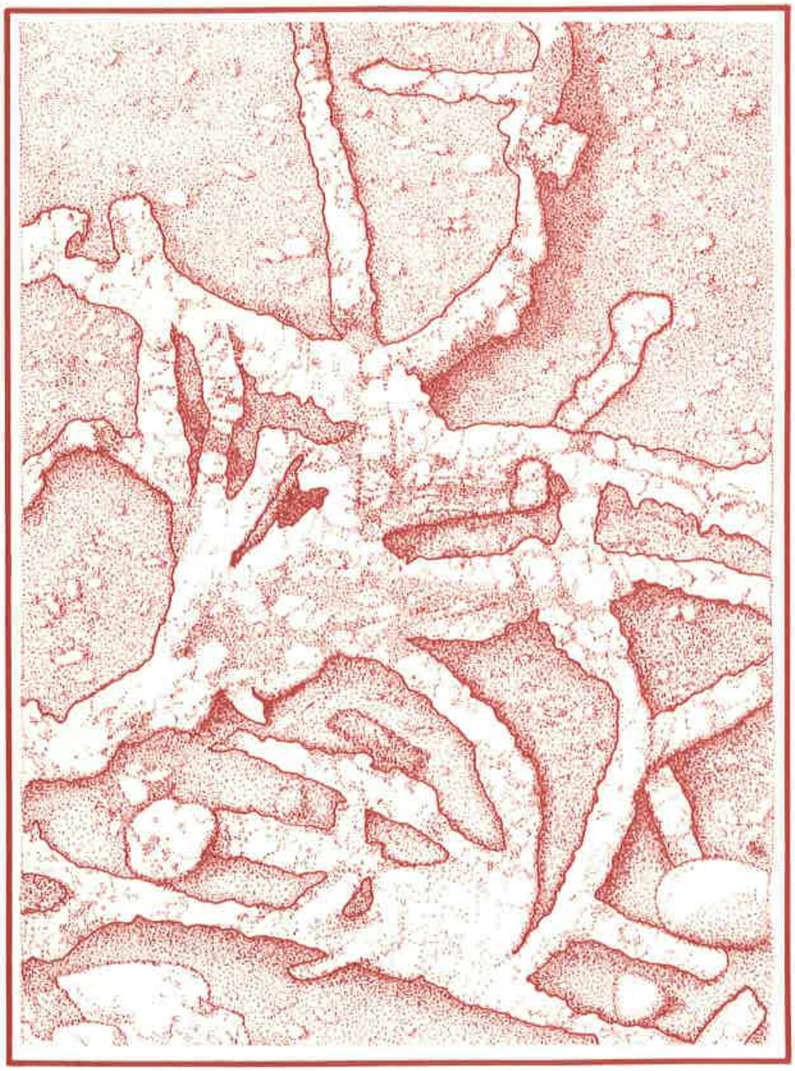
TRACE FOSSILS OF THE OCONEE GROUP AND BASAL BARNWELL GROUP OF EAST-CENTRAL GEORGIA

by

Charles H. Schroder



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Georgia Geologic Survey

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Cover illustration: Typical configuration of *Ophiomorpha* sp. Oblique view of nearly horizontal surface. (See figure 6, page 11.)

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DEPARTMENT OF NATURAL RESOURCES
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Atlanta

1982

This work is dedicated to Robert Duryea Schroder of Charleston.

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Charles H. Schroder

ABSTRACT

Analysis of trace fossils, grain size, and physical sedimentary structures of the kaolin-bearing Oconee Group and overlying basal Barnwell Group of east-central Georgia reveals new information about the depositional and diagenetic histories of these sediments. Understanding of paleoenvironmental parameters such as salinities, water depths, current energies, relative rates of erosion and sedimentation, amounts of erosion, and degrees of consolidation is increased significantly. Twenty trace fossil types and one problematical structure are systematically described and discussed. A new method of staining kaolin to enhance biogenic structures is presented. Interpretation of traces sheds considerable light on the timing of erosion, sedimentation, consolidation, jointing, faulting, and environmental change. Information gained from Oconee Group traces provides a unique view of biological activity and environmental conditions in sediments devoid of body fossils.

ACKNOWLEDGEMENTS

Many friends and associates have contributed toward the successful completion of this work. I am most grateful for their contributions.

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I wish to thank the people of Georgia who have, in part, supported my education and research with their tax dollars. It is hoped that this work will, in some way, compensate the people of this State for their generosity.

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INTRODUCTION

Sediments of the Late Cretaceous to middle Eocene Oconee Group (Huddlestun, 1980) and of the overlying late Eocene Barnwell Group (Huddlestun and Hetrick, 1979, p. 6, 7) are exposed in the Upper Coastal Plain of east-central Georgia. These sediments form a homoclinal wedge which thickens southeastward and rests unconformably upon crystalline rocks similar to those exposed in the adjacent Piedmont.

During the past few years, the stratigraphy of these sediments has undergone significant revision. Table 1 places earlier terms and subdivisions in perspective with current stratigraphy. Other stratigraphic terms applied to these sediments are contained in Cook (1926), Smith (1929), Carver (1972), and Pickering and others (1976). The reader should note that, despite the fact that Oconee Group sediments examined in this study are from the group's uppermost portion and therefore probably assignable to the Huber Formation (Buie, 1975, p. 1-3, tab. 1), no attempt is made to differentiate the Oconee into the Huber and "Cretaceous Undifferentiated (Post-Cenomanian)" (Hurst and others, 1979, p. 7, fig. 2).

Sedimentology

Oconee Group sediments in the study area (fig. 1) typically consist of light-colored, irregularly distributed sequences of poorly sorted gravels, sands, and muds. The term "mud" refers to detrital sediment composed of silt and/or clay. Common lithologies are crossbedded and parallel-bedded muddy sand to sandy mud. Well-sorted materials make up a small percentage of the total sediment volume. Scour surfaces overlain by fining-upward sequences are common, as are mud clasts generated within the basin of deposition by erosion of semiconsolidated muddy sediments. Vertical and lateral lithologic variation are great. Identifiable beds or bed sequences are typically less than 6 m thick and traceable laterally over distances of a few meters to a few tens of meters. Exceptions are sinuous, elongate massive mud (kaolin) lenses, which reach lengths of 1.5 km (Kesler, 1963, p. 7), and the persistent massive mud unit which constitutes the upper few meters of the Oconee Group in most places. Mineral assemblages are almost entirely composed of quartz and kaolinite. A mature heavy mineral assemblage is nearly ubiquitous (Austin, 1976, p. 10). Occurrences of lignitic materials, goethite, hematite, marcasite, pyrite and montmorillonite are minor and sporadic. Minor occurrences of bauxite (gibbsite) have been reported from the upper few meters of the formation (for example, La Moreaux, 1946, p. 45 after Warren, 1943). An exception to the general pattern is again provided by the massive mud unit occupying the upper few meters of the Oconee Group. This unit contains appreciable montmorillonite. Kaolinitized muscovite (?) and extremely embayed quartz occur throughout, indicating pervasive leaching has affected the sediments subsequent to deposition (Austin, 1972, p. 80-83, fig. 26). The only animal fossils which have been observed within the Oconee Group of east-central Georgia are those of marine invertebrates transported down Barnwell age burrows which extend downward from the disconformity at the Oconee's upper surface.

Basal Jackson Group sediments encountered in this study consist of massive and parallel-bedded sand to sandy mud, variably fossiliferous and gravelly, and crossbedded sand to muddy sand or sandy mud. Sediments are both oxidized and reduced, often within the same exposure. Pisolitic cobbles and boulders ≤ 2 m in diameter are occasionally present. Fossils frequently are decalcified and, in some instances, are silicified. Dominant minerals are quartz, kaolinite, and montmorillonite. Minor amounts of iron are present in the form of oxides, hydrous oxides, and sulfides. Barnwell Group sediments generally contain more iron than those of the Oconee.

Purpose and Scope

The purpose of this investigation was to document the trace fossils and lithologic characteristics of the Oconee Group and to utilize this information in an attempt to determine depositional environments and diagenetic changes. Penetration of the upper surface of the Oconee by Barnwell-age burrows necessitated inclusion of basal Barnwell Group sediments in this study. This investigation was concentrated in two areas: (1) northwestern Washington County and (2) western Wilkinson County (fig. 1).

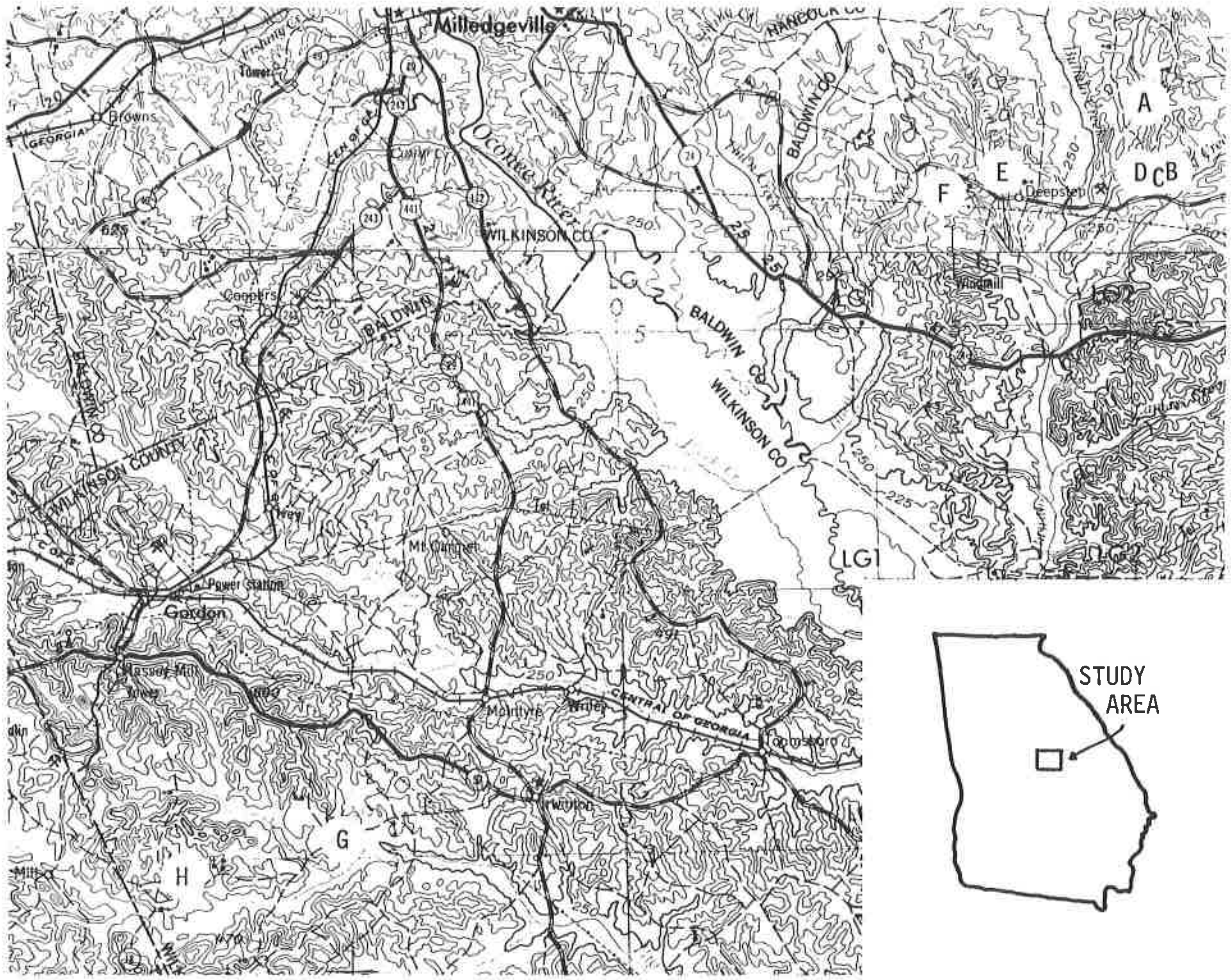


Figure 1. Map of study area, showing localities studied. For specific locations of Localities "A" through "H", see appendix A. Adapted from parts of 1:250,000 topographic maps NI 17-7 (Athens) (1965) and NI 17-10 (Macon) (1956), (U.S. Army Map Service, Corps of Engineers).

Methods

Lithologic characteristics described in this study include grain size, color and physical structures.

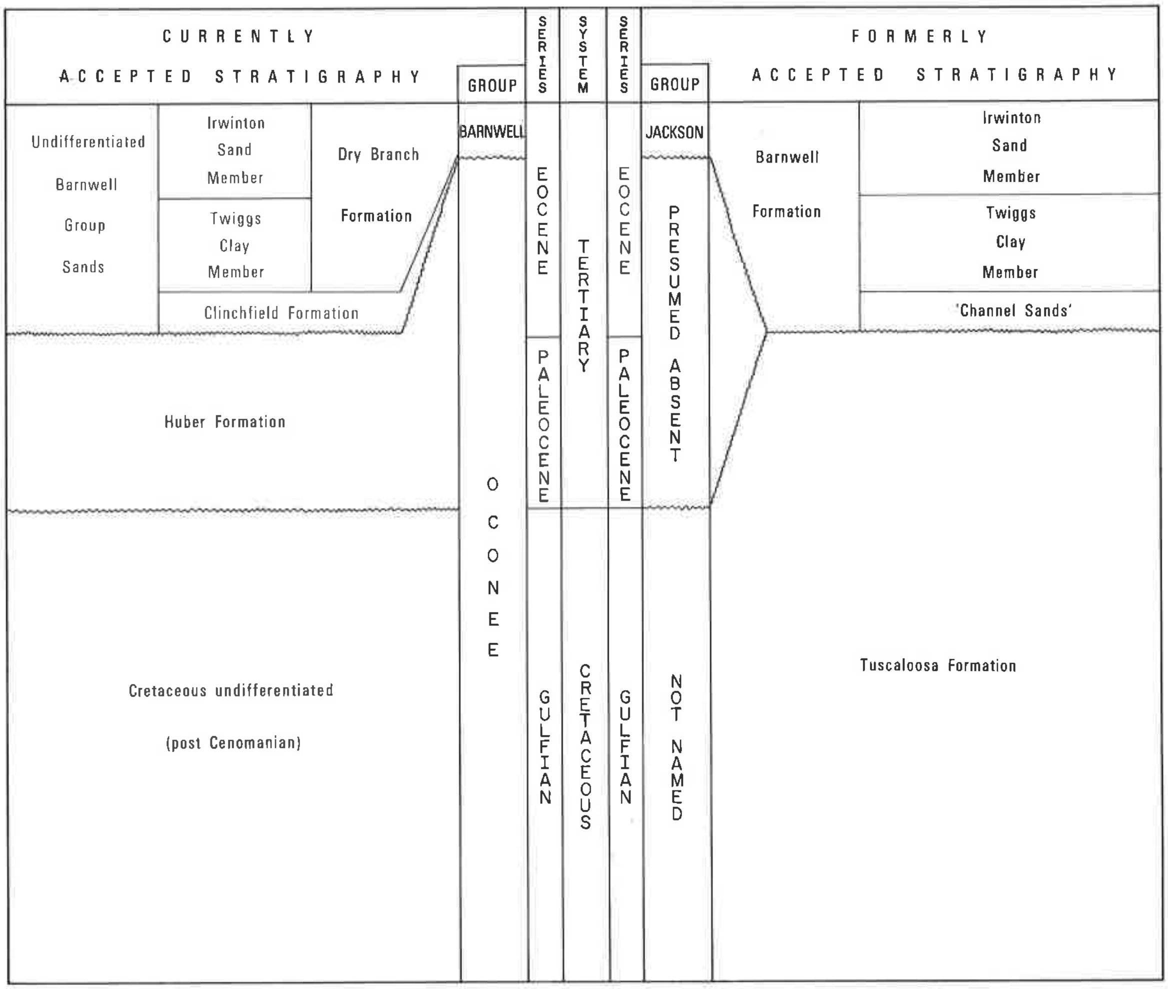
Grain size was estimated visually. Samples of most units were scrutinized under a 32X binocular microscope equipped with a micrometer eyepiece. An effort was made to distinguish between mud (< 0.0625 mm), fine sand (0.0625-0.25 mm), medium sand (0.25-0.5 mm), coarse sand (0.5-2.0 mm), and gravel (< 2.0 mm). A sand gauge prepared from corresponding sieve fractions was employed for comparison. Grain size of unsampled units contained in the stratigraphic descriptions (appendix A) was estimated by inspection at the outcrop. These units are listed as "not sampled" in appendix B.

Color was estimated at the outcrop using a GSA Rock-Color Chart.

Description of physical structures included primary sedimentary structures and deformational structures. Some sedimentological terms are defined in Appendix A.

The presence of marcasite and pyrite in burrows at one locality was determined by optical reflectance and confirmed by x-ray diffraction.

Table 1. Equivalence of currently accepted stratigraphy with formerly accepted stratigraphy. (Adapted from LaMoreaux, 1946, p. 42-44, fig. 4; Hurst and others, 1979, p. 4-7, fig. 2; Huddlestun and Hetrick, 1979, fig. 4; Huddlestun, 1980.)



Ichnology

Ichnology—the study of fossil and recent traces of animals—has provided much information of value in such fields as sedimentology and paleoenvironmental reconstructions and, though little utilized thus far, has a large potential for contribution toward our understanding of diagenesis (Frey, 1973, p. 6). Trace fossils provide a record of life of soft-bodied animals unavailable from any other source. Several advantages of trace fossils over body fossils are that trace fossils (1) directly reflect behavior patterns, (2) are likely to be preserved and even enhanced by diagenesis, (3) are governed in their abundance and distribution by environmental conditions, and (4) are not ordinarily reworked or transported (Frey and Chowns, 1972, p. 25). Of particular relevance to this study is the observation that trace fossils commonly provide the only evidence of animal life in otherwise nonfossiliferous sediments (Hakes, 1976, p. 13, 14). This is the case with the Oconee Group in east-central Georgia.

Trace fossils have been sporadically reported from the Oconee Group for 50 years. The most widely recognized of these is the "'worm-cast' structure" (Smith, 1929, p. 39). This type structure has also been recognized by Hinkley (1965, p. 1869) and Austin (1976, p. 5) and undoubtedly corresponds to *Planolites* sp. A of this work. Networks of burrows originating at the upper surface of the Oconee have also been described and used in a limited way in diagenetic interpretation (Austin, 1972, p. 44, fig. 16). These burrow networks probably correspond to structures herein assigned to *Thalassinoides*.

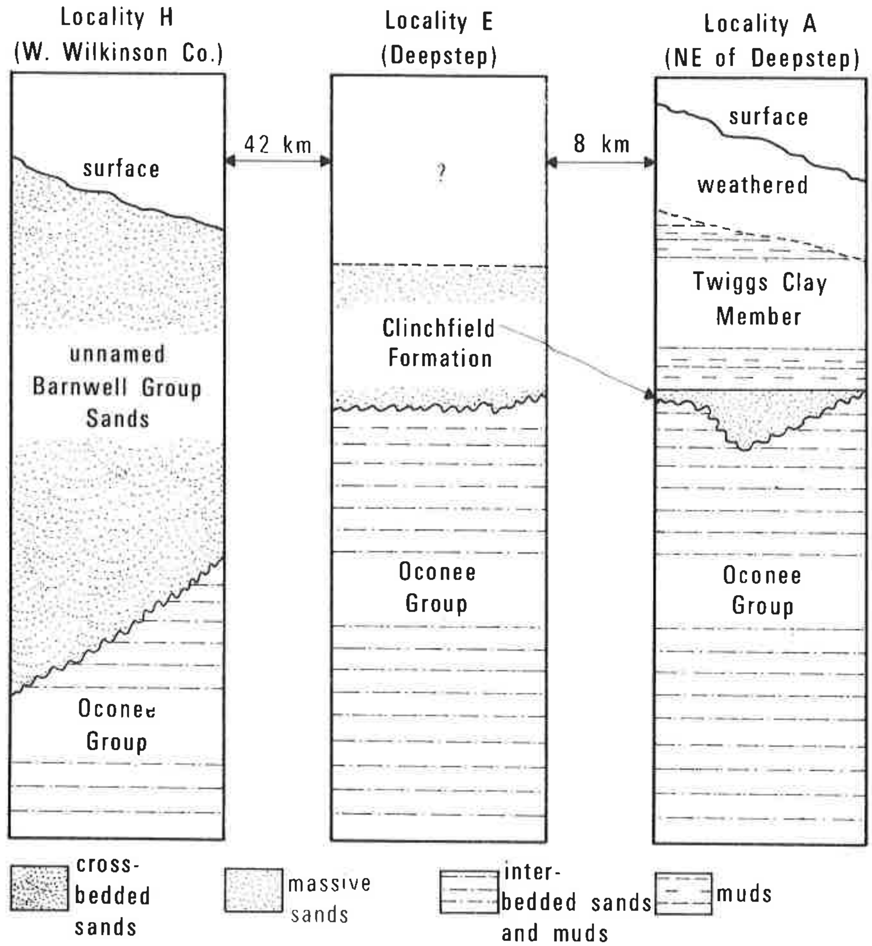


Figure 2. Representative stratigraphic sections from the study area. These sections and others are presented in greater detail in appendix A.

Terminology

Most of the descriptive ichnological terms used are precisely defined in Frey (1973). Other terms are described below. The reader is also referred to the preservational classification below (fig. 3B).

commensalism - a close association between two kinds of organisms, in which one benefits and the other neither benefits nor is harmed.

duodecimal - divided into twelve parts.

ethological - in ichnology, of or pertaining to the study or interpretation of the behavior of organisms as reflected by their traces (Frey, 1973, tab. 2).

flabellate - fan-shaped; spreading like a collapsible hand fan.

latero-vertical - diagonal; movement with appreciable sideways and upwards components.

lebensspuren - fossil and recent traces produced by the activity of organisms.

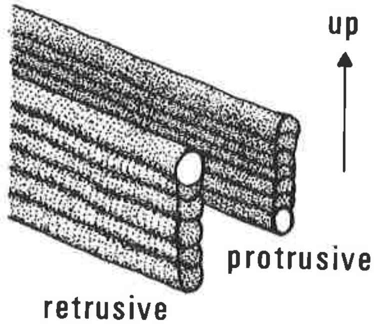
mammilla - a nipple-shaped protuberance.

meniscoid - a concave or convex surface whose periphery contacts the inner wall of a cylinder.

omission surfaces - discontinuity surfaces of the most minor nature, which mark temporary halts in deposition, but involve little or no erosion. Where omission surfaces occur repeatedly in a vertical sequence, the sequence may be referred to as omission bedding (Bromley, 1975, p. 400).

spreite—a blade-like to sinuous, U-shaped, or spiraled structure consisting of sets of closely appressed, serialed, parallel or concentric feeding or dwelling burrows (fig. 3A) or grazing traces (Frey, 1973, p. 10).

thixotropy—the property of certain colloidal substances to lose cohesiveness and flow when disturbed and to gain cohesiveness when left undisturbed.



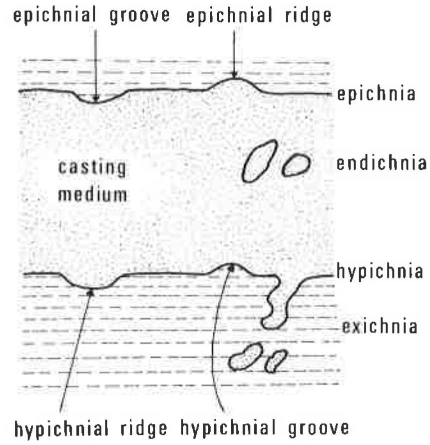


Figure 3A. Examples of protrustive and retrusive spreite. Last tunnel constructed is shown unfilled.

Figure 3B. Toponomic preservational classification by A. Martinsson (1965, 1970), based upon trace fossils and the casting medium (Frey and Chowns, 1972, fig. 1).

SYSTEMATIC ICHNOLOGY

Ichnogenus *Amphorichnus* Myannil, 1966
Amphorichnus sp.

Figures 4, 5

Description: short, vertical, conical to subconical structures, 1.5 to 4.0 cm in diameter, having blunt, convex downward apices and smooth, unlined walls (fig. 4); enlarged crowns (fig. 4A, 4B) common; apical mamillae (figs. 5B, 5C) rare; maximum length observed, about 10 cm.

Preservation: exichnia, subjacent to omission surfaces; burrow fill, exclusive of apical mamillae, is unpatterned coarse sand, unlike enclosing sediments; apical mamillae filled with fine sandy mud, somewhat similar to enclosing sediments, and arranged in concave-up, meniscoid laminae.

Occurrence and distribution: occurs in parallel-bedded, poorly sorted muddy sands and sandy muds, within a few meters of the upper surface of the Oconee Group at localities "B" and "F"; individual structures having crowns and those lacking crowns commonly occupy separate stratigraphic horizons; maximum density observed, about 100 m^2 on a vertical face; lateral crowding common (figs. 4C, 4D); latero-vertical succession rare (fig. 5D).

Interpretation: dwelling or resting structures produced by an anemone or anemone-like animal; truncated burrows, especially those which occupy adjacent positions at the same stratigraphic horizon, and the striking difference between most burrow fills and enclosing sediments, suggest omission bedding (Bromley, 1975, p. 400); latero-vertical succession probably represents the animal's response to sedimentation, a type of "escape structure".

Discussion: Although these specimens show affinities with various other ichnogenera, they are here assigned to *Amphorichnus*. Hantzschel (1975, p. W36, W52), following original descriptions by Myannil (1966), differentiated *Amphorichnus* from *Conichus* by the presence of a distinct apical "mamilla" in the former and its absence in the latter. However, I agree with Frey (1978, personal commun.) that presence or absence of an apical mamilla is an insufficient criterion for creation of separate ichnogenera. Mamillae aside, these specimens conform well to the morphology and dimensions of *Amphorichnus* as described in Hantzschel (1975, p. W36).

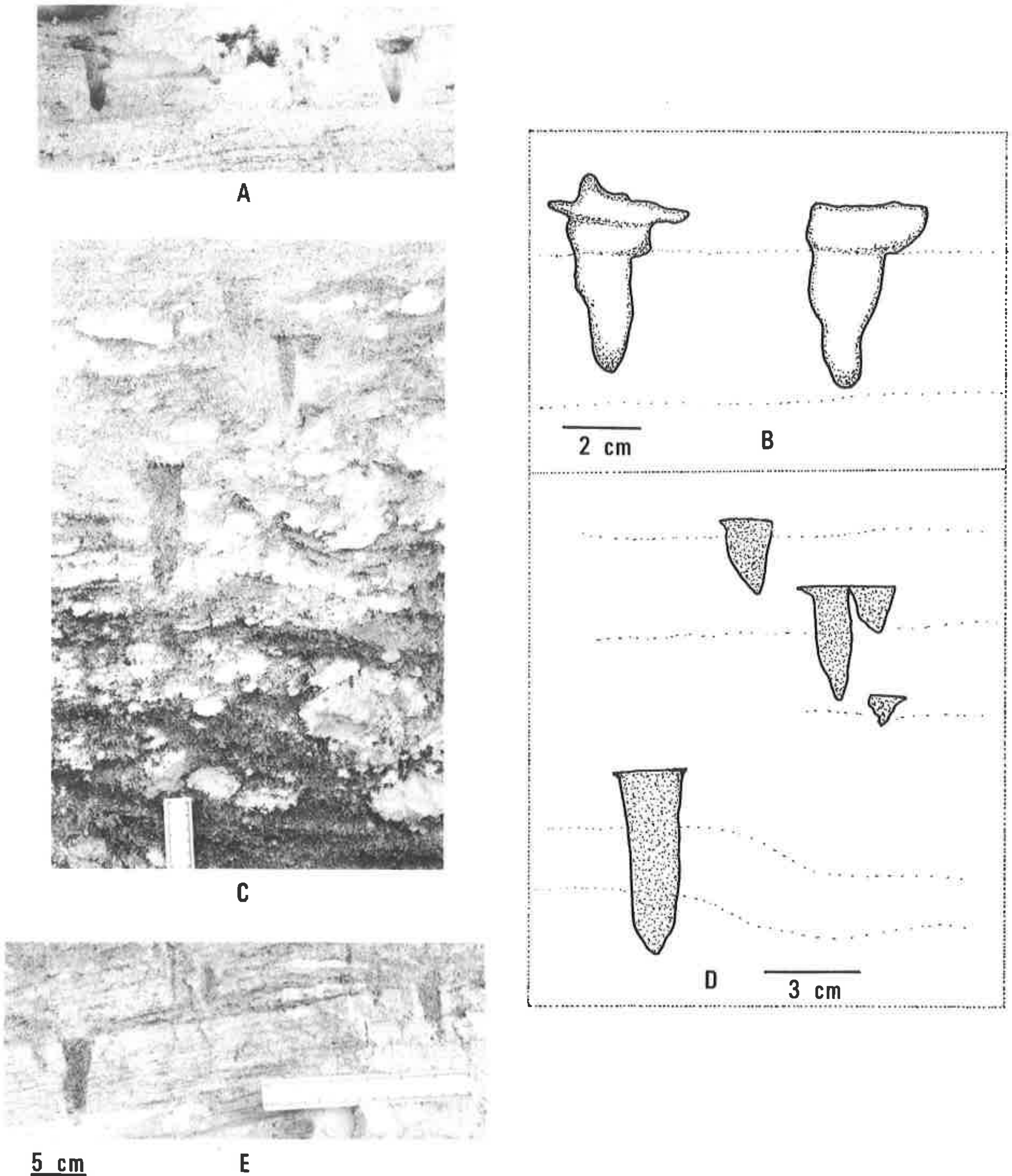


Figure 4. Typical examples of *Amphorichnus* sp. Vertical views, outcrop face. Dark parts of photos largely indicative of areas of relatively high hydrous iron oxide concentration. A, specimens illustrating enlarged crowns (top). B, adapted from A, with distance between specimens shortened. C, specimens illustrating lateral crowding and erosional truncation. D, adapted from C. E, specimens truncated at same omission surface. Apparent tonal differences in fill due to differences in hydrous iron oxide concentration. A-D, from locality "B"; E, from locality "F".

These specimens also show affinities with *Conostichus* (Chamberlain, 1971, p. 220-221; Hantzschel, 1975, p. W146) and *Bergauria* (Albert, 1973 p. 919; Hantzschel, 1975, p. W45, W46). However, Georgia specimens do not exhibit internal duodecimal or medusoid symmetry such as that associated with these ichnogenera.

Amphorichnian structures are morphologically and dimensionally similar to dwelling burrows produced by some modern sea anemones (Stephenson, 1935, p. 104-106; Frey, 1970, p. 308, 309). Two rarely observed features further support this view. Crudely radial shallow depressions in the substrate surface surrounding enlarged crowns (fig. 5A) are filled with "clean" sand similar to burrow fill. These radial depressions are similar to tentacle impressions produced by some modern burrowing anemones, "especially during low tide in the littoral zone" (Frey, 1970, p. 310). Also, apical mamillae correspond closely to the shape of physa, which are used by modern anemones in digging and rapid retraction of upper body parts into the burrow (Stephenson, 1935, p. 104-106; Frey, 1970, p. 308).

Except for vertically nested "v"-shaped laminae, unlined anemone burrows are poorly suited for preservation in thixotropic substrates, such as "clean" sand (Shinn, 1968, p. 888, 889; Frey, 1970, p. 310). Not surprisingly, traces in the fossil record attributable to burrowing anemones are associated with substrates composed of various combinations of sand and mud (for example, Chamberlain, 1971, p. 221). Such combinations may provide suitable substrate for the animal and afford a high potential for burrow preservation, if buried.

The poorly sorted, muddy sand/sandy mud substrates in which these structures occur must have been stable enough to support themselves about the burrows from the time the animals vacated, at least until filling.

Distribution of anemones is worldwide, ranging from brackish intertidal situations to the abyss (Stephenson, 1928, p. 81; Kaestner, 1967, p. 109; MacGintie and MacGintie, 1968, p. 117). Thus, their lebensspuren do not appear to be good indicators of bathymetry or water temperature. They do appear to be useful indicators of salinity, in that all known modern burrowing forms occur in brackish or marine waters (MacGintie and MacGintie, 1968, p. 117). Distribution of *Amphorichnus* sp. in the study area is confined to parallel-bedded muddy sand/sandy mud in the top few meters of the Oconee Group at locations "B" and "F". The presence of these structures argues strongly in favor of brackish or marine deposition of sediments containing them.

Typical density of *Amphorichnus* sp. is about 20 to 30/m^2 on a vertical face. Lateral crowding (figs. 4C, 4D) is common. Chamberlain (1971, p. 221) observed similar relations in anemone-produced *Conostichus*, which he attributes to the "gregarious, ubiquitous, and hemivagrant nature" of anemones. Latero-vertical succession (fig. 5D) is less common.This array probably represents the animal's response to erosion and/or sedimentation.

Adjacent burrows which terminate upward at the same bedding surface commonly show a similar degree of erosional truncation (figs. 4A, 4E). Truncated burrows are more abundant than complete ones, suggesting that periods of minor erosion commonly preceded periods of deposition. This sequence constitutes "omission bedding" (Bromley, 1975, p. 400).

Further evidence of sediment omission may be gained by comparison of burrow fills with enclosing sediments. Burrow fills, exclusive of apical mamillae, consist of unpatterned, "clean", coarse sand, thinly encrusted with hydrous iron oxide. This lithology is in sharp contrast to enclosing sediments, which are muddy, bedded, and generally lighter in color (fig. 4C). The absence of suprajacent sediment similar to burrow fills is suggestive of sediment trapping at an omission surface (Bromley, 1975, p. 401).

Also of interest regarding omitted sediments are differences in the concentration of hydrous iron oxide in fillings of adjacent burrows truncated at the same surface (fig. 4E). This relationship is suggestive of original differences between burrow fillings. These differences may have resulted from differences in the times of escape of the animals coupled with changes in grain size and/or composition of sediment travelling over the omission surface. It also suggests that encrustations of hydrous iron oxide on sand grains are or are related to an original property of the fill.

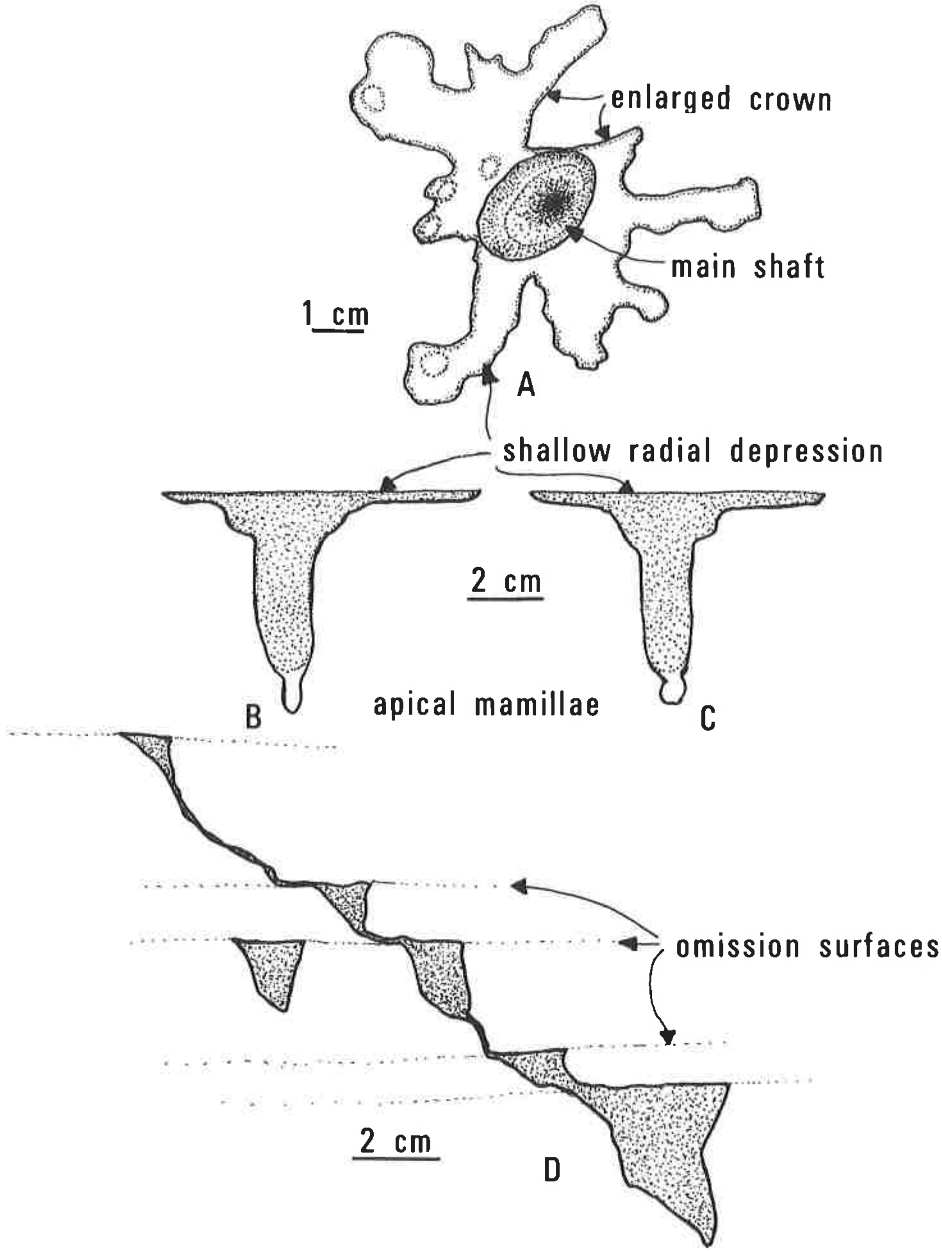


Figure 5. Rarely observed features of *Amphorichnus* sp. A-C, drawn from same specimen, illustrate complete range of morphological components observed among *Amphorichnus* sp. in the study area. A, plan view of specimen top. B, vertical view, outcrop face. C, same as B, but rotated 90° about a vertical axis. Note difference in diameter of apical mamillae between B and C. Unstippled areas at base of B and C indicate presence of white muddy fill, more like substrate than "normal" burrow fill, which is stippled. D, vertical view, outcrop face, showing latero-vertical succession. Burrows apparently are both truncated and linked together. A-D, from locality "B".

Ichnogenus *Ophiomorpha* Lundgren, 1891
Ophiomorpha sp. cf. *O. nodosa*

Figures 6, 7

Description: complex, ramified, dominantly horizontal burrow systems, thinly lined, exhibiting vertically stacked, retrusive spreiten structures and sparsely nodose exteriors; irregularly "Y"- or, less commonly, "T"-branched; individual burrow segments cylindrical, smoothly curved or straight, and 1.5 to 2.0 cm in diameter (fig. 6); spreiten up to 30 cm in height; maximum length of burrow segments observed, about 30 cm.

Preservation: endichnia; except for spreite, fill is unpatterned and similar in appearance to enclosing sediments; thin lining consists of mud-size material, lighter in color than burrow fill or host substrate; exterior slightly nodose to irregular (fig. 6); coherence of lining causes burrows to stand in positive relief on erosion surfaces (figs. 6, 7B). Systems truncated at clay-ball-gravel horizon (fig. 7A).

Occurrence and distribution: occurs in coarse sand fill of shallow channels cut into upper surface of Oconee Group at Locality "A"; confined to lower 50 cm or less of channel fill, where systems may occupy more than 75% of the substrate volume.

Interpretation: dwelling structures of a species of thalassinidean shrimp, possibly a callianassid; retrusive spreiten probably represent animal's response to slowly aggrading substrate surface; high density of burrows indicates that, at the time of burrow construction, channel fill was relatively stable and no longer subject to strong erosive currents which cut the channel originally (R. W. Frey, 1979, personal commun.); thin lining and poorly developed nodose exteriors represent animal's response to moderate instability of the sandy substrate with respect to burrow construction and maintenance.

Discussion: These structures seem to be identical to the blade-like form of *Ophiomorpha* described by Hester and Pryor (1972, p. 678-681, figs. 2, 4, 5). These authors assigned to their blade-like forms the name *O. nodosa* var. *spatha*. Their practice is not followed here, due to the poorly preserved nodose exteriors of these specimens and the resultant difficulty in differentiating them according to ichnospecies (Frey and others, 1978, p. 222-225). The vertically stacked, blade-shaped spreiten structures exhibited by *Ophiomorpha* sp. and *Ophiomorpha nodosa* var. *spatha* are reminiscent of *Teichichnus* (see Frey and Howard, 1970, fig. 8g). However, Hester and Pryor (1972, p. 686) and Frey and others (1978, p. 207) considered ramified burrow systems exhibiting spreiten structures and knobby exteriors to be a form of *Ophiomorpha*, not *Teichichnus*, which lacks a nodose exterior.

Several morphological details exhibited by these specimens deserve mention. Although burrow segments are dominantly horizontal, some are vertical or inclined. Also, burrows are occasionally inflated at points of bifurcation. Some intersections are merely points of burrow interpenetration and not true branchings (fig. 6). Such interpenetrations may account for the absence of inflations at some points of intersection. The presence of inflations at points of bifurcation is a regular feature of many occurrences of *Ophiomorpha* and its modern analogues (for example, Frey and others, 1978, p. 201). In addition, this occurrence of *Ophiomorpha* probably represents an extensive, integrated burrow system, typical of the "communal structures" of Frey and others (1978, p. 201). Finally, the poorly developed nodose exteriors of *Ophiomorpha* sp. were also observed in specimens of *O. nodosa* var. *spatha* by Hester and Pryor (1972, p. 680), who noted that the nodes are easily destroyed by gentle abrasion that accompanies surface weathering. Such abrasion probably accounts for the poorly developed nodose exteriors of *Ophiomorpha* sp.

Knobby-walled burrows and burrow systems similar to *Ophiomorpha* are constructed by some modern thalassinidean shrimp, most of which are species of *Callianassa* (Weimer and Hoyt, 1964, p. 763; Frey and Howard, 1969, p. 428; Frey and others, 1978, p. 212, 214). Knobby-walled burrows are also produced by *Upogebia pugettensis* (Frey and others, 1978, p. 209, after MacGintie, 1930).

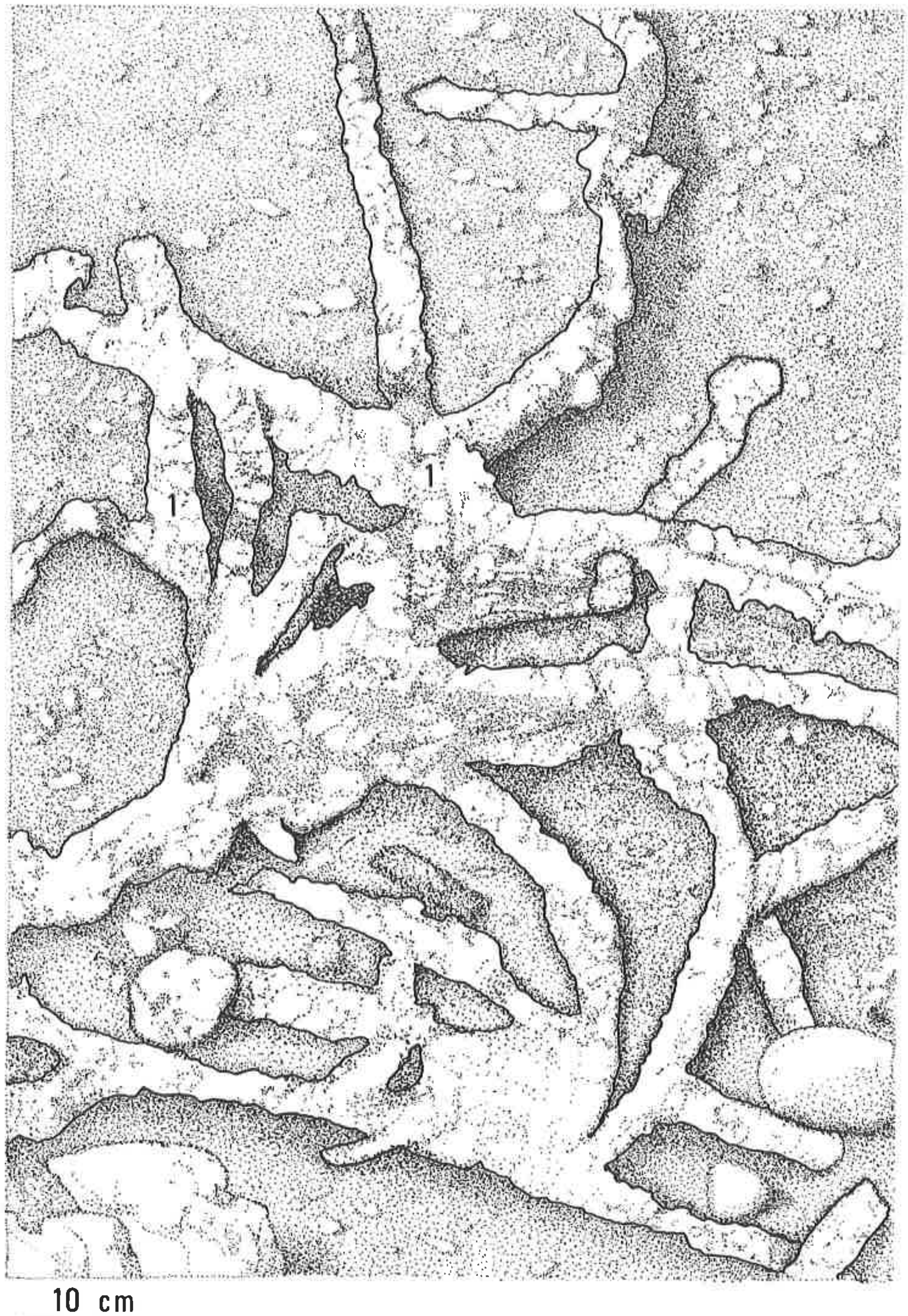


Figure 6. Typical configuration of *Ophiomorpha* sp. from lower 0.6 m of U. Eocene channel fill at Locality "A". Oblique view of nearly horizontal surface. Spreiten truncated by erosion, exposing internal laminae (l). (see Hester and Pryor, 1972, fig. 4).

