the soil profile, as well as with sufficient time for clay to be stripped from the upper part of the argillic and translocated downward. Determination of the duration of pedogenesis involved in these processes is difficult due to a lack of datable features and surfaces, and even the two AMS ^{14}C ages of bulk soil humates at circa 2 m soil depth likely only provide average ages of the soil carbon pool at that depth, and thus do not constrain the true soil age (Table 1).

One of the primary objectives of the study was to test whether the Ultisols at this site formed *in situ* as a single residuum from the long-term, top-down weathering of underlying carbonate bedrock. To address this objective one must first consider whether sufficient quantities of weatherable materials existed during the time of soil formation, based on the properties of the underlying bedrock as well as reconstructions of overlying bedrock materials once present (based on the mapped stratigraphic succession) but subsequently removed by weathering processes. The measured thickness of the Mascot Fm. dolostone in the vicinity of the study site is about 180 m, and geologic mapping indicates at least 90 m of Kingsport Fm. dolostone occur stratigraphically below the Mascot Fm. (Harris, 1969). From this one can conclude that there once was (and still is) ample carbonate bedrock for weathering requisite for Ultisol genesis at the site. Ciolkosz et al. (1995) used a simple method to estimate ages of 2-3 million years (m.y.) for limestone-parented soils in the central Pennsylvania Valley and Ridge province (mainly Alfisols due to their higher base status). The same method is also useful for estimating ages of soil geomorphic surfaces at our study sites in eastern Tennessee, based on the following important assumptions: (1) measured recovery of approximately 7-15% insoluble (non-carbonate) residue from the Mascot dolostone bedrock samples is typical for the entire formation, (2) a very conservative dissolution rate of 10 mm/1000 yrs was typical during weathering (because dolostone is much less soluble than limestone: e.g., Jennings, 1983), (3) the average bedrock bulk density is 2.85 g/cm^3 and the average soil bulk density is 1.65 g/cm^3, and (4) Mascot Fm. bedrock was the sole parent material for the residuum. Calculations, based on the preceding assumptions, suggest that it would have required 11 m.y. to have accumulated the 11 m of soil material at borehole 1 in this manner solely by dolostone dissolution and concentration of non-carbonate constituents. Assuming a more rapid dolostone dissolution rate of 30 mm/1000 yrs would reduce the amount of time to 3-4 m.y. to form 11 m of soil material in place. This lower estimate is perhaps more reasonable in light of many other studies of rates of weathering and saprolite formation suggesting 4 m per m.y. for crystalline Piedmont soil and saprolites in Virginia (Pavich, 1986, 1989) and 1.2-2.2 m per m.y. for Maryland (Cleaves, 1989, 1993, 2000). Of course, these calculations assume no erosion or relocation of insoluble material, as well as no introduction of additional materials. Absence of introduced new materials and of reworking of materials seems unlikely in geomorphic settings involving the types of moderate to steep slopes typical in the Valley and Ridge Province of eastern Tennessee. Whether there was reworking or only *in situ* soil formation, the conclusion appears inescapable that the soil profiles studied in eastern Tennessee, which formed on carbonate bedrock surfaces, represent a significant amount of time for pedogenesis, on the order of perhaps as much as several million years.

In order to address the second objective, which was to test the hypothesis that the Ultisols at this site are polygenetic and formed from multiple parent materials, additional supporting data must be considered. Geomorphologically the site location on moderate to steep slopes with active sinkholes, and proximal to the Holston River, is one with the potential for polygenetic soil-forming processes. The soil morphology revealed in deep boreholes (to 11 m) points to a major discontinuity at 6 m depth in both boreholes 1 and 4, as evidenced by concentrations of carbonate and siliciclastic lithorelicts, as well as by possible buried soils with fossil root traces at 9.5 m depth in borehole 1 (Fig. 2). This major discontinuity is also apparent in the particle-size data showing increased coarse-grained materials at this depth (Fig. 6) as well as in the clay mineralogical data showing increased halloysite at this depth (Table 4). The clay mineralogical data indicate that inheritance of illites from primary parent materials dominates below the 6 m depth discontinuity (Table

4). Highly ordered illites dominate the clay fractions in Paleozoic bedrock in the Appalachian basin (e.g., Hower et al., 1976; Mora et al., 1998) because of the elevated thermal history and time associated with burial diagenesis during which K-fixation transformed smectites to illites. The increased halloysite at the top of the 6 m depth discontinuity, as well as the progressive upward increases in kaolinite reflect increasing importance of mineral weathering and pedogenesis on the clay mineralogy of soils towards the surface, and decreasing influence of illite inheritance from bedrock clays (Table 4). Both hydroxy-interlayer micas (HIM) and chlorite are at a maximum at the soil surface and would seem to suggest influx of other weathered materials, possibly dust, added recently to the soil surface (Table 4). Mahowald et al. (2006) predicted a 92% increase in mineral aerosols during the last glacial maximum based on climate model simulations, and repeated maximal dust fluxes increasing by an order of magnitude during Pleistocene glacial maxima are well-documented in the Vostok Ice Core by Petit et al. (1999).

The polygenetic hypothesis is further supported by the presence of a prominent stone line of "exotic" metaquartzite rock fragments in the Bt3 and Bt4 horizons of soil pit 2 at ~240 cm depth. Based on micromorphological analysis (Fig. 4F) the buried stone line is interpreted as probable Chilhowee Group (Lower Cambrian) metaquartzite cobbles and pebbles derived from >50 km away in the foothills of the Great Smoky Mountains. If this interpretation is correct then it requires that the study site was influenced in the past by alluvial inputs from the ancestral Holston and Tennessee River systems, though no fluvial terraces are currently mapped or recognizable at the site. Reworked saprorelicts observed in the Bt4-Bt5 horizons of soil pit 1 (150-200 cm depth) and in both the soil boreholes also provide evidence for mixing of colluvium into the residuum (Figs. 3, 4, 5). Evidence for mixing in the highest topographic position (ridge-top) further reflects a long-term duration for residuum development on a dynamic geomorphic surface.

Further insight into Ultisol genesis at this site is provided by the mass-balance geochemical data. If the strain calculations of >90% volume loss are correct then the formation of the soils would have required dissolution and removal of extremely great thicknesses (circa 100 m) of carbonate bedrock to accumulate 11 m of soil material; such a conclusion was also reached by Olson et al (1980) for terra rosa soils in southern Indiana formed on Mississippian limestone strata. Mascot dolostone parent material is notably deficient in both TiO_2 and Al_2O_3 compared with the residual materials and hence high amounts of residual enrichment are necessary to achieve the concentrations of these elements measured in the soil (Fig. 7A, B). In an earlier study of Ultisol genesis Syers et al. (1969) concluded that eolian sediment influxes to Ultisols during the Quaternary was significant, primarily as aerosolic dust finer in size than the silt comprising loess. From this one could therefore conclude that there may have been inputs of other weathered materials (with higher concentrations of TiO_2 and Al_2O_3) to the soil profiles during pedogenesis, and that *in situ* top-down genesis of Ultisols was only of one of several processes leading to formation of residual materials at this site (Figs. 8A, B). Reworking and erosion during soil development likely relocated much of the above-mentioned non-carbonate materials, as evidenced by the discontinuities detected in the boreholes (Fig. 2) and variations in the clay mineralogy with depth (Table 4), thereby supporting a polygenetic pathway for pedological and geomorphological development. Extensive pedogenic clay illuviation is evident in thin-sections (Figs. 3, 4), thus lessivage and translocation of clays from the thin (<50 cm) A and BE horizons also constituted a significant role in the development of thick, clay-rich Bt horizons.

Proposed Pedo-Geomorphological Model for Carbonate-Derived Residual Materials

A conceptual pedogeomorphological model for the formation of carbonate-parented Ultisols formed on upland landscapes at this site and based on the data shown previously, which

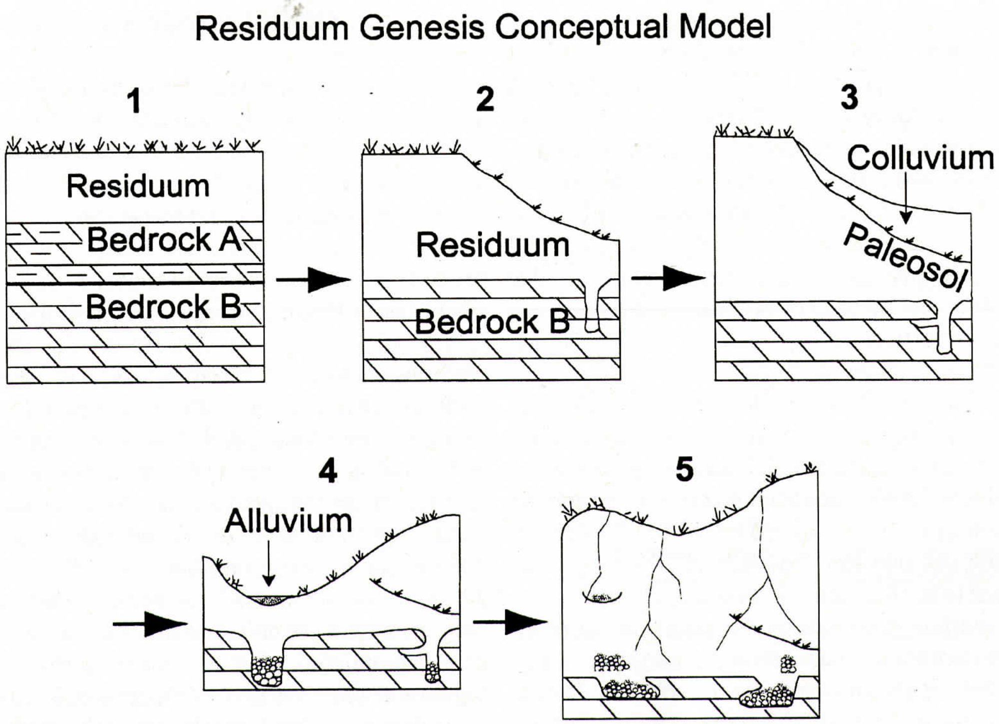

Figure 9. Conceptual 2-D model for the polygenetic formation of carbonate-derived residual materials in an upland landscape in humid southeastern US at site near Knoxville, Tennessee. (1) Development of *in situ* clayey residuum by dissolution of upper Mascot Formation shaly dolostone bedrock (A). (2) Residual materials extend downward into lower Mascot Formation dolostones (B) and interact with karst sinkhole- (doline) induced subsidence, which creates slopes and mass-wasting, followed by landscape stabilization. (3) Paleosol developed on stabilized surface is buried by additional colluvial materials, while karst processes extend deeper. (4) Incision and lateral migration of ancestral Holston River results in alluvial deposition and additional karst processes. (5) Additional colluvial and dust inputs (not shown) followed by landscape stabilization and pedogenesis forms thick Ultisol (Typic Paleudult) profile at upland site. See text for detailed discussion.

might be applicable for other upland landscapes in similar geomorphological settings in the humid southeastern US, is shown in Figure 9. This conceptual model identifies a polygenetic pathway for pedogenesis and landscape evolution, and at least five stages of development of residual materials at this site in eastern Tennessee, USA (Fig. 9):

Stage 1: Development of initial residuum on upper Mascot Fm. dolostone bedrock parent material (labeled A), in which weathering was characterized by lowering of the bedrock due to chemical weathering and *in situ* clay formation.

Stage 2: Disruption of original residuum formation due to erosion, with associated landscape instability and subsequent development of sinkholes within lower Mascot Fm. dolostone bedrock (labeled B), which accelerated erosion rates in areas in close proximity to active sinkholes: this resulted in the incorporation of older residual soil with younger, Mascot-derived residuum.

Stage 3: Continued mixing of residuum of multiple parent materials due to erosion and later influx of colluvial material (e.g., 6 m deep discontinuity in soil boreholes), with accumulations of residual materials in topographic low positions and the development of thick, clayey Bt horizons. Paleosol at 9.5 m depth in borehole 1 formed prior to establishment of geomorphic surface represented by 6 m deep discontinuity.

Stage 4: Continued chemical weathering, *in situ* clay formation and lowering of bedrock work in tandem with illuviation and lessivage of pedogenic clay derived from uppermost horizons, which are replenished by additions of colluvium and alluvium from ancestral Holston River. Introduction of alluvial gravel (Chilhowee metaquartzite pebbles) may have occurred at this time. Later stages of thick soil development and significant pore occlusion by clay illuviation occur at 2-3 m depth.

Stage 5: Continued pedogenic overprinting "blurs" boundaries between genetic units of residual materials, which results from advanced Ultisol development and maturation during the Holocene, as evidenced by AMS ^{14}C ages of bulk soil humates. Possible additions of eolian dust to profiles are not shown.

Although we are unable constrain an absolute age for our pedo-geomorphological model, other reports of mappable terrace gravels consisting of "rotted" Chilhowee metaquartzite pebbles and cobbles embedded in clay-rich residual materials and elevated along upland summits in the vicinity of our study site by Roberts et al. (1955), and confirmed by one of us (SGD) at a site some 12 km to the southeast within 0.75 km of the modern Tennessee River, attest to the antiquity of these upland surfaces, which are almost certainly much older than late Pleistocene in age. Whittecar and Duffy (2000) used a clast weathering scale for Chilhowee (Antietam) quartzite clasts (developed from dated deposits in eastern Virginia) to "date" fans west of the Blue Ridge and postulated that some fan deposits there may date from the Pliocene or possibly even the Miocene. Antiquity of these upland surfaces is also supported by the simple calculations of rates of landscape lowering by carbonate bedrock dissolution presented previously (using calculations formulated by Ciolkosz et al. 1995) indicating that this geomorphic surface in eastern Tennessee might be several million years old (i.e., late Pliocene in age). Further refinements in dating methods are necessary before ages of these geomorphic surfaces can be reliably determined.

CONCLUSIONS

Morphological, textural, geochemical and clay mineralogical data indicate a polygenetic origin for the genesis of Ultisols and carbonate-derived residual materials attaining a thickness of up to 11m at a Valley and Ridge Province upland site in eastern Tennessee, USA. From this study it is apparent that the Cambrian-Ordovician Mascot Fm. dolostone, which averages 7-15% insoluble (non-carbonate) material, was an important source of parent material for these soils. However, so much clay has accumulated and translocated from A and BE to Bt horizons during soil genesis that it would have required dissolution and weathering of very significant thickness (> 100 m) of dolostone bedrock over a time span of several million years. We interpret that illuviation and lessivage of pedogenic clay from multiple colluvial and alluvial sources, in conjunction with *in situ* clay formation, together explain the genesis of soils developed on carbonate bedrock at this site. Related studies on advanced Ultisol pedogenesis suggest that hundreds of thousands to millions of years are required for their development (Birkeland, 1999; Retallack, 2001). The significant maturation of this residual material may have allowed for genesis to span intervals of dynamic landscape changes.

