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Abstract

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GULF COASTAL PLAIN REGIONAL CONTRASTS: KEY TO LOWSTAND AND UPLIFT-DRIVEN EXTENSIVE PLEISTOCENE DENUDATION

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ABSTRACT

The narrow Pleistocene–Holocene coastal belt on the NE Gulf of Mexico contrasts sharply with the broad Louisiana-east Texas coastal plain, composed of three wide Pleistocene terraces. Consecutive late Pliocene and Pleistocene marine lowstands drove more intensive surface erosion. In addition to well preserved deposits of the last Interglacial and Glacial from fewer major streams than in the NW and central coast only limited remnants of the penultimate terrace survive. Only a single, thin Sangamon Interglacial complex that narrows to <10 km remains east of Mobile Bay. Neogene beds usually underlie the Pleistocene at -20 to -7 m. But a single Pleistocene nearshore interval, correlated with seismic and engineering profiles is identifiable in the subsurface. Extensive erosive lowering of the land surface and valley incision have been major factors between the late Pliocene and Sangamon highstands, respectively, during the Wisconsin glacial stage. The data suggests slow, steady uplift since the late Pliocene, punctuated by accelerated removal of nearly all pre-Sangamon Pleistocene coastal units. Late Pleistocene deposits *directly* overlie the Neogene. Each major glacial lowstand contributed to the prolonged pre-Sangamon hiatus associated with major amalgamated valley entrenchment. The maximum thickness (6-24 m) of inshore and nearshore Holocene deposits is comparable with Pleistocene thickness values that reflect a much longer, more varied development. In sharp contrast to the Pleistocene, Holocene coastal units underwent no apparent uplift, only limited erosion.

INTRODUCTION AND OBJECTIVES

The lesser width, thickness, and age range of the Quaternary deposits that underlie the NE Gulf of Mexico coastal plain stand in sharp contrast to the far greater extent and temporal continuity of Quaternary Louisiana and Texas coastal plain units on the N and NW Gulf coast. Pleistocene or "Pliocene-Pleistocene" dates have been previously assigned to the extensive Citronelle (-Williana) Formation and its land surface (e.g., Fisk, 1938; Saucier and Snead, 1989; Spearing, 1995). Recognition of the Citronelle's Pliocene age has drastically reduced the area, assigned to the Quaternary coastal plain (Otvos, 1988; 1991). Extensive drill data between southwest Mississippi and the eastern Florida Peninsula established the depth, thickness, and ages of Pleistocene and Holocene coastal and nearshore units and subsurface depths of the buried Neogene (Otvos, 1997, 2005b).

The objective was to identify, review, and compare widely scattered data that relate to Neogene, Pleistocene, and Holocene coastal units. These were collected from a large body of published papers, reports, and drill log files. Integration with microfossil logs linked to reinterpreted Pleistocene seismic profiles guided stratigraphic reevaluation. Data compiled from these sources document a shallow Neogene "basement" and overlying Quaternary coastal and nearshore deposits. Recognition of the Neogene-Pleistocene boundary in numerous surface and subsurface locations helped in the definition of the stratigraphic units; depositional and sea-level change-related erosional and aggradational events.

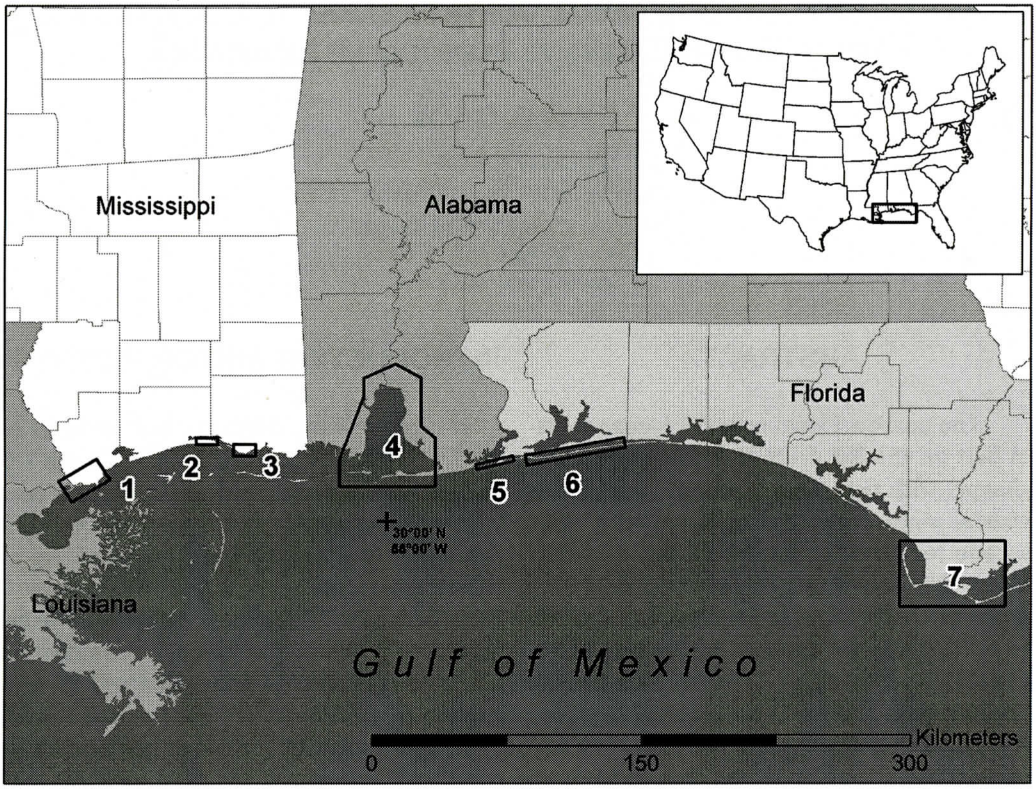

Figure 1. Location index. 1- Pearl Delta-Hancock marshland; 2- Biloxi Peninsula 3- Belle Fontaine area; 4- Mobile Bay-eastern Dauphin Island, and Morgan Peninsula; 5-Perdido Key area; 6- Santa Rosa Island and Sound; 7-Apalachicola Coast

METHODS

The stratigraphy, including thickness and depth of Quaternary units is based on numerous publications, results of extensive earlier and recent field work. Data from drill logs came from granulometric analyses by the sieve and pipette-methods, and consequent sediment designations. Detailed studies utilized foraminifer faunas or their absence in drill core and field samples. Age-diagnostic *Neogene* fossils in the shallow subsurface in SE Mississippi, at Perdido Key, and the Apalachicola Coast were key to the statigraphic reassessment (Figure 1; Table 1). Well-defined lithological characteristics, even absence of microfossils plays a role in identifying the critical Neogene-Quaternary boundary. Reevaluation involved reclassification of Dauphin Island and other drill hole intervals from "undifferentiated" or "Pleistocene" to Neogene. Application of high-resolution chirp seismic profiles, reinterpreted from Greene *et al.* (2007) plays a major role in correlating Neogene and Pleistocene units.

Data from the "gray literature" came from engineering, USGS open file, and state agency reports (e.g., Otvos, 1985a, 1986b, 1990), guidebooks, and drill logs at the USM Gulf Coast Research Laboratory, Ocean Springs, MS. Lack of space limits the number of figures. The referenced literature also provides numerous additional pertinent illustrations.

STRATIGRAPHY AND TERRACE UNITS, NORTHEASTERN GULF COASTAL PLAIN

Neogene Subperiod Deposits

The Neogene Subperiod is defined by the

Table 1. Geological units and ages, Northeastern Gulf Coastal Plain.

Ages (with oxygen isotope stages)	Units and depositional facies
Holocene Epoch (OIS 1)	Highstand coastal eolian, fluvial, lacustrine, river delta, bay, lagoonal, barrier island chain and barrier spit deposits, Early Holocene eolian inland sandsheets, dunes, fluvial terrace deposits
Pleistocene Epoch Wisconsin Glacial (Eowisconsin, OIS 5d-a and Wisconsin OIS 4-to-2) (marine lowstand)	Inland coastal plain eolian deposits; river terrace alluvium, fill in entrenched valleys, coastal plain alluvial deposits (latest Prairie units)
Sangamon Interglacial Stage (OIS 5e) (marine highstand)	Prairie Formation- alluvial deposits Gulfport Formation- barrier deposits Biloxi Fm- paralic-to-open marine deposits Pre-Sangamon and Sangamon remnant fill in the older set of entrenched valleys
Penultimate Interglacial Stage (OIS 7) (marine highstand)	Montgomery alluvial terrace deposits
Pliocene Epoch	Citronelle Formation- alluvial deposits; interspersed with thin paralic deposits east of Mobile Bay Early-mid Pliocene fluvial and paralic thick sandy and muddy interval ("Pensacola Fm"), including thin lenses of open marine Perdido Key Fm. Open marine siliciclastics and limestones in eastern Florida Panhandle

23.0-1.75 Ma time interval; its youngest Epoch, the Pliocene, by the 5.0-1.75 Ma time span (Neuendorf *et al*., 2005). A thick series of alluvial deposits and minor paralic, even marine units represents the Neogene on the NE coast. Characteristic gray, bluish-gray, and greenish-gray, very well-to-moderately consolidated, muddy-sandy, clayey, locally sandy deposits dominate.

The late Miocene-to-mid Pliocene alluvial-paralic clayey-sandy complex in the Alabama-Mississippi area was incorporated into a tentatively suggested Miocene-Pliocene "Pensacola Formation" (Otvos, 1994). Prior to the discovery of the Pliocene fossils in the shallow subsurface at Perdido Key (Figure 1; Table 1; Otvos, 1988; Fig. 3 *in*: Otvos, 1997; Fig 38 *in*: Otvos, 2005a), corresponding fine siliciclastic-sandy beds had been dated Upper Miocene. Fossiliferous siliciclastic marine facies overlie shallow calcareous Pliocene deposits in the Apalachicola Coast (Figure 1; Otvos, 1988, 1992, 2001). The age of the calcareous clastic units and limestones had been also regarded as Upper Miocene (Schnable and Goodell, 1968).

The Citronelle is the youngest Neogene formation in the region. It underlies the coastal upland surface and consists of a thin (15-27 m) fine-to-coarse sandy, occasionally gravelly sequence. Muddy-fine sandy Citronelle lithofacies often display bright orange or yellowish-brown oxidized colors (Table 1). Unconformably overlying the muddy-fine siliciclastic Pliocene interval, it is predominantly of alluvial origin, with interlayered estuarine facies present only east of Mobile Bay. Attaining ca. +120 m elevation at 210 km inland, its surface declines coastward to +15-30 m. Previously defined as the oldest Pleistocene coastal unit (Fisk, 1938), fossil and other evidence substantiated the Citronelle's late Pliocene age (Otvos, 1988, 1997, 2005b).

Pleistocene Epoch

Fisk (1938) described three Pleistocene coastal plain terraces; gulfward descending, broad shore-parallel steps in Louisiana and east Texas. In descending order, these are the Bentley, Montgomery, and Prairie (Beaumont, in Texas). The combined Bentley-Montgomery terrace belt is maximum 50 km wide; the Prairie-Beaumont terrace is 100 km, at its widest (Bernard and LeBlanc, 1965). Predominantly alluvial deposits, at their base occasionally interlayered with thin brackish (paralic) intervals underlie the Montgomery and Beaumont-Prairie terrace surfaces (Otvos, 2005b). The Pleistocene interval was shown as ca. 450 m thick in south-central Louisiana, (Akers and Holck, 1957).

Except at major recent stream deltas, the Pleistocene coastal plain significantly narrows east of the Pearl River in SW Mississippi. Well developed in adjacent Louisiana, remnants of the Montgomery Terrace, formed during the OIS 7 Interglacial (Table 1) occupy but small areas in Mississippi. An earlier valley phase of entrenchment that cut into the luminescence-dated (216 to 188 ka) Montgomery highstand (OIS 7) terrace alluvium in the Louisiana coastal plain coincided with lowstand stage OIS 6 (Otvos, 1997, 2005a, b). Only the Prairie-Gulfport Sangamon Interglacial complex, overlain locally by late Pleistocene alluvial, respectively late Pleistocene-to-early Holocene eolian deposits has been preserved east of Mobile Bay.

Sangamon Interglacial (OIS 5e), Eowisconsin (OIS5d-a), and Wisconsin Glacial Stage (OIS 4-2) Deposits

Muddy-sandy nearshore and brackish paralic sediments of the Biloxi Formation formed during the Sangamon transgression and highstand (Table 1). Semi-continuous, narrow Gulfport barrier strandplain sectors skirt the present shoreline. Prograded from the last interglacial highstand shoreline, they overlie the Biloxi. Sandy-silty, rarely gravelly-sandy alluvial deposits aggraded the Prairie Formation during the Sangamon and early-mid Wisconsin. Combination of the Prairie alluvial plain with intermittent narrow Gulfport barrier sectors forms the youngest Pleistocene coastal surface. Near its base the Prairie occasionally interfingers with paralic-brackish Biloxi deposits in the shallow subsurface. Luminescence dating revealed continued Prairie alluviation *inland,* even during Wisconsin glacial low sea-levels (Otvos, 2005b).

Biloxi Formation

The moderately consolidated-to-unconsolidated medium gray, greenish-gray (5G6/1, 5G5/1) Biloxi clays and sandy clays, poorly sorted sands and muddy sands, fine sandy muds display a sharp lithological contrast to underlying stiff, well-consolidated, often stiff-to-very stiff, greenish- and bluish-gray characteristic Neogene clays and associated coarser siliciclastics. The highly fossiliferous open nearshore marine to brackish, sandy-muddy deposits of the Biloxi underlie Holocene barrier islands and lagoons. Paralic Biloxi sediments form a landward-tapering narrow wedge beneath the seaward margin of the Prairie coastal plain (Otvos, 1975, 1991, 1997). Usually 13.5-to-26 m thick, the Biloxi occurs in the shallow subsurface. A record, 36-m Biloxi sequence aggraded in a

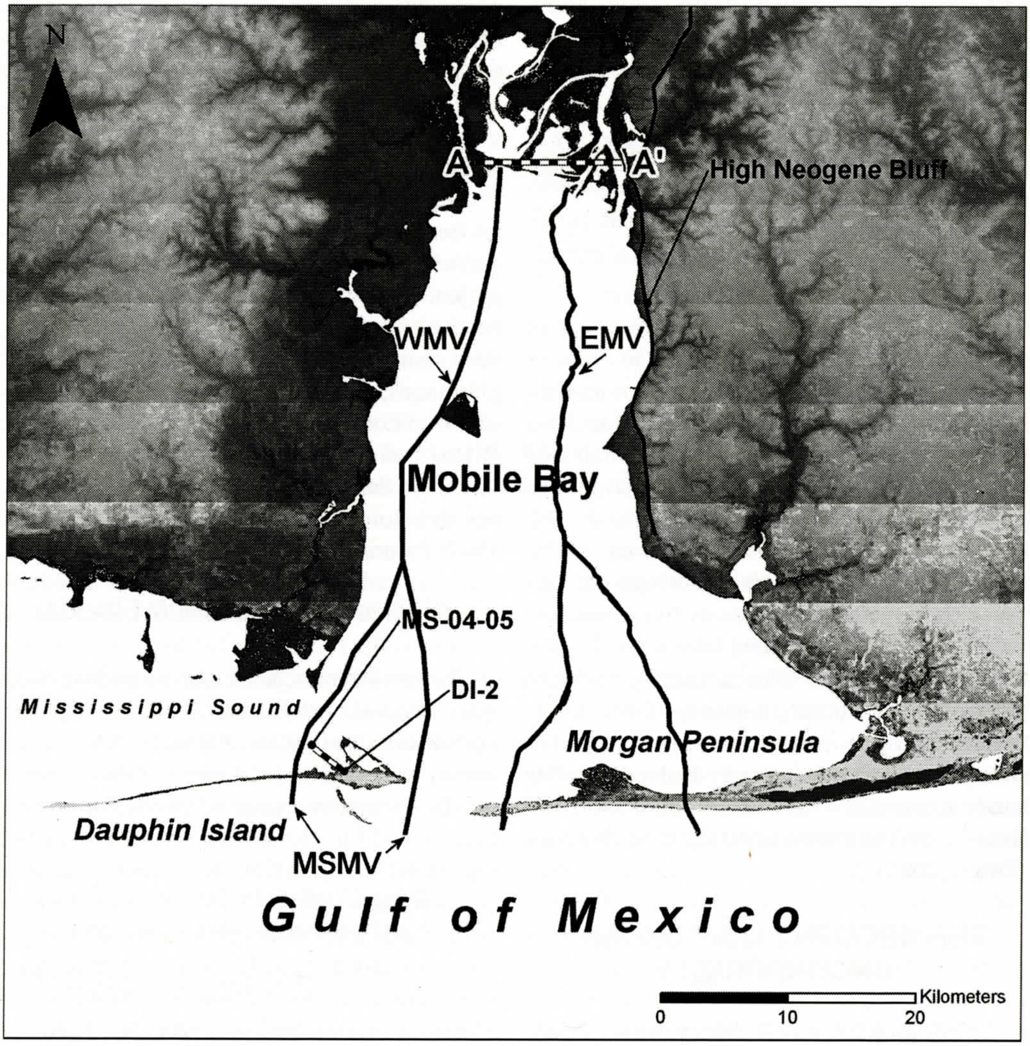

Figure 2. Mobile Bay bayhead (line A-A *in*: Greene *et al.*, 2007), adjacent Neogene bluffline, and east Dauphin Island area drill hole locations. Generalized valley thalweg outlines WMV, EMV, and MSMV based on Kindinger *et al.* (1994), Otvos (1997, 2005b), and Greene *et al.* (2007).

deeply entrenched pre-Sangamon stream valley at Pt. aux Chenes, SE Mississippi (Otvos, 1985a; 1991). 35-m Biloxi fills a similar relict Apalachicola River channel cut into (Figure 1 and Otvos, 1992). The formation aggraded during Sangamon Interglacial highstand OIS 5e, between ca. 132-116 ka (Otvos, 2005b).

Prairie Formation

The Prairie Formation named *Beaumont* in Texas, earlier designated as *Pamlico* in Florida, poorly sorted alluvial muddy, silty and clayey fine sands and well sorted medium and fine-to-very fine sands underlie the gulfward inclined low Prairie Terrace surface. Clay and gravel beds also occur. Generally 6-12 m thick in the Northeast, Prairie surface exposures display yellow, yellowish-brown oxidized colors; at greater depth, yellowish-gray, greenish-gray, and gray. Plant fossils are uncommon; vertebrate remains, rare. The width of the slightly dissected Prairie surface reaches 50 km along the Pearl River but it is only 0.8 km wide north of St. Louis Bay (Otvos, 1990, 1991, 1997, 2005a, b). The youngest Prairie alluvium dated 40-to-25 ka (Table 1; Figure 4 *in* Otvos, 2005b), indicating continued alluviation in the coastal plain interior that widened as sea-level fell. Prairie luminescence dates thus extend well into the Wisconsin Stage.