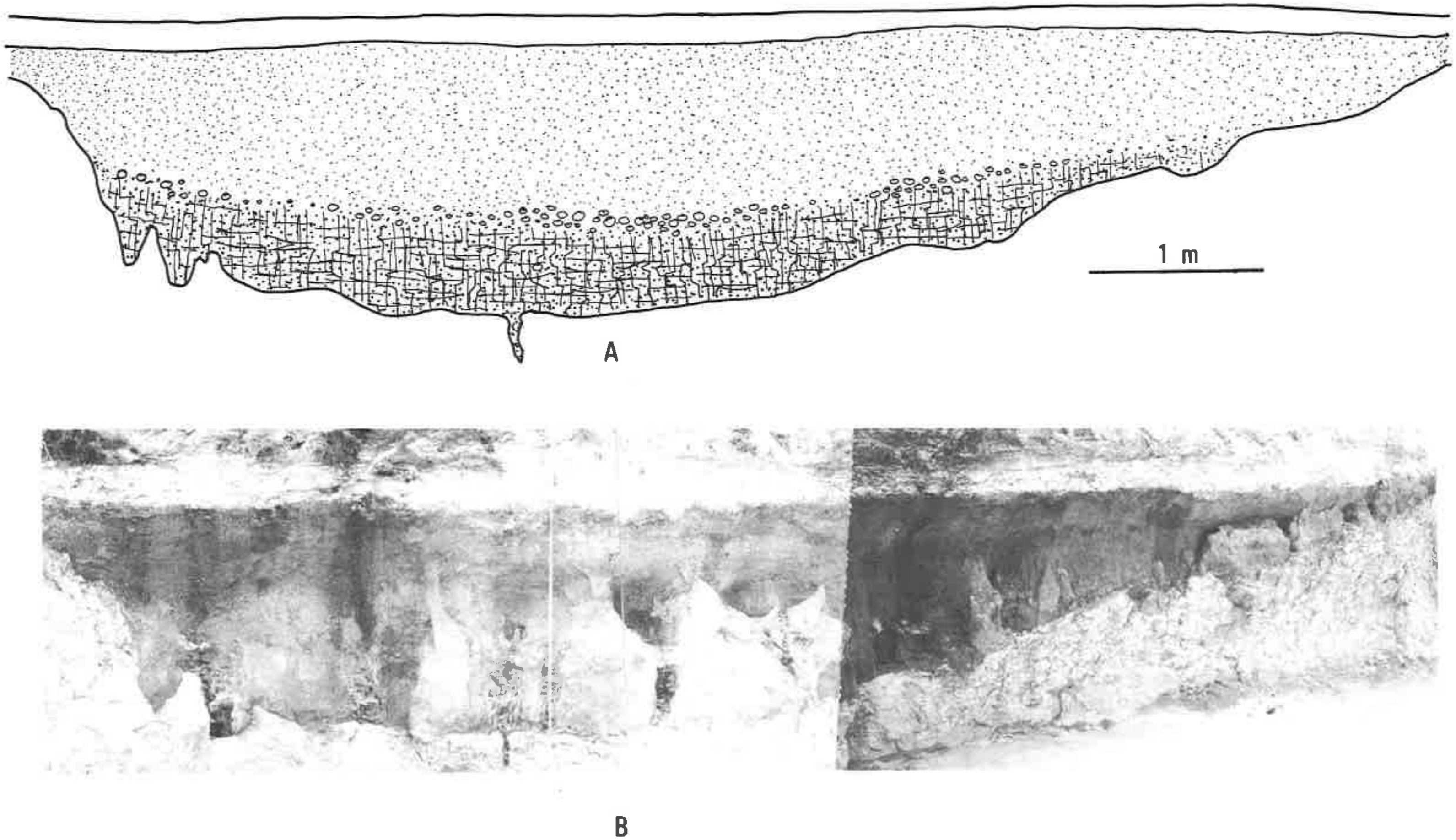


Figure 7. Cross sections of fill of U. Eocene channel cut into upper surface of Oconee Group at Locality "A", showing distribution of *Ophiomorpha* sp. in lower portion. Upward extent of burrows limited by layer of large mud clasts, above which channel fill is "structureless". A, adapted from B.

Correct interpretation of the function of these burrows depends in large measure upon determination of the feeding behavior of producer organisms. Among modern shrimp capable of constructing such burrows, three types of feeding behavior are possible: filter-feeding (MacGintie and MacGintie, 1968, p. 289, 291, 292); deposit-feeding (Weimer and Hoyt, 1964, p. 762; MacGintie and MacGintie, 1968, p. 284; Braithwaite and Talbot, 1972, p. 265; Ott and others, 1976, p. 72); culture of edible microorganisms within burrows (Braithwaite and Talbot, 1972, p. 280; Ott and others, 1976, p. 72, 73), which may also be considered a form of deposit-feeding. Multiramos burrow systems are generally thought to indicate sediment exploitation by deposit-feeders (for example, Braithwaite and Talbot, 1972, p. 265), suggesting these structures may have served a combination feeding-dwelling function. However, Frey (1972, personal commun.) points out that, although such burrows may begin as feeding structures, during the excavation stage,they are essentially domiciles by the time pellets have been added to the burrow walls.

Paleosalinity implications of *Ophiomorpha* range from brackish to marine (Smith, 1967, table 5; Frey and others, 1978, p. 220). This salinity range is apparently compatible with field relations in the study area, because sediments occupied by *Ophiomorpha* sp. are channel fillings demonstrably associated with a marine transgression (p. 86, this volume).

The high density and dominantly horizontal orientation exhibited by the occurrence of *Ophiomorpha* suggest construction under conditions of reduced current energy. In a survey of *Callianassa major* burrow densities in an eastern Gulf of Mexico shore area, highest aperture densities were found in shallow protected areas and in deeper offshore areas (Frey and others, 1978, p. 215-217). Also, among *Ophiomorpha* and modern equivalents, "box-works" and "mazes" predominate over "shafts" in low energy environments (Frey and others, 1978, p. 218).

Moderate substrate instability with respect to burrow construction and maintenance is indicated by the presence in these specimens of a thin distinct burrow lining and sparsely nodose exteriors (Frey, 1971, p. 116; Bromley and Frey, 1974, p. 324; Frey and others, 1978, p. 205-207).

Previous authors have advanced several theories on the origin of spreiten structures associated with burrows attributed to thalassinidean shrimp. For example, the shrimp's attempt to eliminate unwanted sediment or waste, not pumped out of the burrow (Fursich, 1972, p. 131; Frey and others, 1978, p. 207) and upward migration away from putrifying substrate conditions have been suggested as possible causes (Hester and Pryor, 1972, p. 685). However, the most plausible explanation for spreiten-producing behavior manifested by *Ophiomorpha* sp. from the study area seems to be upward shifting of a dominantly horizontal burrow system by the animal in response to a slowly aggrading substrate surface (Frey and others, 1978, p. 207).

Ichnogenus *Phycodes* Richter, 1850
Phycodes sp.

Figures 8, 9

Description: straight to smoothly curved, somewhat flattened, tubular structures, which may anastomose into closely appressed bundles, suggestive of spreiten structures (fig. 9B); segments commonly grade into boudinagelike segments or elongate, discontinuous, podiform structures (fig. 9D); cemented to, or otherwise associated with, "parallel ferruginous tunnels"; typically originating on ventral side of "parallel ferruginous tunnels"; with closely appressed individual tubes curving around and obliquely upward, toward dorsal side (figs. 8A-C, 9A, 9D); true branching not observed; rare, short, tonguelike protusions may extend obliquely outward from walls of structure (fig. 9C); terminations rounded; distinctly lined by 1 mm thick sheath; apertures or interconnections with "parallel ferruginous tunnels" not observed; diameters range from 0.5 to 1.5 cm and are rarely constant, even within individual tubes; maximum length observed, about 15 cm.

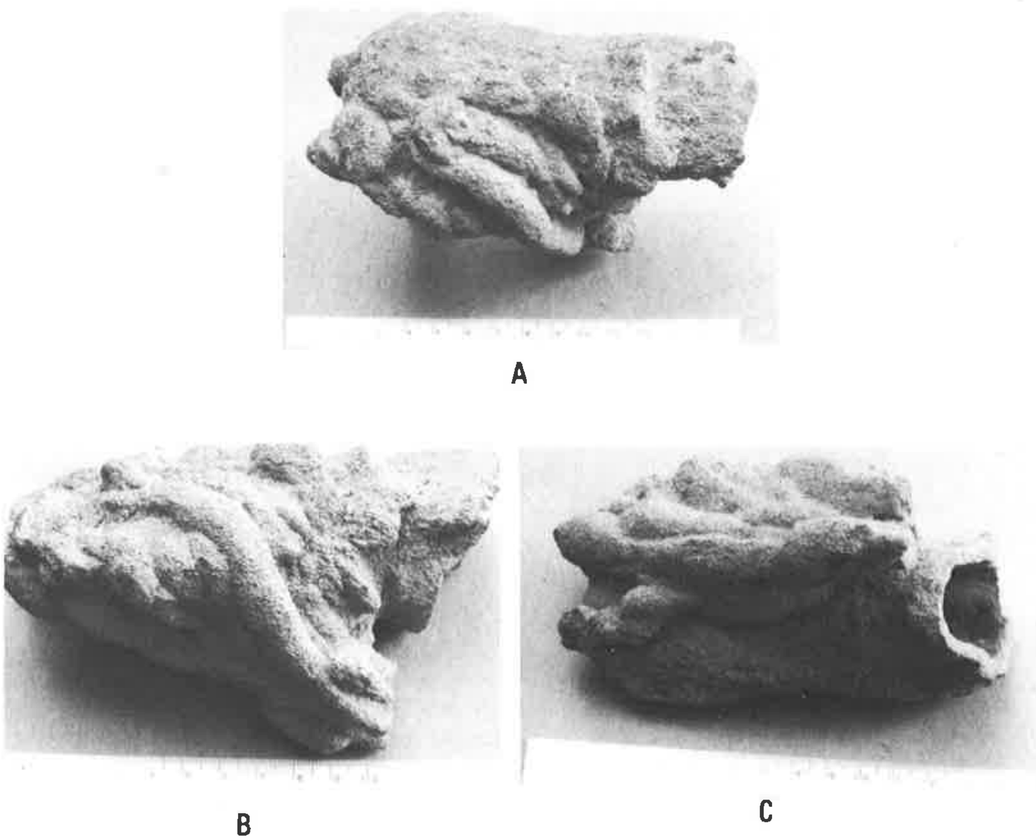
Preservation: endichnia; fill apparently unpatterned, similar to enclosing sediments, and loosely cemented by hydrous iron oxide; lining cemented by dense concentration of hydrous iron oxide.

Occurrence and distribution: occurs in close association with "parallel ferruginous tunnels" in weathered, crossbedded (?), poorly sorted, muddy, medium sand of channel fillings (?), suprajacent to the Oconee Group, at Locality "G"; commonly confined to external surfaces of ventral sides and terminations of "parallel ferruginous tunnels" (figs. 8A-C, 9A, 9D); distribution irregular.

Interpretation: feeding structures produced by vermiform, sediment-ingesting animal; close association with "parallel ferruginous tunnels" suggestive of commensalism; discreet, thin, hydrous iron oxide lining suggestive of original organic lining; structures formed later than "parallel ferruginous tunnels," with which they are associated.

Discussion: Bundled, spreitenlike versions of these structures conform well to Hantzschel's (1975, p. W93-W95) description of *Phycodes*, except for the absence in these specimens of "delicate annulation beneath thin smooth, bark" on free tunnels. However, *Phycodes* sp. have been preserved through diagenetic concentration of iron compounds, suggesting absence of annulations and "bark" may be a preservational matter. Also, some bundled, spreitenlike versions of these structures (figs. 8B, 8C) closely resemble the specimen of *Phycodes palmatum* (Hall) illustrated in Hantzschel (1975, fig. 59, 2e).

Flabellate burrows, such as certain examples of *Phycodes* sp. (9B, 9C), have been interpreted as feeding structures probably produced by a sediment-ingesting vermiform animal (Hantzschel, 1975, p. W94; Simpson, 1975, p. 50). I agree with this interpretation. The closely spaced, anastomosing pattern exhibited by these burrows (figs. 8B, 9C) is suggestive of foraging behavior. Burrow segmentation observed in some instances (fig. 8A) is suggestive of fecal backfill, further supporting this view.



A

B

C

Figure 8. Three views of a specimen of *Phycodes* sp. from Locality "G". Specimen is attached to and curves upward around the termination of a "parallel ferruginous tunnel". A, topview; B, side view (see Hantzschel, 1975, fig. 59, 2e); C, bottom view.

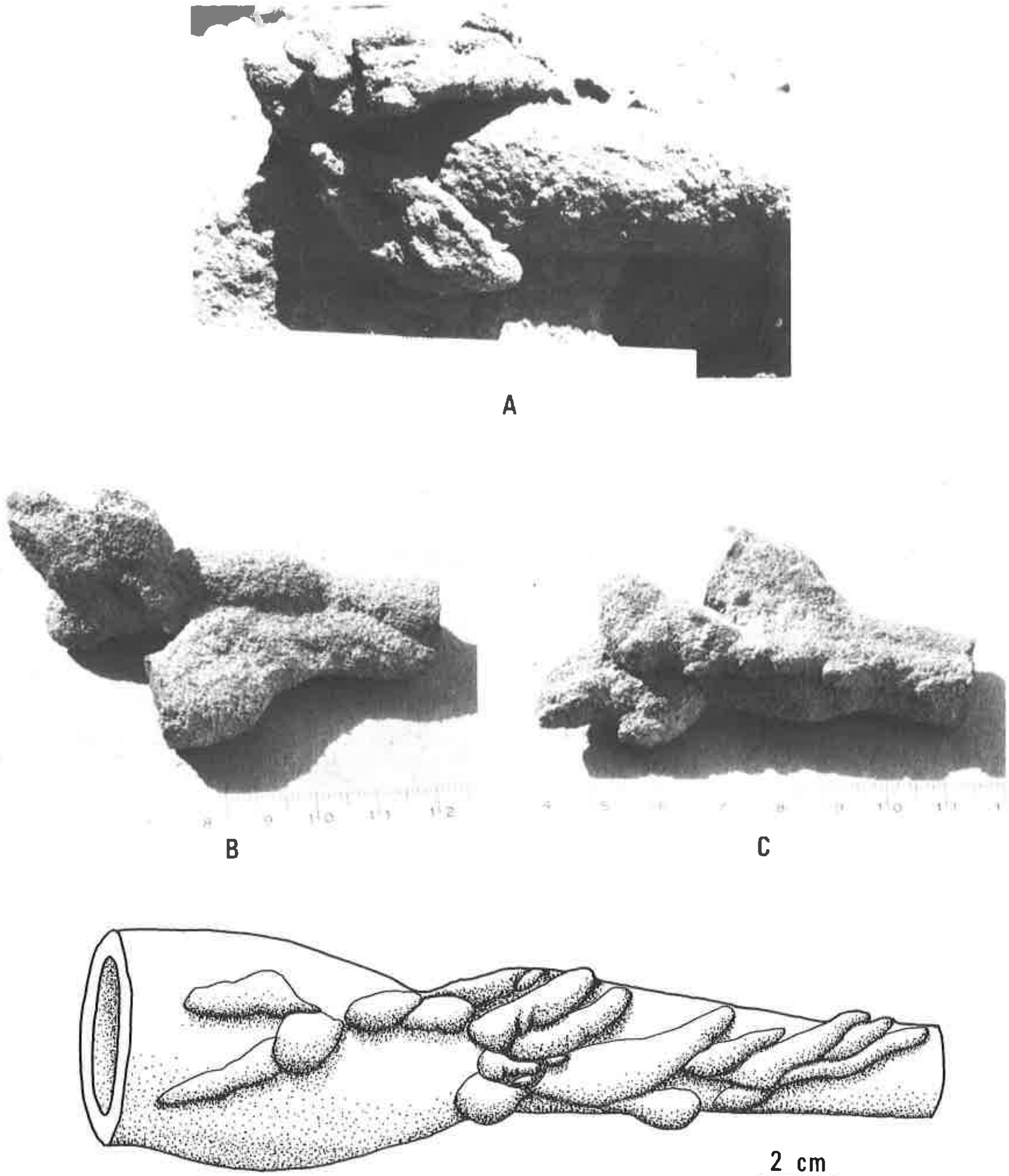


Figure 9. *Phycodes* sp. from Locality "G". A, specimen curving upward around the termination of a "parallel ferruginous tunnel"; B, C, top and bottom views respectively of a small anastomosing specimen; C, small tongue-like features protrude from burrow wall; D, discontinuous structures gradational with *Phycodes* sp., attached to lower surface of a "parallel ferruginous tunnel".

The close association between *Phycodes* sp. and the exterior walls of "parallel ferruginous tunnels" suggests lining material of the larger structures may have provided a source of food for the *Phycodes* sp. animal. However, no breaks or deformations are discernible in the walls of "parallel ferruginous tunnels" where they are contacted by *Phycodes* sp., suggesting linings of the larger structures were not consumed as food by the *Phycodes* sp. animal.

These observations seem to increase the likelihood that the *Phycodes* sp. animal was in pursuit of nutrients passing through the walls of the larger structures. Other distributional aspects also suggest this relationship.

Most *Phycodes* sp. occur or originate on the ventral side of "parallel ferruginous tunnels." Relatively dense liquid or liquifiable wastes collecting on floors of the larger structures probably would have enriched the subjacent sediment in materials useful to microorganisms. Resultant concentration of microorganisms probably would have tended to attract sediment ingestors, where grain size and other substrate characteristics were favorable. Also, in some cases, *Phycodes* sp. is conspicuously associated with terminations of the larger burrows. These terminations were probably among the more stagnant parts of the larger burrows, places where wastes would have tended to collect and migrate into the surrounding sediment.

The close association of *Phycodes* sp. and "parallel ferruginous tunnels" suggests a genetic link between these two structures. This link is based on feeding behavior of the *Phycodes* sp. animal and food production of the "parallel ferruginous tunnels" animal and is suggestive of a commensal relationship.

Preservation of *Phycodes* sp. and related structures is a direct consequence of the diagenetic concentration of iron. Hydrous iron oxide is densely concentrated in thin, well-defined linings. Lesser concentrations cement fill materials. The resulting indurated structures are surrounded by loose sands and weather out in positive relief (figs. 41, 42).

Ichnogenus *Planolites* Nicholson, 1873

The current confusion concerning the ichnogenera *Paleophycus* Hall, 1847 and *Planolites* Nicholson, 1873 has been noted and dealt with by a number of authors in a variety of ways (Osgood, 1970, p. 375, 376; Frey and Chowns, 1972, p. 32; Alpert, 1975, p. 512; Hantzschel, 1975, p. W88, W89, W95-W97; Hakes, 1976, p. 32). No attempt is made to resolve this controversy here.

Assignment of the two burrow types described below to *Planolites* is based on a broad interpretation of this ichnogenus (see Frey, 1970, p. 16, description of *Planolites* sp.).

Planolites sp. A

Figure 10

Description: closely spaced, unbranched (?), sinuous, randomly oriented burrows, 1 to 4 mm in diameter, frequently truncating or interpenetrating one another (figs. 10A, 10B); unlined walls leathery in appearance due to poorly defined, discontinuous, circumferential ridges (fig. 10B); maximum length observed, about 5 cm.

Preservation: Endichnia; burrow fill is segmented, relatively porous mud; fill segments of larger diameter specimens, about 5 mm in length, each having a convex and concave end which are concentric with one another (figs. 10B, 10C); some fills contain appreciable void space.

Occurrence and distribution: occurs in massive muds and slightly sandy muds; widespread, but confined stratigraphically to upper few meters of Oconee Group; at Locality "A", maximum density of nearly 100% of substrate volume occurs in the 2 to 3 m depth interval below upper Oconee surface.

Interpretation: cumulative feeding-dwelling structures of sediment-ingesting vermiform animals, possibly oligochaetes; actively backfilled with fecal trains; voids within some fills may have been created by surface casting or by diagenetic destruction of undigested organics.

Discussion: These structures are similar to *Planolites* as originally envisioned by Nicholson (1873, p. 309). Burrow morphology and regular annulation and segmentation of fill (fig. 10C) suggest active backfill of burrows with material passed through the alimentary canal of a vermiform animal, possibly a species of oligochaete. Unfortunately, little description of the nature of subterranean structures produced by earthworms is available (Satchell, 1967, p. 295), necessitating reliance on indirect evidence to support this view: i.e., the nature of the unit to which these structures are restricted and the apparent timing of their construction.

Planolites sp. A was observed only in the massive muds that constitute the upper few meters of the Oconee Group at widely separate locations. Evidence indicates that these massive muds are a paleosol (p. 85-86). If these muds are a paleosol, structures preserved within them are quite likely related to soil development or were constructed after soil development had ceased. These conclusions follow from (1) the well-known homogenation of pre-existing structures which accompanies soil development generally, and (2) the physical evidence of such homogenation here (p. 86). The excellent preservation exhibited by these rather delicate structures, even those subjacent to the upper boundary of the Oconee, suggests soil development processes had all but ceased by the time of their construction.

Thus, the time interval in which *Planolites* sp. A could have been constructed appears to lie between the ending of soil formation and burial. This leaves open the possibility of burrow construction during the time of exposure of the substrate to brackish and/or marine conditions associated with transgression (p. 86). However, regarding production of *Planolites*-like structures under such conditions, Curran and Frey (1977, p. 146) state that "few modern vermiform animals known to us produce actively backfilled burrows of the classical *Planolites* type." Furthermore, infaunal worms require a source of oxygen. Depth and density at depth of these actively backfilled burrows suggest the producers spent considerable time deep in the substrate. It seems unlikely that such behavior could be sustained under flooded conditions (Dales, 1967, p. 95, 105; Schaller, 1968, p. 61). Modern earthworms of the tropical savannah provide us with an example of burrowing mainly at depth, in response to seasonal drought (Wallwork, 1976, p. 67). These points seem to strengthen the case for an earthworm producer, which, in turn, suggests construction prior to the late Eocene transgression.

These structures were examined in some detail at Locality "A". Here, high porosity of burrow fills relative to the adjacent substrate is apparent in some instances. Obvious void spaces are especially prominent in some burrow fills near the top of the unit. Also, some burrow fills stratigraphically lower in this unit exhibit greater apparent whiteness than the adjacent substrate. This is due to greater dryness of the fill, probably caused by its greater porosity. Increased porosity is suggestive of the former presence of relatively soluble constituents within burrow fills. However, an alternative explanation for the noticeable voids which occur within burrow fill near the upper surface of the unit is that they may be spaces created by surface casting (defecating above ground). Surface casting is of minor importance in increasing soil pore space (Satchell, 1967, p. 297), presumably because of the relatively short time earthworms spend above ground. The amount of pore space attributable to voids within *Planolites* sp. A at Locality "A" is small, making it compatible with Wallwork's observations (Satchell, 1967, p. 297). Concentration of these voids near the upper surface of the Oconee at Locality "A" may reflect the decreasing importance of surface casting with depth to production of pore spaces.

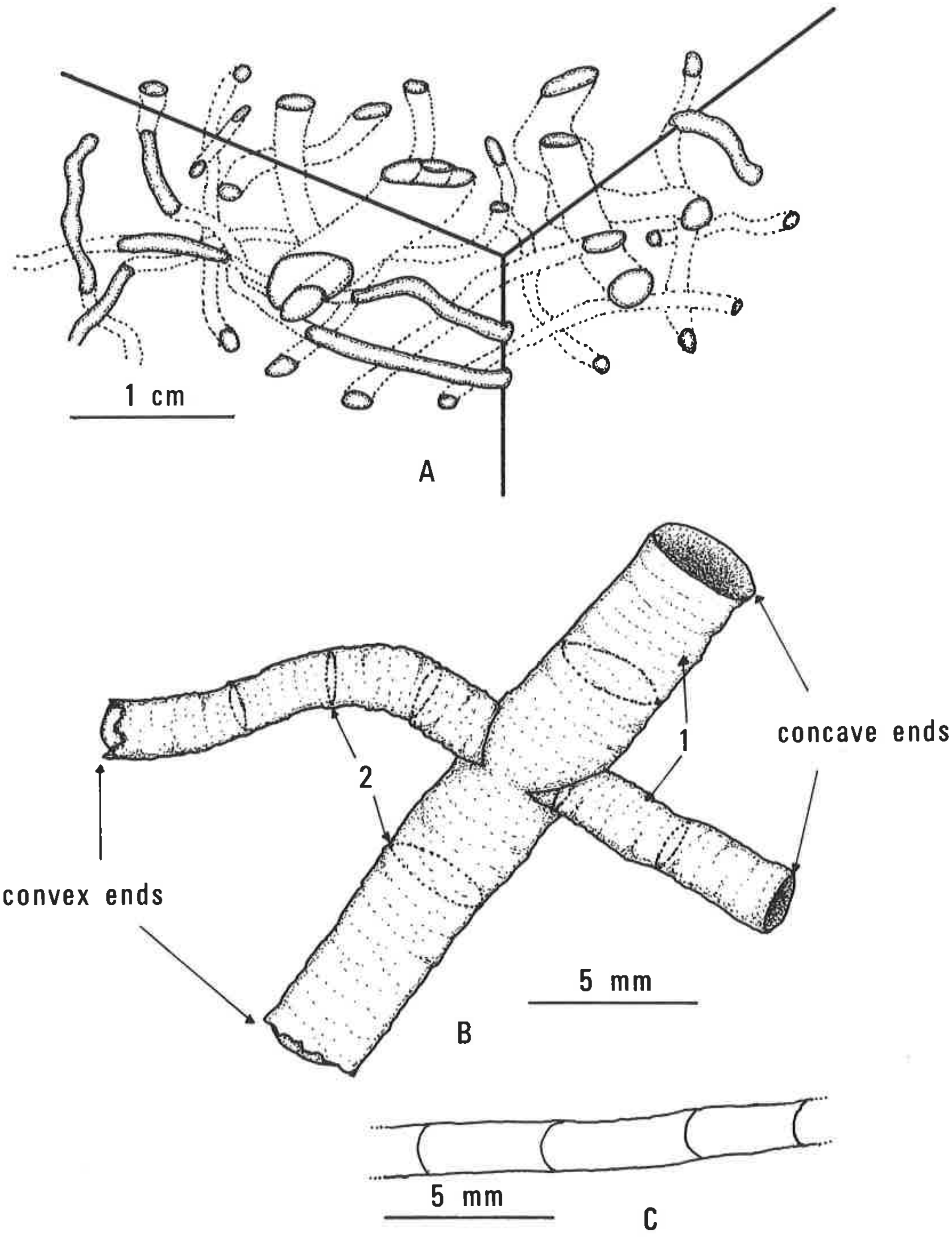


Figure 10. *Planolites* sp. A. A, characteristic random orientation of burrows; B, interpenetrating specimens, showing poorly defined circumferential ridges (1) and annulations (2) at fill segment junctions; C, internal structure of burrow fill.

Planolites sp. B

Figure 11

Description: sparse, unbranched, smoothly curved, cylindrical or subcylindrical slightly sinuous shafts, tunnels, and inclined burrows, 1 to 3 mm in diameter (figs. 11a, 11B); diameters within individual burrows constant; walls smooth, thinly lined; burrows commonly exhibit preferred orientation with preference vertical, horizontal, or inclined in order of decreasing frequency; maximum length observed, about 1 m.

Preservation: Endichnia; burrow fill unpatterned mud, similar in appearance to enclosing sediments; distinctly lined by somewhat diffuse concentrations of hydrous iron oxide (figs. 11C, 11D).

Occurrence and distribution: occurs in some massive muds of the Oconee Group in northeastern part of study area at Localities "D", "E", and "F"; maximum density observed, 20 intersections/m^2 on a vertical face.

Interpretation: dwelling structures or feeding-dwelling structures of infaunal vermiform animal, possibly a species of polychaete; probably originated as open, lined burrows that were later passively filled.

Discussion: Although these specimens show affinities for several other ichnogenera, notably *Skolithos, Paleophycus,* and *Sabellarifex* (Hantzschel, 1975, p. W106-108, W88, W89, W102) they are here assigned to *Planolites,* in the broader sense of this ichnogenus (see Frey, 1970, p. 16, description of *Planolites* sp.).

Small, simple, slightly sinuous, open, lined tubes similar to *Planolites* sp. B are constructed by modern polychaetes in brackish and marine environments (Howard and Frey, 1975, p. 52-63; Curran and Frey, 1977, p. 146, 148, 150). These animals utilize their burrows generally according to feeding mode: as dwelling structures for filter-feeders and surficial deposit-feeders (Howard and Frey, 1975, p. 51-54, 56-61). In some cases, burrows of subsurface deposit-feeders may consist of thinly lined, more or less permanent, "main" burrows from which unlined, ephemeral feeding burrows protrude (Howard and Frey, 1975, p. 57).

Construction and maintenance of these structures as open, dwelling burrows are suggested by the absence of segmentation or annulation of burrow fill and the presence of a distinct hydrous iron oxide lining. Lined burrows filled with unpatterned material similar to enclosing substrates are considered suggestive of passive fill of open burrows (Frey and Howard, 1972, p. 173, 179; Frey, 1973, p. 10, 11).

Recognition of *Planolites* sp. B is entirely dependent upon the presence of hydrous iron oxide concentrations associated with the walls of these burrows. These concentrations occur as burrow linings (fig. 11C) and as rarely observed liesegang bands, concentrically arranged about the burrows (fig. 11D).

In a commercial kaolin at Locality "E", specimens of *Planolites* sp. B cut across and are undeformed by extensively developed bioturbate textures (fig. 48). These relations indicate that construction of *Planolites* sp. B postdates activity which generated the bioturbate textures. These relations also suggest that *Planolites* sp. B was constructed in relatively stable mud substrates not subject to pervasive soft sediment deformation. However, if the hydrous iron oxide linings of *Planolites* sp. B represent original organic linings, some sediment instability is indicated (Frey, 1971, p. 116).

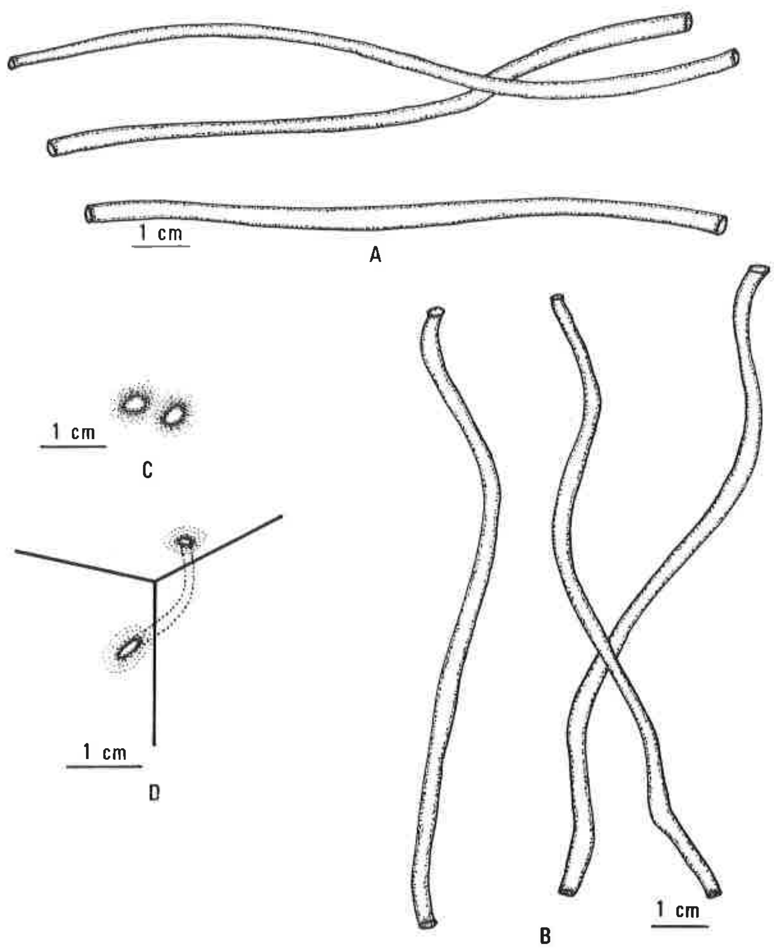


Figure 11. *Planolites* sp. B. from muds of the Oconee Group. A, B, burrow segments showing typical morphology and orientation; C, transverse sections; stippled areas show distribution of hydrous iron oxide; D, specimen from Locality "E", showing delicate liesegang bands of hydrous iron oxide surrounding the burrow.

Ichnogenus *Skolithos* Haldemann, 1840
Skolithos sp.

Figures 12, 47A, 48, 49, 50, 56

Description: unbranched, discontinuous, straight to slightly sinuous shafts and steeply inclined burrows, roughly circular in transverse section, and 1 to 2 cm in diameter; maximum observed length, about 1 m; unlined walls exhibit colliform or irregular structure (fig. 12).

Preservation: endichnia or exichnia; burrow fill is unpatterned and consists of mud of greater whiteness than adjacent substrate (fig. 56); burrows may grade into bioturbation textures (fig. 47A).

Occurrence and distribution: occur in massive to vaguely horizontal laminated muds and slightly sandy muds at Localities "F" and "H"; observed within upper 5 m of the Oconee Group; structures may occur as isolated burrows (fig. 12), with maximum density observed, about 25 intersections per horizontal linear meter on a vertical face, or as closely spaced burrows within "large conical structures" in muds (figs. 50, 56).

Interpretation: feeding structures or feeding-dwelling structures of a vermiform deposit-feeding animal; burrows were probably constructed in soft, unconsolidated mud substrates; greater whiteness of burrow fills relative to adjacent sediments is apparently due to relative absence of iron compounds within burrow fills, which is probably, in turn, related to passage of burrow fills through the gut of the tracemaker.

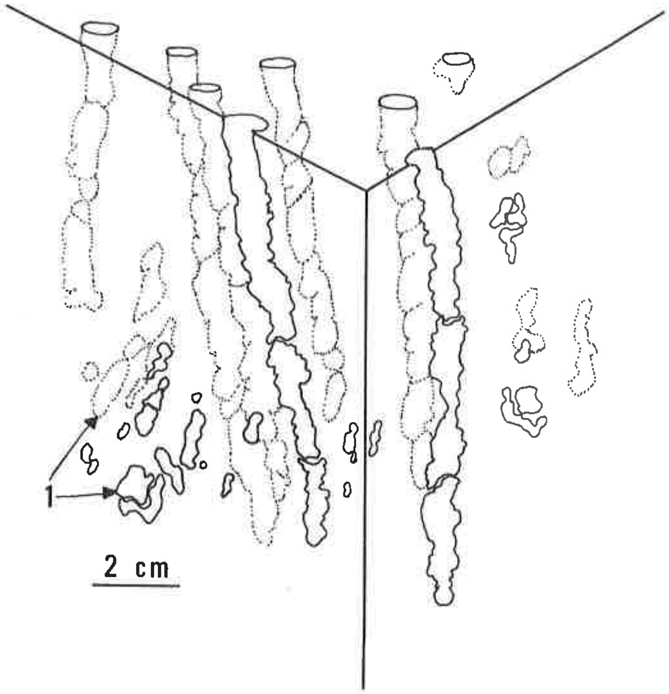


Figure 12. *Skolithos* sp. Burrow fill consists of very white (N10) mud, whereas adjacent sediment is generally darker, very pale orange (10YR 8/2) mud. Bioturbate textures (1) also present.

Discussion: These structures are assigned to *Skolithos* based on comparison with the description of the ichnogenus by Hantzschel (1975, p. W106, W107). Both burrow types consist of parallel tubes that are roughly cylindrical, vertical, perpendicular to bedding, and of similar dimensions (Hantzschel, 1975, p. W106, W107).

The discontinuity and elongate, tubular morphology of these structures, their unlined, irregular to colliform walls, and their occurrence in mud substrates suggest that the tracemakers were ethologically similar to mud-dwelling, vermiform sediment ingestors.

The discontinuity of these burrows and their irregular to colliform walls are also suggestive of construction in a soft, unconsolidated substrate, soon after deposition. This idea is further supported by observations of these structures grading into bioturbation textures (figs. 47A, 48) that were clearly generated in soft muddy substrates. Vertical, tubular burrows such as these are "normally" constructed as dwellings in response to environmental extremes and/or a high potential for erosional disinterment (Frey, 1971, p. 111), suggesting sediments containing *Skolithos* sp. may be intertidal to shallow subtidal in origin (Rhoades, 1967, p. 161). However, dwelling burrows constructed in soft, muddy substrates are generally lined to prevent walls from collapsing (Frey, 1971, p. 111). No evidence of burrow linings was observed among specimens examined, supporting the idea that these structures are feeding burrows of sediment ingestors.

Burrow fills consist of mud of greater relative whiteness than adjacent substrate: burrow fills are generally very white (N10), whereas adjacent substrates are generally very pale orange (10YR 8/2), creating a subtle contrast that in many places is difficult to perceive. These color differences appear to be due to the absence of hydrous iron oxide within burrow fills, relative to enclosing substrates (see Ekdale, 1977, p. 176-178). Similar relationships exist between bioturbation textures and adjacent mud substrates (p. 139, fig. 47A) and between roughly horizontal, deformed laminae and enclosing sediment (for example, fig. 49), both of which commonly accompany occurrences of *Skolithos* sp.

The apparent absence of hydrous iron oxide in burrow fills relative to surrounding sediments is most likely a direct result of the fill materials having been passed through the tracemaker's gut (Frey, 1971, p. 108). Assuming original distribution of iron was homogeneous on a scale smaller than *Skolithos* sp. burrows (Hanor and Marshall, 1971, p. 130), present iron distribution must have involved diffusion of iron away from these burrows. Iron depletion within burrow fills was probably a two-stage process: (1) solubilization of iron due to high acidity in the tracemaker's gut (Anderson and others, 1958, p. 190) or acidity produced by respiration (Ekdale, 1977, p. 177, 178); (2) subsequent outward diffusion of solubilized iron into the surrounding sediment (Ekdale, 1977, p. 177, 178).

Ichnogenus *Thalassinoides* Ehrenberg, 1944

Figures 13-29

Description: cylindrical to subcylindrical, smooth-to slightly irregular walled burrows, 0.7 to 10 cm in diameter, forming branching systems that connect with substrate surface (figs. 15, 20B); branching typically dichotomous and "Y"-shaped (figs. 15, 20B, 23C, 25).

Preservation: exichnia; burrows open, or filled with unpatterned or graded, commonly fossiliferous, sandy material, similar to suprajacent sediments; burrow walls and fill commonly exhibit hydrous iron oxide impregnations or encrustations (figs. 12, 13, 24C); structures show varying degrees of truncation at top of Oconee (figs. 18A, B, 25B).

Occurrence and distribution: occur throughout study area in muddy substrates at top of Oconee and within Clinchfield; lateral distribution, patchy; typical densities, 2 to 6 intersections per horizontal linear meter on vertical exposures, 30 cm below substrate surface.

Interpretation: feeding-dwelling structures excavated by various burrowing crustaceans, most of which apparently were species of shrimp; probably excavated and inhabited in warm, intertidal to shallow subtidal marine environments under a broad range of current energies; Oconee substrates were firm or coherent at the time of *Thalassinoides* excavation, Clinchfield substrates were less so.

Discussion: These specimens are assigned to *Thalassinoides* based on comparison with descriptions of the ichnogenus by Kennedy (1967, p. 132) and Hantzschel (1975, p. W115, W117) and with the description of *Spongeliomorpha paridoxica* by Fursich and Palmer (1975, p. 172, 176). Following the arguments of Bromley and Frey (1974, p. 329), *Spongeliomorpha* is considered a "nomen dubium" and is abandoned in favor of *Thalassinoides* for designating burrows of this type.

The great variability of specimens of *Thalassinoides* observed in the study area necessitates some elaboration and qualification of the foregoing description. Most specimens are circular or subcircular in transverse section. However, a few display ovoid (fig. 23B) or semi-circular (fig. 20C) transverse sections (see Kennedy, 1967, p. 134; Fursich and Palmer, 1975, p. 172). Wall structure ranges from smooth (fig. 20B) to slightly irregular (figs. 13, 23C) (see Bromley, 1967, p. 162; Fursich and Palmer, 1975, p. 172). In the latter case, pits and, less commonly, grooves sculpted by burrow inhabitants adorn the walls (fig. 16C) (see Bromley, 1967, p. 163). Although diameters of burrows range from 0.7 to 10 cm, typical diameters range from 1 to 5 cm. Diameters in excess of 5 cm occur mainly in chambers and chambered intersections (figs. 15, 16A, B) (see Kennedy, 1967, p. 142; Fursich and Palmer, 1975, p. 172). Branching is typically dichotomous and "Y"-shaped (figs. 15, 20B, 24A) (see Kennedy, 1967, p. 132; Hantzschel, 1975, p. W117). However, "T"-shaped branching is common among some examples (figs. 15, 17D, 19B) (see Fursich and Palmer, 1975, p. 172). Swellings at points of bifurcation (figs. 15, 21B) are common, but not ubiquitous (see Kennedy, 1967, p. 132; Hantzschel, 1975, p. W117). Absence of these features at some points of bifurcation may be a function of the coherent nature of substrates at the time of burrow excavation (Bromley, 1967, p. 159). Overall burrow distribution within a given system may be two- or three-dimensional. Two-dimensional arrays appear to coincide with vertical joint surfaces in the substrate (figs. 21, 22). It is possible that such jointing may result from burrowing activity (Basan and Frey, 1977, p. 1b). However, the coincidence of normally three-dimensional *Thalassinoides* systems with essentially two-dimensional vertical joint surfaces, coupled with the absence of *Thalassinoides* on some joint surfaces, suggests jointing predated associated *Thalassinoides* and, to some extent, controlled burrow system excavation.

Thalassinoides in the study area extend downward from the surface of substrates in which they were excavated (figs. 15, 20A, 25A). Although connection with the substrate surface is not always visible in outcrop, burrow fill is clearly related to suprajacent sediments (figs. 24A, 25B) (see Curran and Frey, 1977, p. 155).

Some specimens of Thalassinoides are unlined (figs. 19A, C) (see Fursich and Palmer, 1975, p. 172). A few examples have a thin, well-defined, smooth lining of hydrous iron oxide (figs. 20B, 24C), suggestive of replacement of an original organic lining (see Curran and Frey, 1977, p. 155). Such well-defined hydrous iron oxide linings are rarely associated with a thin carbon residue (for example, the system in fig. 24C), further suggesting the existence of an organic precursor. However, the walls of most specimens exhibit irregular impregnations and/or encrustations of hydrous iron oxide.

Several decapod and stomatopod crustaceans are capable of producing burrows attributable to *Thalassinoides*. Most prominent among these are species of the shrimp *Callianassa*, *Alpheus*, *Upogebia* (Bromley and Frey, 1974, p. 319-324), and *Axius* (Pemberton and others, 1976, p. 790, 791, fig. 2). Also, fossil *Glyphaea* have been found in association with *Thalassinoides* from the Jurassic of England (Sellwood, 1971, p. 589, 590). Less prominent are species of the crabs *Sesarma* and *Eurytium* (Basan and Frey, 1977, table B, pl. 4a), astacid lobsters, crayfish (Bromley and Frey, 1974, p. 319-321), and the stomatopod, *Squilla empusa* (Frey and Howard, 1969, pl. 4, fig. 2). Comparison of burrows constructed by these animals with the various forms of *Thalassinoides* observed in the study area is made in the following pages on a case by case basis.

Thalassinoides systems probably performed a dual function. Although initial excavation of these structures probably served as a means of sediment exploitation, the structures ultimately served as dwellings (Bromley and Frey, 1974, p. 325). Recent studies suggest open burrows may continue to play a role in feeding-related sediment exploitation through use in the culture of edible micro-organisms (Braithwaite and Talbot, 1972, p. 280; Frey and Howard, 1975, p. 285, 294; Ott and others, 1976, p. 72, 73).

Evidence suggests *Thalassinoides* in the study area were excavated and occupied in an intertidal to shallow subtidal, warm marine environment with a broad range of current energies. Overall configuration of these burrow systems ranges from shallow, dominantly horizontal systems (figs. 23A, B) to deep, dominantly vertical ones (figs. 15, 17A). Analogous modern burrow systems are excavated in intertidal and shallow subtidal environments. Dominantly horizontal systems are excavated in relatively low energy situations, whereas dominantly vertical systems are excavated in relative high energy situations (Frey, 1971, p. 111; Basan and Frey, 1977, fig. 4; Frey and others, 1978, p. 217, 218, fig. 11). *Thalassinoides* are generally absent from highly irregular, boulder-strewn surfaces at the Oconee-Barnwell disconformity (for example, fig. 34). This absence may be due to strong scour operating at these places during times when *Thalassinoides* otherwise would have been excavated, or to their subsequent removal by erosion.

Fossiliferous suprajacent Clinchfield and, in many instances, fossiliferous burrow fill, are suggestive of marine conditions. Furthermore, at Locality "A", suprajacent Clinchfield consists in part of abundantly fossiliferous decalcified limestone. This material contains gastropods, pelecypods (including abundant pectens), bryzoans, and solitary corals. This assemblage is generally indicative of warm shallow marine conditions. Also suggestive of marine conditions is the presence of abundant and diverse crustacean burrows such as the various *Thalassinoides* which occur at the top of the Oconee.