This study contributes to additional understanding regarding genesis of Ultisols from carbonate bedrock containing low amounts of insoluble materials and weatherable grains. It also demonstrates that these soils have a "pedo-geomorphological history" that can be deciphered through careful integration of many lines of investigation, some of which are "traditional" in the pedological realm (e.g., conventional backhoe-excavated pit studies to standard depth, using 1 m deep control section for classification and conventional wet-chemical and textural soil characterization), and some of which are not (e.g., DPT soil coring across a landscape, to depths of up to 11 m, careful logging of depth-related features and identifying morphostratigraphical units, coupled with extensive thin-section micromorphological analysis, whole soil geochemical, and clay mineralogical studies). This research highlights the likelihood that Ultisols and carbonate-derived residual materials may record key features critical to understanding past surficial processes and associated changes in climate.

ACKNOWLEDGMENTS

This project is based upon the M.S. research of Schultz (2005) and was supported by facilities and equipment within the University of Tennessee (UT) Department of Earth and Planetary Sciences, as well as the Baylor University Department of Geology. Additional financial aid was provided by a graduate student grant from the Geological Society of America. Other funding was provided by the UT Center for Environmental Biotechnology and the UT Institute for a Secure and Sustainable Environment. B. Schultz was also supported during preparation of this manuscript by NSF grant DGE-0538420. We thank G. Richard Whittecar for his review of the manuscript.

REFERENCES

Birkeland, P.W., 1999, Topography-soil relations with time in different climatic settings, *in* Soils and Geomorphology (3rd ed.): Oxford University Press, New York, p. 230-267.

Blake, G.R., and Hartge, K.H., 1986, Bulk density, *in* Klute, A. ed., Methods of soil analysis, Part I: Physical and mineralogical methods (2nd ed.): Soil Science Society of America, Agronomy Monograph 9, p. 363-375.

Brimhall, G.H., Lewis, C.J., Ford, C., Bratt, J., Taylor, G., and Warin, O., 1991a, Quantitative geochemical approach to pedogenesis: importance of parent material reduction, volumetric expansion, and eolian influx in laterization: Geoderma, v. 51, p. 51-91.

Brimhall, G.H., Chadwick, O.A., Lewis, C.J., Compston, W., Williams, I.S., Danti, K.J., Dietrich, W.E., Power, M., M., Hendricks, D., and Bratt, J., 1991b, Deformational mass transfer and invasive processes in soil evolution: Science v. 255, p. 695-702.

Buol, S.W., Hole, F.D., McCracken, R.J., and Southard, R.J, 1997, Soil Genesis and Classification: Iowa State University Press, Iowa, 527 p.

Chadwick, O.A., Brimhall, G.H., and Hendricks, D.M., 1990, From a black to a gray box – a mass balance interpretation of pedogenesis: Geomorphology, v. 3, p. 369-390.

Chowns, T.M., and Elkins, J.E., 1974, The origin of quartz geodes and cauliflower cherts through the silicification of anhydrite nodules: Journal of Sedimentary Petrology, v. 44, p. 885-903.

Ciolkosz, E.J., Carter, B.J., Hoover, M.T., Cronce, R.C., Waltman, W.J., and Dobos, R.R., 1990, Genesis of soils and landscapes in the Ridge and Valley province of central Pennsylvania: Geomorphology, v. 3, p. 245-261.

Ciolkosz, E.J., Cronce, R.C., Sevon, W.D., and Waltman, W.J., 1995, Genesis of Pennsylvania's limestone soils: Pennsylvania State University, Agronomy Series Number 135, 28 p.

Ciolkosz, E.J., Waltman, W.J., Simpson, T.W., and Dobos, R.R., 1989, Distribution and genesis of soils of the northeastern United States: Geomorphology, v. 2, p. 285-302.

Cleaves, E.T., 1989, Appalachian Piedmont landscapes from the Permian to the Holocene: Geomorphology, v. 2, p. 159-179.

Cleaves, E.T., 1993, Climatic impact on isovolumetric weathering of a coarse-grained schist in the northern Piedmont Province of the central Atlantic states: Geomorphology, v. 8, p. 191-198.

Cleaves, E.T., 2000, Regoliths of the Middle Atlantic Piedmont and evolution of a polymorphic landscape: Southeastern Geology, v. 39, p. 199-222.

Crownover, S.H., Collins, M.E., and Lietzke, D.A., 1994a, Soil-stratigraphic correlation of a doline in the Valley and Ridge Province: Soil Science Society of America Journal, v. 58, p. 1730-1738.

Crownover, S.H., Collins, M.E., and Lietzke, D.A., 1994b, Parent materials and stratigraphy of a doline in the Valley and Ridge Province: Soil Science Society of America Journal, v. 58, p. 1738-1746.

Driese, S.G., McKay, L.D., and Penfield, C.P., 2001, Lithologic and pedogenic influences on porosity distribution and groundwater flow in fractured sedimentary saprolite: an application of environmental sedimentology: Journal of Sedimentary Research, v. 71, p. 843-857.

Driese, S.G., Mora, C.I., Stiles, C.A., Joeckel, R.M., and Nordt, L.C., 2000, Mass-balance reconstruction of a modern Vertisol: implications for interpreting geochemistry and burial alteration of paleoVertisols: Geoderma, v. 95, p. 179-204.

Fitzpatrick, E.A., 1993, Soil Microscopy and Micromorphology: John Wiley & Sons Ltd., New York, 304 p.

Harris, L.D., 1969, Kingsport Formation and Mascot Dolomite (Lower Ordovician) of East Tennessee, *in* Papers on the stratigraphy and mine geology of the Kingsport and Mascot formations (Lower Ordovician) of East Tennessee: Tennessee Division of Geology, Report of Investigations No.23, p. 1-39.

Hower, J., Eslinger, E., Hower, M.E., and Perry, E.A., 1976, Mechanism of burial metamorphism of argillaceous sediment, mineralogical and chemical evidence: Geological Society of America Bulletin, v. 87, p. 725-737.

Jennings, J.N., 1983, Karst landforms: American Scientist, v. 71, p. 578-586.

Mahowald, N.M, Muhs, D.R., Levis, S., Rasch, P.J., Yoshioka, M., Zender, C.S., and Luo, C., 2006, Change in atmospheric mineral aerosols in response to climate:

Last glacial period, preindustrial, modern, and doubled carbon dioxide climate: Journal of Geophysical Research, v. 111, D10202, doi: 10.1029/2005JD006653.

McKay, L.D., Driese, S.G., Smith, K.H., and Vepraskas, M.J., 2005, Hydrogeology and pedology of saprolite formed from sedimentary rock, eastern Tennessee, USA: Geoderma, v. 126, p. 27-45.

Merino, E., and Banerjee, A., 2008, Terra rossa genesis, implications for karst, and eolian dust; a geodynamic thread: Journal of Geology, v. 116, p. 62-75.

Moore, D.M., and Reynolds, R.C., 1997, X-Ray Diffraction and the Identification and Analysis of Clay Minerals (2nd ed.): Oxford University Press, New York, 379 p.

Mora, C.I., Sheldon, B.T., Elliott, W.C., and Driese, S.G., 1998, An oxygen isotope study of illite and calcite in three Appalachian Paleozoic vertic paleosols: Journal of Sedimentary Research, v. 68, p. 456-464.

Oder, C.R., and Miller H.M., 1945, Stratigraphy of the Mascot-Jefferson City zinc district, Tennessee: American Institute of Mining, Metallurgical, and Petroleum Engineers, Technical Publication, 9 p.

Olson, C.G., Ruhe, R.V., and Mausbach, M.J., 1980, The *terra rossa* limestone contact phenomena in karst, southern Indiana: Soil Science Society of America Journal, v. 44, p. 1075-1079.

Pavich, M.J., 1986, Processes and rates of saprolite production and erosion on foliated granitic rock of the Virginia Piedmont, *in* S.M. Coelan and D.P. Dethier, eds., Rates of chemical weathering of rocks and minerals: Academic Press, Orlando, FL., p. 551-590.

Pavich, M.J., 1989, Regolith residence time and the concept of surface age of the Piedmont "Peneplain": Geomorphology, v. 2, p. 181-196.

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.M., Basile, I., Bender, M., Chapellaz, J., Davis, J., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V., Lorius, C., Pépin, L., Ritz, C., Saltzman, E., and Stievenard, M., 1999, Climate and atmospheric history of the past 420,000 years from the Vostok Ice Core, Antarctica: Nature, v. 399, p. 429-436.

Retallack, G.J., 2001, Soils of the Past: An Introduction to Paleopedology (2nd ed.): Blackwell Science, New York, 404 p.

Richter, D.D., and Markewitz, D., 1995, Soil, the zone of the earth's crust that is biologically active, is much deeper than has been thought by many ecologists: Bioscience, v. 45, p. 600-609.

Roberts, W., Nichols, B.C., Odom, J.N., Gallatin, M.H., Odom, L.E., and Beesley, T.E.,1955, Soil Survey of Knox County, Tennessee: US Department of Agriculture Series 1942, No. 10, 241 p. + maps.

Schultz, B.S., 2005, Morphological, textural, geochemical, and mineralogical properties of dolostone-derived residuum in Knox County, Tennessee [unpublished M.S. Thesis]: Knoxville, University of Tennessee, 117 p.

Singer, M.J., and Janitzky, P., 1986, Field and laboratory procedures used in a soil chronosequence study: U.S. Geological Survey Bulletin 1648, 49 p.

Soil Survey Staff, 1999, Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys (2nd ed.): US Department of Agriculture, Natural Resources Conservation Service, Agriculture Handbook Number 436, Washington, D.C. 871 p.

Soil Survey Staff, 2006, Keys to Soil Taxonomy (10th ed.): US Department of Agriculture, Natural Resources Conservation Service, Washington, D.C. 325 p.

Stoops, G., 2003, Guidelines for analysis and description of soil and regolith thin sections: Soil Science Society of America, Madison, WI, 184 p. + CD w/images.

Syers, J.K., Jackson, M.L., Berkheiser, V.E., Clayton, R.N., and Rex, R.W., 1969, Eolian sediment influence on pedogenesis during the Quaternary: Soil Science, v. 107, p. 421-427.

Whittecar, G.R., and Duffy, D.F., 2000, Geomorphology and stratigraphy of late Cenozoic alluvial fans, Augusta County, Virginia, U.S.A.: Southeastern Geology, v. 39, p. 259-279.

SOUTHEASTERN GEOLOGY
V. 48, No.1, February 2011, p. 23-35

Barrier Island Geology and Union Strategy for the Assault and Siege of Charleston, South Carolina, 1862 - 1863

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ABSTRACT

The Union strategies for taking Charleston, South Carolina, in 1862 and 1863 were dictated by the geomorphology of the Quaternary and modern barrier island systems south of the city. Troop movement across the majority of the depositional environments on and around modern and older barrier islands, including Folly and Morris Islands, was impossible and the disastrous Union assaults at Fort Lamar (Secessionville) and Battery Wagner (Morris Island) were largely determined by the lack of alternate strategies available for attacking shoreline-perpendicular sand fortifications. The geology of the island also proved ideal for the Confederate defense, both in terms of the narrow dune ridges and the nature of the sediment. Well rounded and sorted quartz sand allowed rapid entrenching and minimized the effectiveness of an overwhelming artillery advantage of the Union field and naval forces. The character of the sediment was also favorable to Union sappers, and trenching ultimately led to the abandonment of Battery Wagner by Confederate defenders. Geology was also a contributing factor in terms of fresh water supply for the troops of both sides during the conflict.

INTRODUCTION

Overview of the Siege of Charleston

During the Civil War, the Union's goal to capture the city of Charleston, South Carolina, had both strategic and symbolic value. Charleston represented the most important Confederate shipping port along the Atlantic Coast and offered excellent railroad connections to other major Confederate cities and military depots throughout the southeast. These factors, combined with the economic relationships between the commercial houses of Charleston and Great Britain, made the capture of the city essential to the North if the Confederacy was to be defeated.

This paper is focused on how the geologic setting determined the defense of the most accessible land route towards Charleston, through the barrier islands from the south. While Fort Sumter and Fort Moultrie protected Charleston from a direct Union naval attack through the harbor entrance, the defenses on James Island, Folly Island, and Morris Island helped slow the Federal advance from the south. Geology dictated the tactics and strategies used in the Union assaults, and the geomorphology of the islands largely assured Union disasters at the Battle of Secessionville and the repeated attacks on Battery Wagner in 1862 and 1863.

REGIONAL GEOLOGY AND GEOGRAPHY OF CHARLESTON, SOUTH CAROLINA

Barrier Island Geology

A littoral sand body must have six interactive sedimentary environments in order to be characterized as a barrier island: 1) mainland; 2) inlets; 3) back-barrier lagoon (or marsh); 4) barrier platform; 5) shoreface; and, 6) inlet deltas (Oertel, 1985). This paper discusses how the spatial distribution of these sedimentary environments dictated the strategy of the advancing Union forces during the assault on Charleston

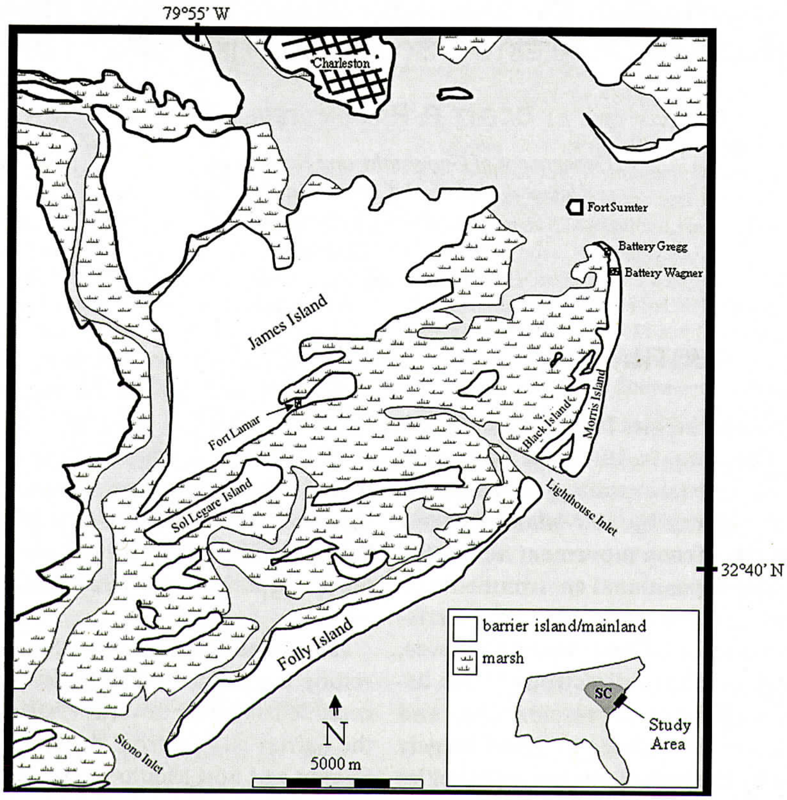

Figure 1: The Quaternary and modern barrier island system south of Charleston, South Carolina as it was in 1862 – 1863. Note Morris Island is well seaward of its present-day position.

in 1862 and 1863, and how Confederate military engineers took advantage of the favorable island geomorphology when constructing the city's defenses.