Gulfport Formation

The Gulfport barrier formation consists of medium to fine-grained, very well to well-to-moderately sorted sands. It forms a semicontinuous belt of narrow (0.7-3.6 km wide) and 3-6 m thick strandplain sectors along the mainland shoreline. A 2-6 m high ridgeplain prograded gulfward during the Sangamon highstand. OSL dates range between 124-116 ka (Otvos, 2005a, b). Induced by postdepositional processes, carbon-rich humate impregnations form semiconsolidated dark brown sand layers and lenses. *Ophiomorpha* trace fossils; knobby-surfaced shrimp burrows occur frequently. Often masking the Gulfport ridgeplain morphology, the overlying Wisconsin-to-early Holocene eolian sands accumulated under drier conditions, well inland from the distant lowstand Gulf shoreline (Otvos, 2004).

THE NEOGENE-QUATERNARY UNCONFORMITY

Lithology plays a key diagnostic role in distinguishing between the generally fossil-free Neogene and the overlying Pleistocene deposits in outcrops and the subsurface. Differential erosion of the preexisting land surface, faulting, and gulfward tilt explain the variable depths of the buried Neogene surface.

Mississippi

Near the Louisiana-Mississippi state line and north of the Hancock marshland (Figure 1) 7-18 m thick Biloxi and Prairie deposits cover the Neogene (Otvos, 1997, Figure 43). Stiff muddy and sandy Neogene underlies the Quaternary at comparable depths in Belle Fontaine and Ocean Springs (Figure 1; Otvos, 1997, 2001; Figs. 12-13 *in* Otvos, 2005). Rare age-diagnostic Pliocene fossils in the upper Neogene interval, previously considered Upper Miocene, between 45-53 m included *Pterocarya* pollen and *Impagidinium fenestroseptatum* dinocysts at 26 m (Edwards and Willard, *in* Gohn *et al.*, 2001).

Semiconsolidated, plastic-to- very stiff, fossil-free, medium bluish-gray Neogene clays occurred at few meters below sea-level in a dredge pit just east of Rhodes Pt on Biloxi Back Bay's south shore (Figure 1). Of similar consistency, brownish-gray, medium gray clays, very dense gray sands, and sandy silts rise to -10 m beneath late Pleistocene deposits on the SE shore of Biloxi Peninsula (Capozzoli and Associates, 1993). To the SE at Belle Fontaine, the Neogene occurs below 12-27 m (Figures 14a, b, *in* Otvos, 1997; Figures 12-13 *in* Otvos, 2005a).

Alabama-Western NW Florida

The fossiliferous, lenticular-shaped late Neogene interval, designated as the Perdido Key Formation underlies the Alabama- NW Florida border area (Table 1, Figure 1; Otvos, 1994). Drillholes have encountered this neritic unit between ca. -15 to -30 m (Fig. 39 *in* Otvos, 1997; Fig. 38 *in* Otvos, 2005a). Including *Globigerina riveroae, G. nepenthes, Globorotalia plesiotumida* planktonic forams and ostracods *Puriana mesocostalis* and *Malzella evexa*, this fauna represents Pliocene foraminifer zones N19-20. The bivalve *Nuculana trochilia* also characterizes the Pliocene Jackson Bluff fauna of SW Georgia and NW Florida (Huddlestun, 1988; Otvos, 1994; Otvos,1997, p. 5-7). 5-15 m thick fine siliciclastic-sandy fossil-free Neogene overlies this unit.

Eastern NW Florida

Schnable and Goodell (1968) were the first to provide a detailed shallow stratigraphy of the Apalachicola Coast (Figure 1). First considered Upper Miocene, subsequent sediment and microfossil studies have also revealed the Pliocene age of the shallowest, stiff greenish- and olive-gray marine siliciclastics that cover Pliocene limestones and limey marls (Otvos, 1992). Occasionally almost reaching sea-level, the heavily dissected and buried Neogene surface often attains -10 m in the coast and nearshore (Figure 2 *in* Otvos, 1985b; Otvos, 1990).

SEISMIC PROFILE CORRELATION WITH SEDIMENT UNITS

Providing critical information on the shallow stratigraphy of two linked entrenched valley generations in the Mobile Bay-east Mississippi Sound area, after age revision certain seismic chirp profiles (Greene *et al.*, 2007; Figure 15) correlate well with our drill hole and field data.

Greene *et al.* defined Sequence Boundaries A and B by two widespread seismic horizons. With critical implications for the depth and thickness of the Quaternary sequences in the Alabama inshore and offshore, they have assigned deposits that underlie Sequence Boundary B to an "undifferentiated Pleistocene" interval. Greene *et al.* recognized two sets of superimposed entrenched valleys in seismic profiles, in their view both incised into Pleistocene deposits. The authors claimed that they extend below -40 m; much deeper than even the thickest valley fill encountered.

Offshore stratigraphy and entrenched-buried valleys

Late Neogene Deposits

Fossil-free siliciclastic deposits of typical Neogene lithology occur also at quite shallow depths in Alabama and Mississippi barrier island and in eastern Mississippi Sound drillholes. Dark-to-medium dark greenish-gray and light olive-gray, stiff, well-consolidated muds, clays, sandy muds often are interlayered with unconsolidated sandy silt, sand, and sandy clay. Plant fragments are not very common. Our 1970s coreholes encountered two broad valleys, subsequenly linked by seismic profiles to buried major valleys EMV and MSMV (Figure 2). These were cut into Neogene and Pleistocene deposits that underlie western Morgan Peninsula, respectively, east Dauphin Island (Otvos, 1997). Sea-level decline and valley incision followed the Sangamon highstand (Figure 38 *in* Otvos, 2005). Under the Ship islands and Mississippi Sound, west of Dauphin, the buried Neogene surface occurs between -18 and -23 m (GCRL Drillcore Log Files).

Neogene-Pleistocene Boundary, Mississippi Sound-South Mobile Bay; Seismic Profile And Drill hole Correlations

Unconformities, corresponding to Seismic Sequence Boundaries A and B have long been recognized in Dauphin Island and Morgan Peninsula drillholes (Corehole DI-2; GCRL Drill-log Collection and Otvos, 1997, Fig. 39, Otvos, 2005). Boundary B, the regional Late Quaternary-Pliocene unconformity is contiguous with buried valley slopes cut from Neogene beds. DI-2 (Figures 2 and 3) was located 4 km SE of recently drilled MS-04-5 (Fig. 15 *in* Greene *et al.*, 2007).

Drill hole DI-2 encountered characteristic fossil-free medium stiff-to-stiff, dark greenish-gray (5G4/1), greenish-gray (5G6/1), moderate greenish-gray (5G3/1) and light olive gray (5Y6/1) Neogene muds beneath the Pliocene-Pleistocene unconformity. Moderately-sorted interspersed granular medium and fine sand and light olive gray, very fine sandy, coarse, medium-stiff silt also occur. As in MSMV, the fill-covered slope in entrenched EMV (Figure 2) coincides with Boundary Surface B. Although located *seaward* of Drill hole MS-04-5, Drill hole DI-2 penetrated the buried MSMV valley slope, cut from Neogene beds, *higher;* closer to present sea-level (Figures 2, 3).

Greene *et al.* described Seismic Sequence B between -10.0 and -19.0 m as representing a *paralic "bayhead delta"* interval in Corehole MS-5-04. It correlates in part with the *open-marine* Biloxi facies in nearby Corehole DI-2. The facies here included moderate greenish-gray (5G 6/1) unconsolidated very fine sandy muds and muddy fine sands (Table 1; Figures 2, 3). The well-to- moderately well sorted, unconsolidated Biloxi sands display medium gray and white colors. Indicating marine-to-nearshore marine conditions also by the high taxonomic diversity, the 12.3 m horizon contained 52 foram taxa, including eight marine planktonic

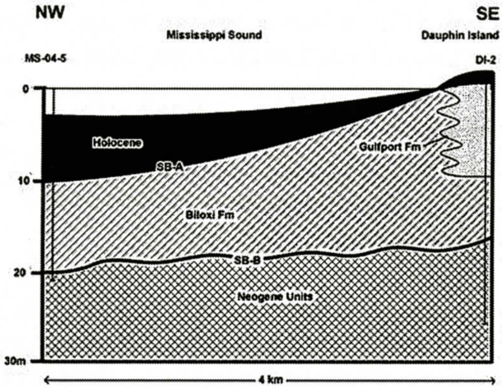

Figure 3. East Dauphin Island- southeast Mississippi Sound cross section. Correlation between Drill holes DI-2 (corrected from Figure 48 *in* Otvos, 1997) and MS-04-5 (Greene *et al.*, 2007, Figures 4, 5, 10).

Quinqueloculina and *Triloculina* species. Open-marine *Hanzawaia strattoni* and *Textularia mayori* occurred in greater concentrations. Similar high-salinity Biloxi depositional facies provided high *Rosalina columbiensis, Nonion depressulum matagordanum*, and *Bulimina elegantissima* values in nearby drill holes (GCRL Core Log Archive). Reflecting greatly reduced salinities, due to salinity fluctuations or regressive termination of Biloxi deposition, at Horizon 11.7 m *Ammonia beccarii parkinsoniana* and *A. b. tepida* represented 50% of the foram taxa. A total of only 25 species indicate abrupt diversity decline due to brackish water influx. In DI-2, located on the western flank of the east Dauphin Gulfport barrier sector (Table 1; Otvos, 1997), the top Pleistocene interval consists of ca. 3 m well- to moderately-well sorted, white and greenish-gray, medium and fine Gulfport barrier sands (Figures 2 and 3).

Blue-green clays were assigned to "undifferentiated Pleistocene" by Greene *et al.* in Drill hole MS-04-5. Their "alluvial valley-fill", represented by grayish-blue and grayish-green clayey sands of undetermined total thickness overlies the Boundary B unconformity. Apparent correlative of the Prairie Formation, the alluvium overlies estuarine-to-marine clay. This Biloxi-correlative included paralic *Rangia cuneata* and nearshore *Nuculana acuta* bivalves. Greene *et al.* also reported *Ophiomorpha* and *Thalassinoides* trace fossils. Lack of microfossil data in MS-04-5 prevented a detailed facies correlation with Drill hole DI-2.

Age of Seismic Sequence Boundary and Seismic Sequence B

Assigning this unconformity boundary to the OIS 6 marine lowstand, Greene *et al.* (2007, Figure 15) have included *Sequence Boundary B* in a >40 m thick Pleistocene sequence. This figure conflicts with Pleistocene regional depth and thickness values. The buried summits of Neogene interfluves that flank incised valleys under Dauphin Island and Morgan Peninsula (Figure 39 *in* Otvos, 1997, Otvos, 2005a) occur at less than half that depth. Drillholes DI-2 and MS-04-5 reveal that Sequence Boundary B coincides with the unconformity surface between the late Pleistocene Biloxi Formation and the Neogene, below (Figure 3). The term "undifferentiated Pleistocene" thus has also been misapplied to Neogene deposits that *directly underlie* Sequence Boundary B and include only locally recognized Seismic Units C and D (Greene *et al.*, 2007).

Based on the glacial-interglacial chronology of Shackleton and Opdyke (1976), Krantz (1991), and Berggren *et al.*(1995) and history of the NE Coast, the Neogene surface corresponds to Sequence Boundary B that represents a major hiatus. It resulted from recurring prolonged erosional and nondepositional events; the cumulative effect of late Pliocene regression and at least six major pre-Sangamon Pleistocene glacial lowstands. The total time span of the hiatus that created the younger amalgamated regional unconformity has far exceeded the 19 ka duration of OIS 6 lowstand, assumed by Greene *et al.* as time of the older valley entrenchment phase. In the western coast the older phase was also attributed to the OIS 6 lowstand (Abdulah *et al.*, 2004; Wellner *et al.*, 2004). The several hundred m thick Pleistocene interval that buried the Neogene in Louisiana and Texas, offers a sharp contrast to the far less preserved correlative units in the NE.

The thicker Pleistocene units in the western and central coastal region provided vertical separation for the entrenched valleys, excavated during multiple Pleistocene lowstand stages. Because entrenched valleys that formed before OIS 6 have been buried and thus separated by the thick under- and overlying Pleistocene units of previous highstands, they remained in isolation and unamalgamated. In contrast, a lesser sediment deposition during highstands and lesser preservation of stratigraphic units due to intensive lowstand-linked surface denudation did drive valley amalgamation in the NE. Coinciding with erosional removal of older Pleistocene units, this prolonged total time interval may explain the greater intensity of valley entrenchment, surface denudation and lowering that created Sequence Boundary B on a regional scale.

Initiated by entrenchment of the late Pliocene Citronelle Formation and older units, the onset of erosive lowering of the land surface and valley downcutting had predated the Quaternary. Valley entrenchment during OIS 6 determined only the final configuration of amalgamated Boundary unconformity in the coastal plain, including the associated buried valley slopes. The hiatus due to nondeposition and erosive removal of late Pliocene and pre-Sangamon Pleistocene sediments may have represented two million years.

Age of Seismic Boundary and Sequence A

Seismic Sequence Boundary A marks the youngest regionally recognizable unconformity surface. it separates Seismic Sequence A, the most recent sediment interval from Pleistocene beds and is contiguous with the slopes of the younger generation of entrenched valley generations. Seismic Sequence A consists mostly of Holocene alluvial, paralic, and marine sediments. The oldest alluvial fill interval in the younger entrenched valley generation may have predated the late Wisconsin transgression. Boundary A is contiguous with the present subaerial land surface. When eustatic sea-level rise resumed after LGM, erosive lowering of the coastal surface inland from the shoreline continued in a time-transgressive fashion. Progressively covered by paralic sediments, the buried unconformity surface was gradually extended landward (Table 1).

Greene *et al.* (2007) dates the boundary unconformity to the last glacial maximum (LGM) in OIS 2. However, only the deepest entrenchment phase may be linked to this brief record lowstand, ca. 22,000-17,000 yr. Unconformity development represented a much longer process, still in progress. Initiated by the post-Sangamon sea-level decline ca. 116,000 yr ago, evolution of the Boundary A unconformity thus exceeded duration of the LGM interval by more than one hundred thousand years. Seismic Sequence A consists mostly of Holocene alluvial, paralic, and marine sediments.

Reinterpreted Neogene-Pleistocene Stratigraphy at Head of Mobile Bay

Utilizing engineering descriptions from I-10 Causeway drill holes along the bayhead, Greene *et al.* (2007) defined the sandy clay, sand, and stiff greenish-gray clay interval that underlies *Sequence Boundary B* here as well, as "undifferentiated Pleistocene" (Figures 2 and 4). Contrary to the authors' assumptions, the -15 m to -40 m sediment interval clearly predates the Pleistocene. It is *laterally contiguous* and coeval with the muddy-clayey, occasionally sandy Neogene units beneath the Citronelle Formation in the adjacent eastern bay bluffs (Figures 2, 4; also, Isphording and Flowers, 1983). Accompanied by stream entrenchment following Citronelle deposition, eastward bluff retreat kept widening the Mobile River valley since the late Pliocene marine lowstand. Bluff retreat may have further enlarged the basin during bay stages of earlier highstands. The consolidated, stiff or plastic greenish-gray and gray muds and clays, identical to those that underlie Sequence Boundary B typify Neogene deposits in coastal Mississippi and Alabama (Isphording, 1976; Otvos, 1991). While stream entrenchment did remove most of the Prairie and Biloxi in the Bay area during Wisconsin lowstands, a narrow Prairie alluvial plain still flanks several bayshore sectors. Kindinger *et al.* (1994, Figure 4) have identified a Biloxi interval in a mini-sparker profile under the bay.

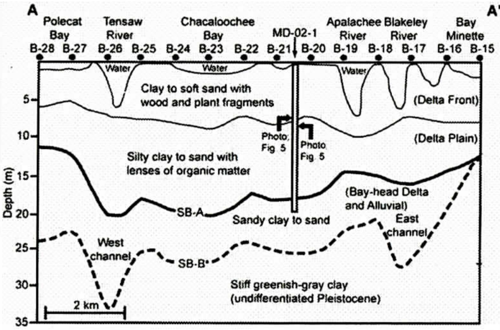

Figure 4. Mobile bayhead cross section (Figures 1, 2), based on causeway foundation coreholes as interpreted by Greene *et al.*, 2007, Figure 7. The adjacent high bay bluff consists of late Neogene deposits. Stiff greenish-gray clays beneath the SB-B unconformity linked to Pleistocene valley incision, are contiguous and coeval with consolidated clayey-muddy Neogene units beneath the eastern bay bluff (to the right). The term "undifferentiated Pleistocene" is invalid.

HOLOCENE

Thickness Variations In Holocene Inshore And Nearshore Sequences

Paralic, including fluvial deltaic, lagoonal, bay sediments; coastal deposits of barrier island, barrier spit and underlying regressive marine intervals, as well as mainland eolian dune complexes are widespread in the coastal region. Salinity-sensitive foram faunas document transgressive-regressive depositional hemicycles. Reduced nearshore salinities that followed the initial transgression resulted in regressive hemicycles driven by barrier chain emergence and barrier spit progradation. Sediment and microfossil studies have revealed these depositional trends in the Mississippi Sound, Mobile Bay, and other estuarine basins (Otvos, 1997, 2001).

The thickness of the Holocene Mississippi delta complex in southern and southeastern Louisiana increases gulfward from ca. 12 to 120 m. In the absence of significant subsidence and gulfward tilt, the Holocene coastal sequence is only 12-15 m thick adjacent to the seaward margin of the Pleistocene in Louisiana (Gould, 1970; Saucier and Autin, 1991). Variations in sediment supply and available accommodation space explain the impressive thickness of certain paralic-nearshore Holocene sequences on the NE coast (Figure 1). While the Pleistocene accumulated over a much longer time interval, its thickness is still compatible with that of the Holocene sediment sequences. Sediment and microfossil studies suggest that thickness differences between Holocene intervals may be explained by the uneven pre-transgression topography, variable surface erosion rates, variations in relative sea-level rise, tectonic and compactional subsidence and uplift of the coastal hinterland. In contrast with the consolidated Pleistocene deposits, severely re-eroded during their post-Sangamon exposure in the land surface, the muddier, fine-grained Holocene sediments underwent lesser compaction and no erosion.

