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Abstract

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EVIDENCE FOR PLIO-PLEISTOCENE POLYGENETIC DEVELOPMENT OF OKEFENOKEE ARCUATE RIDGES

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ABSTRACT

Arcuate sand ridges are prominent features of the Okefenokee Swamp (southeast Georgia/northeast Florida). They are generally convex to the south or southeast, and are up to 1680 m in width, 10 km in length, and 7 m in height above the subpeat sandy surface. Vibracores collected from a sample of ridges display bedforms characteristic of estuarine, deltaic, or fluvial environments. Grain sizes range from pure clays to fine gravels, though most samples are moderately sorted fine sands. Okefenokee sand ridge grain size distributions range in parametric character from clusters similar to nearby fluvial environments to those associated with beaches and coastal dunes, with most samples intermediate in nature. Post-depositional solutional etching dominates grain surface textures, though water transport and wind modification is indicated in some samples. Heavy mineral suites indicate a Pleistocene or greater age with closest correspondence to terrace upland sediments to the west. Taken together, the form and sedimentology of arcuate sand ridges within the Okefenokee Swamp (southeast Georgia/northeast Florida) indicates a polygenetic origin, with older ridges formed within a deltaic system dissimilar to modern environments in the region, and somewhat younger ridges formed as Carolina bay rims.

ARCUATE RIDGE LOCATIONS AND MORPHOLOGY

Ridges of predominantly sandy composition form some of the more prominent islands and non-paludial upland features of the Okefenokee swamp-marsh complex. Seen in aerial photography and Landsat imagery, these ridges clearly form arcuate shapes with many intriguing spatial patterns and trends (Figure 1).

Most of these arcuate features are convex towards the south or southeast and most have high length/width ratios (ranging from 4.5 to 71.0). The apparent surface morphology of the ridges is in part determined by their relationship to the present swamp surface, which has undoubtedly buried much of their extent. The maximum vertical relief, 2.5 m, occurs on Floyd's Island, while many ridges are at or below the swamp surface and can be seen in imagery only through the effect of shallow sands on vegetation patterns. Some of the larger islands appear to be composed of multiple parallel ridges; this tendency is most apparent on Floyd's Island (Figure 2) and was confirmed by a leveling survey.

The distribution of arcuate ridges and their orientations do not appear random. Groups of ridges with related shapes and orientations can be identified in several areas. The group consisting of The Pocket, Billy's Island, Honey Island, and perhaps Bugaboo Island appears to be segments of related arcs that intersect at a point near the present swamp outlet of the Suwannee River. Other more distant islands form arc trends that also appear to converge at this outlet (e.g. Floyd's and Minnie's islands).

Groups of nested or perhaps concentric arcuate features are apparent on aerial photographs (Figure 3) of the northeast quadrant of the swamp (between Floyd's Island and Cowhouse Island). None of these features are identified on maps as islands; they appear as arcs of distinct vegetation and oriented lakes. Another group of similar arcs includes Floyd's Island

Figure 1. Landsat Multispectral Scanner (MSS) image. Source: North American Landscape Characterization program, Mission to Planet Earth, National Aeronautics and Space Administration, 1980's image.

and arcs of distinct vegetation to the north of this ridge.

Islands (including Craven's Island and Hickory Hammock) to the north and northwest of The Pocket group appear to be parts of ovals or ellipses, which are also represented by arcuate extensions of the swamp margin into the northwest terrace uplands (Figure 4). Another ellipse can be traced in the center of the swamp (Figure 5) to the north of Bugaboo Island as an arc of aquatic and shrub/prairie vegetation (based on a map by McCaffrey and Hamilton, 1980). It appears to be bounded on the south by a small arcuate sand ridge extending from the northeast corner of Honey Island and probably continues eastward as a submerged ridge. Followed to the west, the arc appears to truncate Honey Island. The trace continues through Bil-

Figure 2. Northeast Margin of Floyd's Island, showing subparallel submerged ridges.

ly's Island and can be seen here as a string of sink ponds. To the north of Billy's Island, the arc recurves to the northeast and is apparent in the forced orientation of Minnie's Lake. The trace is less distinct near Floyd's Island, but can be picked up again to the south where it forms the western margin of Chase Prairie. This ellipse or oval is such an intriguing feature in im-

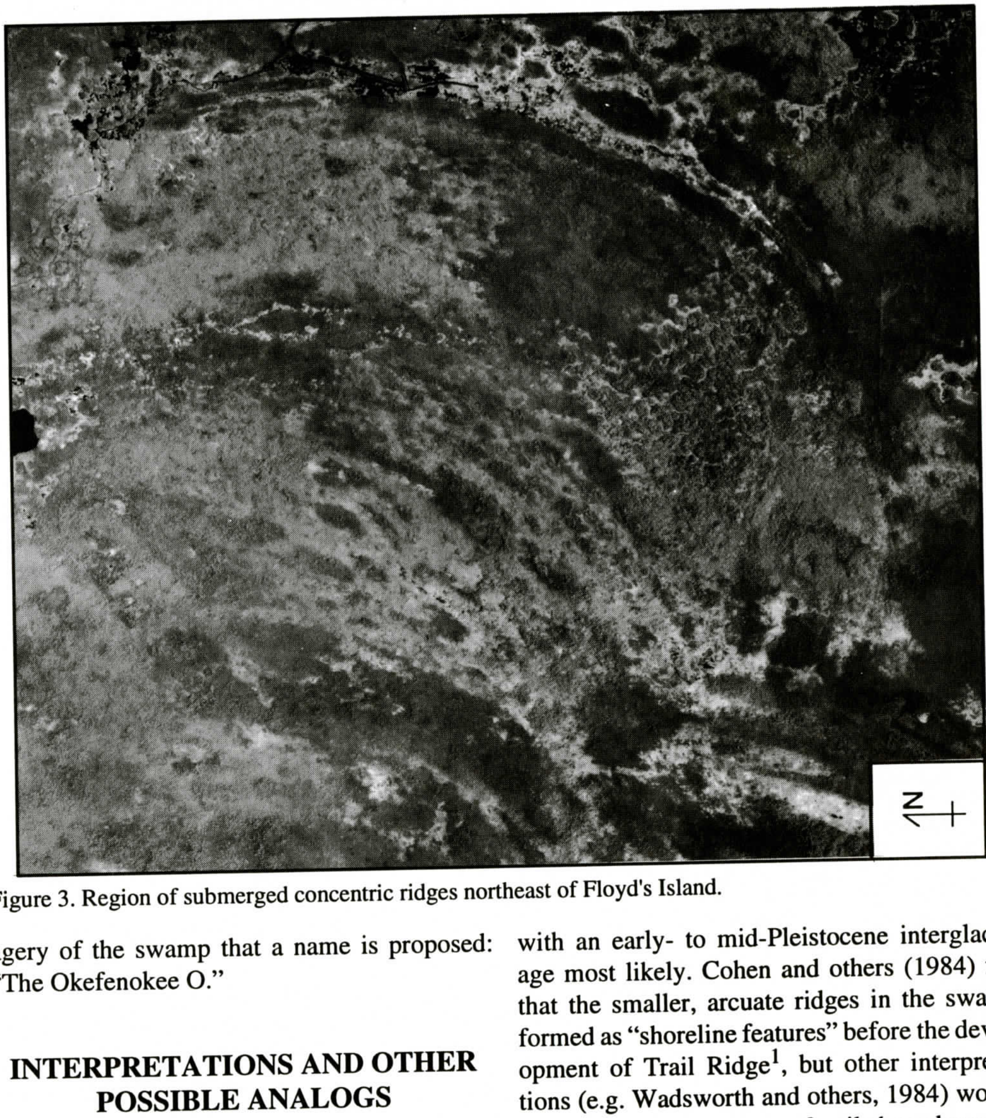

Figure 3. Region of submerged concentric ridges northeast of Floyd's Island.

agery of the swamp that a name is proposed: "The Okefenokee O."

INTERPRETATIONS AND OTHER POSSIBLE ANALOGS

Interpretation of these ridges must be made in the context of the regional geologic history and interpretations of related Okefenokee features such as Trail Ridge. Establishing a time frame is the most difficult part of the interpretation. The general lack of fossils and other dateable materials in these deposits, probably the result of acid weathering conditions, makes establishment of ages difficult. Fossil discoveries have limited the maximum age of Trail Ridge, which forms the eastern margin of the swamp, to the late Pliocene (Pirkle and Czel, 1983), with an early- to mid-Pleistocene interglacial age most likely. Cohen and others (1984) felt that the smaller, arcuate ridges in the swamp formed as "shoreline features" before the development of Trail Ridge[1], but other interpretations (e.g. Wadsworth and others, 1984) would suggest a younger age; no fossils have been recovered to help sort this out. Cohen and others (1984) noted that Chesser Island and Waycross Ridge are truncated by Trail Ridge, which

1. In his review of the manuscript for this article, Art Cohen noted "Arcuate ridges also appear to me to be typical of a 'macrotidal shoreline' (as per Hayes 1979); whereas, Trail Ridge is 'microtidal.' This perhaps suggests some major change in gradient of shoreline between time of formation of the arcuate ridges and time of formation of Trail Ridge."

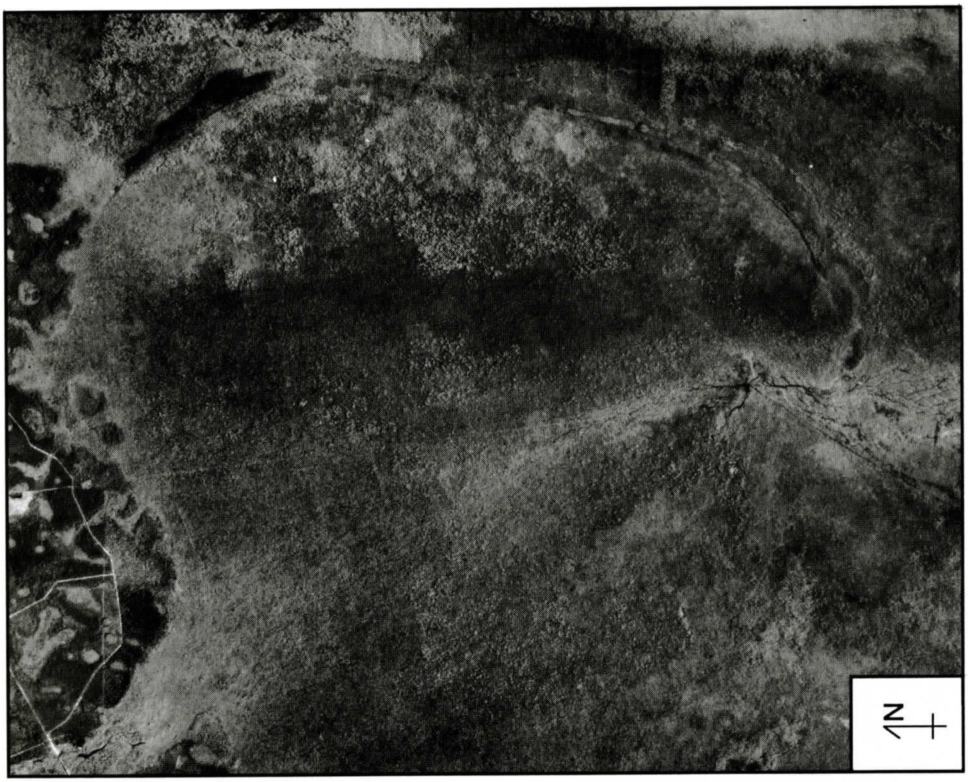

Figure 4. Narrow arcuate ridges forming subelliptic traces in northwest region of Okefenokee Swamp. Composed of Hickory Hammock, Craven's Island, and Craven's Hammock.

clearly places these features (but not necessarily all arcuate ridges) as older.

Though most studies have not focused on the arcuate ridges themselves, interpretations have most often described them as bars or dunes formed in the coastal or near-coastal environment. Pirkle (1972, p. 60) described the ridges as bar-like features "built along a prograding shore line of a regressing sea." Cohen (1973) assigned the development of the bars to marine current action.

Fluvial and/or deltaic bars were implied by Brooks (1966) in his proposal that a proto-Suwanee River flowed to the Atlantic (the Suwanee presently flows to the Gulf of Mexico *from* the Swamp) leaving downstream sediment deposits in the vicinity of the present Okefenokee. Deltaic and estuarine sediment systems appear to hold the most promise for producing arcuate ridges of similar plan morphology; in particular, deltaic subaqueous levees described by Wright (1977) as resulting from plane-jet diffusion are similar in morphology and sediment characteristics.

Wind is another possibility. Smedley (1968) referred to the Okefenokee ridges as "Pleistocene sand dunes and bars." Parrish and Rykiel (1979), in their review of swamp origins, advanced a wind hypothesis. Wadsworth and others (1984), who studied the Okefenokee ridges in most detail, noted their morphological similarity to raised rims associated with Carolina bays, including their tendency to "crosscut," and proposed that similar lake basins may have existed in the Okefenokee. Unfortunately the question of the origin of Carolina bays themselves has engendered considerable controversy, though the most plausible cause of raised rims on the southeastern margins of these features involves seasonal storm-driven winds during full-glacial low lake stands (Thom, 1967, 1970; Kaczorowski, 1977).

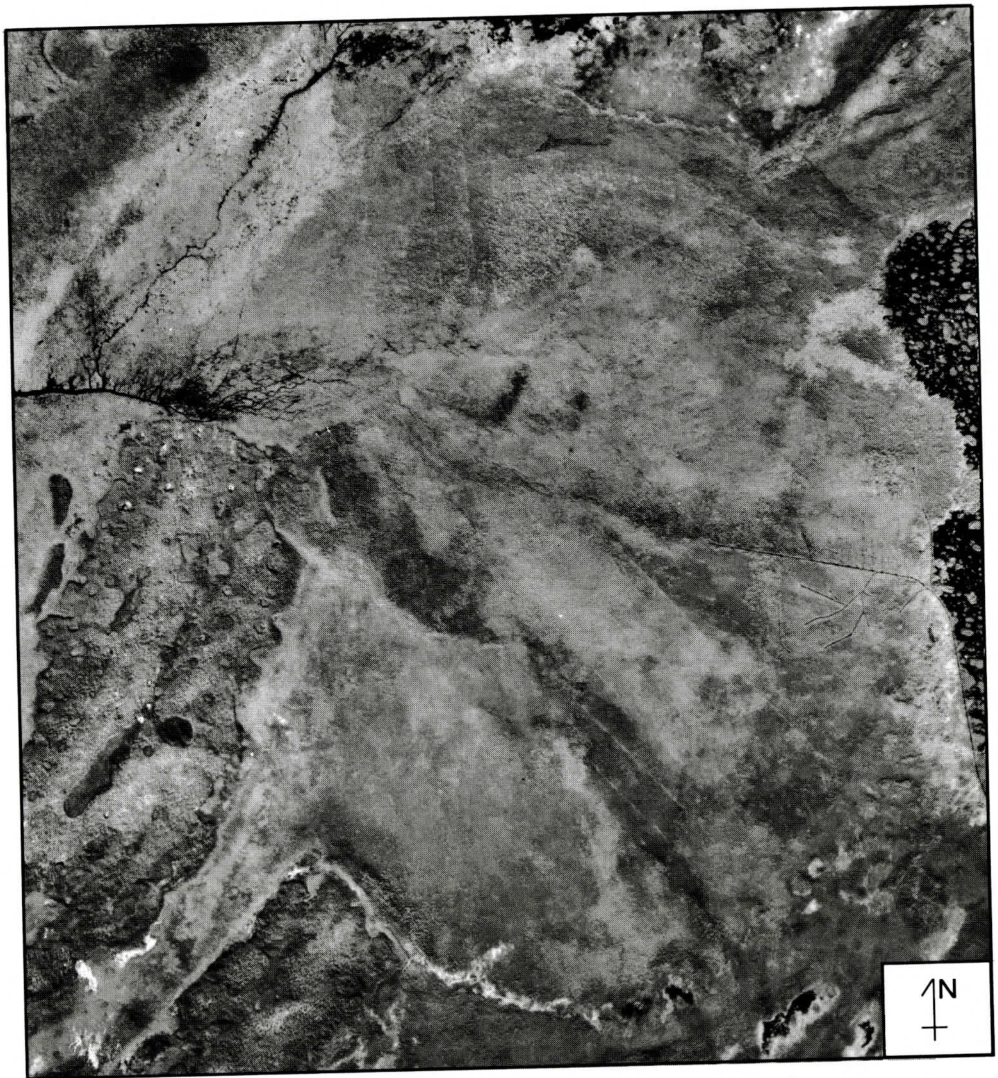

Figure 5. The Okefenokee 'O', a subelliptic trace in the center of the Okefenokee Swamp.

Other analogs might be considered, including various aeolian dune systems. The "pan margin dunes" of South Africa (Lancaster, 1978), and the similar lunettes described in Texas, North Africa, and Australia (Hills, 1940; Campbell, 1968) are, like Carolina bay ridges, associated with relict lake margins. Parabolic dunes have been described developed on the northeast flanks of NW-SE trending rivers on the coastal plain of Georgia (Asmussen, 1971; Thames, 1982) and North Carolina (Miller, 1979; Daniels and others, 1970), and appear to result from blowout of sandy channel sediments during dry periods.

ANALYSIS OF THE RIDGES

A viable interpretation of puzzling features such as the Okefenokee arcuate ridges cannot rely upon a single layer of information. In this study, morphological characteristics (described above), bedding characteristics, sediment size parameters, grain surface texture and heavy mineral assemblages were used in conjunction to describe and interpret the ridges and samples from cores. Sediments were analyzed from 21 vibra-cores of the Okefenokee arcuate ridges, and 10 other comparative sites from various upland and ridge sites around the swamp, including Trail Ridge; two Georgia coastal plain river margin sand ridges, on the Altamaha and Ohoopee rivers; and a Carolina bay, Alligator Bay in South Carolina. Information on other analogs was derived from the literature.

Core Descriptions and Sediment Size Characteristics

Transects from The Pocket and Floyd's Island provided the most detailed information on sediment patterns along and across the ridges (Figures 6 & 7). In each of the 16 cores arranged in 4 cross-ridge transects, visible inspection of cut cores revealed alternating layers of relatively clean fine-to-medium sands, less well-sorted sands with finer sediments, and clay-rich sediments, with significant bioturbation in many sections. Significant clay-rich layers halted penetration of the vibracoring system at depths ranging from 1.72 to 4.82 m; these layers typically exhibited mud cracks indicating periods of subaerial dessication. Cores from The Pocket exhibited grass-like root traces. Such characteristics are typical of deltaic/estuarine sedimentation patterns of fluctuating channels, with alternating deposition of sands, muds, and organic matter (Reineck and Singh, 1980; Coleman, 1981; Howard and Scott, 1983; Frey and Howard, 1986).

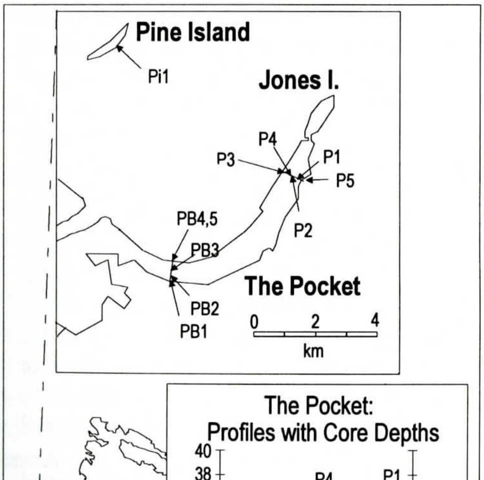

Figure 6. Transect and core locations on The Pocket.

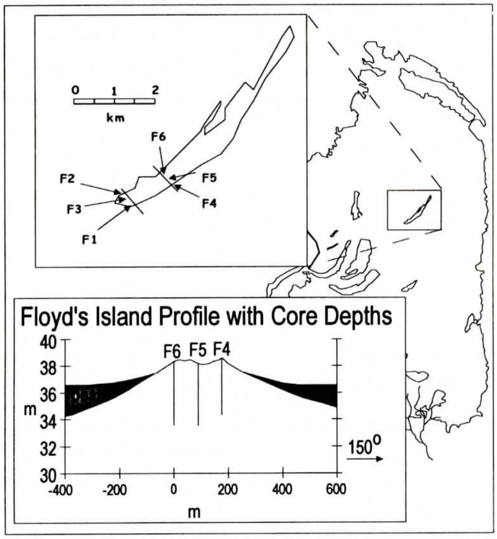

Figure 7. Transect and core locations on Floyd's Island.