The state of preservation and the presence or absence of linings of *Thalassinoides* may be indicators of substrate stabilities in the study area. For example, in the upper 3-5 m of the Oconee the presence of unlined, open burrows up to 10 cm in diameter, many of which show no signs of deformation (fig. 16B), attests to the high degree of coherence of substrates in this stratigraphic interval during and after burrow construction. However, lower portions of some *Thalassinoides*, which penetrate this interval to depths in excess of 2 m, show signs of compactional deformation, such as "pinch marks" and irregular diameters along some burrow segments (fig. 12). Additionally, *Thalassinoides* in overlying Clinchfield sediments commonly are thinly lined and show signs of compactional deformation (figs. 24, 28), suggesting these sediments were generally less coherent than those penetrated by *Thalassinoides* in the Oconee below.

Thalassinoides sp. A

Figures 13-19

Description: *Thalassinoides* composed of systems of irregularly "Y"-or "T"-branched, slightly sinuous tunnels, 1 to 5 cm in diameter (figs. 13, 14, 16, 19); typical orientation of systems, dominantly vertico-horizontal, with some systems becoming more random in lower portions (figs. 13, 14); intersections dichotomous and inflated, or multiple and chambered, with 5 or 6 intersections per chamber (figs. 15, 16A, B, 17B, 19B). Chambers may exceed 10 cm in diameter (for example, figs. 16B, 17A); walls are unlined, moderately to slightly irregular, commonly exhibiting small, bluntly conical pits (fig. 16C); maximum depth of penetration observed, about 5 m.

Preservation: "Pinch marks" and irregular diameters apparent along some segments of lower portion (fig. 14); truncation of tunnels observed at substrate surface in some instances.

Occurrence and distribution: Occurs in massive muds and slightly sandy muds at Localities "A" and "C"; structures originate at upper surface of Oconee; density typically 2 intersections per linear meter on a vertical face, 30 cm below substrate surface.

Interpretation: Probably excavated by a thalassinidean shrimp, possibly a species of *Callianassa,* in an intertidal or shallow subtidal, marine or estuarine environment of high current energy; observed truncations indicative of post constructional erosion; "pinch marks" and irregular burrow segment diameters may be an indication of post constructional compaction.

Discussion: An additional aspect of burrow system morphology is included here. Where these systems are dominantly vertico-horizontal, "Y"-branching is produced in the following manner. Subjacent to intersections, otherwise vertical shafts are steeply inclined for a distance of about 5 cm. At such intersections, inclined shaft exit directions are opposite exit directions of tunnels (fig. 15).

Also deserving of mention is the occurrence at Locality "C" of a smaller version (fig. 19) of the *Thalassinoides* sp. A morphotype. These smaller systems typically consist of interconnected segments 10 to 15 cm in length and 1 to 1.5 cm in diameter. Maximum observed depth of penetration into the substrate is about 1 m. These smaller systems particularly resemble larger *Thalassinoides* sp. A systems (for example, fig. 15) in that chambered, multiburrow intersections, "T"- and "Y"-shaped branching, and stratigraphic occurrence are common to both burrow sizes (see figs. 15, 19B). Also common to both is the interconnection of shafts with 5 cm-diameter tunnels (see figs. 17D, 19E). However, this feature was not observed among many examples of smaller burrows, leaving confusion as to whether such interconnections were accidental or by design. Apparently, the only major morphological differences between these two burrow sizes are a lesser degree of chambering and the absence of inclined shafts subjacent to intersections to produce "Y"-branching (for example, fig. 15) in the smaller burrows. Thus, the major difference appears to be one of scale, making differentiation of large and small systems unwise at present.

Morphologically similar burrow systems of different scale may be produced by adults of the same species living under significantly different environmental conditions (Ott and others, 1976, p. 68), by juveniles and adults of the same species (Frey and Howard, 1975, p. 283), or by different, but ethologically similar species. No determination as to which of the foregoing was responsible for the smaller scale version of *Thalassinoides* sp. A is made here.

Burrow systems assigned to *Thalassinoides* sp. A are morphologically similar to shaft-dominated *Ophiomorpha* described by Frey and others (1978, p. 202, fig. 2A), except that *Thalassinoides* sp. a lacks an exteriorly mamillated lining and "apertural necks." The validity of morphological comparison between these two ichnogenera is confirmed by observations of knobby-walled *Ophiomorpha* passing into smooth-walled *Thalassinoides* as substrates become more cohesive due to grain-size change or other factors (Ager and Wallace, 1970, p. 4, 8; Frey, 1971, p. 104, 116; Bromley and Frey, 1974, p. 324, 329, 330; Frey and others, 1978, p. 205). Such shaft-dominated *Ophiomorpha* systems are constructed by *Callianassa major*(Say) in the foreshore of Georgia beaches (Weimer and Hoyt, 1964, p. 763; Frey and Mayou, 1971, p. 57, 58, fig. 3). However, *Callianassa major* has been observed to avoid "highly coherent," relict marsh mud exhumed by erosion along some Georgia beaches. The animal shows a decided preference for sandy substrates in this setting (Frey and others, 1978, p. 209). Substrates penetrated by *Thalassinoides* sp. A producers are though to have been at least as coherent as these "highly coherent" marsh muds (p. 85-86).

Other callianassids and thalassinideans, including the deep-burrowing *Axius serratus* (Pemberton and others, 1976, p. 790, 791) are possible modern analogues to *Thalassinoides* sp. A producers (Frey and others, 1978, p. 204).

Deeply penetrating, shaft-dominated burrow systems similar to *Thalassinoides* sp. A are characteristic of high energy environments and of situations where a buffer is needed as protection against environmental extremes or erosion (Frey, 1971, p. 111; Frey and others, 1978, p. 217, 218, fig. 11). These conditions are most commonly obtained in beach-associated intertidal and shallow subtidal zones, although this may not always be the case (Frey and others, 1978, p. 218).

The lower portions of some deeply penetrating *Thalassinoides* sp. A systems (for example, fig. 15) were possibly excavated in a less coherent substrate than the upper portions of these systems. Some shaft segments in these lower portions exhibit roughly horizontal "pinch marks" along their lengths (figs. 13, 14). According to R. W. Frey (1978, personal commun.) such features are indicative of soft sediment compaction following burrow construction. Other evidence suggestive of compaction is variability of burrow diameters along some segments (figs. 13, 14, 27, 28A).

Figure 13.

Figure 14.

Figure 13. *Thalassinoides* sp. A from Locality "A", illustrating typical morphology and orientation. Dark staining of burrow fill and some areas surrounding burrows due to concentration of hydrous iron oxide. Upper surface of Oconee Group at top. Vertical view, outcrop face. Ruler is 15 cm long.

Figure 14. View of right side of *Thalassinoides* sp. A systems illustrated in figure 13, showing "pinch marks" and irregular diameters along some burrow segments in lower center of figure. Ruler is 15 cm long.

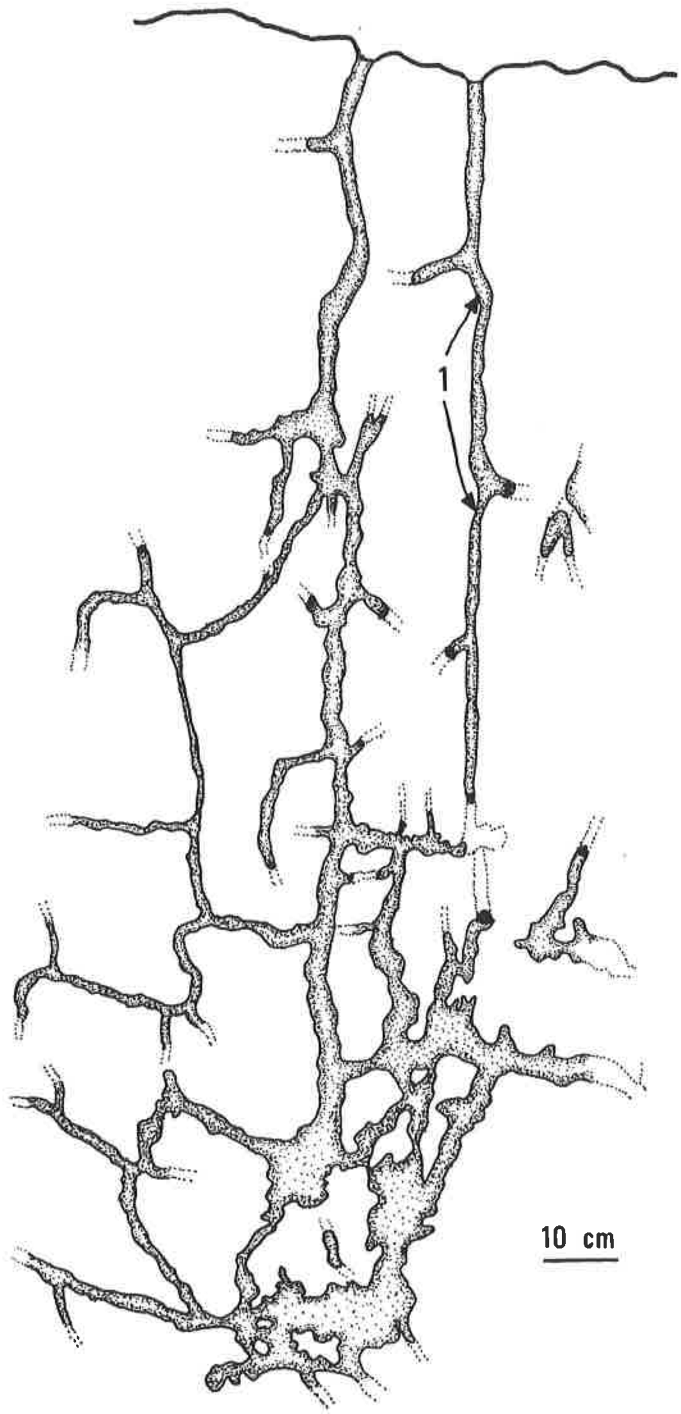


Figure 15. *Thalassinoides* sp. A from Locality "A", adapted from figure 13. Upper surface of Oconee Group at top. vertico-horizontal orientation is pronounced. (See Frey and others, 1978, fig. 2A). Inclined shaft exit directions (1) are opposite exit directions of tunnels.

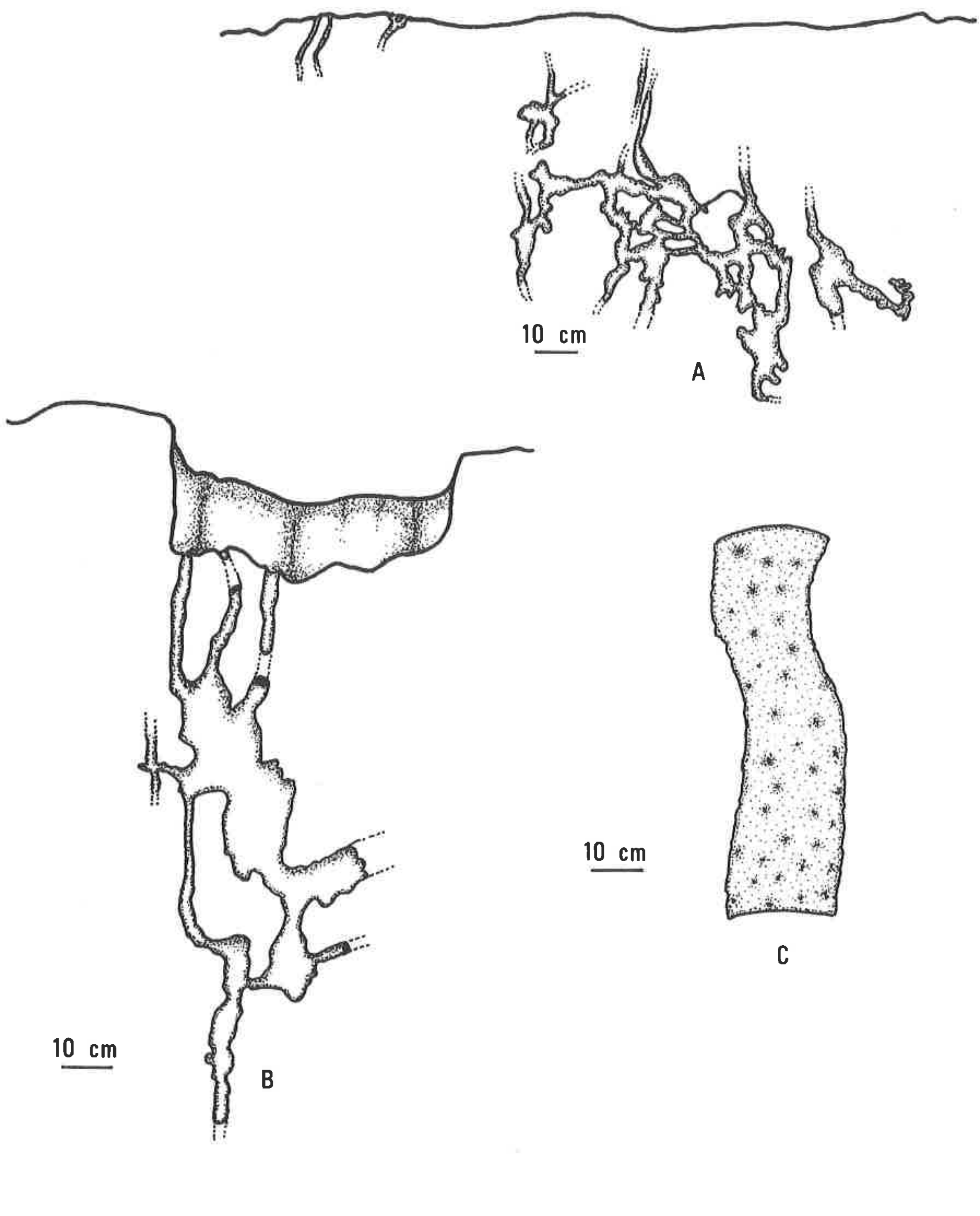


Figure 16. *Thalassinoides* sp. A from Locality "A". A, B, burrow systems showing pronounced vertico-horizontal orientation and chambering. Upper surface of Oconee Group at top; C, longitudinal section of a *Thalassinoides* sp. A burrow segment, showing pitted wall structure. Distribution of pits is not always this uniform. Vertical views, outcrop face.

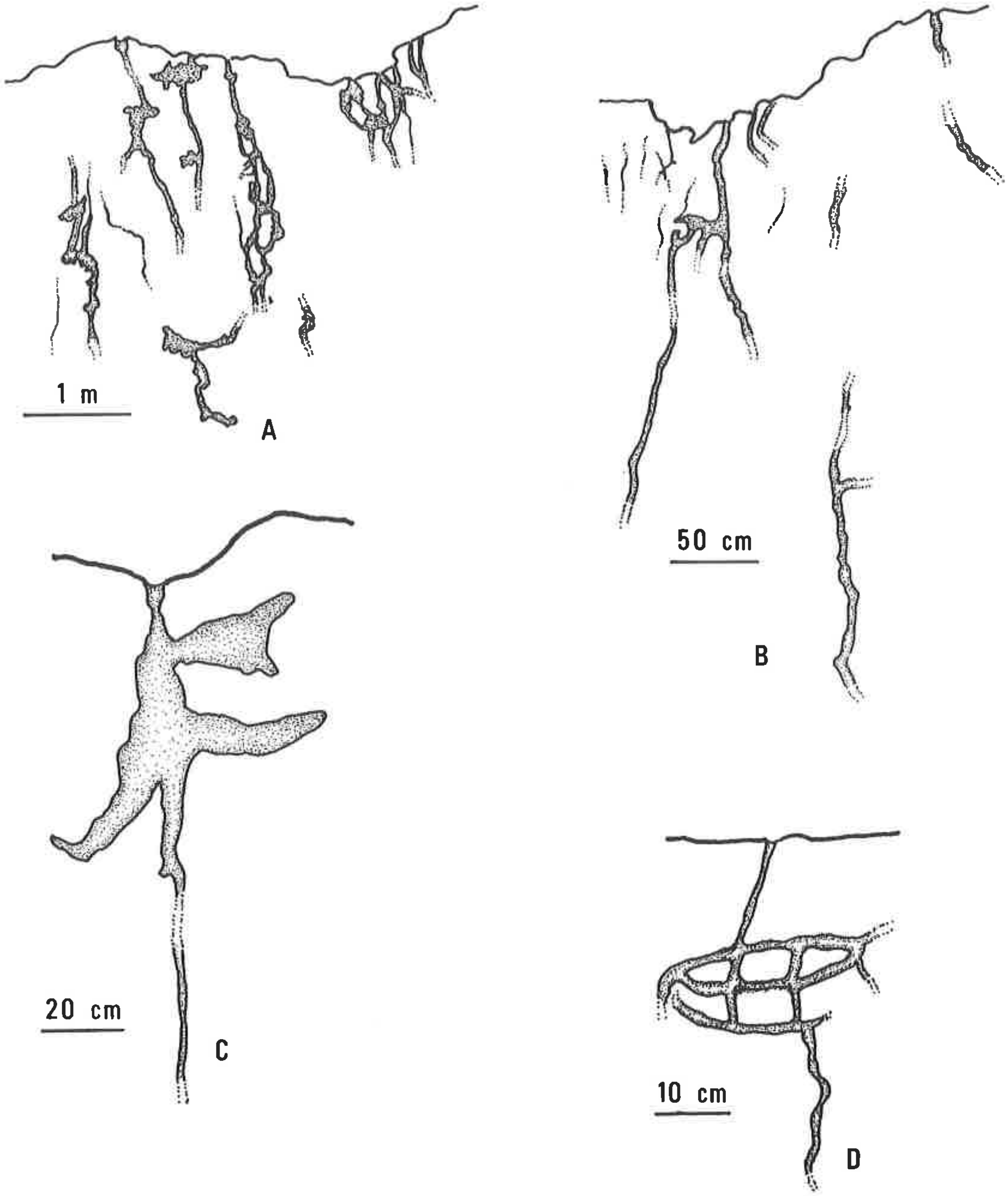


Figure 17. *Thalassinoides* from Locality A, opening onto upper surface of Oconee Group. Vertical views, outcrop face. A, B, *Thalassinoides* sp. A systems; C, D, possible examples of *Thalassinoides* sp. A.

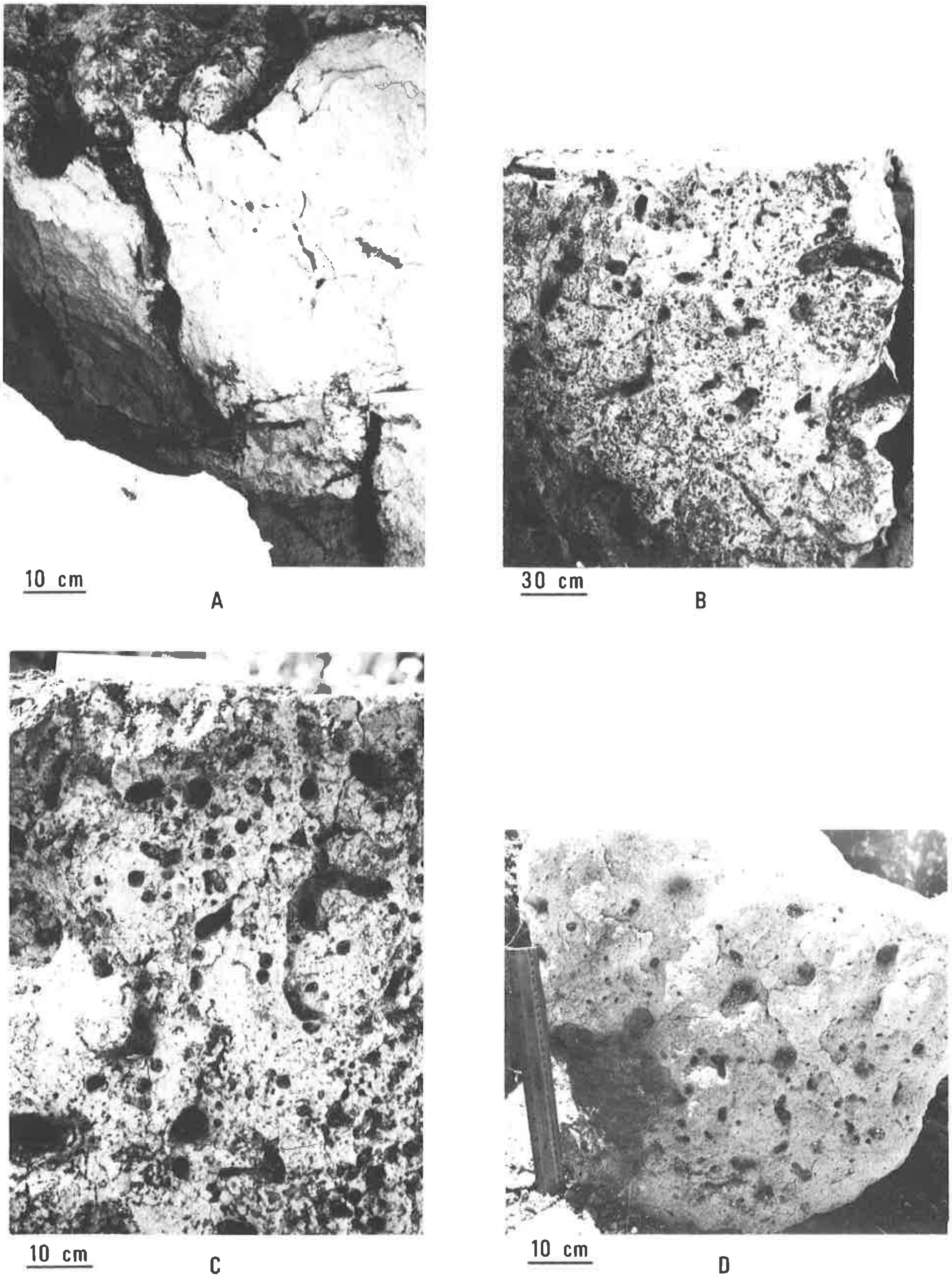


Figure 18. Burrowed erosion surfaces at the top of the Oconee Group in northwestern Washington County. A, *Thalassinoides* sp. A system from Locality "A", showing erosional truncation of tunnels (upper center and upper left). Oblique view outcrop face; B, horizontal view of erosion surface at Locality "A", showing many truncated specimens of *Thalassinoides* and *Trypanites*. Truncated tunnels of *Thalassinoides* sp. A system illustrated in fig. A visible at extreme right; C, detail of B, showing truncated *Thalassinoides* shafts (larger, subcircular dark holes) and tunnels (grooves) and truncated *Trypanites* (smaller, circular light and dark holes); D, horizontal view of erosion surface at Locality "C", showing features similar to those seen in B and C.

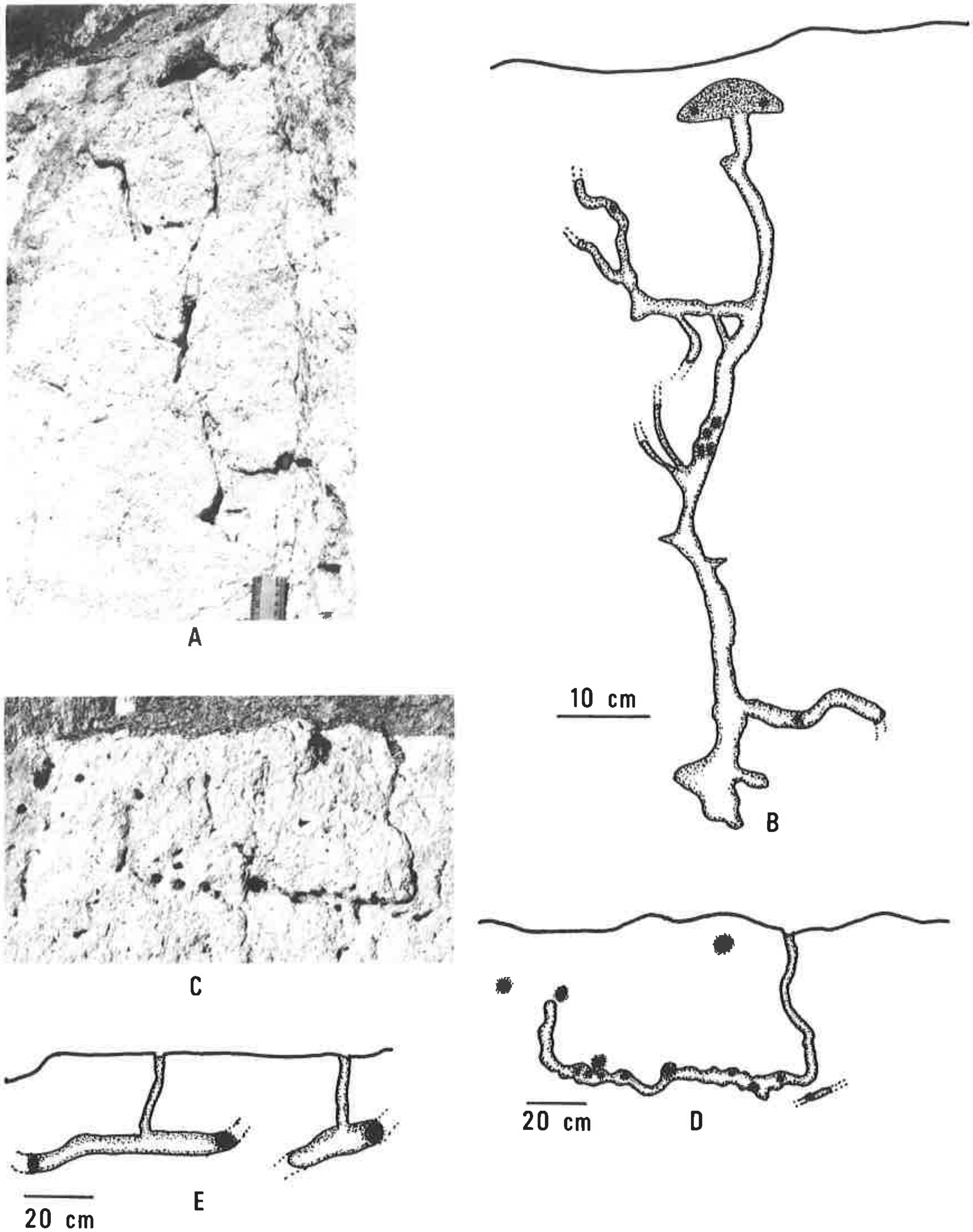


Figure 19. Small version of *Thalassinoides* sp. A from Locality "C". Upper surface of Oconee Group at tops of A-E. A, oblique view of vertical face, showing chamber near upper surface; B, adapted from A. Black spots indicate roughly perpendicular intersection with outcrop face; C, vertical view, outcrop face; D, adapted from C; E, 1.0 to 1.5 cm diameter shafts connected to 5 cm diameter tunnels.

Thalassinoides sp. B

Figures 20-23

Description: *Thalassinoides* composed of regularly or irregularly "Y"-branched, sinuous to slightly sinuous, inclined burrows, 0.7 to 10 cm in diameter, typically anastomosing downward (figs. 20A, 21A, 23A, B); intersections inflated; branching is dichotomous (fig. 22B) or multiple (fig. 23C); walls slightly irregular and unlined or thinly lined with non-mamillated exteriors (for example, the system illustrated in fig. 20B); overall configuration, two-or three-dimensional; maximum depth of penetration observed,about 2 m.

Preservation: fill unpatterned; burrow linings, where present, consist of hydrous iron oxide encrustations and may also contain some quartz sand and carbon residue; where sands are penetrated, structures grade into bioturbate texture (for example, the system illustrated in fig. 23C).

Occurrence and distribution: occurs in massive muds, slightly sandy muds, and rarely in bioturbated sands at Localities "A", "D", and "E"; originates at upper surface of Oconee Group or within Clinchfield Formation; density ranges from 4 to 6 intersections per linear m, 30 cm below upper surface of Oconee.

Interpretation: probably excavated by burrowing shrimp, possibly species of *Upogebia* and/or *Alpheus*, in an intertidal or shallow subtidal, marine or estuarine environment of moderate current energy; excavation of two-dimensional systems probably was controlled by vertical joint surfaces (figs. 21, 22).

Discussion: *Thalassinoides* sp. B differs from *Thalassinoides* sp. A in the following respects: sp. A components are dominantly vertico-horizontal, whereas those of sp. B are dominantly inclined; sp. A may be "T"- or "Y"-branched, whereas sp. B is almost invariably "Y"-branched; sp. B systems tend to anastomose downward, whereas sp. A systems do not.

Two types of sp. B systems are recognizable. These two types are herein referred to as *Thalassinoides* sp. B1 (figs. 20-22) and *Thalassinoides* sp. B2 (fig. 23). Comparison of these two system types yields the following results: *Thalassinoides* sp. B1 is typically composed of slightly sinuous, steeply inclined, "Y"-shaped components, 0.7 to 2.0 cm in diameter, with diameters tending to be uniform within a given system; *Thalassinoides* sp. B2 is typically composed of sinuous, gently inclined, "U"- and "Y"-shaped components, 2.0 to 10 cm in diameter, with chambers and burrow segments of variable diameter within a given system. These two burrow types will be discussed separately.

Thalassinoides sp. B1 systems were observed at Localities "A" and "D". Several unique morphological features of *Thalassinoides* sp. B1 not mentioned in the foregoing descriptions are included here. Although most transverse sections through *Thalassinoides* sp. B1 burrows are roughly circular, one example of a section with flat floor and arched roof was observed (fig. 20C). Orientation of the burrow segment displaying this section was nearly horizontal. Transverse sections similar to this one have been observed in modern burrows of *Alpheus floridans* (Shinn, 1968, p. 882) and *Axius serratus* (Pemberton and others, 1976, p. 790, 791). Three observed features, a subspherical chamber (fig. 20A), a constricted interconnection between burrows of slightly different diameter (fig. 20A), and a bluntly conical "dead end" (fig. 20B), are similar to features constructed by modern *Upogebia affinis* (Bromley and Frey, 1974, figs. 9, 10; Frey and Howard, 1975, figs. 1, 3, 4). However, construction of these features is not restricted to this species of shrimp.

At Locality "D", an occurrence of smaller, dominantly vertical, "Y"-branched burrows, 1 to 7 mm in diameter, emanating from "normal" *Thalassinoides* sp. B1 was observed (figs. 20A-C). Similar associations have been observed in *Thalassinoides* from the Upper Cretaceous of Utah and in systems of modern *Alpheus hetrochaelis* (Basan and Frey, 1977, pl. 2e), *Upogebia affinis* (Frey and Howard, 1975, p. 287, figs. 2, 6B, 7), and *Callianassa kraussi* (Forbes, 1973, fig. 4). In such cases, the smaller burrows are presumed to be the work of different aged juveniles of the same species as larger burrow producers (Forbes, 1973, p. 363, 364; Frey and Howard, 1975, p. 287, 290). The dominantly vertical orientation of smaller burrows associated with *Thalassinoides* sp. B1 may be due in some way to their occurrence on a vertical joint surface.

Occurrence of *Thalassinoides* sp. B1 at Locality "D" is not restricted to essentially two-dimensional vertical joint surfaces (for example, fig. 21B). These burrows may also occur as three-dimensional systems where vertical jointing of substrates is not pronounced (fig. 20C). Coexistence of two- and three-dimensional configurations of *Thalassinoides* sp. B1 in the same outcrop and association of these configurations with strongly and weakly jointed strata respectively, suggest that jointing, where present, largely controlled lateral burrowing directions. The distribution of burrows and joints at Locality "D" also suggests that jointing preceded burrowing.

Burrow systems assigned to *Thalassinoides* sp. B1 have several notable affinities with modern systems produced by the thalassinidean shrimp, *Upogebia affinis*. Burrow systems of *Upogebia affinis* typically consist of irregularly branched networks of "Y"-shaped components (see Bromley and Frey, 1974, fig. 10), thinly lined, and enlarged at points of bifurcation (Frey and Howard, 1975, p. 286). Burrow segments are 1 to 2 cm in diameter and diameters tend to be constant within a given system (Curran and Frey, 1977, p. 156). Openings to the surface are multiple and constricted. Individual systems may extend in excess of 50 cm vertically and 2 m laterally. Burrowing seems to be restricted to muddy substrates (Curran and Frey, 1977, p. 156).

Aside from the general absence of linings and apertural necks in specimens of *Thalassinoides* sp. B., comparison with burrow systems of modern *Upogebia affinis* on the basis of individual burrow components is favorable. However, comparison of the overall configuration of illustrated *Upogebia affinis* systems (see Frey and Howard, 1969, pl. 4, fig. 5; Bromley and Frey, 1974, figs. 9, 10; Frey and Howard, 1975, fig. 3) with that of observed *Thalassinoides* sp. systems (see figs. 20B, D, 19A, 21A) shows no such favorable comparison.

Consideration of the occurrence of *Thalassinoides* sp. B1 yields plausible explanations for these three observational discrepancies. The substrate penetrated by *Thalassinoides* sp. B1 was presumably a highly coherent one (p. 85-86, this volume). This could easily account for the general absence of linings in these specimens. Many other types of *Thalassinoides* penetrating this stratigraphic interval do not show definite linings. Given the apparent high potential for variability of burrow system configuration displayed by modern *Upogebia affinis* systems (see previous references), the unusually firm substrate could conceivably account for differences between them and that of *Thalassinoides* sp. B1. Variation in morphology of *Thalassinoides* systems caused by variation in substrate firmness was observed by Bromley (1967, p. 158-164). Where the tracemakers burrow in hardened substrates, they tend to (1) follow paths of least resistance and (2) enlarge existing burrows. Finally, the upper surface of the Oconee, which *Thalassinoides* sp. B1 open onto, is an erosion surface. Apertural necks constructed just below such a surface easily could have been removed by erosion prior to burial.

The foregoing comparisons serve to illustrate the many similarities between *Thalassinoides* sp. B1 and modern burrow systems constructed by a species of *Upogebia*. The morphological and dimensional similarities between these burrow systems suggest ethological and possibly ecological similarities between tracemakers. The comparisons are not intended to infer that *Thalassinoides* sp. B1 producers could have been only from this genus of shrimp. Other possible producers include various species of callianassids, alpheids, and fossil glyphioids (Curran and Frey, 1977, p. 155).

Burrows of modern *Upogebia affinis* are characteristic of lower intertidal to shallow subtidal, muddy estuarine, lagoonal, and nearshore substrates swept by gentle waves or tidal currents at near normal salinities (Frey and Howard, 1975, p. 286; Curran and Frey, 1977, p. 156).

Of special interest here is a modern occurrence of *Upogebia affinis* in a relict marsh mud. This deposit is exposed as a low tidal flat adjacent to a protected inlet on St. Catherines Island, Georgia (Morris and Rollins, 1977, p. 123, 124, fig. 28). Beach sand is swept over this mud flat at high tide, and some is deposited as veneers of variable thickness on the mud surface (Morris and Rollins, 1977, fig. 28) and as burrow fillings. Relict marsh muds exhumed along the Georgia coast by erosion are "very coherent" (Frey and Howard, 1969, p. 435), a property quite likely shared by substrates penetrated by *Thalassinoides* sp. B1 animals at the top of the Oconee. Furthermore, a thin sand bed of the Clinchfield covers the unit containing *Thalassinoides* sp. B1 and burrow fill is clearly derived from this material. Thus, it appears that environmental conditions on the St. Catherines Island mud flat (Frey and Howard, 1969, p. 435) may be somewhat analogous to those in existence on the upper surface of the Oconee at Locality "D" during excavation and occupation of *Thalassinoides* sp. B1.

One other aspect of this occurrence of *Thalassinoides* sp. B1 deserves mention. At Locality "D", Clinchfield sediments suprajacent to the upper surface of the Oconee are of two types: reduced interlayered mud and muddy sand and oxidized slightly muddy sand (appendix B). *Thalassinoides* sp. B1 was observed only beneath the latter sediment type, which also constitutes its filling. The occurrence of *Thalassinoides* sp. B1 at Locality "A" also displays this association in its positive aspect. These associations suggest the tracemaker may have preferred an environment with open circulation and moderate to high current energy.

Thalassinoides sp. B2 systems were observed at Localities "A", "D", and "E". Two additional aspects of *Thalassinoides* sp. B2 deserve mention here. In transverse section, burrows are circular, oblate, or irregular. Also, irregular hydrous iron oxide encrustations and impregnations were observed along burrow walls generally.

Burrow systems assigned to *Thalassinoides* sp. B2 have affinities with modern burrow systems produced by certain alpheid shrimp. Of particular interest in this regard are the descriptions and figures of *Alpheus heterochaelis* from muddy sediments along the Georgia coast by Basan and Frey (1977, pls. 2d, e, 3a, table 3; see also Howard and Frey, 1975):

> *Alpheus heterochaelis* - complex but finite system of multibranched, well integrated U- to Y-shaped components, 2-5 cm in diameter, circular to oblate in cross section, anastomosing downward into a single, irregular trunk .... Walls thinly lined; more irregular on roof than on floor. Numerous apertures .... lead to gently inclined or nearly horizontal components enlarged at points of bifurcation, like trace fossil *Thalassinoides*, with dead-end tunnels and enlarged "turn-arounds". Lower trunk exhibits approximately right-angle bends, and terminates in nearly horizontal tunnel at sediment depth of about 60 cm. System commonly includes components made by juveniles and commensals.

This description is barely distinguishable from that of *Thalassinoides sp. B2*. Also, the *Thalassinoides* sp. B2 system at left in fig. 23A bares striking morphological and dimensional similarities to *Alpheus heterochaelis* systems illustrated in Bromley and Frey (1974, fig. 8). Additional descriptions of the burrow systems of alpheid shrimp are contained in Shinn (1968, p. 881-883, pl. 109, fig. 1) and Farrow (1971, p. 482). These, too, are generally compatible with observations on *Thalassinoides* sp. B2.

Other possible, although less likely, producers of *Thalassinoides* sp. B2 are fossil glyphioid and callianassid shrimp, including various species of *Upogebia* (Curran and Frey, 1977, p. 156). Also capable of producing shallow versions of *Thalassinoides* sp. B2 are the stomatopod, *Squilla empusa* (Frey and Howard, 1969, pl. 4, fig. 2) and the mud crabs *Panopeus herbsti* and *Sesarma reticulatum*, where populations are locally dense and burrows of individuals are interconnected (for example, Basan and Frey, 1977, pl. 3d and 4a respectively).

Alpheid shrimp and their burrow systems are characteristic of muddy substrates of the intertidal and shallow subtidal zones (Shinn, 1968, p. 882; Farrow, 1971, p. 482; Basan and Frey, 1977, p. 60). They have also been reported from subtidal sands (Braithwaite and Talbot, 1972, p. 281). These conditions are compatible with substrates and postulated surface environments with which *Thalassinoides* sp. B2 is associated in the study area.

Undifferentiated *Thalassinoides* species

Figures 24-29

As mentioned previously, many thalassinoid burrows within the study area cannot be differentiated consistently. Examples are given in figures 24-29.

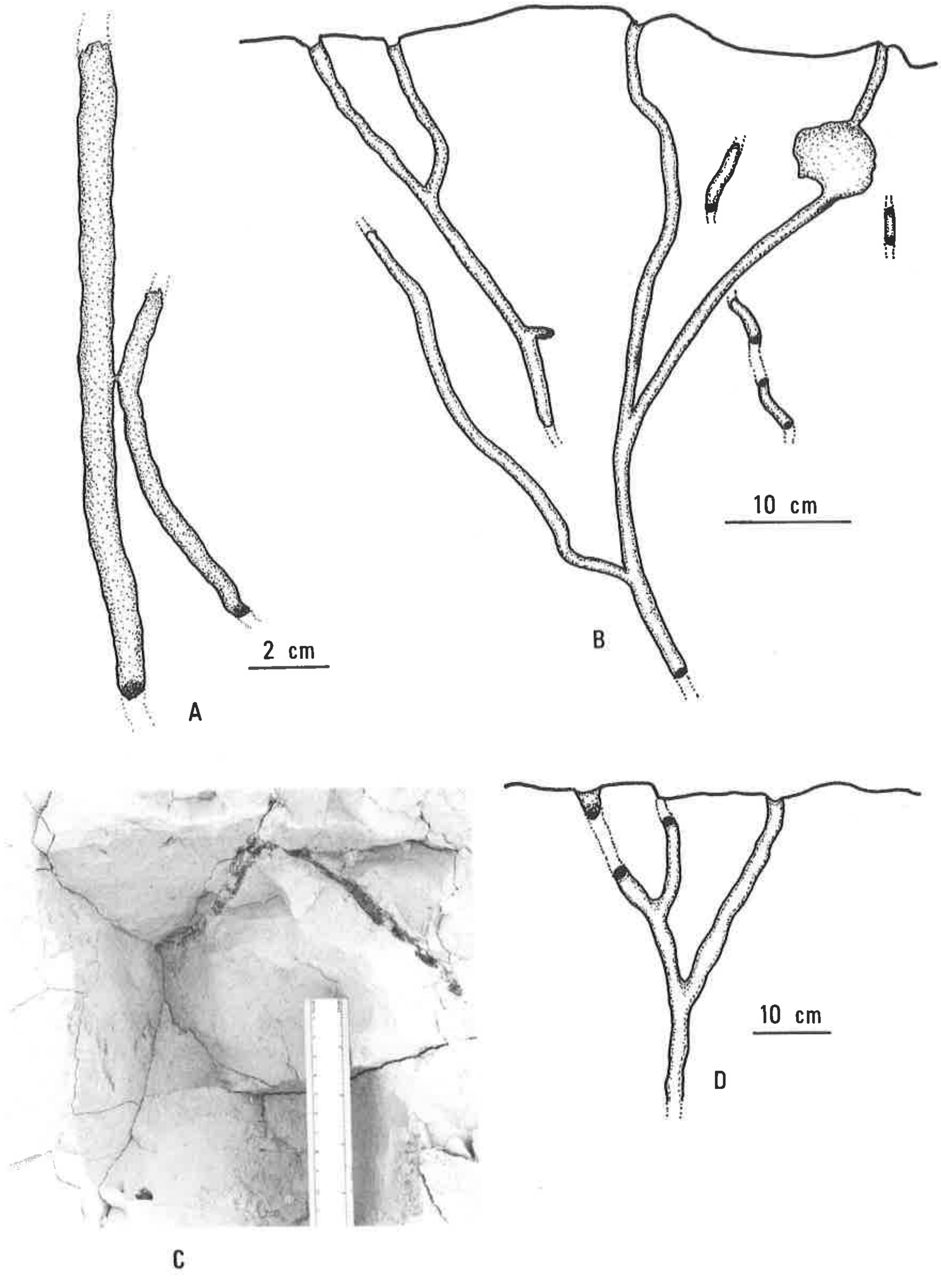
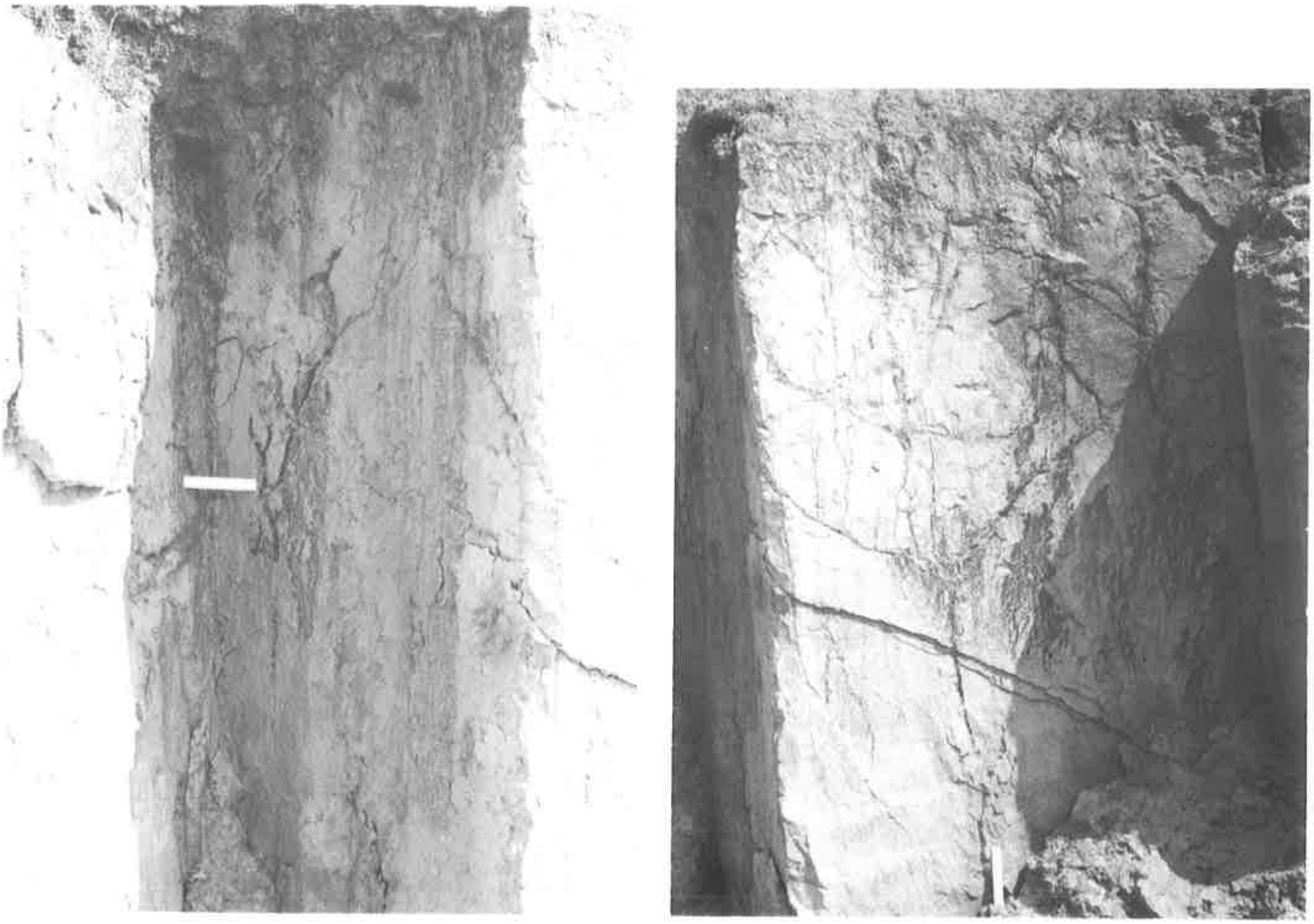
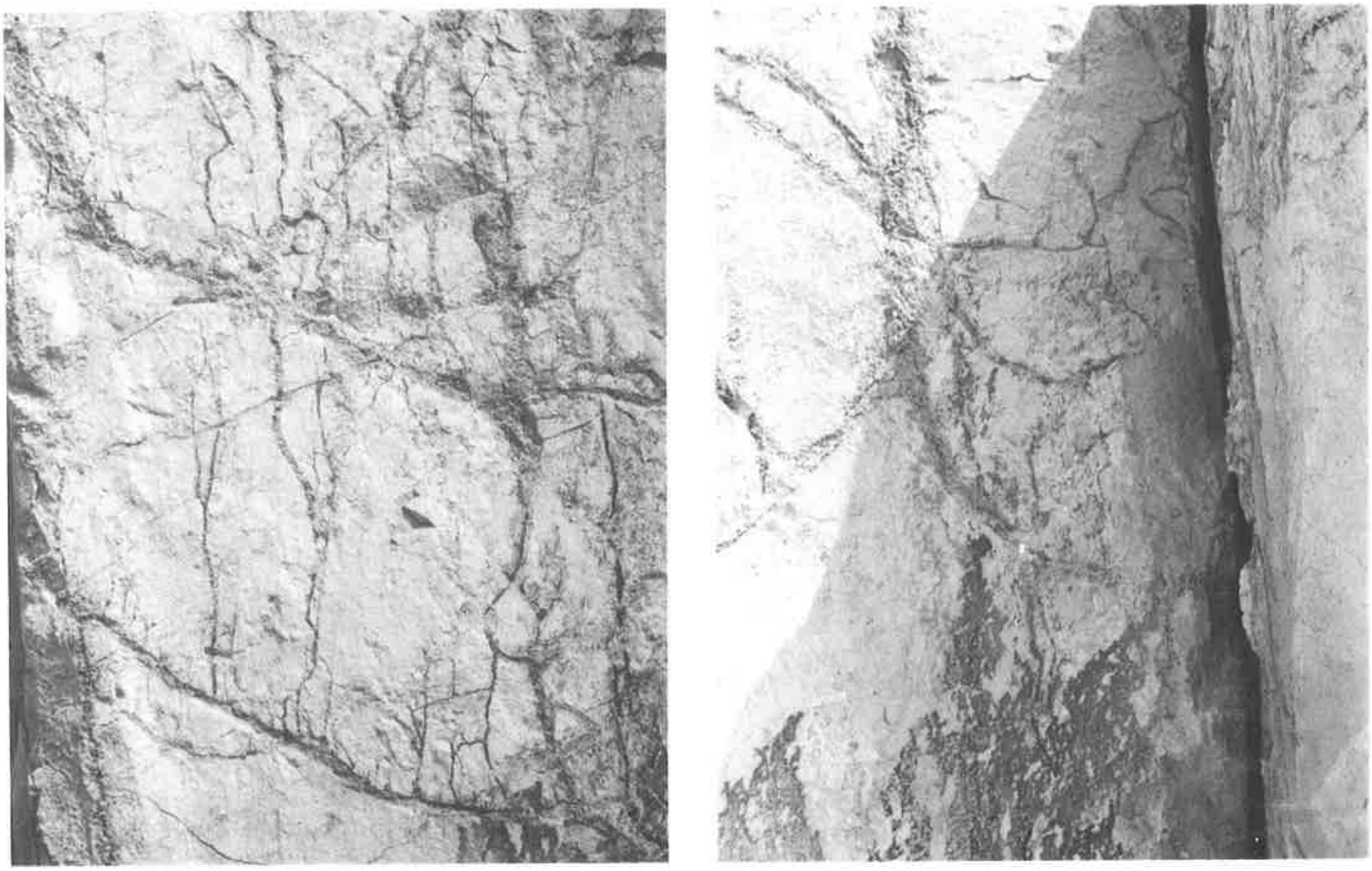


Figure 20. *Thalassinoides* sp. B1 from upper 2 m of the Oconee Group. Vertical views, outcrop faces. A, burrow segments of slightly different diameters, exhibiting constricted interconnection; B, typical downward anastomosing pattern exhibited by *Thalassinoides* sp. B1. Upper surface of Oconee at top; C, specimen showing three dimensional aspect of *Thalassinoides* sp. B1 in absence of vertical jointing. Transverse section of burrow at lower left shows arched roof and flat floor. A-C from Locality "D"; D, Thalassinoides B1 from Locality "A". Upper surface of Oconee at top.