Slow sinking of the Holocene Mississippi delta plain influenced its marginal zone in the Pearl Delta-South Hancock region and adjacent Cat Island. Subsidence contributed to the 15 m maximum thickness of the south Hancock mainland Holocene (Figure 1 and Figures 36, 43 *in* Otvos, 1997; Otvos and Giardino, 2004) and to continuing drowning of the Cat Island strandplain swales. While the Holocene is 5-12 m thick under Mississippi Sound, the sub-sea barrier intervals thin eastward, from 12-to-24 m (Ship and Horn) to 8-to-12 m (Petit Bois and Dauphin islands). Originating in the large Mobile-Tensaw river system, 14-16 m of Holocene was encountered under central and south Mobile Bay (Greene *et al.*, 2007). 13 m Holocene exists in Pensacola Bay (Otvos, 1997, Figures 40, 41), 4-15 m in Apalachicola Bay, and 17 m of Holocene was drilled below sea-level in nearby St. Joseph Peninsula (Otvos, 1986a, 1990, 1992; Twichell *et al.*, 2007). The Holocene is maximum 8 m thick in Santa Rosa Sound; 10 m beneath St. George Sound and Island (Figure 1; Schnable and Goodell, 1968; Otvos, 1990, 1992). Sediment supply, the pre-transgression topography, variable relative sea-level rise, and resulting accommodation space - all have influenced sediment accumulation. In contrast with conditions that prevailed during the prolonged Pleistocene interval, no uplift has yet been detected in the NE coast during the brief Holocene Epoch.

Holocene Fill In Alabama Entrenched Valleys

Our Dauphin Island and Morgan Peninsula coreholes (Otvos,1997, see Otvos 1985b), produced the first evidence in the mid-1970s for the gulfward continuation of the buried valley network found under Mobile Bay (Kindinger *et al.,* 1994). Documented by foram assemblages in east-central Dauphin Island Drillholes #3, 4, and 6 (revised, Symbol 1, Figure 24, Otvos, 2005a, represents Neogene deposits *only*) paralic-to-marine transgressive sequence fills and buries Mississippi Sound- Mobile Incised Valley (Figure 2), branch of West Mobile Valley (WMV; Greene *et al.*, 2007, Figure 4).It was identifiable in the east-central Dauphin Island drill core profile (Fig. 48 *in* Otvos, 1997).

Predominantly marine, >30 m thick Holocene deposits fill the more deeply entrenched western branch of East Mobile Valley (EMV) under the western tip of Morgan Peninsula (Figure 2). The late Wisconsin-Holocene valley bottoms at > 33 m below present sea-level; >21 m below the buried Pleistocene interfluve surface. Biloxi deposits located on the valley flank (Otvos, 1997; Figure 24 *in:* Otvos, 2005a) confirm the protracted and amalgamated character of valley development. Several major lowstand phases between the late Pliocene and the Sangamon Interglacial drove the recurring entrenchment. The older valley network was cut wider and deeper than was the younger, post-Sangamon valley generation. Paralic and marine deposits filled this valley as well during Sangamon highstand. Re-excavation followed during the Wisconsin lows. Comparable in dimension, a 22-m Holocene sediment sequence fills an entrenched Apalachicola valley channel (Otvos, 1990, 1992).

CONCLUSIONS

The stratigraphy, spatial extent, and elevations of the extensive, thick Pleistocene units of the wide central and northwestern Gulf of Mexico coastal plain in Texas and Louisiana provide a marked contrast with the northeastern coastal units. Major differences exist between the two regions in terms of geological history and tectonic influences. The morphology and thickness of Quaternary units and associated unconformity surfaces are closely linked to a variety of depositional and erosional processes and events.

Differences in tectonic settings and lesser fluvial sediment supply may account for the striking contrast between units of the NW and central coastal plain, on one hand and the narrower, thinner northeastern Pleistocene complex of fewer terrace units, on the other. Uplift and consequent wholesale sediment removal from preexisting Pleistocene terraces followed each phase of highstand deposition.

Enhancing these sharp contrasts, the recent reassignment of the widespread Citronelle Formation and its associated land surface from the Pleistocene to the Pliocene Epoch highlights the relatively limited development of the coastal Pleistocene in the NE. The late Pleistocene directly overlies the Neogene at shallow depths. Combination of lithological characteristics, fossil data, reinterpreted ages of seismic sequences, and the shallow depth of the Neogene-Quaternary boundary helped to decipher stratigraphy and to identify depositional facies of the bracketing sediment intervals.

Prolonged denudation; erosional lowering of the land surface and valley entrenchment linked to recurring marine lowstands left but few small remnants of the pre-Sangamon (OIS 7) terrace in the narrow northeastern Pleistocene coastal plain. No coastal terraces that predate interglacial stage OIS 7, survive. Only the continuous late Pleistocene Prairie-Gulfport surface complex remains east of Mobile Bay.

Unaffected by lowered base-level during lowstand stages, Wisconsin alluvium was laid down in inland portions of the Prairie coastal plain (Otvos, 2004, 2005a, b). Surface erosion of high intensity and duration led to formation of regional Unconformity B. In terms of its spatial and temporal dimensions, it has far exceeded the late Pleistocene-early Holocene Unconformity A. Contrary to Greene *et al.*

(2007, p. 149), the associated hiatus was not restricted to the OIS 6 lowstand. It formed between the late Pliocene and Sangamon highstands through the cumulative impact of recurring, prolonged surface denudation and valley downcutting. Erosion and nondeposition of pre-Sangamon coastal units may have dominated in a cumulative time interval of nearly two million years.

Formation of *Sequence Boundary A* in a similar fashion was not restricted to the brief LGM record lowstand and maximum entrenchment. Erosional lowering of the land surface that underlies the unconformity commenced with the post-Sangamon sea-level decline and surface exposure and progressed in a time-transgressive fashion during the regression.

Denudation continued until transgressing Gulf waters have covered and buried the land surface under paralic deposits. The resulting unconformity has been gradually extended landward throughout the Holocene. Striking contrasts in the Pleistocene geological development between the two coastal regions include differences in the duration of erosive and nondepositional events and contrasts in the area extent and elevation of coastal sediment and terrace units. Steady uplift of the Citronelle upland, the shallow nature of the Neogene, the incomplete and discontinuous nature of the Pleistocene terraces and the nearshore sequence suggest major differences in tectonic development between the northeastern and the northwestern-central Gulf coastal regions. When compared with the West, the lesser sediment supply by fewer major eastern coastal streams and significant prolonged Pleistocene uplift may account for lesser sediment preservation and much more extensive erosion of the older coastal units in the NE coastal plain.

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THE COASTAL COMPARTMENT MANAGEMENT PLAN: USING PUERTO RICO AS A MODEL

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ABSTRACT

Coastal management planning is usually standardized for an entire coastal entity (e.g., the island of Puerto Rico) in a legalistic, one-size-fits-all approach. In contrast, a Coastal Compartment Management Plan (CCMP) approach fosters attention on local variability of the natural setting (i.e., geology, hydrodynamics, oceanography) as the guiding principle for management, vulnerability assessment, and hazard mitigation. CCMPs can be either an alternative to or complement of Integrated Coastal Zone Management (ICZM). The coast of Puerto Rico provides an excellent example of natural compartmentalization in which individual compartments operate independently of adjacent compartments; often in sharp contrast to each other in terms of vulnerability to hazards, and corresponding best management practices. Adjacent compartments are also highly variable in terms of types of onshore/offshore economic resources and development. CCMPs involve a five-step approach in which coastal compartments are defined; evaluated utilizing geoindicators; prioritized in terms of potential risks, sensitive environments, and economic uses; potential mitigation options developed; and final plans for each compartment developed in which allocation of resources reflects compartment prioritization. Extensive past studies of the eastern one-third of Puerto Rico, including shoreline mapping, post-hurricane assessments, hazards analyses, and risk assessment, provide a basis for delineating five coastal compartments in the San Juan area. One of these compartments is presented as an example of the CCMP approach in which its characteristics are utilized to make specific recommendations for their individual management. This approach to coastal management is appropriate to most Caribbean Islands, as well as any variable shoreline composed of numerous headlands, embayments, and patchy distribution of shore materials.

INTRODUCTION

Many Caribbean island coasts are naturally compartmentalized owing to differences in their hydrodynamics and geology, and compartments often have little interaction with adjacent compartments. Compartmentalization provides

Figure 1. Puerto Rico is the smallest and easternmost of the Greater Antilles islands. Its capital and largest city is San Juan, located on the northern coast. The study area is Balneario Carolina, a public swimming beach at the eastern end of the metropolitan San Juan area.

a physical basis for considering coastal reaches as separate entities, and should lead to a compartmentalized approach to coastal management. Both environmental and economic management decisions can then be focused by compartment, and on the basis of environmental sensitivity, geologic setting (including natural hazards), and level and type of existing development. Puerto Rico (Figure 1) provides a good model for the coastal-compartment approach which will be illustrated in detail for a single compartment along the metropolitan San Juan shoreline.

The Coastal Compartment Management Plan (CCMP) begins with collection of information on the basic geologic/oceanographic setting of the coast in question. That information is combined with data on coastal hazards and development to delineate individual coastal compartments. Vulnerability, or the likely impacts that different hazardous coastal processes may have on different compartments, including development within each compartment, is then evaluated. Finally, hazard mitigation management strategies can be developed for specific compartments. Implementation of selected strategies will depend on local political and economic driving forces.

Puerto Rico is an ideal place to develop and implement the Coastal Compartment Management Plan. The highly crenulated and embayed shoreline has been studied in detail for over 50 years, dating back to Kaye (1959). The Commonwealth government has a well organized Department of Natural and Environmental Resources and Planning Board, and each Municipio (county equivalent) has regulatory agencies for land use planning and management. Perhaps most importantly, Puerto Rico has resources of the United States Federal Government to draw upon. The United States Geological Survey and the National Oceanic and Atmospheric Administration, through the University of Puerto Rico Sea Grant College Program, have driven much of the research leading up to the CCMP concept.

ISLAND COASTAL MANAGEMENT

Coastal zone management in developing countries, particularly island states, is problematic (Leatherman, 1997; Maul, 1996; Nicholls and Leatherman, 1995). Many island nations are facing growing pressure to develop their coastal zones for tourism or industry with serious environmental degradation (McElroy and Albuquerque, 1998). Management strategies vary, but in general a philosophy of Integrated Coastal Zone Management (ICZM) is recommended; that is, agencies apply coordinated programs, "integrated with the various economic sectors and resource conservation programs" (Clark, 1996, p. 2). This multiple-use approach attempts to balance economic development and environmental conservation, combining coastal-zone land and water resources. Whether island states will ever achieve ICZM is questionable (Cambers, 1998). Examples of case studies which seem to confirm this conclusion are given in Clark (1996). Management failures are in part political, but also may be due to a lack of resources, inadequate databases, and the need for managers to make quick decisions in the absence of reliable data. Actual management approaches often are modeled on strategies developed for other geologic settings, or a one-size-fits-all approach (e.g., a standardized set-back requirement).

Compartmentalized shorelines are common on many islands with rocky headlands and intervening sandy pocket beaches. In Puerto Rico, for example, adjacent beach compartments may vary from calcium carbonate sands where sediment is shelf-derived, to siliciclastic sediments where the compartment is associated with a stream mouth, indicating limited sediment transport past the headlands. This provides a physical basis for considering coastal compartments as separate entities. For example, a beach nourishment project deemed necessary in one compartment has a low probability of losing sand from the project area by longshore transport; though sand can still be lost offshore during storms. The hypothetical example just described is not uncommon, and it is a simple example of how a compartmentalized approach to coastal management can be applied. Both environmental and economic factors may be important in any given compartment, including environmental sensitivity, geologic setting, level and type of existing development, and economic resources.

A coastal-compartment approach is illustrated herein for the metropolitan San Juan, Puerto Rico shoreline with hypothetical recommendations for a single compartment. The Coastal Compartment Management Plan is a five-step approach as outlined below. Successful development of such a plan will provide a blueprint methodology exportable to developing island states throughout the Caribbean and beyond. A main goal of the CCMP is to bridge the gap between coastal geology/oceanography and coastal management.

DEVELOPMENT OF THE CONCEPT

The idea of a CCMP first developed during studies of sediments on the northern beaches and insular shelf of Puerto Rico. Surficial sediments on the northern shelf of Puerto Rico have been well studied; both the beaches (Morelock, 1978, 1984; Morelock and others, 1985; Morelock and Taggart 1988; Morelock and Barreto, 2003), and the offshore shelf sediment cover (Schneidermann and others, 1976; Pilkey and others, 1987; Pilkey and others, 1988; Bush, 1991a). The sediment cover is patchy and diverse with little lateral continuity, and with sharp boundaries between sediment types. These studies led to the concept of the coastal zone being broken into compartments.

After Hurricane Hugo (1989), the United States Geological Survey (USGS) began a program to assess the impact on coastal resources and environments caused by this storm, and to provide baseline data against which to measure the impact of future storm events (Schwab and Rodríguez, 1992; Thieler and Danforth, 1993; Delorey and others, 1993; Thieler and Danforth, 1994a, b; Rodríguez and others, 1994; Schwab and others, 1996a, b). Storms are only one of many hazards affecting coastal areas; multiple geologic hazards and their identification are discussed in Bush and others (1995).

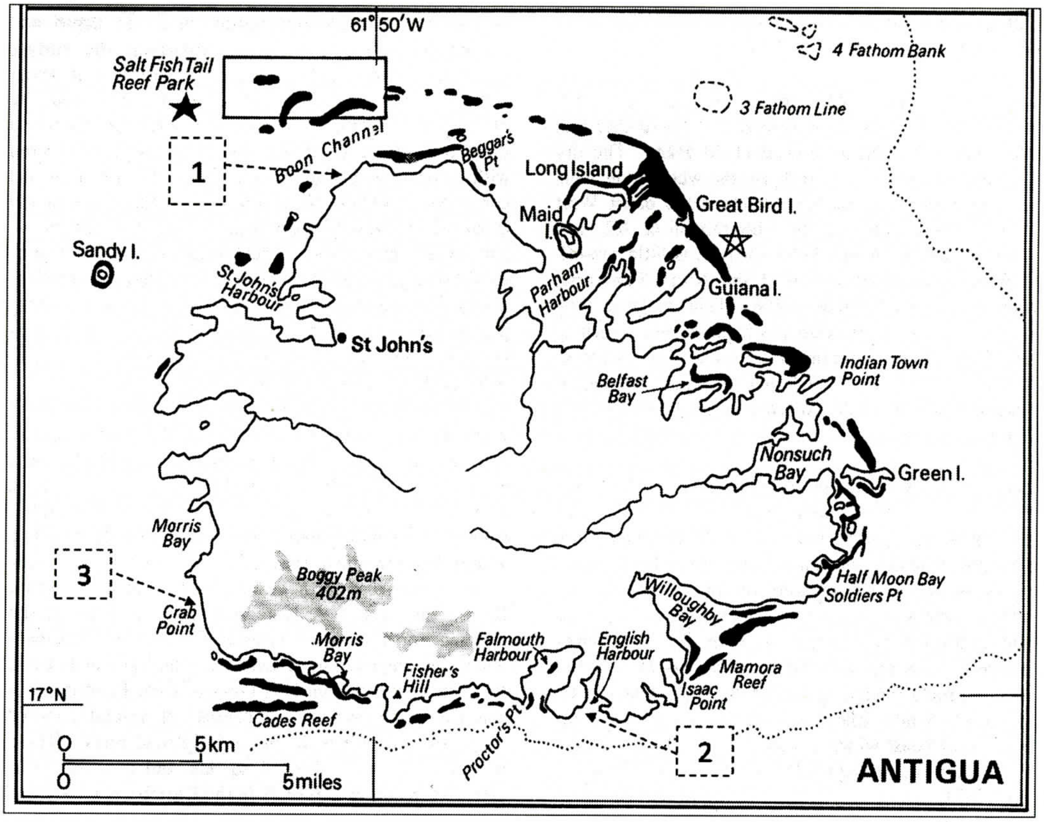

Figure 2. Examples of evaluated coastal compartments on the Caribbean island of Antigua (Bush and others, 2001b). Numbered boxes indicate locations of compartments referred to in the text. Dickenson Bay is box 1, English Harbor is box 2, and Darkwood Beach is box 3.

Bush and others (1996; 2001a) present coastal-zone hazard maps for eastern Puerto Rico (the area most impacted by Hurricane Hugo), depicting coastal geology and geomorphology, beach characteristics, offshore (inner shelf) characteristics, and hazard potential from such events as flooding, marine overwash, erosion, earthquakes, and landslides. In addition, special consideration was given to areas where shoreline engineering or dense development significantly increased the overall vulnerability (potential for property damage) of a coastal stretch.

The post-Hugo studies were geographically organized by "coastal reaches." That is, breaking up the shoreline into stretches with similar geology, similar development, or similar hazards. Often the reaches were sandy pocket beaches between headlands. Sometimes the reaches were stretches with similar types and densities of development. Field investigations, especially post-storm damage evaluations, play an essential role in final compartment delineation. It is important to see in the field how various coastal reaches respond to storm impacts.

Subsequent coastal-hazard assessments built upon the coastal compartment concept. The CCMP approach allows allocation of resources to specific, prioritized compartments, reducing the need for a one-size-fits-all approach; or the need for dealing simultaneously with all island compartments which could overwhelm human and financial resources. Although the Coastal Compartment Management Plan approach has not been put into effect, the basis for defining, evaluating, and prioritizing compartments has been applied in Antigua, Puerto Rico, St. Thomas and St. Croix, USVI, and Roatán, Honduras (Bush and others, 1998; 2001b).

An evaluation of the island of Antigua before and after Hurricane Luis in 1995 (Bush and others, 2001b) resulted in the following defined and prioritized coastal compartments (Figure 2). Dickenson Bay, Antigua, is a top-priority compartment based on its significant shoreline length, wave exposure (no sheltering reefs), historical storm response, state of the shoreline, number of existing hotels, and pressure for more development. In contrast, English Harbor has fewer beaches, and fewer hotels or other large buildings on the waterfront. The combination of a steeper offshore slope, offshore barriers, and steeper onshore topography make this area a lower-risk zone. Darkwood Beach is intermediate. This beach is highly erosive because of its exposure and due to sand mining. This compartment is given a lower priority because of the lack of development. The oceanfront road is the only infrastructure and could be moved if necessary.