In near-surface samples from The Pocket, mean grain size decreased from Transect B (moment mean = 2.52 ϕ) to Transect A (2.77 ϕ), and from seaward to landward margins (Transect A: 2.63 to 2.95 ϕ; Transect B: 2.38 to 2.47 ϕ). Both patterns are also typical of subaqueous levees described by Wright (1977).

Sequences of relatively coarse sands and fine gravels (up to 4 mm), suggestive of fluvial deposition, were noted near the base of cores from Pine Island (mean of sample 8 from core Pi1 = 0.91) and the terrace uplands just to the west of the swamp (mean of sample 8 from core U1 = 0.13). Fining-upward sequences, typical of migrating point bars (Reineck and Singh, 1980) and some progradational sequences

(Klein, 1970) were observed in the Pine Island core (3.0 to 3.5 m depth) and in one core from The Pocket (P2 above 2 m depth). Coarsening-upward sequences, typical of delta front progradation (Tucker, 1981), were apparent in the Pine Island core and the terrace uplands core. These observations are consistent with Brooks's (1966) hypothesized outlet of a proto-Suwannee River in the Okefenokee area.

Nearly all samples exhibited a positive skew; exceptions were primarily in deeper samples of cores from Floyd's and Chesser islands, which also exhibited better sorting than most other samples from the ridges. In general, ridge samples ranged from poorly-sorted to well-sorted fine sands, with somewhat better sorting overall on Floyd's Island due largely to lower mud percentages -- 8.2% in Floyd's Island samples vs. 21.3% in The Pocket samples (2.5% vs. 9.7% in near-surface samples).

Cluster Analysis Based Upon Size Parameters

Sedimentological classification of samples based upon size parameters is a problematic procedure. Errors due to inconsistent sediment source generally indicate the need to compare samples only from similar or at least regional environments, and many features contain sediments that have likely been transported over short distances and thus are little modified by the depositional system being studied. Individual samples were thus compared only with samples from depositional environments close to the Okefenokee. Data derived from the literature were from two suitable sources, both describing features on the Georgia coast and coastal plain: Hails and Hoyt (1969), which included samples from barrier islands, fluviatile dune sands, and lagoon-salt marsh sediments; and Thames (1982), which included samples from river-margin sand ridges, river channel, coastal dune, and beach sediments. Since other depositional environments were also considered but were not represented in the region, cluster analysis was selected as the most suitable method of classification; cluster analysis delineates sample groups without the need for known model categories.

Three variables (moment mean, moment standard deviation, moment skew) grouped the samples clearly into seven clusters, four of which represented known environments (groups 2, 4, 5 and 6), and three represented unknown environments (groups 1, 3 and 7). Each group included some samples from various depths in Okefenokee arcuate ridge cores:

Group 1: somewhat poorly sorted (1.07 ϕ), positive skew (1.38 ϕ), fine sands (2.63 ϕ). Includes many samples from Okefenokee ridges, especially from The Pocket cores.

Group 2: *river-margin sand ridges* -- moderately sorted (0.79 ϕ), positive skew (0.47 ϕ), medium sands (1.74 ϕ). Represented only in a few deeper samples from Pine Island, Floyd's Island, and Chesser Island.

Group 3: moderately sorted (0.79 ϕ), very positive skew (1.58 ϕ), fine sand (2.38 ϕ). Includes several samples from Floyd's, Pine and Chesser islands, especially near the surface; very few from The Pocket; perhaps wind-modified group-1 samples.

Group 4: *river channel* -- moderately sorted (0.79 ϕ), negatively skewed (-0.31 ϕ), coarse sands (0.65 ϕ). Only represented in deepest Pine Island sample and near base of core from the nearby terrace uplands. These samples include fine gravels.

Group 5: *beach* -- well sorted (0.48 ϕ), negatively skewed (-0.43 ϕ), fine sands (2.68 ϕ). Deeper samples from the seaward edge of Floyd's and Chesser islands.

Group 6: *coastal dune* -- well sorted (0.43 ϕ), positive skew (0.61 ϕ), fine sands (2.65 ϕ). Samples at various depths and locations on Floyd's Island; also in deeper samples from Chesser Island and The Pocket Transect A.

Group 7: silty to clayey, poorly sorted (1.54 ϕ), positive skew (0.74 ϕ), fine sand (2.79 ϕ). These are from the thin clay-rich zones at various depths of most cores.

Grain Surface Texture

A limited set of samples from Okefenokee and other sites was studied using a Philips 505 Scanning Electron Microscope (SEM) at the Center for Advanced Ultrastructural Research, University of Georgia. Table 1 lists observed grain surface patterns using terminology from Krinsley and Margolis (1971) and Manker and Ponder (1979). The most prevalent characteristic noted in all samples was chemical etching (Figure 8A-B). This appears to have obscured pre-existing surface textures, making more detailed analysis impossible. V-shaped indentations (a characteristic of either beach or river sediments) were observed on grains from Chesser Island (Figure 8C) and Floyd's Island, as well as from the Ohoopee Dunes. One sample from Floyd's Island exhibited characteristics associated with wind transport -- meandering ridges and well-rounded grains (Figure 8D).

Table 1: Grain surface textural characteristics observed with SEM.

Location	core	depth (M)	observed grain surface characteristics*
Floyd's I.	F3	2.0	MR, ABV, WR, SE
Pocket	P1 P1	2.0 2.7	SE SE, MR?
Chesser I	C1 C1	2.8 2.0	ALV, SE, UP ALV, SE
Trail R.	TR1	1.5	SE
Ohoopee D.	O1	2.0	ALV, UP

* Abbreviations for grain surface characteristics:
MR: meandering ridges — WR: well-rounded grains —
SE: solutional etching — UP: upturned plates —
ALV: aligned V-shaped indentations — ABV: abraded V-shaped indentations

Extensive solutional modification of Okefenokee sands has obliterated many surface patterns, making electron microscopy techniques inadequate for detailed interpretations, but some general statements can be made. Deposition of sediment from an aqueous medium is a part of the history of all of the ridges. Long-term exposure to chemically aggressive water is also evident from the extensive etching of sand grains in all samples. The limited etching on Chesser Island grains may indicate a shorter exposure to acidic waters. Finally, evidence exists for sediments from Floyd's Island having been modified and abraded through wind transport.

Heavy Mineral Analysis

Heavy minerals separated from samples collected between depths of 1-2 meters in each core suggest a terrace uplands sediment source for the main group of arcuate ridges in the swamp. Samples from Transect B of The Pocket were most similar in both mineral suite and relative concentrations to terrace uplands samples, both having 15-20% sillimanite and less than 5% zircon. Samples from Transect A of The Pocket were, like samples from Floyd's and Pine islands, somewhat more enriched in sillimanite (generally over 20%) but comparable in zircon.

Trail Ridge appears to be less closely related to the Okefenokee ridges. Little if any epidote was noted from any other Okefenokee sample, as predicted by Pirkle (1975); and in this regard, the ridges within the Okefenokee are similar to Trail Ridge. However, Trail Ridge samples differed significantly in sillimanite (1.6%) and zircon (22.8%) concentrations. Chesser Island sediments were somewhat closer to Trail Ridge in these concentrations (sillimanite < 10%; zircon > 5%), but there is little evidence to assign them a common source.

CONSIDERATION OF ANALOGS

Several statements can be made concerning possible analogs for the Okefenokee arcuate ridges in light of the results described above:

1. Coastal beach and dune environments may have pre-dated ridge construction. Coastal affinities (beaches and coastal dunes) are most common in deeper samples especially on the seaward sides of Chesser and Floyd's islands.

2. Some sedimentological similarities exist

between upper samples of The Pocket and those of river-margin sand ridges, but differences suggest a unique depositional environment.

3. River deposition is clearly a part of the history of the area where Pine Island was built, and was also significant in the terrace uplands. The western upland watersheds presently drained by small creeks that feed the Okefenokee do not include sources of gravels similar to those found in deeper samples from Pine Island; a much larger fluvial system with a distant source region is indicated (as per Brooks 1966).

4. An aqueous medium transporting sediments from Transect B to Transect A of The Pocket is indicated by a B-to-A decrease in mean grain size.

5. The source of sediments in The Pocket likely was from the west, as indicated by heavy mineral similarities.

6. A prograding deltaic system is a likely interpretation for most of the arcuate ridges. Coarsening-upward sequences were noted in

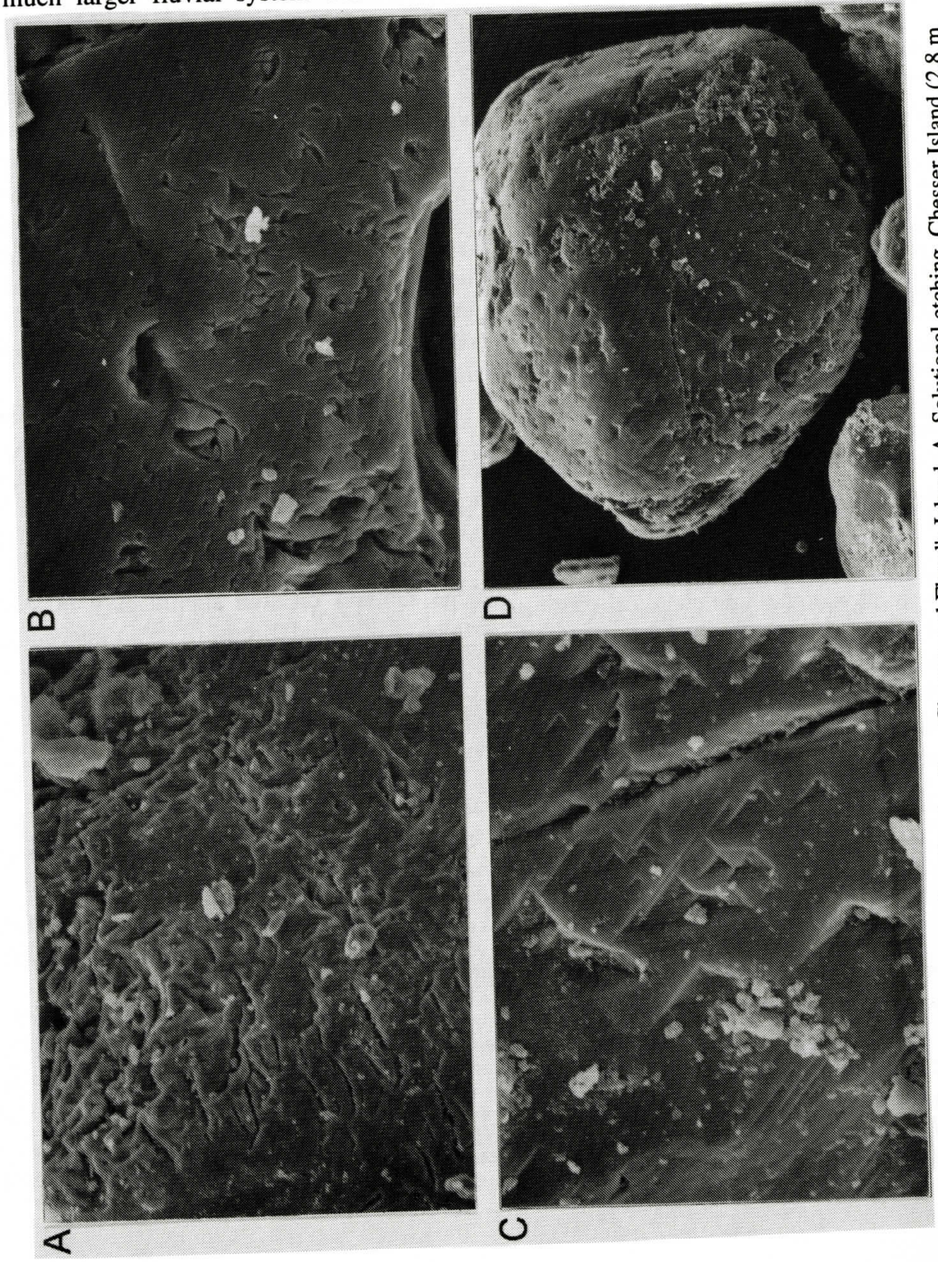

Figure 8 A-D. SEM images of sand grains from Chesser and Floyd's Island. A. Solutional etching, Chesser Island (2.8 m depth), 625X; B. Solutional etching, Floyd's Island (2.0-m depth), 2500X; C. V-shaped indentations, Chesser Island (3.0 m depth), 2500X; D. Surface textures indicative of wind transport - Floyd's Island (2.0 m depth), 156X.9.

cores of the terrace uplands, Pine Island and Floyd's Island, and fluctuating sandy and finer layers were noted in all cores. The plan morphologies of The Pocket, Billy's Island, Honey Island, and New Island are similar to the spreading subaqueous levees described by Wright (1977) and Coleman (1981) as the result of plane-jet diffusion of an otherwise inertial-dominated river delta as it encountered friction from shoaling at its mouth.

7. Tidal marsh deposition may have been significant in some areas, especially The Pocket, as indicated by mud cracks and root traces in split cores.

8. A progression from coastal (beach, coastal dune) sediments to estuarine (mud layers, mud-clasts, root traces) or deltaic (fluctuating channel/marsh) sediments is seen in some cores from all ridges. Cores that do not exhibit this progression (e.g. Transect B of The Pocket) may have been too shallow to provide a complete data set. Progradation is again indicated.

9. A history of wind deposition is suggested not only by deeper seaward samples from Chesser and Floyd's islands, but also in surface samples from Floyd's and Pine islands, based upon sediment size characteristics and grain surface texture. One interpretation of these tendencies that agrees with observed morphologies is that all of the ridges may have been deposited through the same mechanism (probably deltaic). However, The Pocket, Billy's Island, Honey Island, and New Island are the most recent formations; whereas, the other islands formed earlier and have since been modified by wind.

10. Oval traces similar to Carolina bays include arcuate ridge segments. Since these appear to truncate other Okefenokee ridges, they likely represent a system that postdates other ridge-forming processes within the swamp. The wind modification of sediments described above may be associated with Carolina bay ridge development in pre-existing sediments.

THE ORIGIN OF THE ARCUATE SAND RIDGES: A PROPOSED SCENARIO

No **single** interpretation of the arcuate ridges can explain all of the observations. An early assumption in this study -- that such a single interpretation must exist -- has been abandoned in favor of a polygenetic model invoking deltaic and Carolina bay systems. The modern landscape (Figure 9) is a palimpsest resulting from the superimposed impacts of these and other geomorphic systems.

The earliest depositional systems observed in the cores were coastal beaches and dunes. The depth of these samples, coupled with the low areal sampling density of ridge cores, allows little interpretation of these systems. If a statement can be made about these samples, it is that shore-zone depositional systems pre-dated overlying environments in this area.

The first major geomorphic system significant to arcuate ridge morphology in the area is that of a prograding delta with distributary channels bounded by subaerial and subaqueous levees. The central major arcuate ridges, including The Pocket, and Minnie's, Billy's and Honey islands, can be interpreted as remnants of levees from a major deltaic channel. One possible scenario to explain the spatial ridge pattern is illustrated in figures 10-12, which depict both a lateral (southward) shift and a progradational trend typical of many deltas.

We can only speculate about the source region of the river forming the delta here, though subsequent river captures are probably significant. Both the Ocmulgee and Alapaha systems have morphologies suggestive of capture, and the Suwannee River may have changed directions, as suggested by Brooks (1966). The Ocmulgee, now part of the Altamaha basin, presently drains a portion (9300 km^2) of the Piedmont and Coastal Plain provinces of Georgia. The Alapaha is presently an insignificant part (3500 km^2) of the Suwannee basin, but may have been much larger in the past: much of its catchment (now limited to the coastal plain Tifton Uplands) has apparently been captured

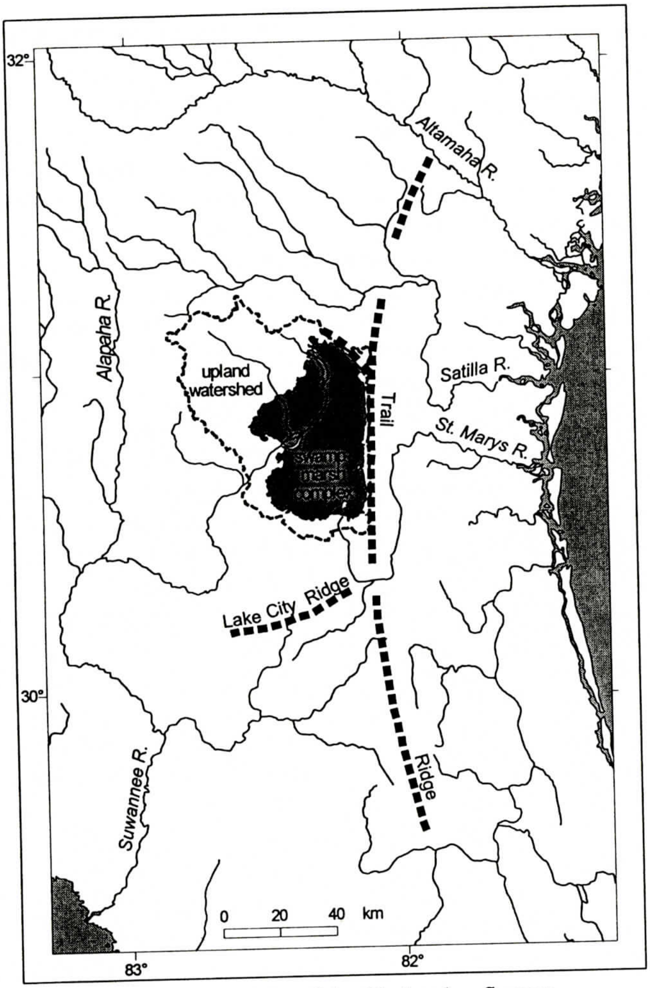

Figure 9. Major drainage networks in the vicinity of the Okefenokee Swamp.

by streams to the west of the Pelham escarpment, now draining via the Flint and Chattahoochee Rivers to the Appalachicola River. The size of this former drainage basin is difficult to estimate; though approximately 50,000 km^2 would have been drained if the basin included portions of the Piedmont and Appalachian Highlands Provinces presently drained by the Chattahoochee and Flint Rivers. The Alapaha in turn was likely captured by the Suwannee after its flow was reversed to the Gulf, as Upper Eocene limestones (Ocala Group) were exposed at the crest of the Ocala Arch. Either the Ocmulgee or the (expanded former) Alapaha system could have provided the coarser sediments found in cores of Pine Island and The Pocket.

Isostatic uplift resulting from karstic removal of underlying limestones may have been a factor in both Alapaha captures. Such uplift was interpreted by Opdyke and others (1984) for northern Florida. Between the Alapaha River and the Okefenokee drainage basin is a major area of Carolina bays believed to have formed on sands underlain by carbonates. Seepage from these sinks into the Principal Artesian Aquifer, which flows beneath the swamp, further reduced the sources of surface runoff into the swamp.