A barrier island is the sub-aerial accumulation of sediment between the shoreface and a back-barrier lagoon or marsh, and between two inlets (Oertel, 1985). Union forces were largely constrained in their movement by the narrowness of modern and Quaternary barrier island complexes. The width of an island is a function of the proximity between back-barrier lagoons (or marshes) and the shoreface. The back-barrier lagoon is the depositional environment that separates the mainland from the barrier island and, during periods of spring or high tide, was largely impassable by large bodies of troops. Whether a barrier island is backed by a marsh or a lagoon is a complex function of sediment supply from both the mainland and the island (via washovers or inlet deltas), the rate at which the island is migrating, and/or the inherited bathymetry (Belknap and Kraft, 1985). Assaults over any terrain other than a high marsh subenvironment during low tide would have been difficult for troops in the best possible conditions, and impossible while encumbered with equipment or under hostile fire. Furthermore, movement across any marsh depositional environment would have been impossible for artillery or cavalry.

Barrier inlets are shore-perpendicular channels that separate one island element from another or from a laterally adjacent mainland element (Oertel, 1985). Without this depositional environment, the barrier island would be classified as either a barrier spit or a baymouth barrier. The inlets along the Charleston coast can be classified as either tidal barrier inlets or fluvial barrier inlets. The nature of the inlet, whether tide-dominated or river-dominated, was an important consideration for movements

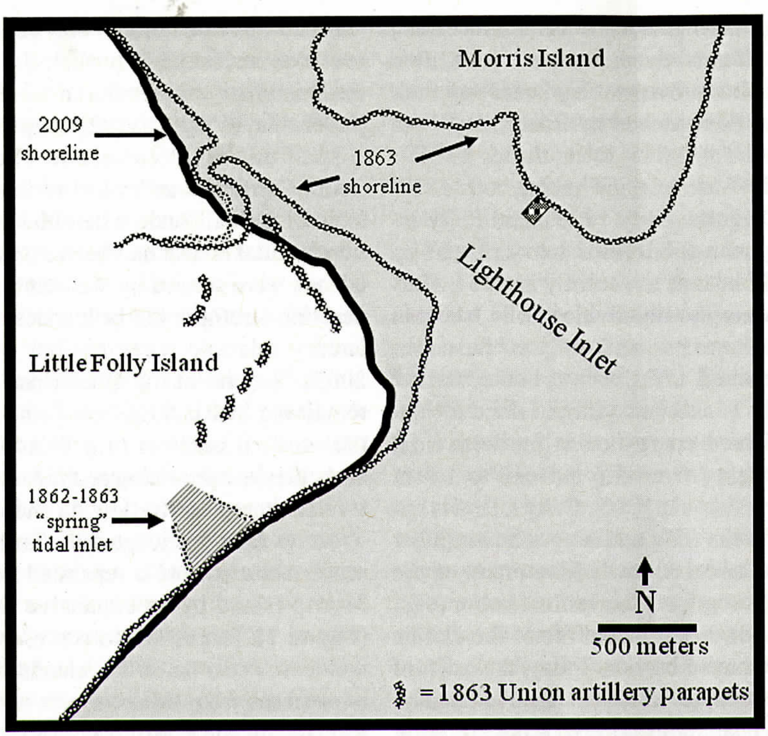

Figure 2: Lighthouse Inlet in 1863 and 2009. Morris Island has retreated at a much higher rate than Folly Island, in large part because of Morris Island's sand starvation due to proximity to the Charleston Harbor jetties.

of both troops and ships. The ebb-tidal delta associated with larger inlets prohibited movement of anything but extremely shallow draft ships near the islands, making naval support of land operations more difficult. The water velocity associated with larger tide-dominated inlets prohibited cross-inlet movement by troops, as the boats would have been carried in a shore perpendicular direction offshore or toward the mainland.

The two modern barrier islands south of Charleston are Morris Island and Folly Island (Figure 1). These islands are separated by Lighthouse Inlet and have eroded at different rates during the 150 years since the Civil War (Figure 2). The 1886 Charleston earthquake increased erosion to both islands as they are on the down-dropped side of the Ashley River fault (Lennon, 1985). Additionally, the construction of the jetties stabilizing Charleston Harbor in 1896 led to a diminished sand supply via beach drift to Morris Island.[1] These factors, combined with steady sea-level rise, caused Morris Island to retreat more than a kilometer landward between 1863 and 2010.

The beach ridges, that eventually became Folly Island and Morris Island, formed approximately 5,000 years ago when the rapid sea-level rise associated with melting of Pleistocene glaciers began to slow. In their original state both islands would have been covered with a pine forest and backed by marginal-marine marshes (or, depending on sediment availability, a lagoon). "Folly" or "volly" are Old English terms for "a tree-crested dune ridge" which would have been descriptive for both Folly and

1. Jetty construction was followed by a collapse and rapid erosion of the large Charleston harbor ebb tidal delta. This caused initial accretion to Morris and Little Folly Islands for approximately twenty years before erosion and shoreline retreat commenced.

Morris Islands at this time (Lennon et al., 1996). The islands' dynamic nature is testified to by both their rapid retreat landward and their propensity to be breached by tidal inlets; both have been subdivided by inlets during the last 200 years with Morris Island having been divided into thirds in the early 1800's and Folly Island having been subdivided into Little Folly and Big Folly Islands as recently as 1864. Hurricane Hugo temporarily divided Folly Island in 1989 when the area known locally as "the washout" was breached.

Both Folly Island and Morris Island are located in a mixed-energy coastline with tidal ranges averaging from 1.6 m neap to 1.9 m spring (Ebersole et al., 1996). Folly Island is approximately 8-km long and ranges in width between 900 m and 100 m. Unlike many of the barrier islands south of Charleston Harbor (e.g., Kiawah Island), Folly Island is not the classic "drumstick" shaped barrier. Today, the town of Folly Beach occupies much of the developed island. Morris Island, by contrast, is not currently occupied, in large part because of the rapid rate at which it has been retreating. Morris Island is approximately 1-km shorter than Folly Island and consists today of a dredge impoundment area and washover fans. During the Civil War the islands would have been more similar in appearance, and Morris Island had sand dunes.

Influence of Quaternary Geology on Modern Islands

A number of Quaternary barrier islands are located between Folly and Morris Island and the mainland. These smaller, older barriers and beach ridges include Cole's Island, Long Island, Black Island, and Sol Legare Island. All of these islands played a role in the Union strategy to take Charleston and many were fortified with artillery.

Transgressions and regressions over the last several interglacial cycles have left a series of stair-stepped marine and estuarine terraces along the coastal plain in this region and six, and possibly more, barrier-ridge systems have been identified behind the modern barriers. However, as Harris et al. (2005, p. 51) indicate, "only two to five terraces may represent climax sea level maximum"; further, the exact age of the Quaternary barriers has not been well established. Gayes et al. (1992) suggest that the record of mid-Holocene sea-level oscillation in South Carolina was limited to tidal-marsh systems of a small scale where the reworking action by tidal creeks had been minimized. These islands were shaped by the combination of underlying stratigraphic influences and a mixed-energy tide and wave regime (Harris et al., 2005). Several of the Quaternary barriers and remaining beach ridges are being truncated by the modern barriers (e.g. Black Island). As such, they are providing sediment to the modern barriers, temporarily slowing shoreline retreat.

James Island is located the farthest from the modern barriers and is separated from Folly and Morris Island by an expansive marsh system (Figure 1). James Island represents the oldest and least dynamic of the islands because of its remoteness from tidal currents and wave energy. During the Civil War, James Island also would have had the largest supply of fresh groundwater and a limited supply of timber (due to the large number of plantations).

INFLUENCE OF GEOLOGY ON UNION STRATEGY

The Union Plan

By 1862, the Union Army had established shoreline bases south and north of Charleston. The Union Army's reliance on supplies and support from the Navy precluded attack on Charleston from the west. The shore-parallel orientation of the modern and Quaternary barrier island complexes dictated that any direct assault on Charleston by the Union Army must come from either the northeast (Isle of Palms and Sullivan's Island) or the south/southwest (Folly and Morris Islands). Advance from the northeast was less strategically favorable for two reasons. First, the Quaternary barrier island system behind Sullivan's Island is not as extensive as those behind Folly and Morris Islands; as a result, any large scale troop movement would have to take place on the modern islands, limiting tactical flexibility. Second, the presence of Fort Moultrie, a fortification with sand covered brick walls and a heavy artillery garrison, on the southern portion of Sullivan's Island discouraged advancement from this direction.

To the south, the expansive marsh system behind Folly and Morris Islands further limited the Union's corridor for attack. Marshes in the southeastern United States are typically flat expanses with little change in elevation and are dominated by halophytes such as salt marsh cordgrass (*Spartina* spp.). Although these plants can reach 3 m in height, they usually do not grow more than 1 m and tend to be patchy in distribution. Also, their need for tidal inundation dictates that they live at lower elevations within the marsh and not more than approximately one meter above mean high tide. Thus, the combination of low vegetation, low relief, and wet, muddy sediments created an impassable barrier for foot soldiers, artillery, or cavalry. The strategic situation facing Major General David Hunter as he planned his advance along the Stono River in June 1862 was constrained by his limited ability to move troops in a shore-perpendicular direction because of the salt marsh sediments and tidal creeks bracketing the Quaternary barrier islands and backing the modern islands.

The First Land Assault on Charleston

In the early summer of 1862, Charleston was being blockaded by the Union Navy. In an attempt to consolidate the limited troops available for defense of the city the Confederate commander, Major General John C. Pemberton, decided it would be prudent to abandon Cole's and Battery Islands south of Folly Island. The Union Army took advantage of this withdrawal by landing two divisions on the southeastern end of James Island under the cover of Federal gunboats. The Confederate response to this invasion was a strengthening of the defenses on the middle and northern portion of James Island. Brigadier General Nathan George Evans was placed in command of the island's defenses and he took advantage of the geomorphology of James Island when selecting the site for his new fort (Fort Lamar) at Secessionville. Fort Lamar was flanked to the north and south by salt marsh and was approachable from only one direction (Figure 1). As such, the Confederates maximized the defensibility of the fort by concentrating their artillery along a single interior wall as they were confident the fort would not be attacked across the unsuitable marsh sediment. In the face of a rapid Union advance, the unconsolidated sandy sediment from the Quaternary barrier island proved ideal for excavation and construction of gun parapets.

When the Union forces attacked Fort Lamar on June 15th their plan was relatively simple: two assault waves were to conduct a frontal attack just before sunrise. The plan immediately began to go awry when the initial wave became disoriented and the narrowing of the island resulted in the left flank of the assault moving into marsh terrain. This slowed the entire mass of soldiers enough that the second wave of the assault began to overrun them. The result was a slow assault by too many men for the narrow approach to the Confederate fort. The Battle of Secessionville consisted of three failed frontal attacks and a failed flanking attack that turned catastrophic when members of the 3rd New Hampshire attempted to assault the fort across the low marsh. After the battle, Union officers repeatedly remarked about the "very soft" marsh mud and the difficulty of troop movement (Jones, 1911). The entire battle lasted less than four hours and resulted in almost 700 Union casualties, while the Confederates suffered just over 200. Had the Union attack succeeded they would have been in a position to attack Fort Johnson from the landward side and flank the Confederate defenses on Morris Island, forcing the isolation and abandonment of the modern barrier islands and perhaps the surrender of the city.

The Second Land Assault on Charleston

After the Federal threat to James Island had been minimized, Confederate General Pemberton considered alternative measures for fortify-

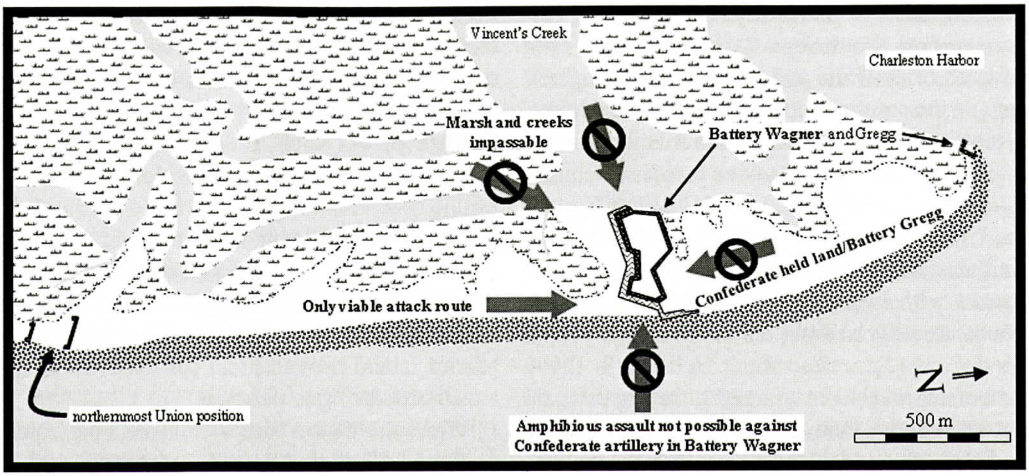

Figure 3: Strategic positioning of Battery Wagner and Battery Gregg, taking advantage of geology of Morris Island. Note the northern-most position of the Union offensive line in July 1863. Ultimately, sappers reached Battery Wagner by trenching and the Confederates were forced to make a strategic evacuation.

ing the city's defenses. Before the Battle of Secessionville, Morris Island had only a single fortification. This stronghold, named Battery Gregg, was located on the extreme northern part of the island on a spit of sand called Cummings Point (Figure 1). The guns in this battery overlooked the main channel into Charleston Harbor and were vulnerable to attack from the south. Pemberton decided the best way to protect Morris Island and Battery Gregg was to build a new battery at the narrowest portion of the island. He instructed his engineering staff to build an earthen (barrier island dune and beach sand) fortification approximately 1000 m south of Cummings Point where the island was extremely narrow. This new battery was to face directly southwest and perpendicular to the shoreline, and be flanked to the south by the Atlantic Ocean and to the north by Vincent's Creek and a low marsh depositional environment (Figure 3). In many respects the design of this battery was similar to Fort Lamar on James Island, but on a larger scale with standing water on the flanks of the fortification instead of marsh mud. The narrow strip of island approaching the Neck Battery, as the fortification was originally named, was only 25-m wide. Any Union assault would need to cross this narrow neck of sand directly in front of the Confederate artillery and well within range of rifled musket fire (Figure 3).