METHODS

The Coastal Compartment Management Plan begins with collection of information on the basic geologic/oceanographic setting of the coast in question. That information is combined with data on coastal hazards and development to delineate individual coastal compartments. Vulnerability, or the likely impacts that different hazardous coastal processes may have on different compartments, including development within each compartment, are then evaluated. Finally, a suite of science-based hazard mitigation management strategies is developed that can be implemented within different compartment types. Ultimate implementation of selected strategies will depend on local political and economic driving forces. The following five-step process is proposed to develop a comprehensive Coastal Compartment Management Plan:

Step 1: Delineate individual coastal compartments based on geologic/oceanographic setting, environmental sensitivity, and economic infrastructure,

Step 2: Evaluate natural hazards, risk vulnerability, and development parameters using the geoindicators approach (see discussion below),

Step 3: Prioritize compartments based on identified risk, sensitive environments, and development/economic use,

Step 4: Develop a suite of potential mitigation alternatives for each compartment in cooperation with community interests (*e.g.,* officials, planners, managers, property owners, business community), and

Step 5: Develop final Coastal Compartment Management Plan where allocation of resources reflects compartment prioritization.

Geoindicators

Geoindicators are defined by the International Union of Geological Sciences as "measures of surface or near-surface geological processes and phenomena that vary significantly over periods of less than 100 years and that provide information that is meaningful for environmental assessment" (Berger, 1996, p. 5). The geoindicators approach identifies a minimum set of parameters that describe short-term environmental dynamics, and are proxies representing all the parameters on which processes depend (Berger, 1997). As a result, geoindicators can provide managers with simple, qualitative tools for rapid identification of coastal property damage risk potential that is scientifically valid. In the coastal zone, shoreline change (usually erosion), risk/hazard assessment, and property damage mitigation are of primary concern. Although highly-sophisticated, high-technology environmental monitoring and historical analysis techniques are available as a means of collecting baseline data for coastal-zone management and policy determinations, these techniques are frequently expensive, time consuming, and require a high level of expertise. The geoindicator approach provides a viable, field-based, low-cost alternative.

The geoindicator approach is an outgrowth of recent experience in coastal hazard mapping, risk assessment, and property-damage mitigation studies summarized in Young and others (1996) and Bush and others (1999). National initiatives to develop coastal tourism potential and other types of development carry the prospects for rapid, unsafe development, and need quick, reliable assessments of coastal-zone processes and associated hazards. Table 1 is an example of a geoindicators assessment for Lindbergh Beach, St. Thomas, U.S. Virgin Islands.

CCMP Management Strategies

The ultimate goal of the coastal-compartment approach is to foster greater attention to the natural setting as the basis for management plans and decisions, and to thus aid in simplifying management strategies by dividing up the shoreline into small segments which can be quickly assessed, prioritized, and managed based on available resources (Bush and others, 2002). Once compartments are delineated and assessed, they can be prioritized for management plans specific to each compartment. This paper, in fact, deals only with steps 1 and 2, above. These steps are both in the realm of the geoscientist. The remaining steps must be carried out by the planners, managers, and decision makers.

It is common in many coastal communities that databases on which to make management decisions are lacking, and mitigation is underfunded. This places an ever greater importance on prioritization of management strategies between and within compartments. Once coastal compartments are delineated and the hazards well understood, it is up to the local political structure to develop a management plan for each compartment. Examples of management and mitigation options for the fictional "Pandora's Island" are given throughout Bush and others, (1995).

Depending on the local situation, a simple three-tier management approach might be:

1. Do nothing. Prohibit development in undisturbed, environmentally sensitive areas, and areas subject to loss from natural hazards. Expenditures would be minimal.
2. Use management tools to protect existing development and limit expansion of new development in areas where infringement on sensitive environments or high-hazard zones has already occurred. Expenditures would be focused locally on problem-specific mitigation.
3. Apply intense management to developed areas crucial to the economy or safety of large numbers of people. For example, such an area might be given priority in funding of storm mitigation projects (beach nourishment), water treatment facilities improvements, surface water runoff reduction, and retrofitting buildings to meet higher wind-resistance or flood requirements, or post-hurricane reconstruction.

EASTERN PUERTO RICO AS A CCMP MODEL

Multiple types of hazards threaten Puerto Rico's coast, including earthquakes and tsunamis (McCann, 1984, 1985; Hays, 1985; Lander and Lockridge, 1989; Díaz-Hernandez, 1990; Mercado and McCann, 1998; Mercado and others, 2002; Grindlay and others, 2005), hurricanes (Bush, 1991b; Solá, 1995), mass wasting (Monroe, 1979; Molinelli, 1984, 1985; Larsen and Torres-Sánchez, 1992, 1998), and shoreline erosion (Morelock, 1978, 1984; Morelock and Taggart 1988; Morelock and Barreto, 2003). Shoreline erosion, a persistent hazard, is both a short-term effect due to storms, as well as long-term due to high wave energy and the sea-level rise. River flooding is a common hazard in the coastal zone due to hurricanes and other high-rainfall events. Tsunamis affecting Puerto Rico are summarized by Lander and Lockridge (1989).

A good source for information on Puerto Rico's coastal hazards is "The Coastal Hazards of Puerto Rico" web site (*http://coastalhazards.uprm.edu/*). It was organized by and is supervised by Aurelio Mercado and Harry Justiniano of the Physical Oceanography Laboratory, Department of Marine Sciences, University of Puerto Rico, Mayagüez, and sponsored by the University of Puerto Rico Sea Grant Program. See also the Sea Grant Technical Report, Rodríguez et al. (2006) and the University of Puerto Rico Sea Grant College Program web site at http://www.seagrantpr.org/.

A preliminary, reconnaissance-level evalua-

Table 1. Geoindicators checklist assessment of risk of property damage for Lindbergh Beach, St. Thomas, United States Virgin Islands, 17 July 2001.

Geoindicators	High Risk		Moderate Risk		Low Risk	
General Parameters *Elevation*	< 3 m	X	3-6 m		> 6 m	
Tidal range	Microtidal	X	Mesotidal		Macrotidal	
Vegetation	barren; sparse; toppled; non-native species	X	well-established shrubs and grasses; none toppled		forested; mature vegetation; no evidence of erosion into vegetation	
Bluff Configuration	bare face; recent or no talus ramp		vegetated face and well-developed ramp		low slope angle (large ramp); mature cover of vegetation	
Evidence of Historical storm impacts	obvious		possible	X	none	
Development Parameters *Type of structures*	Non-engineered (not to code; at grade)		Non-engineered (to code)		Engineered (commercial buildings, high-rises, etc.)	X
Density of development	High		Medium	X	Low	
Engineering Structures	seawalls, bulkheads, docks, piers, major marinas		few structures	X	no structures	
River/Tidal Creek Parameters *Site Relative to River or Creek Mouth*	very near		within sight		very distant	
Inland Parameters *Soil and Drainage*	compactable; lacks suitability for septic facilities (impermeable); drains poorly		reasonable good bearing strength; variable; drains moderately	X	permeable; good bearing strength; drains well	
Surroundings	in/near sound, lagoon, estuary, or swamp (mangrove)		floodplain or low-elevation terrace	X	upland	
TOTAL INDICATORS:	**OF HIGH RISK =** 3		**OF MODERATE RISK =** 5		**OF LOW RISK = 1**	
RISK/COMMENTS	Moderate to high risk. A shallow lunate embayment with areas of revetment to protect the road next to the airport. The entrance of the embayment is somewhat protected by rocky headlands and uplifted landforms.					

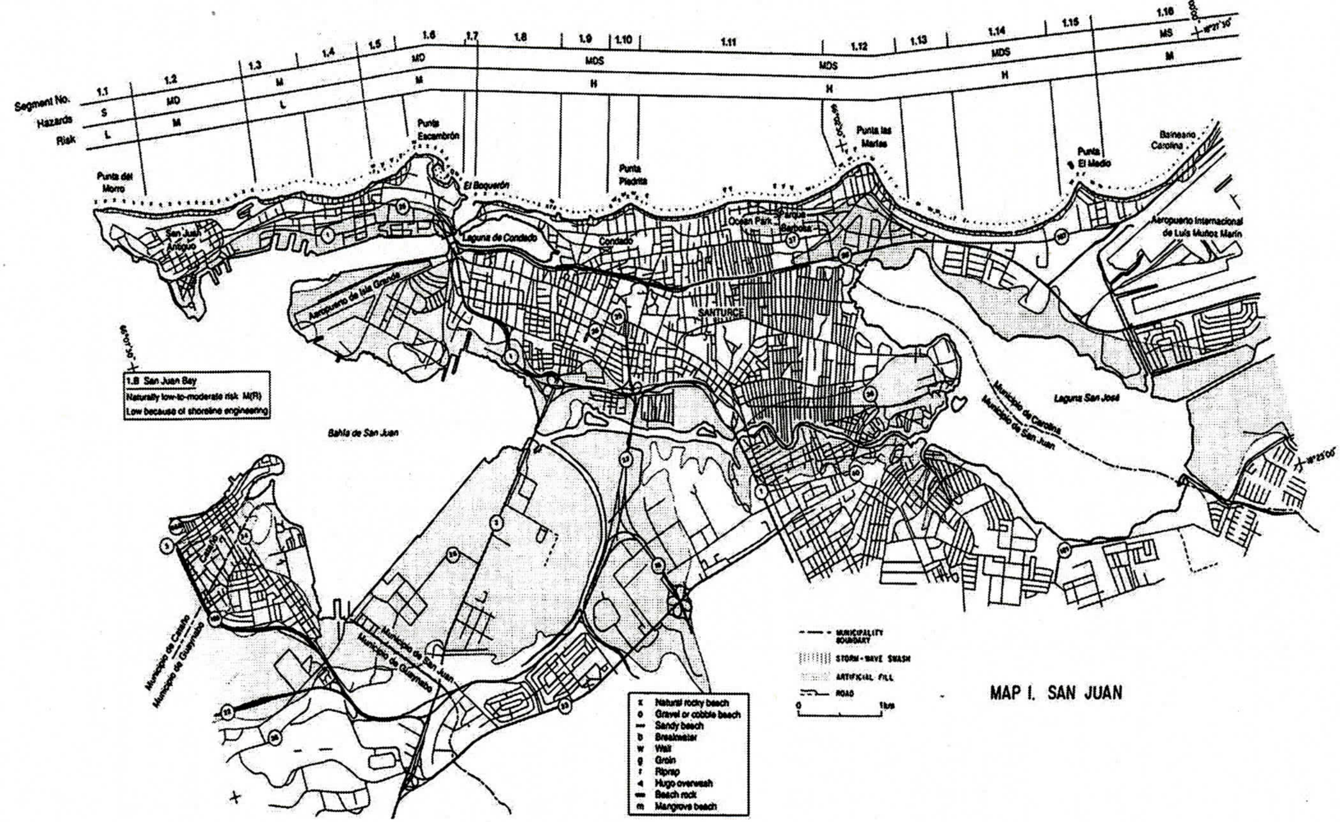

Figure 3. After subdividing the coast into natural compartments, a series of coastal hazards maps were made for Puerto Rico (Bush and others, 2001a) such as this one for the San Juan metropolitan area. In addition, a set of similar maps with hazard descriptions were produced in book form (Bush and others, 1995). Note that headlands form compartment boundaries. Sand budgets are more or less restricted to individual compartments. Risk is categorized as high (H), medium (M), or low (L), and hazards are marine hazards (M), development hazards (D), and shoreline-setting hazards (S). Punta El Medio and Balneario Carolina, the focus of this study, are at the very eastern edge of the hazard map. Not shown is the very eastern portion of the study area, which extends to Punta Cangrejos, visible on Figures 4, 5, 6, and 7.

tion delineated in Step 1 was conducted for the eastern one-third of Puerto Rico as part of a U.S. Geological Survey post-Hurricane Hugo (1989) assessment. After subdividing the coast into natural compartments, a series of coastal hazards maps were made for Puerto Rico. For details on the technique, see Bush and Richmond (1992), Bush and others (1996) and Bush and others (2001a). Figure 3 is an example from the San Juan metropolitan area. In addition, a set of similar maps with hazard descriptions with site-specific evaluations of the entire island, but at a reduced level of detail, were produced in book form (Bush and others, 1995).

To produce the coastal-zone hazard maps mentioned above, USGS topographic maps were used as a base. Then the shoreline was subdivided on the basis of geomorphic units representing "reaches" or "stretches" such as shores downdrift of a particular river-mouth sediment source, or pocket beaches between adjacent rocky headlands (coastal cells or coastal compartments). Each Coastal-Zone Hazard Map contains detailed information by shoreline segment including shoreline type, dominant hazards, and an overall risk assessment. Hazard categories will vary from island to island and compartment to compartment. For the Puerto Rico study, the hazard categories are:

Shoreline-Setting Hazards — Shorelines with chronic or severe erosion history, or low elevation.

Marine Hazards — Impacts include wave run-up, overwash, storm surge, and storm-surge ebb, plus potential tsunami impact.

Earthquake and Slope Hazards — Areas with active faults and steep slopes are prone to slope failure, and areas underlain by unconsolidated material or artificial fill are prone to liquefaction.

Riverine Hazards — Floodplains that have had severe floods, or where flood potential is high, including potential dam failure.

Development Hazards — High-density development with considerable property at risk or low-density development in high-risk areas.

Engineering Hazards — Shoreline engineering projects that have detrimental shoreline effects. Removal of natural protection such as dunes and beaches through sand mining is included.

Hazard assessment for each shoreline segment is assigned as follows: Extreme = more than 4 identifiable hazards, High = 3 to 4 identifiable hazards, Moderate = at least 2 hazards, Low = 1 or no hazard. That study amounted to completing Steps 1 and 2, above. Steps 3-5 necessitate involvement and commitment of Puerto Rico authorities and decision makers. The CCMP philosophy places the onus of management decisions on the local community that is going to benefit.

PUERTO RICO EXAMPLE–BALNEARIO DE CAROLINA

San Juan's shoreline is highly variable in terms of geology, development, and environmental sensitivity. The coastal hazards maps for the San Juan metropolitan area (Bush and others, 2001a) were the ideal starting point for the more detailed analysis necessary for the CCMP approach (Figure 3). The base maps for that study were updated and converted into digital format. Then the entire area was mapped and management recommendations made for each shoreline segment. This example illustrates the goal of the coastal-compartment approach by fostering greater attention to the natural setting as a guide for management and to simplify management strategies. Once the compartments were delineated and assessed (Figure 4), they were prioritized for management plans specific to each compartment. The technology can be exported to the U.S. Virgin Islands and other Caribbean islands, and anywhere that coastal compartments are the dominant shoreline type.

The compartment of interest, labeled "V" on Figure 4, is located at the eastern flank of the study area in a small embayment between two rocky headlands, Punta El Medio and Punta Cangrejos. The tide range for the embayment is approximately 0.3 m with an average land elevation of about 3.5 m. A public swimming beach, Balneario de Carolina, is centrally located in the embayment and accounts for a considerable length of shoreline. The primary user group of this beach is mainly local residents; however, there also is use by a growing number

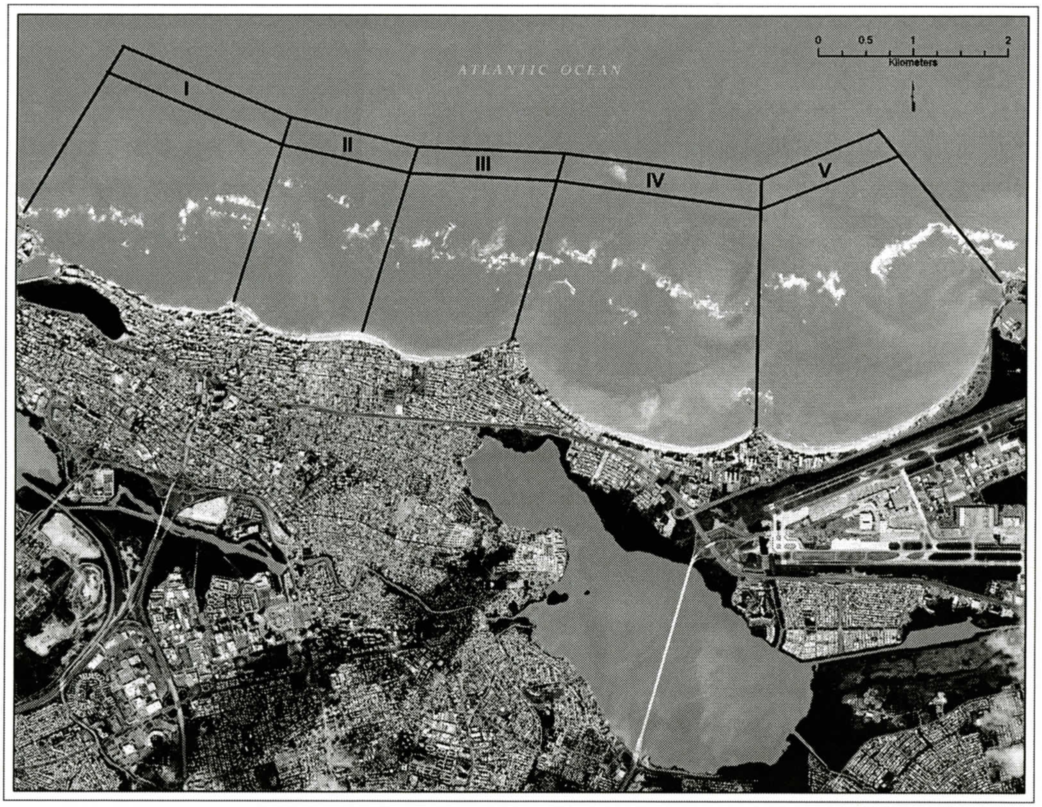

Figure 4. Location map of coastal compartments within the study area. This study focuses on Compartment V, just seaward of the international airport. The easternmost point of land is Punta Cangrejos. The next headland to the west is Punta El Medio.

of tourists. The beach here is mainly comprised of subrounded, medium to coarse-grained quartz sands with coral and shell debris.

The western 1 km of shoreline is backed predominantly by resort hotels and condominiums while the remaining shoreline is backed by areas containing parking lots, small recreational buildings, and patchy grassy areas. A thin, vegetated buffer about 50 m wide containing shrubs, grasses, and mangroves separates the central portion of the compartment along the oceanfront road, Route 187, from San Juan's Luis Muñoz Marín International Airport (Figure 5). The eastern extent of the compartment contains Boca de Cangrejos, an inlet to Laguna La Torrecilla and a small marina situated therein. The flanks of the lagoon are densely covered with mangrove forest.

The offshore area of the embayment contains linear reefs trending NNE located approximately 1.2 km offshore (Figure 5). Another linear reef trending NW fronts the western 600 m of the compartment's shoreline and extends about 1 km offshore. The protective reefs of this compartment are both patchy organic buildups and coral assemblages growing on top of submerged eolianite ridges, common along the northern coast of Puerto Rico. Regardless of the type, reef degradation will lead to reduced protection and increased hazard of the coastal compartment. Impact of sediment runoff and nutrient discharge on the reefs of Puerto Rico is discussed by Larsen and Webb (2009).