A   B

Figure 21. *Thalassinoides* sp. B1 confined to vertical joint surfaces at Locality "D". Right side of A overlaps left side of B. Upper surface of Oconee Group at top. Systems in A interconnect with those of B. Ruler is 15 cm long.



A B

Figure 22. Details of figure 21B, showing interconnection of smaller and larger diameter burrows. A, numerous smaller diameter burrows of dominantly vertical orientation emanate upward from larger burrows, following the vertical joint surface; B, larger and smaller burrows exhibit Y-branching typical of *Thalassinoides*.

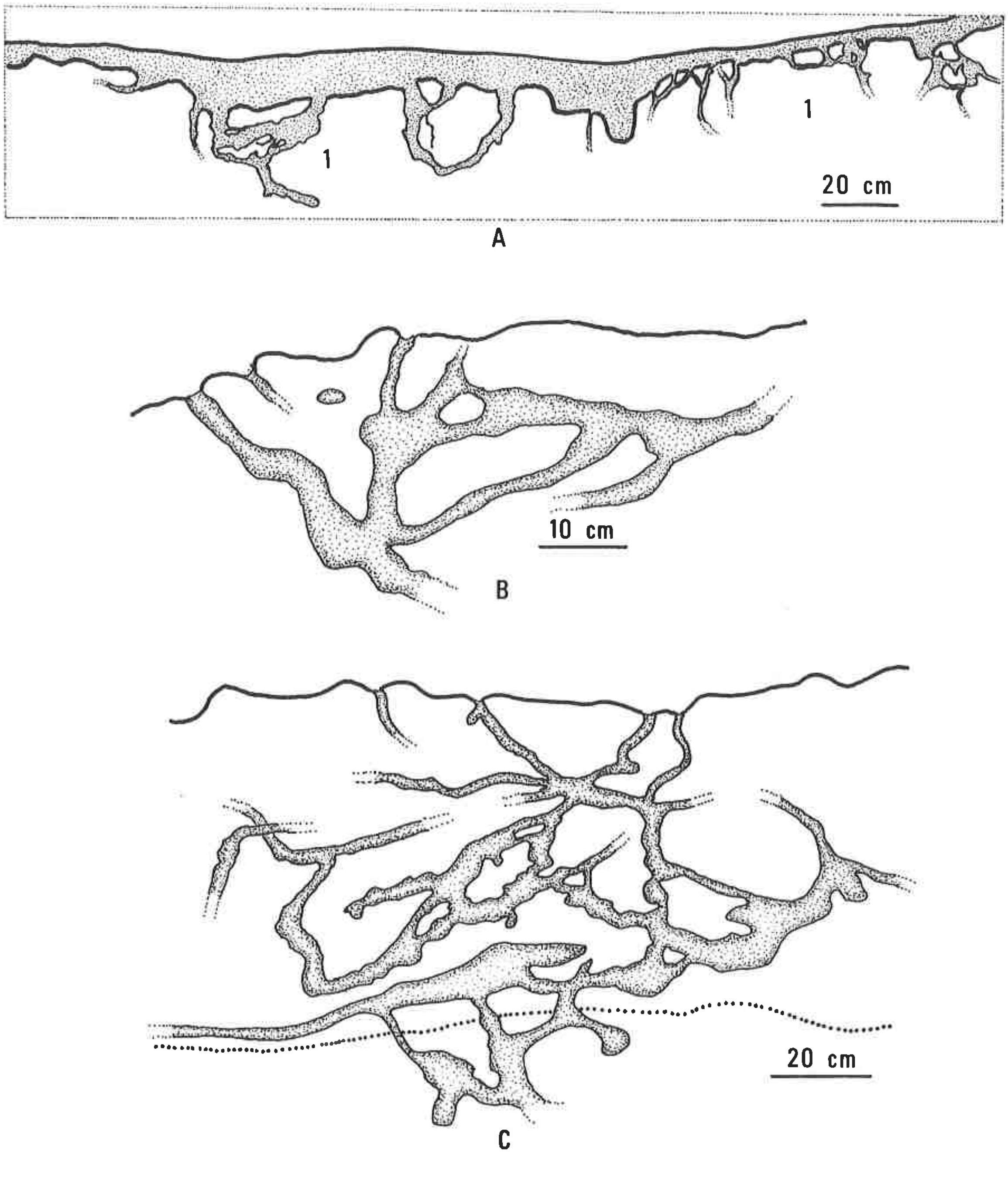


Figure 23. *Thalassinoides* sp. B2. Vertical views, outcrop face. Burrow systems open onto upper surface of Oconee Group, which is overlain by Clinchfield Formation. A, *Thalassinoides* sp. B2 systems (1) from Locality "A". Other burrows attributable to Thalassinoides are undifferentiated. B, from locality "D". C, system from Locality "E" which extends downward into crossbedded muddy sand, where it grades into bioturbate texture.

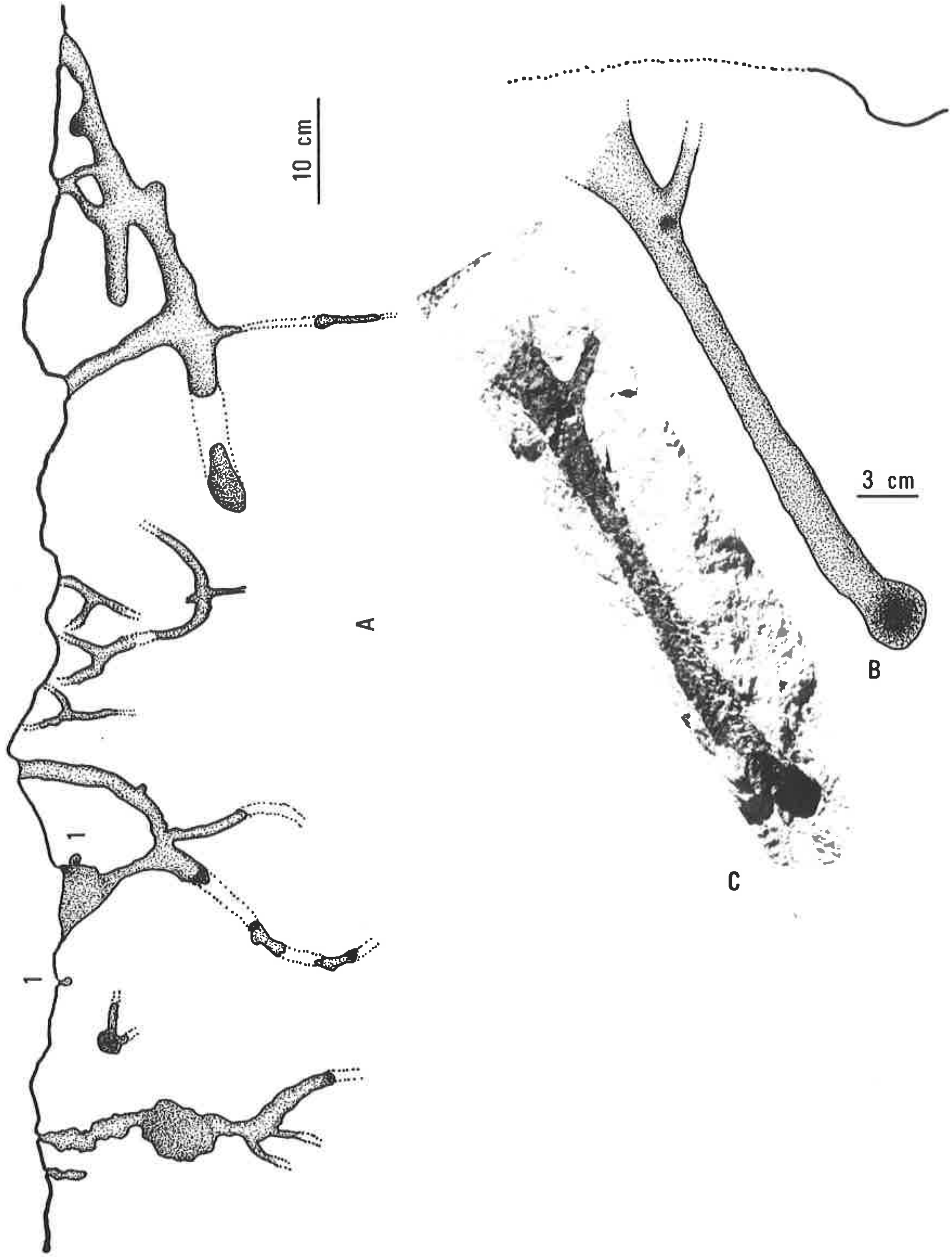


Figure 24. Undifferentiated *Thalassinoides* species from Locality "A". Burrows open into upper surface of Oconee Group. Black spots represent points of burrow entry into outcrop face. A, *Trypanites* sp. (1) also exposed Up is to left; B after C; C, darkness of burrow walls indicative of hydrous iron oxide encrustation.

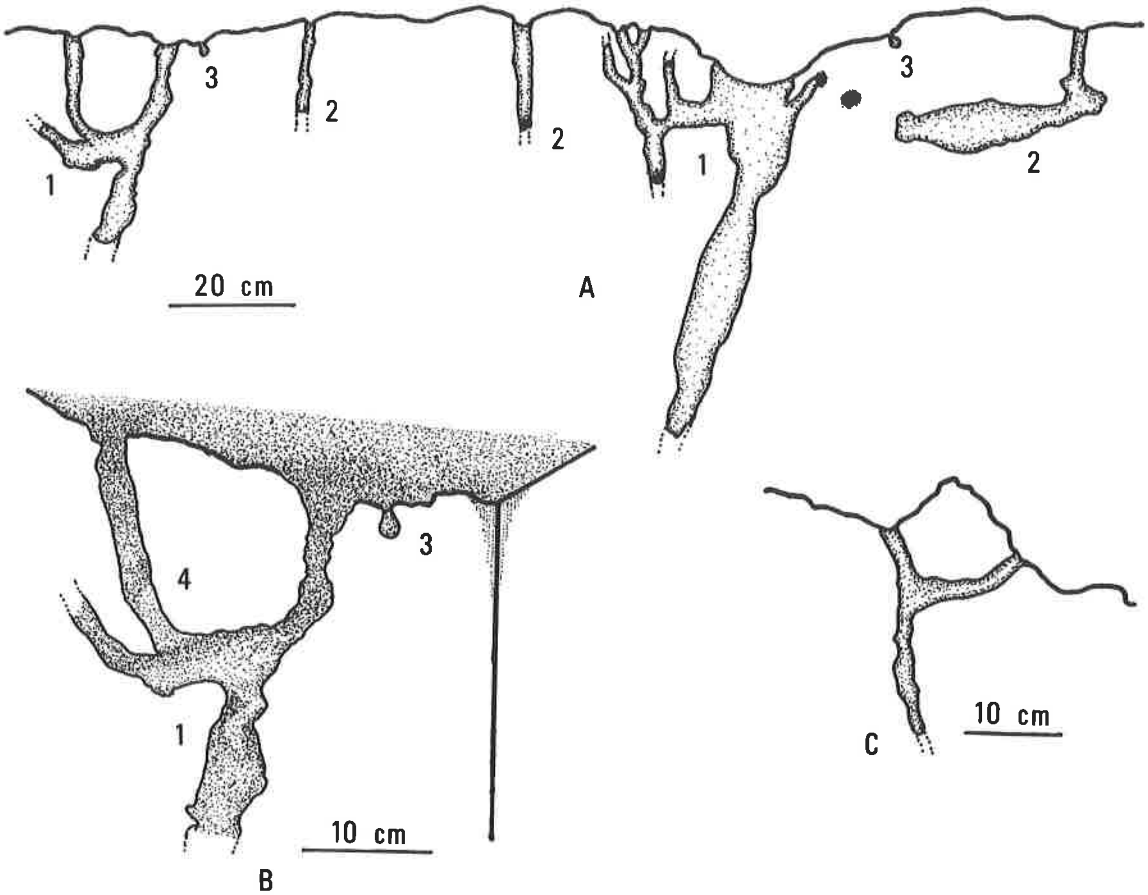


Figure 25. Undifferentiated *Thalassinoides* species from Locality "A". Upper surface of Oconee Group at top of figures. A, B, undifferentiated *Thalassinoides* species (1), other burrows of probable crustacean origin (2), and *Trypanites* sp. (3). Oblique views of vertical outcrop face; B, detail of left end of A, showing early filled abandoned aperture (4); C, Y-branched dual apertures typical of many undifferentiated *Thalassinoides* sp. at Locality "A" (see fig. 21A).

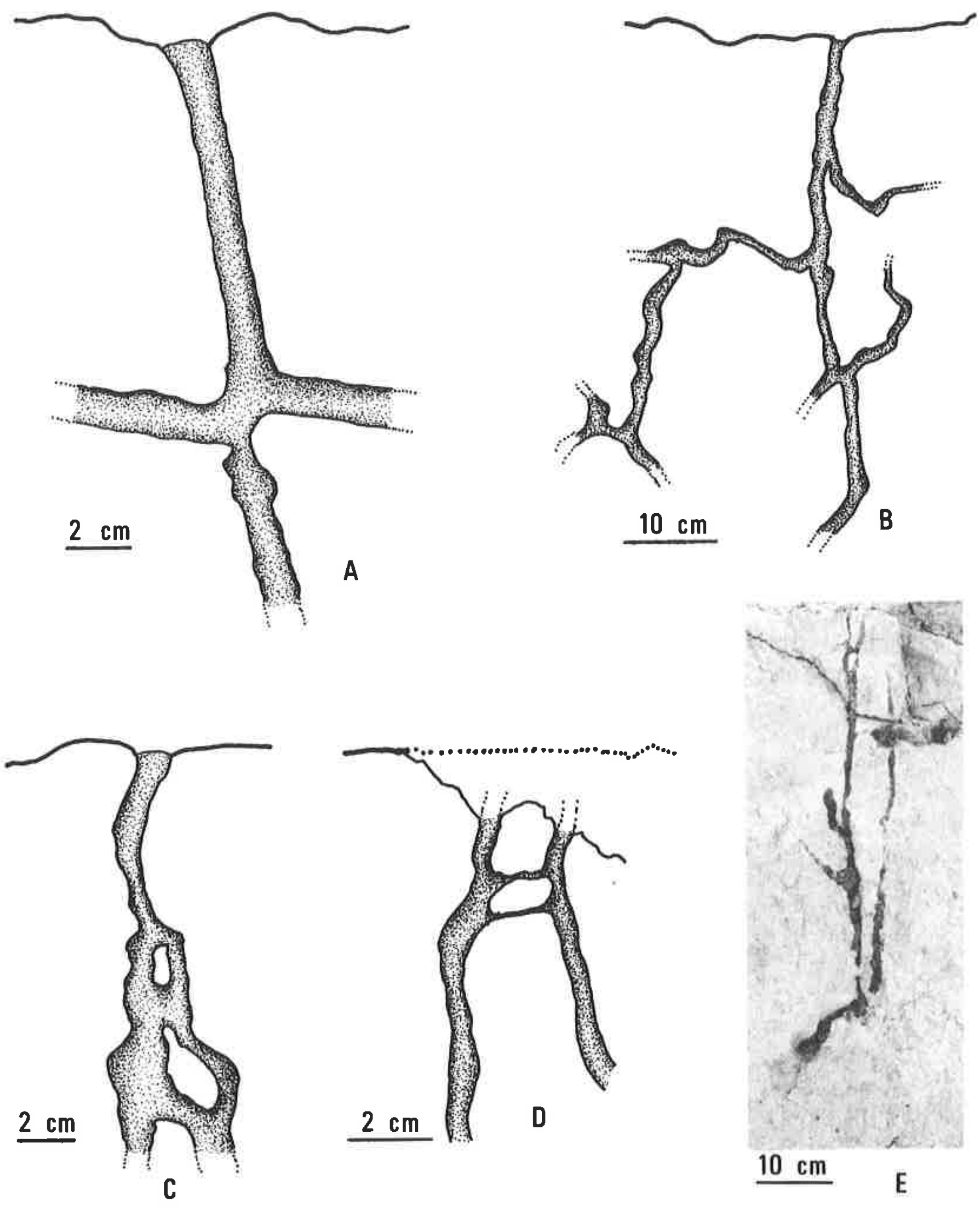
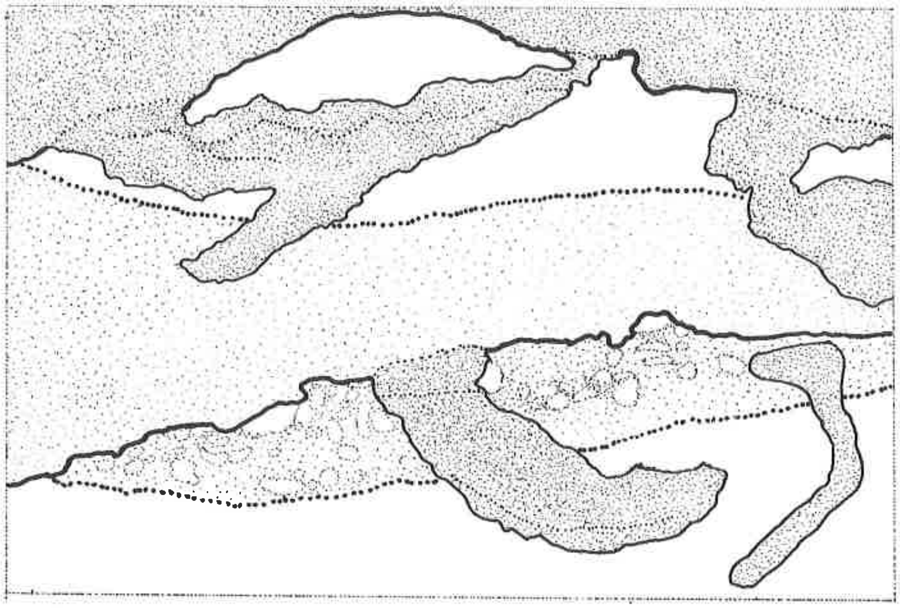
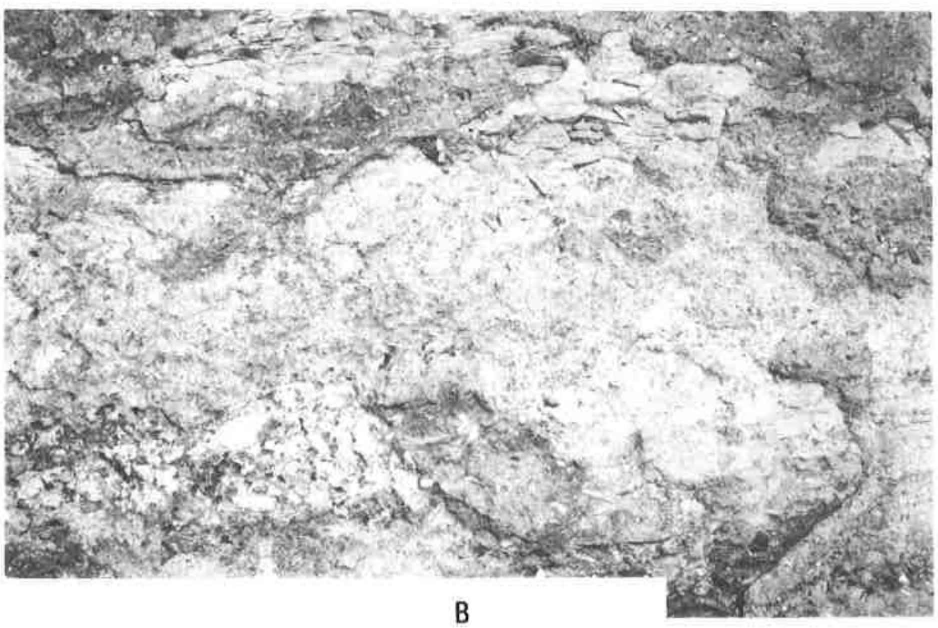


Figure 26. Undifferentiated *Thalassinoides* species from Locality "A". Vertical views, outcrop faces. A-D, burrows open onto upper surface of Oconee Group; E, top of figure about 1.2 m below upper surface of Oconee.



5 cm

A



B

Figure 27. Undifferentiated *Thalassinoides* sp. and "L-shaped burrow" from Clinchfield Formation at Locality "D", about 2 m above upper surface of Oconee. Vertical view, outcrop face. Burrow fills composed of dark fossiliferous sandy mud, similar to material in uppermost unit in figures. A after B.

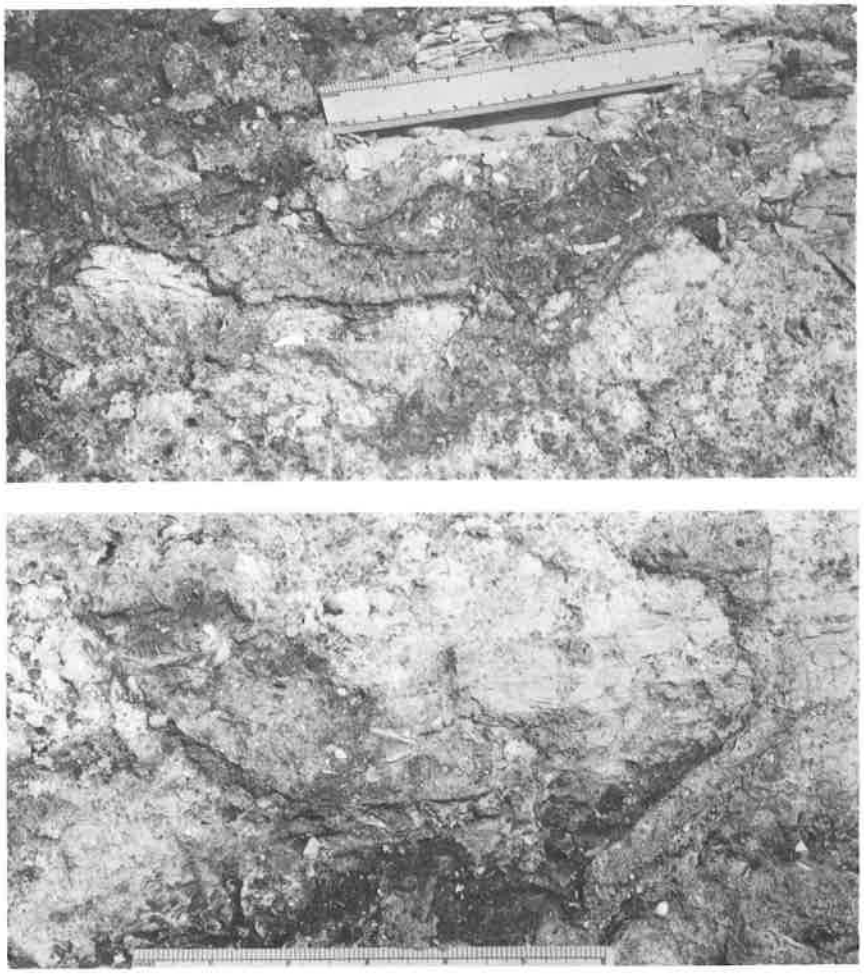


Figure 28. Details of figure 27B. A, broad U-shaped, Y-branched undifferentiated *Thalassinoides* sp. constructed in mud and filled with fossiliferous sandy mud, similar to suprajacent sediment. Laminae within fill apparently deformed; B, "L-shaped burrow" (right) and undifferentiated *Thalassinoides* sp. similar to burrow in A (left) constructed in sandy mud and mud and filled with fossiliferous sandy mud, unlike suprajacent sediment, suggesting omission bedding.

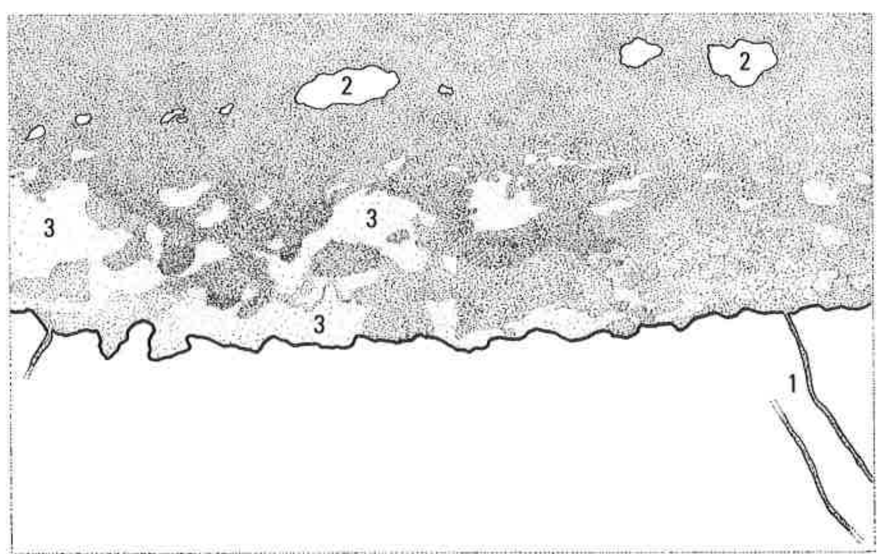


Figure 29. Probable *Thalassinoides* from Clinchfield Formation at Locality "D", grading laterally and vertically into bioturbate textures. Density of stippling indicates relative concentration of hydrous iron oxide. Oconee-Barnwell disconformity at center; *Thalassinoides* sp. B1 (1); mud clasts probably derived from Oconee below (2); unburrowed areas (3). Vertical view, outcrop face.

Ichnogenus *Trypanites* Magdefrau, 1932
Trypanites sp.

Figures 18B-D, 24A, 25A, B, 30

Description: short, cylindrical straight to slightly curved, steeply inclined borings, having constricted upper necks and enlarged, bulbous lower terminations (fig. 30A); diameters range from 3 to 4 mm across upper openings to 10 to 12 mm across lower bulbous portions; maximum length observed, about 40 mm; walls are unlined and commonly ornamented with circumferential striations (figs. 30A, B).

Preservation: exichnia, subjacent to erosion surfaces; boring fills are clearly related to suprajacent sediments and consist of unpatterned or, less commonly, horizontally laminated mixtures of sand and mud; complete specimens are commonly capped by a short plug of sandy hydrous iron oxide; complete individuals occupy substrate alongside severely truncated ones (fig. 30B).

Occurrence and distribution: occurs in massive, slightly sandy muds at the upper surface of the Oconee Group at Localities "A" and "C"; distribution is patchy, and borings may occur as isolated individuals or as laterally crowded aggregations (fig. 30E); maximum density observed, about $1000/m^2$.

Interpretation: dwelling structures of a marine borer, probably a species of pholadid bivalve; borings probably were excavated into a firm mud substrate under intertidal to shallow subtidal, intermediate to high current energy conditions; truncated borings indicate scour and their coexistence with non-truncated borings suggests these structures continued to be excavated and inhabited up to cessation of scour and burial.

Discussion: These specimens are assigned to the ichnogenus *Trypanites* Magdefrau, 1932, as redefined in Hantzschel (1975, fig. 76) and Warme (1975, p. 193, fig. 11.9), both after Bromley (1972).

Trypanites sp. are morphologically and dimensionally similar to borings and burrows produced by some modern infaunal clams. For example, borings of the pholadid clam *Nettastomella rostrata* are "clubshaped" and gently curved, penetrating 2 to 3 cm into rock substrates (Warme, 1970, p. 517, pls. 1c, 3a).

Other evidence in support of a pholadid excavator is the observation of a poorly preserved mud cast of the anterior portion of a bivalve, snugly fit inside a partially eroded boring. Ornamentation, shape, and size were similar to that of the modern pholadid clam *Penitella penita*, illustrated by Evans (1970, pl. 2).

Oconee Group substrates penetrated by *Trypanites* in the study area are slightly sandy muds which are overlain by the Clinchfield Formation. The presence of these borings indicates substrates into which they were excavated were at least firm or highly coherent at the time of excavation (Frey and Howard, 1969, p. 435; Evans, 1970, p. 127; Warme, 1975, p. 210). The highly coherent nature of these substrates also is indicated by several other independent lines of evidence (p. 85-86).

Another indication of substrate coherence is circumferential striations observed on some boring walls, especially those of some lower bulbous enlargements (figs. 30A-C). These probably were sculpted by shell prominences during rotary movements of the borer (Evans, 1970, p. 129; Warme, 1975, p. 210, 211). These striations consist of transverse parallel ridges and grooves of moderate (1 mm) relief. Warme (1970, p. 210, 211) correlates sculpture on the walls of pholadid borings directly with substrate hardness: deep grooves are produced in "soft mudstones" and polished surfaces in hard rock. Thus, at the time of boring, substrates penetrated by *Trypanites* probably were harder than Warme's "soft mudstones" but not his "hard rock".

Borings of pholadid bivalves have been reported as indicators of intertidal or shallow subtidal marine conditions (Bromley, 1970, p. 64; Evans, 1970, p. 128, 139; Radwanski, 1970, p. 371, 372; Warme, 1975, p. 187). However, Evans (1970, p. 128) points out that *Nettastomella rostrata* has been reported from depths of 100 m. Thus, caution should be exercised in assigning occurrences of fossil pholadid borings to intertidal-shallow subtidal environments, even though they may represent optimum conditions for the growth of these organizations.

Where borings occur, densities are typically $500/m^2$ (fig. 18C). However, distribution is uneven. Densities in some laterally crowded patches are as much as 1000 per m^2. Typical densities of *Trypanites* sp. are within the limits of 50 to 500 individuals per m^2 for shallow water species of pholadid bivalves reported by Warme (1975, p. 191).

Trypanites is associated only with the disconformity at the top of the Oconee Group, where it constitutes part of the omission suite ichnocoenose (Bromley, 1975, p. 399-402). The varying degree of truncation exhibited by adjacent individual borings (fig. 30B) and the relative abundance of truncated versus complete individuals, suggest these borings were excavated and inhabited up to the cessation of scour (Radwanski, 1970, p. 365; Warme, 1975, p. 210). Fill is clearly similar to suprajacent Clinchfield sediments, suggesting borings may have remained open until burial (Bromley, 1975, p. 401). It is also possible that some borings may have been filled by sediment in transit across a periodically scoured seafloor, prior to final burial.

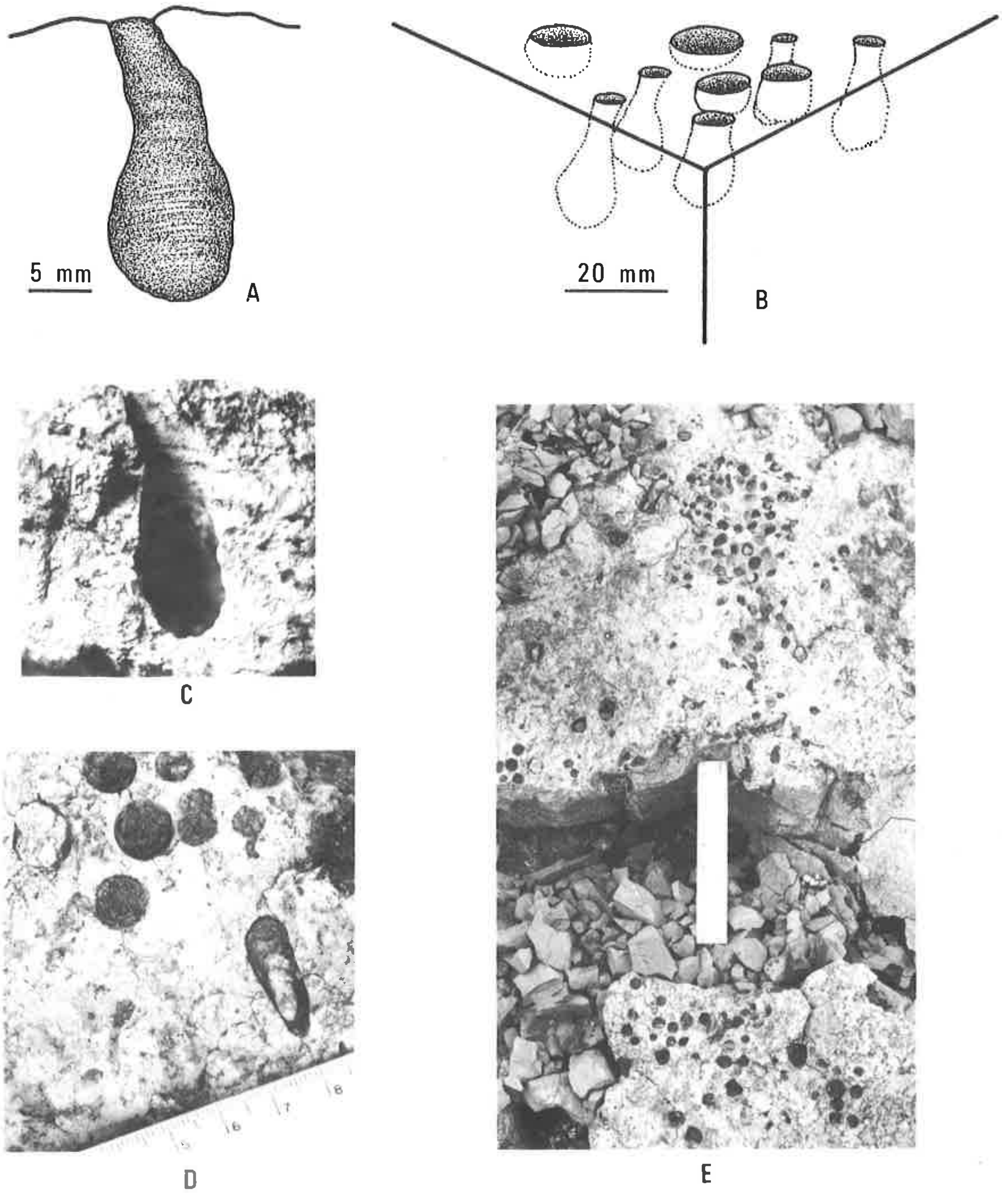


Figure 30. *Trypanites* sp. from upper surface of Oconee Group at Locality "A". A, typical complete specimen, showing circumferential striations on walls. Vertical face view, after C; B, schematic three dimensional view of truncated and complete borings; C, boring pictured in A; D, detail of E (left center); E, laterally crowded *Trypanites* sp., showing erosional truncation. Oblique view.

Complete individual borings at Locality "A" are commonly capped by a plug of hydrous iron oxide. Also, the adjacent surface is discontinuously encrusted and impregnated with hydrous iron oxide. Such "ferruginous impregnations" are common where "hardgrounds" have been exposed to seawater at omission surfaces (Bromley, 1975, p. 400, 401).

"*Arenicolites*-like burrow

Figure 31

Description: U-shaped burrow perpendicular to bedding; diameter highly variable, ranging from 2 to 17 mm; maximum depth of penetration of substrate observed, about 6 cm; limbs not closely appressed, with distance between limbs of "U", about 5 cm; walls unlined and highly irregular (fig. 31).

Preservation: endichnia; burrow fill consists of unpatterned, nearly mud-free sand, slightly darker in color than surrounding sediment, due to absence of white mud fraction.

Occurrence and distribution: occurs in parallel bedded muddy sands, about 4 m below the upper surface of the Oconee Group at Locality "B"; only one specimen observed.

Interpretation: probably feeding structure or possibly combination feeding-escape structure or dwelling-escape structure; possible producers include species of holothurians, echiurids, enteropneusts, polychaetes, and ethologically similar animals; fill may represent substrate material washed free of clay and fine silt by the tracemaker in the course of feeding and respiration.

Discussion: This structure has affinities with the ichnogenus *Arenicolites* (Hantzschel, 1975, p. W38, fig. 2). Both burrow types consist of simple U-tubes perpendicular to bedding and lacking spreiten. However, the highly variable diameter of this specimen, together with the absence of other specimens with which to compare it, makes its assignment to *Arenicolites* tenuous at best.

Schafer (1972, p. 299) listed several animals which produce U-shaped burrows in modern marine environments. Of these, the most likely producers of these burrow types are polychaetes, holothurians, and enteropneusts. Polychaetes and enteropneusts produce U-shaped burrows with more or less vertical arms, at least one of which intersects the substrate surface (Schafer, 1972, p. 301-305, figs. 174, 175). In the case of the polychaete *Arenicola*, one of these arms serves as a fecal tube, the other, as a feeding tube. The fecal tube is relatively permanent compared to the feeding tube, which is ephemeral and may be missing altogether (Schafer, 1972, p. 302). This description compares favorably with the U-shaped burrow specimen described here, except for its lack of a well-defined, lined arm corresponding to the fecal tube of *Arenicola*.

Other possible, though less likely, producers of this specimen include species of echiurids, and other species of polychaetes (Schafer, 1972, pl 301, 305-309, 317-347; figs. 177-181, 187-190, 205).

U-shaped burrows similar to those described and discussed here are constructed in "water covered" (Schafer, 1972, p. 298) and intertidal (MacGintie and MacGintie, 1968, p. 202) marine sediments. Such environments are compatible with that proposed for *Amphorichnus* sp., with which this specimen occurs at Locality "B".

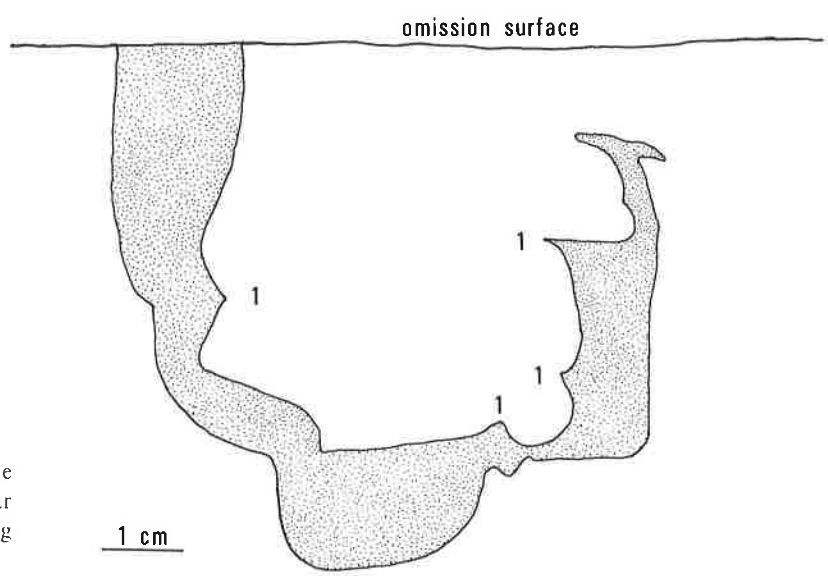


Figure 31.

"Arenicolites-like burrow", showing probable collapse features: pinch marks (1) and irregular diameter. Burrow fill is loose sand; enclosing sediment is sandy mud.

"Ferruginous cones"

Figures 32-34

Description: short, subcylindrical, straight, vertical to steeply inclined, elongate, pouch-like structures, having pointed upper terminations and blunt lower terminations (fig. 32A); exteriors commonly bear longitudinal ridges (fig. 33A); most structures have major and minor transverse diameters (fig. 32A), the former typically 5 to 6 mm, the latter, 2 to 4 mm; maximum length observed, about 5 cm; length to width ratio, about 5 or 6 to 1.

Preservation: endichnia; fill is unpatterned and compositionally similar to enclosing sediments, except for abundant hydrous iron oxide cement; lined with thin, well-defined, slightly irregular sheath of hydrous iron oxide (fig. 33B); orientation of some structures suggests they are reworked (fig. 33C); some structures seem to be composites (fig. 33A).

Occurrence and distribution: occurs in large-scale, crossbedded, slightly muddy medium undifferentiated Barnwell Group sands suprajacent to the upper surface of the Oconee Group at Locality "H", where densities locally reach $105/m^2$ on a vertical face (figs. 32, 34); possible reworked examples occur in upper portion of unit H-2 and in unit H-3 (appendix A).

Interpretation: dwelling structures, possibly of polychaetes similar to *Pectinaria*; longitudinal ridges (fig. 33A) may represent differential collapse of wall structure; thin, distinct hydrous iron oxide lining (fig. 33B) strongly suggestive of original organic lining; hydrous iron oxide cement in structure fill suggestive of original presence of organic material (fig. 33B).

Discussion: The thin, well-defined hydrous iron oxide lining exhibited by these structures argues in favor of an organic precursor, suggesting these structures are of biologic origin (R. W. Frey, 1978, personal commun.).

These structures are morphologically and dimensionally similar to portable arenaceous tests constructed by the foraging marine polychaete, *Pectinaria* (Schafer, 1972, fig. 202, p. 340, 341; MacGintie and MacGintie, 1968, p. 201, fig. 69). Such tests are portable body extensions and, thus, are not considered biogenic structures (Frey, 1973, p. 7). Nevertheless, these structures are included here based on their trace-like nature and the importance of fossil data from otherwise nonfossiliferous sediments.

Portable arenaceous tests of modern polychaetes are constructed of carefully fitted sand grains, set in mucous so that tube exteriors are smooth (Schafer, 1972, p. 340). Although sand grains are embedded in the lining of "ferruginous cones," distribution of these grains shows no sign of regularity. Careful examination of structure linings reveals a possible explanation for the apparent lack of regularity. When viewed in longitudinal section with a 10x lens, one can see somewhat regular, lateral "pinch marks" on either side of some segments. These features probably are related to vertical compaction of the structure (R. W. Frey, 1978, personal commun.), which presumably also would disrupt existing grain fabrics.