During the Civil War a fortification was only referred to as a 'fort' if it was enclosed on all sides. Because of the unlikelihood of attack from the flanks or the rear, the fortification on Morris Island needed only be a battery with the rear of the fortification left largely unprotected; thus, firepower could be concentrated in one direction, providing a great defensive advantage. As was the tradition with most batteries in this region during the Civil War, Neck Battery was renamed Battery Wagner for a fallen Confederate officer.

Pemberton also fortified the southern portion of Morris Island with batteries and earthworks on Black Island. Black Island is one of a series of Quaternary barrier islands that has been truncated by Morris Island and Lighthouse Creek as the island has retreated with rising sea-levels and the inlet has shifted through time. The older islands were not as expansive as the modern barriers yet still offered ideal defensive positions for an attack arising from across Lighthouse Inlet.

After being defeated at Secessionville, the Union strategy changed from being primarily a land assault on Charleston to a combined land and naval assault. Morris Island and Battery Wagner were to be taken by a joint land assault and naval bombardment. With the capture of

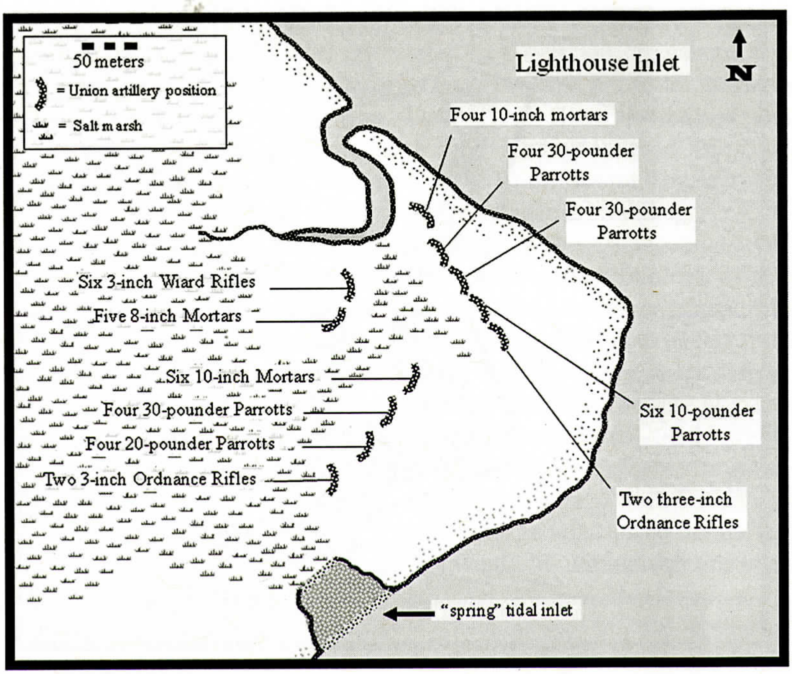

Figure 4: Location of the strategically important "spring tide" inlet and artillery parapets on Folly Island in 1863. Studies using foraminifers in the back-barrier marshes from Folly Island indicate that this inlet was not located in the present day "washout" region of Folly Island but was instead 1.8 km to the north.

Batteries Wagner and Gregg, Union artillery could reduce Fort Sumter (Figure 1). The destruction of Fort Sumter would allow passage of Union vessels into Charleston Harbor, presumably forcing the surrender of the city.

With the consolidation of Confederate troops in 1862, Folly Island was left largely unprotected and was soon occupied by a small Union infantry force. Folly Island, and especially the northern portion of the island, was to be used by the Union Army as a staging ground for the assault on Morris Island from across Lighthouse Inlet. The first Union occupation of Folly Island occurred by Major General John G. Foster and a small reconnaissance force on February 8, 1863. Over the next several months thousands of Union troops inhabited the central and southern portions of the island. Reinforcement of the northern portion of Big Folly Island and Little Folly Island was made more difficult by the presence of Tabby Creek in an area known today as "the washout". Union engineers constructed four causeways across Tabby Creek, interrupting tidal flow but allowing troop and equipment passage to Big Folly Island. The fourth and largest causeway, and the current location of 13th street on Folly Island, was used for the transport of artillery (G. Lennon, personal communication).

The extreme northern part of the island was further isolated from the larger southern fraction by a second, significantly smaller breach approximately 1.8 km to the north of the causeways. This narrow strip of sand was so low in elevation that it was often inundated by high tides and spring tides (spring tidal inlet: Figures 2 and 4), but was not modified by Union engineers. The inlet was described by Union Major General Quincy Gillmore as "extremely narrow, perfectly barren, and so low that the Spring tides frequently sweep entirely over it. At the extreme north end, however, the sand ridges, formed by the gradual action of the wind and tide, were, when our operations commenced, covered with a thick undergrowth favorable for concealment and the masking of batteries"

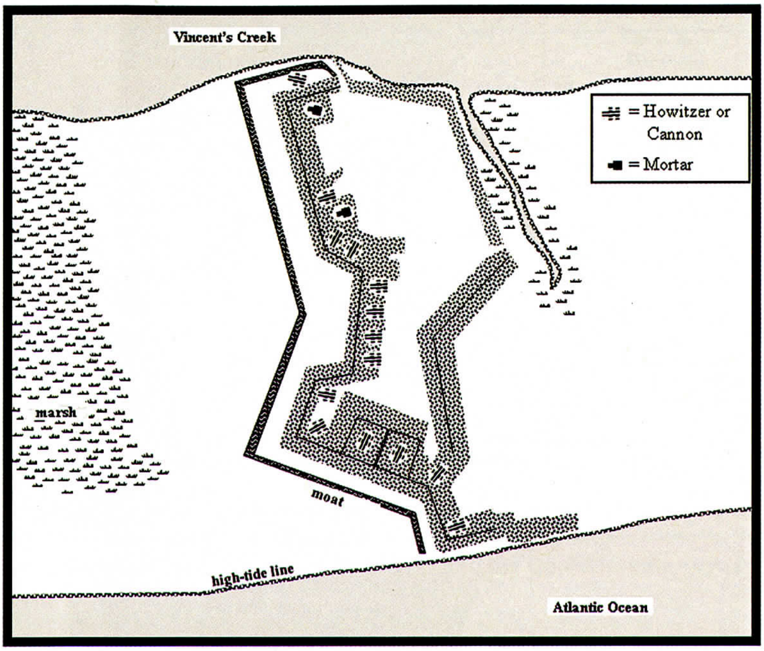

Figure 5: Distribution of artillery in Battery Wagner. All artillery faced in a southern direction, as this was the only practicable route of assault.

(Gillmore, 1890).[2] Thus, to reinforce the northern segment of Folly Island, Union troops needed to move artillery and supplies across a flood-tidal delta similar in origin to a low-energy washover fan. This landscape was difficult to traverse during high tide and impossible to cross during spring tide. The occupation was made even more arduous by the presence of Confederate artillery directly across Lighthouse Inlet on Morris Island. Despite its small size, the inlet made stealthy reinforcement of Little Folly difficult and necessitated the movement of artillery and supplies under the cover of darkness during low tide.[3] As a result, it was not until the middle of April 1863 that the isolated northern portion of the island was occupied and the preparation for the assault on Morris Island could commence.

Eventually, the initial artillery emplacement on Little Folly Island, six Wiard field guns and three rifled howitzers, was fortified by dozens of cannons and mortars. This fortification reached its peak in July 1863 when there were almost fifty artillery pieces on Little Folly Island, including four 3-inch Ordnance rifles, six 10-pounder Parrotts, four 20-pounder Parrotts, and twelve 30-pounder Parrotts (Wise, 1994). Of the eventual 20,000 men that would be stationed on Folly Island, more than 5,000, including detachments from the 6th and 7th Connecticut, 9th Maine, 48th New York, 3rd New Hampshire, and 76th Pennsylvania Regi-

2. *Despite these favorable conditions for covert reinforcement, Confederate Major General Samuel Jones reported that Confederate General Beauregard (and the local commanders) were aware of the Union works on Little Folly Island and were not surprised by the eventual bombardment and attack across Lighthouse Inlet (Jones, 1911).*
3. *Local historians considered the position of the inlet that separated Little Folly Island from Big Folly Island to be in the proximity of "the washout". Hippensteel (2006, 2008a,b) used foraminiferal and sedimentological analysis of the strata immediately behind Folly Island to identify the smaller, spring-tide inlet deposits approximately 1.8 km closer to Lighthouse Inlet.*

ments, were massed on Little Folly Island for the planned assault on Morris Island (Hagy, 1993).

The artillery on Little Folly Island was brought into action on July 10, 1863 when more than 2,500 shells were fired in support of the Union amphibious assault against the lightly defended southern portion of Morris Island and Black Island. The combined bombardment by batteries on Little Folly Island and Union naval vessels minimized what little resistance the Confederates offered and the attack across Lighthouse Inlet proved successful. By the end July 10th, Federal troops had advanced to within rifle-range of Battery Wagner, having successfully and rather easily taken two-thirds of Morris Island.

THE GEOLOGY OF MORRIS ISLAND AND THE ASSAULT ON BATTERY WAGNER

During July 1863 the Triassic red sandstones and Jurassic diabase dikes and sills that underlie the battlefield at Gettysburg, Pennsylvania, were critical in the successful Union defense of Little Round Top and Cemetery Hill (Brown, 1962; Cuffey et al., 2006). During the same month, the beach sands and marsh mud on and around Morris Island played an equally important role in the Confederate Army's successful defense of Battery Wagner. The Union occupied portion of Morris Island was relatively wide and at some places the width of the island exceeded 1000 m. However, the island narrowed to less than 30 m at a defile immediately south of Battery Wagner. As such, the geomorphology of the island, with little distance between the shoreface and low marsh (and tidal creek), provided an ideal defensive position for the Confederates in the fortification. The defensibility of Battery Wagner was further increased as the majority of the Confederate artillery in the fortification faced in a southern direction - geologically the only possible path for a Union attack (Figures 3 and 5).

During the second day's fighting at Gettysburg, Little Round Top would have been unapproachable if the geomorphology of the diabase dikes and sills had created a landscape that dictated the attacking Confederate forces could only pass through a single, 30-m wide pass in Devil's Den. Generals Lee and Longstreet never would have ordered an infantry assault against Little Round Top in such a tactically disadvantageous situation.

Similarly, the Confederates took full advantage of the geomorphology of this portion of Morris Island when constructing Battery Wagner. The fortification extended from low marsh to the north across the beach ridge and ended at the high-tide line. The ease of excavation of the sand allowed for two other defensive measures to be placed across the defile south of the fort: Torpedoes (mines) were buried across the narrow passage adjacent to the defile and a moat that would fill during high tide was constructed adjacent to and south of the fort.

The medium-fine, well-sorted sand comprising the beach and dunes on Morris Island also proved greatly beneficial to the defending Confederates. First, the unconsolidated sediment was ideal for rapid entrenching or construction of gun parapets or larger fortifications. Second, unlike masonry fortification, sand absorbed and minimized the effects of exploding artillery shells. As a result, the overwhelming artillery advantage of the Union forces (largely from naval support) was diminished. While massive sand mounds proved effective against artillery, the use of finer grained, well sorted and rounded dune sands in sandbags proved problematic. According to Wise (1994, p. 143), "By an account kept by the engineers, 46,175 sandbags were expended on Morris Island.... because of the fineness of the sand used in the bags, the Federals kept the bags damp to keep the sand from escaping".

General Gillmore and the Union Army made their first attempt to take Battery Wagner at daybreak on July 11, 1863. The narrowness of the beach approach to the fortification emphasized the need for a rapid assault. As a result, the attacking Union soldiers were ordered not to fire during their approach. The resulting reported losses were predictable, with more than 300 Union soldiers lost compared to twelve Confederate casualties (Wise, 1994).

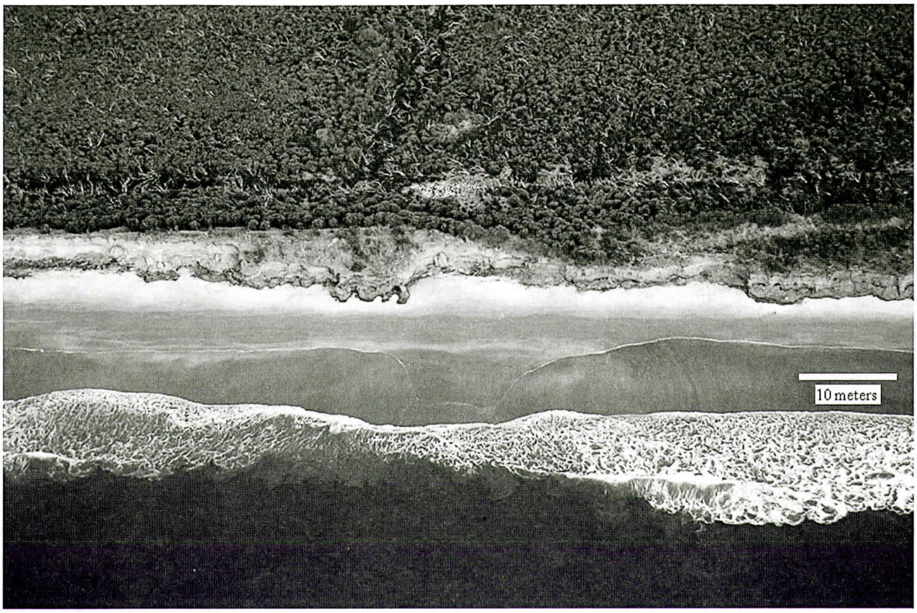

Figure 6. The bluffs and exposed marsh sediments on Morris Island are evidence of rapid shoreline retreat.