A small jetty was emplaced to stabilize the southwestern portion of the inlet leading to Boca de Cangrejos. Immediately south of the jetty a portion of shoreline (~600 m) was stabilized using revetment mainly to protect Route 187.

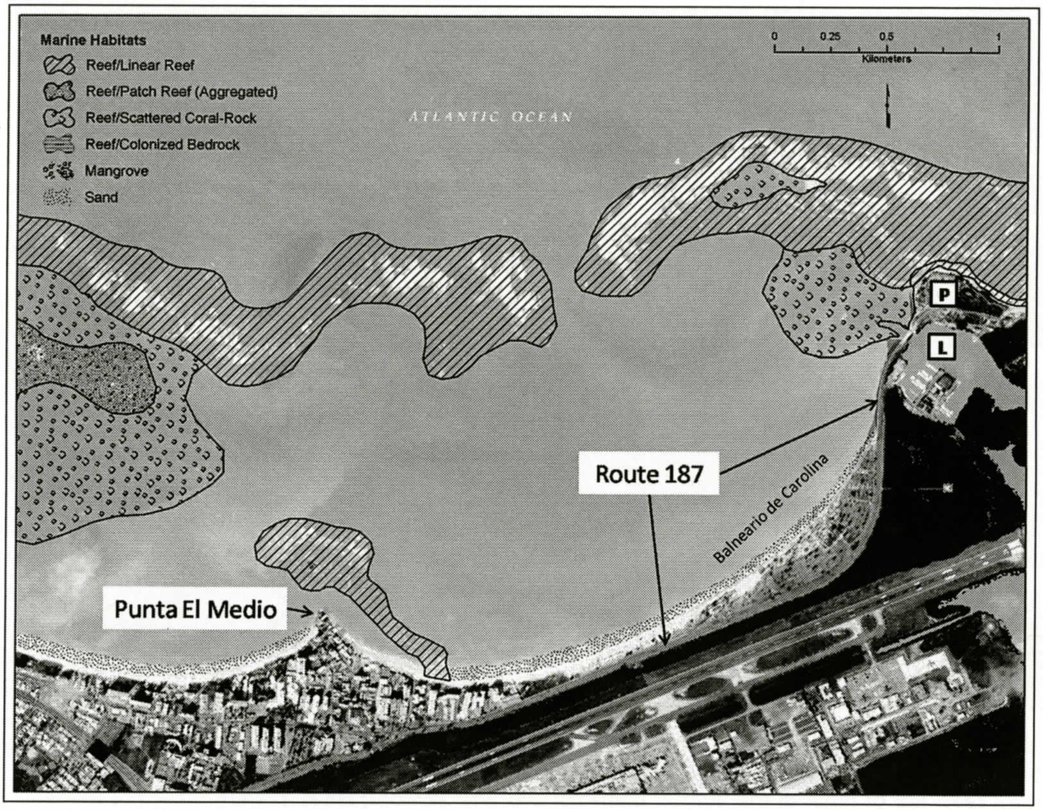

Figure 5. Marine habitats and bathymetry for Compartment V, (modified from NOS Biogeography data). Note that offshore features may be important in defining a compartment; in this case, a protective reef. The coast road, Route 187, is highlighted. The "L" in the right middle part of the photograph denotes Laguna La Torrecilla, with the marina clearly visible. The main part of the lagoon is to the south and east of the "L." The entrance to the lagoon, Boca de Cangrejos, is immediately to the north and west of the "L." Punta Cangrejos is denoted by the letter "P."

Primary Management Concerns/ Recommendations

Using the geologic, oceanographic, engineering, and development data as described above, and considering ecologically sensitive areas, management concerns and recommendations can be made for Coastal Compartment V. The analyses and recommendations below will vary from one study area to another.

Shoreline Erosion and Stabilization Analysis

Approximately 68% of the compartment's shoreline contains useable recreational beach. A majority of the portion of shoreline artificially stabilized in the embayment contains no recreational beach. A coastal risk and geoindicators assessment has identified the bulk of the compartment's shoreline is at a moderate to high risk ranking (Figure 6).

The revetment stabilizing Route 187 produces a slight bulge in the plan view shape of the shoreline and is an important concern due to erosion of downdrift beach fronting and adjacent to the monument shown in Figure 7. Jackson and others (2006) gives a detailed history of engineering of the study area shoreline with particular emphasis on gabions. A gabion had been emplaced since April 1999 to stabilize a 2 m bluff adjacent to the monument. Between August 2002 and May 2003 the collapsing gabion was replaced with a revetment (Figure 7). Unfortunately, a substantial number of small

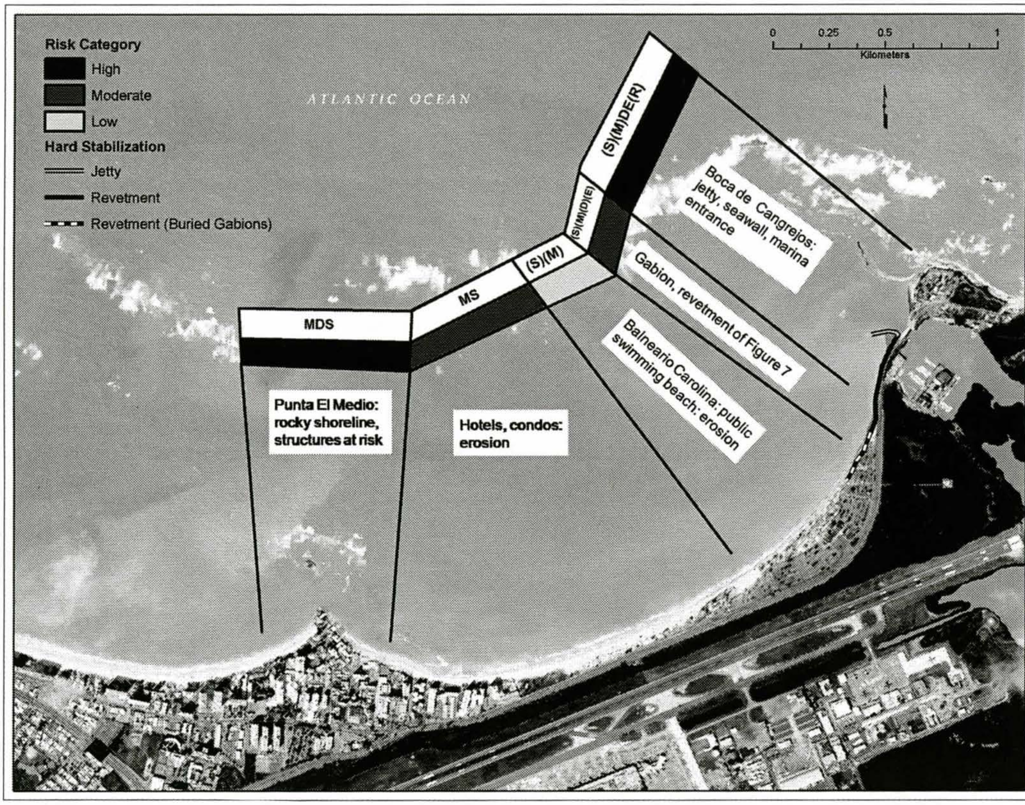

Figure 6. Map depicting coastal risk assessment, geohazards, and hard stabilization in the study area, Balneario de Carolina, Carolina, Puerto Rico. The hazards are shown in the white boxes, and the symbols are the same as Figure 3, plus engineering hazards (E) and riverine hazards (R). The bounding headlands are Punta El Medio to the west and Punta Cangrejos to the east.

cobbles used to fill the gabion mesh were left behind and litter the swash zone. This area undergoes substantial changes due to wave attack and wave refraction on the existing hard structures. These interactions between waves and hard structures lead to the disruption of sediment transport and the sand-sharing system of the beach, and often enhance erosion. It is almost inevitable that beaches immediately downdrift of these structures will erode and ultimately need to be stabilized.

Shoreline Erosion and Stabilization Recommendations

Remove remnants of failed gabions (wire mesh and cobbles) from the surf zone.

Establish a bi-monthly shoreline change monitoring plan for the embayment.

Monitor shoreline change in detail for the recreational beach immediately adjacent to revetment along the eastern portion of the embayment.

Establish a photographic monitoring program along with a database of historical photos.

Abandoned Infrastructure Analysis

A parking lot with some abandoned buildings is located southwest of the monument directly behind the beach. Some of the infrastructure in this area is degrading rapidly and pose a threat to humans. It is noted that some of these buildings contain wires protruding from them as well as areas littered with broken glass, metal, and roofing tiles. Vegetation growing through the parking lot in certain areas conceals these dangers as beachgoers walk to

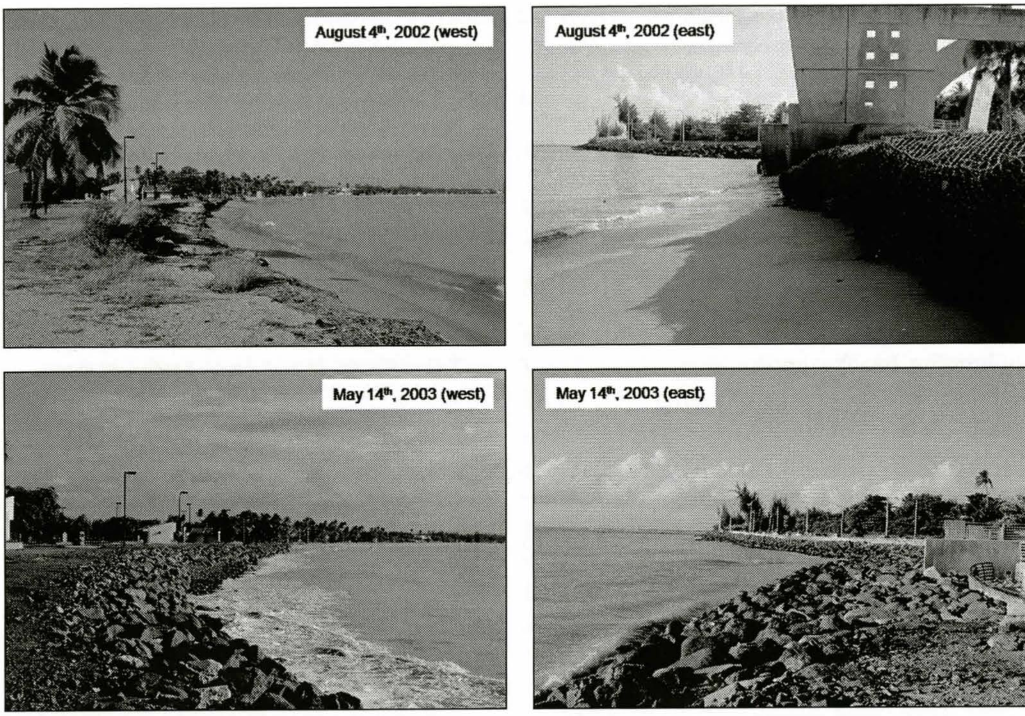

Figure 7. Failed engineering in the far eastern portion of the study area, Balneario de Carolina, Carolina, Puerto Rico. Replacement of failing gabions (2002) with revetment (2003) in front of and adjacent to the monument (east photos). The two left-hand photos are looking to the west from in front of the monument. Note absence of beach in front of revetments. Route 187 and utility poles along it are seen in the background of the two east-looking photographs. The road disappears from view as it crosses the bridge over Boca de Cangrejos.

and from the beach. Also located in this area are remnants of cement columns and a platform from an old boat ramp about 15 m offshore.

Abandoned Infrastructure Recommendations

Remove abandoned infrastructure and unnecessary impervious surfaces (i.e. parking lots).
Remove remnants of old boat ramp from the surf zone.
Relocate or refurbish the monument.
Emplace artificial dunes in largely abandoned areas to add more elevation.
Restore vegetation in barren areas adjacent to the beach.

SUMMARY/CONCLUSIONS

This preliminary proposed Coastal Compartment Management Plan approach has not been tested, however, the basis for defining compartments and evaluating compartments using the geoindicators method has been applied in Antigua, Puerto Rico, St. Thomas, St. Croix, and Roatán. The idea of a CCMP first developed during studies of sediments on the northern insular shelf of Puerto Rico and subsequent coastal-hazard risk vulnerability mapping.

The purpose of this proposed coastal-compartment approach is to foster greater attention to the natural setting as the basis for management plans and decisions. Coastal variability or coastal type is currently taken into consideration, but often in terms of determining a single management tool. The main goal of the CCMP is to aid in simplifying management strategies by dividing up the shoreline into small segments which can be quickly assessed, prioritized, and managed based on available resources. Once compartments are delineated and assessed, they can be prioritized for management plans specific to each compartment. The CCMP philosophy places the onus of management decisions on the community that is going to benefit.

Finally, although beyond the scope of this study, mention should be made concerning impacts of coastal development and engineering on ocean water quality and human health. Given the number of persons who use the public swimming beach, the presence of coral reef habitats, and large area of mangroves, water quality is of great concern. Recommendations from a coastal hazards perspective include removing abandoned infrastructure and unnecessary impervious surfaces (for example, parking lots), actions that will reduce runoff and introduction of toxins into the marine and wetland environments.

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DEPOSITIONAL AND ICHNOFOSSIL CHARACTERISTICS OF THE MEIGS MEMBER, COOSAWHATCHIE FORMATION (MIOCENE), EAST CENTRAL GEORGIA

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ABSTRACT

The coastal plain of Georgia is host to a wide variety of Miocene strata that have been assigned to the Coosawhatchie Formation. The five members of the Coosawhatchie differ greatly in their sedimentological and stratigraphic characteristics, but they are all acknowledged to be of marine, marginal marine, or freshwater origin. The general lack of fossils of any kind has lead to a poor understanding of the origin of much of Coosawhatchie, which is one of the most visible and widespread units on the Georgia coastal plain. We have found abundant, well-preserved burrows of thallasinoid shrimp (ichnogenus *Ophiomorpha*) in the Meigs Member of the Cossawhatchie Fm. where it is exposed near Middleground, Bulloch County, Georgia. Therefore, the sediments are interpreted to have accumulated in near-shore environments of normal salinity.

INTRODUCTION

The Coosawhatchie Formation of coastal Georgia is one of the most widespread and distinctive units in the region. Its characteristic red and yellow sandy clays and siltstones appear in most road cuts, and it is the parent material for the limonitic soils that comprise a vast area of the Georgia farm belt. In spite of those facts, relatively little attention has been paid to the Coosawhatchie Formation by geologists, and it remains true that comparatively little is actually known about this unit. Recent fieldwork has revealed several sites that have provided information relating to the origin of the Coosawhatchie Formation. A roadcut near the community of Middleground, Bulloch County, Georgia, has provided us with data used to construct a geological history for the Coosawhatchie Formation in southeastern Georgia.

GENERAL CHARACTERISTICS OF THE COOSAWHATCHIE FORMATION

The known geographic extent of strata assigned to the Coosawhatchie Formation is illustrated in Figure 1. This map is drawn from the work of Huddlestun (1988), as modified by Slack (2006) and is based on the distribution of strata assignable to the Coosawhatchie as identified in outcrops and core samples. The identity of strata now attributed to the Coosawhatchie Formation has had a complex nomenclatural history. This is recounted in the report prepared by Huddlestun (1988) in his revision of the lithostratigraphic units of the Georgia coastal plain, where he places the Coosawhatchie Formation within the Hawthorn Group. According to Huddlestun, the Coosawhatchie Formation consists predominantly of phosphatic clay, sandy clay, argillaceous sand, and phosphorite, and is divided into five members, as follows: the Tybee Phosphorite Member, the Berryville Clay Member, the Ebenezer Member, the Meigs Member, and the Charlton Member. The spatial and stratigraphic relationships among these members are illustrated in Huddlestun (1988), and he describes the wide variety of lithological characteristics that make the members distinguishable from one another. His lithostratigraphic

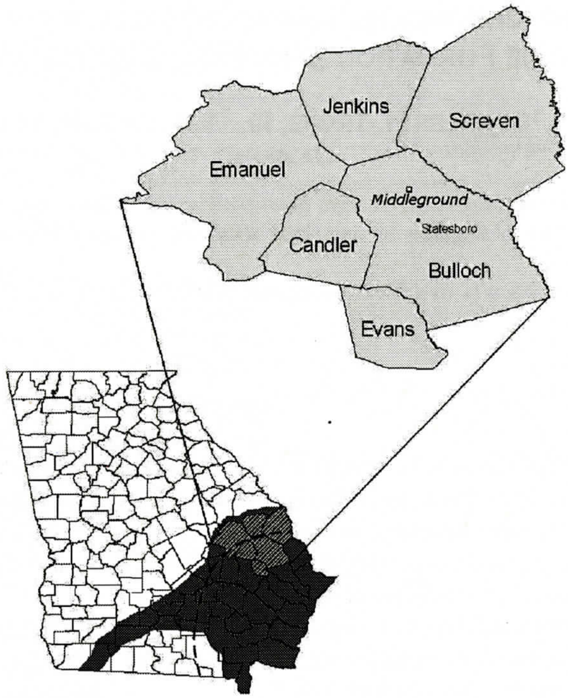

Figure 1. Location of the study site. Shaded area indicates the extent of the Coosawhatchie Fm. in Georgia; dashed line shows the approximate limit of the Southeast Georgia Embayment.

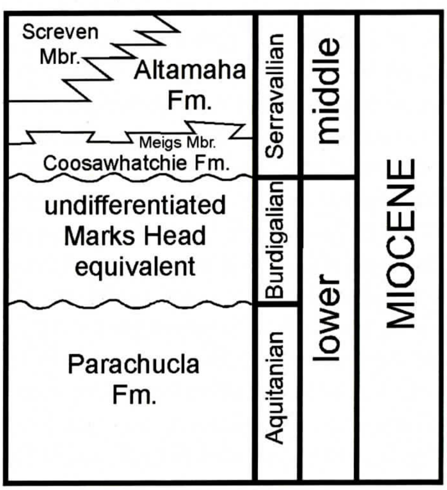

Figure 2. Stratigraphic framework for the Coosawhatchie Formation (from Huddlestun, 1988).

column is reproduced here as Figure 2.