Only with a diversion of major river inputs could Trail Ridge have been constructed with no significant breaks from the St. Marys River

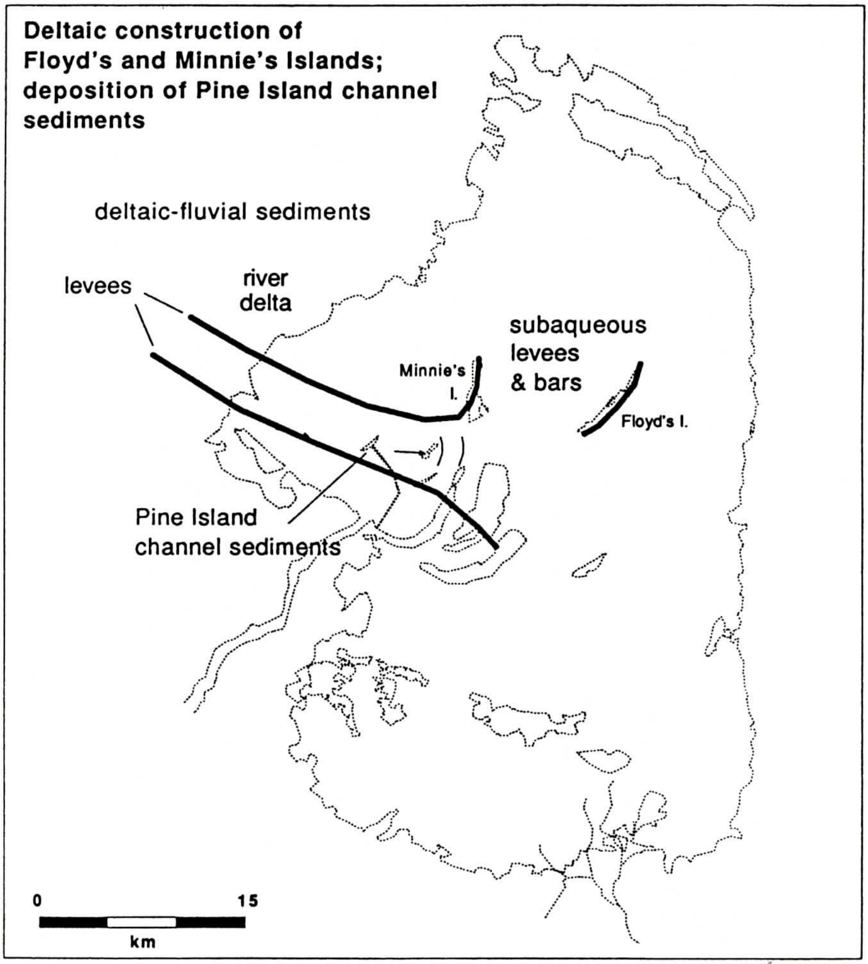

Figure 10. Deltaic construction of Floyd's and Minnie's Islands.

to the Satilla River. The Suwannee River's outlet may have already been established to the southwest. Alternatively, the remaining inputs to the swamp basin may have reached the sea through one or more outlets: the present outlet of the St. Marys River, or a low point in Trail Ridge just south of Chesser Island. One factor that may have been significant (and may continue to be so) is isostatic subsidence due to deltaic sediment accumulation. This may be the cause of the present lower elevations on the western margins of the swamp, where delta sediments would have been thickest.

The developments presented to this point are thus seen as pre-dating the development of Trail Ridge, which is assumed to have been constructed during an interglacial transgression of the early- to mid-Pleistocene. No precise age has yet been established for this major barrier ridge, though we know that several major transgression-regression cycles have occurred since this time (along with the general progradational trend of the southeastern coastal plain) and that fossil evidence places Trail Ridge as no older than the late Pliocene and most likely within the Pleistocene (Pirkle and Czel, 1983). The amount of Trail Ridge structural deformation (an admittedly unreliable dating method) would indicate an age in the vicinity of 0.4 - 1.0 million years.

What has happened in the Okefenokee basin since this time? We know that late Pleis-

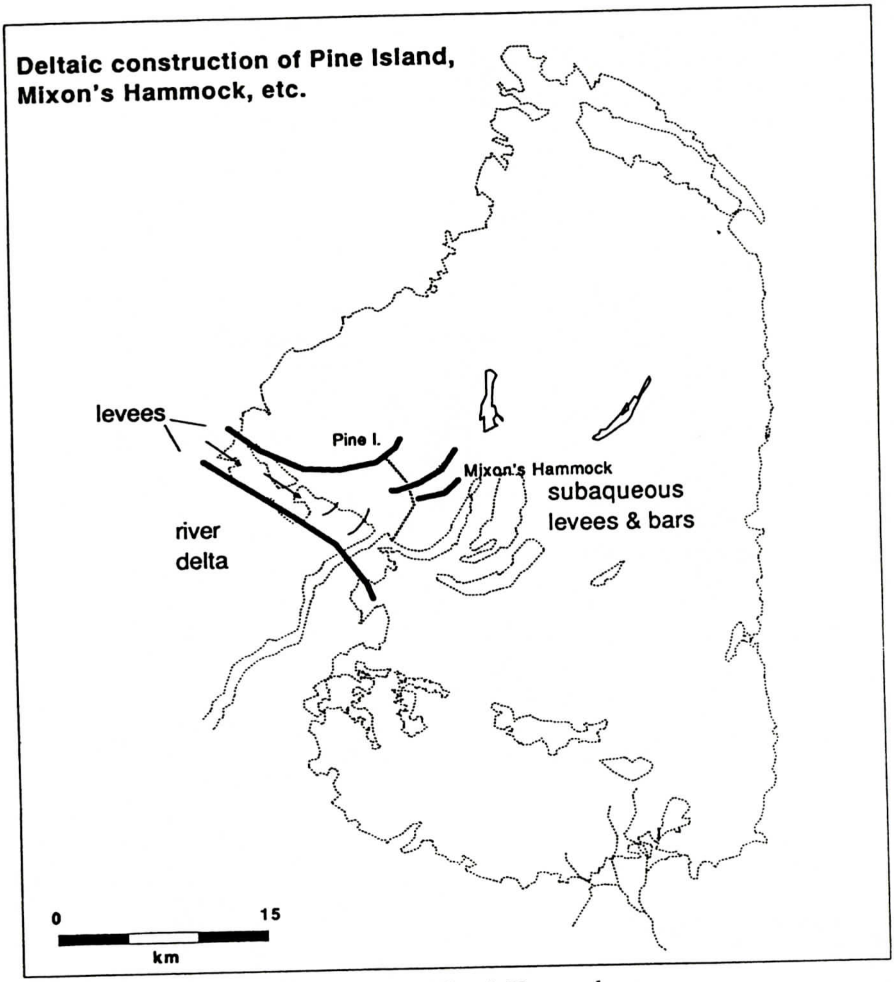

Figure 11. Deltaic construction of Pine Island and Mixon's Hammock.

tocene interglacial conditions in this region were warmer and wetter than the glacials; this is based upon palynological studies of the southeastern coastal plain (Watts, 1971; Watts and Stuiver, 1980). By this time, the Suwannee had captured the Okefenokee basin's drainage, as well as that of Suwannoochee Creek. As they do today, fluviatile swamp developments expanded up river valleys where stream gradients were limited. In areas of structural subsidence, such as the Okefenokee basin, gradients in outward-draining streams were particularly restricted. Lakes developed preferentially in depressions located at groundwater seepage points. The region of sinks to the west of the swamp developed in one of these areas, as discussed above. Ponds within the swamp may also have developed at seepage points, preferentially developed (1) to the northwest of The Pocket, (2) between Billy's and Floyd's Island (the Okefenokee O), and (3) to the northwest of Floyd's Island. Pre-existing deltaic arcs certainly affected the drainage patterns, and thus partially controlled lake development.

Drier and cooler glacial conditions are shown in Figure 13. Regression of sea level, an important regional climatic factor, had increased stream gradients and thus reduced swamp formations, probably aided by peat fires. Wet-season (summer) lake expansions may have been oriented into typical Carolina bay forms, the result of current action; this pro-

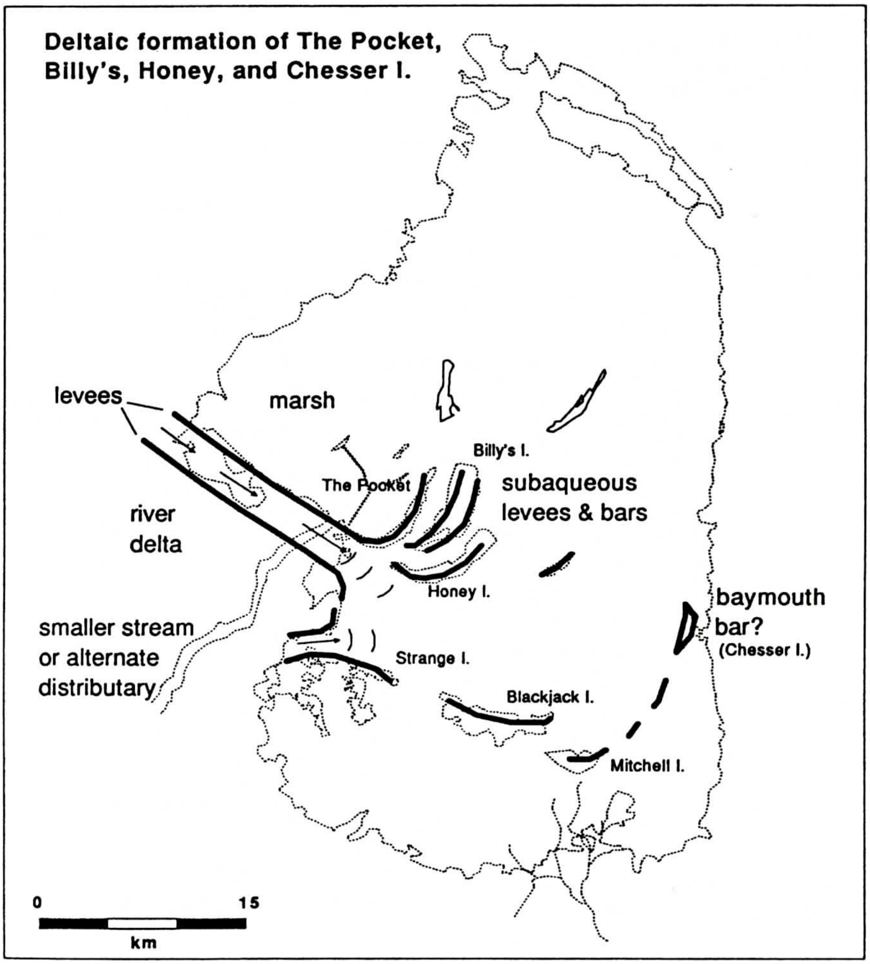

Figure 12. Deltaic construction of The Pocket, Billy's Island, Honey Island, Chesser Island, and other ridges.

cess was demonstrated by Kaczorowski (1977). It was at this time that pre-existing ridges might have been susceptible to erosion by lake margin current action; the truncation of Honey Island, forming part of the Okefenokee O, is an example. During the dry winter season, fire-exposed sands were susceptible to wind modification. Arcuate ridges were constructed as parabolic dunes on the southeastern and eastern margins of shrinking Carolina bay lakes, from strong northwesterly to westerly winds. Craven's Island, Hickory Hammock, parts of Minnie's Island, and many other subswamp ridges (especially to the north and northeast of Floyd's Island) may represent receding lake-margin dunes dating from one of these periods. Floyd's Island may have been heightened at this time, and the multiple ridges on its surface may have migrated as dunes across its crest; similar modifications may have affected Pine Island and Mixon's Hammock.

We are presently in an interglacial cycle, the Holocene, with a return to wetter conditions initiated with the recession of Wisconsinan glaciers prior to 10,000 years B.P. The Okefenokee has again expanded as a multiple riverine swamp of the Suwannee River and Cypress Creek, as outlined by Parrish and Rykiel (1979). The headward development of the St. Marys River has renewed a limited amount of drainage to the Atlantic through a gap in Trail Ridge. Wind is no longer an important factor

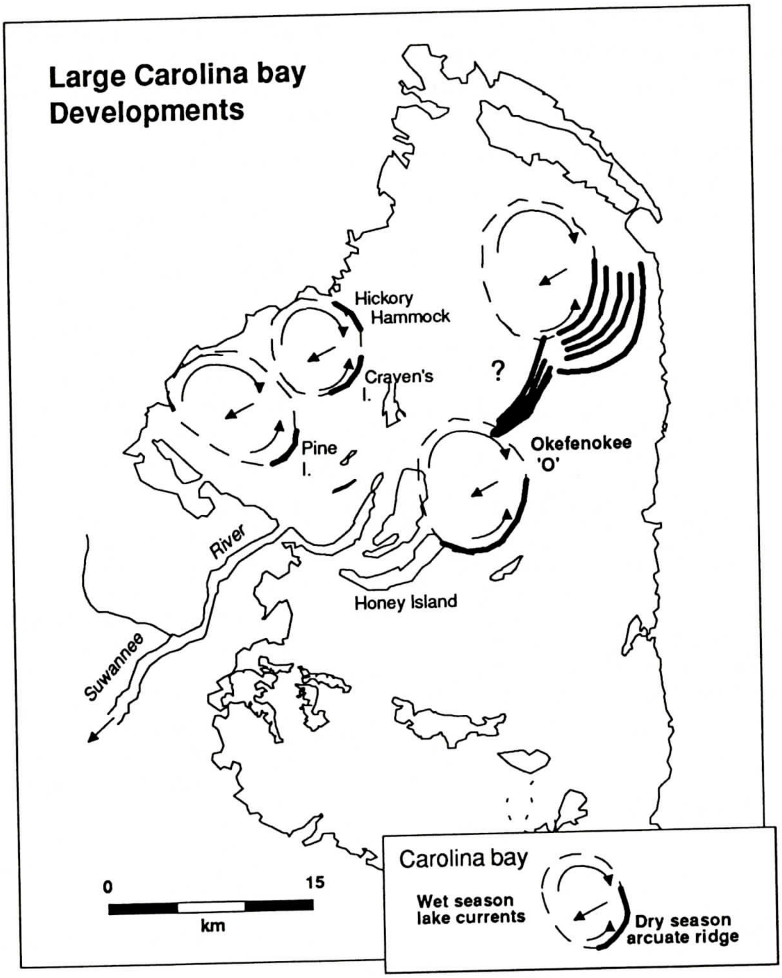

Figure 13. Development of large Carolina bays in the Okefenokee Swamp.

here as vegetation has become more extensive and peat has accumulated. Fires still play a part in retaining the marsh "prairie" components of the Okefenokee complex (Izlar, 1984; Hamilton, 1984), but not until climates become much drier can these significantly reduce the peat cover. The arcuate ridges are well preserved in this environment of limited erosion.

CONCLUSION

This study has demonstrated that the arcuate sand ridges of the Okefenokee Swamp are a result of multiple causes with at least two significant developments occurring within the Quaternary Period. Sedimentological, morphological, and spatial evidence indicate that a fluvial-dominant deltaic environment may have been responsible for many of the sand ridges, especially those in the vicinity of The Pocket (including Billy's Island and Honey Island). The river system responsible for this delta drained large areas to the west of the swamp in the Pliocene and continued to drain into the basin until some time before the development of Trail Ridge in the early- to mid-Pleistocene. This is in agreement with Brooks (1966), who proposed an Atlantic-draining late-Pliocene Suwannee River, with a "strath" in the Okefenokee basin. Similar kinds of evidence support the late-Pleistocene development of Carolina bays, responsible for additional arcuate ridges that truncated earlier deltaic deposits or reflect receding lake shorelines (Craven's Island, Hickory Hammock, and many submerged ridges). Wind modification of pre-existing ridges, especially Floyd's and Pine Islands, occurred as part of a glacial dry cycle at this time.

Swamp developments and arcuate ridge modifications are seen as cyclic. At least over the last few glacial cycles, the wet interglacials have been times of swamp expansion and the dry glacials times of peat reduction by fires. The arcuate sand ridges are only significantly modified during glacials, when the peat cover is reduced and the sands exposed to current and wind erosion. Despite the acidic weathering environment of swamp conditions, effective in reducing the sediments to a quartz-dominant composition, the ridges are well-preserved during these periods. Only after the St. Marys River recaptures the basin to the Atlantic will these curious arcuate sand ridges be removed, and no one will wonder about them again.

ACKNOWLEDGEMENTS

To George Brook, Albert Parker and Philip Suckling, University of Georgia Geography Department; and Ray Freeman-Lynde and Robert Carver, University of Georgia Geology Department, for consultation on the original research. To the many field assistants I talked into a weekend of coring in the swamp. To the reviewers of this article, Art Cohen and Fredrick Rich, for their helpful suggestions. This research was supported by National Science Foundation grants BSR-8114823 and BSR-8215587.

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STRATIGRAPHIC AND DEPOSITIONAL FRAMEWORK OF THE GLENSHAW FORMATION (LATE PENNSYLVANIAN) IN CENTRAL WAYNE COUNTY, WEST VIRGINIA

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ABSTRACT

Outcrops of the Glenshaw Formation at 20 localities in central Wayne County are described and correlated using 1) coal beds and associated paleosols and 2) marine units.Component sedimentary facies are distinguished by lithology, sedimentary structures, body and trace fossils, paleocurrents and facies geometry.

The Glenshaw Formation is about 70 m thick and consists predominantly of trough cross-stratified fine-coarse channel sandstones and interbedded very fine sandstone and mudrocks deposited in alluvial channel and overbank settings. Paludal and lacustrine facies occur in interfluvial portions of the coastal plain and are represented by relatively thin coal, carbonaceous shale and micritic limestone. Paleosols are represented by red, green, and gray hackly mudstone with horizonization and, in some cases, pedogenic carbonate. Shallow marine facies consist of claystone, mudstone, biomicrite, and thinly interbedded siltstone and sandstone representing the Lower Brush Creek, Upper Brush Creek, Cambridge, and Ames marine units. The marine fauna includes brachiopods (productids, chonetids, spiriferids, and lingulids), fenestrate and dendroid bryozoans, gastropods, crinoids, bivalves (nuculids and pectenids), trilobites, fusulinid foraminifera, ostracodes, sponges, and algae. Trace fossils include *Teichichnus* and *Aulichnites*. A delta front facies is well developed in the Lower Brush Creek marine zone and is comprised of a coarsening and thickening upward sequence of parallel laminated and ripple bedded sandstone with interbedded siltstone and shale.

Previous stratigraphic analyses in this part of Wayne County are very limited. The results of this study 1) extend the known geographic distribution of marine units in the southern Dunkard Basin, 2) demarcate the southern limb of the Parkersburg-Huntington Syncline through the Wayne-Prichard area, 3) demonstrate that transgressive-regressive packages of strata recognized further north have considerable lateral continuity. This study should have important consequences for past and future stratigraphic work and geologic mapping in Wayne County and vicinity.

INTRODUCTION

The Glenshaw Formation represents the lower 66-80 m of the Conemaugh Group in the Huntington area. In recent years, the development of extensive exposures during highway construction along the Ohio and Big Sandy Rivers has enabled details of the lithostratigraphy to be examined (Merrill, 1973, 1986; Martino and others, 1985; Fonner and Chappel, 1987; Martino, 1992; Figure 1). In contrast, Conemaugh strata in the Wayne area are not well-exposed and have not been studied since the early work of Krebs and Teets (1913) and Cross and Schemel (1956).

The study area of this report includes approximately 34 square miles in the Wayne-Centerville portion of Wayne County (Figure 1,

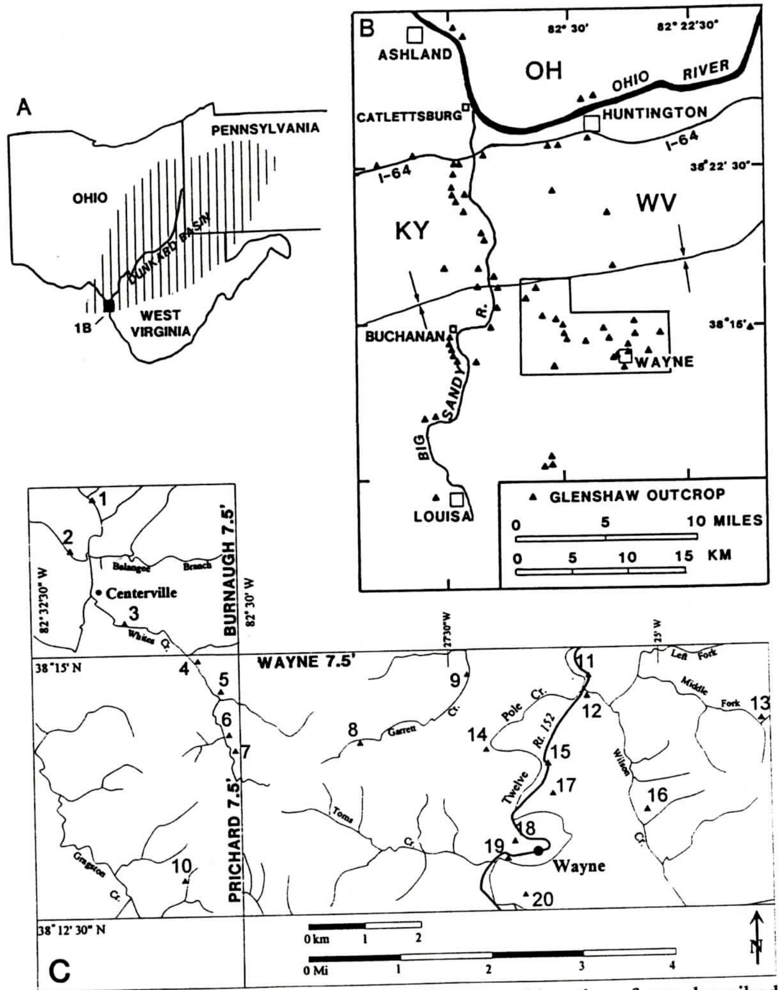

Figure 1 A. Regional map showing extent of the Dunkard Basin and location of area described in 1B; B. Huntington area of West Virginia and adjacent portions of Kentucky and Ohio. Pittsburgh-Parkersburg-Huntington Syncline trends WSW-ENE and is generalized from structural contours on the Pittsburgh coal from Krebs and Teets (1913). Glenshaw Formation outcrops south of the syncline axis in the Wayne area are the focus of this report; C. Detailed map showing outcrop localities in the Wayne-Centerville area of this report. Localities 1-3: Burnaugh 7.5' Quadrangle, localities 4-7, 10: Prichard 7.5' Quadrangle, localities 11-20: Wayne 7.5' Quadrangle.