General Gillmore's second attack came one week later. A bombardment of Battery Wagner from artillery on both Quaternary and modern barrier islands, as well as from ironclads offshore, preceded the second land assault. The Union's "left batteries" were situated on Black Island, a Quaternary barrier ridge that, because of its non-parallel orientation to Morris, offered an offset position for a slight enfilade fire. As sea-level rises and Morris Island retreats, the modern barrier will continue rolling over this older island. As a result, much of the sediment from the older Black Island is being supplied, via erosion and southeastern beach drift, to Lighthouse Inlet and Folly Island (Hippensteel and Martin, 1999).

The majority of the garrison at Battery Wagner survived the estimated 9,000 - shell bombardment by remaining in the sand covered bombproof for the duration of the shelling (Wise, 1994). The effectiveness of the sand at minimizing the effects of exploding shells is documented by the small number of casualties and the primary cause of death: of the approximately ten men injured and killed by the bombardment, the majority suffered from concussion.

As the Federals advanced, they were met with direct fire from the modern barrier island (Battery Wagner) and the modern spit (Battery Gregg) as well as enfilade fire from the Quaternary barrier system (James Island). As dictated by the shape of the island, the second assault followed essentially the same path as the first and met with even more catastrophic results. The Union army lost more than 1,500 men in the unsuccessful attack.

At that point, with the loss of almost 2,000 men and little progress toward taking either Batteries Wagner or Gregg, General Gillmore decided to minimize the effectiveness of Fort Sumter in a different, less direct manner. The Union Army and Navy were to lay siege to Battery Wagner and use artillery located on the southern end of Morris Island and Black Island to bombard Fort Sumter. With Fort Sumter reduced the Union Army could suppress the artillery in Battery Gregg and the Navy could enter Charleston Harbor.

The siege of Battery Wagner began with the entrenchment of the Union Army across Morris Island. Here the unconsolidated sediments proved beneficial to the Union soldiers as digging was not difficult and a series of fort-paral-

Figure 7: The north end of Morris Island and Cummings Point in 2008 and the location of Battery Wagner.

lel trenches slowly began to encroach on the Confederate battery. By early September, these trenches and parapets extended close enough to Battery Wagner to minimize much of the tactical advantage the geomorphology of the island offered the Confederates. While the unconsolidated, non-cohesive sand of Morris Island made building these trenches relatively easy for Union sappers, Confederate sharpshooters continued to inflict substantial casualties. When General Gillmore ordered a third assault on the Morris Island fortifications for September 6th, the Union sappers had reached the edge of Battery Wagner. However, the Confederates, after viewing the proximity of the Union trenches and realizing that their defensive ditches had been filled with sand from the recent massive bombardment, had already abandoned Battery Wagner under cover of darkness (Jones, 1911).

During the siege, batteries on the Quaternary Black Island and southern Morris Island reduced Fort Sumter until the remaining Confederate artillery in the fort was nearly completely ineffective. The Union batteries then began a long bombardment of Charleston city. The range from these batteries to the city was more than eight kilometers, so fire was not particularly accurate or effective. To partly rectify this problem a new battery was constructed on the marsh directly behind Morris Island. Obviously, innovative engineering provisions were required if an 8-inch, 24,000-pound Parrot cannon was to be fired from a marsh battery without the cannon quickly subsiding into the soft sediment (Hagy, 1993). Although the marsh mud behind Morris Island was more cohesive than the barrier sand, compressibility would be more directly influenced by the friction between the sediment grains (marsh mud is particularly weak in this respect, especially when compared with the sands from Morris Island's dunes and beach). As a result, the gun was placed on a parapet that took full advantage of the geological resources available. First, pilings were driven through the marsh into the underlying, compacted, coarse Pleistocene sands. Second, thirteen thousand sandbags from Morris Island were piled on a platform that was an-

Figure 8: Cummings Point in 2008. Nothing remains of Battery Gregg, but its loss to erosion should be a warning to those who have recently considered the site for residential development.

chored to the pilings (Wise, 1994). Despite this engineering, and fortunately for the citizens of Charleston, the battery known as the "Swamp Angel" soon burst in operation.

The abandonment of Battery Wagner largely ended the active phase of the Union efforts to take Charleston as the following months witnessed a lack of cooperation between the Union Army and Navy. Union forces made repairs to Battery Wagner and continued to occupy Morris Island for the remainder of the war. Charleston, however, was not taken.

The lack of relief, narrowness, and sediment comprising the Quaternary and modern barrier island proved ideal for Confederate defense from direct assault, bombardment, and siege strategies. However, the characteristics of the sand favored Union sappers in ultimately reaching Battery Wagner by trenching, forcing its abandonment. Initially, the shallow water table and lack of a thick aquifer in the region (and the resulting lack of freshwater) favored the largely outnumbered Confederate defenders (Zierden et al., 1995), but after the accumulation of buried and unburied corpses, the water became contaminated.

The construction of jetties offshore of Charleston Harbor in 1896 by the United States Army Corps of Engineers dramatically decreased the sediment supply from the Charleston ebb delta to Morris Island via southern drift (Lennon et al., 1996). The result was rapid shoreline retreat and the loss of Battery Wagner and Gregg to coastal erosion (Figures 6, 7, and 8). Folly Island, in contrast, has not eroded as rapidly and several of the 1863 fortifications are preserved.[4] Eventually, in this transgressive, sediment starved setting, Morris Island will mi-

4. Several Union gun parapets have been identified on Little Folly Island, South Carolina. Hippensteel (2008a,b) used the orientation, spacing, and lack of cross bedding in a series of sand mounds adjacent to Lighthouse Inlet to identify them as the highly eroded remains of four Union gun emplacements. Furthermore, their size and spacing would have been appropriate for a portion of the two batteries known to be on Little Folly Island at this approximate location. Either four of the eight 30-pounder Parrotts or four of the six 10-pounder Parrotts could have been located here; the remainder of the battery has probably been eroded by the shifting of Lighthouse Inlet and the breaching of the dunes via washovers along the inlet. Unfortunately, the two parapets closest to Lighthouse Inlet were recently damaged by inlet migration and storm washover (Hippensteel, 2008b).

grate landward and what remains of the Civil War landscape will be lost.

ACKNOWLEDGEMENTS

This paper benefited greatly from the review and constructive criticism of William J. Neal and the discussions of Folly Island with Gered Lennon. The author thanks them for their interest and insightful suggestions. Rebecca Condliffe offered valuable comments for ways to improve the clarity of the manuscript.

REFERENCES

Belknap, D. F., and Kraft, J.C., 1985, Influence of antecedent geology on stratigraphic preservation potential and evolution of Delaware's barrier systems. Marine Geology, v. 63, p. 235-262.

Brown, A., 1962, Geology and the Gettysburg Campaign. Commonwealth of Pennsylvania Department of Conservation and Environmental Resources, Bureau of Topographical and Geological Survey, Educational Series No. 5.

Cuffey, R. J., Inners, J. D., Fleeger, G. M., Smith, R. C. II, Neubaum, J. C., Keen, R. C, Butts, L., Delano, H. L., Neubaum, V. A., and Howe, R. H., 2006, Geology of the Gettysburg battlefield: How Mesozoic events and processes impacted American history. Geological Society of America Field Guides 2006, v. 8, p. 1-16.

Ebersole, B. A., Neilans, P. J., and Dowd, M.W., 1996, Beach-fill performance at Folly Beach, South Carolina. Shore and Beach, v. 64, p. 11-26.

Gayes, P. T., Scott, D. B., Collins, E. S., and Nelson, D.D., 1992, A late Holocene sea-level fluctuation in South Carolina. Quaternary Coasts of the United States: Marine and Lacustrine Systems, SEPM Special Publication 48, p. 155-160.

Gillmore, Q. A., 1890, Report of Major General Quincy A. Gillmore, The War of the Rebellion: The Official Records of the Union and Confederate Armies in the War of the Rebellion. 128 volumes, Washington D.C., Government Printing Office, Series 1, Part 1, p. 7.

Hagy, J.W., 1993, To Take Charleston: The Civil War on Folly Island. Pictorial Histories Publishing Company, Inc.: Charleston, WV, 91 p.

Harris, M. S., Gayes, P. T., Kindinger, J. L. Flocks, J. G., Krantz, D. E., and Donovan, P., 2005, Quaternary geomorphology and modern coastal development in response to an inherent geologic framework: An example from Charleston, South Carolina. Journal of Coastal Research, v. 21, p. 49-64.

Hippensteel, S.P., 2006, Using Foraminifera to Teach Paleoenvironmental Interpretation and Geoarchaeology: A Case Study from Folly Island, South Carolina. Journal of Geoscience Education, v. 54, p. 526-531.

Hippensteel, S.P., 2008a, Foraminiferal Assemblages: A tool for Reconstructing American Civil War Coastal Landscapes. Southeastern Geology, v. 46, p. 17-24.

Hippensteel, S.P., 2008b, Reconstruction of a Civil War landscape: Little Folly Island, South Carolina. Geoarchaeology, v. 23, p. 824-841.

Hippensteel, S.P. and Martin, R.E., 1999, Foraminifera as an indicator of overwash deposits, barrier island sediment supply, and barrier island evolution, Folly Island, South Carolina. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 149, p. 115-125.

Jones, S. A. (Major-General, CSA), 1911, The Siege of Charleston and Operations on the South Atlantic Coast during the War between the States. The Neale Publishing Company: New York.

Lennon, G., 1985, Identification of a Northwest Trending Seismographic Graben near Charleston, South Carolina. Master's Thesis, Department of Geology, University of South Carolina, Columbia.

Lennon, G., Neal, W. J., Bush, D. M, Pilkey, O. H., Stutz, M., and Bullock, J., 1996, Living with the South Carolina Coast. Duke University Press: Durham, NC, 399 p.

Oertel, G. F., 1985, The Barrier Island System. Marine Geology, v. 63, p. 1-18.

Wise, S. R., 1994, Gate of hell: Campaign for Charleston Harbor, 1863. University of South Carolina Press: Columbia, SC, 312 p.

Zierden, M. A., Smith, S. D., and Anthony, R. W., 1995, 'Our Duty Was Quite Arduous': History and Archaeology of the Civil War on Little Folly Island, South Carolina. The Charleston Museum Leaflet Series Number 32.

SOUTHEASTERN GEOLOGY
V. 48, No.1, February 2011, p. 37-44

First Evidence of Predatory Drilling from Upper Cretaceous Eutaw Formation (Santonian), Georgia

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ABSTRACT

Predatory drillholes, although common in many bivalve groups from Cenozoic, are far less common from Cretaceous formations. The Late Cretaceous is an important time in the history of drilling predation because of the appearance of two major groups of modern predatory gastropods during this time. Most Late Cretaceous predatory drillholes were reported from the Ripley and Providence Formations of North America. This is the first report of predatory boreholes from Late Cretaceous Eutaw Formation (Santonian). Two species of bivalves *Ostrea cretacea* and *Anomia argentaria* have been drilled. The drilling frequency is fairly low with some incomplete drillholes. The nature of the drillhole suggests that they are predatory drillholes and most likely created by naticid gastropods.

INTRODUCTION

Predation is a significant agent of natural selection in modern marine environments. However, evidence of predation in the fossil record is generally rare; primarily because most predators destroy the prey or leave no trace on any preservable hard parts of the victim. Drilling predation of shelled marine invertebrates by predatory gastropods represents one of the very rare instances that allow biotic interactions to be evaluated quantitatively in the Recent and in the fossil record. Not surprisingly, drill holes have been used as an important source of information on the nature of biotic interactions and attempts has been made to explore the ecological and evolutionary roles of such interactions (Vermeij, 1987; Kelley and Hansen, 1993; Huntley and Kowalewski, 2007). Quantitative measures employed to study predation include the frequency of drill holes for estimating predation intensity (Taylor, 1970; Stanton and Nelson, 1980; Vermeij et al., 1980; Vermeij and Dudley, 1982; Kabat and Kohn, 1986), frequencies of incomplete drill holes as a measure of failed predation events (but see Kowalewski, 2004), and thus prey-effectiveness (Kelley and Hansen, 2001; but see Chattopadhyay and Baumiller, 2007, 2010), position of drill holes and distribution of sizes of prey for evaluating predatory strategies (Ansell, 1960; Roopnarine & Willard, 2001), and taxonomic distribution of drill holes to explore selectivity (Kitchell et al., 1981). Two main groups of predatory gastropods responsible for modern drill hole belong to naticid and muricid families and these families originated in Cretaceous. Although the report of drillholes goes as far back as Precambrian (Bengtson and Zhao, 1992), it is only during the Cenozoic that global drillhole frequencies reached values comparable to modern day (Kelley & Hansen, 2003). This Cenozoic increase in drilling frequency has been linked to the appearance and subsequent diversification of these predatory gastropod families (Chattopadhyay, 2009). Reports of drillholes from Cretaceous Formations are far less common compared to those from the Cenozoic. Reports of Cretaceous predatory drill hole are important to understand the behavior, ecology and other associated variables of these groups of predatory gastropods during their early radiation. Earlier reports of Late Cretaceous predatory drillholes of North America are dominated by specimens from Ripley and Providence Formation (Vermeij & Dudley, 1982; Kelley et al.,

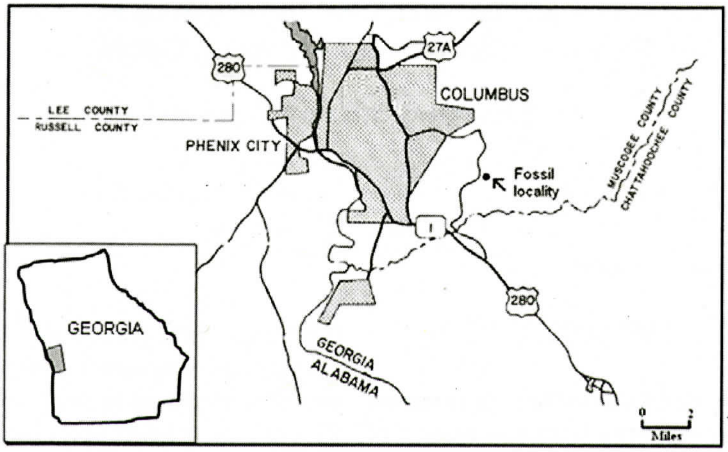


Figure 1. Locality map of the fossil site near Ft. Benning, Georgia.

2001). Both of these formations are Maastrichtian in age. This paper reports the first known example of predatory drillholes from the Late Cretaceous (Santonian) Eutaw Formation.

GEOLOGIC SETTING

The specimens of *Ostrea cretacea* (recombined as *Flemingostrea cretacea* Malchus (1995)), *Anomia argentaria* and *Exogyra upatoiensis,* used in this study were collected during the 1980's from an outcrop of the Upper Cretaceous Eutaw Formation on Fort Benning in Muscogee County, Georgia (Fig. 1). The outcrop is located on the east side of Moye Road, just south of the junction of Moye Road and St. Marys Road.