The strata we discuss from Middleground Community are assignable to the Meigs Member. This is based on the mapped occurrences of the various members of the formation, as shown by Huddlestun. It is also based on our observation that the dominant lithologies at Middleground bear no carbonate, and strata are neither phosphatic nor clayey enough to be assignable to the other members of the formation. Huddlestun (1988) observes that the age of the Meigs Member is middle Miocene, an assignment that is based on the microfossil content of the unit. Huddlestun states that the Meigs Member contains a diatom flora that is typical of an East Coast Diatom Zone (ECDZ) 4, or Atlantic Margin Siliceous Microfossil Zone (AMSMZ) IV assemblage. These are equivalent to foraminiferal Zone N10 or lower Zone N11 of Blow (1969), as described by Huddlestun (1988).

According to Huddlestun, "Well-sorted, fine-grained sand is the dominant lithic component of the unit, but clay is prominent and is the characteristic lithic component of the unit". He also observed, however, that burrows and other clear evidence of bioturbation had not yet been observed in exposures of the Meigs Member. That situation notwithstanding, Huddlestun concluded that "The environment of deposition of the Meigs Member was shallow-water, coastal marine...and the salinity of the water in which the Meigs Member...was deposited ranged from normal marine...through brackish to mainly fresh-water."

Our study site lies within the Southeast Georgia Embayment, a structural feature that influenced the sedimentation patterns and stratigraphy of strata ranging from the Miocene through the Holocene (Figure 1). The characteristically thick layers of Miocene units in the embayment suggest that the area has subsided gradually relative to sites further to the west and north (Huddlestun, 1988).

METHODOLOGY

The initial motivation for the current study was to determine the nature of structural deformation in the Coosawhatchie Formation. This was an extension of a study undertaken by Rich (see Bartholomew and others, 2000) that focused on the structural characteristics of Tertiary strata of the Georgia coastal plain. The Savannah, Dublin, and Sylvania 1:100,000 topographic quadrangle maps were used in conjunction with analyses of fracture systems as seen in outcrops/roadcuts. At each outcrop or roadcut, the general lithologies of the exposed strata were recorded, as well as the characteristics of any structures (fracture systems, generally), and any depositional features, including fossils or burrows. It is the latter that constitute the most significant part of the current report.

Structural characteristics

Though a structural analysis of the Coosawhatchie Formation is not the intent of the current discussion, it is significant that the unit is extensively fractured, and the fractures define some of the outcrop characteristics of the exposure at Middleground. Bartholomew and others (2007) present a discussion of this aspect of the Middleground site.

Stratigraphic Analysis

Strata in the vicinity of Middleground include weakly consolidated, fine- to coarse-grained, locally conglomeratic, clayey sandstones, as well as rhythmically-bedded sand and clay couplets. Preliminary analysis of the units appears in Bartholomew and others (2007). Between November 2005 and September 2007 the authors measured and described a series of stratigraphic profiles at the site, recording characteristics of the units at 5 m intervals along a transect that parallels Metz Road, a County road that runs north of Middleground. Initial observations of the Middleground strata revealed the following:

1. Fine sands at Middleground range from moderate orange pink (5YR 8/4) to moderate reddish brown (10R 4/6); they are typically interbedded with clays and contain discontinuous stringers of hematite-rich sediment.
2. Sand grains differ from bright to frosted, suggesting multiple sources and depositional histories.
3. Some of the quartz grains in the matrix are subrounded to subangular, and may be as large as 4-5 mm in diameter.
4. Pebbles are abundant in the roadcut. Despite the weathered, fragile condition of many of the pebbles, the X-Ray diffraction analyses of three clasts with blocky feldspar morphology identified microcline and microcline plus quartz in three of the larger (> 6mm) samples (R.K. Vance, personal communication).
5. Quartz pebbles up to 5 cm in length are scattered throughout sediments in the roadcut, though they tend to lie in distinct layers.
6. The roadcut is dominated by sand-clay couplets, mentioned earlier, but there is also a large body of cross-bedded sandstone that lies sublateral to, and stratigraphically beneath the alternating layers of sand and clay.

The stratigraphic section at all intervals was described in detail, but the section at the 50 m interval of our transect was found to have prominent sediment couplets that are especially instructive, as can be seen in the weathered profile of the outcrop in Figure 3. In this figure, fine sand units (re-entrants) grade upward into clay-rich sediments (positive features) in each

Figure 3. Channel margin IHS deposits at Middleground. Note erosionally resistant layers that are dominated by clay.

couplet. There are four such couplets at the 50 m location, and they are described as follows:

bottom couplet – fine sand 10 cm thick, overlain by 6 cm of clay

second couplet – fine sand 13 cm thick, overlain by 22 cm of clay that contains sand laminae

third couplet – fine sand 11 cm thick, with 14 cm of clay

fourth couplet – fine sand 8 cm thick, complexly interbedded with a unit of clay/sand/silt that is 36 cm thick

The sandstones and their interbedded claystones bear *Ophiomorpha* burrows, and are therefore interpreted to have been deposited at or just below sea level (see below).

Reference to the literature relating to sedimentary sequences such as we describe here (e.g., Thomas and others, 1987) provides substantial evidence that the strata at Middleground probably accumulated in an intertidal environment that was dominated by point-bar lateral accretion deposits within a tidally influenced river or creek.

Thomas and others (1987) provide a detailed analysis of strata that we refer to here as sedimentary couplets, but that are otherwise known as deposits of Inclined Heterolithic Stratification (IHS). Those authors describe the factors that are believed to control the "...formation and preservation of sand-mud couplets in the tidally influenced point-bar depositional environment...", and their descriptions match the Middleground scenario very nicely. Theoretically, the coarse-fine couplet is produced by an influx of sandy sediment on a rising tide, while the finer clay-rich component accumulates on the falling tide. One characteristic of the clay-rich units at Middleground that appears to run counter to the norm is their thickness. Thomas and others (1987) suggest that mud layers greater than 1-2.5 cm thickness do not conform to what one would expect to find during "sluggish flow"; the clay layers are simply too thick to have accumulated during a normal ebb tide cycle. A likely explanation for the thickness of clay-rich units at Middleground is suggested by Thomas and others (1987), and is borne out by our observations of current-day sediment accumulation along the Georgia coast. The flocculation of clay-sized particles and their accumulation as fecal pellets can lead to unusually rapid accumulation of clay layers, particularly where ghost shrimp are abundant. This phenomenon is well-known to sedimentologists who work on the coast of Georgia. Two shrimp species, the Georgia ghost shrimp, *Biffarus biformis* Biffar (formerly *Callianassa biformis*) and the Carolinian ghost shrimp *Callichirus major* Say produce large quantities of pelletized excrement

Figure 4. Channel lag containing large clasts of kaolinite.

that accumulate as muddy units on beaches and on the banks of tidal channels (Bishop and Brannen, 1993). The pellets produce a fine-grained sedimentary mantle that normally lies in contact with beach sands, and that is fine-grained and smooth enough, and oftentimes thick enough to be treacherous to walk on at low tide (Rich, personal observation). The selective concentration of relatively thick layers of very fine-grained, though pelletized sediment is, thus, facilitated by these invertebrates. The presence of ghost shrimp burrows in conjunction with the IHS at Middleground is strongly suggestive that this particular biological influence on sedimentation occurred during the Miocene.

The sedimentary structures that we observed also indicate that fluvial deposition of the sands at Middleground was significant; the most massive sandstone body in the exposure there has typical channel-sand morphology, and contains large angular clasts of kaolinite that occupy what is clearly the bottom of the ancient channel (Figure 4). The identity of the clasts as kaolinite was confirmed through X-ray diffraction analysis of samples, conducted by R.K. Vance. The large size and sub-angular shapes of the clasts indicate a high-energy environment of deposition where the accumulation of sediment was probably rapid though intermittent. Cross bedded sandstones, clays, interbedded clays and sands (the IHS, of probable tidal channel pointbar origin), and other channel-bottom conglomerates all suggest that the units at Middleground accumulated in a nearshore setting where sedimentation within and adjacent to a tidal channel controlled the sedimentary dynamics of the site. In short, strata at Middleground have the appearance of marginal marine channel deposits that is consistent with the general interpretation of the Meigs Member as an accumulation of coastal plain sediments deposited near the Miocene shoreline.

Ichnology

Huddlestun's (1988) remarks concerning the absence of trace fossils from the Meigs Member show that at the time he wrote his bulletin he was not aware of tracks, trails, or burrows that would help to constrain the environments of deposition that were responsible for accumulation of that unit. Indeed, the Coosawhatchie Formation throughout its observed extent in east-central Georgia seems to be barren of body fossils and trace fossils. Thus, the interpretations of environments of deposition have been couched in rather vague, generalized terms.

The roadcut at Middleground has proven unique in that close examination of the strata has revealed an abundance of burrows. Some of them are exceptionally well-preserved and their presence allows us to draw some distinct conclusions concerning the nature of the environ-

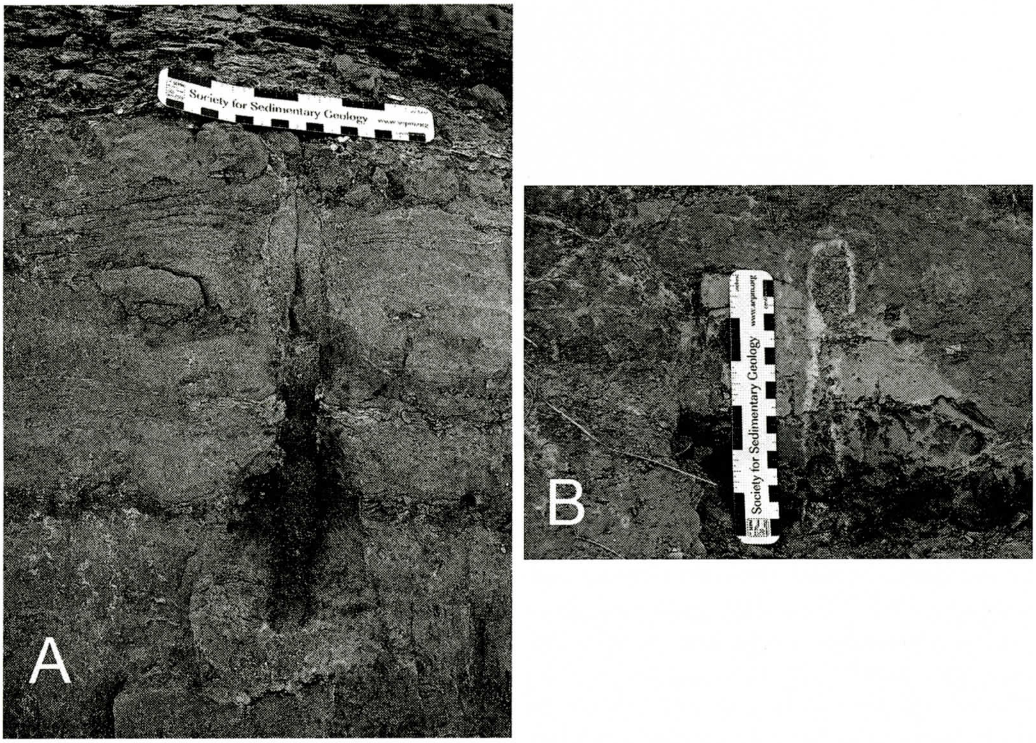

Figure 5A. Ghost shrimp burrow at Middleground. Note scale, the termination of clay layers against the side of the burrow, and the clay pellet lining.
Figure 5B. Ghost shrimp burrow; note light-colored clay lining between the matrix sediments of the Meigs Member and the burrow in-filling.

ment where the sediments accumulated.

One of the most prominent burrows at Middleground is the ichnogenus *Ophiomorpha*, the burrow most often associated with thallasinoid shrimp, i.e., ghost shrimp such as *Callichirus major* and *Biffarius biformis*. As Bromley (1990) has stated, *Ophiomorpha* is celebrated among ichnologists because its construction is so similar to the burrows of the thallasinoids that there is little question in anyone's mind concerning the identity, behavior, or ecology of the burrow maker. *Ophiomorpha* burrows have long been used to identify ancient coastlines and, as Reineck and Singh (1975) pointed out, the burrows have been used elsewhere in Georgia to identify shorelines associated with Pleistocene highstands. Pirkle and others (2007) have illustrated dense concentrations of *Ophiomorpha* as they appear in Pleistocene shoreline deposits along the St. Marys River, on the Georgia Florida state line, and, more recently, Bishop and others (2007) and Chowns and others (2008) have shown how these burrows can be seen to typify modern-day shoreline deposits (i.e., those of the lower foreshore or shallow shoreface). Bishop and Bishop (1992) and Bishop and Brannen (1993) provide considerable detail concerning the nature and distribution of ghost shrimp burrows on Georgia beaches. Bishop and Brannen (1993) note that burrows of the Carolinian ghost shrimp normally consist of a constricted burrow aperture about 5 mm in diameter and 15-20 cm in length. The aperture opens into the main burrow shaft which is nearly vertical, several meters in length, and 1-2 cm in diameter. Where burrows have been constructed in unconsolidated sand, the shrimp lines the burrow with a mucal-mud lining composed of mucus-laden fecal pellets that are packed into the burrow wall. The knobby texture of the wall that results from this array of packed pellets is a distinct characteristic of ghost shrimp burrows, and allows one to identify ancient burrows with some confidence.

While demonstrating convincingly that the shrimp and their burrows are typical of "...sand of beaches and sand flats....fronting on the open ocean or sounds", Bishop and Brannen (1993) urge caution when using *Ophiomorpha* as an indicator of shoreline environments. One species of ghost shrimp, *Callianassa subterranea* Montagu, lives in the center of the North Sea basin, and its numbers decrease shoreward. While we acknowledge the fact that different species of thallassinoids (and, subsequently, their burrows) might well represent a wide variety of water depths, the nature of sediments at Middleground clearly indicates a near-shore setting, as opposed to more open marine conditions. Figure 5A illustrates a cross-section of one of the best-preserved examples of *Ophiomorpha* at Middleground. The burrow is approximately 48 cm deep and 5 cm wide, and possesses a distinctive clay-pellet lining that is about 5 mm thick on each side of the burrow. The bottom half of the burrow in the figure is filled with sediment, while the top half reveals a weathered sediment in-filling that also bears a fracture. Strata surrounding the burrow consisted of moderate red (5 R 5/4) to light brown (5YR 5/6) sandy clays, while the burrow lining was composed of pale red purple (5RP 6/2) clay pellets; the color contrast was quite striking and made the burrow very prominent. Figure 5B illustrates a second ghost shrimp burrow that was nearly 35 cm deep and 6 cm wide, with a 5 mm-thick clay lining composed of white pellets. We consider these ghost shrimp burrows to be excellent indicators of normal coastal marine depositional conditions.

CONCLUSIONS

The Meigs Member of the Coosawhatchie Formation is known to be of middle Miocene age, as determined by diatom and foraminiferal fossil assemblages. Furthermore, the Meigs and, indeed, most of the rest of the Coosawhatchie Formation are known to have accumulated in a variety of coastal environments on the Georgia coastal plain. Lithostratigraphic analyses have been rather vague, however, in that sediment types could only be generalized as "coastal" or "near-shore", with there being very little control over what part of the shore the sediments might have accumulated on. The general lack of fossils of any kind has proven to be an obstacle to our understanding these abundant and wide-spread strata, until now. The presence of *Ophiomorpha* at Middleground Community, Bulloch County, Georgia, has greatly improved our understanding of the environment of deposition of the Meigs Member in that area.

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LOCALIZED STRUCTURALLY-DERIVED TENSILE STRESS DEVELOPMENT OF POLYGONAL CRACKED SURFACES ON POTTSVILLE SANDSTONES (LOWER PENNSYLVANIAN) ALONG THE PERIMETER OF THE CHANDLER MOUNTAIN AND LOOKOUT MOUNTAIN PLATEAUS, NORTHEASTERN ALABAMA AND NORTHWESTERN GEORGIA

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ABSTRACT

Well-indurated Pottsville sandstones (lower Pennsylvanian) cap the Chandler Mountain and Lookout Mountain plateaus. These massive orthoquartzites have experienced varying levels of tensile and compressional stress and strain associated with folding and warping during and following the Alleghanian Orogeny. This has resulted in the development of fractures, joints, and polygonal cracks in some of the exposed Pottsville sandstones. While these structural features are interrelated, they are not viewed as gradational. We interpret the polygonal cracks as the smallest of the three macroscale structural features. The best developed polygonal cracks occur on weathered sandstone surfaces along the perimeters of both plateaus in areas where localized structural tensile stress has developed within the sandstone layers.

INTRODUCTION

Chandler Mountain and Lookout Mountain are two synclinal plateaus in the Appalachian Plateaus Province. Together they extend from northeastern Alabama to northwestern Georgia. These plateaus are capped by massive, well-indurated Pottsville sandstones (lower Pennsylvanian) that have experienced varying levels of tectonic stress and strain in association with folding and warping during and following the Alleghanian Orogeny. As a result, the sandstone layers contain fractures, joints, and polygonal cracks especially along portions of the perimeter of the plateaus. Our investigation focused on the identification and development of the polygonal cracked surfaces across the Pottsville sandstone surfaces from several different locales (Figure 1).

AREA OF STUDY

Field work was restricted to those areas across the Chandler Mountain and Lookout Mountain plateaus that are accessible to the public (Table 1). Despite this limitation, we were able to document the recurring polygonal cracked surfaces across many of the Pottsville sandstones. The individual sandstone layers within the study area are massive, orthoquartzitic, and in places they contain lenses of quartz pebble conglomerate indicative of channel lag deposits. The best exposures of the polygonal cracks that we identified were developed along the perimeter of the plateaus within a kilometer from the edge. We also noted polygonal cracked surfaces within the interior of the Lookout Mountain plateau, near the edge of Little River Canyon. None of the polygonal cracks that we observed across the study area were developed along bedding planes. Rather, this unique surface seems to have formed independently of sedimentary contacts, changes in siliciclastic

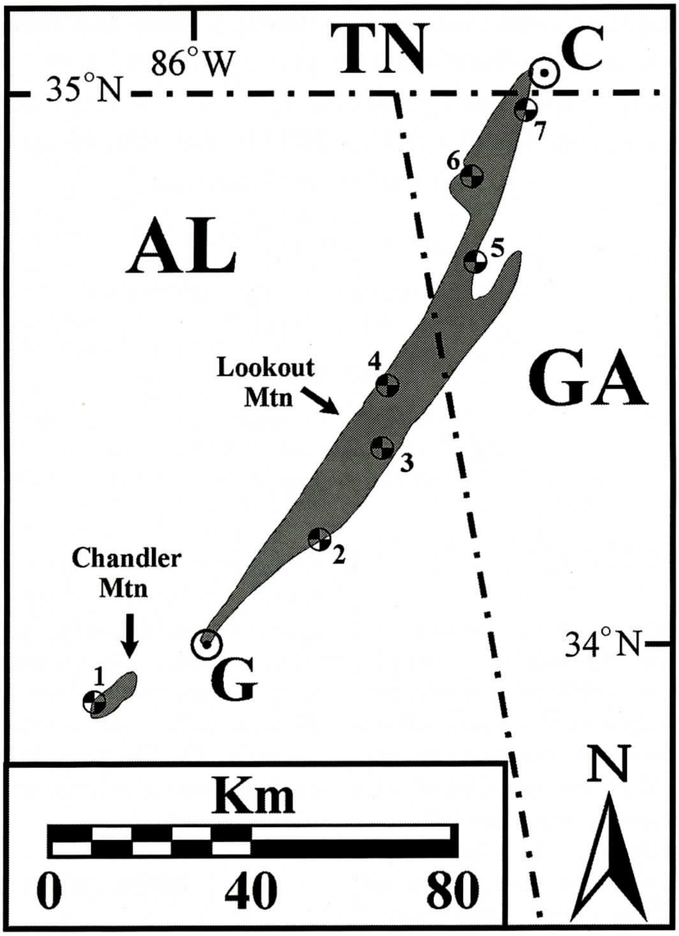

Figure 1. The Chandler Mountain and Lookout Mountain plateaus occur across northeastern Alabama and northwestern Georgia. The numbers correspond to the locations listed in Table 1. The letter G refers to the city of Gadsden, Alabama, and C refers to the city of Chattanooga, Tennessee. Layers of massive, well-indurated, orthoquartzitic Pottsville sandstones cap both of these synclinal plateaus.