Table 1). Outcrops were measured at 20 locations using a Jacob's staff and Brunton compass. The elevations of key beds at each locality were measured using a Micro model M-1 field altimeter. Component facies were distinguished using lithology, sedimentary structures, body and trace fossils, paleocurrents, and facies geometry.

The primary objectives of this paper are 1) to describe the stratigraphic framework of the Glenshaw Formation from Wayne to Centerville utilizing coals and marine units as stratigraphic markers, 2) to describe the faunal content of marine strata, and 3) to distinguish and evaluate sedimentary facies and paleoenvironments within the context of Late Pennsylvanian paleogeography of the southern Dunkard Basin.

Table 1. Location descriptions for Glenshaw Formation outcrops 1-20. Coordinates in latitude and longitude. Marine units at each locality are indicated. 7.5' quadrangles are Prichard (PRI), Burnaugh (BUR), and Wayne (WAY).

Location No.		Quad	Key Units	Coordinates
1	(W36)	BUR	Ames	38° 16' 30" N 82° 31' 56" W
2	(W25)	BUR	Ames	38° 16' 17" N 82° 32' 04" W
3	(W15)	BUR	Cambridge	38° 15' 20" N 82° 31' 25" W
4	(W22)	PRI	L. Brush Cr.	38° 14' 59" N 83° 00' 02" W
5	(W21)	PRI	L. Brush Cr.	38° 14' 42" N 82° 30' 16" W
6	(W23)	PRI	Cambridge	38° 14' 17" N 82° 30' 04" W
7	(W16)	PRI	Cambridge	38° 14' 08" N 82° 30' 04" W
8	(W18)	WAY	Cambridge	38° 14' 12" N 82° 28' 36" W
9	(W19)	WAY	L. Brush Cr.	38° 14' 51" N 82° 27' 17" W
10	(W17)	PRI	Cambridge	38° 12' 54" N 82° 30' 38" W
11	(W14)	WAY	U.B.Cr.,Cam.	38° 14' 51" N 82° 25' 49" W
12	(W10)	WAY	LBC, UBC, Cam.	38° 14' 40" N 82° 25' 49" W
13	(W34)	WAY	LBC, Cambridge	38° 14' 23" N 82° 23' 45" W
14	(W29)	WAY	LBC, Cambridge	38° 14' 08" N 82° 27' 03" W
15	(W11)	WAY	L. Brush Cr.	38° 14' 01" N 82° 26' 20" W
16	(W33)	WAY	Cambridge	38° 13' 34" N 82° 25' 06" W
17	(W37)	WAY	L. Brush Cr.	38° 13' 44" N 82° 26' 16" W
18	(W12)	WAY	L. Brush Cr.	38° 13' 18" N 82° 26' 54" W
19	(W32)	WAY	U. Freeport Coal	38° 13' 08" N 82° 26' 48" W
20	(W30)	WAY	L. Brush Cr.	38° 12' 50" N 82° 26' 36" W

GEOLOGIC SETTING

An ever wet tropical climate predominated during the Middle Pennsylvanian in the central Appalachian Basin. During the Late Pennsylvanian, a markedly more arid climate developed at the beginning of the Stephanian (Dimichele and others, 1985; Cecil, 1990). Collisional tectonics associated with the Allegheny Orogeny produced 2 foreland basins (Dunkard and Pocahontas basins) within the NE-SW trending Appalachian Basin. The Dunkard Basin became the predominant depocenter during the Late Pennsylvanian (Donaldson and others, 1985). The basin was invaded at least 8 times by marine waters from the southwest during deposition of the Glenshaw Formation (Bush and West, 1987). During regressive episodes, fluvially dominated shallow water deltas prograded north and west across the basin (Donaldson, 1979; Donaldson and others, 1985). Possible causes that have been suggested for the transgressive-regressive couplets include glacioeustatic sea level changes (e.g. Bush and Rollins, 1984; Bush and West, 1987; Heckel, 1995), tectonic flexure (Donaldson and Eble, 1992), and delta switching (e.g. Ferm, 1970).

The study area is located along the southern limb of the Huntington-Parkersburg Syncline at the southeast end of the Dunkard Basin (Figure 1). Although strata are generally flat-lying with dips of less than 1 degree in Wayne County, the structural dip may locally reach 9 degrees toward the NNW along the Big Sandy River south of Buchanan, Kentucky.

STRATIGRAPHY

Introduction

Lithostratigraphic correlation of Pennsylvanian strata in the central Appalachian basin has been based on key beds including laterally persistent coal seams and marine units. In western and northern West Virginia, the lower Conemaugh Group (Glenshaw Formation) contains four widespread marine units composed of fossiliferous limestone and shale (Arkle and others, 1979). These include (in ascending order) the Brush Creek, Pine Creek, Woods Run, and Ames marine units.

Krebs and Teets (1913) described 3 of these marine units in Wayne County including the Brush Creek, Pine Creek and the Ames. More recent studies (Merrill, 1986, 1988, 1993; Martino and others, 1985; Martino 1992) have taken advantage of new roadcuts along I-64, U.S. 52 and U. S. 23 and have resulted in the recognition of 4 marine units which are used in this study (Figures 2 and 3). They include the 1) Lower Brush Creek, 2) Upper Brush Creek, 3) Cambridge, and 4) Ames. The current stratigraphic framework for the study area has evolved with the help of recent biostratigraphic studies (Sturgeon and Hoare, 1968; Merrill, 1979; Douglass, 1987).

Description of Stratigraphic Units

Stratigraphic sections at selected localities

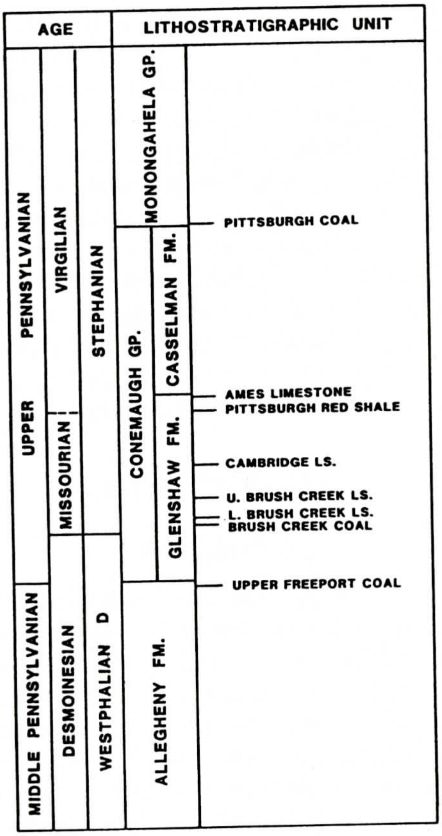

Figure 2. Stratigraphic framework for Late Pennsylvanian strata in the Huntington area (modified from Donaldson and others, 1985, and Merrill, 1993).

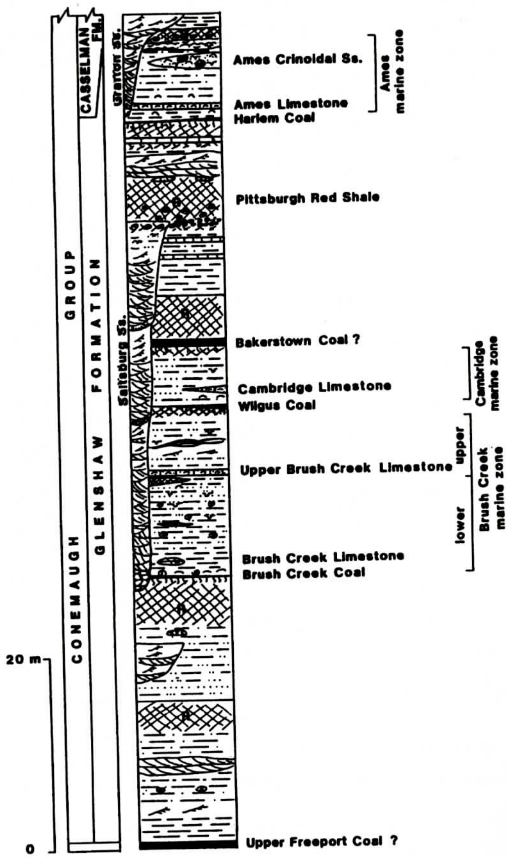

Figure 3. Composite section for the Glenshaw Formation in the Huntington area based out outcrops along I-64 (Huntington, WV to Cannonsburg, KY) and U. S. 52 west of Chesapeake, Ohio (modified from Martino, 1992). Cross-hatched patterns are paleosols (R=red). Palynologic analysis of the Princess 7 coal of Dobrovolny and others (1963) in the Catlettsburg area indicates it is more likely to be the Princess 9 coal, or Upper Freeport coal equivalent (C. Eble, 1996, personal communication).

are shown and correlated in Figures 4 and 5.

Upper Freeport-Brush Creek Coal Interval

In the Wayne area, this interval is 15-26 m thick and is largest where sandstones predominate.

The top of the Upper Freeport coal marks the base of the Glenshaw Formation. This coal has been locally mined in the Wayne area (ex. locality 19, Figure 5).

The Upper Freeport-Brush Creek coal interval contains a variety of facies. Channel-form bodies 6-10 m thick are common. Channel-fills at locality 19 consist of thick, cliff-forming sandstone (Mahoning Sandstone of Krebs and Teets, 1913) with compound cross-stratification. Cross-bedding within the channel-fills at locations 14, 16, and 19 dips toward the northwest. At locality 14, channel-fills contain abundant mudrocks along with thin sandstones.

Tabular or wedge-shaped bodies of ripple cross-laminated sandstone, siltstone, and shale are arranged in 0.5-1.5 m fining upward sequences. Plant fossils (ferns) are well preserved in some shales. Trace fossils at locality 14 include *Cochlichnus*, *Pelecypodichnus*, and *Planolites*.

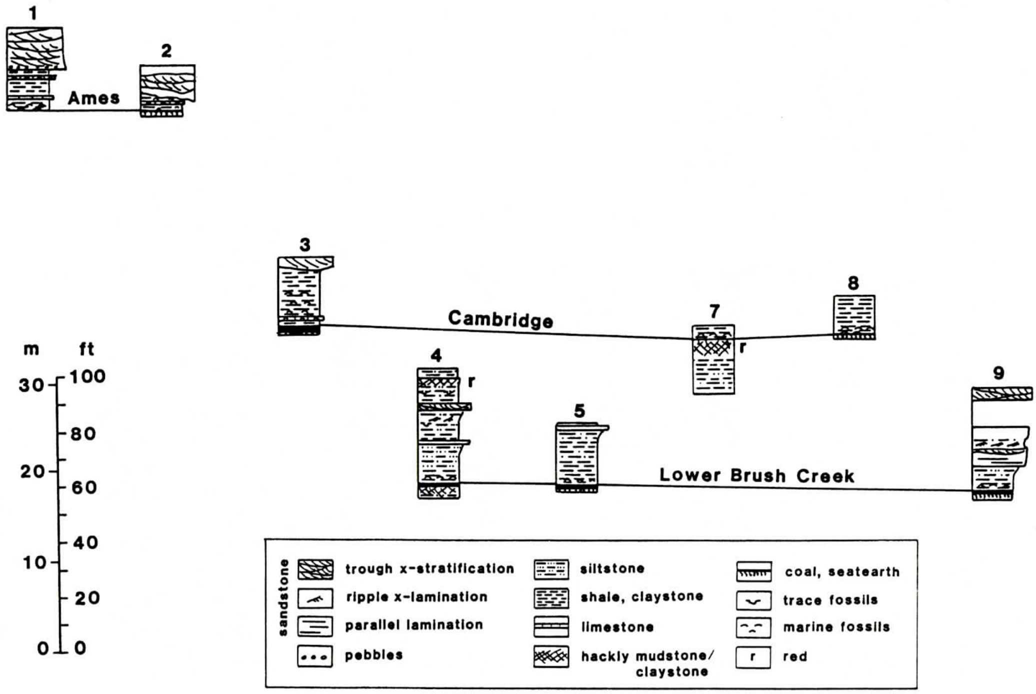

Figure 4. Stratigraphic sections for selected outcrops from Centerville to Wayne (see Figure 1C for locations 1-9). Correlation between sections is made at the base of the Ames, Cambridge, and Lower Brush Creek marine units. The sections descend stratigraphically through Figures 4 and 5 due to the northward structural dip along the southern limb of the Parkersburg-Huntington Syncline.

A thin bed of micritic, laminated limestone occurs about 11 m below the Brush Creek coal at location 14. Hackly, gray to olive green claystone and mudstone intervals 30 cm to 1 m thick also occur within the Upper Freeport-Brush Creek coal interval.

The Brush Creek coal is 2-40 cm thick. It is usually fissile and graded from bright coal at the base to carbonaceous shale toward the top.

Lower Brush Creek Marine Unit

Throughout the Wayne area the Brush Creek coal is overlain by a black, calcareous, fossiliferous shale and mudstone unit 0.5-1.0 m thick. This unit contains a variety of marine bivalves, gastropods, and brachiopods (Table 2, Figures 6 and 7).

The basal fossiliferous interval is succeeded by a 10 m thick coarsening upward sequence. Siderite occurs first as nodules in dark shale, then becomes thin beds which are interbedded with siltstone. The overlying sandstone comprises the Buffalo Sandstone of Krebs and Teets (1913). Flaggy sandstone beds 2-15 cm thick dominate in the lower portion and thicken and coarsen upward from very fine to fine grained. Parallel horizontal lamination is dominant. A flagstone quarry in this facies was opened in the 1950s at locality 12 (Cross and Schemel, 1956). Shale partings, coarse mica, and large plant fragments are abundant in the lower portion. Ripple bedding, ripple cross-lamination, low angle cross-lamination, and medium scale cross-beds in occur the middle and upper portions of the sandstone. Cross-beds have NW-dipping foresets. Burrows are common and include *Planolites* and *Teichichnus*.

A large channel-form sandstone 9 m thick and about 80 m in width truncates the coarsening upward sequence at location 15. Channel sandstones also occurs at this level at locations 13 and 16 (Figure 5). The channels are filled with fine-grained sandstone with medium to large scale trough cross-stratification. The

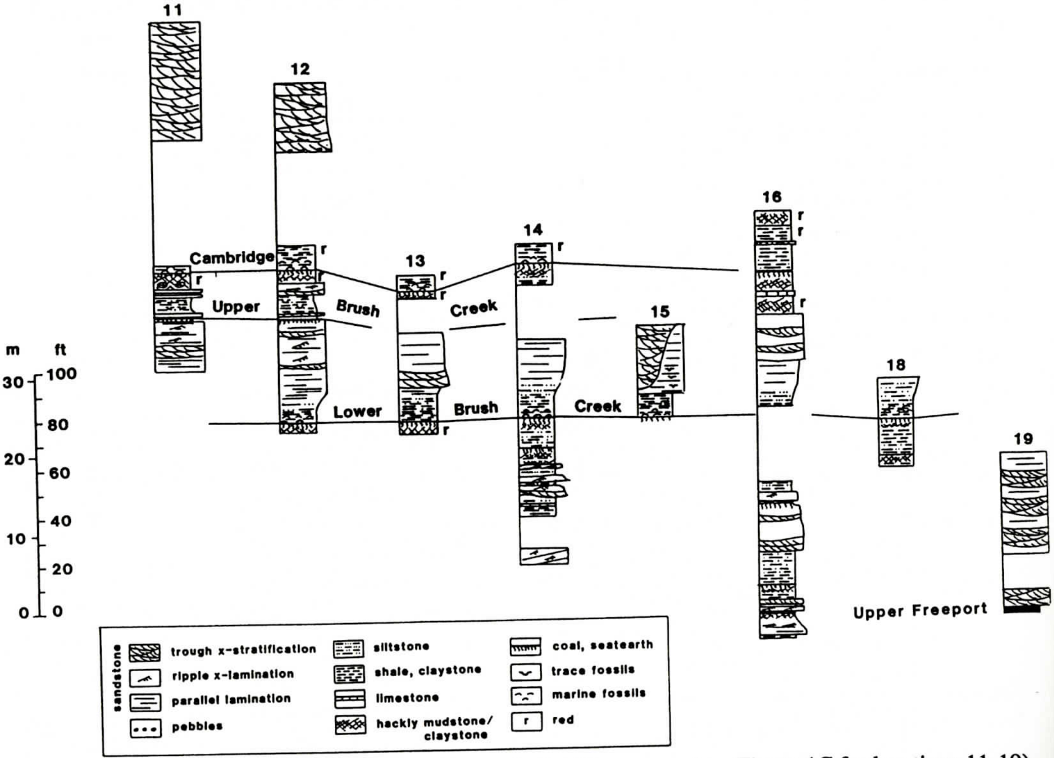

Figure 5. Stratigraphic sections for selected outcrops in the Wayne area (see Figure 1C for locations 11-19). Correlation between sections is made at the base of the Cambridge, Upper Brush Creek, and Lower Brush Creek marine units. Blank portions of columns are covered intervals.

sandstone interval is capped by a 40 cm thick, light gray seat earth and thin carbonaceous shale or coal.

Upper Brush Creek Marine Unit

The Upper Brush Creek marine unit is exposed only at localities 11 and 12 (Figure 5) and consists of light olive gray siltstone and shale with sparse burrows including *Teichichnus* and *Aulichnites*. Isolated sets of trough cross-bedded sandstones also occur. The interval coarsens upward into thin-bedded, current rippled sandstones and has a total thickness of 6.3 m.

A pinchout of the Upper Brush Creek marine unit occurs toward the southeast between locations 14 and 16. Burrowed siltstones and shales representing the marine unit at 14 pass laterally into hackly mudstone seat earths and nonmarine limestone at 16. The carbonate unit at locality 16 is 35 cm thick and contains granular allochems (*Spirorbis*? and ostracodes?) and wavy (algal?) laminations.

The Upper Brush Creek marine unit is bounded above by a 1-3 m thick mudstone seat rock interval which is light olive gray to red with angular blocky fracture. It is capped by thin carbonaceous clay which grades laterally into blocky coal up to 65 cm thick. A mine adit which is recorded on the Burnaugh 7.5' Quadrangle along Whites Creek about 1 mile SE of Centerville corresponds to the stratigraphic level of this coal (Figure 1C). The stratigraphic position of this coal correlates with that of the Wilgus Coal described in the Huntington area (Condit, 1912; Cross and Schemel, 1956).