Several other aspects of these structures may be explained by assuming construction by a *Pectinaria*-like animal and a preservational environment of rapid deposition. The abundant hydrous iron oxide cement present within these structures is suggestive of an original concentration of organic material (Berner, 1969, p. 20-22). *Pectinaria* does not abandon its test (Schafer, 1972, p. 340). Thus, the suggested original organic material may have consisted of the inhabitants' bodies. Although *Pectinaria* can burrow upward with some efficiency (Schafer, 1972, p. 342), habitation of a rapidly prograding crossbedded substrate would seem to be particularly perilous behavior. These structures, except where possibly reworked, are invariably vertical or steeply inclined (figs. 32, 34). These orientations seem to represent escape and feeding positions respectively (Schafer, 1972, p. 342). If so, the escape response was probably geotactic, decreasing the animals' chance of successful escape in crossbedded, prograding substrates (Schafer, 1972, p. 344). However, the absence of clearly disturbed bedding laminae subjacent to these structures argues against this hypothesis.

Scattered specimens of "ferruginous cones" whose long axes are horizontal (fig. 33C), occur in angularly tabular crossbedded sands, 2-3 m above the dense, vertically oriented occurrence previously discussed. The orientation of these horizontal specimens suggests they are reworked. If reworked, these specimens must have been coherent at the time of their erosional exhumation and transport, raising the possibility of penecontemporaneous hardening of these "cones" through syngenetic deposition of iron minerals.

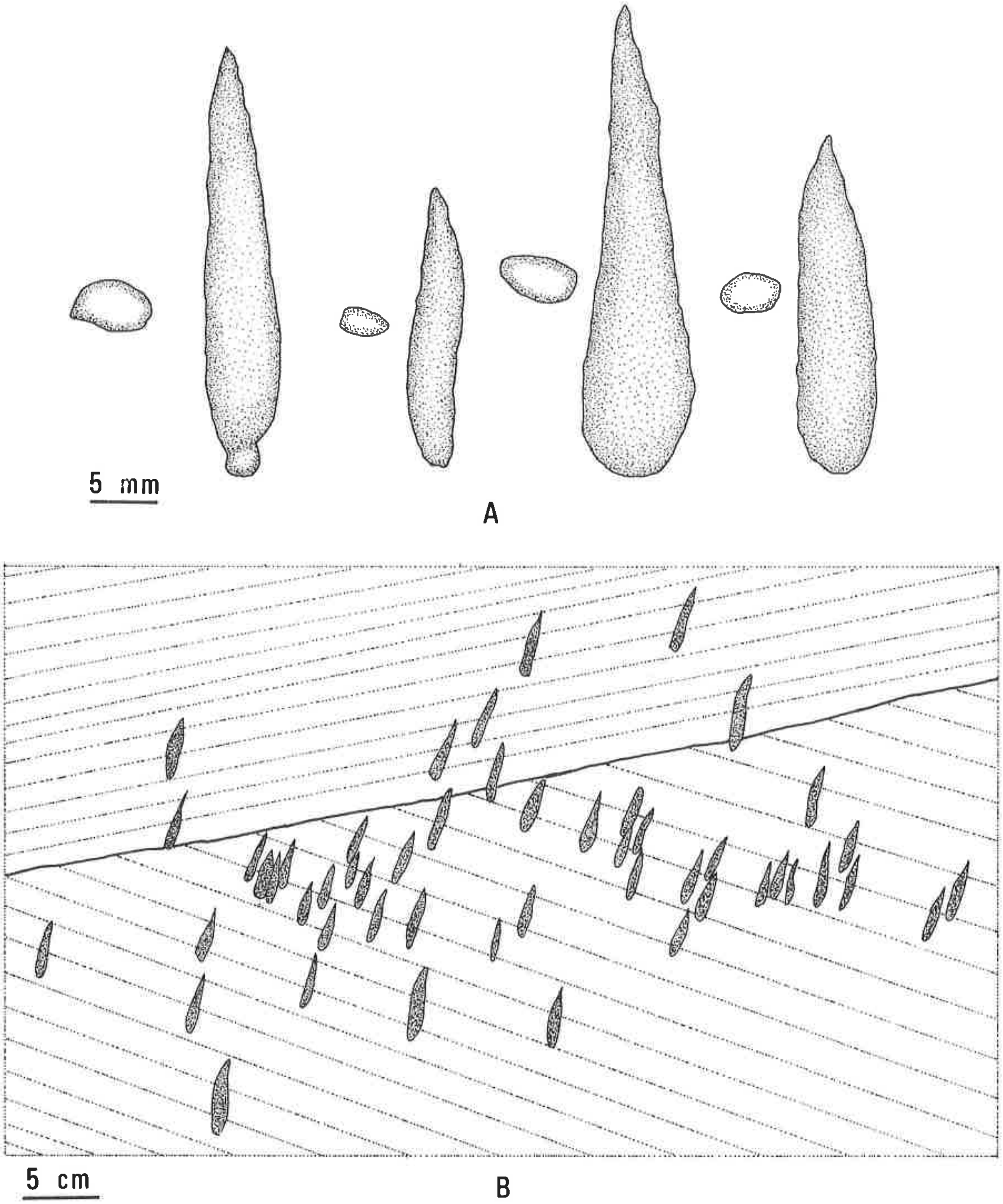


Figure 32. "Ferruginous cones" from undifferentiated Barnwell Group sands at Locality "H", 0.5 - 2 m above upper surface of the Oconee Group. A, individual specimens and their cross sections; B, in situ orientation of structures with respect to bedding; vertical view, outcrop face.

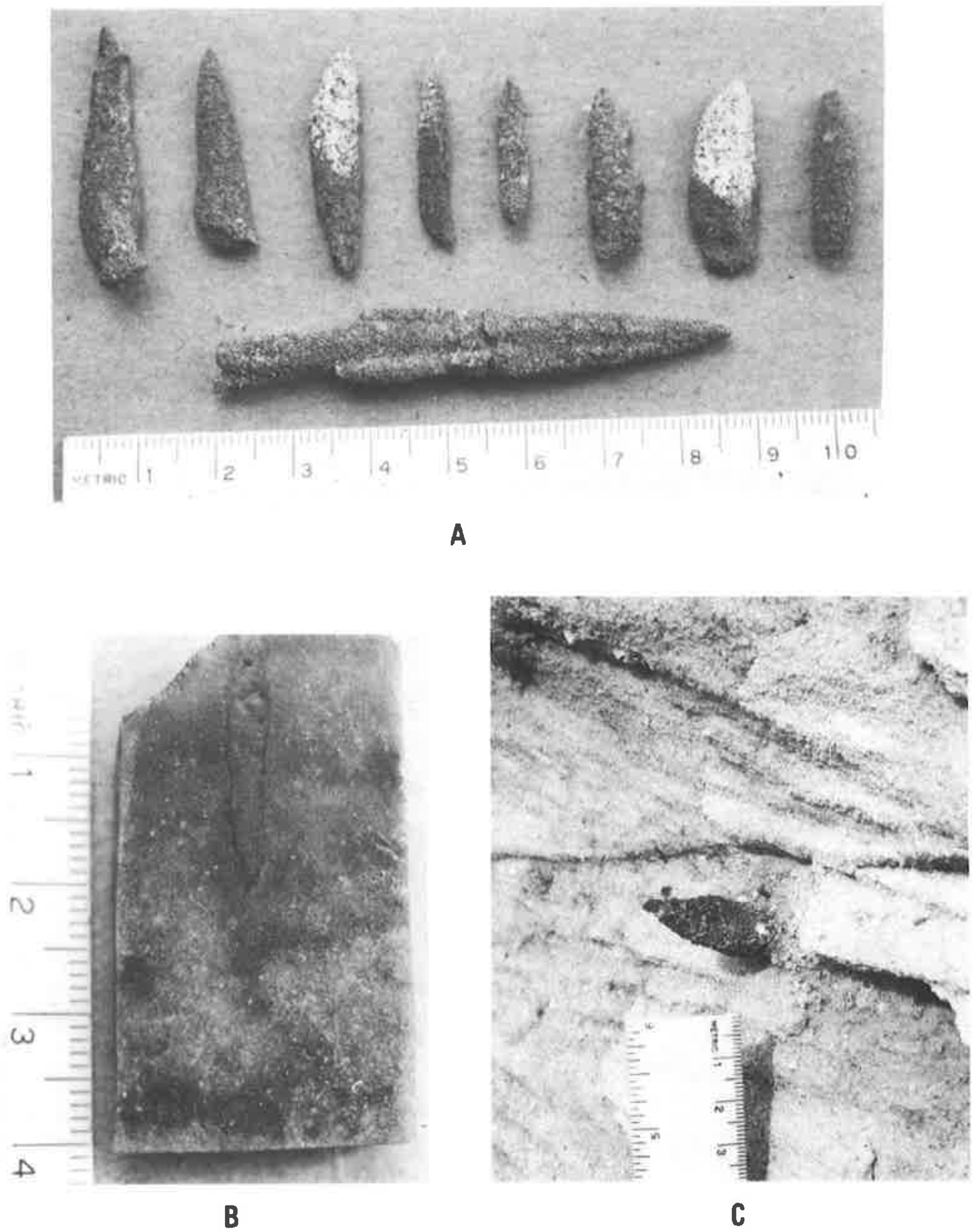


Figure 33. "Ferruginous cones" from undifferentiated Barnwell Group sands at Locality "H". A, several specimens removed from sediments. Specimens in top row correctly oriented with apices up. Lower specimen and one at far left seem to be composites. Lower specimen shows longitudinal ridges and grooves; B, longitudinal section through a specimen, showing distinct lining of hydrous iron oxide; C, horizontally oriented, possibly reworked specimen from sands 2.5 m above in situ occurrence of ferruginous cones pictured in figure 34.

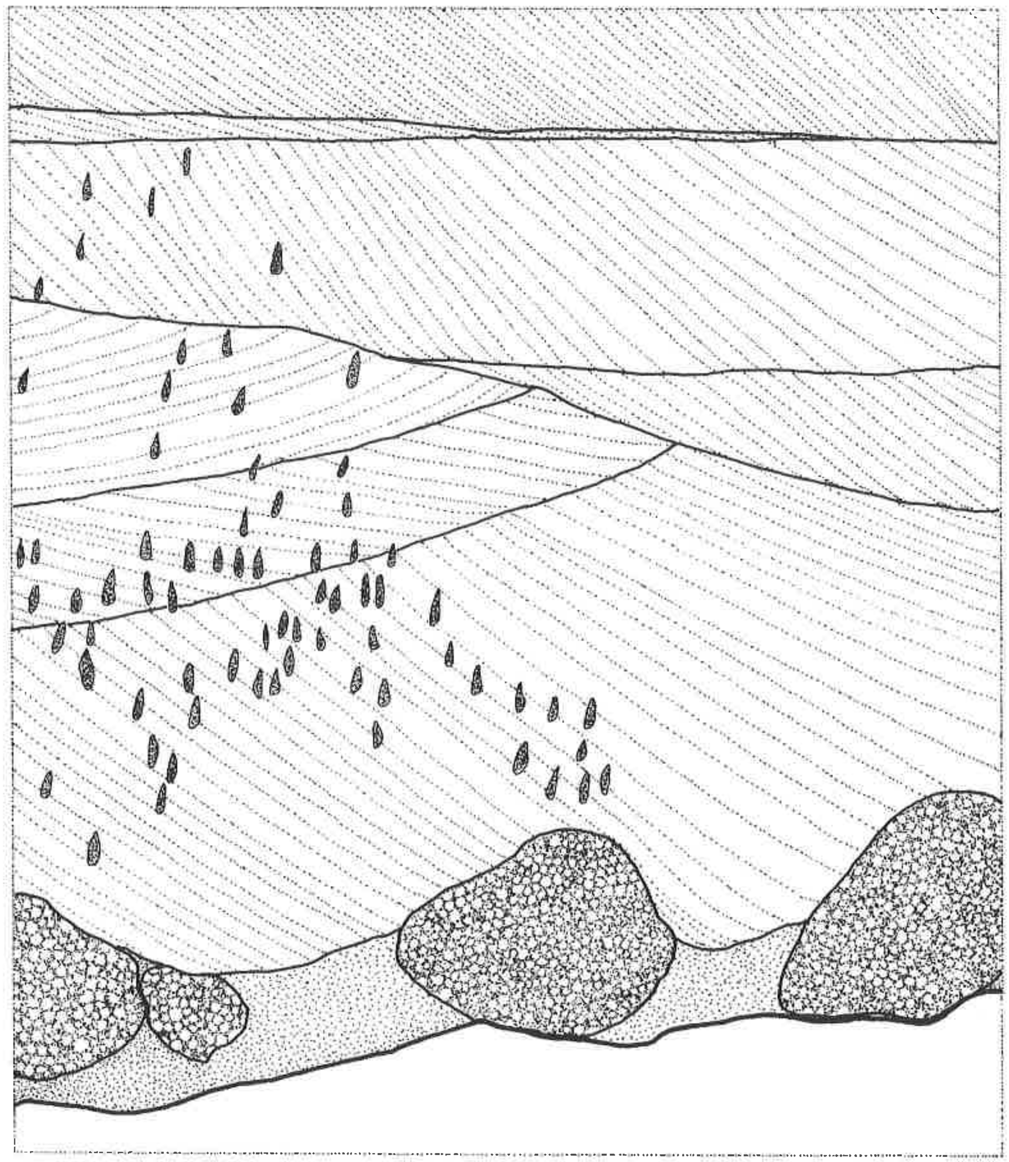


Figure 34. "Ferruginous cones" from undifferentiated Barnwell Group sands at Locality "H", showing distribution relative to crossbeds. Foresets in figure more steeply inclined than those in actual sediments. Pisolitic boulders rest upon upper surface of the Oconee. Vertical view, outcrop face.

"Fraena"

Figure 35

Description: unbranched (?), simple sinuous trails, consisting of a central furrow, flanked by a pair of low ridges (fig. 35A, B); total width, about 3 mm; width of ridges and furrow, about 1 mm; maximum length observed, about 5 cm.

Preservation: hypichnia or possibly endichnia; central furrow apparently enriched in dark heavy minerals, as is flanking substrate surface (fig. 35C).

Occurrence and distribution: occurs in thinly parallel bedded fine undifferentiated Barnwell Group sands rich in heavy minerals, 3 m above the upper surface of the Oconee at Locality "H"; only one specimen observed.

Interpretation: crawling or grazing trace of an animal moving upon, or possibly immediately subjacent to, the substrate surface.

Discussion: This specimen generally fits the description of *"Fraena"* species A of Frey and Chowns (1972, p. 35, 36, fig. 3E).

The primary function of this structure cannot be determined with certainty from the single specimen examined. The presence of nearly straight and markedly sinuous portions is suggestive of crawling behavior and grazing behavior respectively (for example, Frey, 1973, table 4, p. 12, 13). Concentration of dark heavy mineral grains in the central furrow and on the adjacent bedding surface (fig. 35C), suggests this specimen was formed on the substrate surface, rather than beneath it. However, as Seilacher (1964, p. 300) points out:

> . . . . for many benthonic animals it makes little difference whether they creep at the surface or along bedding planes inside the sediment, and for the paleontologist it is often impossible to differentiate these two types of motion.

"L-shaped burrow"

Figures 27, 28B

Description: cylindrical, sharply curved, steeply to moderately inclined, L-shaped burrow, having an "enlarged" aperture (figs. 27, 28B); burrow diameter about 1.2 cm; maximum diameter of aperture, about 5 cm; observed length, about 15 cm; walls unlined and slightly irregular (fig. 28B).

Preservation: exichnia, subjacent to omission surface; burrow fill unlike suprajacent sediment, more closely resembling sediment about 20 cm above aperture (fig. 27); fill consists of sandy, slightly fossiliferous mud.

Occurrence and distribution: occurs in horizontally to irregularly bedded mud and sandy, gravelly mud of the Clinchfield Formation, about 2 m above the upper surface of the Oconee at Locality "D"; coexists with an undifferentiated form of *Thalassinoides* (figs. 27, 28B); only one specimen observed.

Interpretation: dwelling structure, probably of a fiddler crab; probably constructed in a protected, sandy, intertidal substrate, under conditions of normal to near normal salinity; "enlarged" aperture (fig. 28B) may be remnant of hooded entrance.

Discussion: The "L-shaped burrow" described here bears little resemblance to trace fossils described in the literature. However, this burrow is nearly identical to descriptions and illustrations of some modern dwelling burrows constructed by the fiddler crabs *Uca pugilator* and *Uca pugnax* (Frey and Mayou, 1971, p. 64, 65; Allen and Curran, 1974, p. 542-546, figs. 2, 4, table 2; Basan and Frey, 1977, table 2, fig. 4, pls. 4f, 5b, c, f, g).

The "enlarged" aperture exhibited by this specimen is similar in appearance to hooded entrances constructed by the fiddlers *Uca minax* (Allen and Curran, 1974, p. 543) and the mud crab *Sesarma reticulatum* (Allen and Curran, 1974, table 2, fig. 4). These morphological comparisons suggest that the "L-shaped burrow" tracemaker was a small, intertidal crab, probably a species of fiddler.

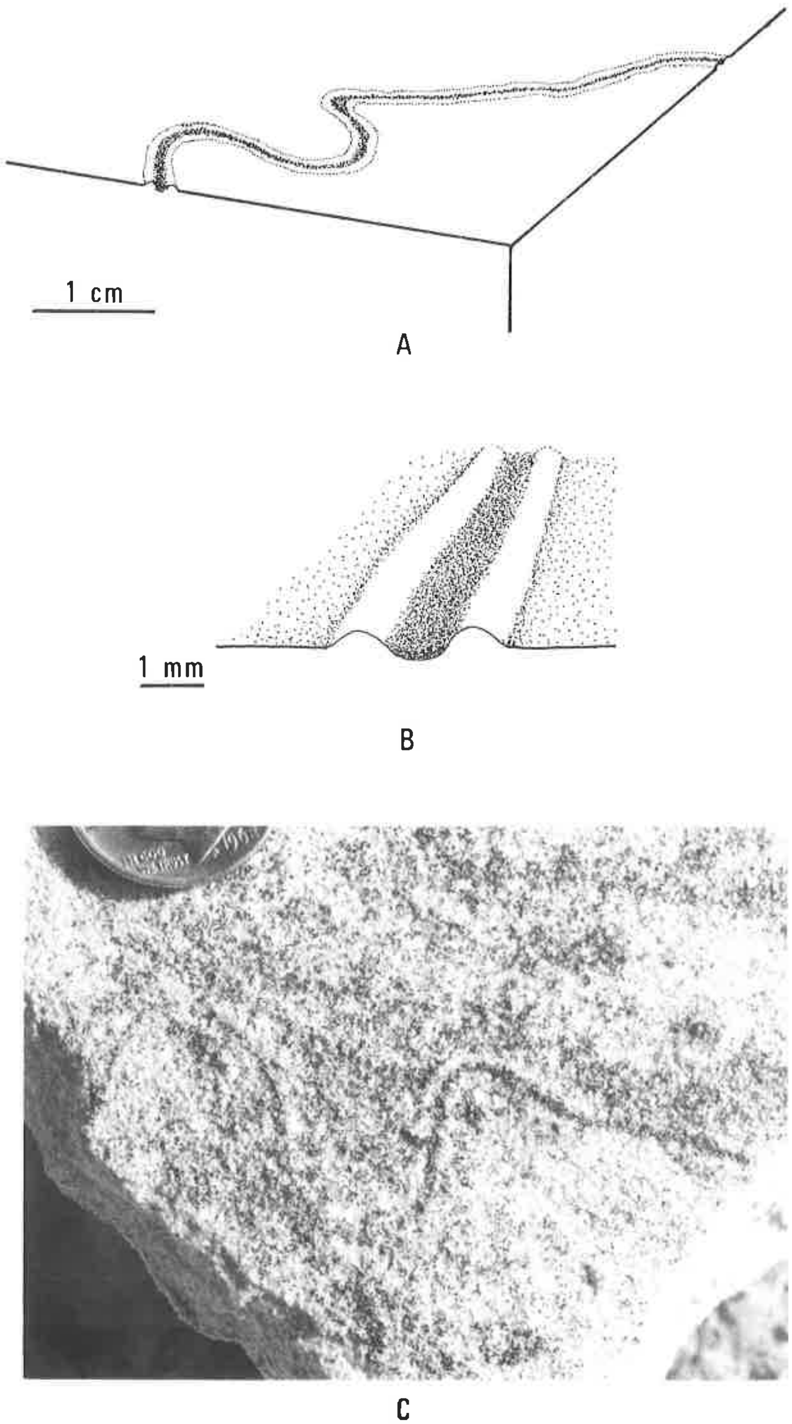


Figure 35. A specimen of "Fraena" from undifferentiated Barnwell Group sands, about 4 m above the upper surface of the Oconee Group. A, adapted from C; B, detail of A, showing distribution of dark heavy minerals with respect to the trail; C, specimen on bed surface.

U. pugnax and *U. pugilator* have been reported from Massachusetts to Texas (Allen and Curran, 1974, p. 541, after Williams, 1965). These crabs construct burrows in muddy and sandy substrates respectively in protected intertidal situations under conditions of normal to near normal salinity (Frey and Howard, 1969, p. 435, 440, 441, table 1; Frey and Mayou, 1971, p. 64; Allen and Curran, 1974, p. 541-547; Basan and Frey, 1977, p. 60, 63, 64, 66, table 2). In muddy sand and sandy mud substrates, the range of these crabs may overlap each other (Allen and Curran, 1974, p. 541; Basan and Frey, 1977, p. 64, 66, table 2) and the range of *U. minax* (Basan and Frey, 1977, p. 66, table 2).

This specimen occurs in the parallel to irregularly bedded fossiliferous sandy mud to muddy sand unit which constitutes the Clinchfield at Locality "D". A large diameter form of undifferentiated *Thalassinoides* also occurs here (figs. 27. 28B). The abundant presence of marine fossils (pectens, pelecypods, oysters, bryzoas, shark teeth, ray plates, turtle bones, etc.) indicates the onset of marine deposition upon the upper surface of the Oconee. This event was undoubtedly related to the early stages of the Upper Eocene transgression which affected the entire study area. The presence of the "L-shaped burrow" suggests deposition of sandy Clinchfield sediments at Locality "D" occurred in a protected intertidal setting.

"Large sinuous shafts"

Figures 36-39

Description: unbranched, slightly to markedly sinuous, cylindrical to subcylindrical burrows, 3 to 5 cm in diameter, consisting of straight to slightly sinuous shafts and steeply inclined burrow segments 30 to 60 cm in length (fig. 36). Uppermost segments steeply inclined, commonly exhibiting preferred orientation (fig. 37A); lower terminations bluntly conical; unlined, slightly irregular walls show numerous claw sculptings (fig. 37B) and occasional small pits; maximum length observed, about 2 m.

Preservation: exichnia, subjacent to erosion surface; burrow fill is clearly related to suprajacent sediments and consists of unpatterned gray muddy sand; some burrows are truncated by root casts which originate above them (fig. 37A).

Occurrence and distribution: occurs in massive to vaguely laminated muds and crossbedded muddy sands at the upper surface of the Oconee Group at Locality "H"; distributed in broad patches of laterally crowded burrows, with maximum observed density of 20 intersections / m^2 on a horizontal surface, about 1 m below substrate surface (fig. 37C).

Interpretations: interpreted as dwelling structures; tracemaker ethologically similar to some modern species of supratidal crabs; constructed in coherent mud and muddy sand substrate from an erosion surface; preferred orientation of uppermost segments possibly a response to a prevailing wind direction.

Discussion: Several additional morphological details deserve mention here. These burrows descend via a series of straight to slightly curved segments, joined at obtuse angles (fig. 36). The net result may be a faintly spiraled burrow. Also, a low raised rim may surround the burrow aperture on the substrate surface (fig. 37A). This feature may have been constructed by the burrow inhabitant. Similar features are constructed by some burrowing intertidal and supratidal crabs (Braithwaite and Talbot, 1972, p. 271; Basan and Frey, 1977, p. 59).

Three extant species of supratidal crabs, *Cardisoma guanhumi* (Shinn, 1968, p. 886, text fig. 12), *Cardisoma carnifex*, and *Sesarma longipes* (Braithwaite and Talbot, 1972, p. 271, pl. I, 1), produce dwelling burrows morphologically and dimensionally comparable to these specimens. All three burrow types consist of a single, unbranched, roughly cylindrical, somewhat segmented burrow that is steeply inclined and commonly exhibits a spiraled aspect. Also, burrow segment junctions form obtuse angles. Braithwaite and Talbot (1972, p. 271) report that *Cardisoma carnifex* burrows range up to 10 cm in diameter and penetrate as deeply. Claw sculptings and pits similar to those on the walls of "large sinuous shafts" (fig. 37B) have been reported from the burrow walls of various intertidal and supratidal crabs (Basan and Frey, 1977, p. 59).

Where "large sinuous shafts" and root casts occur together (fig. 37A), similarities of morphology, size, and fill make differentiation of these structures difficult. Observation of wall structure is the most reliable method of differentiation. The walls of "large sinuous shafts" are adorned with claw sculptings, which are particularly well developed where these burrows penetrate muds (fig. 37B). The walls of root casts are irregular. Cross cutting relationships are of limited use in differentiating these structures. Root casts originate above the surface at which "large sinuous structures" originate. Also, root casts occasionally penetrate "large sinuous shafts" (fig. 37A).

Burrows of these extant crabs differ from "large sinuous shafts" in that the modern burrows have a broad, funnel-shaped opening and enter the substrate at angles ranging from 10° to 75°. Erosion of the uppermost portions of these burrows may account for these differences. However, the presence of low raised rims surrounding some burrow openings and the preferred orientation of the uppermost segments of many burrows suggest the effects of erosion on these structures was minimal (fig. 37A).

The above comparisons illustrate the close similarity of burrowing behavior between ancient and modern animals. They are not intended to suggest that a species of *Cardisoma* or *Sesarma* was the producer organism, although this possibility cannot be dismissed.

The aforementioned species of *Cardisoma* and *Sesarma* generally inhabit stable substrates in somewhat protected, supratidal environments at elevations that allow the lower parts of their burrows to reach the water table (Shinn, 1968, p. 887; Braithwaite and Talbot, 1972, p. 273). These environments may be vegetated (Braithwaite and Talbot, 1972, p. 268), and plant debris was observed by Shinn (1968, p. 887) within *Cardisoma guanhumi* burrows. Thus, it is not surprising that some "large sinuous shafts" contain minor amounts of carbonaceous debris.

The absence of a lining in these large diameter burrows indicates enclosing sediments were coherent and stable at the time of burrow excavation.

Another burrow-associated feature may be indicative of differential substrate coherence. Spheroidal pisolites, generally less than 1 cm in diameter, occur in parts of the mud unit penetrated by these burrows at Locality "H". In some cases, pisolites extend through burrow walls where they form positive hemispherical reliefs on wall interiors. This relationship indicates the generation and existence of pisolites prior to burrow construction and suggests avoidance of pisolites by burrowers, probably in response to their greater relative hardness.

Where they occur in muds, many of these burrows are closely surrounded by a system of cracks and pockets filled with gray clay, similar in color to burrow fillings (fig. 39). These cracks may be due to shrinkage induced by dessication upon exposure of burrow walls to air. The absence of spalls or other obvious collapse features suggests these cracks are not incipient cave-ins.

The preferred orientation of uppermost burrow segment descent directions may reflect the tracemaker's response to the prevailing wind direction (Hill and Hunter, 1973, p. 27) or to the slope of the depositional surface (Frey and Mayou, 1971, p. 63), as has been suggested as the cause of similar orientation in burrows of the supratidal crab, *Ocypode Quadrata.*

As Braithwaite and Talbot (1972, p. 283) point out, high intertidal and supratidal crab burrows constructed in unlithified sediments seem to be particularly vulnerable to erosional destruction, except where construction is closely followed by a prograding phase of sedimentation. Thus the apparent completeness of preservation of "large sinuous shafts" is strongly suggestive of rapid burial following their construction.

Where "large sinuous shafts" occur in muds, approximately the upper 1 m of most burrows is surrounded by an inner "bleached" zone from which iron apparently has been removed and an outer "stained" zone in which iron oxide and/or hydrous iron oxide has been concentrated in diffuse belts and liesegang bands (figs. 37C, 39). Degree of concentration in this outer zone decreases with depth. Burrow fills contain disseminated pyrite which probably contributes to their gray color.

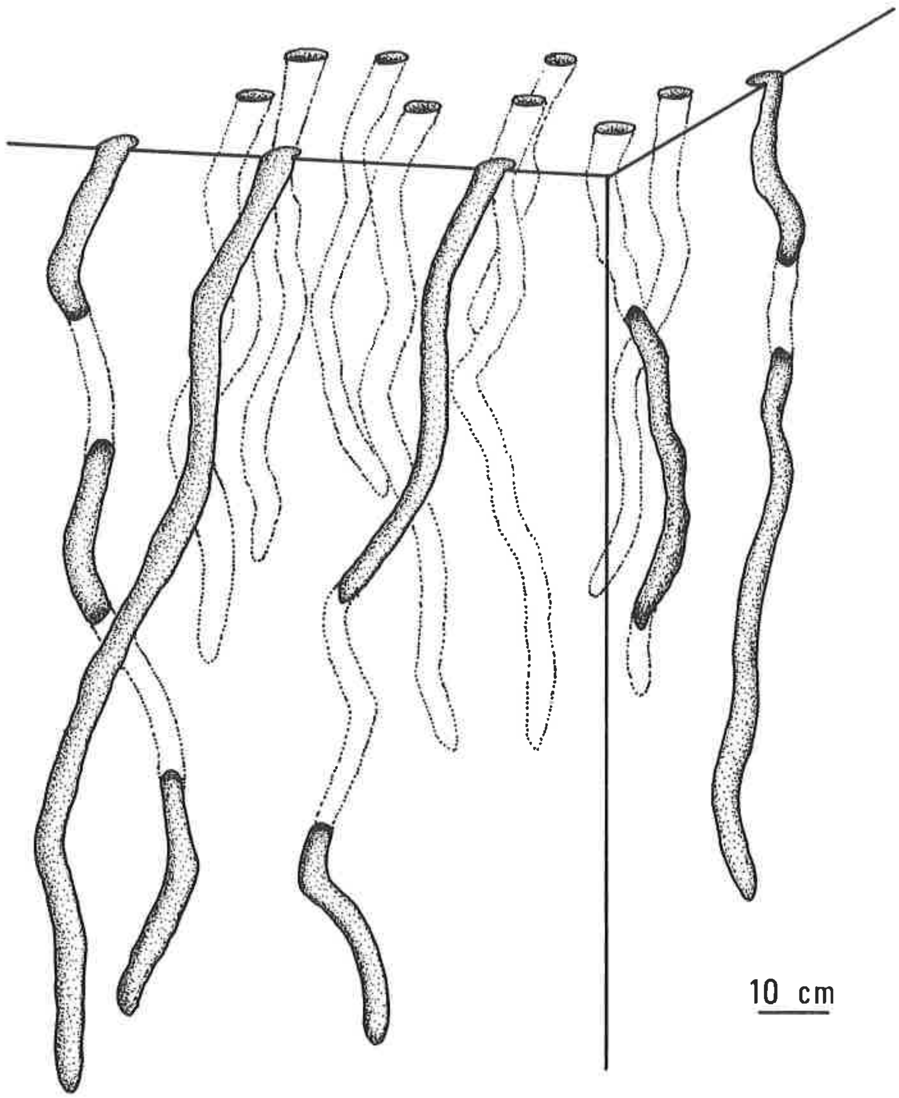
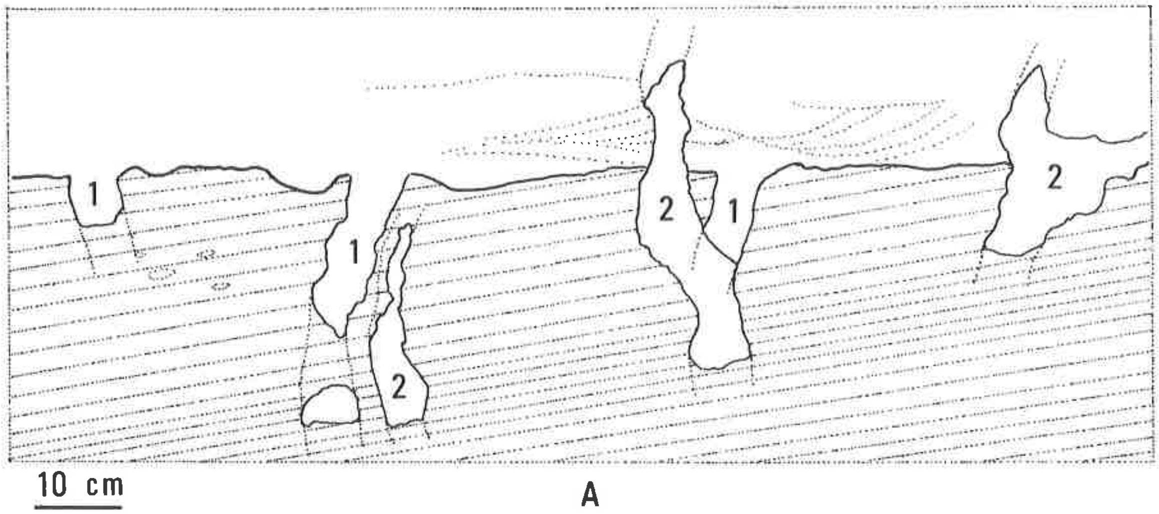


Figure 36. "Large sinuous shafts" which extend downward from upper surface of Oconee Group at Locality 'H".



A

B

Figure 37. "Large sinuous shafts" from Locality "H". A, "large sinuous shafts" (1) opening onto upper surface of Oconee Group. Root casts (2) originate 2 to 3 m above this horizon and may penetrate "large sinuous shafts". Vertical view, outcrop face; B, detail of burrow wall showing delicate and broad claw sculptings. Scale in centimeters.

Figure 38. Transverse section through "large sinuous shafts", about 1 m below upper surface of Oconee Group at Locality "H", showing distribution of iron minerals and typical density of burrows. (see fig. 39). Oblique view, horizontal surface.

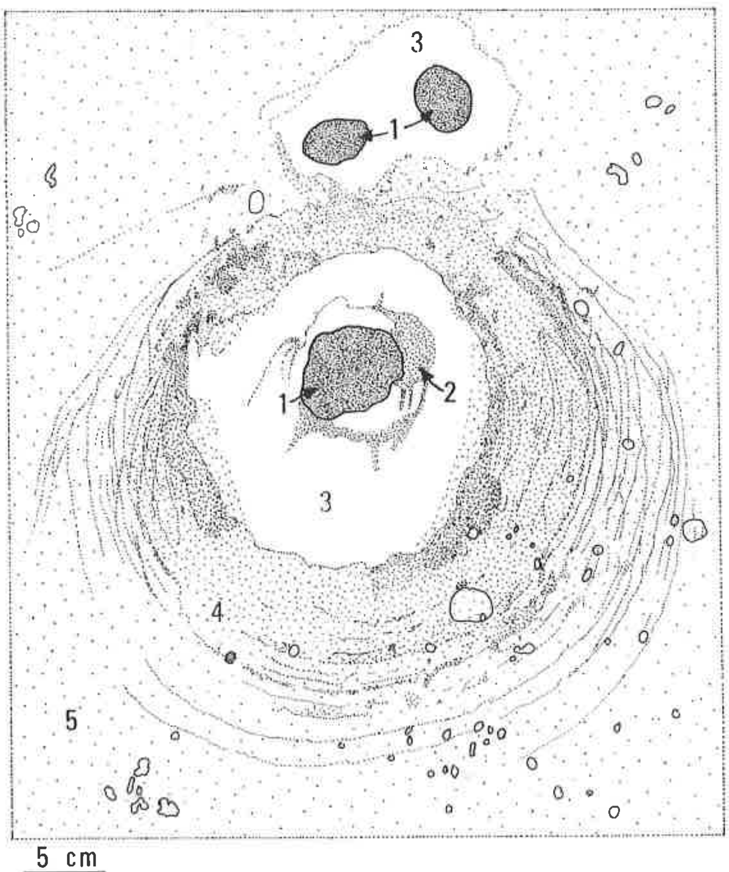


Figure 39. Transverse section through "large sinuous shafts" and associated features, about 1 m below upper surface of Oconee Group at Locality "H", showing gray burrow fills (1) surrounded by gray cracks and pockets (2), in turn surrounded by bleached zone (3), in turn surrounded by diffuse belts and liesegang bands of iron oxide and/or hydrous iron oxide (4), in turn surrounded by "normal", slightly pisolitic sediment lightly stained by iron oxide and hydrous iron oxide (5). Plan view of horizontal surface. (see fig. 38).

"Parallel ferruginous tunnels"

Figures 8, 9A, D, 40-44

Description: infrequently "Y"-branched, straight to slightly sinuous, discontinuous, cylindrical to sub-cylindrical tunnels, commonly close-spaced in vertical or lateral series (figs. 40, 42B, 43), rarely connected by short vertical shafts (fig. 40B); lateral terminations bluntly to pointedly conical (for example, fig. 40A); surface apertures not observed; diameters range from 0.5 to 10 cm, and are typically 3 to 4 cm; maximum length observed, about 1.5 m.

Preservation: endichnia; vertical stacking of some tunnels suggestive of spreiten structures (figs. 41, 42); many tunnels show collapse features (figs. 43D, 44A, B, F); fill is unpatterned, similar to enclosing sediments, and may be cemented by hydrous iron oxide or iron sulfide, commonly showing concentric zoning (fig. 44E); lining, where present, is of variable thickness and consists of hydrous iron oxide; structures commonly discontinuous (fig. 44G) and may grade into unlined portions and bioturbate textures (fig. 44H).

Occurrence and distribution: occurs in large-scale tangentially crossbedded, gravelly, muddy sands and sands within the Oconee Group at Locality "A", in crossbedded (?), muddy sands suprajacent (?) to the upper surface of the Oconee at Locality "G", and in horizontally bedded muddy undifferentiated Barnwell Group sands overlying the upper surface of the Oconee at Locality "H"; distribution is uneven, with structures occurring in closely spaced vertically or horizontally oriented arrays (for example, fig. 40A); maximum density observed, 24 intersections/m^2 on an oblique face.

Interpretation: dwelling structures or feeding-dwelling structures, possibly of a decapod crustacean; vertical stacking may represent a response to slowly aggrading or degrading substrate surfaces; parallel alignment of groups of tunnels suggests response to current direction; hydrous iron oxide linings, especially where they preserve collapse features, are suggestive of diagenetic replacement of original organic linings.

Discussion: When considered together, several aspects of "parallel ferruginous tunnels" indicate these structures are biogenic. The most conclusive evidence for biologic origin was observed at Locality "A", where solidly cemented "parallel ferruginous tunnels" graded into uncemented burrows, spreitenlike structures, and bioturbate textures. The interiors of these gradational structures were sandfilled and nearly devoid of iron compounds relative to enclosing sediments (fig. 44H).

The tubular morphology displayed by many specimens at Localities "G" and "H" and the dichotomous branching rarely observed at Localities "A" and "H" are typical of many modern and ancient biogenic structures described in the literature (for example, *Thalassinoides* and modern analogs). Even where "parallel ferruginous tunnels" occur as solid rods cemented by iron sulfide minerals, the concentric zoning of mineral species (cores of marcasite enveloped by sheaths of pyrite) exhibited by many specimens is suggestive of an original tubular morphology.

Although many specimens observed at Locality "G" have a grotesque, "unburrowlike" appearance, many of these clearly preserve the effects of compactional deformation (figs. 43D, 44A, F). Deformation of these structures must have occurred prior to concretionary induration, strongly suggesting the existence of an original organic lining. An organic lining easily could have undergone compactional deformation, then acted as a foci for concentration of iron minerals (Berner, 1969, p. 20-22).

For a discussion of the relationship of *Phycodes* sp. to "parallel ferruginous tunnels", see pages 26, 29 and figure 9, 40A, 42A, 43C.

"Parallel ferruginous tunnels" show slight affinities with the ichnogenus *Thalassinoides*. For example, *Thalassinoides* are tubular, "Y"-branched burrows (Hantzschel, 1975, p. W115, W117), which may be smoothly or irregularly lined in unstable substrates (for example, Curran and Frey, 1977, p. 153). Vertical stacking exhibited by these structures (fig. 40A) is reminiscent of spreiten structures observed in some *Thalassinoides* (Bromley & Frey, 1974, table 1). However, these structures are only rarely branched and do not exhibit the three-dimensional, interconnected burrow networks that are characteristic of most occurrences of *Thalassinoides* (Hantzschel, 1975, p. W115, W117). An exception to this three-dimensional pattern was noted in some examples of *Thallassinoides* sp. B1, where burrowing was likely controlled by vertical joint surfaces (p. 68, figs. 21, 22). However, no such joint surfaces are associated with occurrences of "parallel ferruginous tunnels".

As previously mentioned, the presence of distinct hydrous iron oxide linings in many specimens, some preserving burrow collapse features (figs. 43D, 44A, A), and the occurrence of these burrows in unconsolidated sandy sediments are strongly suggestive of replacement of an original organic lining. Such linings are indicative of substrate instability with respect to burrow construction and maintenance (Frey, 1971, p. 116; Bromley and Frey, 1974, p. 324; Frey and others, 1978, p. 205-207).

Lined, tubular, "Y"-branched burrows are constructed in loose sandy substrates by some modern decapod crustaceans, particularly some shrimp and shrimplike decapods (Weimer and Hoyt, 1964, p. 763; MacGintie and MacGintie, 1968, p. 284-293; Frey and others, 1978, p. 199). Parallel orientation of crustacean burrows has been reported by a number of authors (Farrow, 1966, p. 145; Frey and Mayou, 1971, p. 63, fig. 2; Hill and Hunter, 1973, p. 27, fig. 5). Finally, spreiten structures, of which some of these specimens are suggestive, have been observed in burrows attributable to thalassindean shrimp (Hester and Pryor, 1972, p. 687; p. 10, this volume). Thus, several aspects of "parallel ferruginous tunnels" are suggestive of ethology observed among some burrowing decapods. However, a close analog for these structures is unknown, making their attribution to shrimp or other decapods highly speculative.

Well lined burrows, such as these, constructed in unstable sandy substrates may be excavated initially in the process of feeding (Bromley and Frey, 1974, p. 325). The ultimate function of most such structures, however, is to provide more or less permanent dwellings where substrates are unstable (Bromley and Frey, 1974, p. 325). Thus, the discontinuity of many specimens (for example, fig. 44G) can be interpreted in two ways: burrows were lined along segments where sediments were especially unstable; or, aggrading substrate surfaces precluded dwelling burrow extention in many instances. The latter explanation is preferred here, due to the presence of spreitenlike examples and apparent homogeneity of substrates in which discontinuous examples occur.

As discussed previously, solidly cemented "parallel ferruginous tunnels" at Locality "A" were observed to grade into burrows, spreitenlike structures, and bioturbation textures which are nearly devoid of iron compounds, in contrast to unburrowed portions of the adjacent substrate (fig. 44H). Unlined burrows have been observed protruding through the walls of well-lined *Ophiomorpha* (Bromley and Frey, 1974, p. 325). These ephemeral structures are attributed to feeding behavior and are in sharp contrast to the "permanently occupied, well-maintained living burrows from which they emerge."

The environment of construction of "parallel ferruginous tunnels" was probably one of directed, intermediate to high current energy and slowly aggrading substrates. The sandy, generally crossbedded sediments in which these structures occur are commonly associated with channel fillings. Such sediments are deposited under intermediate to high current energy conditions. That currents were directed is indicated by occurrence of these structures in channel fillings at Localities "A" and "G" and is further suggested by the generally parallel orientation of groups of these structures (figs. 40A, 4). Where groups occur several meters apart, their orientation with respect to one another may be slightly oblique. However, within single exposures, observed differences in orientation between groups did not exceed 45°. Parallel orientation of crustacean burrows in response to prevailing air and water current directions has been noted by several authors (Farrow, 1966, p. 145, 146; Frey and Mayou, 1971, p. 63; Hill and Hunter, 1973, p. 27).

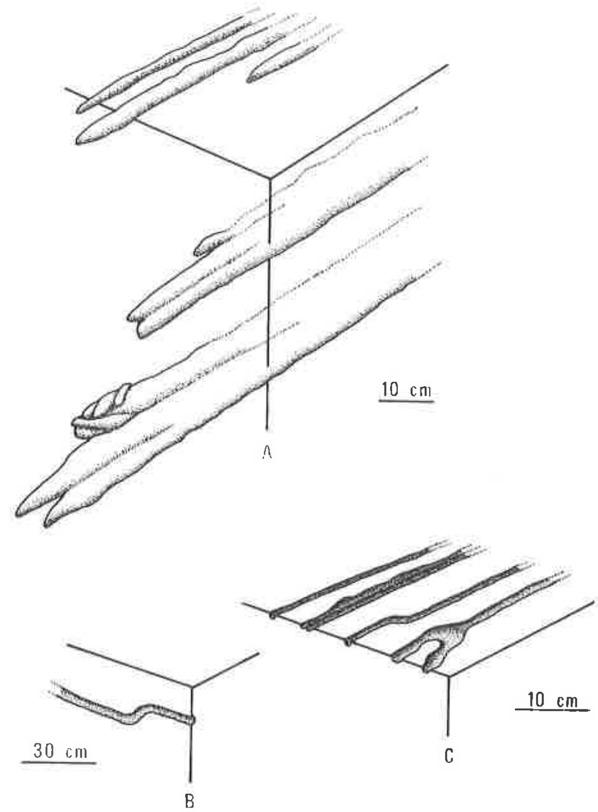


Figure 40. "Parallel ferruginous tunnels". A, typical **configuration from** Locality "G", showing terminations at left. Specimen of *Phycodes* sp. associated with a **burrow termination** at lower left. (see fig. 8); B, specimen from Locality "A", showing tunnel segments connected by short shaft; C, typical configuration from Locality "H", showing smaller burrow size, parallel arrangement in lateral series, and rare bifurcation.