Table 1. The approximate location and global positioning system coordinates for the polygonal cracked surfaces examined in this study. Abbreviations: Chandler Mountain - CM, Lookout Mountain - LM

Map Key	Location	Latitude	Longitude
1-CM	Horse Pens 40	N33° 55.256	W86° 18.516
2-LM	Cherokee Rock Village	N34° 10.838	W85° 48.934
3-LM	Little River Canyon Area	N34° 22.457	W85° 37.891
4-LM	Citadel Rocks	N34° 28.495	W85° 40.218
5-LM	Zahnd Natural Area	N34° 38.834	W85° 28.147
6-LM	Cloudland Canyon	N34° 50.118	W85° 28.954
7-LM	Rock City	N34° 58.373	W85° 20.944

particle size, or sedimentary structures.

FRACTURES, JOINTS, AND POLYGONAL CRACKS

Tectonic forces associated with the Alleghanian Orogeny have resulted in the formation of structural features such as fractures, joints, and polygonal cracks in the many Pottsville sandstone layers. We believe these structural features reflect different scales of stress and strain encountered by the Pottsville sandstones. The polygonal cracks appear to be reflective of smaller-scale stress and strain forces and are therefore more localized. This would explain why we do not observe these features everywhere the Pottsville sandstones are exposed. We view joints and polygonal cracks as interrelated but not gradational structural features. Joints are defined as:

> A planar fracture, crack, or parting in a rock, without shear displacement; the surface is usually decorated with a plumose structure. Often occurs with parallel joints to form part of a joint set (Neuendorf and others, 2005, p. 345).

Joints have deep rock penetration:

> They [joints] are a widespread plane of potential slip… [Brackets ours] (Suppe, 1985, p. 169).
>
> Tectonic joints are nearly vertical and cut through the entire rock mass (Chan and others, 2008).

Polygonal cracks are defined as:

> A network of shallow penetrating cracks perpendicular to the rock surface that outline pentagonal, hexagonal or rectilinear polygons. With extensive weathering the rock surface displays the appearance of a tortoise shell. They can develop on the surfaces of granites and massive sandstones (Williams and Robinson, 1989).

Polygonal cracks have very shallow rock penetration. Williams and Robinson (1989) placed maximum depth of crack penetration at 30 mm with most extending no more than 10 mm. Chan and others (2008) set perpendicular crack penetration as deep as 30 cm.

POLYGONAL CRACKED SURFACES

Polygonal surfaces of varying sizes can be derived from many different geological processes. These features have been described from the poles to the equatorial lowlands (Williams and Robinson, 1989). Polygonal cracked surfaces that formed on granites and massive, well-indurated sandstones have been described as polygonal cracks, polygonal weathering, cauliflower-like weathering, tortoise-shell weathering, elephant-skin weathering, schildkrotenmuster, crocodilages, polygonations, pseudosquames polygonales, tessellated pavements, and pachydermal weathering (Chan and others, 2007; Thomas and others, 2005; Williams and Robinson, 1989). These features are not considered primary sedimentary structures as they typically cut across strata, rather than form within a given bed (Chan and others, 2008).

The origin of the polygonal cracking on the sandstone surfaces is uncertain. It is thought to develop from a variety of geologic processes including:

1) Sandstone contraction by desiccation of montmorillonite clays (Netoff, 1971).
2) Evaporite cemented sandstones provided the cohesion and thermal contraction that caused the tensional stress necessary for polygonal fracturing (Kocurek and Hunter, 1986).
3) Diagenesis, tectonism, unloading, insolation weathering, clay shrinkage, moisture movement, frost weathering, lichen weathering, surface precipitation of iron and manganese oxides, and **surface crusting** (Williams and Robinson, 1989; their choice in bold).
4) Shrinkage of silica gel during the formation of the surface crust (Robinson and Williams, 1989, 1992).
5) Possible thermal contraction in response to uplift (Rawnsley and others, 1998).
6) Possible wet/dry, heating/cooling cycles (Robinson and Williams, 2005).
7) Thermal contraction/expansion, salt weathering, desiccation, surface moisture cycles, and dirt cracking (Chan and others, 2008).

Netoff (1971) noted polygonal crack development in the Upper Cretaceous Laramie and

Figure 2. Extensive weathering along the cracks in the sandstone has developed an excellent example of a polygonal cracked surface. This outcrop is located on the southwestern side of Chandler Mountain at Horse Pens 40 (Figure 1 - Location 1). Scale in 15-cm divisions.

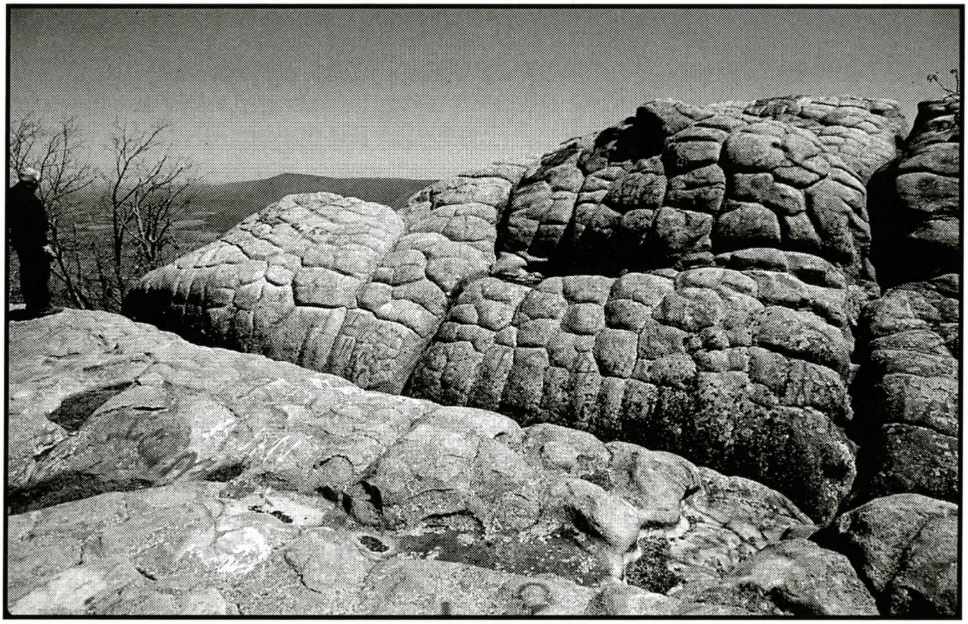

Figure 3. Extensive weathering of the sandstone surface has enhanced the development of this polygonal cracked surface. This unique surface is not a function of bedding despite the horizontal appearance of the cracks. The more distant sandstone block has separated from the foreground sandstone along a fracture. This outcrop is located on the eastern side of Lookout Mountain in the Zahnd Natural Area (Figure 1 - Location 5). The gentleman is approximately 1.78 m in height.

Fox Hills Sandstones where they contain montmorillonite clays. Polygonal fracturing by the thermal contraction of former groundwater-derived evaporative cements was the process invoked by Kocurek and Hunter (1986) to explain polygonal crack development in the Jurassic Navajo Sandstone and along four surfaces on the Jurassic Page Sandstone. Williams and Robinson (1989) proposed that polygonal cracking is initiated by tensile rock stress created by the process of surface crusting (i.e., case-hardening). Russian investigators have also linked tensile rock stress and polygonal cracks (Revuzhenko and Klishin, 1999, 2002). More recently, polygonal crack development has been interpreted to occur in massive horizontally isotropic sandstones due to effective rock tension created by thermal contraction, moisture changes, partial dehydration of some minerals and the precipitation or dissolution of salts (Chan and others, 2008; Rawnsley and others, 1998).

The Pottsville sandstones do not contain any silt or clay and are not cemented by evaporites. However, some of the processes listed above could be used to explain polygonal crack development within the study area. Problems occur if case-hardening and/or weathering-derived tensile stress were the primary cause of crack development as we would expect a greater abundance of polygonal cracked surfaces across the exposed Pottsville sandstones than is presently found.

REGIONAL OR LOCAL CAUSE FOR POLYGONAL CRACK DEVELOPMENT

We investigated a possible link between polygonal crack development and regional tectonism. This correlation might be supported where polygonal cracks would associate or align with fractures and joints developed from regional stress fields. Direct correlation between fractures and joints has been demonstrated on the adjacent Appalachian Plateau in Virginia, New York, and Pennsylvania (e.g., Nickelsen and Hough, 1967; Engelder and Geiser 1980; Engelder, 1982, 1985, 2004; Hancock and Engelder, 1989). We also reviewed regional fracture/joint sets reported for several areas in the western United States in an attempt to define a link among fractures, joints, and polygonal cracking (e.g., Kelley and Clinton, 1960; Dyer, 1983; Zhao and Johnson, 1992; Gross, 1993; Cruikshank and Aydin 1995; Condon, 2003; Rogers and Engelder, 2004). No direct structural link could be identified among the regional fractures, joints, and polygonal cracks.

Aerial and satellite images of the two synclinal plateaus were examined in an effort to delineate a possible link among fractures, joints, and polygonal cracks that might extend across the Pottsville sandstone surfaces. Again, we were unable to establish any direct structural link. However, all three of these structural features are present at each of the locations that we investigated along the plateaus. Our examination of the polygonal cracked surfaces then shifted to the local outcrop in an effort to understand the stress fields that possibly created them (Figures 2 and 3). We measured several surface transects by projecting the more prominent cracks from the edge of the sandstone toward the plateaus' synclinal axes. The polygonal crack traces essentially ceased a short distance (often measured in just a few meters) from the edge of the massive sandstone (Figure 4). This was demonstrated repeatedly and suggests that the stress fields that developed the polygonal cracked surfaces are likely localized. In several areas we noted radial polygonal cracked surfaces across the exposed top and along the sides of some of the massive sandstone layers (Figures 5 and 9).

Across the area of investigation, the polygonal cracks do not appear to be oriented in any specific pattern; rather, in many instances they are unevenly spaced and follow a nonlinear trace (Figure 6). This was also noted along some of the sandstone sidewalls (Figure 7). We observed case-hardened "tortoise-shell" polygons where extensive weathering of the sandstone surface had occurred irrespective of the location (i.e., top or side) of that surface (Figure 8).

Figure 4. The polygonal cracked surface fades moving from the edge of the sandstone layer toward the plateau interior (foreground). This outcrop is located on the eastern side of Lookout Mountain in the Zahnd Natural Area (Figure 1 - Location 5). Scale in 15-cm divisions.

Figure 5. The polygonal cracked surface extends to the sides of this massive sandstone layer. This unique surface is not a function of bedding despite the horizontal appearance of the cracks. This outcrop is located on the western side of Chandler Mountain at Horse Pens 40 (Figure 1 - Location 1). Scale in 15-cm divisions.

Figure 6. The weathering of this sandstone has enhanced the polygonal cracked surface. This outcrop is located on the eastern side of Lookout Mountain in the Zahnd Natural Area (Figure 1 - Location 5). Scale in inches and centimeters.

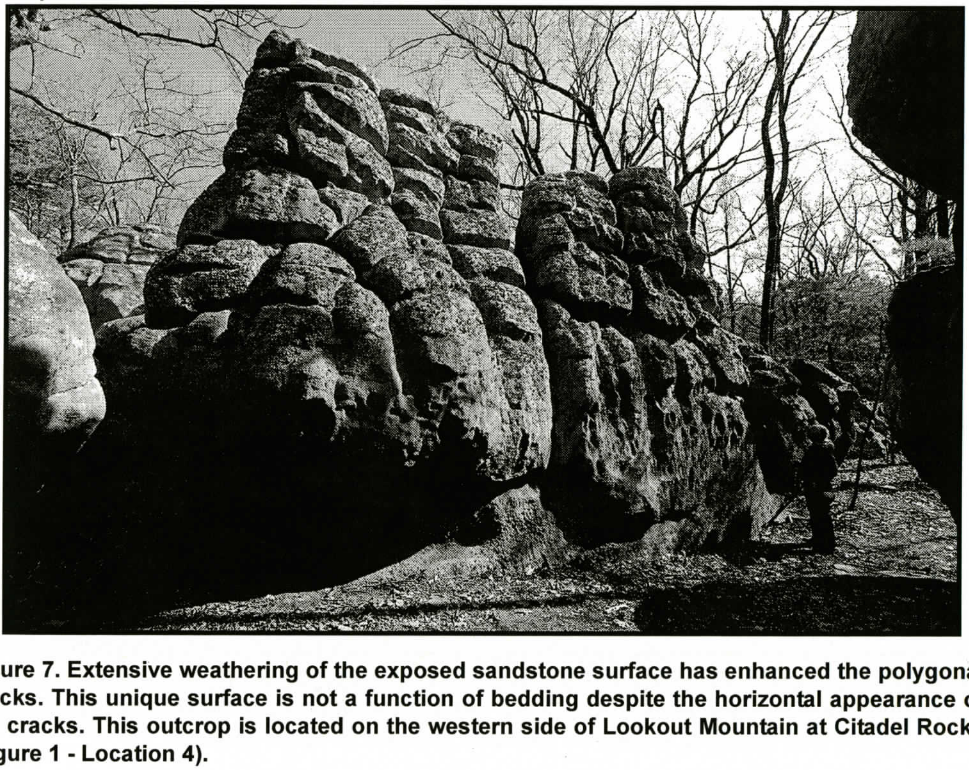

Figure 7. Extensive weathering of the exposed sandstone surface has enhanced the polygonal cracks. This unique surface is not a function of bedding despite the horizontal appearance of the cracks. This outcrop is located on the western side of Lookout Mountain at Citadel Rocks (Figure 1 - Location 4).

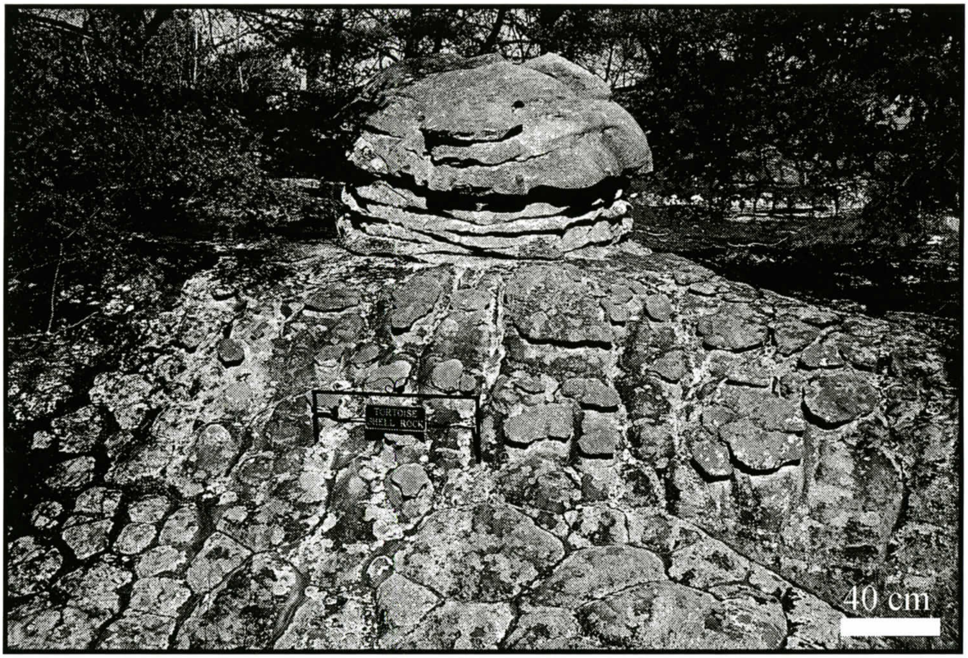

Figure 8. A sloped and highly weathered polygonal cracked surface exhibits areas of elevated case-hardened sandstone. A pulpit rock is on the top of the sandstone outcrop (see Froede and Akridge, 2003). This locale is on the eastern side of Lookout Mountain at Rock City, Georgia (Figure 1 - Location 7).