Cambridge Marine Unit

This interval is up to 5.7 m thick. The basal portion consists mainly of highly fossiliferous olive green claystone 1.0-1.5 m thick. A 10-20 cm thick biomicritic limestone is present within this basal interval at localities 3 and 16. The rest

Table 2. Fauna from the Lower Brush Creek marine unit

	Relative Abundance
Bivalves	
Aviculopecten occidentalis	A
Aviculopecten sp.	A
Dunbarella knighti	A
Dunbarella striata	A
Edmondia anodontides	A
Edmondia gibbosa	A
Edmondia ovata	A
Edmondia reflexia	A
Edmondia sp.	A
Euchondria levicula	C
Nuculopsis croneisi	A
Nuculopsis girtyi	A
Nuculopsis sp.	A
Paleyoldia stevensoni	R
Permorphus sp.	R
Phestia arata	A
Phestia bellistriata	R
Schizodus wheeleri	C
Schizodus sp.	C
Brachiopods	
Composita sp.	R
Chonetinella (?)plebeia	R
Derbyia crassa	A
Derbyia parvicostata	A
Juresania nebrascensis	C
Lingula carbonaria	C
Linoproductus sp.	C
Gastropods	
Anomphalus sp.	C
Glabrocingulum sp.	C
Pharkidonotus girtyi	A
Schizostoma sp.	C
Stegoceolia sp	C
Trochonema sp.	R
Worthenia sp.	C

Table 3. Fauna from the Cambridge marine unit.

	Relative Abundance
Bivalves	
Acanthopecten meeki	C
Acanthopecten carboniferous	C
Aviculopecten sp.	C
Dunbarella striata	R
Edmondia nodulifera	C
Fasciculiconcha knighti	R
Parallelodon tenuistriatus	R
Brachiopods	
Antiquatonia portlockiana	
var. crassicostata	A
Cancrinella boonensis	R-C
Chonetinella flemingi	C
Chonetinella verneuliana	A
Derbyia parvicostata	C
Derbyia crassa	R
Juresania nebrascensis	
var. pulchra	A
Linoproductus magnispinus	R
Linoproductus sp.	C
Neospirifer latus	C
Pulchratia symmetrica	
var. regularis	R
Gastropods	
Bellerophon sp.	R
Bryozoans	
Fenestrellina sp.	R-A
Echinoderms	
crinoid plates, stems	C
Foraminifera	
fusulinids	C
Arthropoda (Trilobita)	
Ditomopyge	R
or	
Griffithides	

of the unit consists of thin-bedded predominantly pale red to olive-gray shale. Fossils are sparse or absent in this portion of the section.

The claystone-shale fauna includes brachiopods (productids, spiriferids, chonetids), crinoids, pectenid bivalves, and fenestellid and

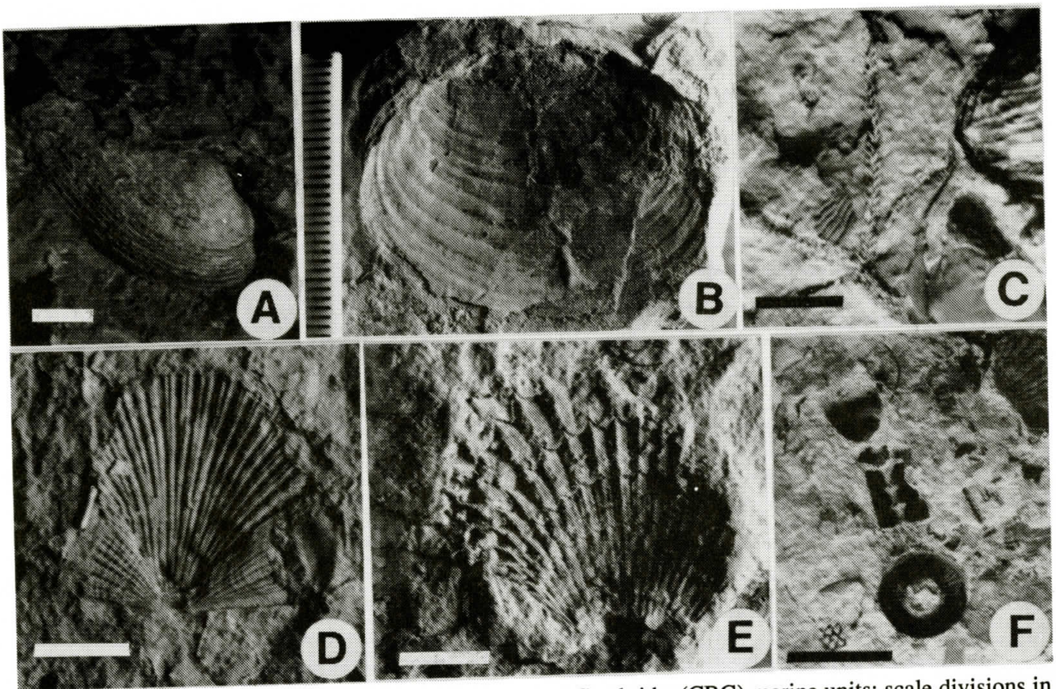

Figure 6. Fauna from the Lower Brush Creek (LBC) and Cambridge(CBG) marine units; scale divisions in mm, bar scale is 5 mm. A: *Phestia arata*, LBC; B: *Edmondia* sp., CBG; C: dendroid bryozoan, CBG; D: *Aviculopecten* sp., CBG; E: *Acanthopecten carboniferous*, CBG; F: crinoid plate and column, CBG. (See Tables 2 and 3 for complete list of taxa).

branching bryozoans (see Table 3, Figures 6 and 7). Thin sections reveal the carbonate unit to be a packed biomicrite with disarticulated echinoderms, branching bryozoans, brachiopod shells and spines, ostracodes, green algae, and fusulinid foraminifera 0.8-0.9 mm in length.

Saltsburg Sandstone-Ames Limestone Interval

At most locations in the study area, this interval is covered or occupied by thick channel sandstone which corresponds to the Saltsburg Sandstone of Krebs and Teets (1913). At localities 11 and 12, pebbly trough cross-stratified channel-fills 9-15 m thick occur from 16 to 31 m above the base of the Cambridge marine unit (Figure 5).

A coal underlies the Ames marine unit and is exposed at locality 2. This coal is 25 cm thick and is bright and blocky with a dulling upward into carbonaceous shale. The coal corresponds with that described as the Harlem coal by early workers in Wayne County (Krebs and Teets, 1913; Cross and Schemel, 1956).

Ames Marine Unit

The Ames marine unit is exposed only at locations 1 and 2 in the northwestern corner of the study area (Figures 1C and 4). At most locations, outcrops at this interval are composed of channel sandstones that may have truncated the Ames Member. It is also possible that the Ames Member pinches out southeastward between Centerville and Wayne, but conformable continuous sections that could confirm this are lacking.

At locality 1, the Ames Member is 4.5 m thick. Olive gray mudstone predominates with three sideritic, biomicrite beds that are 10-25 cm thick. Thin sections reveal brachiopod shells and spines, bivalves, crinoid plates, rare dendroid bryozoans, and red? and blue-green algae. Allochems show moderate sorting.

At locality 2, the Ames Member is 1.5 m

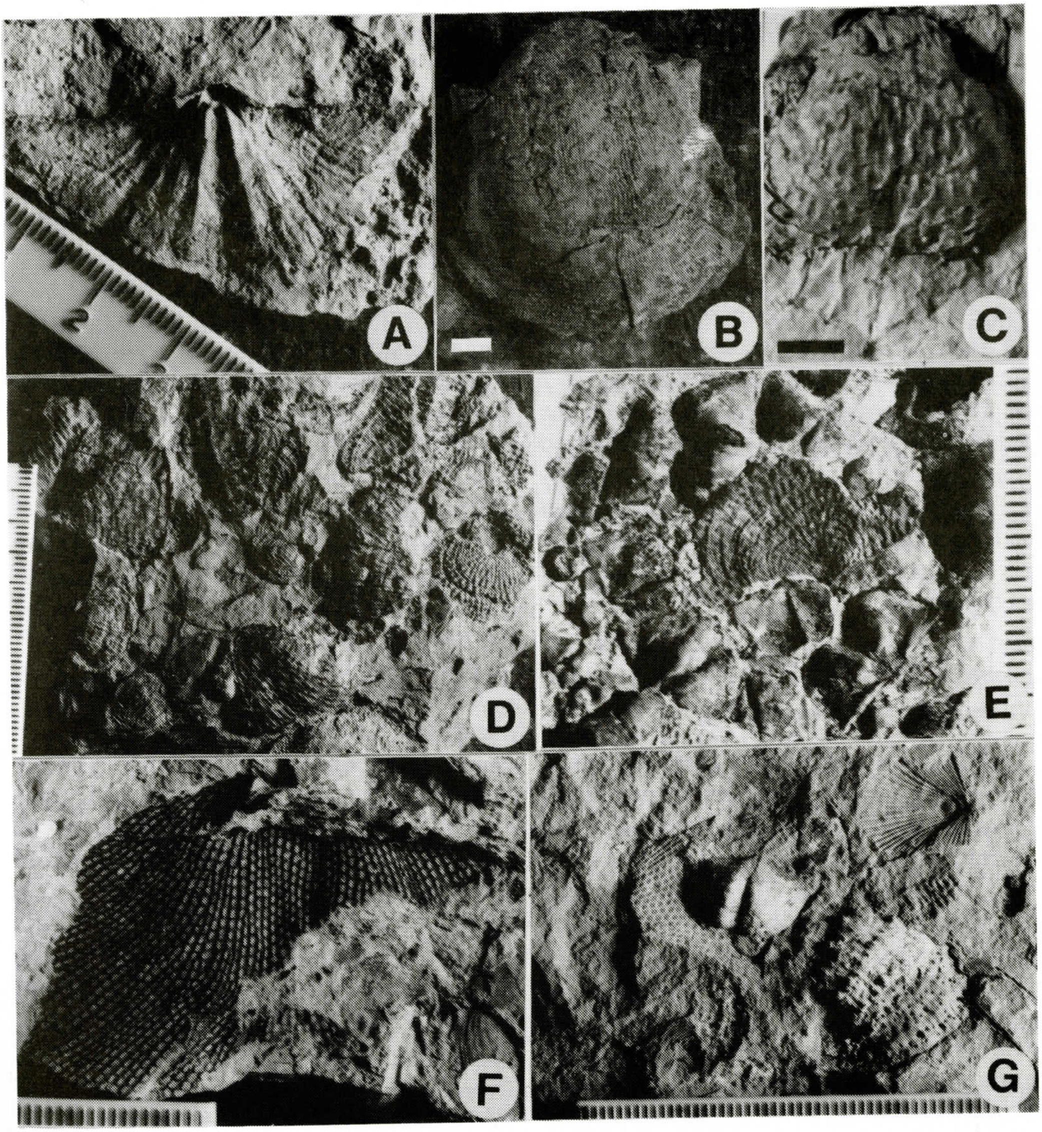

Figure 7. Fauna from Lower Brush Creek (LBC) and Cambridge (CBG) marine units; scale divisions in mm, bar scale = 5 mm. A: *Neospirifer latus*, CBG; B: *Linoproductus* cf. *L. magnispinus*, LBC; C: *Juresania nebrascensis* var. *pulchra*, LBC; D: abundant productid brachiopods, mainly *Juresania* sp., CBG; E: *Chonetinella flemingi*, and brachial valve of *Juresania* sp. (center), CBG; F: fenestrate bryozoan, CBG; G: *Chonetinella flemingi* (center), fenestrate bryozoan (left center), *Aviculopecten* sp. (upper left), and *?Pulchratia* sp. (lower right), CBG.

thick and is composed mainly of olive green mudstone. Two thin biomicrite beds also occur in this interval. Fossils include abundant chonetid brachiopods; bivalves, gastropods and crinoids are also present.

The original thickness of the Ames Member at location 1 and 2 has been reduced by subsequent erosion in association with the overlying channel sandstone.

DISCUSSION

Stratigraphic Correlation

The principle key units that permit correlation throughout the Wayne-Centerville area include the Brush Creek coal, Lower Brush Creek marine zone, and Cambridge marine zone. These units can be readily correlated with extensive outcrops previously described along the Big Sandy River (Martino and others, 1985; Merrill, 1986, 1988; Martino, 1992; Figures 2 and 3). The correlation of marine units of this study is consistent with the chonetid brachiopod ranges of Sturgeon and Hoare (1968). *Neochonetes granulifer* is found in the Ames and not the Cambridge, while *Chonetinella flemingi* and *C. verneuliana* occur in the Cambridge but not the Ames.

Depositional Environments

Fluvial Channel Sandstones

Sandstones interpreted as river channel facies occur 1) between the Upper Freeport-Brush Creek coals 2) between the Cambridge and Ames marine units, and 3) above and in place of the Ames marine unit. Field observations of cross-bed dips toward the W, NW and N are consistent with paleogeographic reconstruction of Donaldson (1979). The channel-fills are comparable to those described from the Glenshaw along the Big Sandy River (Martino and others, 1985; Merrill, 1986). Cosets of medium to large scale trough cross-stratification form in response to the migration of 3-dimensional dunes under unidirectional flow in the upper part of the lower flow regime (Harms and others, 1982). Horizontally laminated fine to medium sandstone in these channel-fills may indicate the development of upper plane bed conditions as river discharge fluctuated through time. The fining-upward trend within these units likely reflects decreasing flow strength from the channel thalweg up the slipface of laterally accreting point bars that produced epsilon cross-strata.

Flood Basin Facies

Crevasse splays are represented by fining-upward sandstone units 0.5-4 m thick below the Brush Creek coal at locality 14. These units have sharp bases with minor relief and mud intraclasts that are indicative of minor scouring of the flood plain followed by deposition during waning flow. Trough cross-stratification with sets thicknesses of 2-15 cm are indicative of the formation and migration of small 3-dimensional dunes and ripples (Harms and others, 1982).

The trace fossils *Cochlichnus*, *Pelecypodichnus*, and *Planolites* have been described from crevasse splay facies in the Westphalian coal measures of Britain (Pollard, 1988). Hakes (1985) reported these traces in Late Pennsylvanian brackish water facies of Kansas. *Cochlichnus* has been attributed to crawling/feeding activities of small worm-like animals in sediments of low salinity paleoenvironments (Eagar and others, 1985), whereas *Pelecypodichnus* is interpreted as a bivalve resting track common in marginal marine and nonmarine facies (Pollard, 1988).

Paleosols are represented by massive, hackly mudstones and claystones that contain soil horizons and soil structure. Paleosols have been found at 7 levels within the Glenshaw in the Wayne-Centerville study area. The hackly character of these units is the result of the development of peds and cutans. These commonly manifest themselves in outcrop as angular blocky fracture. Slickensides are common in the paleosols. These commonly develop where highly smetitic clays are subjected to shear stresses produced by swelling and shrinkage in response to wetting and drying (Retallack, 1988, 1990). The paleosol intervals are laterally persistent although lateral variations in character are typical.

At many locations, paleosols are capped by coals. These coals may pinch out laterally into thin carbonaceous bands about 1 cm thick. The lateral variability in paleosols is analogous to that reported by Bush and Brezinski (1984) for Glenshaw paleosols, the tops of which they interpreted as representing climate change surfaces which bound fifth-order transgressive-regressive units (see "Transgressive-Regressive Cycles").

Paleosol horizons are distinguished by variations in color, grain size, soil structure and composition. Complete profiles may begin with a coal overlying a gleyed (dark to light grey underclay). The underclay is underlain by greenish gray mudstone which may grade downward into variegated mudstone (red-green-gray), or predominantly red mudstone. Carbonate nodules (siderite or micritic calcite) are common in the lower portions of many profiles. Distinct root traces are uncommon. Their paucity is probably due to destruction by oxidation.

While paleosol development is a process that operates in flood basin environments, the relatively thick profiles and distinctness of horizons suggests long periods of time without significant sediment influx. It seems more likely that such soils would have developed in interfluves above the level of regular flooding. Such areas would have been broadly developed during times of lowered base level and channel incision during sea level lowstands, a view recently reiterated by Heckel (1995).

Donaldson and others (1985) correlated the dry portion of Late Pennsylvanian climate cycles with the development of lacustrine carbonates in topographic lows and Vertisols in higher, better drained portions of the coastal plain. Both Vertisols and Aridisols developed during the Late Pennsylvanian (Cecil, 1990). Wet phases of the climate cycles led to the developement of planar swamps in topographic lows. Heckel (1995) proposed that wet portions of the climate cycle were induced by higher moisture availability at times of maximum extent of epeiric seas (i.e. glacioeustatic highstands).

Lacustrine Carbonates

Two micritic limestone beds occur which are likely to have formed as alkaline lacustrine deposits.The first unit occurs at locality 14 (11 m below the Brush Creek coal) and contains abundant flat platy shale clasts. It occurs just beneath the splay facies previously described. The second example occurs at locality 16 below the Wilgus coal. It is 35 cm thick with crude thin wavy layers, and occurs between two hackly claystones interpreted as paleosols. Both limestones are brecciated.

The appearance and abundance of lacustrine carbonates during the late Middle and Late Pennsylvanian in the Appalachian Basin has been linked to northward drift of the North American continent across the equator, causing the climate to become increasingly more arid (Schutter and Heckel, 1985; Cecil, 1990). The long term drying continued during deposition of the Glenshaw Formation and is indicated by the development of Aridisols and associated caliche, and increasing frequency of lacustrine carbonates and Vertisols (Cecil, 1990).

Marine Units

Marine zones typically consist of a package of sedimentary facies deposited in open to marginal marine environments (Martino, 1994). They are usually bounded by paleosols or fluvial channel facies. During the Pennsylvanian Period, an epeiric sea made numerous incursions from the southwest into the study area advancing along the axis of the Appalachian Basin (Donaldson and others, 1985). The Ames Seaway and likely other Glenshaw seas were elongated and somewhat restricted by the Appalachian Orogen to the southeast and the emergent craton to the northwest (Donaldson and Schumaker, 1979; Bush, 1984).

The Lower Brush Creek marine zone contains a dominantly mollucsan fauna (Table 2). Body fossils are restricted to the basal 1.0-1.5 m of the marine zone which begins at the top of the Brush Creek coal. At some locations, a transitional interval dominated by *Lingula* separates the Brush Creek coal from highly fossiliferous shale containing a variety of bivalves and gastropods (Figures 8 and 9). Bivalves commonly include Nuculoids (*Nuculopsis*, *Phestia*), *Schizodus*, and *Edmondia* which are burrowing forms, and *Dunbarella* and *Aviculopecten* which were probably epibyssate suspension feeders (Stanley, 1970, 1972; Hoare and others, 1979). Ostracodes are also abundant in this interval.

Boardman and others (1984) have described depth-related benthic assemblages associated with North American mid-continent cyclothems. The Brush Creek assemblages correspond to their *Lingula* dominated nearshore community and shallow water, nearshore molluscan community. The constituent taxa are generally eurytopic and tolerant of restricted marine conditions. Boardman and others (1984) also described eurytopic, mollusc-rich communities from deeper water. However, these are accompanied by abundant cephalopods and phosphorite, elements that are absent in the Brush Creek localities of this study.

The upward decrease and disappearance of marine invertebrates occurs in association with increasing amounts of siderite (first as nodules, then as thin beds), silt-very fine quartz sand, mica, and plant fragments. These features reflect the onset of more rapid rates of sedimentation, turbidity, and dilution that inhibited colonization of the substrate by shelly invertebrates which had been successful during the peak of the transgression.

The coarsening upward interval is interpreted as a prograding delta front facies produced by rapid deposition from sediment-laden outflow of deltaic distributaries. Cross-stratified channel-fills that are incised into these coarsening upward intervals were produced by active deltaic distributaries. The trace fossil *Teichichnus* is found in Pennsylvanian shallow to marginal marine facies of the Appalachian Basin (Miller and Knox, 1985; Martino 1989, 1994; Greb and Chesnut, 1994) and is thought to be the product of an intrastratal deposit-feeder, possibly a polychaete worm (Hantzschel, 1975). *Planolites* also represents an endichnial burrow produced and actively backfilled by a worm-like deposit feeder (Hantzschel, 1975; Pemberton and Frey, 1982).

Interbedded sandstones and shales of the Upper Brush Creek marine zone include the trace fossils *Teichichnus* and *Aulichnites*. *Aulichnites* is a bilobed trail thought to have been produced by crawling and/or grazing gastropods (Hantzschel, 1975). It has been reported from Pennsylvanian deltaic and marginal marine facies in West Virginia (Martino, 1989), Kansas (Hakes, 1977), and England (Eagar and others, 1985). Though marine-influenced, this environment was apparently too stressful to allow colonization by shelly invertebrates. Likely sources of stress include substrate instability due to periodic traction transport and high depositional rates, turbidity, and freshwater influx. This stratigraphic interval does contain lenticular bodies of crinoidal sandstone to the northwest along the Big Sandy River (Martino and others, 1985).