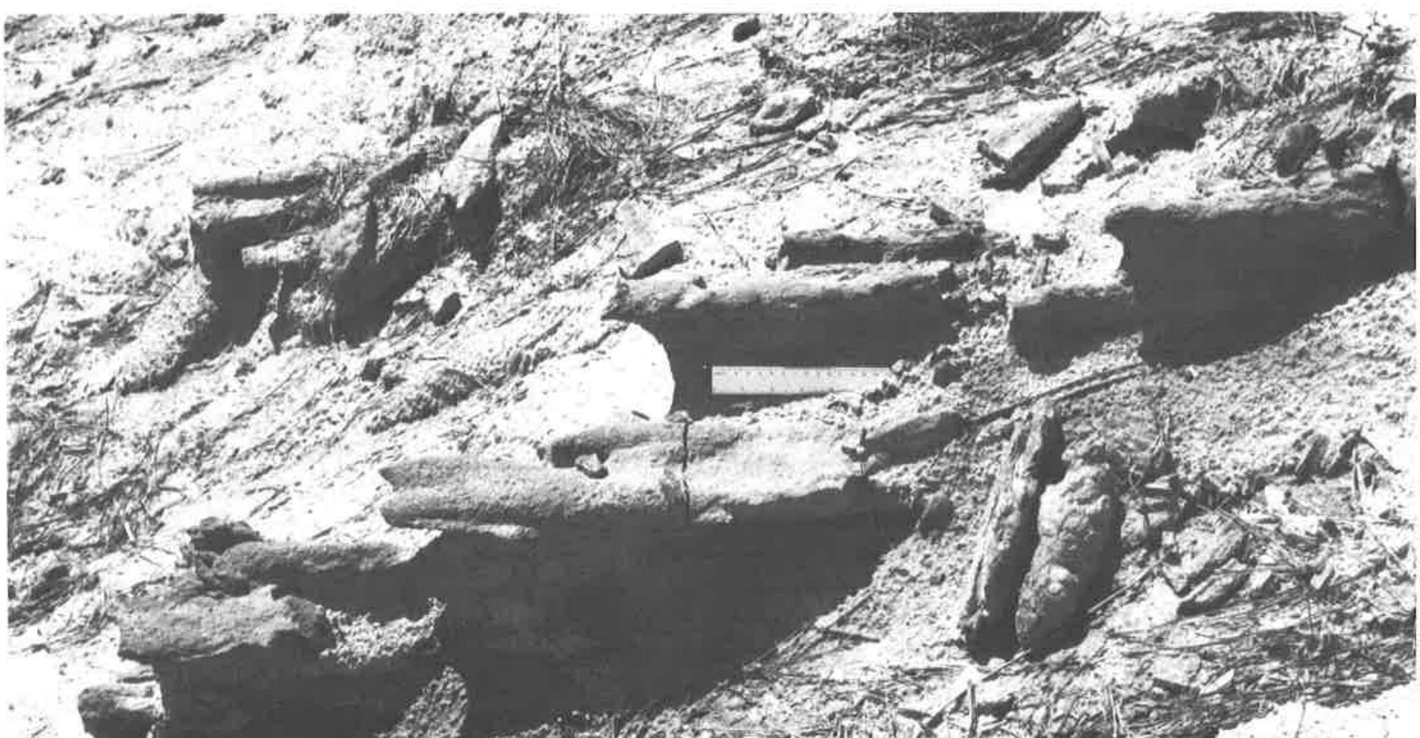
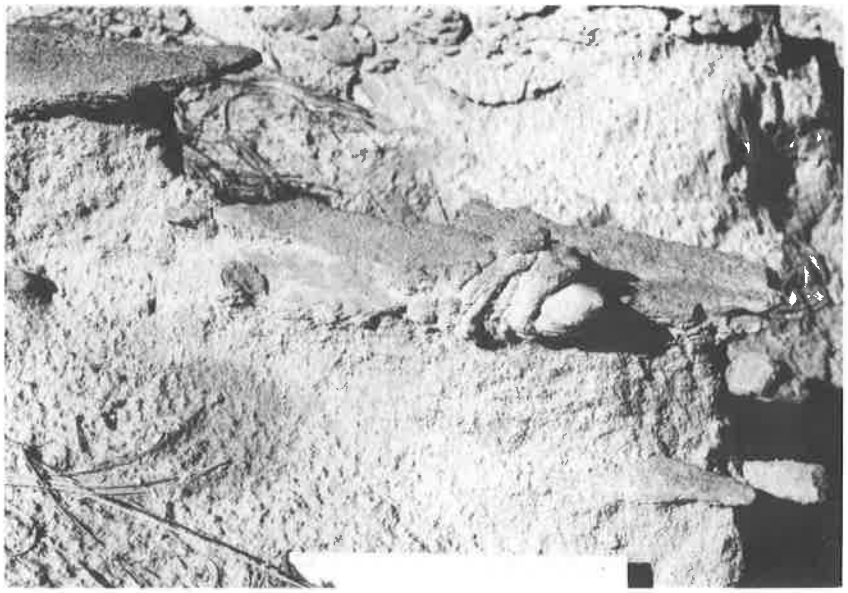
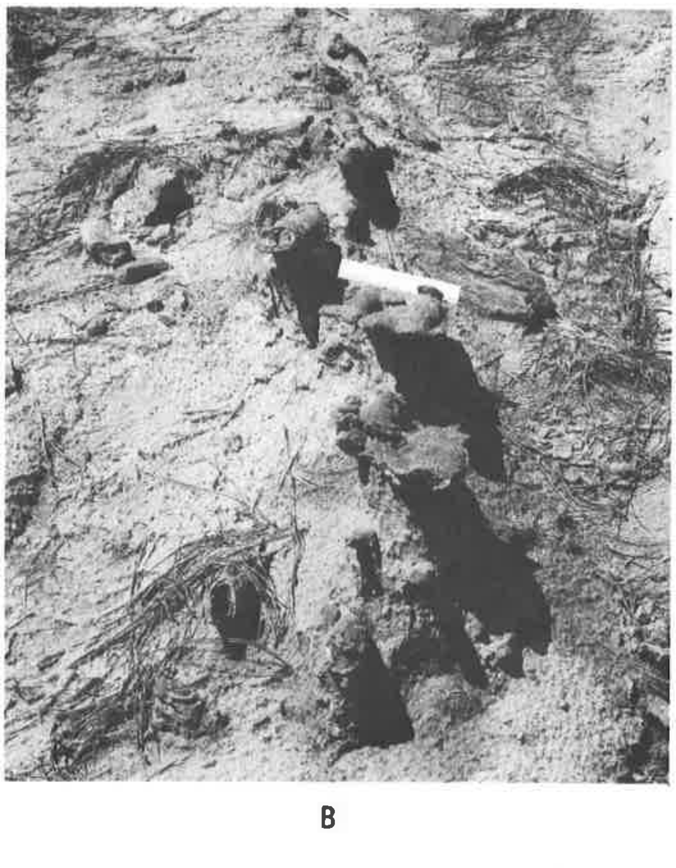


Figure 41. "Parallel ferruginous tunnels" from undifferentiated Barnwell Group sands at Locality "G", showing typical orientation. Vertical view of sloping surface. Burrows weather out in positive relief. Ruler is 15 cm long. (see fig. 42).



A



B

Figure 42. Details of "parallel ferruginous tunnels" pictured in figure 41—A, detail of burrows shown in lower left of figure 41, taken from opposite side. *Phycodes* sp. attached to termination of "parallel ferruginous tunnel" at center. Vertical view of sloping surface; B, view of burrows rotated 90° from view in figure 41 and parallel to long axes of burrows, showing vertical stacking. Overturned burrow fragment at upper left preserves compactional deformation. Surface slopes downward into foreground.

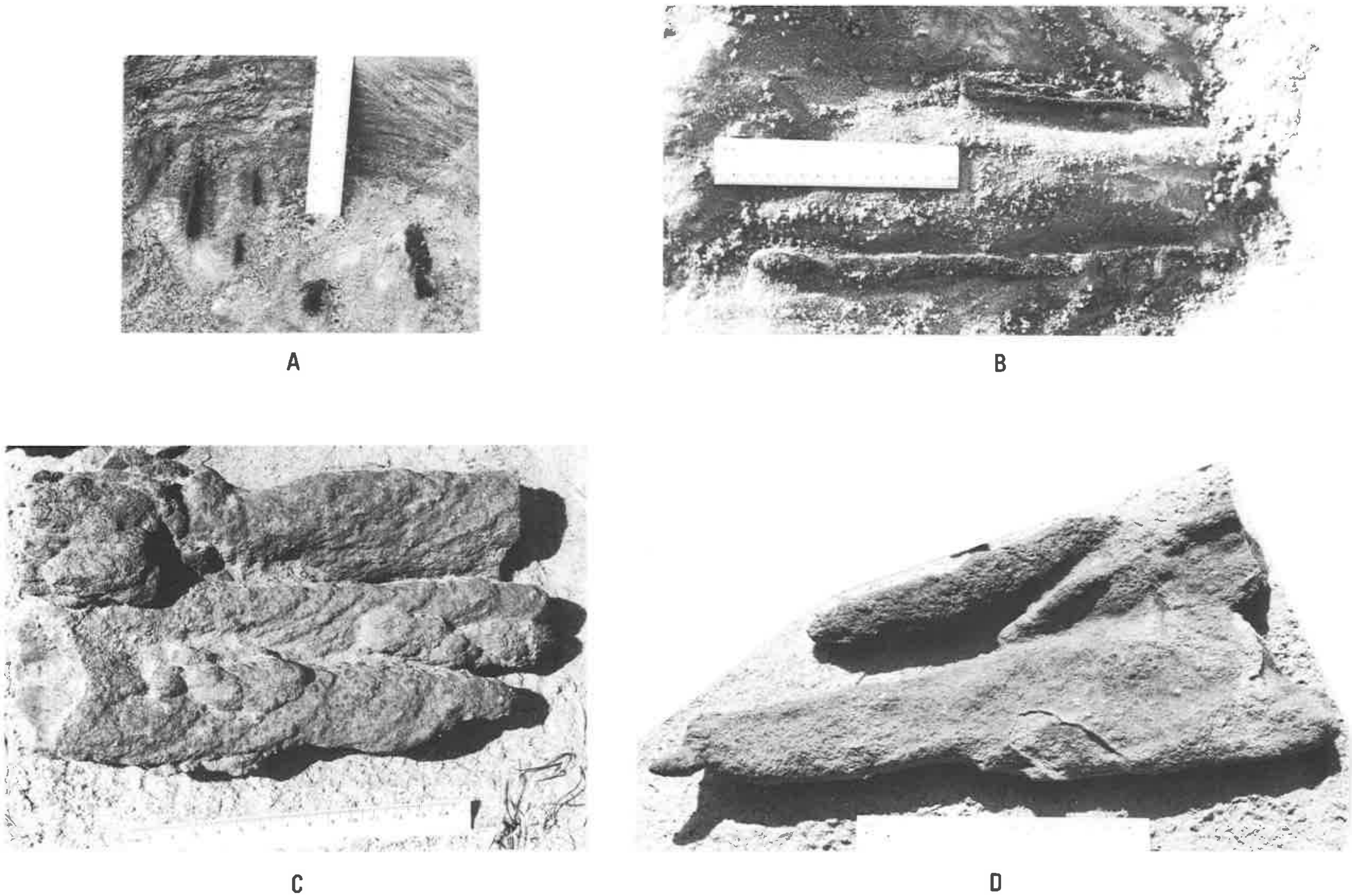
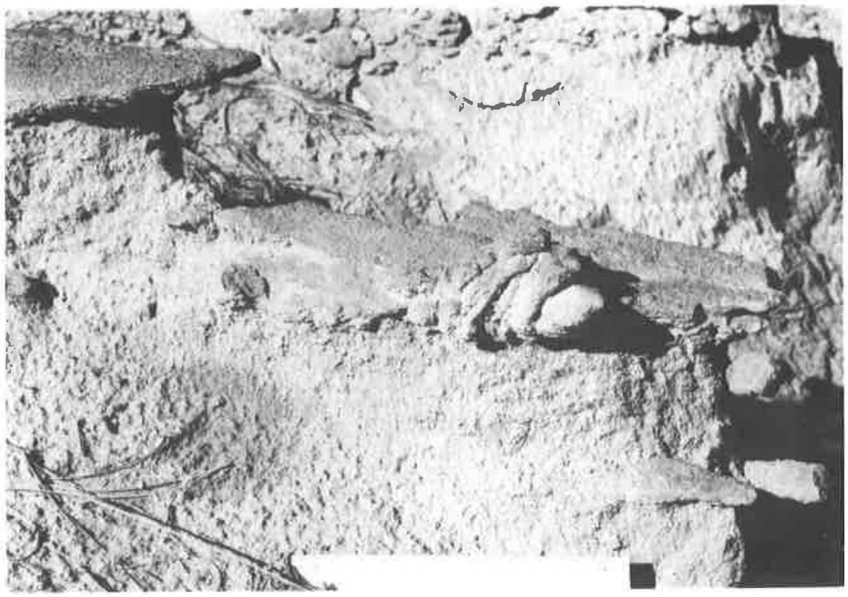


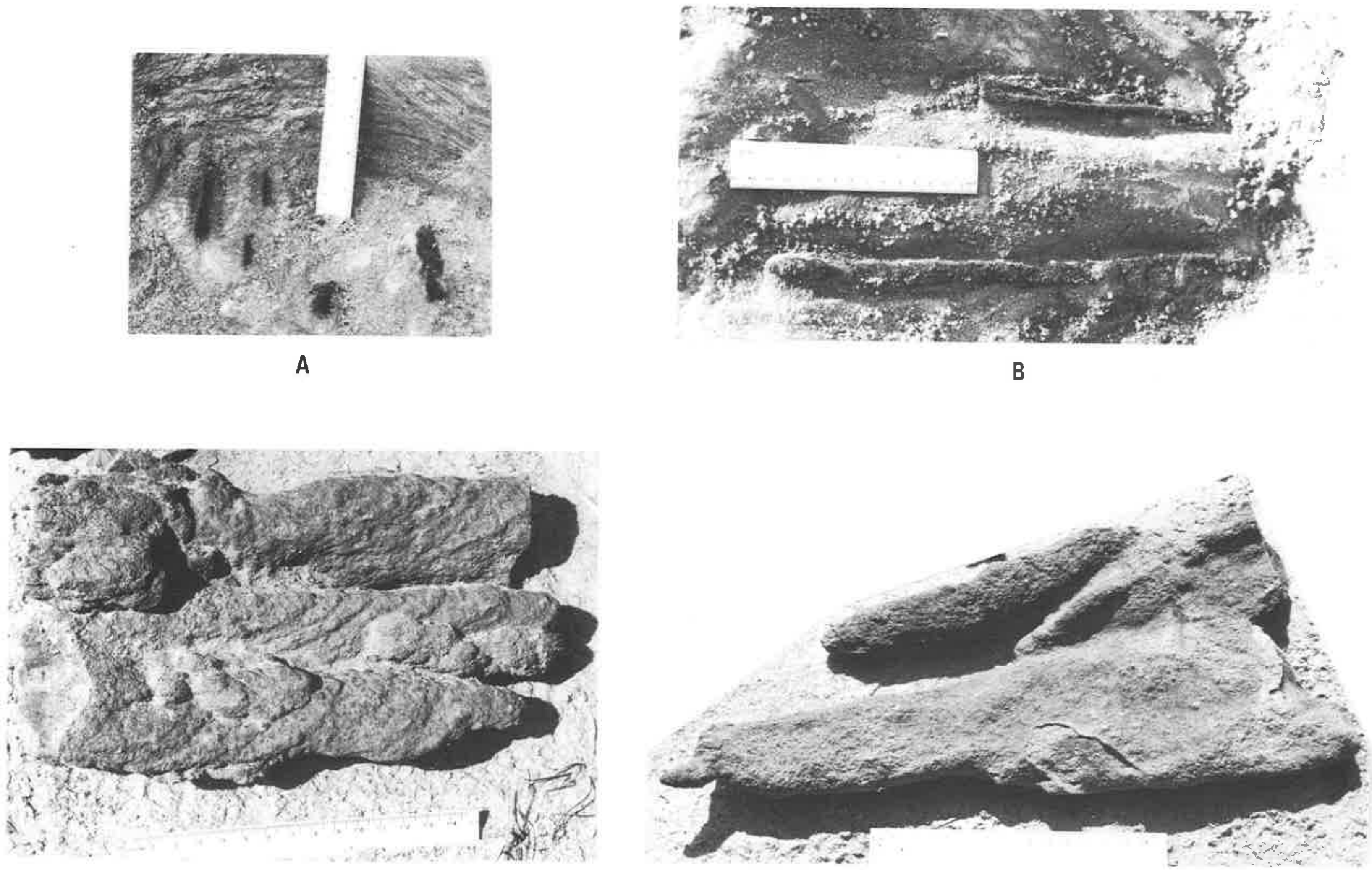
Figure 43. "Parallel ferruginous tunnels". A, B, typical arrays from undifferentiated Barnwell Group sands at Locality "H", showing parallel construction of burrows in lateral series. Burrows are of smaller diameter than those observed at Localities "A" and "H". Oblique views of nearly horizontal surfaces. C, burrows from Locality "G", exhibiting parallel construction in lateral series. C, oblique, parallel ridges reflect bedding attitudes in sediment. D, collapsed specimen from Locality "G", showing small conical "dead end" at left, typical of burrows of some decapods (see fig. 20B).



A

B

Figure 42. Details of "parallel ferruginous tunnels" pictured in figure 41—A, detail of burrows shown in lower left of figure 41, taken from opposite side. *Phycodes* sp. attached to termination of "parallel ferruginous tunnel" at center. Vertical view of sloping surface; B, view of burrows rotated 90° from view in figure 41 and parallel to long axes of burrows, showing vertical stacking. Overturned burrow fragment at upper left preserves compactional deformation. Surface slopes downward into foreground.



A

B

C

D

Figure 43. "Parallel ferruginous tunnels". A, B, typical arrays from undifferentiated Barnwell Group sands at Locality "H", showing parallel construction of burrows in lateral series. Burrows are of smaller diameter than those observed at Localities "A" and "H". Oblique views of nearly horizontal surfaces. C, burrows from Locality "G", exhibiting parallel construction in lateral series. C, oblique, parallel ridges reflect bedding attitudes in sediment. D, collapsed specimen from Locality "G", showing small conical "dead end" at left, typical of burrows of some decapods (see fig. 20B).

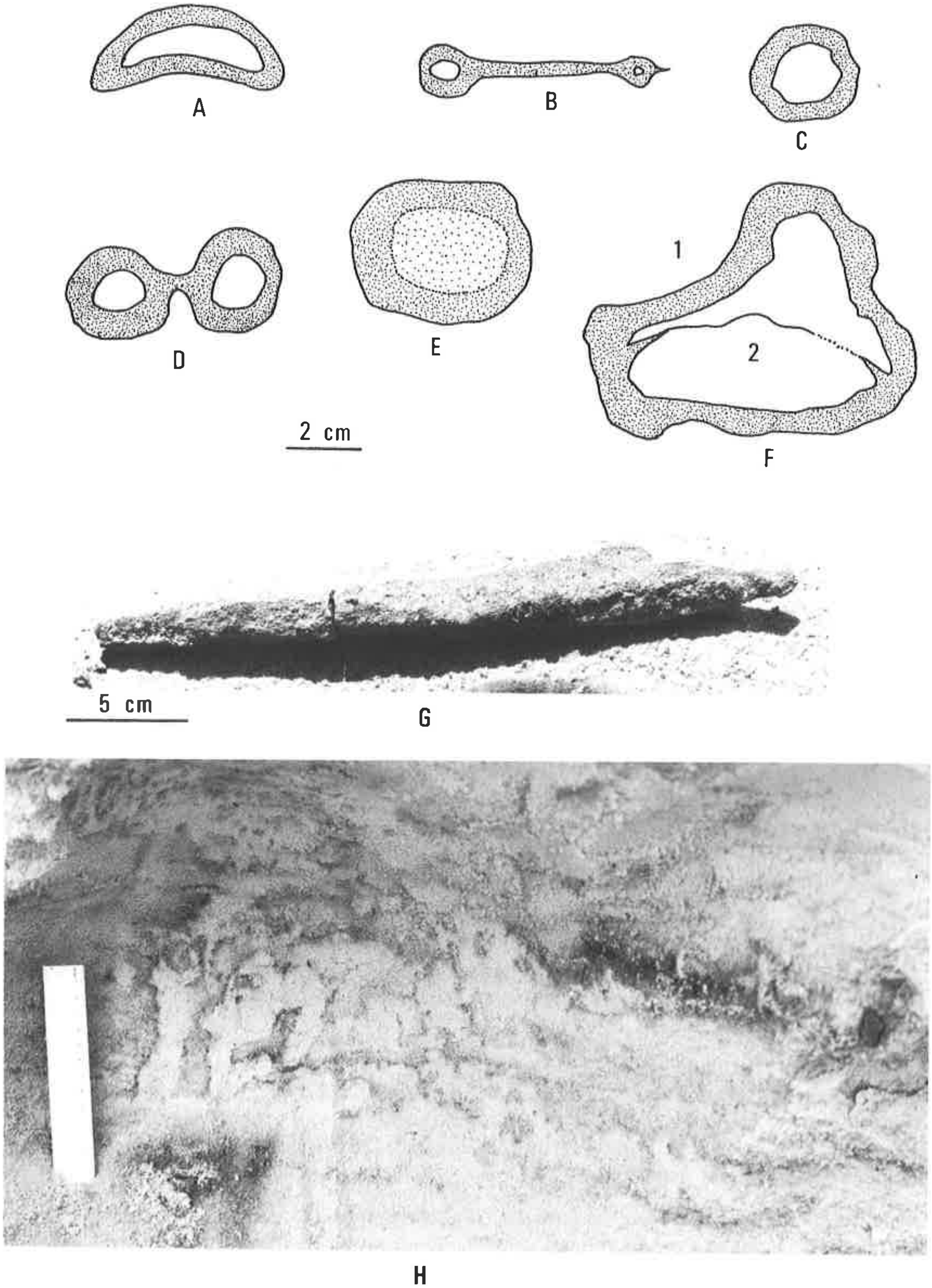


Figure 44. "Parallel ferruginous tunnels". A-F, transverse sectional views; A, collapsed tunnel; B, possibly collapsed tunnel; C. D, typical transverse sections of sand-filled tunnels; E, rod-shaped example exhibiting concentric zoning of iron sulfide minerals (marcasite core and pyrite rind); F, specimen preserving collapse feature (1) and possible spreite (2); G, doubly terminated rod-shaped specimen; H, sprietenlike bioturbate texture which is gradational with "parallel ferruginous tunnels". Transverse section through well defined, iron sulfide cemented specimen at right (3); A-D, F, G, from locality "G"; E, from Locality "A"; H, vertical view, outcrop face, from Oconee Group at Locality "A".

"Rhizocorallium-like burrows"

Figures 45, 46

Description: unbranched (?), straight to smoothly curved, dominantly inclined, sheath-like, U-shaped burrows (fig. 45A); transverse section, "dumbbell-shaped" (fig. 45B); major transverse diameter of sheath, typically 1.0 to 1.5 cm; minor transverse diameter typically about 2 mm, but may be as great as 5 mm; maximum length observed, about 12 cm; walls are unlined and smooth in appearance.

Preservation: exichnia, subjacent to erosion surfaces; burrow fill is unpatterned or, in some instances, reverse graded, and / or suggestive of spreiten structures (fig. 45A); fill is generally coarser than adjacent sediment and finer than suprajacent sediment, and is commonly cemented by iron sulfide. Truncated burrows commonly intersect sediment surface alongside more complete ones (fig. 46).

Occurrence and distribution: occurs at the upper surface of a massive, slightly sandy mud unit, about 9 m below the upper surface of the Oconee Group at Locality "A"; only one occurrence, covering about 5 m along a vertical face, observed; burrows laterally crowded, with maximum density observed, 15 intersections per linear meter on a vertical face.

Interpretation: dwelling structures, or possibly feeding-dwelling structures; tracemaker ethologically similar to the marine amphipod *Corophium*; probably constructed from scour surface, under conditions of intermediate to high current energy.

Discussion: These structures have affinities with several ichnogenera, including *Arenicolites, Corophiodes, Diplocraterion, Rhizocorallium,* and *Tisoa* (Hantzschel, 1975, p. W38, W53, W62, W101, W117 respectively). "*Rhizocorallium*-like burrows" usually are not vertical or perpendicular to bedding and thus are significantly different from all of the above except *Rhizocorallium. Rhizocorallium* is "generally protrusive, or somehwat oblique to bedding (Hantzchel, 1975, p. W101). However, "*Rhizocorallium*-like burrows" lack clearly defined spreiten and thus are apparently excluded from this ichnogenera as well. "*Rhizocorallium*-like burrows" are also smaller than typical *Rhizocorallium.*

Rhizocorallium-like burrows" are considered to have greatest affinity with *Rhizocorallium,* based on obliqueness of orientation common to both burrow types. The parallel construction of U-limbs, maintained even where burrows curve, suggests absence of spreiten is due to nonpreservation rather than ethology (Schafer, 1972, p. 307). Differences in size between these specimens and *Rhizocorallium*, though considerable, are probably not of major ethological significance.

Possible modern analogues to the tracemaker include: Ephemerid (insect) larvae; the amphipod *Corophium volutator*; and the polychaete *Polydora ciliata.* These organisms are known to construct small, U-shaped dwelling burrows in "semi-consolidated mud exposed to highly turbulent water": Ephemerid larvae in riverbanks and *Corophium volutator* and *Polydora ciliata* in intertidal situations (Seilacher, 1967, fig. 1).

Of the possible tracemakers listed above, the burrowing behavior of *Corophium volutator* is especially interesting. Digging into "ragged," muddy erosion surfaces adjacent to intertidal creeks, this animal constructs a small, sometimes curved, U-shaped burrow, in which the limbs are parallel and rather closely appressed. Extension of U-limbs creates a central cavity, which is backfilled with material often showing no clearly defined spreiten structure (Schafer, 1972, p. 307, pl. 30a). This illustration of ethological similarity is not intended to suggest that "*Rhizocorallium*-like burrows" were excavated by *Corophium volutator.*

As noted above, modern structures analogous to "*Rhizocorallium*-like burrows" are constructed primarily as dwellings. The trophic mode of most potential tracemakers is one of suspension feeding or surface deposit feeding (Seilacher, 1967, p. 318, 319). Sellwood (1970, p. 494, 495) suggested the possibility that *Rhizocorallium* producers were deposit feeders during burrow construction,and upon burrow completion, became suspension feeders. However, as Sellwood points out, even if this were the case, suspension feeding would probably still be the dominant trophic mode. Thus, it seems apparent that "*Rhizocorallium*-like burrows" served primarily as dwelling structures.

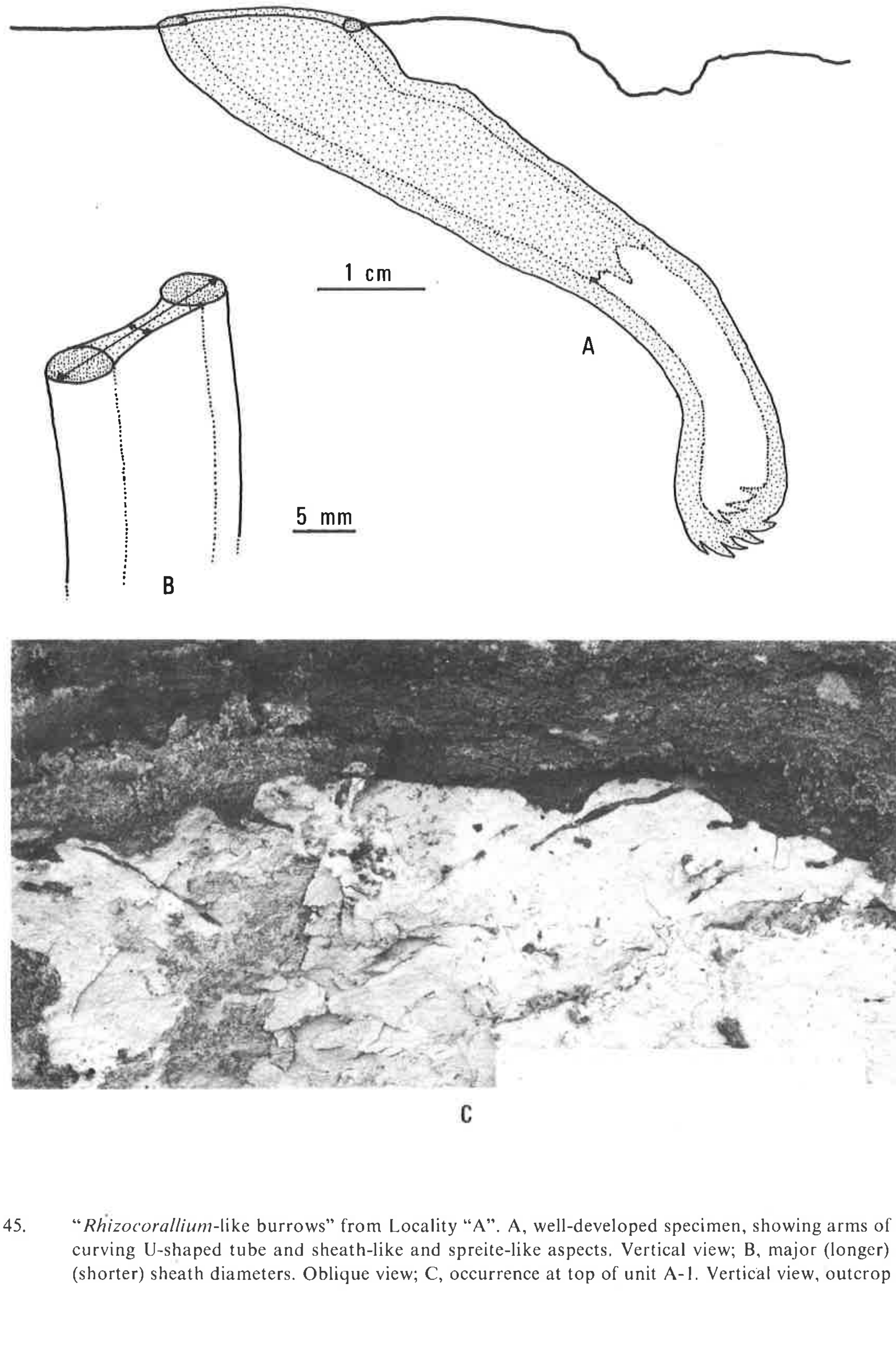


Figure 45. "*Rhizocorallium*-like burrows" from Locality "A". A, well-developed specimen, showing arms of downward curving U-shaped tube and sheath-like and spreite-like aspects. Vertical view; B, major (longer) and minor (shorter) sheath diameters. Oblique view; C, occurrence at top of unit A-1. Vertical view, outcrop face.

Only one occurrence of "*Rhizocorallium*-like burrows" was observed in the study area. These burrows penetrate the irregular upper surface of slighty sandy mud, about 10 m below the upper surface of the Oconee at Locality "A". The irregularity of this surface, together with the occurrence of many truncated "*Rhizocorallium*-like burrows", suggests erosion of a semi-consolidated substrate. Variation in degree of truncation of adjacent burrows suggests tracemakers were tolerant of erosional conditions and attendant elevated current energies. Thse conclusions are compatible with observations of modern analogs and their preferred environments (Seilacher, 1967, fig. 1; Schafer, 1972, p. 307).

Erosional truncation of some individuals, combined with a general absence of suprajacent sediment similar to burrow fillings, indicates the surface penetrated by "*Rhizocorallium*-like burrows" is an omission surface (Bromley, 1975, p. 400, 401). Burrow fill consists mainly of fine sand, in many places cemented by iron sulfide. Similar material, thinly interbedded with mud, was observed resting on the burrowed unit several meters laterally from the observed occurrence of "*Rhizocorallium*-like burrows."

The attitude of *Rhizocorallium* with respect to the surface of penetration has been used as an indicator of bathymetry, where sedimentary units are laterally continuous over considerable distances (Ager and Wallce, 1970, p. 18). In general, horizontal *Rhizocorallium* is thought to indicate deeper water, vertical *Rhizocorallium* shallow water, and oblique *Rhizocorallium* depths intermediate between the two end members. However, the authors state that the actual determinant of burrow attitude is the degree of need to "escape dessication and disinterment," a condition which is most commonly, although not always obtained, in shallow water.

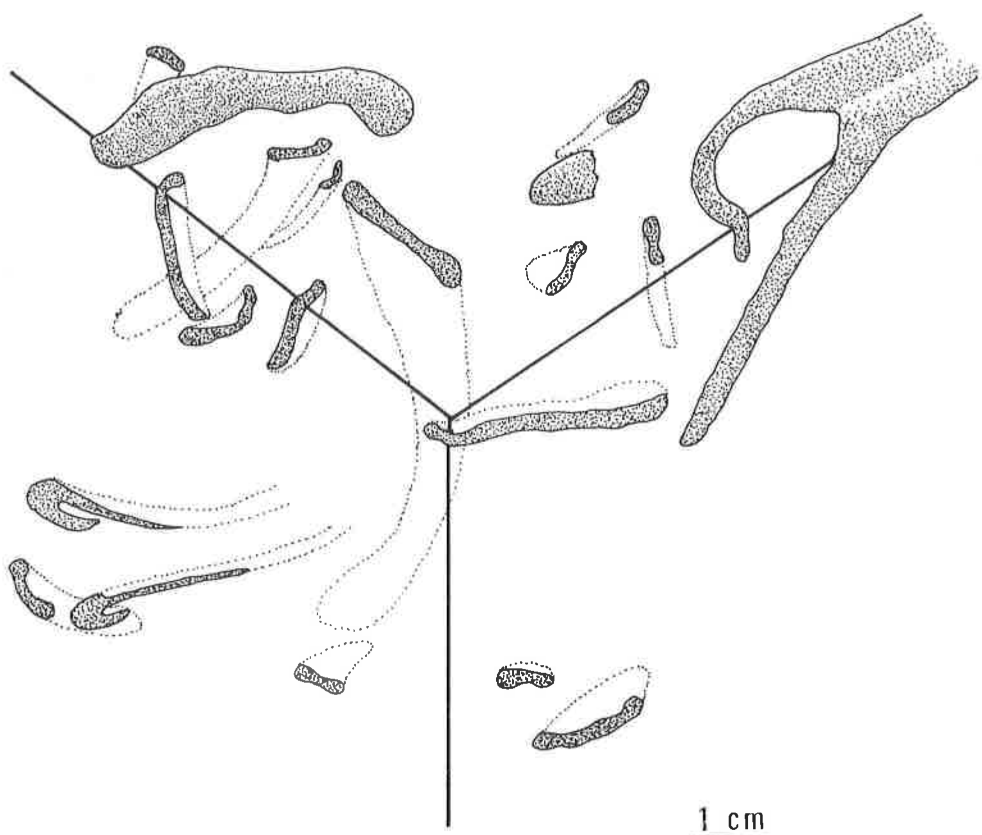


Figure 46. "*Rhizocorallium*-like burrows" from Locality "A", showing random orientation.

Bioturbate textures in muds

Figures 47, 48

Bioturbate textures produced by the activity of deposit-feeding animals were observed within commercial kaolin deposits of the Oconee group at Localities "E", "F", and "H". Where observable, these textures consist of mud-filled pockets, chambers, and tubular segments of highly variable morphology and size. Wall structure ranges from nearly smooth, to colliform, jagged, or highly irregular. These textures may grade into *Skolithos* sp. (for example, fig. 47A).

Bioturbate textures are made visible in outcrop by a subtle color contrast between burrowed and "unburrowed" areas. Burrowed areas are very white (N10), while "unburrowed" areas are very pale orange (10YR 8/2) to grayish orange pink (10R 8/2). This contrast is due to the relative absence of iron oxide and hydrous iron oxide within burrowed areas. For a more complete discussion of the genesis of iron distribution in these textures, see pages 43, 44.

Due to the difficulty in observing these textures, staining was performed using an epoxy dye dissolved in Krylon. The stained surface was then mounted onto a frosted glass plate with Cadex epoxy (fig. 48). Darker areas correspond to lighter, relatively iron-poor areas of unstained specimens, whereas lighter portions correspond to iron-rich areas. The degree of darkness in stained samples (for example, fig. 48) apparently results from differential penetration of Krylon and dye; greater penetration is represented by darker areas in stained samples. An effect of greater penetration which is not obvious in figure 48 is that the darker areas are somewhat transparent, giving the actual sample surface a three dimensional appearance.

At Locality "E", samples of unit E-1 were taken in vertical series subjacent to the upper contact and 0.3 m and 1.5 m below the upper contact. When stained, these samples revealed the following.

The sample taken subjacent to the upper contact appeared nearly homogeneous, with only a few small scalloped islands of lighter material, similar to that at the extreme left in figure 48. The samples taken 1.5 m and 0.3 m below the upper contact correspond to figure 47A and 48 respectively. Taken together, these samples suggest a downward trend towards decreasing bioturbation, but the results are far from conclusive.

The morphologies exhibited by these bioturbate textures indicate they probably were generated in a soft, unconsolidated muddy substrate not long after deposition. For discussion of the relationships between these textures and *Planolites* sp. B and *Skolithos* sp., see pages 39 and 42 respectively.

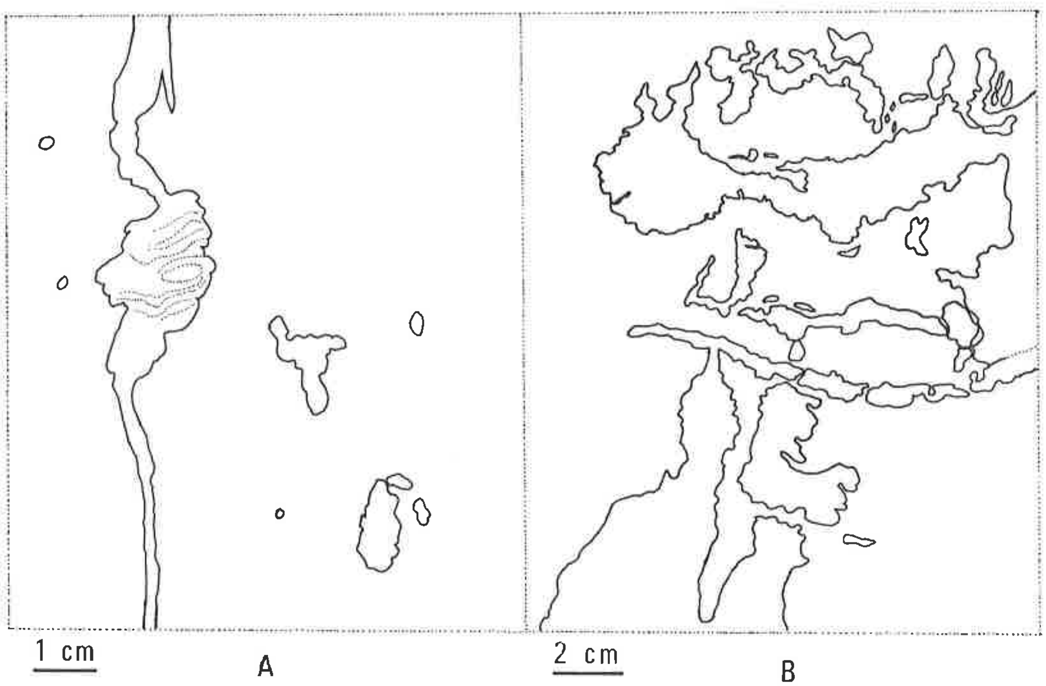


Figure 47. Bioturbate textures in muds; vertical face views; after blocks taken 1.5 m below upper surfaces of units in which these textures occur. A, after stained specimen from Locality "E". B, after unstained specimen from Locality "F"; burrowed areas are very white (N10), unburrowed areas are light pinkish gray (5 YR 9/1) to pale pink (5 RP 8/2).

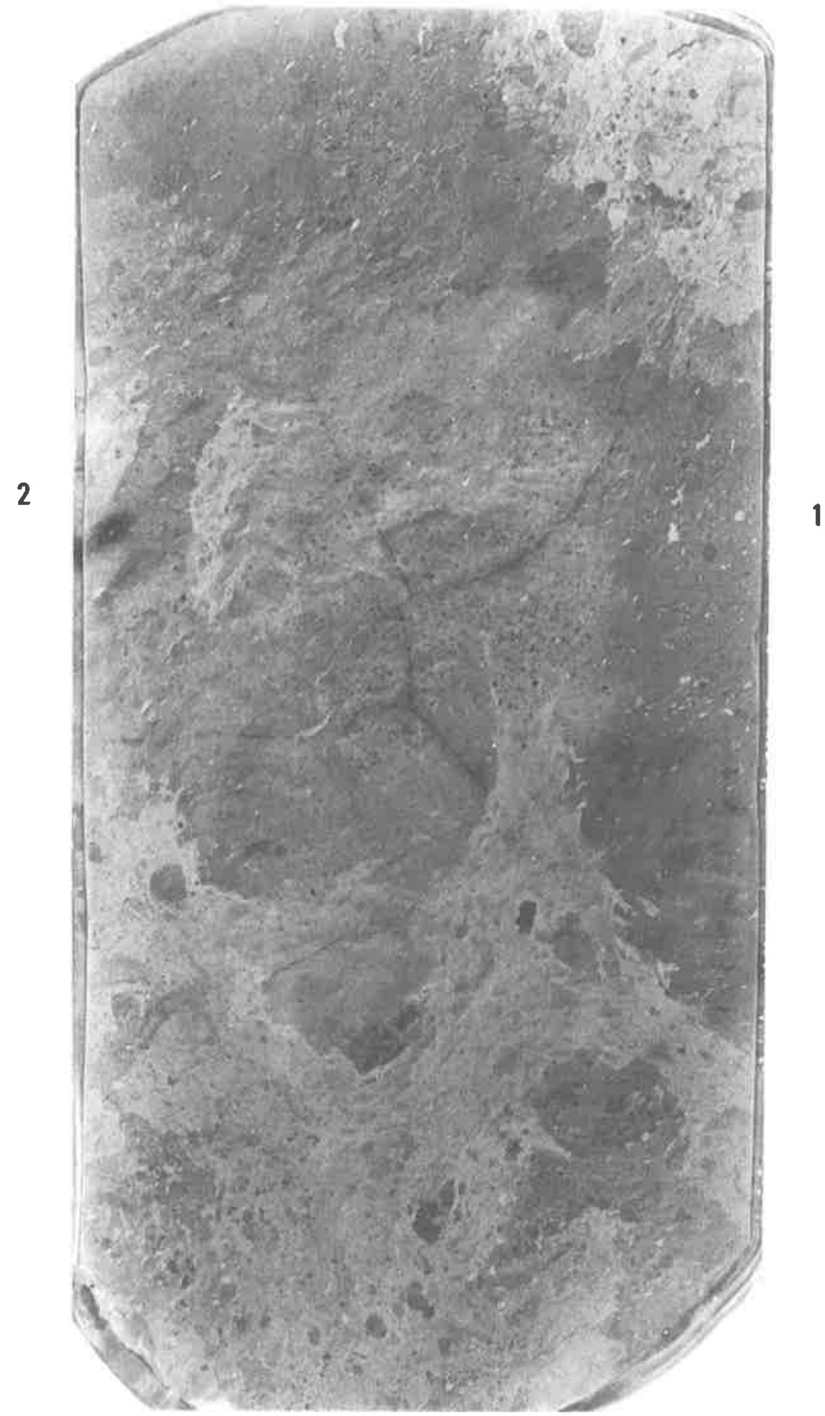


Figure 48. Stained block, showing bioturbate texture in mud. Sample taken 30 cm below upper surface of commercial kaolin lens at Locality "E". Darker areas more bioturbated than lighter ones. Small "islands" of lighter material, show scalloped edges (1). Oblique section through specimen of *Planolites* sp. B visible at center left (2). Vertical view.

PROBLEMATICAL STRUCTURES

"Large conical structures"

Figures 49-58

Large mud-filled conical structures which occur in mud substrates were observed within a commerical kaolin deposit at Locality "H", about 3 to 6 m below the upper surface of the Oconee Group (figs. 49-58). These structures originate at the top of a very pale-orange (10 YR 8/2) pisolitic mud unit, which contains some deformed, very white (N10) roughly horizontal laminae (for example, figs. 49B, 56B). Suprajacent to this unit is a more homogeneous, darker, pale yellowish brown (10 YR 6/2), (?) pyritic mud, which seems to have contributed to structure fillings (for example, figs. 49A, 55).