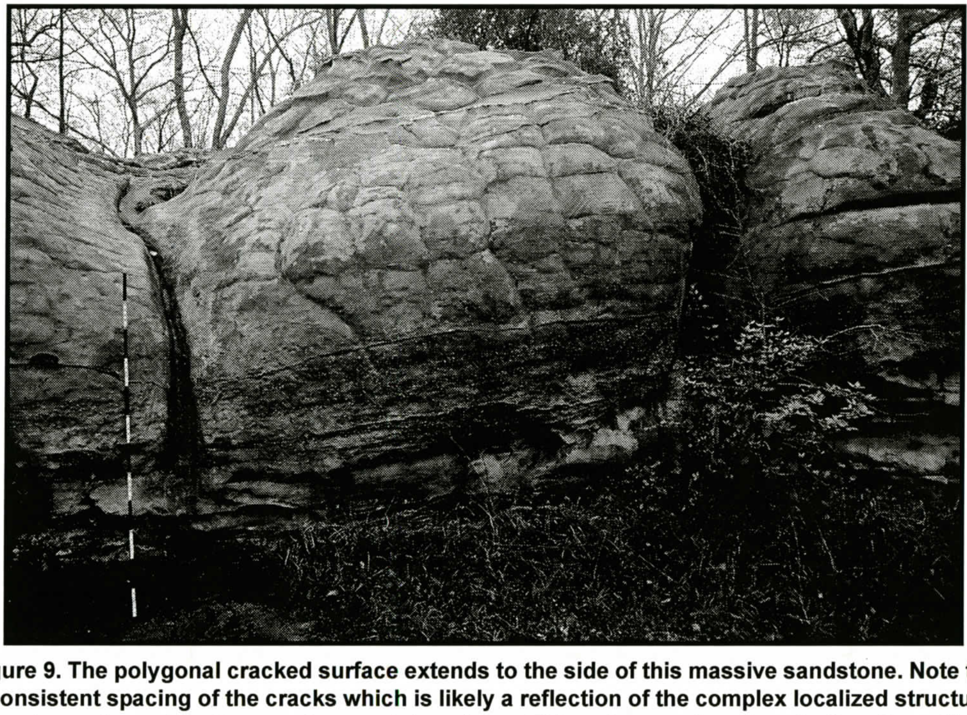

Figure 9. The polygonal cracked surface extends to the side of this massive sandstone. Note the inconsistent spacing of the cracks which is likely a reflection of the complex localized structural stress experienced by the massive sandstone layer. This unique surface is not a function of bedding despite the horizontal appearance of the cracks. This outcrop is located near Little River Canyon on Lookout Mountain (Figure 1 - Location 3). Scale in 15-cm divisions.

CONCLUSIONS

Extensive polygonal cracked surfaces have developed across massive, well-indurated Pottsville sandstone layers along portions of the perimeter of the Chandler Mountain and Lookout Mountain plateaus. Williams and Robinson (1989) proposed case-hardening to explain polygonal crack development. However, Chan and others (2008) noted that case-hardening is not ubiquitous and this process is not required to explain all weathered cracks. They counter proposed that polygonal cracks have developed due to tensile weathering stresses. While both of these processes could possibly account for the polygonal cracked surfaces we observed across the Pottsville sandstones, they cannot explain why these features are not much more widespread across both plateaus. Why would case-hardening and tensile weathering stresses generally be limited to the sandstone surfaces exposed along the plateau perimeters? The polygonal cracks exposed across certain portions of the Pottsville sandstone surfaces are of limited horizontal and vertical dimension. They do not appear to be part of a larger more organized fracture/joint system. This is consistent with the work of Williams and Robinson (1989) and Rawnsley and others (1998) who noted the limited extent of the polygonal cracks in their investigations. Additionally, it has been noted that new polygonal cracks develop beneath eroding, existing cracks (Williams and Robinson, 1989) [Figure 8]. This suggests that the polygonal crack forming process may be related to internal stresses within the Pottsville sandstone layers.

The best developed polygonal cracks occur on the highly weathered sandstone surfaces within one kilometer of the plateau perimeters where localized structural tensile stress has developed within the sandstone layers. On a local scale, some of the weathered polygonal surfaces exhibit rather uniform, case-hardened, tortoise-shell shapes whether exposed on the top or sides of the massive sandstone layers. While weathering processes are important in accentuating the cracks on the sandstone surfaces, they are not the source of the features. Likewise, polygonal cracking is not directed or controlled by bedding since it cuts across strata, rather than forming within a given bed. Therefore, we propose that the polygonal cracks in the Pottsville sandstones found along the perimeters of the Chandler Mountain and Lookout Mountain plateaus are linked to locally-developed internal structural stress and strain associated with warping and folding created during and following the Alleghanian Orogeny.

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NEW CALCEOCRINID CRINOIDS FROM THE EARLY SILURIAN BRASSFIELD FORMATION OF SOUTHERN OHIO AND NORTHERN KENTUCKY

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ABSTRACT

Two new calceocrinids are described from the Brassfield Formation of southern Ohio and northern Kentucky. One is a new species of *Trypherocrinus*, the second known species of this genus, which confirms the unusual arm branching pattern that characterizes this genus. The other may be a new genus, but the only known specimen is too incomplete to justify the description of a new taxon. Thus, it is left in open nomenclature as calceocrinid indeterminate.

INTRODUCTION

The Calceocrinidae is the longest ranging crinoid family (Webster 2003), known from the Ordovician through Early Permian. In many instances long-ranging taxonomic groups result from a convergent, simplified morphology that is assumed, incorrectly to represent the same family. However, calceocrinid morphology is highly derived and certainly represents a single lineage of crinoids. Common during the Ordovician, calceocrinids underwent a marked radiation during the Silurian (Ausich, 1986) that further diversified this unique family. One genus in this Early Silurian radiation was *Trypherocrinus* Ausich, 1984 whose arms displayed a reversal from the highly specialized bilateral heterotomous arm branching to nearly isotomous arm branching that is typical for many primitive crinoids. A legitimate question is whether the unusual arm branching in the type species, *T. brassfieldensis* Ausich, 1984, is an aberrant character from a small population in Greene County, Ohio and not worthy of generic distinction. However, a second, new species of *Trypherocrinus*, *T. adamsensis*, from Adams County, Ohio, is described herein. This species is also from the Brassfield Limestone, but is from much farther south than the type species of the *Trypherocrinus* from the greater Dayton, Ohio area. This new crinoid further demonstrates the justification for this calceocrinid genus.

Also, another calceocrinid is described from Bath County, Kentucky. This crinoid is known only from a very well preserved aboral cup; but unfortunately, no arms are preserved. The fused basal circlet is unique among Silurian calceocrinids, as known. Although unique, sufficient morphology of this crinoid is not known to justify designation of a new genus. However, noting this crinoid is important to further establish the morphological diversification during the Early Silurian calceocrinid radiation.

SYSTEMATIC PALEONTOLOGY

Terminology follows Moore (1962) and Ubaghs (1978), and classification follows Ausich (1998). Repository abbreviations are as

Figure 1. *Trypherocrinus adamsensis*, holotype, OSU 50496, lateral view of crown displaying A-ray and part of E-ray arms, scale bar is 1 cm.

follows: OSU, Orton Geological Museum, Ohio State University and CMCIP, Cincinnati Museum Center, Cincinnati, Ohio. All measurements are in mm; * indicates that character is incomplete or compressed.

CLASS CRINOIDEA, MILLER 1821
Subclass Disparida Moore and Laudon, 1943
Order Calceocrinida Ausich, 1998
Family Calceocrinidae Meek and Worthen, 1869
Trypherocrinus adamsensis n. sp.

Material: The holotype and only specimen of *Trypherocrinus adamsensis* is OSU 50496.

Diagnosis: Four plates above anal X, E arm branches three times, lateral arm axillaries approximately the same size as other brachials, all lateral arm brachitaxes with three non-axillary brachials.

Description: Crown small, slender, and pendant on column. Aboral cup relatively small, laterally compressed, and slender. Basal circlet broken, so overall shape unknown and other characters difficult to confirm. Apparently three basal plates, with one triangular plate from fusion of EA and DE basal plates; this plate articulates with radial circlet. Column equally supported by the AB and CD basals. Radial circlet laterally compressed, rectangular from aboral view. A and D radials majority of radial plate circlet. E inferradial and E superradial narrow toward the center of radial circlet with narrow sutural contact. E superradial 100 percent of aboral cup distal margin, supports E-ray arm. A lateral arm from upper lateral facet of A radial; two lower lateral facets support B inferradial and B superradial.

Anal X pentagonal supported beneath on one side by B superradial and, presumably the C superradial on other side; four known anal plates above anal X; at least three proximal anal plates rectangular. Anal sac interpreted as very short, not projecting above the E-ray first primibrachitaxis.

Three arms. E-ray arm slender and branched, brachials variable height. Fourth primibrachial, third secundibrachial, and fourth tertibrachial axillary. E-ray brachial height:width ratio from 1.5 to 1.

Lateral arms with weakly developed main axil series and arm branching pattern different from normal calceocrinid heterotomy. Three axillaries in main axil, one non-axillary brachial

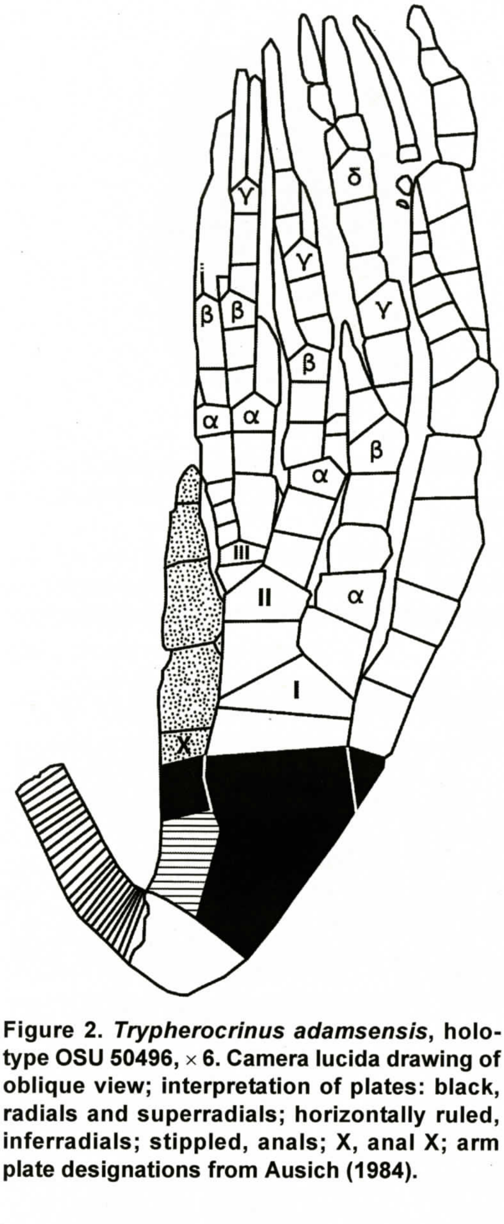

Figure 2. *Trypherocrinus adamsensis*, holotype OSU 50496, × 6. Camera lucida drawing of oblique view; interpretation of plates: black, radials and superradials; horizontally ruled, inferradials; stippled, anals; X, anal X; arm plate designations from Ausich (1984).

between each axillary. Bifurcations of lateral arms isotomous or nearly isotomous but described traditionally as in Moore (1962) and Ausich (1984). Axil arm axillaries approximately the same size as other brachials.

Alpha ramule on the primaxil arm bifurcates on the second alphabrachial and supports the betabrachitaxis adanally; the abanal alpha ramule is completely covered by other arms. Third betabrachial axillary with a gammabrachitaxis abanally and beta ramule, which is mostly buried, adanally. Third gammabrachial axillary with only the adanal deltabrachitaxis visible. Third deltabrachial axillary, which is the final bifurcation; unbranched epsilonbrachials above.

On the secundaxil arm third alphabrachial axillary, supports the betabrachitaxis adanally and abanally branch mostly covered. Third betabrachial axillary; third gammabrachial axillary; and no further branching preserved on this arm.

Tertaxil arm bifurcates on third alphabrachial with betabrachitaxis adanally and the alpha ramule abanally. Distally, the abanal branch is mostly covered. Third betabrachial axillary and supports the gammabrachitaxis abanally and the beta ramule adanally. The adanal beta ramule is mostly covered. Gamma ramule bifurcates on the third gammabrachial; no further branching known, but gammabrachials severely weathered.

Omega ramule branched (axil arm terminology applied). Alpha ramule bifurcates on fifth alphabrachial and supports the betabrachitaxis adanally. At least one more bifurcation but poorly preserved.

Proximal-most columnals very thin; distally columnal height increases. Mesistele and dististele unknown.

Remarks: *Trypherocrinus adamsensis* has four plates above anal X, an E arm that branches three times, lateral arm axillaries are approximately the same size as other brachials, and lateral arm brachitaxes commonly with two non-axillary brachials. This contrasts with *T. brassfieldensis* that has one plate above anal X, an E arm that branches twice, lateral arm axillaries are commonly larger than other brachials, and all lateral arm brachitaxes with more than two non-axillary brachials. *T. adamsensis* is the second species of this unusual calceocrinid and demonstrates that the arm branching that characterizes this genus (isotomy or near isotomy, as opposed to heterotomy in other calceocrinids) is a reliable character even though it is not typical of calceocrinids in general. Species distinctions, such as fewer number of non-axillary brachials in *T. adamsensis,* could represent ju-

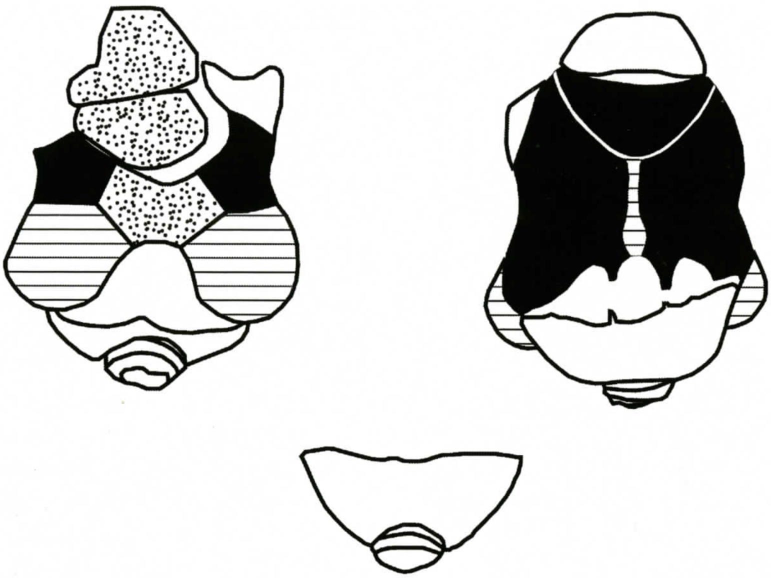

Figure 3. Calceocrinid indeterminate, CMCIP 51205, × 7.2. Camera lucida drawing; A, abanal view of aboral cup; B, adaxial view of aboral cup; C, adaxial view of basal circlet. Interpretation of plates same as Figure 2.

venile characteristics. However, available specimens of both species are approximately the same size, and more anal plates and increased arm branching of *T. adamsensis* cannot be regarded as juvenile characteristics.

Occurrence: Specimen from roadcut on the southern side of Ohio State Highway 32, 0.9 km west of the intersection of Highway 32 with Unity Road, approximately 4.7 km east of Seaman. The location of this roadcut is 38°55′35″N lat., 83°31′05″W long., Oliver Township, Adams County, Seaman, Ohio, 7.5-min quadrangle. This specimen is from the Brassfield Formation (Aeronian, Llandovery, Silurian), from the top of the section illustrated by Ausich and Dravage (1988, fig. 1).

Measurements: Holotype (OSU 50496), crown height, 24.0; basal circlet height, 1.4; radial circlet height, 5.0*, radial circlet width, 3.8*; and column height, 17.6*.

Etymology: The species is named for Adams County, Ohio, where the specimen was collected.

Calceocrinid indeterminate

Material: Calceocrinid indeterminate is known from one specimen, CMCIP 51205.

Description: The aboral cup is small, abanally-adanally compressed, and pendant on the column.

The basal circlet is more than twice as wide as high, subtriangular in shape. All basal plates fused into a single plate; basal circlet widest at distal margin. Subelliptical pit along entire basal circlet:radial circlet articulation, subdivided into three smaller pits by extensions from each circlet that articulate in the center of the subelliptical pit.

The radial circlet is abanally-adanally compressed and subrectangular in aboral view. A and D radials comprise the majority of the radial plate circlet. E inferradial and E superradial in narrow contact; E superradial subtriangular. E inferradial-basal circlet articulation approximately 5 percent of proximal radial circlet articulation. E superradial occupies entire distal margin of aboral cup and supports E-ray arm. Upper lateral facet of A radial supports A lateral arm; two lower lateral facets support B superradial and B inferradial. Upper lateral facet of the D radial supports D arm, lower two lateral facets support C superradial and inferradial. B inferradial very convex, larger than B superradial. C inferradial larger than C superradial.

Anal X pseudo-hexagonal, supported on one

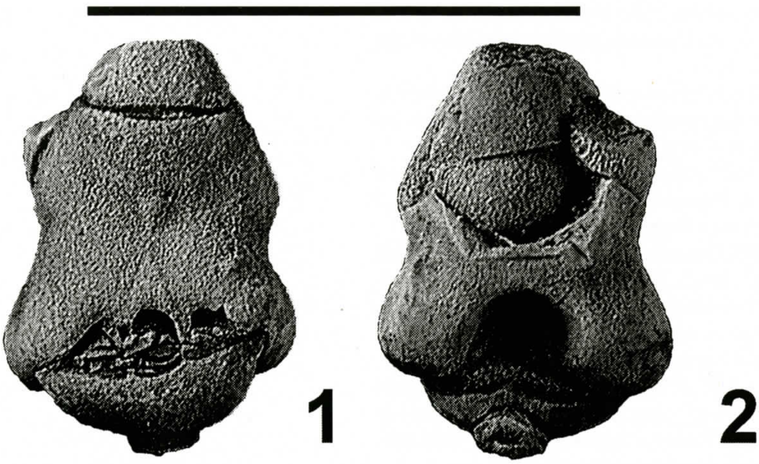

Figure 4. Calceocrinid indeterminate, CMCIP 51205, scale bar is 1 cm. A, abanal view of aboral cup; B, adaxial view of aboral cup.

side by both the B superradial and the B inferradial and on other side by both the C superradial and the C inferradial. Two additional anal plates preserved above anal X.

The proximal-most columnals are thin and circular. Three proximal columnals are present.

Remarks: This is a very unusual calceocrinid; and although it may represent a new genus, generic assignment is not possible because the specimen is incompletely known. The aboral cup preservation is outstanding, but the arms are absent. It is impossible to discern sutures on the basal circlet, and the basal plates appear to be fused into a single plate. If true, this is unique among at least Silurian calceocrinids. It is also possible that the condition of the basal circlet should be regarded as a species-level character, but other preserved characters are not definitive for any particular genus. For example, *Calceocrinus*, *Charactocrinus*, *Diaphoracrinus*, *Grypocrinus*, and *Synchirocrinus* all have the aboral cup aborally compressed and the E inferradial and E supraradial in narrow sutural contact. Consequently, for the present time, we leave this crinoid in open nomenclature and refer to it as calceocrinid indeterminate.

Occurrence: This specimen is from a roadcut on I-64 near mile marker 121, Bath County, Kentucky (38°08′5″N lat., 83°42′56″W long.). It was collected from 3 m above the base of the Brassfield Formation (Aeronian, Llandovery, Silurian).

Measurements: CMCIP 51205, basal circlet height, 1.5; basal circlet width, 5.3; radial circlet height, 5.7; radial circlet width, 6.4; and column length, 0.4*.

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