The Cambridge marine zone contains a fauna that is distinguished from that of the Lower Brush Creek by the greater abundance of productid and chonetid brachiopods, and the presence of fenestellid bryozoans, crinoid columns and plates, sponge fragments and fusulinid foraminifera.

The Cambridge assemblage is similar to the moderate depth, stenohaline communities of Boardman and others (1984) for mid-continent Pennsylvanian cyclothems. The prevalence of epifaunal suspension feeders (brachiopods, pectenid bivalves, bryozoans, sponges, crinoids) suggests generally slow rates of deposition and relatively clear water that was likely to have been well-oxygenated. The Cambridge assemblage appears to be more open marine compared to the mollusc-dominated Lower Brush Creek marine zone. However, seaways extending into the Dunkard basin were elongated and restricted (Bush, 1984) and conodont biofacies suggest that salinities were somewhat reduced during deposition of Glenshaw marine units in the Huntington area (Merrill, personal communication). Furthermore, Bush and West (1987) have suggested the maximum water depth for Glenshaw marine units was probably less than 15-20 m.

The reduction or absence of marine invertebrates in overlying red and green shales probably reflects substantially increased turbidity, sedimentation rates, and dilution in salinity associated with regression of the Cambridge Sea. The absence of any evidence of exposure in these shales (ex. mudcracks, rain drop impres-

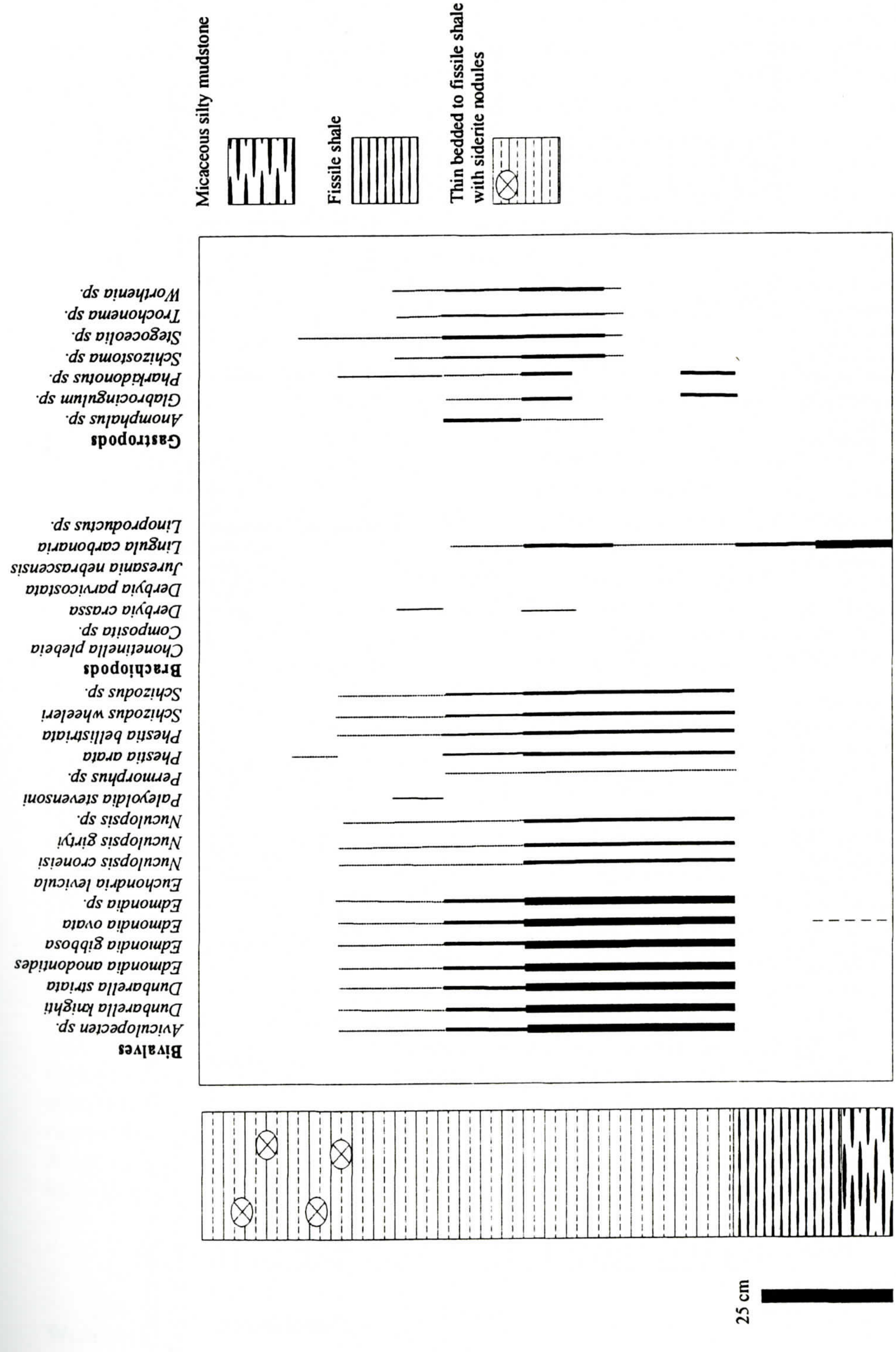

Figure 8. Stratigraphic column and vertical distribution of invertebrates from the Lower Brush Creek marine zone at location 15. Ranges are based on continuous incremental sampling of 10 to 30 cm thick intervals from the top of the Brush Creek coal to the highest occurrence of body fossils. A = abundant, C = common, R = rare.

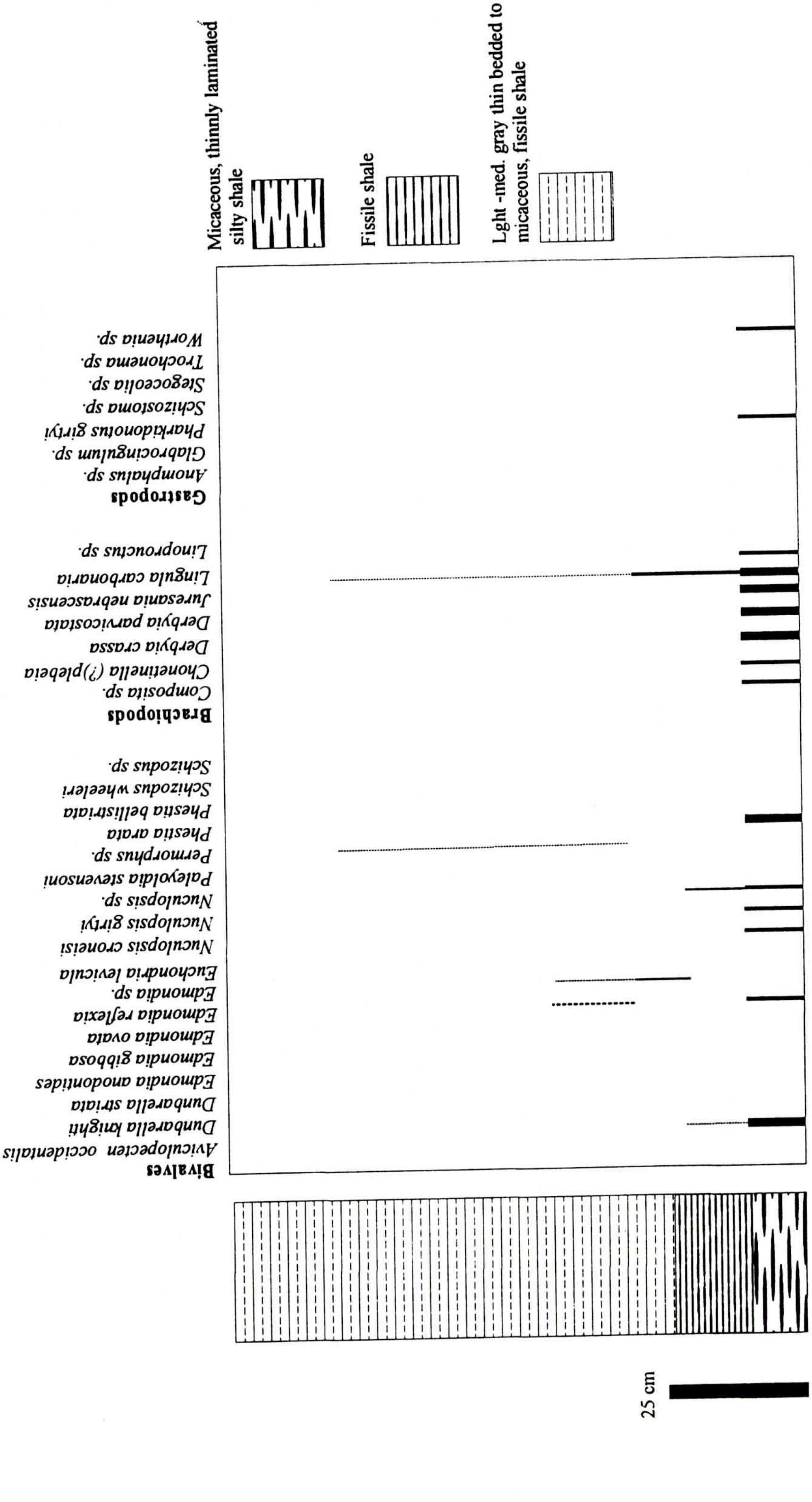

Figure 9. Stratigraphic column and vertical distribution of invertebrates in the Lower Brush Creek marine zone at location 12. Sampling procedure as in Figure 8. A = abundant, C = common, R = rare.

sions, root traces, peds and cutans) suggests sedimentation was entirely subaqueous. The red color may have been inherited from well-drained paleosols which were reworked by fluvial erosion and deposited in stressed nearshore environments with insufficient organic material to reduce the hematite-stained pedogenic clays.

The Ames marine unit at locations 1 and 2 contains a basal interval that corresponds to the green chonetid shale facies of Merrill (1993). A lagoonal origin has been suggested for this Ames facies (Saltsman, 1986; Merrill, 1993). Chonetid brachiopods have been perceived as eurytopic and tolerant of nearshore eurytopic conditions that occur immediately following marine inundation of coastal swamps during the Pennsylvanian (Saltsman, 1986; Merrill, 1993; Bennington, 1996).

The biomicrites from the upper part of the Ames marine unit at locality 1 contain abundant echinoderms and brachiopod shells and spines that suggest somewhat more open marine deposition than the basal chonetid rich shales, but some transport is indicated by size sorting, disarticulation, and presence of quartz sand.

The abundance and dominance of mollusks in the Lower Brush Creek marine unit may be the result of higher organic matter in the enclosing mud which may have protected aragonite from dissolution prior to compaction. This phenomenon has been reported elsewhere in the Ames marine unit (Saltsman, 1986; Merrill, 1993). Furthermore, the well-preserved condition of mollusk shells in the black shales of the Lower Brush Creek compared to their occurrence as molds where present in the green mudrocks of the Cambridge and Ames marine units offers additional support for the idea that organic matter insulated the molluscs from dissolution even after compaction. Early carbonate cement in biomicritic limestone nodules of the Ames may also have helped to preserve mollusks (Merrill, 1993).

Transgressive-Regressive Cycles

Pennsylvanian cyclothems were defined by Weller (1930) and Wanless and Weller (1932) for repetitive sequences of transgressive-regressive strata in the Illinois and northern Appalachian Basins. Since that time much debate has surrounded the origin of these facies sequences, particularly with regard to relative importance of autocyclic or allocyclic causative mechanisms.

The four transgressive-regressive marine units of this study are 5-13 m thick and correspond to the fifth order cycles of Bush and Rollins (1984) and the minor allocycles of Donaldson and Eble (1991). These and other workers (Bush and West, 1987; Veevers and Powell, 1987; Heckel, 1995) attribute this type of cycle to glacioeustatic sea level changes. Alternative mechanisms for allocycles include climate change (Cecil, 1990) and tectonic factors (Tankard, 1986; Donaldson and Eble, 1991). Merrill (1986) questioned the use of the term cyclothem for Glenshaw transgressive-regressive couplets citing a lack of lateral continuity for individual rock types ("lithosomes"). The perceived local extent of marine units was attributed to shifting deltaic depocenters as conceived by Ferm (1970) for Middle Pennsylvanian strata of the central Appalachian Basin. Indeed, some beds of crinoidal limestones can be traced laterally into faunally barren calcareous sandstones which in turn pinch out within a single outcrop. In other cases, the lack of lateral continuity is due to incision of later fluvial channel systems. While individual marine beds do not persist for great distances, packages of marine-influenced strata as well as their bounding paleosols do have considerable areal extent.

The data in this study are from a small area of approximately 34 square miles. Yet they suggest that the 4 marine units and certain paleosols may be correlated throughout the southern part of the Dunkard Basin. Further fieldwork is needed to test this idea and the degree to which the 11 fifth order T-R cycles of Bush and Rollins (1984) may be distinguishable in the southern portion of the Dunkard Basin.

Implications for Paleoshorelines

Previous attempts to identify paleoshorelines of Glenshaw marine units (e.g. Bush, 1984; Bush and West, 1987) in West Virginia have been hindered by a lack of data.

The Cambridge marine unit had not previously been reported in southern West Virginia. Its occurrences in the study area allow for refinement of the paleogeography during the Cambridge transgression (Figure 10). Furthermore, the relatively open marine stenotopic character of its fauna in the Wayne area suggests that it is likely be the most geographically extensive of the Glenshaw marine units in this part of West Virginia.

The paleogeography of the Lower Brush Creek marine invasion portrayed by Bush and West (1987) is consistent with Lower Brush Creek data in our study area, while their Upper Brush Creek shoreline is a few miles north of the Upper Brush Creek localities in this study.

Merrill (1988) projected a shoreline for the Ames Sea between Buchanan and Louisa based on southward thinning trends and apparent absence of the Ames Member in the Louisa area. Syndepositional flexure was suggested as a structural constraint for the southern limit of the Ames Sea. This view is consistent with the currently known distribution of the Ames Member being limited to the region north of the southern limb of the Parkersburg-Huntington Syncline.

Recent fieldwork in the Hamlin-West Hamlin areas of Lincoln County (11 miles east of current study area) suggests that none of the Glenshaw marine units are present. The paleoshorelines for the Lower Brush Creek, Upper Brush Creek, and Cambridge marine units probably lie between Wayne and West Hamlin.

CONCLUSIONS

Outcrops from 20 locations in the Wayne, Prichard, and Burnaugh 7.5' quadrangles have enabled the stratigraphy of the Glenshaw Formation to be elucidated in this area and correlated with the stratigraphic framework established for the Glenshaw Formation in the Huntington area (Martino and others, 1985; Merrill, 1986; Martino, 1992). Four marine units including the Lower Brush Creek, Upper Brush Creek, Cambridge, and Ames are present and their occurrence helps to confirm or refine previous paleogeographic reconstructions. The fauna of these marine units reflect marginal marine eurytopic taxa to moderate depth stenotopic forms and includes bivalves, gastropods, brachiopods, crinoids, bryozoans, trilobites, sponges, ostracodes, red? and green algae, and fusulinid foraminifera.

The Cambridge marine unit has been recognized for the first time in southern West Virginia and was found at 10 localities in central Wayne County. Its persistent distribution and relatively open marine fauna, combined with the scarcity or absence of the Ames marine unit, make it and the Lower Brush Creek marine unit the primary marine units for stratigraphic correlation and geologic and structural mapping in central and southern Wayne County.

The Glenshaw Formation is about 70 m thick and is comprised of 3 broad divisions. The lower 15-26 m (Upper Freeport-Brush Creek coal) consists of alluvial channel and flood plain deposits representing swamps, lakes, crevasse splays, and interfluvial paleosols. The medial portion of the formation contains 3 paleosol-bounded marine units (Lower Brush Creek, Upper Brush Creek, Cambridge) over a stratigraphic interval of about 25 m. The upper 25 m is composed mainly of fluvial channel sandstones with the Ames marine unit being locally preserved in the northwest portion of the study area.

The continuity of marine units and the presence of well-developed, widespread paleosols in the Huntington-Wayne area suggests that most or all of the 11 allocycles proposed for the Glenshaw Formation in Ohio and Pennsylvania (Bush, 1984; Bush and Rollins, 1984) may be recorded at the southern end of the Dunkard Basin. Further work on a larger scale is needed to clarify those stratigraphic features that are due to autocyclic processes, local syndepositional tectonics (growth faults, flexures),

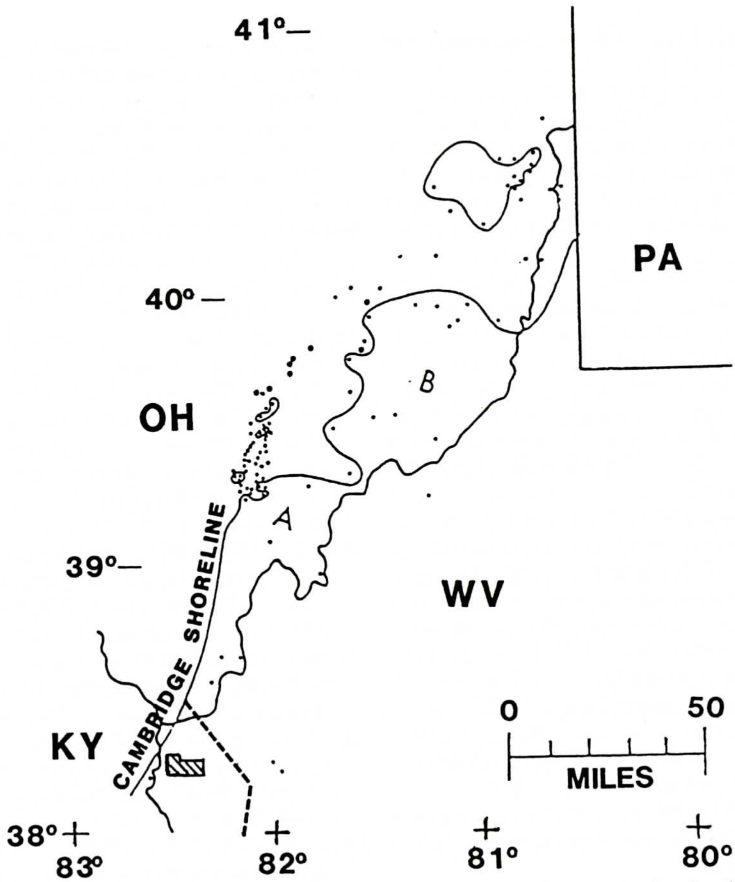

Figure 10. Cambridge Sea paleoshoreline from Bush and West (1987) and revised paleoshoreline position (shown by dashed line) in the Huntington-Wayne area based on 10 Cambridge localities described in this study (shaded area, corresponding to Figure 1C). Data points and possible delta lobes (A and B) are from Bush and West (1987).

and basinwide or interbasinal processes including sea level, climate, and tectonic factors.

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BIOTITE PHENOCRYST COMPOSITION SHOWS THAT THE TWO K-BENTONITES IN THE LITTLE OAK LIMESTONE (ORDOVICIAN) AT THE OLD NORTH RAGLAND QUARRY, ALABAMA, ARE THE SAME STRUCTURALLY REPEATED TEPHRA LAYER

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ABSTRACT

Biotite phenocrysts in two Ordovician K-bentonites in the Little Oak Limestone at the Old North Ragland quarry, near Ragland, Alabama, are nearly pristine compositionally, and electron microprobe analyses provide a precise geochemical fingerprint of each bed. Graphs of Al_2O_3 vs. FeO*, MnO vs. FeO*, MgO vs. FeO*, Al_2O_3 vs. MgO, and FeO*/MgO vs. TiO_2 show that the compositional variability between biotite phenocrysts from the two beds is very small. From this we conclude that these two K-bentonite beds, whose texture (color, grain size, fissility) is essentially identical as well, are the same tephra layer that has been repeated. The upper bed wedges out abruptly within the quarry, and our findings suggest that the repetition is the result of wedging and structural duplication rather than stratigraphic pinchout.

INTRODUCTION

Discrete beds of altered tephra known as potassium bentonites (K-bentonites) occur throughout Middle and Upper Ordovician strata of the central and southern Appalachians. Since the initial descriptions of these beds by Nelson (1921, 1922, 1926), Butts (1926), and Ross (1928), many additional investigations have been made (see summaries in Haynes 1992, 1994). The potential stratigraphic value of these Ordovician tephras has been recognized by nearly all who have studied them, but regional correlations between even the most well-studied sections have generally been only moderately successful because of difficulties in discriminating one bed from another. This is a very real problem in this region, where upwards of 15 such beds have been reported at a single exposure. As a result, attempts by many geologists — including us initially — at corroborating or even repeating earlier correlations were largely unsuccessful.