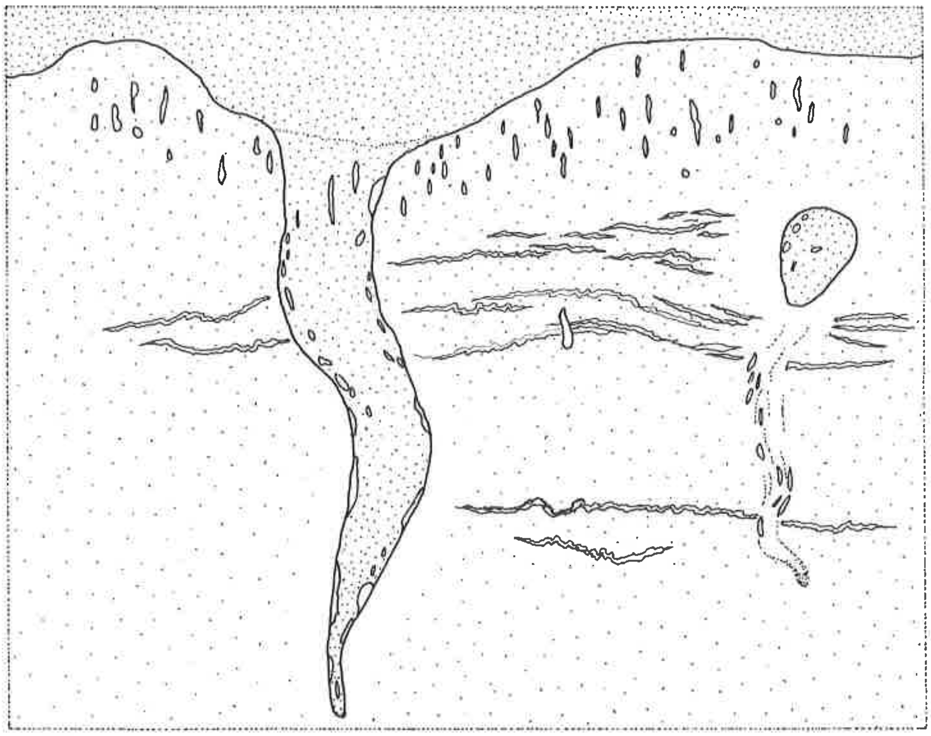
The morphology of these structures is basically that of a downward tapering, vertical to steeply inclined, straight to slightly sinuous cone (figs. 49, 52, 53, 55, 56A, 57). Median diameters range from 5 to 25 cm. Maximum length observed was about 1 m. Lower terminations are blunt (fig. 55) to pointed (figs. 49, 52, 53). "Openings" to suprajacent unit are broadly to narrowly conical (for example, figs. 53 and 55 respectively), and the structures "open" into broad, shallow, concave-up depressions (figs. 52, 53). Wall structure is highly to slightly irregular to colliform (for example, figs. 55, 57, 58) and definition ranges from poor (fig. 53) to good (fig. 55). Concentration of very white (N10) mud near outer margins of structures is suggestive of a lining (for example, figs. 55, 57). Maximum density observed, 6 intersections/linear m on a vertical face.

These structures are characterized internally by stretched pisolites and discontinuous *Skolithos* sp. (?) whose long axes are more or less vertical (for example, figs. 55, 58A). Many specimens exhibit irregular concentric zoning of colors apparently due to differences in the concentration of iron: such specimens are generally darker in the center and lighter on the periphery, due to high and low iron concentration, respectively (for example, fig. 57). Although relatively iron-rich material contained within these structures was apparently derived from the suprajacent unit (figs. 52, 55), colors of this material and that of suprajacent sediment differs: iron-rich structure fill is generally very pale orange (10 YR 8/2), whereas suprajacent sediment is pale yellowish brown (10 YR 6/2). The degree of oxidation or mixing could account for this minor difference.

Many specimens exhibit halos several centimeters wide in which structures in the surrounding substrate are obliterated (for example, fig. 49). Obliteration of deformed white laminae and pisolites indicates these features predate "large conical structures".

Many specimens are slightly offset or truncated by horizontal faults (figs. 56B, 57, 58). These faults also truncate and offset pisolites (fig. 58A). Fault blocks appear to be wedge shaped in some cases (fig. 58B). Horizontal faults are also associated with pillar structures in muddy sands at Locality "B" (fig. 60). Two points concerning these faults seem clear: (1) they postdate development of sediment fabric and large conical structures; (2) the muds and muddy sands in which they occur behaved competently during faulting, indicating the sediment was considerably consolidated prior to faulting.

These structures physically resemble "pillar structures" formed in "unconsolidated" sands and coarse silts by upward movement of water during sediment dewatering (Lowe and LoPiccolo, 1974, p. 493, 494, fig. 2a; Bromley and others, 1975, figs. 16. 14-16.16). However, pillars characteristically form in sediments ranging in grain size from coarse silt to coarse gravelly sand (Lowe and LoPiccolo, 1974, p. 484) and apparently have not been reported from fine muds such as these.



20 cm

A

15 cm

B

Figure 49. "Large conical structures from Locality "H", showing truncation of deformed white laminae. A adapted from B.

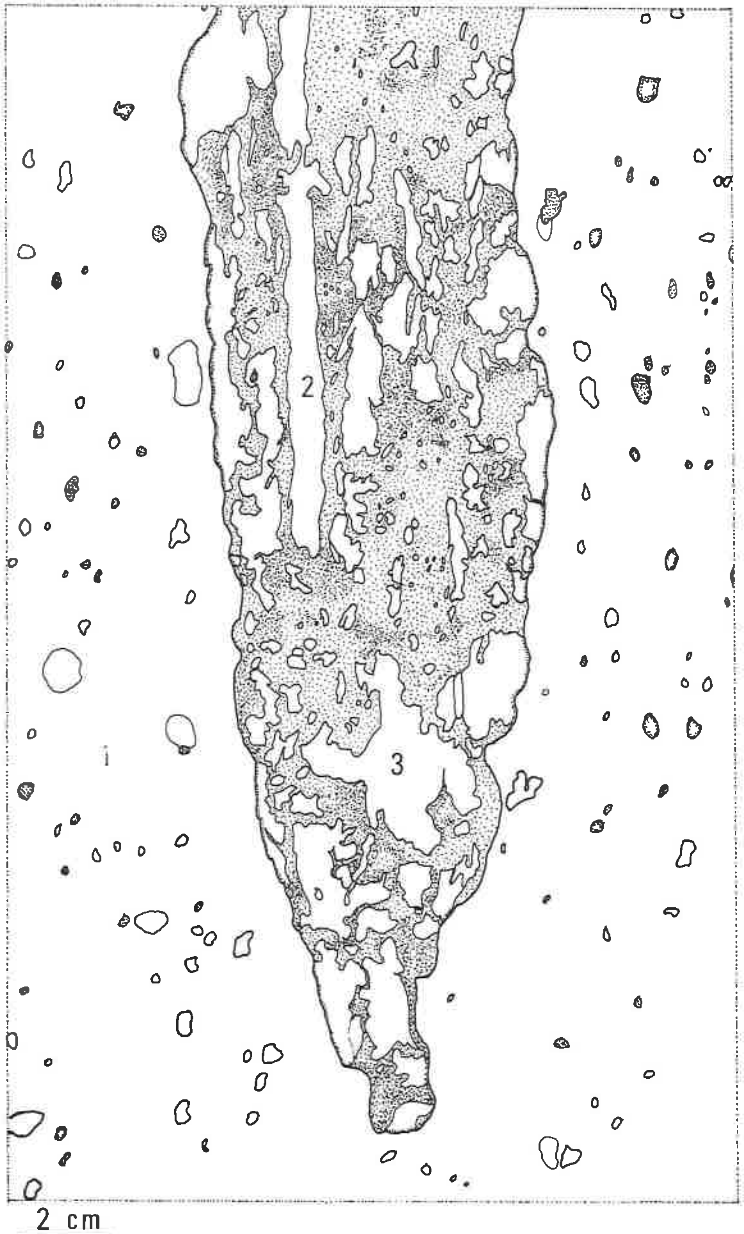


Figure 50.

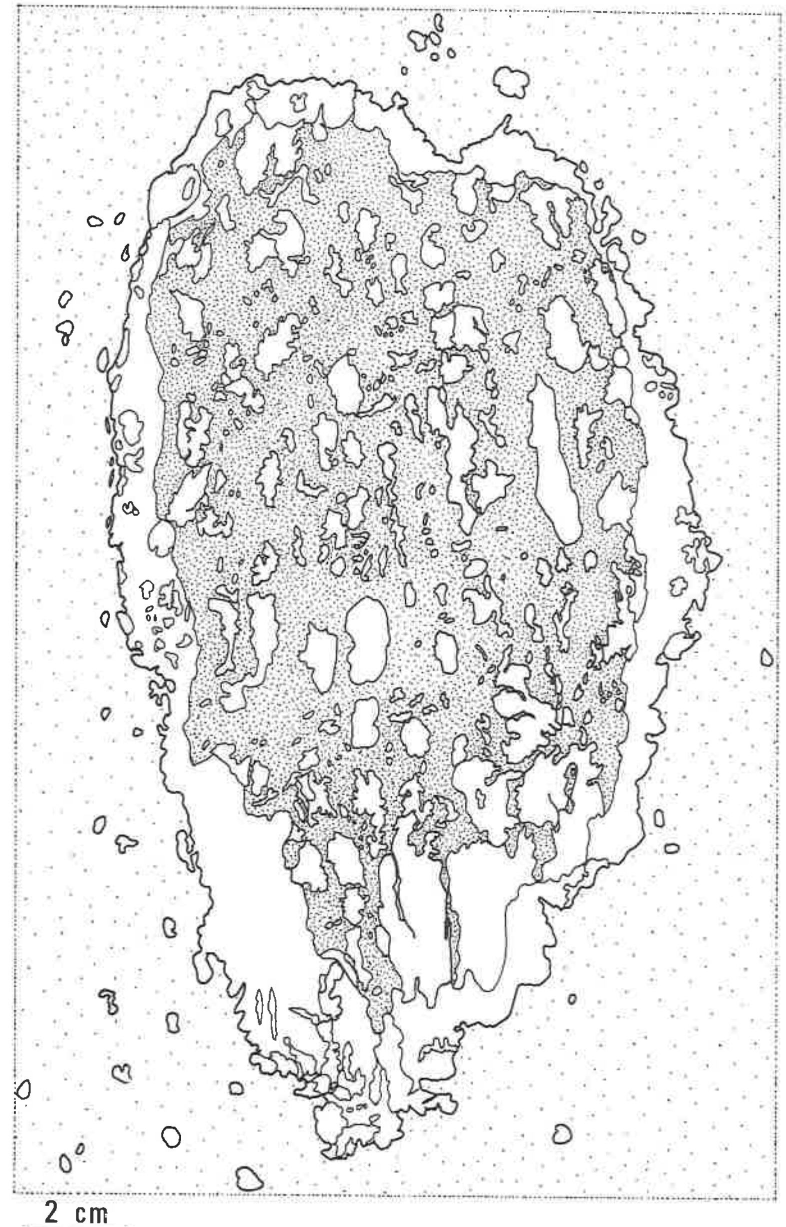


Figure 51.

Figure 50. Longitudinal section through lower portion of a "large conical structure" from Locality "H", showing irregular, colliform wall structure, pisolites (1), discontinuous *Skolithos* sp. (?) (2), and irregular bioturbate textures (3). Vertical view, outcrop face.

Figure 51. Oblique section through a "large conical structure" from Locality "H". Stippled areas relatively rich in hydrous iron oxide. "Halo" of very white (N10) mud (1) typical of many specimens observed. Surface slopes slightly away from viewer toward top of figure (see fig. 50).

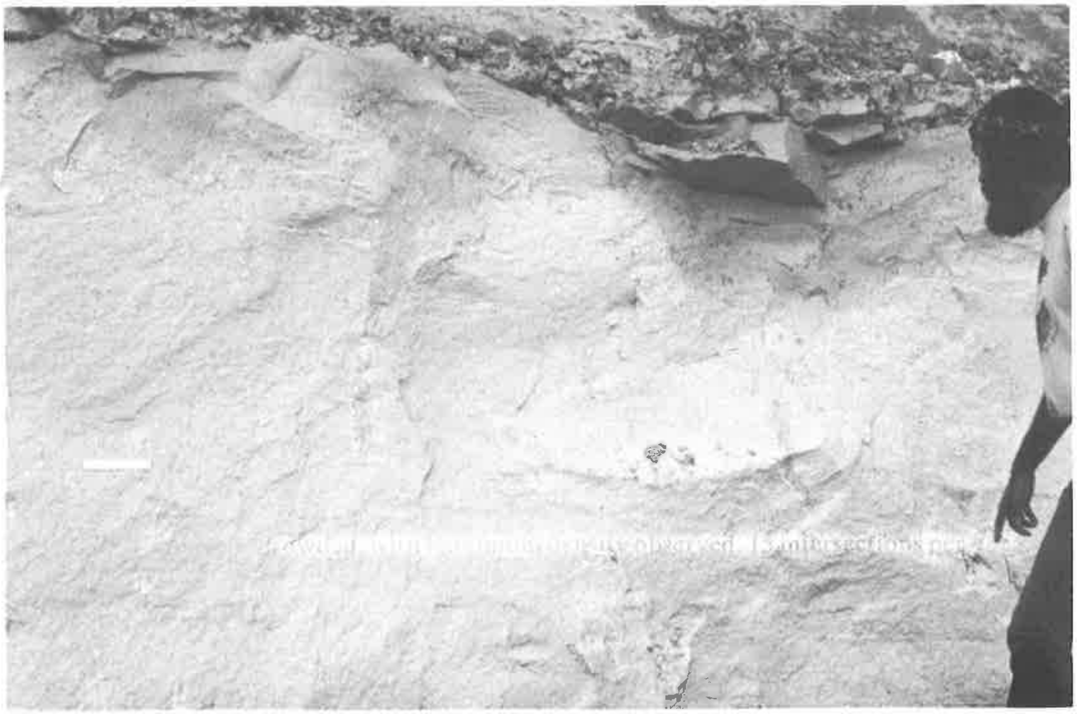


Figure 52. Spacial relationship of "large conical structures" to suprajacent and adjacent sediments. Vertical views, outcrop face. From upper 1 m of commercial kaolin lens, 1-4 m below upper surface of Oconee Group. Shallow depressions filled with darker mud of overlying unit occur suprajacent to "large conical structures". This darker material also seems to constitute fill of "large conical structures". Ruler is 15 cm long.

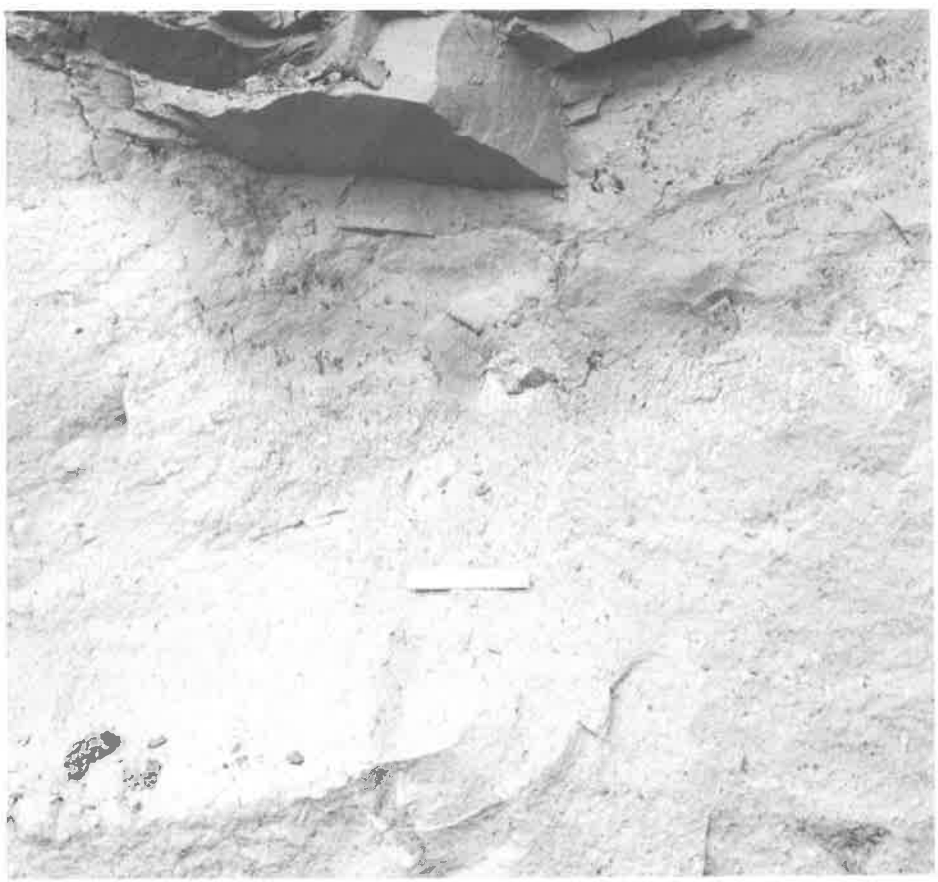


Figure 53. Detail of right side of figure 52, showing a "large conical structure" and associated suprajacent shallow depression. White structures surround the "large conical structure and extend laterally subjacent to shallow depression, showing poorly developed vertical orientation. (see fig. 54).

Figure 54.

Figure 55.

Figure 54. Detail of a portion of figure 53 at center right, showing vertically attenuated pisolites (light and dark spots) and white structures suggestive of plasic deformation. Sediment fabric at lower right shows no deformation.

Figure 55. Detail of figure 52, showing trucation of deformed white laminae by "large conical structure". Internal structure shows parallel orientation with external margins of "large conical structure". White "halo" visible at external margins.

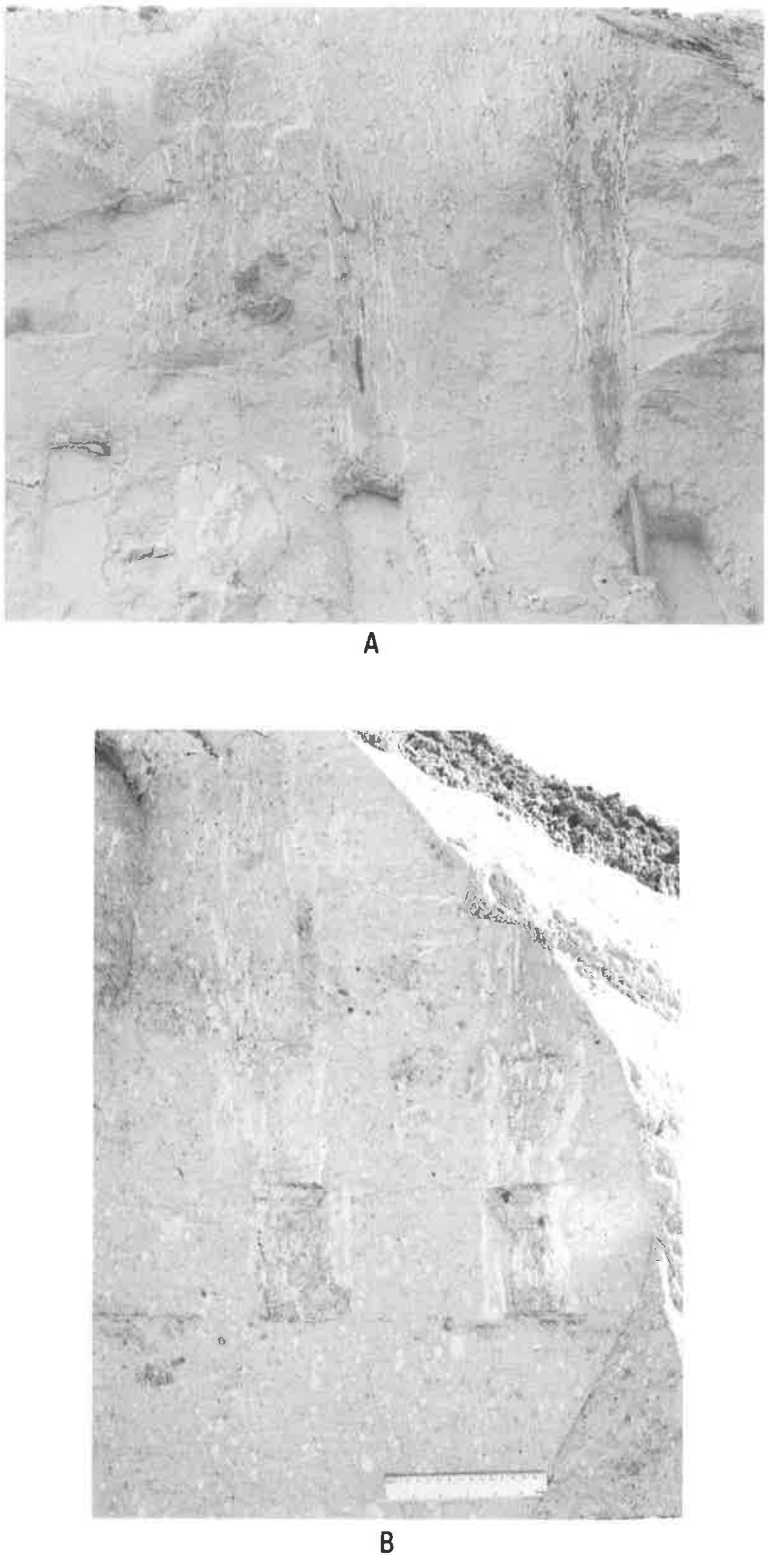


Figure 56. "Large conical structures" from commercial kaolin lens, 1 - 4 m below upper surface of Oconee Group at Locality "H". Vertical views, outcrop faces. Rulers are 15 cm long. A, with vertically oriented white structures similar to *Skolithos* sp.; B, shows vertically oriented internal structure, random orientation of pisolites in adjacent sediment, and truncation and offset by horizontal faults.

Figure 57. "Large conical structures" from commercial kaolin lens, 1 - 4 m below upper surface of Oconee Group at Locality "H", showing truncation and offset by horizontal faults. Deformed white laminae at top. Ruler is 15 cm long.

A

B

Figure 58. Lower portions of "large conical structures" from commercial kaolin, 2-5 m below upper surface of Oconee Group at Locality "H", showing truncation and offset by horizontal faults.

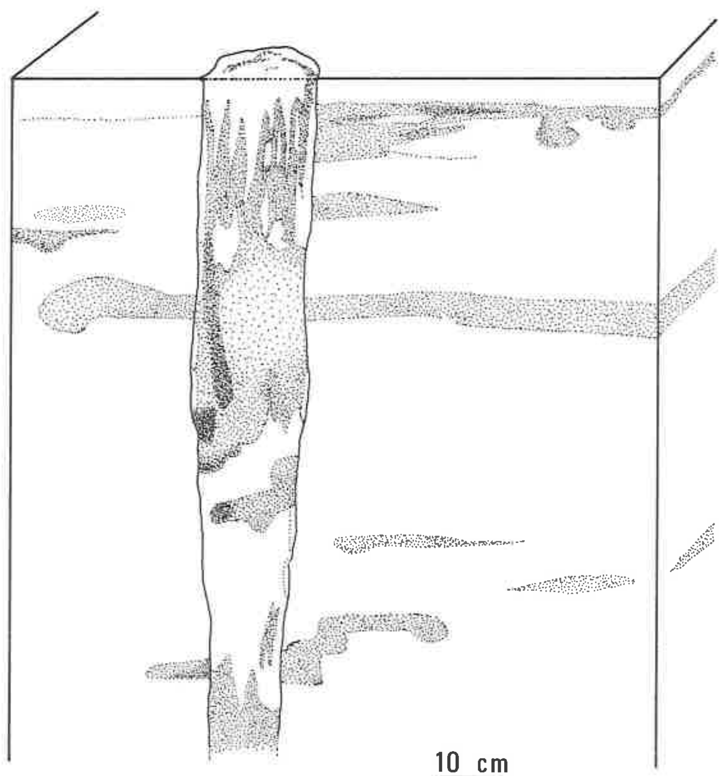


Figure 59.

A

B

Figure 60.

Figure 59. Pillar (?) structure in muddy sand/sandy mud, 2-3 m below upper surface of Oconee Group at Locality "C". Stippled areas relatively rich in hydrous iron oxide. Vertical faults and offsets apparent in sediment near base.

Figure 60. Pillar (?) structures in bedded sandy mud at Locality "B", about 3-4 m below upper surface of Oconee Group. Darker areas stained by hydrous iron oxide. Similarities between these structures and "large conical structures" from Locality "H" include overall morphology and size, orientation, stratigraphic position, and truncation by horizontal faults. A, B, at same stratigraphic horizon. Ruler is 15 cm long. Vertical views outcrop face.

STRATIGRAPHIC AND ENVIRONMENTAL DISTRIBUTION OF TRACE FOSSILS

Figures 61 through 69 summarize the stratigraphy, lithology and environmental interpretations of sediments from Localities "A" through "H". Stratigraphy and Lithology were adapted from the more detailed descriptions contained in Appendix A. Environmental interpretations are elaborated on in Conclusions(p. 85-87).Figures 61 through 69 also show the stratigraphic distribution of trace fossils.

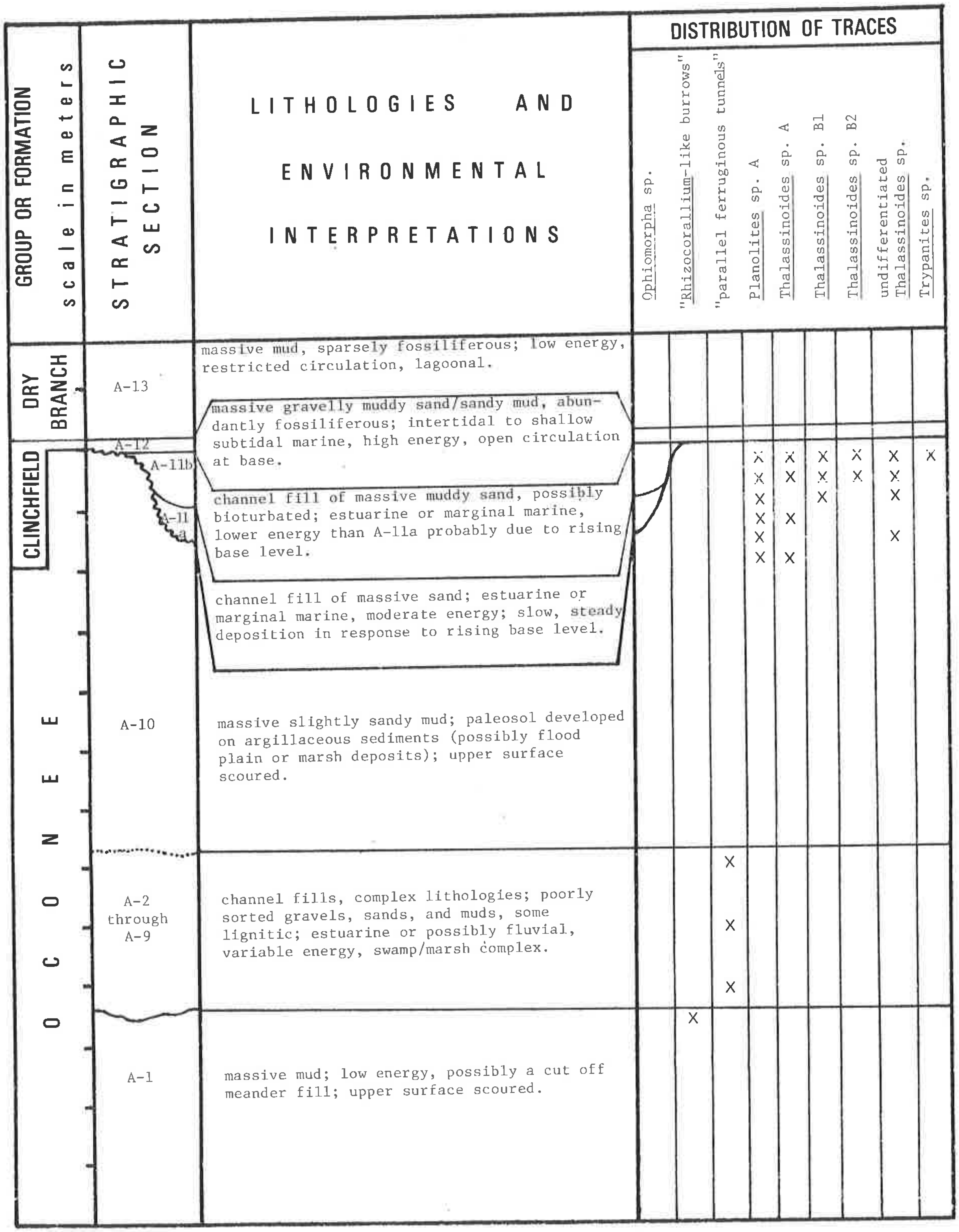


Figure 61. Locality "A": stratigraphy, lithologies, environmental interpretations, and trace fossil distribution.

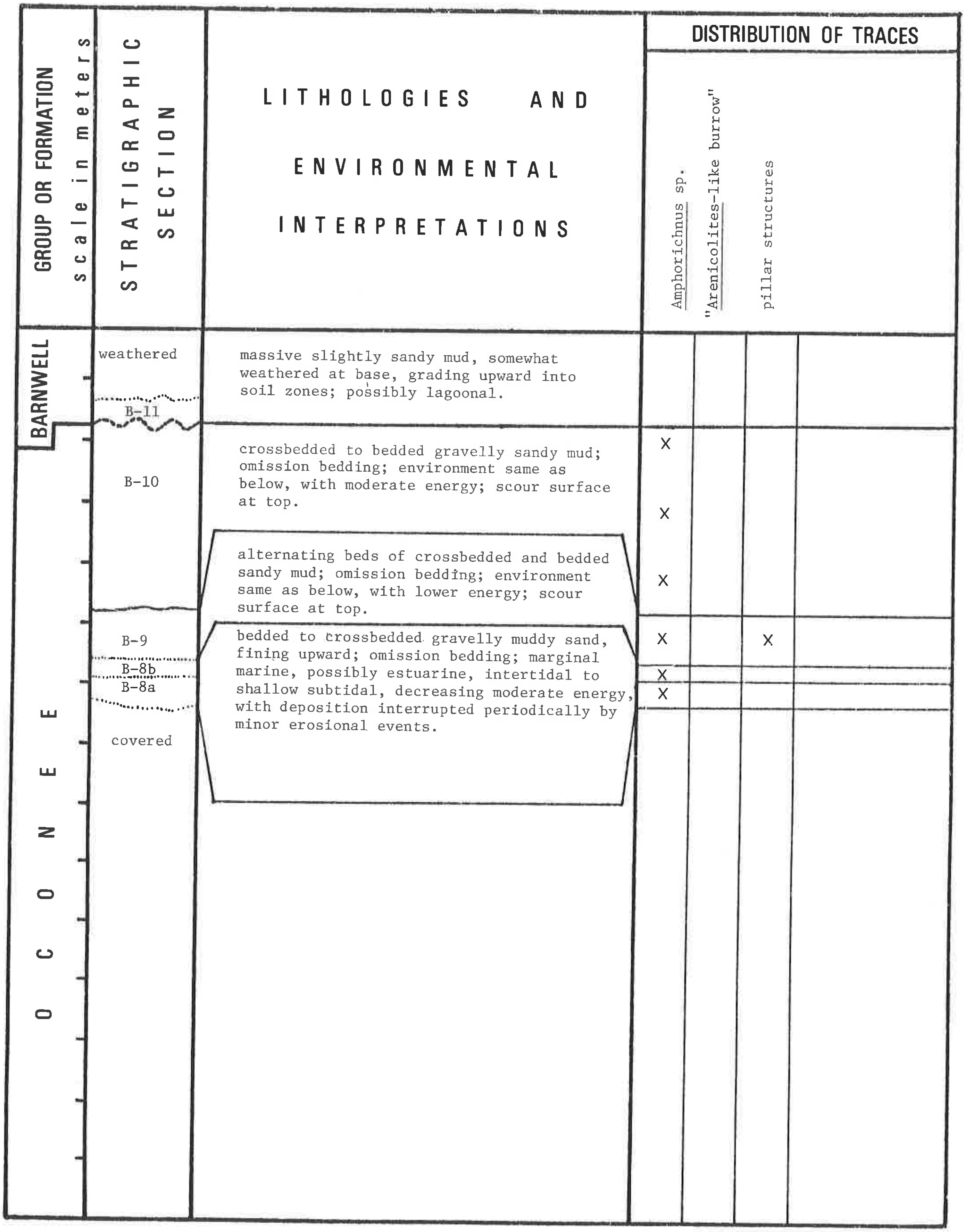


Figure 62. Locality "B": stratigraphy, lithologies, environmental interpretations, and trace fossil distribution.

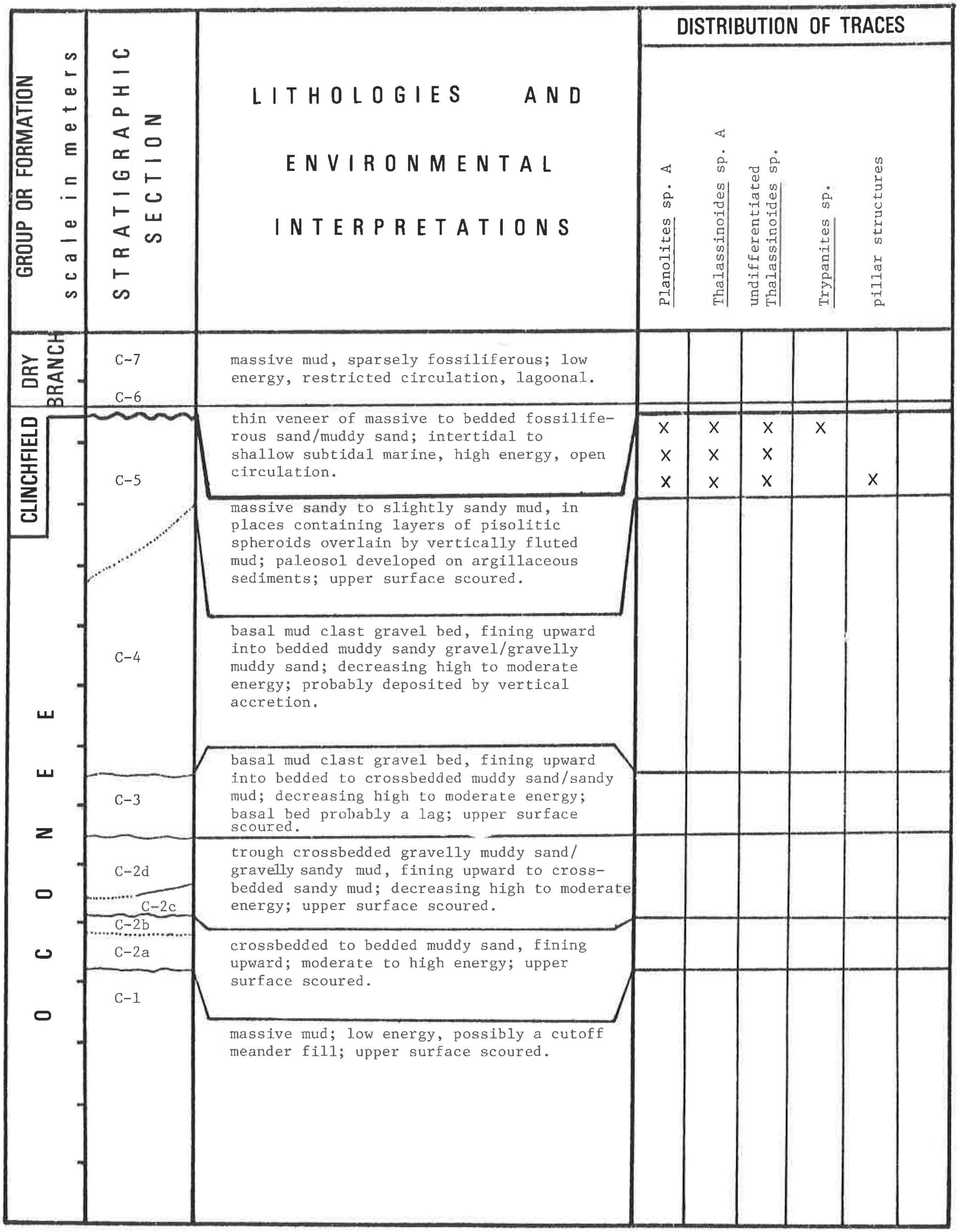


Figure 63. Locality "C": stratigraphy, lithologies, environmental interpretations, and trace fossil distribution.

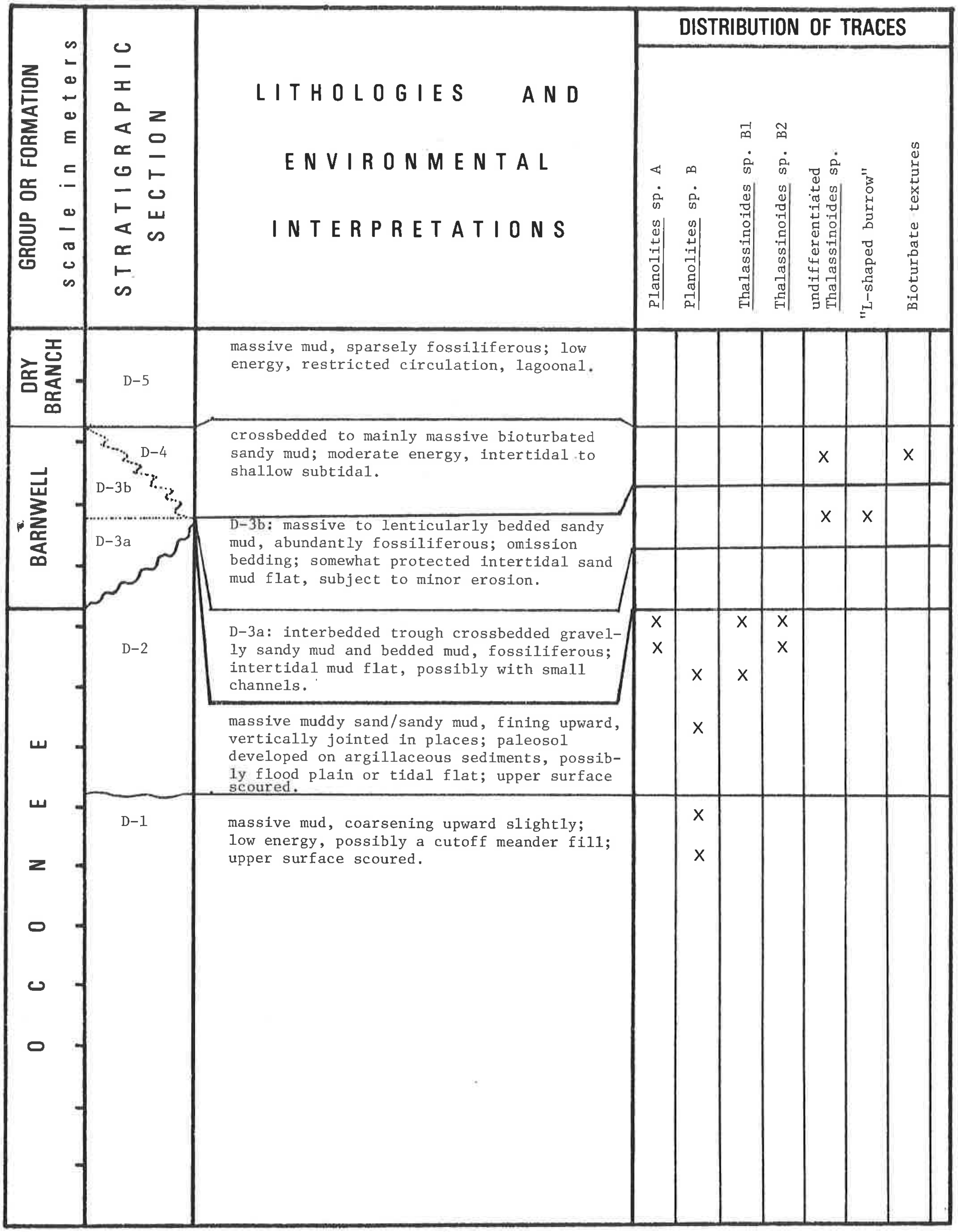


Figure 64. Locality "D": stratigraphy, lithologies, environmental interpretations, and trace fossil distribution.

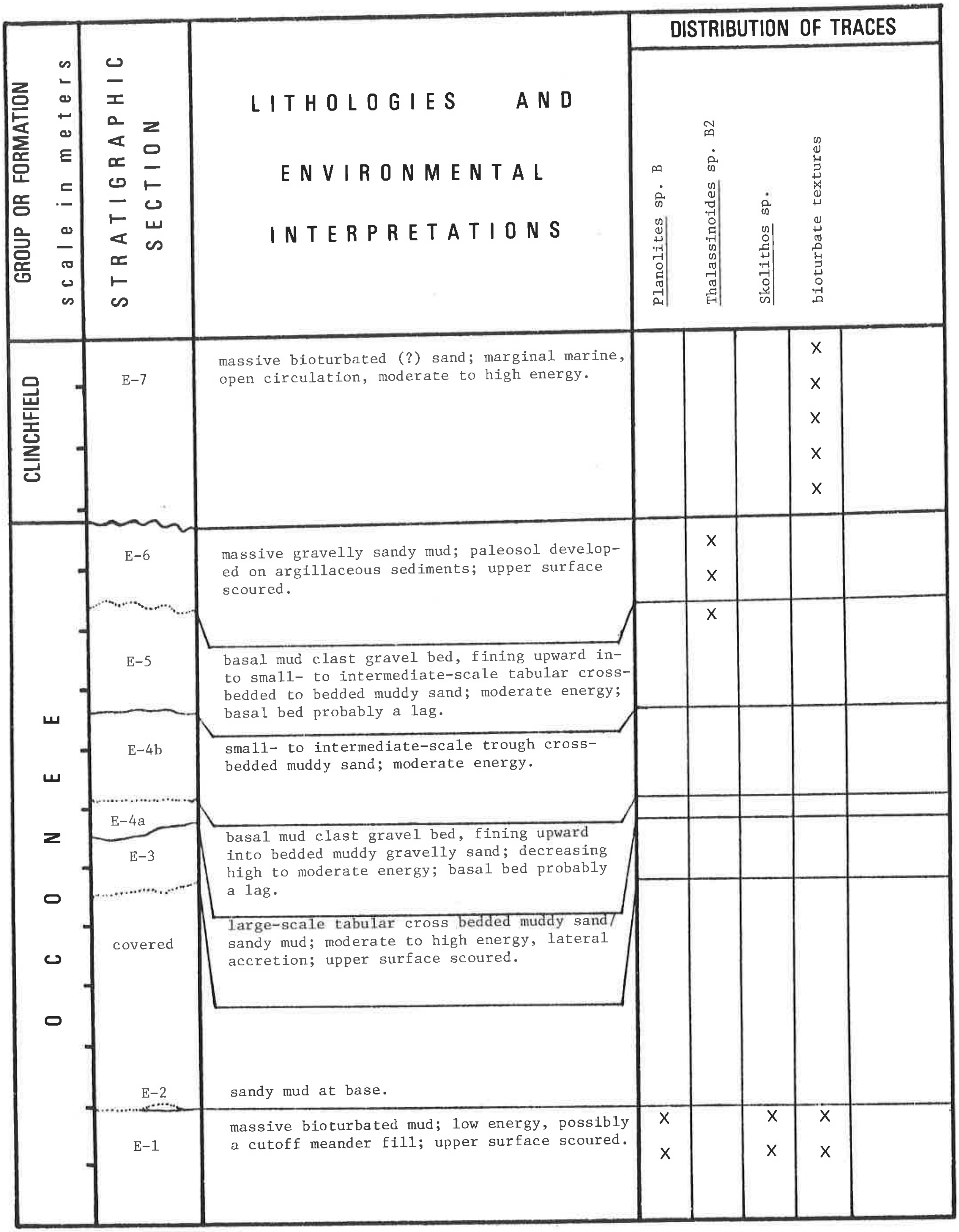


Figure 65. Locality "E": stratigraphy, lithologies, environmental interpretations, and trace fossil distribution.

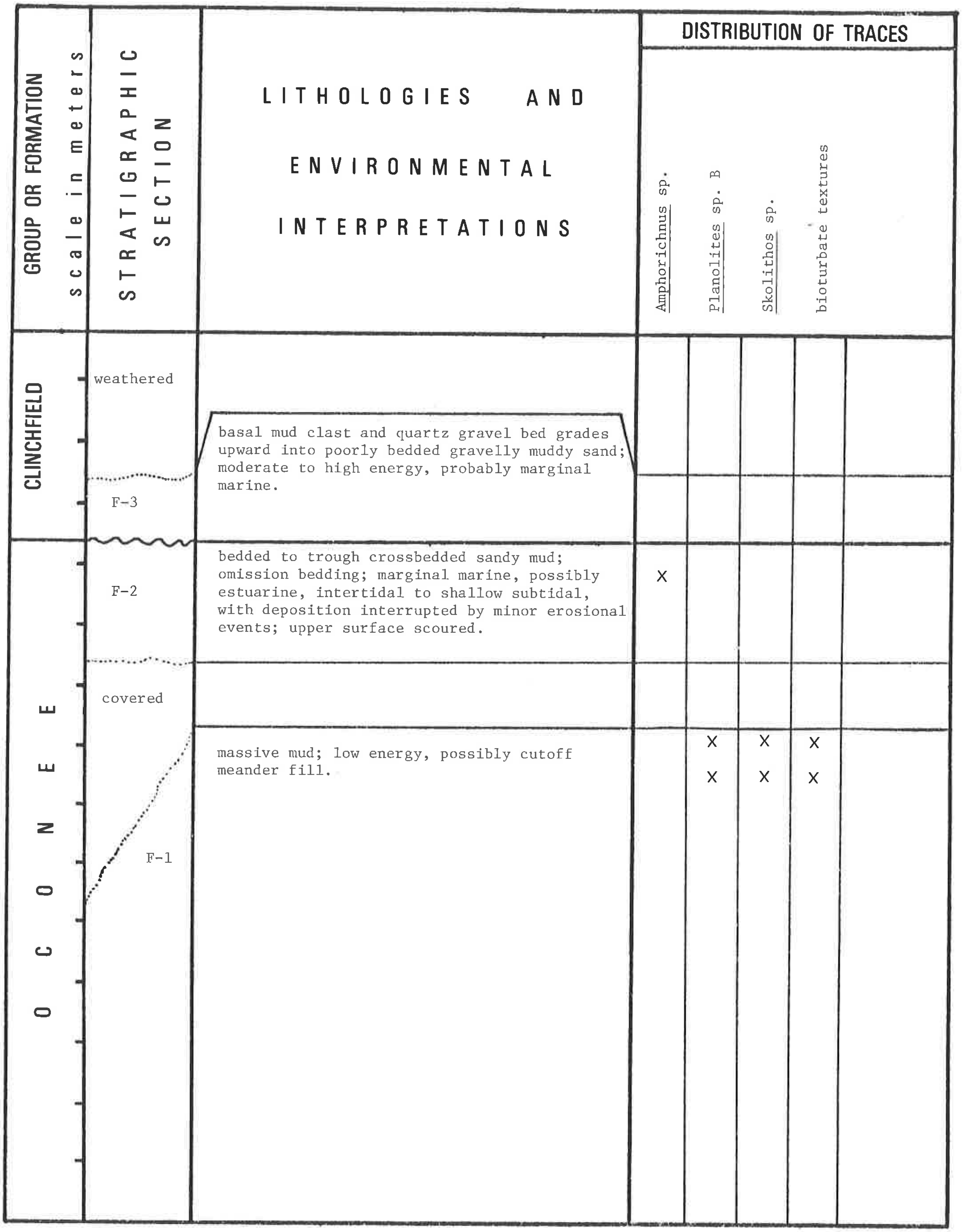


Figure 66. Locality "F": stratigraphy, lithologies, environmental interpretations, and trace fossil distribution.