The Eutaw Formation was first named by Hilgard in 1860 (Keroher et al., 1966) for exposures near Eutaw, Alabama. The formational boundaries have been shifted several times by various authors. In eastern Alabama, Stephenson and Monroe in 1938 (Keroher et al., 1966) restricted the Eutaw to the sediments between the Tuscaloosa and Blufftown Formations. This criterion was later used by Cooke (1943) in extending the Eutaw into Georgia. The Eutaw Formation unconformably overlies the Tuscaloosa Formation and is unconformably overlain by the Blufftown Formation (Fig. 2). The Eutaw, in the Chattahoochee River valley, is composed of two conformable units. The basal unit is a coarse grained, feldspathic, burrowed, cross-bedded quartzose sand layer varying in thickness from 18 feet at the intersection of Moye and St. Marys Road to 40 feet or more in the northern portion of Muscogee County. The upper unit is comprised of light gray to olive black, micaceous, carbonaceous, fossiliferous, silty sand, sandy silt and silty clay layers (Marsalis & Friddell, 1975). This upper unit ranges in thickness from 35 to 75 feet in the outcrop area and often contains fossils including *Ostrea cretacea, Anomia argentaria* and *Exogyra upatoiensis*.

CRETACEOUS	Maastrichtian	Louvale Group	Ripley Formation
	Campanian		Cusseta Sand
			Blufftown Formation
	Santonian		Eutaw Formation
	Coniacian		Tuscaloosa Formation

Figure 2. Generalized Stratigraphy of the study area (after Marsalis and Friddell, 1975)

The two main features of the basal part of Eutaw formation, 1) strong bimodality in cross-bed directions within single outcrops and 2) extremely abundant *Ophiomorpha nodosa*, indicate back-barrier to open marine sedimentation (Weimer and Hoyt, 1964; Frey et al., 1978).

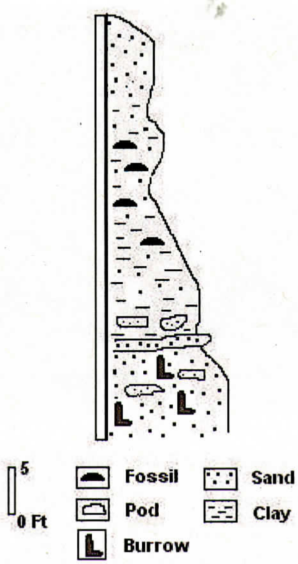


Fig.3. Stratigraphic section at Moye Road and St. Marys Road intersection on Ft. Benning, Muscogee County, Georgia

Well-defined clay-lined channels occur within this lithofacies, apparently representing tidal channel fillings within a barrier-island complex. These features (barrier-bar facies) are especially well displayed in the updip Eutaw sections.

This bottom layer is commonly overlain by a poorly bedded, micaceous, clayey sand interval with abundant bivalve fossils suggesting a slightly to moderately restricted back-barrier (moderately open bay) environment. For such a vertical sequence to be deposited, the barrier system had to migrate seaward or prograde indicating that the sequence could reflect either a local or regional marine regression (Reinhardt & Gibson, 1981).

The specimens were collected from the upper unit of the Eutaw Formation characterized by medium-grey to yellowish-grey silty sand. It also contains carbonaceous clay. This zone is intensely bioturbated in the south end of the outcrop. This layer occurs at the top of a clayey sand layer dominated by clay balls and distorted clay laminae (Fig. 3). An equivalent horizon occurs at several localities further north along the Mayo road. The specimens are currently housed in the Department of Geosciences, University of West Georgia.

DESCRIPTION

Two species of bivalves have been found to be targeted by predatory drilling, *Ostrea cretacea* and *Anomia argentaria.* The other species present in the formation, *Exogyra upatoiensis*, is rare in our collection. I have calculated the complete and incomplete drilling frequency for each species. Since all of our bivalve specimens were disarticulated, I used the formulae recommended by Kowalewski (2002) dividing the number of individuals with drillholes by half the total number of valves. The formula for incomplete drill hole frequency is calculated by dividing the number of incomplete drill holes by the sum of complete and incomplete drill holes (it is the same formulae used to calculate prey-effectiveness defined by Vermeij 1987). *Ostrea cretacea:* Out of 141 specimens, there are 4 complete drillholes (Fig. 4A) and 5 incomplete drillholes (Fig. 4B). The drilling frequency is extremely low (0.06). The outer diameter of the drillhole ranges between 0.5mm-2mm. There was no apparent valve preference for the drillings. Incomplete drilling frequency is relatively higher (0.56). It seems as though there is no strong stereotypic pattern of the position of complete or incomplete drillholes, but the sample size is too low to derive any meaningful result from statistical analysis. However, the generalized diagram shows that most of the complete drillholes are located at the central portion of the bivalve shell (Fig. 5) very close to the muscle scar. The placement of incomplete drillholes is mainly concentrated in two locations, a) the central part, b) close to the commisure line near the umbo. One of the complete drillholes is also located at the commisure line near the umbo. A single valve contains three drillholes, two incomplete and one complete (Fig. 4B). The diameters of these three drillholes are markedly different; one of the incomplete drillhole diameters is much smaller compared to the other drillholes which indicates the involvement of multiple predators.

The drillhole morphology is often indicative of the identity of driller. In this case, the parabolic nature of the complete drillholes and the presence of the elevated central boss in the in-

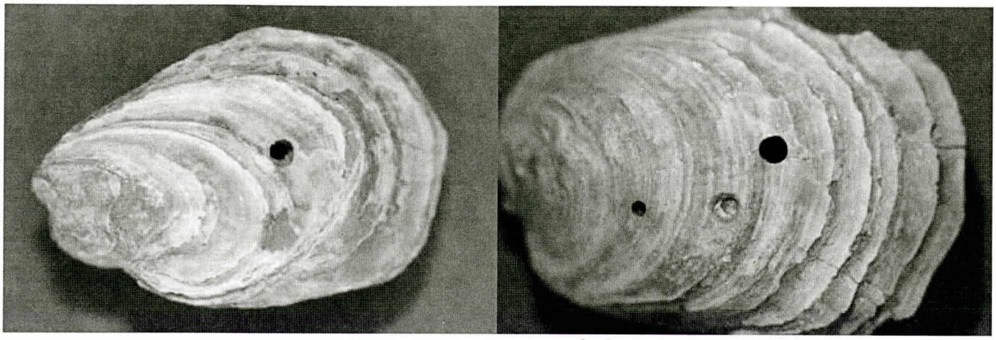


Figure 4. Left. *Ostrea cretacea* with one complete drillhole. Right. *Ostrea cretacea* with one complete drillhole and two incomplete drillholes.

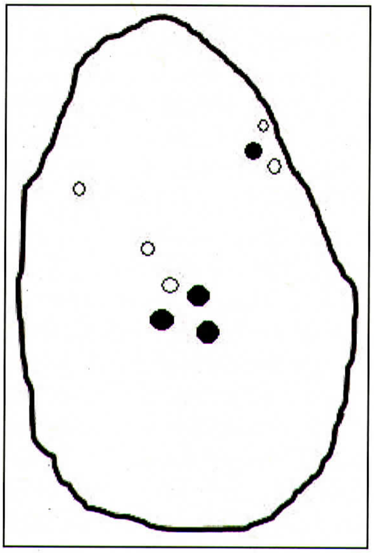


Figure 5. Distribution of drillholes in *Ostrea cretacea*. The solid circles represent complete drillhole and the open circles represent incomplete drillholes.

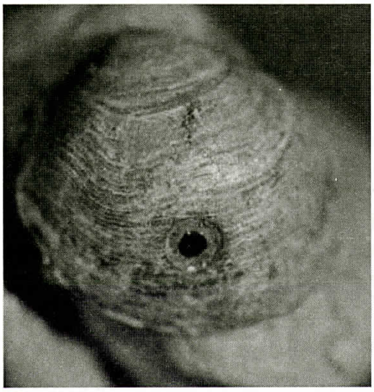
complete drillhole is a indicative of naticid predation.However, there are instances where similar holes can be drilled by muricids (personal communication with G. Dietl). Variable drillhole diameter indicates involvement of multiple predators of different sizes.

Anomia argentaria: Out of 20 specimens, only 2 are drilled (drilling frequency: 0.20). There are no incomplete drillholes in *Anomia* specimens. Both of the complete drillholes are located in the central part of the valves (Fig. 6A). The average size range of the specimens is between 0.9 cm-2.1cm with average size of the drilled specimens is 1.2 cm. The drillhole shows a clear difference between the outer diameter and the inner diameter and exposes the parabolic nature of the drillhole shape characteristic of naticid predation (Kelley & Hansen, 2003).

Exogyra upatoiensis: There is only a single specimen of *Exogyra upatoiensis* in our collection and it has a centrally located complete drillhole (Fig. 6B). The specimen is 1cm in length and the diameter of the centrally located drillhole is 0.02cm. The parabolic nature of the drillhole suggests the attacker to be a naticid gastropod.

DISCUSSION

Although drill holes in molluscan shells have been reported from Paleozoic (Kowalewski et al., 2000; Hoffmeister et al., 2001), the identity of the predators is largely unknown. Few drill holes have been reported from early Mesozoic (Kowalewski et al., 1998), but the primary drillers of modern molluscs, muricids and naticids, did not radiate until the Cretaceous. Even though predatory drilling behavior is known from several families of gastropods (Sohl, 1969), most drillholes resemble those produced by naticid or muricid gastropods. The earliest holes resembling those of naticids are Triassic (Newton, 1983; Fursich & Jablonski, 1984), and Harper et al. (1998) reported muricid like drill holes from Jurassic. However, body fossils of these groups are unknown before Cretaceous. Both naticids and muricids di-



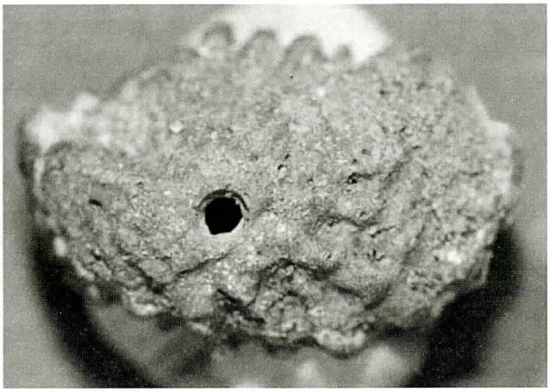


Figure 6. Left. *Anomia argentaria* with one complete drillhole. Right. *Exogyra upatoiensis* withone complete drillhole.

versified beginning in the Cretaceous (Sohl, 1969; Kabat, 1990). This early phase of predatory radiation and its relationship to the drilling frequency (interpreted as predation intensity) has been a topic of special interest for paleobiologists (Kowalewski et al., 1998; Kelley & Hansen, 1993, 1996, 2001; Vermeij, 1987).

Studies that assessed the Late Cretaceous history of drilling predation is mostly based on specimens from Ripley and Providence Formations. Vermeij & Dudley (1982) reported predatory drilling in some gastropods from the Ripley Formation (Upper Cretaceous) of the south-eastern USA. Although the study examined only gastropod prey, the predation intensity is comparable to our findings. Kelley et al. (2001) constructed a temporal pattern of naticid predation during the Cretaceous and Cenozoic using specimens from United States Coastal Plain. In their study, the Late Cretaceous is represented by Ripley Formation, Providence Formation and Corsicana Formation. Their observations show that Late Cretaceous is characterized by low to moderate drilling frequencies (0.06-0.19 for bivalves). This result is consistent with their findings. However, they did not find any occurrence of multiple drilling from any of their formations. Also, their incomplete-drilling frequency is much lower compared to what I observed in the *Ostrea* specimens.

Bromley (1981) designated the ichnofossil typically produced by naticid drilling as *Oichnus paraboloides* and that characteristic of muricids as *Oichnus simplex*. They are usually distinguishable based on their morphology. All of our drilled specimens are examples of *Oichnus paraboloides*. Reports from other Eutaw localities confirm the existence of naticid predators such as *Polinices halli* (Marsalis & Friddell, 1975), even though these fossils are absent from the current locality. So there is one strong possibility that these drillholes are created by naticid gastropods. However, this simple explanation becomes complicated with the fact that in modern environment some muricids are reported to produce similar drillhole that can be misidentified as *Oichnus paraboloides*. The other way to address this issue would be to focus on the differences in feeding ecology between naticids and muricids. Muricids are epifaunal and drill on the sediment water interface. The modern naticids are infaunal and typically engorge their foot with water, envelop their prey with the enlarged foot, and feed below the sediment water interface. Given that these prey items (*Exogyra* and *Anomia*) were living near or above the sediment water interface and more importantly were likely attached to hard surfaces, they were unlikely to be drilled by an infaunal predator like modern naticids. It seems more likely that an epifaunal predator was the culprit. However, these arguments are primarily based on behavior in the modern naticid and muricids. It could have been different in the Santonian since this was the very early stage of drilling predation where they might still were experimenting with their predatory behavior.

The number of specimens is too low to conduct any meaningful statistical analysis. Nevertheless, some apparently interesting patterns have emerged from this study. A number of drillholes in *Ostrea cretacea* are located near the commisure line that qualifies as edge drilling. Edge drilling is generally considered to be a rare phenomenon (Vermeij & Roopnarine, 2001; Deline et al., 2003; Dietl et al., 2004). It is also indicative of certain behavioral and ecological conditions. By drilling the prey at the thin valve edge, rather than through the thicker shell wall, snails can significantly reduce their predation time. However, it involves a risk. When the snails try to drill close to the commissural line of bivalve, often the drilling organ or the foot of the snail can be clipped off by the abrupt closure of the valves of the prey. This could lead to amputation of the foot or even death. It is argued that associated mortality risk is reason why there are so few instances of edge drilling even though it requires less energy. Dietl et al (2004) observed that muricid predators are generally less likely to drill near the edges. Their neontological experiments also confirm that edge drilling is used only when the risks of competition are high, while wall drilling is used when these risks are low. Similar patterns can be expected from naticid drilling behavior and might explain observed rarity of edge drilling in a less competitive scenario (Kitchell et al., 1981). The present pattern could be indicative of intense competition or presence of enemies.