With continual improvements in the

geochemical basis of tephra stratigraphy, many earlier proposed correlations have been refuted or reinterpreted (Haynes and Huff 1990; Haynes 1992; Haynes and others 1995). This geochemical scrutiny has also resulted in the substantiation of other proposed correlations (Haynes 1992, 1994), including the across-strike correlations proposed by Fox and Grant (1944) and Milici and Smith (1969), and the essentially along-strike correlations proposed by Rosenkrans (1936), Hergenroder (1973), and Huff (1983). Wireline logs have also been successfully used in the regional correlation of two of the most widespread tephras, the Deicke and Millbrig K-bentonites (Huff and Kolata 1990).

Attempts at using whole rock geochemical data obtained by neutron activation analyses to correlate the Deicke and Millbrig into and within the Valley and Ridge have met with little success (Huff and Kolata 1990; W.D. Huff, personal communication, 1994). This method, which employs discriminant analysis, has been effective at demonstrating correlations in the Valley and Ridge only in local areas characterized by unchanging facies (e.g. Cullen-Lollis and Huff 1986). Nonetheless, correlation of the Deicke and Millbrig along and across strike within the Valley and Ridge has been successfully accomplished on the basis of phenocryst composition in conjunction with physical stratigraphic methods (Haynes 1992, 1994; Haynes and others 1995). This successful correlation of the Deicke and Millbrig K-bentonite beds has accelerated the development of a regional stratigraphic framework for Middle and Upper Ordovician strata in the southern Appalachians (Haynes 1992, 1994). This framework has facilitated other lithostratigraphic investigations throughout the region as well (Haynes and Goggin 1993, 1994; Goggin and Haynes 1995).

In this paper we present our study of biotite phenocryst compositions in two Ordovician K-bentonites that are present in the uppermost Little Oak Limestone at an abandoned quarry in the Cahaba Valley near Ragland, Alabama (Figures 1-3). This is a more detailed account of initial results presented in an abstract (Haynes and Melson 1995) and it is part of our continuing study of Ordovician K-bentonites in eastern North America. The two K-bentonites near Ragland were first mentioned by Butts (1926), and then subsequently they have been discussed to varying extents by Cooper (1956), Kiefer (1970), Drahovzal and Neathery (1971), Schmidt (1982), Haynes (1994), and Haynes and Melson (1995). Based on handwritten notes accompanying the samples that Butts deposited in the Smithsonian collection, Butts visited the quarry in November 1925 and sampled both beds at that time. Butts (1926) noted that both the Little Oak and Stones River limestones in Alabama contained K-bentonites, and on this basis he suggested that the K-bentonites in the Little Oak were of Blackriveran age, like the K-bentonites in the Stones River, which were better constrained paleontologically. Because the outcrops of the Little Oak near Ragland are separated from those of the Stones River to the northwest by two major regional faults, the Helena and Coosa (Eden), and probably by other faults as well (Butts 1926; Drahovzal and Neathery 1971; Haynes 1994), the stratigraphic relations of the K-bentonites on either side of these faults have remained poorly understood. Butts (1926) suggested that they might somehow be correlative with the K-bentonites he observed at many places from Birmingham to Ft. Payne, but on the basis of conodont studies Drahovzal and Neathery (1971) and Schmidt (1982) argued that the K-bentonites in the Little Oak are older than the K-bentonites in the Stones River.

Although the stratigraphy, paleontology, and sedimentology of the Little Oak Limestone at Ragland have been described in varying degrees of detail, there has been no petrologic investigation of these two K-bentonites to date, even though most geologists who have studied these exposures have noted their presence. We began our study of the two beds in 1994, focusing on phenocryst assemblages and compositions. The composition of biotite phenocrysts in both beds is strikingly similar, suggesting that the two beds may be a single tephra layer. The simplest explanation for the apparent repetition of the bed is a structural one, possibly a wedg-

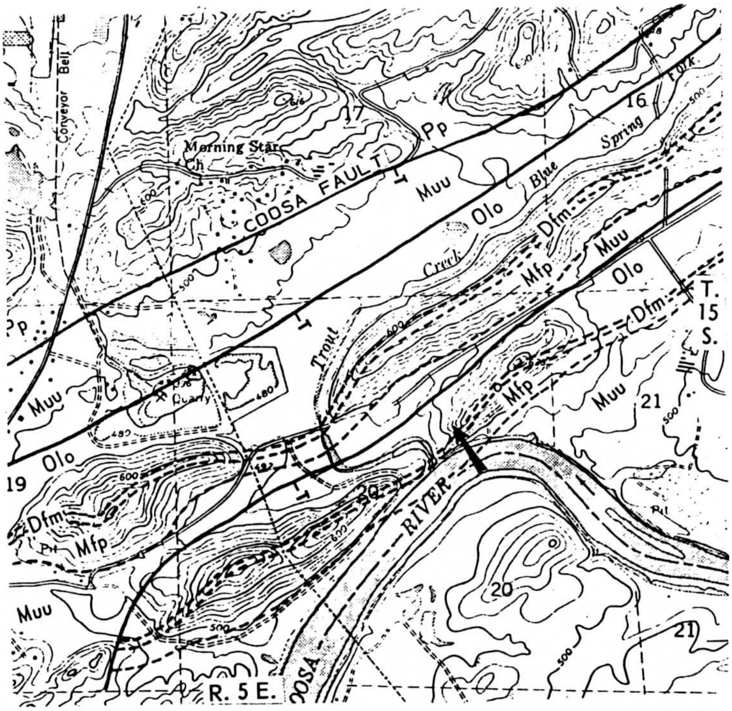

Figure 1. Geologic map of part of the Ragland 7 minute quadrangle, scale 1:24000. The location of the Old North Ragland Quarry is shown by the arrow. Olo = Little Oak Limestone (Ordovician), Dfm = Frog Mountain Formation (Devonian), Mfp = Fort Payne Chert (Mississippian), Muu = Parkwood Formation and Floyd Shale (Mississippian), Pp = Pottsville Formation (Pennsylvanian). Solid lines denote thrust faults with "-T" on the upthrown side; dashed lines denote formation boundaries. From Thomas and Drahovzal (1974, p. 4).

ing of strata in and around the quarry. Wedging and bedding plane slips are common Appalachian structures at all scales (Cloos 1964), and wedging may provide the most straightforward explanation for the duplication of what we interpret to be a single layer of altered volcanic ash. We refer herein to this bed informally as the Ragland K-bentonite pending a more rigorous regional stratigraphic comparison with the Ordovician K-bentonites in the Stones River Group (Haynes 1994).

REGIONAL SETTING OF THE LITTLE OAK LIMESTONE

In the vicinity of Ragland, St. Clair County, Alabama, the Middle (?) Ordovician (Chazyan) Little Oak Limestone, named and first formally described by Butts (1926), occurs in two principal outcrop belts (Figure 1) that are on subparallel imbricate thrust sheets in the structurally complex Coosa Deformed Belt (Thomas and Drahovzal 1974). Along the leading edge of both sheets the Little Oak is the hanging wall rock and the Mississippian Floyd Shale is the footwall rock (Figure 1). The Little Oak has been quarried for decades in the Ragland area for raw material to manufacture cement. Some older, smaller, and abandoned quarries occur in the southern of the two thrust slices, whereas the larger and currently active quarries are in the northern thrust slice. In Figure 1 the location of the abandoned Old North Ragland quarry in the southern thrust slice is indicated by the arrow. One of the larger active quarries in the northern slice is evident at the left-center of the map immediately southeast of the unnamed thrust fault just south of the Coosa fault; this unnamed fault is actually exposed in the quarry (J. A. Drahovzal, personal communication, 1995). In this northern thrust slice the

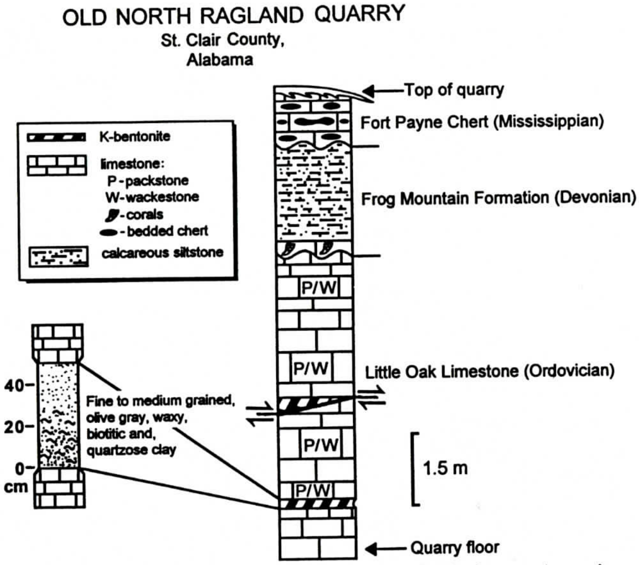

Figure 2. Stratigraphy of the Old North Ragland Quarry. Shown is the internal stratigraphy of the lower K-bentonite, which has no remarkable features; the internal stratigraphy of the upper bed is identical to that of the lower bed. Also shown is the apparent location of a fault, with direction of movement as indicated, which has caused wedging and repetition of the K-bentonite bed. The two beds are about 1.4 m apart, and the upper bed, which wedges out abruptly in the quarry face, is about 2 m downsection from the major unconformity that separates the Little Oak Limestone from the Frog Mountain Formation. Although the standard unconformity symbol is used, it should be noted that the contact between the Little Oak and the Frog Mountain seems to show no evidence of scouring or other disconformity, but instead is a remarkably planar surface at this exposure.

Little Oak is about 240 m (800 ft) thick, but in the southern slice it is only about 120 m (400 ft) thick (Thomas and Drahovzal 1974). The base of the Little Oak in both belts is faulted out. The upper contact of the Little Oak is a major unconformity of regional extent that separates the Ordovician Little Oak from the Frog Mountain Formation of Middle Devonian (Erian) age (Butts 1926; Kiefer 1970; Drahovzal and Neathery 1971; Thomas and Drahovzal 1974; Thomas 1982).

At Ragland and elsewhere the Little Oak Limestone is a thick-bedded, dark gray argillaceous wackestone to packstone with anastomosing silty laminae and some chert. Depositionally the Little Oak is interpreted as a shallow to medial ramp deposit intermediate between the peritidal shelf carbonates of the Lenoir Formation to the west and northwest and the basinal black argillaceous limestones of the Athens Formation to the east and southeast (Benson 1986). Stratigraphic relations to the northwest are complicated by tectonic shortening across major thrust faults.

The age of the Little Oak is poorly constrained because of lack of exposure at the base and erosion beneath the pre-Devonian unconformity at the top. A diverse fauna including conodonts indicates a Chazyan to latest Blackriveran age (Butts 1926; Drahovzal and Neathery 1971; Schmidt 1982; Hall and others 1986). By contrast, an isotopic age of 454±2.1 Ma (latest Blackriveran to Rocklandian) has been obtained from $^{40}Ar/^{39}Ar$ age spectrum dating of biotite and sanidine in one of the K-bentonites at the Old North Ragland quarry by Michael J. Kunk of the U.S. Geological Survey in Reston, Virginia (M.J. Kunk, personal communication, 1994). This is younger than the youngest age indicated by conodont biostratigraphy (Drahovzal and Neathery 1971; Schmidt 1982), but it is the same age given by $^{40}Ar/^{39}Ar$ age spec-

Figure 3. Exposure of the upper Little Oak Limestone in the Old North Ragland quarry showing the upper K-bentonite bed where it pinches out abruptly (arrow) and the contact of the Little Oak (Olo) and the Devonian Frog Mountain Formation (Dfm). The upper and lower contacts of the bed just to the left (northeast) of the termination are shown by the solid black lines. The lower K-bentonite bed, which is continuous within the quarry and better exposed out of view to the right, is covered by debris at lower left.

trum dating of biotites in the Deicke and Millbrig K-bentonites in the Stones River Group at Big Ridge on Interstate 59 about 50 km northeast of Ragland (Kunk and Sutter 1984). Although Haynes (1994) suggested that the Ragland K-bentonite might be correlative with the Millbrig, based on the presence of biotite in some abundance, more detailed study has produced results which show that the biotite phenocrysts in the Ragland K-bentonite are more similar compositionally to those in the Deicke than in the Millbrig, but not similar enough to support correlation of the Ragland and Deicke K-bentonites (Haynes and Melson 1995).

GEOLOGY OF THE OLD NORTH RAGLAND QUARRY

One of the oldest quarries in the Ragland area is on the north side of the southwest end of the ridge that is bisected by Trout Creek where that stream enters the Coosa River (Figure 1). This small and long abandoned quarry (location E ½ NE ¼ SW ¼ NE ¼ Sec. 20, T15S R5E, Ragland 7 ½ minute quadrangle; Locality 31 of

Haynes 1994) is known as the Old North Ragland quarry. Just to the southwest, immediately across the mouth of Trout Creek in the continuation of the low ridge held up by the Little Oak Limestone and the Frog Mountain Formation, is a slightly larger and also abandoned quarry (location SW ¼ SW ¼ NE ¼ Sec. 20), the Old Ragland quarry (Drahovzal and Neathery 1971).

At present, at least the uppermost 4.5 m (15 ft) or so of Little Oak Limestone is exposed in the Old North Ragland quarry (Figure 2). Unconformably overlying the Little Oak is the Frog Mountain Formation, which at this particular locality is especially noteworthy for the presence of abundant corals in the thin calcareous beds immediately above the unconformity (Butts 1926; Kiefer 1970; Drahovzal and Neathery 1971). The unconformity between the Ordovician Little Oak and the Devonian Frog Mountain is remarkably planar within the quarry face exposure, and there is an apparent absence of erosional scouring. The presence of two K-bentonites in the uppermost Little Oak, including an upper bed that abruptly pinches out within the quarry (Figure 3), has been noted in two previous studies (Butts 1926; Drahovzal and Neathery 1971). Close inspection of the quarry and bed-by-bed tracing across the exposure by us shows that this pinchout requires that a bed about 45 cm (1.5 ft) thick thin to zero thickness abruptly, within a distance of less than a meter (Figure 3). In addition, inspection in January 1996 of the Old Ragland Quarry just across Trout Creek indicated that only a single thick K-bentonite is present near the top of the highwall, well above water level in that now-flooded quarry.

Conodonts in the Little Oak Limestone at the Old North Ragland quarry have been studied by Drahovzal and Neathery (1971) and Schmidt (1982), and forms of North Atlantic and Midcontinent affinity are present. A Chazyan age is indicated, although Schmidt (1982) sampled only the lower 7.6 m (25 ft) or so of the 14 m of Little Oak he reported, and as a result his report includes no information on conodont ranges in the uppermost Little Oak just beneath the Frog Mountain Formation. There is a discrepancy in the various stratigraphic measurements reported in the literature to date, however. Whereas Drahovzal and Neathery (1971) reported that about 4.6 m (15 ft) of Little Oak are exposed in the Old North Ragland quarry, a measurement we agree with, Schmidt's (1982) measurements of the Little Oak immediately beneath the sub-Devonian unconformity total 14 m (46 ft). This suggests to us that Schmidt actually measured and sampled the Little Oak in the Old Ragland (not the Old *North* Ragland) quarry, just across the mouth of Trout Creek. Both Glass (1934) and Kiefer (1970) measured a section in the Old Ragland quarry, where over 10 m (35 ft) of Little Oak are in fact present in a large highwall exposure. Unfortunately Schmidt (1982) did not include precise coordinates of the quarry he studied. Of stratigraphic interest, a comparison of measurements made by Butts (1926), Kiefer (1970), and Drahovzal and Neathery (1971) at the two quarries shows that the Frog Mountain Formation apparently increases more than 9 times in thickness across Trout Creek, from about 1.8 m (6 ft) in the Old North Ragland quarry, where the Mississippian Ft. Payne Chert overlies the Frog Mountain, to 16.8 m (55 ft) in the Old Ragland quarry, where the Little Oak - Frog Mountain - Ft. Payne sequence is also present. The ground distance between these two quarries is less than 500 m.

SAMPLING AND ANALYSIS

Samples of both K-bentonites from the Old North Ragland quarry were collected on November 30, 1925, by Charles Butts of the U.S. Geological Survey, and these are currently reposited — with accompanying brief handwritten notes giving the date and locality information — in the Petrology collection at the National Museum of Natural History as USNM specimens 112779 (lower bed) and 112784 (upper bed). Samples of the two K-bentonite beds were also collected by us on March 6, 1994, following the sampling methodology of Haynes

(1994), and these samples are also in the USNM collection alongside specimens 112779 and 112784. These collections provided us with four sets of samples with which to work, two of each bed collected some 70 years apart.

With a hand lens, some notable characteristics of the two beds include their identical color, a light olive gray (5Y 6/1), their waxy or soapy texture, their apparent translucence, their fissility, and the presence of small biotite phenocrysts. Individual samples picked at random from either the 1925 or 1994 collections, and from either the upper or lower bed, are nearly indistinguishable from each other visually. Based on our ongoing study of other Ordovician K-bentonites in the Appalachian region (Haynes 1992, 1994; Haynes and others 1995), these similarities seemed too great to be coincidental. We hypothesized that the two beds might instead be the same bed, and if we could show this to be true, a structural rather than stratigraphic explanation would be needed to explain the duplication of this tephra layer.

Biotite phenocrysts are moderately abundant in the samples, and are suitable for analysis using an electron microprobe. Our analyses showed that many of the phenocrystic biotites are nearly pristine compositionally. Comparison of major and trace element distributions obtained by microprobe analysis of biotite phenocrysts has been used successfully to differentiate between multiple layers of tephra (Desborough and others 1973; Yen and Goodwin 1976; Haynes and others 1995), and we speculated that analysis of biotites in the two K-bentonites at the Old North Ragland quarry would be a suitable means of determining if these two altered tephras are the same layer. With nearly pristine volcanogenic phenocrysts, a comparison of biotite populations is much more sensitive to original differences in magmatic composition than are bulk rock analyses, which can be greatly affected by diagenesis (Delano and others 1994, Haynes and others 1995).

To separate sufficient biotite phenocrysts for major element analysis the four sets of samples were processed as follows. About 50 g of sample were crushed non-vigorously in an agate mortar. This mixture was placed into a beaker of distilled water and thence into an ultrasonic bath for 2 minutes. The resulting suspension was then wet sieved through stacked 250μm, 62μm, and 38μm standard sieves. This process was repeated continually until the water remained clear following repeated sonification, an indication that all clay had been removed. The nonclay minerals retained on the sieve were washed into a watchglass, dried, and then separated into light and heavy fractions using sodium polytungstate with a standard heavy liquid setup. The heavy fraction that was collected on filter paper was then rinsed with distilled water repeatedly to remove all residual heavy liquid, and then it was dried and examined under a binocular microscope. In addition to the relatively abundant biotite phenocrysts, the heavy mineral fraction also contains zircons, apatites, and leucoxene/TiO_2 that is psuedomorphic after ilmenite. The light fraction contains quartz and feldspar.