The other enigmatic aspect is the multiple boring scenario. Often muricid gastropods attack their prey simultaneously and create multiple drillholes (Chattopadhyay & Baumiller, 2007). However, this process does not explain multiple naticid drillholes. Most naticids are infaunal carnivores that plow through the sediment in search of prey. After attack, the prey is enveloped in the snail's large mesopodium and, using the radula and secretions of the accessory boring organ, a hole is drilled in the shell of the prey over a period of hours to several days (Ziegelmeier, 1954; Carriker, 1981). This excludes the possibility of simultaneous attack. It has been reported that naticids could reoccupy the same drillhole after abandoning it. That explains the low frequency of multiple drillholes made by the naticids. Since the drillhole diameters are different for multiple drillhole in the present case, they are probably resulted from subsequent attacks by different individuals. The complete drillhole is presumably the result of the last lethal attack in view of the fact that naticids generally do not attack empty shells.

CONCLUSION

The fossil record of Cretaceous predatory drillholes gives us an opportunity to study the behavior and ecological aspects of early muricid and naticid communities. Presence of drillholes in molluscan specimens from the Santonian Eutaw Formation has never been reported before. This drilled assemblage characterized by low drilling frequency and is consistent with the overall pattern of Late Cretaceous gastropod predation reported from other Formations such as Ripley and Providence. However, the presence of relatively high frequency edge drilling might be indicative of unique behavior of naticids during their early radiation. On the whole, this assemblage represents an important yet understudied fossil-bearing deposit that could facilitate our understanding about different aspects of predation during the early stages of the radiation of naticids and muricids.

ACKNOWLEDGMENTS

I would like to thank Dr. Johnny Waters (Appalachian State University) who collected the specimens and housed them in the Department of Geosciences of University of West Georgia. Dr. Timothy Chowns provided valuable information about local geology and stratigraphy. The manuscript was greatly improved by the suggestions of Dr. Brad Deline. I thank Dr. J. Huntley for a very constructive review.

REFERENCE

Ansell, A.D., 1960, Observations on predation of *Venus striatula* (Da Costa) by *Natica alderi* (Forbes). Proceedings of the Malacological Society of London, v.34, p. 248-249.

Bengtson, S., and Yue Zhao, 1992, Predatorial borings in late Precambrian mineralized exoskeletons. Science, v. 257, p. 367-369

Bromley, R. G., 1981, Concepts in ichnotaxonomy illustrated by small round holes in shells. Acta Geologica Hispanica, v. 16, p. 55-64

Carriker, M. R., 1981, Shell penetration and feeding by naticacean and muricacean predatory gastropods: a synthesis. Malacologia, v. 20, p. 403-422

Chattopadhyay, D., 2009, Cenozoic history of drilling predation. A multi-taxon approach. North American Paleontological Conference, Cincinnati, USA. vol.3, p.17

Chattopadhyay, D. and Baumiller, T. K., 2007, Drilling under threat: An experimental assessment of the drilling behavior of Nucella lamellosa in the presence of a predator. Journal of Experimental Marine Biology and Ecology, v. 352, p. 257-266

Chattopadhyay, D., and Baumiller, T.K., 2010, Effect of durophagy on drilling predation: A case study of Cenozoic molluscs from North America. Historical Biology, DOI:10.1080/08912961003600445

Cooke, C. W., 1943, Geology of the Coastal Plain of Georgia. U. S. Geological Survey Bulletin, v. 941, 121 p.

Deline, B., Baumiller, T., Kaplan, P., Kowalewski, M. and Hoffmeister, A., 2003, Edge-drilling on the brachiopod *Perditocardinia cf. P. dubia* from the Mississippian of Missouri (USA). Palaeogeography, Palaeoclimatology, Palaeoecology, v. 201, p.211-219.

Dietl, G. P., Herbert, G. S. and Vermeij, G. J., 2004, Reduced competition and altered feeding behavior among marine snails after a mass extinction. Science. v. 306, p.2229-2231

Frey, R. W., Howard, J.D.,and Pryor, W. A., 1978, Ophiomorpha: its morphologic, taxonomic and environmental significance. Paleogeography, Paleoclimatology, Paleoecology, v. 23, p. 199-229

Fursich, F. T. & Jablonski, D., 1984, Late Triassic Naticid Drillholes: Carnivorous Gastropods Gain a Major Adaptation but Fail to Radiate. Science, vol. 224, p. 78 - 8

Harper, E. M., Forsythe, G. T. W. and Palmer, T., 1998, Taphonomy and the Mesozoic Marine Revolution: preservation state masks the importance of boring predators. Palios, v. 13, p. 352-360.

Hoffmeister, A. P. and Kowalewski, M., 2001, Spatial and Environmental Variation in the Fossil Record of Drilling Predation: A Case Study from the Miocene of Central Europe. Palios, v. 16, p. 566-579

Huntley, J. H. and Kowalewski, M., 2007, Strong coupling of predation intensity and diversity in the Phanerozoic fossil record. Proceedings of the National Academy of Sciences, v.104, p. 15006–15010.

Kabat, A. R. and Kohn, A.J., 1986, Predation on Early Pleistocene naticid gastropods in Fiji. Paleogeography, Paleoclimatology, Paleoecology, v. 53, p. 255-269

Kabat, M.R., 1990, Predatory ecology of naticid gastropods with a review of shell boring predation. Malacologia, Kelley, P. H. and Hansen, T. A., 2003, The fossil record of drilling predation on bivalves and Gastropods. In Kelley, P. H., Kowalewski, M. and Hansen, T. A., eds., Predator-Prey Interactions in the Fossil Record: Topics in Geobiology Series 20, Plenum Press/Kluwer, New York,pp.113-133

Kelley, P. H., Hansen, T. A., Graham, S. E., and Huntoon, A. G., 2001, Temporal patterns in the efficiency of naticid gastropod predators during the Cretaceous and Cenozoic of the United States Coastal Plain, Paleogeography, Paleoclimatology, Paleoecology, v. 166, p. 165-176

Keroher, G. C. and others, 1966, Lexicon of geologic names of the united States for 1936-1960. U.S. Geological Survey Bulletin, v. 1-3, 4341p.

Kitchell, J. A., Boggs, C. H., Kitchell, J. F. and Rice, J. A., 1981, Prey selection by Naticid gastropods: experimental tests and application to the Fossil record. Paleobiology, v. 7, p. 533-552

Kowalewski, M., 2004, Drill holes produced by the predatory gastropod *Nucella lamellosa* (Muricidae): paleobiological and ecological implications. Journal of Molluscan Studies, v. 70, p. 359–370

Kowalewski M., 2002, The fossil record of predation: an overview of analytical methods.Paleontological Society Special Papers, v. 8, p.3–42

Kowalewski, M., Dulai, A. and Fuersich, F. T., 1998, A fossil record full of holes; the Phanerozoic history of drilling predation. Geology, v. 26, p. 1091-1094

Kowalewski, M. Simões, M.G., Torello, F.F., Mello, L.H.C., and Ghilardi, R.P., 2000, Drill holes in shells of Permian benthic invertebrates. Journal of Paleontology, v. 74, p. 532-543.

Marsalis, W. E. and Friddell, M.S., 1975, A guide to selected Upper Cretaceous and Lower Tertiary outcrops in the Lower Chattahoochee river valley of Georgia. Guidebook 15, Georgia Geological Survey, pp.79

Newton, C. R., 1983, Triassic origin of shell boring gastropods. Geological Society of America Abstract with Program, v. 15, p. 652-653

Reinhardt, J. and Gibson, T.G., 1981, Upper Cretaceous and lower Tertiary geology of the Chattahoochee river valley, western Georgia and eastern Alabama. 16th Annual Field Trip Guidebook, Georgia Geological Society, pp.88

Roopnarine, P. D. and Willard, S., 2001, Bivalve prey morphology as a guide to drilling stereotypy of Naticid and Muricid gastropods: venerids, naticids and muricids in Tropical America. PaleoBios, 21, v. 2, p. 109-110

Sohl, N. F., 1969, The Fossil Record of Shell Boring by Snails. American Zoologist, v. 9, p. 725-734

Stanton Jr., R. J. and Nelson, P. C., 1980, Reconstruction of the trophic web in paleontology: community structure in the Stone City Formation (middle Eocene, Texas).

Journal of Paleontology, v. 54, p. 118–135.
Taylor, J. D., 1970, Feeding habits of predatory gastropods in a Tertiary (Eocene) molluscan assemblage from the Paris basin. Palaeontology, v. 23, p. 254-260.
Vermeij, G. J., 1987, Evolution and escalation: An ecological history of life. Princeton University Press, Princeton, NJ, 527pp
Vermeij, G. J. and Dudley, E. C, 1982, Shell repair and drilling in some gastropods from the Ripley Formation (Upper Cretaceous) of Southeastern U.S.A. Cretaceous Research, v. 3, p. 397-403
Vermeij, G. J. and P. D. Roopnarine. 2001. Edge-drilling: history and distribution of a novel method of predation. PaleoBios, v. 21. Supplement 2130.
Vermeij, G. J., Zipser, E. and Dudley, E. C., 1980, Predation in time and space: peeling and drilling in Terebrid gastropods. Paleobiology, v. 6, p. 352-364.
Weimer, R. J., and Hoyt, 1964, Burrows of Callianassa major Say, geologic indicators of littoral and shallow neritic environments. Journal of Paleontology, v. 38, p. 761-767
Ziegelmeir, E., 1954, Beobachtungen fiber den Nahrungserwerb bei der Naticide Lunatia nitida Donovan (Gastropoda Prosobranchia). Helgolander Wissenschaftliche Meeresforschung, v. 5, p. 1-3

SOUTHEASTERN GEOLOGY
V. 48, No.1, February 2011, p. 45-50

LITHOLOGIC CHANGES CAN MASK THE IDENTIFICATION OF VERTICALLY-TO-SUBVERTICALLY ORIENTED TRACE FOSSILS

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ABSTRACT

Changes in lithology can affect the identification of vertically-to-subvertically oriented trace fossils and lead to incorrect assumptions regarding the presence or absence of former trace makers. This is demonstrated at the Campbell Mountain road cut in Clarke County, Alabama (U.S.A.), where bioturbated sediments in the Meridian Sand Member and an overlying, unnamed clay layer (both Eocene - Tallahatta Formation) are exposed. Within the Meridian Sand, highly visible and abundant clay-filled burrows (i.e., endichnial traces) contrast sharply in lithology and color with the white, micaceous, quartzose sand. The overlying clay appears to only have widespread *Gyrolithes* traces. Based on the visible presence or absence of endichnial traces, it would appear that major changes occurred in the ichnofacies and specific ichnotaxa between the two lithologic units. However, a closer examination indicates that the difference is a matter of lithologic contrast. An awareness of the interplay between matrix lithology and trace composition can aid in understanding possible changes in ichnofacies and specific ichnotaxa, and caution is urged where lithologic changes occur.

INTRODUCTION

Trace fossils can provide valuable paleoenvironmental information that cannot be gained from sediments or sedimentary features. As behavioral indicators, they can reflect changing environmental conditions associated with such factors as sediment composition, pH, salinity, temperature, and oxygen levels. Lithologic changes can affect sediment bioturbation as a function of changing paleoenvironmental conditions.

A cursory examination of the sediments and traces in the Meridian Sand Member and the overlying, unnamed clay layer exposed at the Campbell Mountain road cut in Clarke County, Alabama, suggests a pronounced change, not only in lithology but also in specific ichnotaxa. This study was conducted to determine if vertically-to-subvertically oriented trace fossils could be traced from the Meridian Sand up into the overlying unnamed clay layer from which they originated.

MERIDIAN SAND MEMBER

The Meridian Sand Member outcrops from southwestern Alabama, along an arcuate northwesterly strike, to east-central Mississippi, a distance of approximately 130 kilometers (Wermund, 1965). The Campbell Mountain exposure is located in southwestern Alabama on the northern flank of the Hatchetigbee Anticline, east-southeast of Mount Campbell. The rolling hills across the area are a function of resistive weathering and deep-seated salt movement (Copeland, 1968). The road cut was created in the early 1960s with the construction of Alabama State Highway 69 (Figure 1). The outcrop exposes strata from the Hatchetigbee Formation (Lower Eocene – Middle Ypresian) to the Lisbon Formation (Middle Eocene – Middle Lutetian) and was first measured and reported by Toulmin and Newton (1963).

CAMPBELL MOUNTAIN STRATIGRAPHY

This investigation examined the two lowest

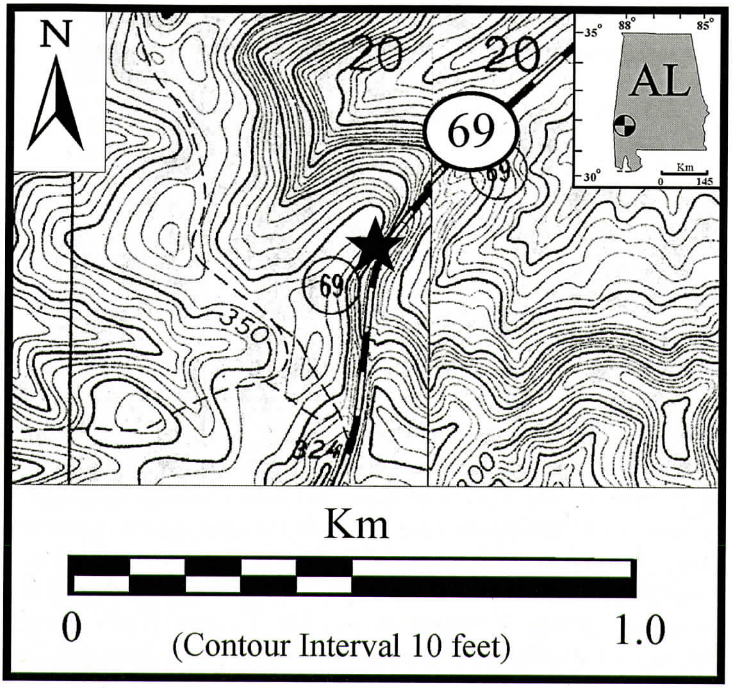

Figure 1. The study area is indicated by the star along Alabama State Highway 69 in Clarke County, Alabama. The approximate coordinates for this locale are: N 31.90718 latitude and W 88.00077 longitude (according to the ACME Mapper 2.0 internet website).