The heavy fraction from each sample was mounted on 1 inch round glass slides, with many grains projecting above the epoxy. Where exposed above the epoxy, the biotites from the four sample collections of these two K-bentonite beds took an excellent polish, a good preliminary textural indication of their pristine igneous character. Major element analysis was accomplished using the automated ARL microprobe in the Department of Mineral Sciences at the Smithsonian, which was operated at a 15 kV acceleration potential and 0.015 μA counting times of 10 s and with spectrometers arrayed to count Si, Al, Fe (as total Fe, FeO*), Mg, Ca, K, Ti, Na, and Mn simultaneously, and F separately. Backgrounds were determined on quartz and corundum standards (USNM 657s and USNM R17701, respectively). A hornblende standard (USNM 143965) was repeatedly analysed to monitor analytical precision, and those analyses are the basis for the precision bars in the accompanying scatter graphs. As a test, some biotites were analyzed first with a focused beam (5 μm width) and then with a defocused beam (≈ 20 μm width) on the same spot to determine wheth-

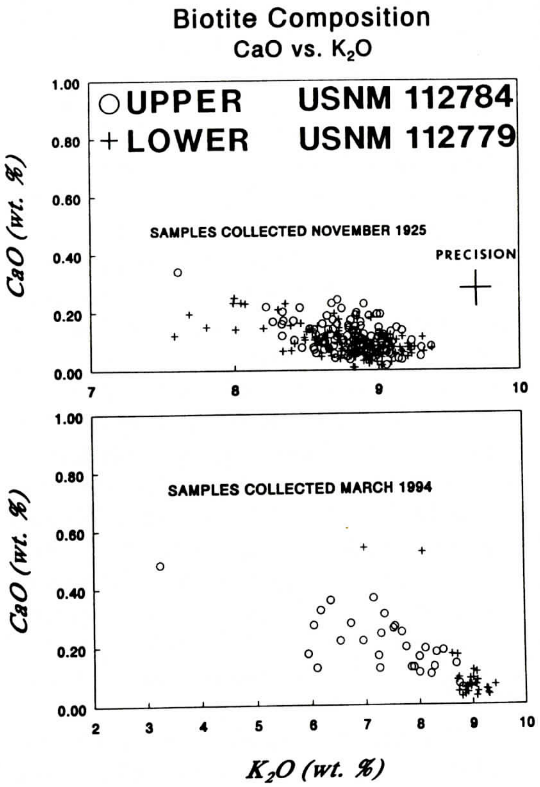

Figure 4. Bivariate plot showing variability of K_2O and CaO in biotite phenocrysts from the four samples of the two K-bentonites in the Old North Ragland quarry. Note the difference in scale of x-axis between graphs. The K_2O and CaO content in biotites from the samples collected by Butts in 1925 are little altered, and they compare favorably with the K_2O and CaO content of biotites from the Millbrig K-bentonite at Big Ridge, Alabama (inset, Fig. 5). The K_2O and CaO content in biotites from the lower bed in samples collected by us in 1994 compare favorably with those in Butts's lower bed samples, but the biotites in the upper bed have clearly weathered significantly in 70 years. The K_2O and CaO content of those biotites is more variable and the loss of K_2O and gain of CaO results in a compositional trend similar to that observed for the biotites in the Millbrig at Tidwell Hollow, Alabama (Fig. 5).

er Na mobility would be a concern; no significant differences in precision were noted, so a focused beam was used.. Also, many biotites were initially analysed five times at separate spots for total counting times of 50 s on a single grain as a test of grain homogeneity. We found that compositional variation within grains is insignificant and so a single analysis per biotite was deemed adequate A 10 s counting time on a single point minimizes sodium diffusion and at the same time produces high counts, with excellent peak-to-background ratios, for the major elements

RESULTS

Examination of the variation of K_2O and CaO in the biotites from the two K-bentonites was the first step in data analysis (Figure 4). Unaltered phenocrystic biotites in many Cenozoic tephras contain K_2O values over 8.0% and CaO values less than 0.25%, and similar amounts of K_2O and CaO in biotites from older tephras can be considered as a first indication that the biotites have not been diagenetically altered. Conversely, biotite phenocrysts that have been altered by weathering or some other diagenetic process exhibit a clear increase in CaO as K_2O decreases. We have observed this trend in biotite phenocrysts from the biotite-rich Millbrig K-bentonite at many localities in the southern Appalachians where that bed is exposed in very shallow cuts at or near original grade, i.e., the original undisturbed land surface, and so has been subjected to soil weathering processes for a relatively long time. A graph of this trend (Figure 5) shows how much variation there can be in the K_2O and CaO content of biotites from the Millbrig between two exposures in the Alabama Appalachians. Comparison of Figure 5 with Figure 4, showing the K_2O and CaO content of biotites from the Ragland K-bentonite, suggests that most biotite phenocrysts in the Ragland bed retain nearly all their K_2O. The sections at Tidwell Hollow and Big Ridge from which the Millbrig biotites in Figure 5 were obtained (Haynes 1994) are each along superb roadcuts (Tidwell Hollow — see measured section of Faust 1984, p. 9-13, with the bed identified as "Bentonite" being the Millbrig; Big Ridge — see measured section of Drahovzal and Neathery 1971, p. 217-223, with bed 21 be-

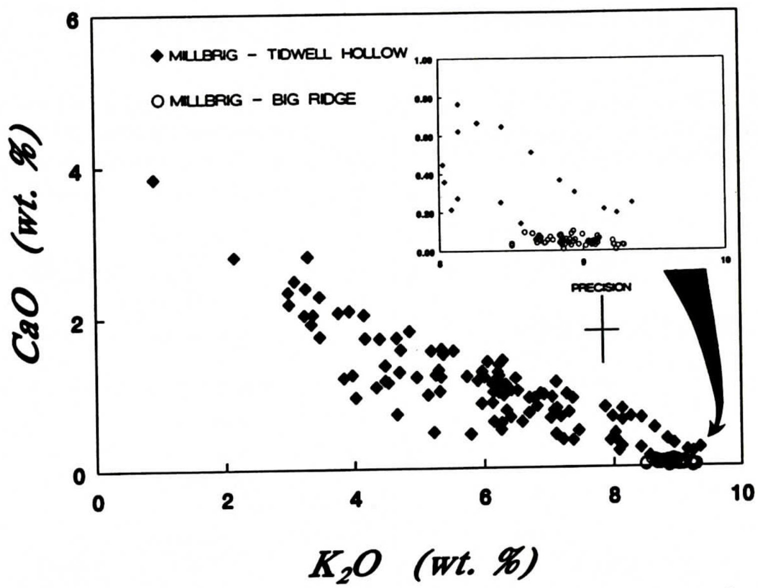

Figure 5. Bivariate plot showing variability of K_2O and CaO in biotite phenocrysts in samples of the Millbrig K-bentonite from two localities in the Alabama Appalachians, Tidwell Hollow and Big Ridge (Haynes 1994). The exposure at Tidwell Hollow, although superb, is closer to original grade than is the exposure in the deep roadcut through Big Ridge. As a result the biotites in the Millbrig at Tidwell Hollow have been exposed to the long-term effects of near-surface weathering processes and the distribution of K_2O and CaO in them has been significantly affected. By contrast, Big Ridge is a locality where biotite phenocrysts in the Millbrig are nearly pristine (Haynes and others 1995), and the inset shows that biotites from the Millbrig at Big Ridge are clustered around mean values of about 9% K_2O and 0.01% CaO.

ing the Millbrig). But at Tidwell Hollow the Millbrig is closer to original grade than it is at Big Ridge, where it is exposed near the base of the deep cut that takes Interstate 59 through the ridge. So, the biotites in the Millbrig at Tidwell Hollow have evidently been exposed to surficial weathering processes for a longer time and are thus more weathered. The loss of K_2O and associated gain of CaO, very evident graphically (Figure 5), reflects this weathering.

The distribution of data in Figure 4 suggests that many of the biotites we analyzed from the Ragland K-bentonite are nearly pristine, stoichiometrically igneous biotites, notably those collected in 1925. Many biotites in our 1994 samples, especially from the upper bed, have lost appreciable K_2O and have gained CaO, and so are distinctly more altered than the biotites collected by Butts from the same bed in 1925. Although weathering rates of biotite are presumably variable under different conditions, the observed difference may reflect the 70 years of exposure and wetting and drying of the quarry face since the 1925 samples were collected. Even though the quarry was apparently abandoned when Butts visited it, the K-bentonite beds had been exposed to the elements for far less time than today because the original quarrying operations had ceased relatively recently. As time passes the zone of weathering is evidently extending farther into the quarry face, even though the beds are exposed several meters below the top of the quarry highwall, where the quarry intersects the original grade. Also, some of the variation in K_2O and CaO content in individual biotites that is evident in both the 1925 and 1994 samples in Figure 4 is probably attributable to slight alteration of some grains at their edges. Because of the platy habit of biotites our attempts at ensuring that only the centers of biotite grains are polished and analyzed have met with little success, and it is evident from examination of the polished grain mounts that some biotite grains we ana-

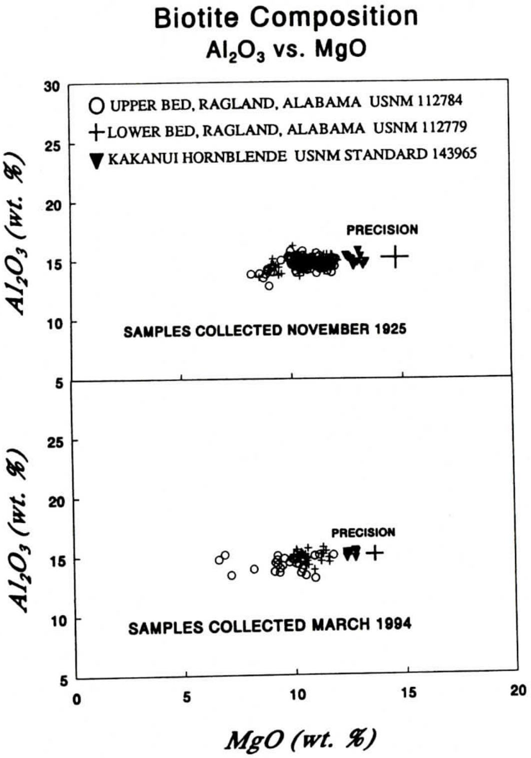

Figure 6. Bivariate plot of Al_2O_3 vs. MgO in biotites from the two K-bentonite beds in the Old North Ragland quarry.

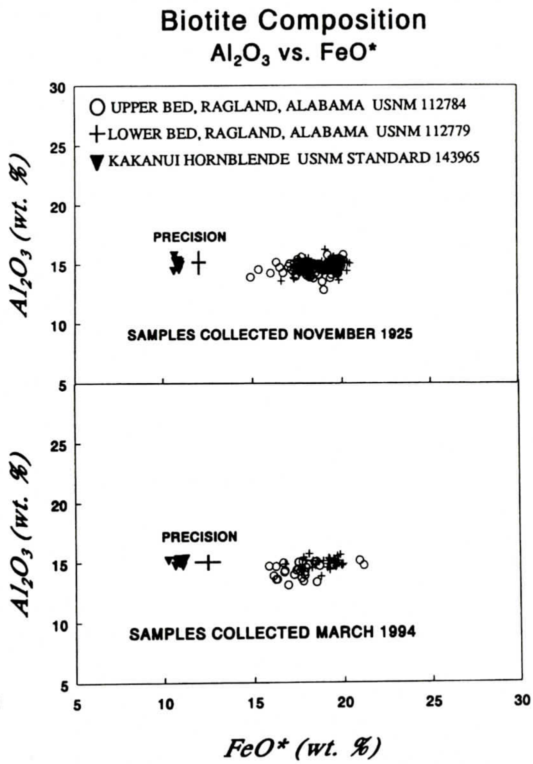

Figure 7. Bivariate plot of Al_2O_3 vs. FeO* in biotite from the K-bentonites in the Old North Raglan quarry.

lyzed are exposed above the epoxy only along their edges. We encountered this problem during recent study of biotites in the Deicke and Millbrig K-bentonites as well (Haynes and others 1995).

Subsequent to comparison of the K_2O and CaO contents of the biotites, we compared the Al_2O_3, FeO (as total iron, FeO*), MgO, TiO_2, and MnO content of the biotites in the four sample sets to obtain a precise geochemical fingerprint of each bed. From inspection of data distribution in scatter graphs of Al_2O_3 vs. FeO*, MnO vs. FeO*, MgO vs. FeO*, Al_2O_3 vs. MgO, and FeO*/MgO vs. TiO_2 of Al_2O_3, MnO, and MgO vs. FeO* (Figures 6 to 10), we conclude that the 1925 and 1994 samples are essentially identical, reinforcing our certainty that in 1994 we sampled the same two beds that Butts had sampled in 1925.

The major element distributions present in Figures 6 to 10 indicate that most data points for the two beds cluster almost on top of each other rather than in separate fields. Scrutiny of these data leads us to conclude that biotite phenocrysts from the upper and lower beds are essentially identical in composition within analytical precision, even accounting for the scattering of data points that is attributable to the varying degrees of alteration of some biotite grains. The range of compositional variability in magmatic biotites has been illustrated by Abdel-Rahman (1994), and while it might be argued that biotites of identical composition could occur in two adjacent tephras, the work by Desborough and others (1973), Yen and Goodwin (1976), and Haynes and others (1995) suggests that variability among at least some of the major elements being compared in Figures 6 to 10 is characteristic of magmatic biotites in tephra suites associated with explosive volcanic erup-

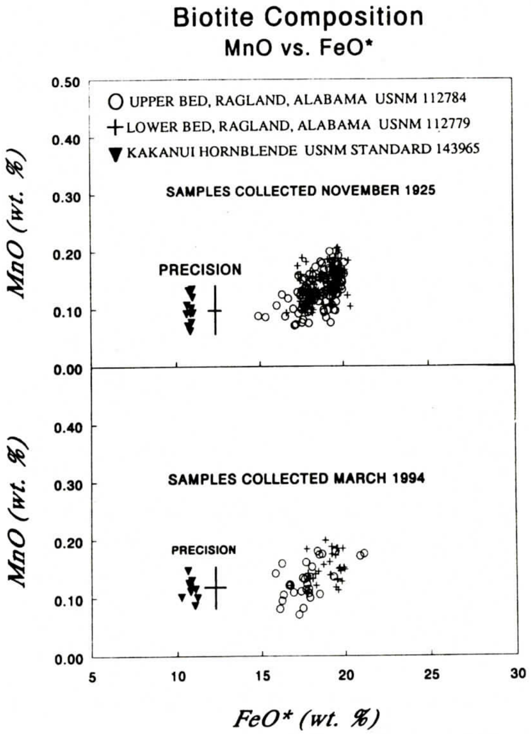

Figure 8.-Bivariate plot of MnO vs. FeO* in biotites from the K-bentonites in the Old North Ragland quarry.

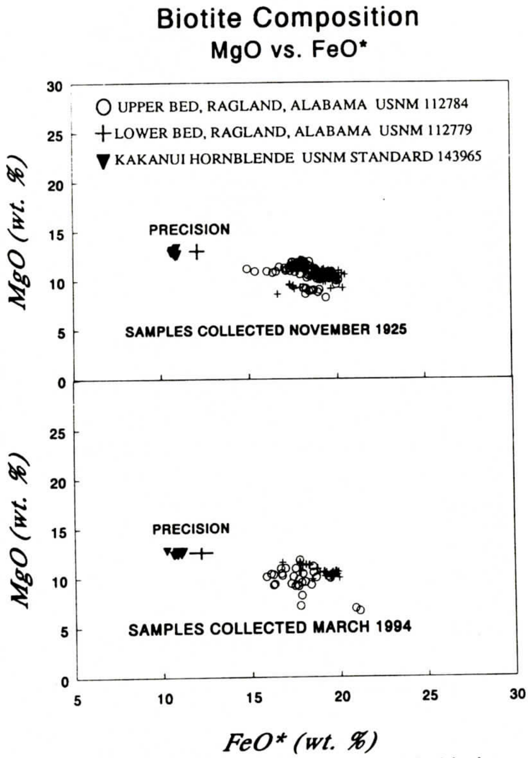

Figure 9.-Bivariate plot of MgO vs. FeO* in biotites from the K-bentonites in the Old North Ragland quarry.

tions. The overlap of data points from analyses of the least altered biotites on all graphs is apparent without any statistical manipulation. From this comparison of the abundances of Al, Fe, Mg, Mn, and Ti we infer that the biotites in the upper and lower Ragland K-bentonite beds came from the same magma batch, and that the two K-bentonites are in fact the same tephra layer.

STRUCTURAL REPETITION OF THE RAGLAND K-BENTONITE

During detailed inspections of the quarry in March 1994 and January 1996, we examined the nature of the wedging out of the upper K-bentonite, clearly described by Drahovzal and Neathery (1971). If the two K-bentonites at the Old North Ragland quarry are in fact the same tephra layer that has been repeated in the exposure, as our comparison of biotite phenocryst compositions indicates, then a structural rather than stratigraphic explanation is needed to explain the duplication. The simplest interpretation is that slip along a bedding plane fault has occurred, with attendant wedging and telescoping of the section, including the K-bentonite layer. With this interpretation the upper K-bentonite bed wedges out abruptly within the quarry along the leading edge of a wedge. Wedges and bedding plane slips are common structures in the Appalachian Valley and Ridge. The illustrations of Cloos (1964), especially his Figures 2 and 3, show the nature of the bedding plane slip and wedging process, which Cloos observed at all scales in many Appalachian exposures. Wedging of the Little Oak in the Old North Ragland quarry is a logical explanation for the duplication and abrupt wedging of a single tephra layer, the Ragland K-bentonite; however, during our visits to the quarry in both 1994

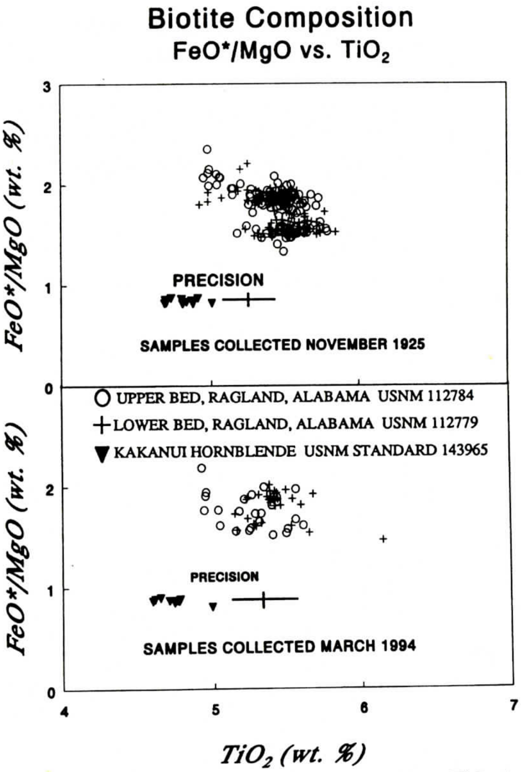

Figure 10. Bivariate plot of FeO*/MgO vs. TiO_2 in biotites from the K-bentonites in the Old North Ragland quarry.

and 1996 we failed to observe structural features that would likely accompany a bedding plane slip. Such structures might include warping of overlying strata and numerous tension gashes along the alleged plane of slip. As a result we regard as tentative our explanation of the apparent duplication as being caused by wedging, but the presence of only a single K-bentonite bed in the Old Ragland Quarry southwestward across Trout Creek suggests that a structural explanation is more likely than a stratigraphic one. If exposures continued northeastward from the quarry, which they do not, we expect that the lower K-bentonite bed would be observed to wedge in that direction, but the lack of exposure prevents us from making a definitive judgment. Cloos (1964) in fact stated that poor exposure commonly prevents a visible matching of wedges in Appalachian outcrops, and our study of the Ragland quarry is consistent with that statement.

CONCLUSIONS

Striking similarity of the abundances of Al, Fe, Mg, Mn, and Ti in phenocrystic biotite from two Ordovician K-bentonites in the Little Oak Limestone near Ragland, Alabama, originally sampled and described by Butts (1926), suggests that these two tephra layers are the same bed, informally designated the Ragland K-bentonite. With this interpretation, the abrupt pinchout of the upper K-bentonite bed is best interpreted as a structural rather than a stratigraphic feature, quite possibly the leading edge of a bedding plane fault that behaved as a wedge in the manner described by Cloos (1964). There is scant evidence in the quarry for slippage of strata, but as noted by Cloos (1964) bedding plane slips are (1) easily overlooked if the wedge is larger than the outcrop, and (2) commonly quite difficult to detect in the absence of extensive stratigraphic exposure. Furthermore, Cloos (1964) stated that without extensive exposure there may be no way of estimating the amount of displacement in strata that are adjacent to an obviously telescoped and wedged bed.

Although our findings do not yet resolve the uncertainties regarding the possible stratigraphic relationships between the Ragland K-bentonite and the K-bentonites in the Stones River Group to the northwest, they do demonstrate that in our ongoing studies of Ordovician K-bentonites in the southern Appalachians and their relationships to Ordovician K-bentonites elsewhere (e.g. Baltoscandia and the Argentine Precordillera; Haynes and others 1995), we will have to investigate the stratigraphic relations of only one layer of altered volcanic ash, not two, in the uppermost Little Oak Limestone.

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