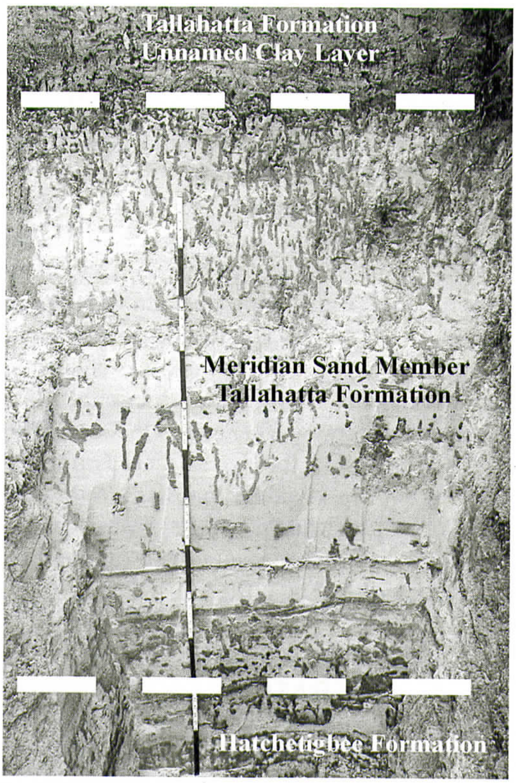

Figure 2. The entire section of the Meridian Sand Member is exposed in this trench (bounded by the dashed white lines) and the upper portion is the most intensively bioturbated. The endichnial traces are composed of clay derived from the overlying stratum. Scale in 15-cm divisions.

stratigraphic units in the Tallahatta Formation (Lower Eocene – Upper Ypresian) exposed at the Campbell Mountain road cut: 1) the Meridian Sand Member and 2) an overlying, unnamed clay layer. At this location the Meridian Sand Member is approximately two meters thick. It is the lowest stratigraphic unit in the Tallahatta Formation and has been described as a white, fine-grained, micaceous sand that contains abundant trace fossils and thin (<2.5 cm), horizontally oriented limonitic layers (Toulmin and Newton, 1963). No sedimentary structures were noted in the sand at this exposure, although cross-bedding has been reported at other locales (Wermund, 1965). Directly above the Meridian Sand is an unnamed clay layer approximately 1.5 meters thick. It is grayish-olive to dark-

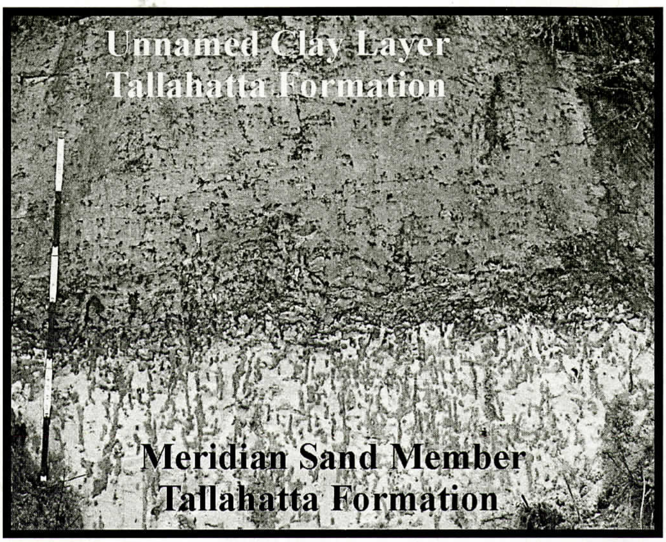

Figure 3. In many places, the contact between the unnamed clay layer and underlying Meridian Sand is highly bioturbated. Note the sand-filled vertical to subvertical traces that extend up into the clay layer. These are endichnial traces in due to their lithologic contrast. Moving further up the section, these sand-filled traces seemingly disappear as the lithologic contrast no longer occurs between the exterior, interior, or lining of the traces. However, the traces can be linked to faint, discontinuous, rust-colored, vertically-to-subvertically oriented stains within the unnamed clay. Scale in 15-cm divisions.

greenish-gray, and weathers to a light gray. It is thin-bedded to massive, silty, sparsely micaceous, and contains some trace fossils (Toulmin and Newton, 1963).

FIELD METHODS

The study was limited to the Campbell Mountain exposure located adjacent to Alabama State Highway 69. Decades of weathering have resulted in the formation of talus and a vegetative cover over most of the Meridian Sand exposure. Five trenches were excavated along the outcrop to examine both the Meridian Sand and overlying clay layer. Two of the five trenches exposed the entire Meridian Sand stratigraphic unit (Figure 2) and the remaining three focused on the stratigraphic contact between the Meridian Sand and overlying, unnamed clay layer (Figure 3).

ICHNOFACIES/ICHNOTAXA

Seilacher (1964, 1967) originated the concept that the morphology of specific trace makers (i.e., ichnotaxa) could be combined with a specific lithofacies to create an ichnofacies. Generally defined within this framework, the vertically-to-subvertically oriented traces within the quartzose Meridian Sand Member have been considered a part of the *Skolithos* ichnofacies (Reynolds, 1992). However, the traces actually originate from the overlying clay and as such they may not be solely characterized by the *Skolithos* ichnofacies and further investigation is warranted. Savrda (2008) identified nine specific ichnotaxa in the Tallahatta Formation in Mississippi, some or all of which may be present at this particular outcrop. However, this article does not attempt to identify the specific ichnofacies or ichnotaxa that might be present in either the Meridian Sand or the overlying, unnamed clay layer. Rather, the focus is on determining if the vertically-to-subvertically oriented trace fossils can be visually identified between both sedimentary units at this locale.

In the micaceous, quartzose Meridian Sand, the toponomy (i.e., morphological expression) of the trace fossils is endichnial (Figure 4), i.e., trace fossils preserved as full relief casts within

Figure 4. The Meridian Sand Member of the Tallahatta Formation is bioturbated at varying levels moving laterally across the Campbell Mountain outcrop. At this particular exposure there is an abundance of clay-filled, vertically-to-subvertically oriented endichnial traces. Scale in centimeters and inches.

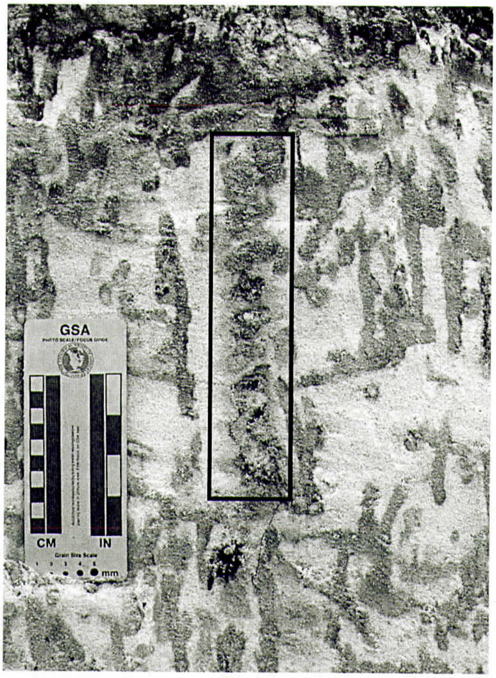

Figure 5. A sand-lined, clay-filled *Gyrolithes* trace (in the Meridian Sand) is located in the black box. These specific traces are more easily identified in the overlying gray clay layer due to their lithologic contrast being white-sand lining and white-clay fill. Scale in centimeters and inches.

the host stratigraphic unit (Martinsson, 1970; Savrda, 2007). Much of the Meridian Sand Member at this outcrop contains an abundance of vertically-to-subvertically oriented clay traces. Also present are lesser numbers of *Gyrolithes* traces which are white-sand-lined and filled with a white sandy-clay (Figure 5). The ichnosedimentological nature of the Meridian Sand indicates deposition in a neritic, inner shelf setting, which is consistent with other outcrops across eastern Mississippi (Wermund and Moiola, 1966; Reynolds, 1992).

Along the Campbell Mountain outcrop, the contact between the Meridian Sand and overlying clay has been extensively bioturbated in places and the burrows are predominately sand-filled (Figure 3). The abrupt change in lithology to clay suggests an increase in water depth, possibly corresponding to a sea-level transgression (Siesser, 1984; Mancini and Tew, 1988).

The overlying, unnamed clay layer appears to be ichnologically barren with the exception of an occasional, highly visible, white-sand-lined and white-clay-filled endichnical *Gyrolithes* trace (Figure 6). Missing is the visible evidence of the vertically-to-subvertically oriented traces that originated in the clay and

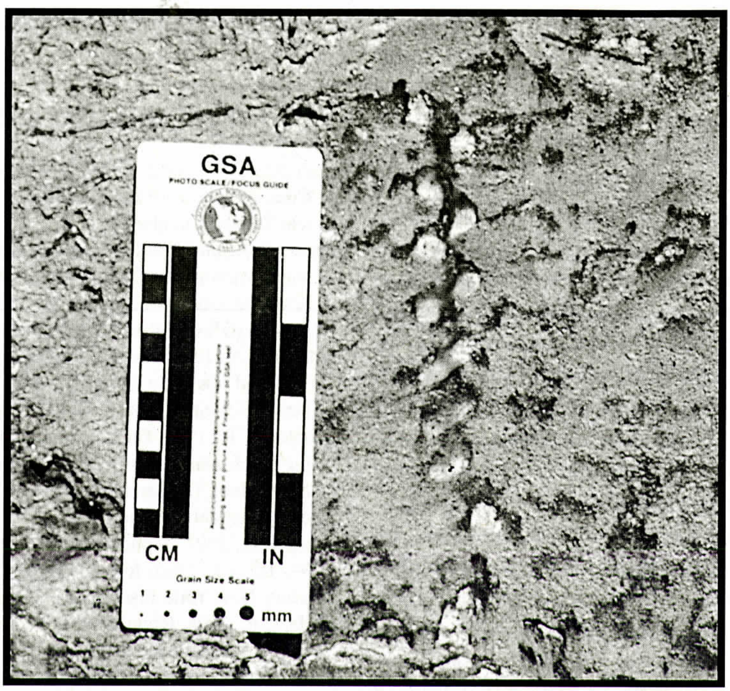

Figure 6. Within the gray unnamed clay layer, the *Gyrolithes* traces are endichnial and prominent, being white-sand lined and filled with a white sandy-clay. Scale in centimeters and inches.

Figure 7. The faint and discontinuous, vertically-to-subvertically oriented iron-stains in the unnamed clay layer make identification of the specific ichnotaxa difficult if not impossible. The lack of any lithologic contrast between the clay substrate and the clay-lined and filled traces could create the misperception that changes in the sedimentary environment also resulted in changes to the ichnotaxa. Sole reliance on lithologic contrast in identifying ichnofossils can lead to an incorrect assessment. Scale bar is 30 cm.

extend downward into the underlying Meridian Sand. However, a careful examination of the clay in places reveals faint iron-stains oriented in the vertical to subvertical (Figure 7). These stains appear to correlate with the endichnial traces found in the underlying Meridian Sand.

CONCLUSIONS

The ichnological assessment of any former marine facies/paleosetting should include the identification of the ichnofacies and where possible, the specific ichnotaxa. The cessation of traces between differing lithologic units might suggest that paleoenvironmental conditions changed sufficiently to modify or possibly terminate trace makers.

In the Meridian Sand Member, the vertically-to-subvertically oriented endichnial traces are abundant and highly visible due to their contrasting lithology and color within the substrate. While *Gyrolithes* traces are present, they are few in number and less visible. The visibility of the traces changes dramatically moving vertically upward from the Meridian Sand into the unnamed clay. Within the clay layer, the vertical-to-subvertical burrows seem to disappear while the white-sand-lined and white-clay-filled *Gyrolithes* traces become much more visible (although they remain consistent in number compared to those found in the Meridian Sand). Only with the recognition of the vertical-to-subvertical faint iron stains within the clay layer can the trace makers be identified that formed the traces in the Meridian Sand.

This study suggests that problems may occur where the identification of trace fossils (endichnial or otherwise) is based on contrasting lithology between the trace and surrounding matrix. This is not new information. Rather, the concern is in the possible assumption that sedimentary changes mark ichnological boundaries where traces apparently terminate. Caution is urged where lithologic changes do occur because traces may be preserved in different ways due to the changes in sediment composition.

ACKNOWLEDGMENTS

I am indebted to W.J. Huff (*deceased*) for introducing me to this locale. Gratitude is expressed to G.W. Isphording for field assistance. Ichnologist J.H. Cowart (*deceased*) provided helpful technical assistance. I am appreciative to P. Vierheller and K. Piselli for their reference assistance. Gratitude is expressed to A.J. Akridge, J.K. Reed, and F. Mekik for their helpful and constructive comments. This work neither represents the views or opinions of the U.S. Environmental Protection Agency or the United States, nor was this investigation conducted in any official capacity. Any mistakes are the responsibility of the author.

REFERENCES CITED

Copeland, C.W., (ed.), 1968, Geology of the Alabama Coastal Plain: University, Alabama, Alabama Geological Survey, Circular 47.

Mancini, E.A., and Tew, B.H., 1988, Paleogene stratigraphy and biostratigraphy of southern Alabama: Tuscaloosa, Alabama, Guidebook for the 38th annual convention of the GCAGS-GCS/SEPM, Alabama Geological Survey.

Martinsson, A., 1970, Toponomy of trace fossils, *in* Crimes, T.P., and Harper, J.C., eds., Trace fossils: Liverpool, United Kingdom, Seel House Press, p. 323-330.

Reynolds, W.R., 1992, The heavy mineral population within the beach sand facies of the Meridian Sand exposed in Mississippi: Transactions of the Gulf Coast Association of Geological Societies, v. 42, p. 633-646.

Savrda, C.E., 2007, Taphonomy of trace fossils, *in* Miller, W., III., ed., Trace fossils: Concepts, problems, prospects: New York, Elsevier, p. 92-109.

Savrda, C.E., 2008, Ichnofabric character and preservation in storm-influenced shelf deposits, Eocene Tallahatta Formation, eastern Mississippi: Geological Society of America Abstracts with Programs, v. 40, p. 9.

Seilacher, A., 1964, Biogenic sedimentary structures, in Imbrie, J., and Newell, N.D., eds., Approaches to paleoecology: New York, John Wiley, p. 296-316.

Seilacher, A., 1967, Bathymetry of trace fossils: Marine Geology, v. 5, p. 413-429.

Siesser, W.G., 1984, Paleogene sea levels and climates: U.S.A. Eastern Gulf Coastal Plain: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 47, p. 261-275.

Toulmin, L.D., and Newton, J.G., 1963, Profile showing geology along Alabama Highway 69 and Clarke County Highway 15, Clarke County, Alabama: University, Alabama, Alabama Geological Survey, Special Map 27.

Wermund, R.G., 1965, Cross-bedding in the Meridian Sand: Sedimentology, v. 5, p. 69-79.

Wermund, R.G., and Moiola, R.J., 1966, Opal, zeolites, and clays in an Eocene neritic bar sand: Journal of Sedimentary Petrology, v. 36, p. 248-253.