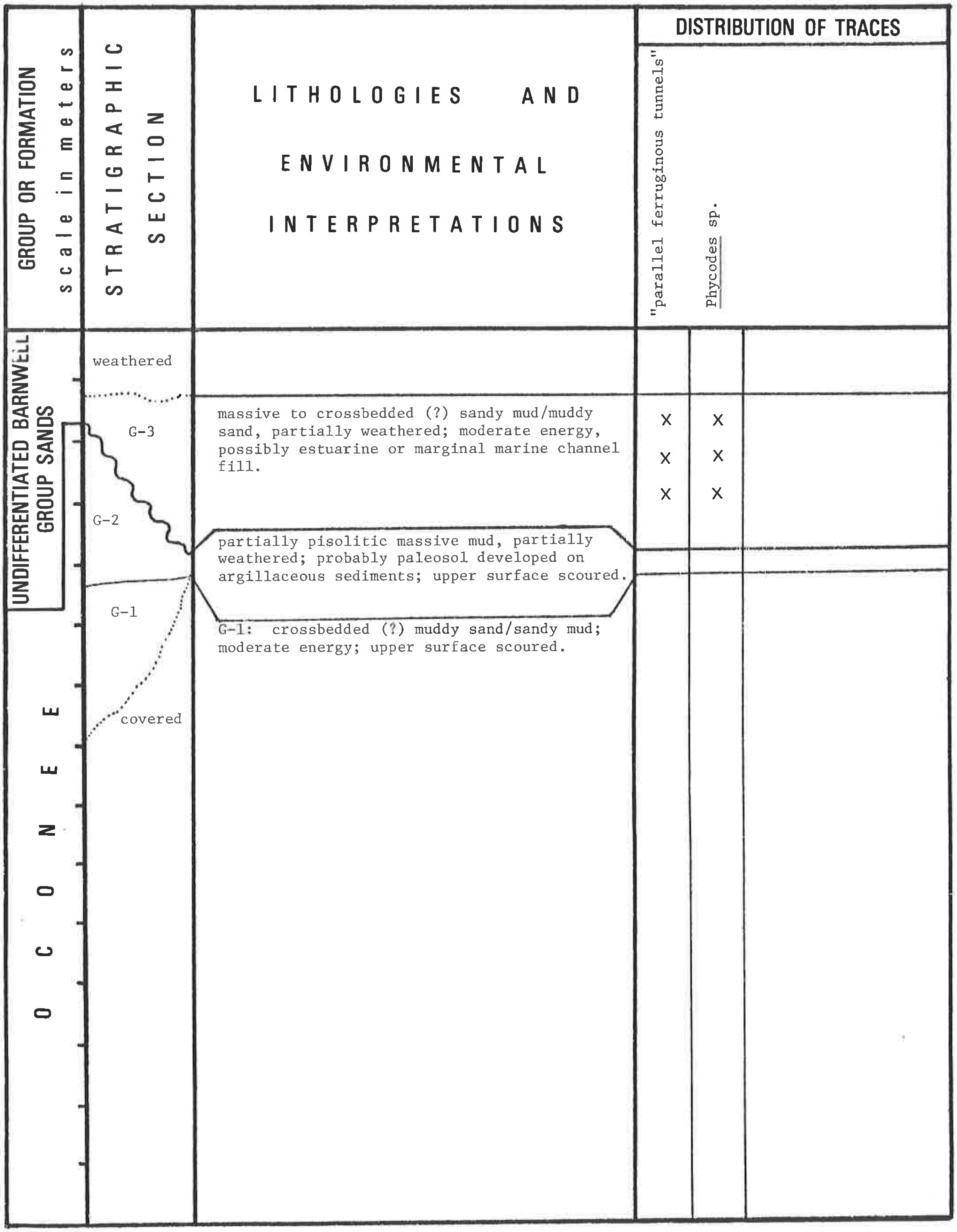


Figure 67. Locality "G": stratigraphy, lithologies, environmental interpretations, and trace fossil distribution.

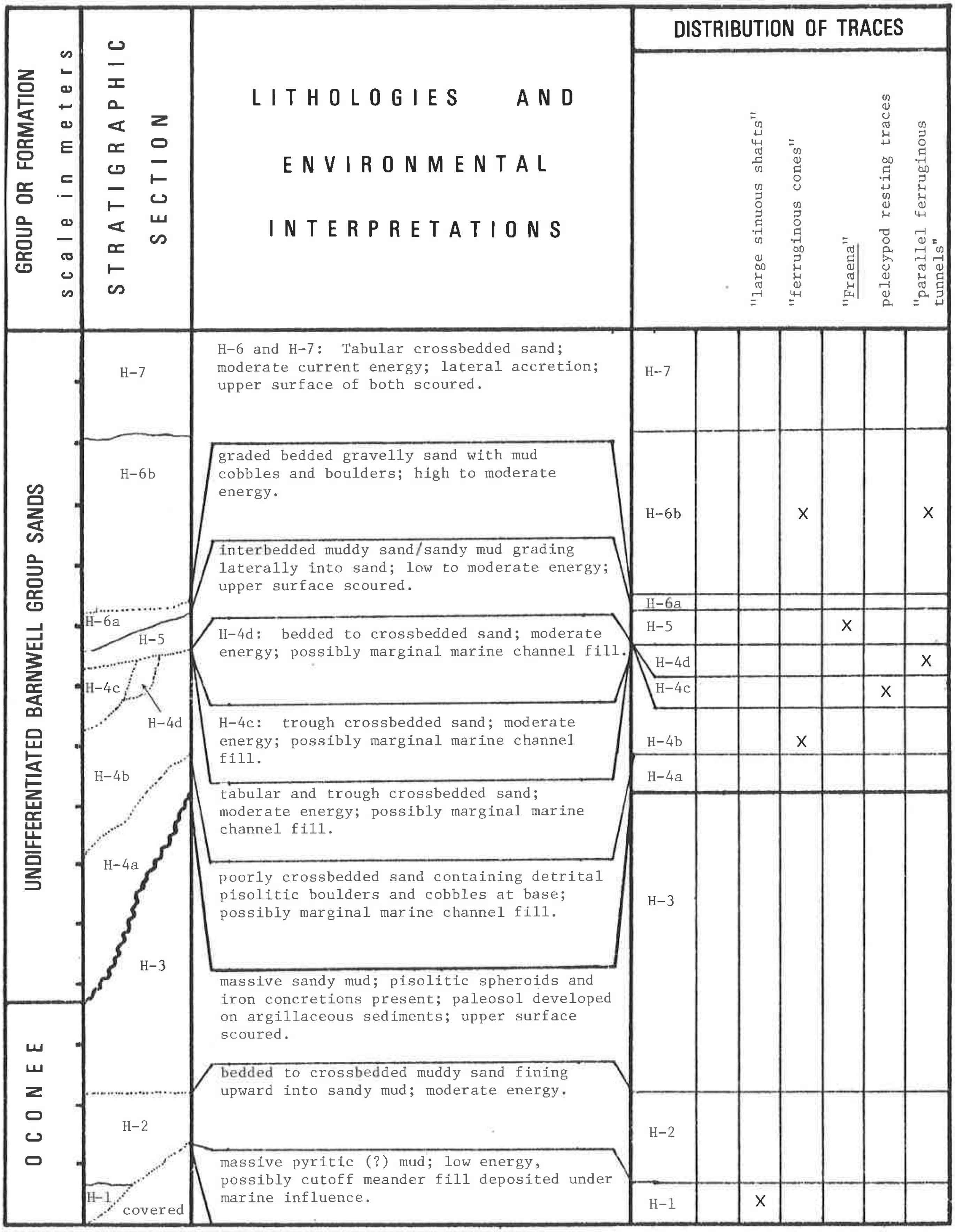


Figure 68. Locality "H": stratigraphy, lithologies, environmental interpretations, and trace fossil distribution

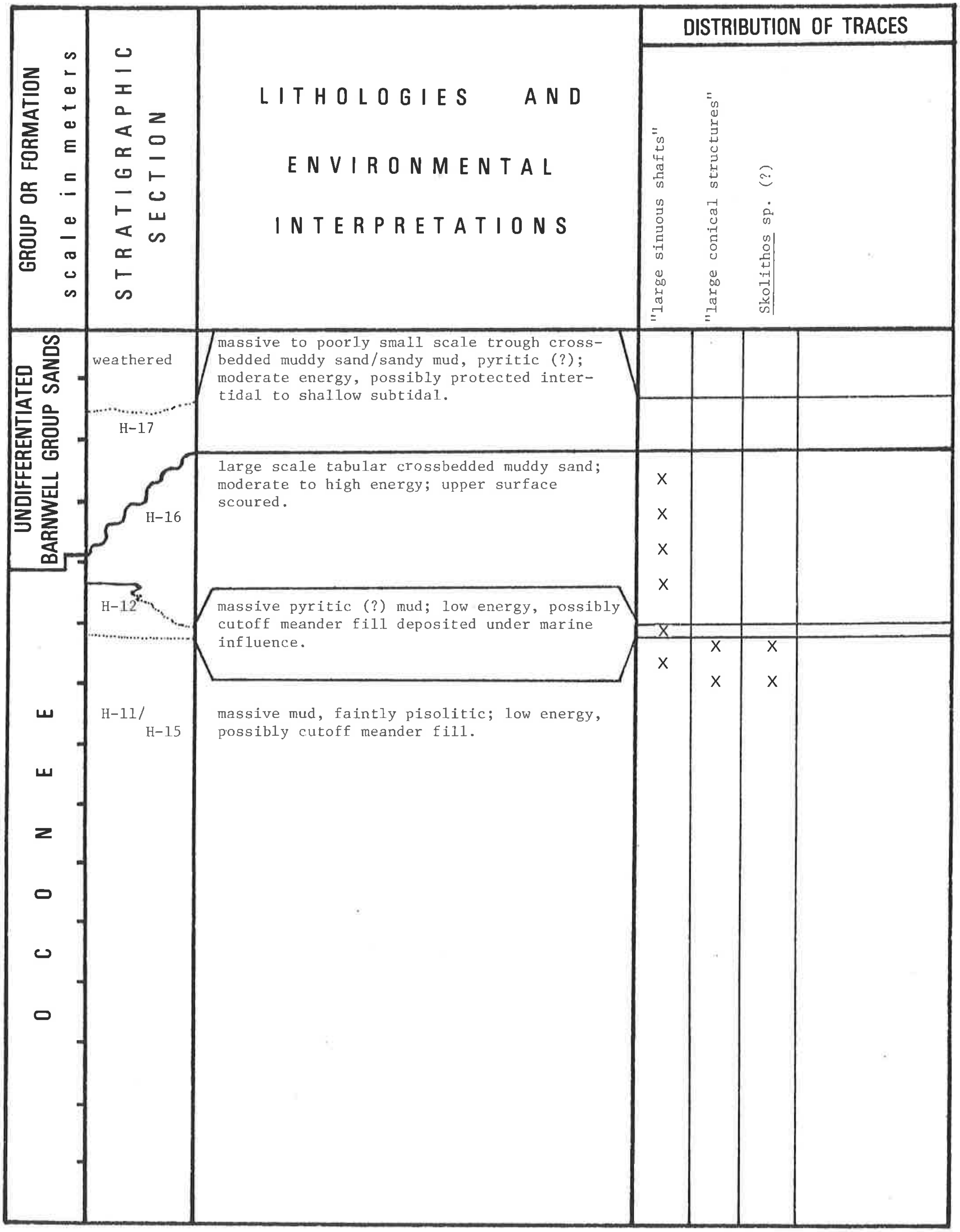


Figure 69. Locality "H": stratigraphy, lithologies, environmental interpretations, and trace fossil distribution. Stratigraphic section after parts of Figs. 73B, C.

CONCLUSIONS

Probably the most significant finding of this study is the discovery of traces of animal life, in some instances abundant, in Oconee Group sediments which are completely devoid of body fossils. These traces provide a view of animal activity and environmental conditions unavailable from any other source. Absence of fossils has often been cited as evidence for a nonmarine or fluvial environment of deposition for these sediments. Furthermore, observation of *Amphorichnus* sp. within bedded sediments near the top of the Oconee in northwestern Washington County strongly suggests deposition of this portion of the Oconee was marine influenced.

Deposition of Oconee sediments seems to have (1) occurred in shallow water environments of highly variable current strength, (2) been interrrupted by numerous erosional events, (3) been accompanied by high turbidity, and (4) been rapid for coarser sediments.

Great lateral and vertical variability and discontinuity of bedding types and grain size among Oconee sediments is suggestive of shallow water deposition by currents of highly variable strength. These conditions are reflected in the two major facies which are recognizable in the Oconee. The dominant facies is composed of highly lenticular, fining-upward sequences of bedded and trough crossbedded gravelly muddy sand to sandy mud which rest on scoured surfaces. These sediments were probably deposited by floods and/or laterally shifting currents, at least some of which were marine influenced. The other recognizable facies constitutes a much smaller volume. This facies consists of elongate, sinuous massive mud (kaolin)lenses, possibly deposited in cut off or flooded meanders in a marginal marine or deltaic setting. A possible third major facies which is recognizable within the Oconee is the massive mud unit which occurs at the top of the group in most places. The characteristics and genesis of this unit are discussed below.

Numerous interruptions in deposition are apparent throughout the Oconee. These interruptions are suggestive of widespread reworking of Oconee sediments.These depositonal interruptions may be grouped into two classes: (1) periods of considerable scour, exemplified by surfaces at the base of fining-upward sequences; (2) periods of minor scour or nondeposition,exemplified by omission surfaces associated with *Amphorichnus* sp. Ubiquitous mud lumps derived from underlying or adjacent strata are also indicative of numerous depositional interruptions as well as widespread reworking.

Poor sorting and appreciable mud content of most Oconee sediments suggest most deposition occurred during periods of high turbidity. High turbidity of bottom waters may also have contributed to the generally low abundance and diversity of trace fossils in Oconee sediments.

Low abundance of traces among sandy and gravelly sediments of the Oconee has contributed to the excellent preservation of primary physical sedimentary structures exhibited by these coarser materials. Low trace abundance and excellent preservation of bedding are suggestive of rapid deposition and burial. The massive structure of the more muddy Oconee sediments, combined with evidence of pervasive bioturbation of some mud bodies, suggests rates of deposition of these finer sediments were considerably slower than for coarser deposits.

At most localities, the uppermost few meters of the Oconee are occupied by a laterally extensive massive mud unit of variable thickness. Much of this unit may have accumulated as argillaceous sediments immediately prior to the emergence which produced the disconformity at the top of the Oconee. Regardless of the depositional environments of materials included in this massive mud unit, several of its features suggest the unit was a subareally exposed, hardened mud paleosol prior to innundation and burial: (1) This unit is the only one within the Oconee which is laterally continuous over a wide area. The few instances where this unit is absent are probably due to its removal by erosion. (2) Materials consist of massive slightly sandy mud to sandy mud which grades downward into a wide variety of bedding types and grain sizes, suggesting homogenization of sediments by soil-forming processes. (3) Pisolitic spheroids, similar to bauxite spheroids which form in some tropical weathering profiles, occur within this interval at some localities. Pisolitic cobbles and boulders litter the Group's upper surface at several localities. These large clasts probably are lag deposits derived by erosion of the Oconee's weathered upper surface. Also, a zone of vertically fluted mud similar in appearance to the structure of some tropical weathering profiles occurs in the upper 1 to 2 m of the Oconee at Locality "C". (4) Quartz grains which show evidence of solution occur throughout the Oconee, indicating these sediments were subjected to an episode of acid leaching *in situ*. Acid leaching is the rule where materials are weathered in a warm, humid climate. (5) The widespread occurrence in this unit of fecal backfilled burrows. (*Planolites* possibly produced by oligochaetes, is compatible with, if not suggestive of, a paleosol origin.) (6) Unlined, large diameter *Thalassinoides*, similar to various species of this ichnogenus from Locality "A", have been observed elsewhere in limestone "hardgrounds". Also, the occurrence of *Trypanites* sp. borings at the upper surface of the Group at Localities "A" and "C" is indicative of a highly coherent or firm substrate. (7) A high degree of sediment coherence is also indicated by the blocky, often highly irregular, eroded upper surface of the Group and by channels, some with steep sides, cut into this surface. (8) Finally, vertical joint surfaces which extend down 2 to 3 m from the upper surface of the Oconee at Locality "D" predate *Thalassinoides* sp. B1 burrows which are associated with these surfaces. This relationship places consolidation and jointing of this interval prior to the Barnwellian transgression which was accompanied by excavation of *Thalassinoides* sp. B1.

Barnwell Group sediments rest disconformably on the Oconee Group. Deposition of these sediments was related to the Barnwellian (Late Eocene) marine transgression. Although all basal Barnwell Group sediments examined were probably deposited under marine or marine influenced conditions, sediments of northwestern Washington County differ markedly from those of western Wilkinson County.

During the initial stages of the Barnwellian transgression, environmental conditions across northwestern Washington County were both varied and changing. Evidence of changing environmental conditions is contained in the omission suite ichnocoenose excavated into the hardened, eroded upper surface of the Oconee Group. Of particular interest are species of *Thalassinoides* which occur in close proximity and exhibit dominantly vertical and dominantly horizontal orientations. These two classes of *Thalassinoides* are generally indicative of higher and lower current energy respectively, suggesting surfaces from which these burrows were excavated were subjected to at least two separate levels of current energy over time. Excavation and habitation of *Trypanites* sp. and various *Thalassinoides* were likely accompanied by erosion and/or nondepositon under intertidal to shallow subtidal, brackish to marine, moderate to high current energy conditions. Truncation of some of these burrows and borings indicates that erosion of the Oconee's upper surface continued in some places after the transgression had at least partially covered the area. Burial of this surface signaled the transition from a nondepositional and/or erosional environment to a depositional one, presumably with lower current energy, slightly deeper water, and possibly more truly marine salinity.

The first Barnwell Group sediments to be deposited in northwestern Washington County were probably laid down in channels and shallow depressions in the eroded upper surface of the Oconee; for example, Basal Barnwell Group channel fillings, attributable to the Clinchfield Formation, occur at Locality "A". The lower one-third of these fillings consists of massive coarse sand, containing *Ophiomorpha* sp., which imply conditions of brackish to marine salinity. The high density and dominantly horizontal orientation exhibited by these burrows suggest construction under reduced current energy. Ubiquitous retrusive spreiten probably resulted from the tracemaker's response to slow aggradation of the substrate surface. Lower portions of these channel fillings are frequently separated from upper portions by scour surfaces, upon which rest cobble and gravel-sized mud clasts derived from the Oconee. The upper portions of channel fillings consist of muddy sand, whose massive structure may be due to complete reworking by burrowers, suggesting a slower rate of accumulation for these materials than for those in lower portions. Thus, accumulation of basal Barnwell Group channel fillings seems to have taken place under conditions of rising sea level, resulting in (1) reduced and diminishing current energy, (2) brackish to marine salinity, (3) slow and possibly diminishing rates of sediment accumulation, rarely interrupted by scour.

Basal Barnwell Group depression fillings are less positively identifiable. A probable example of such deposits occurs at Locality "D". These sediments (unit D-3), also attributable to the Clinchfield, are reduced and consist of intercalated bedded mud and small-scale trough crossbedded sandy gravelly mud, overlain by massive to lenticularly bedded abundantly fossiliferous sandy mud, which contains undifferentiated *Thalassinoides* species and an "L-shaped burrow". The presence of the "L-shaped burrow" sugggests that deposition of these materials occurred in a protected intertidal setting with brackish to marine salinity. Also, fossil and sand contents increase upward in these sediments, suggesting a trend toward higher energy and open circulation with more marine salinity over time. In addition to their occurrence as channel fillings, massive sands, muddy sands, and sandy muds occur as laterally extensive beds, in some places greater than 4 m thick, at the base of the Barnwell. Such deposits constitute the dominant basal Barnwell lithology at the westernmost localities studied in Washington County. These beds are typically underlain by an Oconee erosion surface which is penetrated by various species of *Thalassinoides*, suggesting deposition was accompanied by shallow subtidal, moderate current energy conditions. The massive structure of these sediments was observed to grade into clearly bioturbate texture in some instances, suggesting all such massive sandy basal Barnwell deposits have been thoroughly reworked by burrowers. This, in turn, suggests slow rates of deposition for these sediments.

Eastward, the laterally extensive massive sandy basal Barnwell is clearly assignable to the Clinchfield Formation. This unit becomes fossiliferous and more muddy and decreases in thickness to as little as a few centimeters. In some instances where the Clinchfield was virtually absent above the disconformity, its sediments were well represented below the disconformity as the fill of *Thalassinoides*. In addition to overlying the burrowed and bored upper surface of the Oconee, these deposits overlie basal Barnwell channel fillings previously discussed. They are overlain, in turn, by the Twiggs Clay Member of the Dry Branch Formation, a sparsely fossiliferous, reduced, lagoonal mud, which seems to occupy a position of time-stratigraphic equivalence to much of the thicker sandy basal Barnwell to the west. The thinness and lateral extensiveness of these fossiliferous deposits combined with their stratigraphic position subjacent to the Twiggs Clay suggest they represent a lagoon margin facies, laid down as deepening marine waters swept across the area.

In western Wilkinson County, the only clear view of the eroded upper surface of the Oconee and suprajacent basal Barnwell Group sediments was provided by outcrops at Locality "H". Here, the upper surface of the Oconee varies from slightly irregular to highly irregular, showing as much as 4 m of relief locally. Two observations suggest this surface seems to have undergone more erosion than its northwestern Washington County equivalent: (1) the upper surface of the Oconee shows greater irregularity in western Wilkinson County than in northwestern Washington County: (2) the massive mud paleosol which is laterally continuous at the top of the Oconee across most of northwestern Washington County is preserved only at high elevations on the erosion surface at Locality "H". This latter observation also suggests that erosion of the Oconee's upper surface in western Wilkinson County postdates paleosol development.

A slightly irregular portion of the Oconee's upper surface at Locality "H" is penetrated by numerous "large sinuous shafts", dwelling burrows which probably are the work of supratidal crabs. These burrows probably were constructed in a marginal marine, supratidal environment related to the approaching Late Eocene transgression. The excellent preservation of these burrows suggests their construction was closely followed by deposition of suprajacent materials, an event which probably was accompanied by at least partial transgression.

Most basal Barnwell sediments at Locality "H" consist of trough to mostly tabular crossbedded sand to muddy sand deposited as laterally extensive beds and as channel fillings. Deposition of these sediments probably took place under shallow water moderate to high energy conditions in a deltaic or intertidal to shallow subtidal marine environment. Preservation of bedding structures in most basal Barnwell Group sediments at Locality "H" suggests these materials were deposited more rapidly than the massive sandy sediments which typify the basal Barnwell in northwestern Washington County.

REFERENCES

Ager, D.V. and Wallace, P., 1970, The distribution and significance of trace fossils in the uppermost Jurassic rocks of the Boulonnais, northern France: *in* Crimes, T.P., and Harper, J.C.,eds., Trace fossils, Geol. Jour. Spec. Iss., v. 3, p. 1-18.

Allen, E.A. and Curran, H.A., 1974, Biogenic sedimentary structures produced by crabs in lagoon margin and salt marsh environments near Beaufort, North Carolina: Jour. Sed. Petrology, v. 44, p. 538-548.

Alpert, S.P., 1975, Planolites and Skolithos from the Upper Precambrian-Lower Cambrian, White-Inyo Mountains, California. Jour Paleontology, v. 49, p. 508-521.

Anderson, A.E., Jonas, E.C., and Odom, H.T., 1958, Alteration of clay minerals by digestive processes of marine organisms: Science, v. 127, p. 190-191.

Austin, R.S., 1972, The origin of the kaolin and bauxite deposits of Twiggs, Wilkinson, and Washington counties, Georgia. Unpub. Ph.D. dissertation, Univ. Georgia, Athens., 195 p.

________, 1976, The origin of Georgia's kaolin deposits, *in* Twelfth forum on the geology of industrial minerals, Georgia Geol. Survey Info. Cir. 49, p. 10-15.

Basan, P.B. and Frey, R.W., 1977, Actual palaeontology and neoichnology of salt marshes near Sapelo Island, Georgia: *in* Crimes, T.P. and Harper, J.P., eds., Trace fossils 2. Geol. Jour., Spec. Iss., v. 9, p. 41-70.

Berner, R.A., 1969, Migration of iron and sulfur within anaerobic sediments during early diagenesis : American Jour. Sci. v. 267, p. 19-42.

Braithwaite, C.J.R. and Talbot, M.R., 1972, Crustacean burrows in the Seychelles, Indian Ocean. Paleogeography, Paleoclimatology, Paleoecology, v. 11, p. 265-285.

Bromley, R.G., 1967, Some observations on burrows of thalassinidean Crustacea in chalk hardgrounds: Geol. Soc. London, Quart. Jour, v. 123, p. 157-182.

________, 1970, Borings as trace fossils and *Entobia Cretacea* Portlock, as an example: *in* Crimes,T.P., and Harper, J.C., eds., Trace fossils: Geol. Jour., Spec. Iss., v. 3, p. 49-90.

________, 1972, On some ichnotaxa in hardsubstrates, with a redefinition of Trypanites Magdefrau. Palaont. Zeitschr., v. 46, p. 93-98.

________, 1975, Trace fossils at omission surfaces: *in* Frey, R.W., ed., The study of trace fossils: New York, Springer-Verlag, p. 399-428.

Bromley, R.G. and Frey, R.W., 1974, Redescription of the trace fossil Gyrolithes and taxonomic evaluation *Thalassinoides, Ophiomorpha* and *Spongeliomorpha*. Geol. Soc. Denmark, Bull. 23, p. 311-335.

Buie, B.F., 1978, The Huber Formation of eastern central Georgia *in* Short contributions to the geology of Georgia, Georgia Geol. Survey, Bull. 93, p. 1-7.

Byers, C.W. and Stasko L.E., 1978, Trace fossils and sedimentologic interpretation - McGregor Member of Platteville Formation (Ordovician) of Wisconsin: Jour. Sed. Petrology, v. 48, p. 1303-1310.

Carver, R.E., 1972, Stratigraphy of the Jackson Group in eastern Georgia: Southeastern Geol., v. 14, p. 153-181.

Chamberlain, C.K., 1971, Morphology and ethology of trace fossils from the Ouachita Mountains, southeast Oklahoma: Jour. Paleonotology, v. 45, p. 212-246, pl. 29-32.

________, 1975, Recent lobensspuren in nonmarine aquatic environments: *in* Frey, R.W., ed., The study of trace fossils: New York, Springer-Verlag, p. 431-458.

Cook, C.W., 1926, Correlation of basal Cretaceous beds of the Southeastern States: U.S. Geol. Survey Prof. Paper 140.

Curran, H.A. and Frey, R.W., 1977, Pleistocene trace fossils from North Carolina (U.S.A.), and their Holocene analogues: *in* Geol. Jour., Spec. Iss., v. 9, p. 139-162.

Dales, P.R., 1967, Annelids: London, Hutchinson Univ. Lib., 200 p.

Ekdale, A.A., 1977, Abyssal trace fossils in worldwide Deep Sea Drilling Project cores: *in* Crimes, T.P. and Harper, J.C., eds., Trace Fossils 2: Geol. Jour., Spec. Iss., v. 9, p. 163-182.

Farrow, G.E., 1966, Bathymetric zonation of Jurassic trace fossils from the coast of Yorkshire, England: Paleogeography, Paleoclimatology, Paleoecology, v. 2, p. 103-151.

________, 1971, Back-reef and lagoonal environments of Aldabra Atoll distinguished by their crustacean burrows: Zoo. Soc. London, Symp., v. 28, p. 455-500.

Forbes, A.T., 1973, An unusual abbreviated larval life in the estuarine burrowing prawn *Callianassa* kraussi (crustacea: decapoda: thalassinidea): Marine Bio., v. 22, p. 361-365.

Frey, R.W., 1970 a, Trace fossils of the Fort Hays Limestone member of Niobrara Chalk (Upper Cretaceous), west-central Kansas: Paleontology Contr., Univ. Kansas, no. 53.

________, 1970 b, The lebensspuren of some common marine invertebrates near Beaufort, North Carolina. II. Anemone burrows: Jour. Paleontology, v. 44, p. 308-311.

________, 1970 c, Environmental significance of recent marine lebensspuren near Beaufort, North Carolina: Jour. Paleontology, v. 44, p. 507-519.

________, 1971, Ichnology - the study of fossil and recent lebensspuren: *in* Perkins, B.F., ed.,Trace fossils: a field guide to selected localities in Pennsylvanian, Permian, Cretaceous, and Tertiary rocks of Texas and related papers: Sch. Geosci., La. State Univ. Misc. Pub. 71-1, p. 91-125.

________, 1973, Concepts in the study of biogenic sedimentary structures: Jour. Sed. Petrology, v. 43, p. 6-19.

Frey, R.W. and Chowns, T.M., 1972, Trace fossils from the Ringgold Road Cut (Ordovician and Silurian), Georgia: *in* Chowns, T.M., ed., Sedimentary environments in the Paleozoic rocks of northwest Georgia: Georgia Geol. Survey Guidebook 11, p. 25-55.

Frey, R.W. and Howard, J.D., 1969, A profile of biogenic sedimentary structures in a Holocene barrier island-salt marsh complex, Georgia. Gulf Coast Assoc. Geol. Socs., Trans., v. 19, p. 427-444.

Frey, R.W. and Howard, J.D., 1970, Comparison of Upper Cretaceous ichnofaunas from siliceous sandstones and chalk, Western Interior Region, U.S.A.: *in* Crimes, T.P. and Harper, J.C., eds., Trace fossils: Geol. Jour. Spec. Iss., v. 3, p. 141-166.

Frey, R.W. and Howard, J.D., 1972, Georgia coastal region, Sapelo Island, U.S.A.: Sedimentology and biology. VI. Radiographic study of sedimentary structures made by beach and offshore animals in aquaria: Senckenburgiana Maritima, v. 4, p. 69-182.

Frey, R.W. and Howard, J.D., 1975, Endobenthic adaptations of juvenile thalassinidean shrimp: Geol. Soc. Denmark, Bull. 24, p. 283-297.

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

Frey, R.W. and Mayou, T.V., 1971, Decapod burrows in Holocene barrier island beaches and washover fans, Georgia: Senckenbergiana Maritiana, v. 3, p. 53-77.

Fursich, F.T., 1973, *Thalassinoides* and the origin of nodular limestone in the Corallian Beds (Upper Jurassic) of Southern England: Neues Jahrb. Geol. Palaont, Mh., 1973, p. 136-156.

Fursich, F.T. and Palmer, T.J., 1975, Open crustacean burrows associated with hardgrounds in the Jurassic of the Cotswolds, England: Proc. Geol. Assoc., v. 86, p. 171-181.

Hakes, W.G., 1976, Trace fossils and depositional environment of four clastic units, Upper Pennsylvanian megacylocothems, northeast Kansas. Paleont. Contr. Univ. Kansas, no. 63.

Hanor, J.S. and Marshall, N.F., 1971, Mixing of sediment by organisms: *in* Perkins, B.F., ed., Trace fossils: a field guide to selected localities in Pennsylvanian, Permian, Cretaceous, and Tertiary rocks of Texas and related papers: Sch. Geosci., La. State Univ. Misc. Pub. v. 71-1, p. 127-135.

Hantzschel, W., 1975, Trace fossils and problematica: *in* Teichert, C., ed., Treatise on invertebrate paleontology, Part W, Supplement 1: Geol. Soc. America and Univ. Kansas, p. 269.

Hester, N.C. and Pryor, W.A., 1972, Blade-shaped crustacean burrows of Eocene age: a composite form of *Ophiomorphia*: Geol. Soc. America, Bull. 83, p. 677-688.

Hill, G.W. and Hunter, R.E., 1973, Burrows of the ghost crab *Ocypode quadrata* Fabricus on the barrier islands, south central Texas coast. Jour. Sed. Petrology, v. 43, p. 24-30.

Hinckley, D.N., 1965, Mineralogical and chemical variations in the kaolin deposits of the Coastal Plain of Georgia and South Carolina. Amer. Min., v. 50, p. 1865-1883.

Howard, J.D. and Frey, R.W., 1975, Estuaries of the Georgia coast, U.S.A.: Sedimentology and biology. II. Regional animal-sediment characteristics of Georgia estuaries: Senckenbergiana Maritima, v. 7, p. 33-103.

Huddlestun, P.F. and Hetrick, J.H., 1979, Stratigraphy of the Barnwell Group of Georgia, Georgia Geol. Survey, Open-File Rept. 80-1.

Huddlestun, P.F., and Hetrick, J.H., 1981, Upper Eocene stratigraphy of central and eastern Georgia, Georgia Geol. Survey, Info. Circ. 55, in press.

Hurst, V.J., and others, 1979, Field conference: kaolin, bauxite, fuller's earth , Ann . Mtg., Clay Min. Soc., 107 p.

Kaestner, A., 1967, Invertebrate zoology: New York, Interscience Publishers 597 p.

Kennedy, W.J., 1967, Burrows and surface traces from the Lower Chalk of southern England: British Mus. Nat. Hist. (Geol.) Bull 15, p. 127-167.

Kesler, T.L., 1963, Environment and origin of the Cretaceous kaolin deposits of Georgia and South Carolina: Ga. Min. Newsletter, Georgia Geol. Survey, v. 16, p. 3-11.

La Moreaux, P.A., 1946, Geology and ground-water resources of the Coastal Plain of East-Central Georgia: Georgia Geol. Survey; Bull. 52, 173 p.

Lowe, D.R. and LoPiccolo, R.D., 1974, The characteristics and origins of dish and pillar structures: Jour Sed. Petrology, v. 44, p. 484-501.

McGintie, G.E. and McGintie, N., 1968, Natural history of marine animals: New York, McGraw-Hill, 523 p.

Martinsson, A., 1965, Aspects of a Middle Cambrian thanatotope on Oland. Geol. Foren. I. Stockholm Forhand., v. 87, p. 171-230.

———, 1970, Toponomy of trace fossils: *in* Crimes, T.P., and Harper, J.C., eds., Trace fossils: Geol. Jour. Spec. Iss., v. 3, p. 323-330.

Morris, R.W. and Rollins, H.B., 1977, Observations on intertidal organism associations of St. Catherines Island, Georgia I. General description and paleoecological implications: American Mus. Nat. Hist., Bull. 159, p. 89-128.

Nicholson, H.A., 1873, Contributions to the study of the errant Annelides of the older paleozoic rocks: Geology, v. 10, p. 309, 310.

Osgood, R.G., 1970, Trace fossils of the Cincinnati area: Paleontographica Americana, v. 6 (41), p. 281-444.

Ott, J.A., Fuchs, B., Fuchs, R., and Malasek, A., 1976, Observations on the biology of *Callianassa stebbingi* Borrodaille and *Upogebia litoralis* Risso and their effect upon the sediment: Senckenberg. Marit., v. 8, p. 61-79.

Pemberton, G.S., Risk, M.J., and Buckley, D.E., 1976, Supershrimp: deep bioturbation in the Strait of Canso, Nova Scotia: Science v. 192, p. 790-791.

Pickering, S.M., and others, 1976, Geologic map of Georgia. Georgia Geol. Survey, scale 1:500,000.

Radwanski, A., 1970, Dependence of rock-borers and burrowers on the environmental conditions within the Tertonian littoral zone of southern Poland: *in* Crimes, T.P. and Harper, J.C., eds., Geol. Jour., Spec. Iss., v. 3, p. 371-390.

Rhoades, D.C., 1967, Biogenic reworking of intertidal and subtidal sediments in Barnstable Harbor and Buzzards Bay, Massachusetts: Jour. Geol., v. 75, p. 461-476.

Rickard, D.T., 1974, Kinetics and mechanism of the sulfidation of goethite. Amer. Jour. Sci., v. 274, p. 941-952.

Satchall, J.E., 1967, Lumbicidae: *in* Burges, A., and Raw, F., eds., Soil biology: New York, Academic Press, p. 259-322.

Schafer, W., 1972, Ecology and paleoecology of marine environments: Univ. of Chicago Press., 568 p.

Schaller, F., 1968, Soil animals: Ann Arbor, Univ. of Mich. Press, 144 p.

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

———, 1967, Bathymetry of trace fossils: Marine Geol., v. 5, p. 389-412.

Sellwood, B.W., 1970, The relation of trace fossils to small sedimentary cycles in the British Lais: *in* Crimes, T.P., and Harper, J.C., eds., Trace fossils: Geol. Jour., Spec. Iss., v. 3, p. 489-504.

———, 1971, A *Thalassinoides* burrow containing the crustacean *Glyphia udressieri* (Meyer) from the Bathonian of Oxfordshire: Paleontology, v. 14, p. 589-591.

Simpson, S., 1975, Classification of trace fossils: *in* Frey, R.W., ed., The study of trace fossils: New York, Springer-Verlag, p. 39-54.

Shinn, E.A., 1968, Burrowing in recent lime sediments of Florida and the Bahamas: Jour Paleontology, v. 42, p. 879-894.

Smith, K.L., 1967, Callianassid crustacean burrows as possible paleoenvironmental indicators: Unpub. M.A. thesis, Univ. Delaware, 63 p.

Smith, R.T., 1929, Sedimentary kaolins of the Coastal Plain of Georgia: Georgia Geol. Survey Bull. 44, 482 p.

Stephenson, T.A., 1928, The British sea anemones, 1: Ray Soc., London, 148 p.

———, 1935, The British sea anemones, 2: Ray Soc., London, 426 p.

Taylor, J.D., 1971, Reef associated molluscan assemblages in the western Indian Ocean: Zool. Soc. London, Symp. v. 28, p. 501-534.

Wallwork, J.A., 1976, The distribution and diversity of soil fauna: New York, Academic Press, 355 p.

Warme, J.E., 1975, Borings as trace fossils, and the processes of marine bioerosion: *in* Frey, R.W., ed., The study of trace fossils: New York, Springer-Verlag, p. 818-228.

———, 1970, Traces and significance of marine rock borers, *in* Crimes, T.P. and Harper, J.C., eds., Trace fossils: Geol. Jour. Spec. Iss., v. 3, p. 515-526.

Weimer, R.J. and Hoyt, J.H., 1964, Burrows of *Callianassa major* Say geologic indicators of littoral and shallow neritic environments: Jour Paleontology, v. 38, p. 761-767.

APPENDIX A

Stratigraphic Descriptions

Terms

Some terms used in the following stratigraphic descriptions are defined below.

unit - a bed or, more commonly, a set of related beds which may be differentiated from enclosing strata by differences in bedding type, grain size, color, and/or prominent scour surfaces. Beds within a unit may be related by apparent continuity of deposition, in addition to similarity of bedding type, grain size, and/or color. Nearly all units are lenticular.

mud intraclast - large coherent fragments composed of mud which is similar in appearance to nearby sediments of the formation in which the fragments occur.

apparent foreset width - the length of inclined bedding laminae as exposed in outcrop.

Letter/number color designations used in the following stratigraphic descriptions are taken from the Geological Society of America Rock-Color Chart (Goddard and others, 1963). The designation N10, "very white", is used to describe the extreme whiteness of some kaolins. This designation is not found in the Rock-Color Chart.

Descriptions

Locality "A": Cyprus Mines Clay pit, Renfroe property, Washington Co.; N33° 2' 54" W 82° *55' 13"*.

Figures 7, -61-64

4.5m+ A-1 (fig. 72): massive mud, grading upward into slightly sandy mud in upper 1 m of unit; where overlain by sand or gravel, color subjacent to upper contact is 10 YR 8/2 to 10 YR 8/1 with 10 YR 7/1 spots; where overlain by lignitic materials, color subjacent to upper contact is 5 YR 8/1 to N8; iron sulfide occurs as nodules $\leq$ 2 cm in diameter scattered throughout unit and becoming more abundant upward, as irregular, discontinuous crusts $\leq$ 1 cm thick on upper surface of unit, and as sparsely abundant liesegang bands subjacent to upper surface.

$\leq$ .5m A-2: (figs. 72B,C): graded bedded to massive muddy, slightly sandy gravel, composed largely of mud intraclasts $\leq$ 6 cm in diameter (fig. 72B); intraclasts welded and/or deformed in places (fig. 72C); color of intraclasts is 5 Y 1/8 or rarely 5 YR 8/1; color of slightly sandy mud matrix is 10 YR 6/2 to 10 YR 5/4; irregular iron sulfide concretions $\leq$ 5 cm in diameter sparsely scattered throughout unit, showing slight increase in abundance upward; upper contact slightly gradational and irregular.

2.0m A-3: angularly to tangentially tabular crossbeds containing dark mineral laminae along some foresets and ranging in grain size from slightly muddy coarse sand to slightly muddy fine sand and muddy fine sand; unit shows fining upward trend; mud intraclasts $\leq$ 5 cm in diameter are scattered along bottomsets of coarser crossbeds; apparent foreset width, typically 15 to 20 cm in angularly tabular crossbeds and 1 m in tangentially tabular crossbeds; angularly tabular crossbeds are typically 5 to 10 cm thick and tangentially tabular crossbeds are 20 to 30 cm thick; distinct grain size differences occur at 15 to 50 cm intervals; color of sands in basal 1 to 2 cm is N4, due to presence of abundant iron sulfide, grading upward to 5 YR 8/4 to 10 YR 6/6 in lower 30 cm;above 30 cm, sands are 10 YR 8/6 to 10 YR 8/2 or N8; mud intraclasts are N9 to N10; upper contact is gradational.

0.3m A-4 (fig. 73C): angularly tabular crossbedded muddy sand, containing dark mineral laminae along some foresets; apparent foreset width, typically 1 m; single bed constitutes unit; color is 5 YR 8/1 to 5 Y 8/1; upper contact is sharp and slightly irregular.

≤ 2.5m A-5 (fig. 73D): angularly to tangentially trough crossbedded sand, increasing in mud content upward; apparent foreset width, typically 2 m; beds are typically 30 to 60 cm thick; upper contact is gradational.

≤ 2m A-6 (fig. 73B): cycles of interbedded slightly muddy fine sand and muddy fine sand; sand layers contain spheroidal iron sulfide concretions ≤ 0.3mm in diameter; sand beds are typically 2 to 5 cm thick; muddy sand beds are typically ≤ 1.5 cm thick; beds of small scale angularly tabular to trough crossbedded fine sand ≤ 50 cm thick are present; color of fine sand is typically N5 to N4; color of muddy sand is 5 Y 4/1; upper contact is sharp and highly irregular.

0.6 to 0.8m A-7 (fig. 73E): angularly to tangentially trough crossbedded gravelly, slightly muddy sand, fining upward to sandy mud and containing mud intraclasts ≤ 5 cm in diameter; intraclasts commonly occur as lenses of welded grains; apparent foreset width, typically 2 m; beds are typically 30 cm thick; color of sand is N5 to N7 or 5 Y 8/l; color of intraclasts is typically 10 YR 8/2; upper contact is gradational.

≤ 2m A-8 (fig. 72A, C): interbedded lignite and sandy lignite, grading upward into similar material intercalated with lenses of trough crossbedded sand and finally into lignitic mud; beds are 5 to 30 cm thick; sand lenses are ≤ 1m long; color of lignite is N1; color of muddy lignite becomes lighter upward with increasing mud content ranging from N1 through 5 Y 5/1, 5 YR 2/1, and 5 YR 4/1; sand is 5 YR 8/1 to 5 YR 6/1; upper contact is gradational.

≤ 2m A-9 (fig. 73A, B, E): interbedded sandy lignitic mud; abundant mud intraclasts ≤ 5 cm in diameter are present at lower contact; tree limbs are common and bedding and tree limbs show evidence of compactional deformation; tree limbs show upward increase in abundance; beds are typically ≤ 1 cm thick; color of lignite is N1; color of lignitic mud and slightly lignitic mud is 5 YR 6/4 to 10 YR 7/4; upper contact is gradational.

7m A-10 (fig. 7): massive slightly sandy mud; channel fillings 3 to 7.5 m wide and 0.5 to 1.0 m thick occur 30 to 40 m apart, 3 to 5 m below upper contact and are composed of small scale trough crossbedded muddy sand/sandy mud; color of massive mud is 10 YR 8/2 except near upper contact, where color is 5 Y 8/1, mottled 10 YR 8/6 to 10 YR 7/4; upper contact is sharp and irregular.

≤ 0.6m A-11a (fig. 7): massive slightly gravelly coarse sand, extensively burrowed; mud and sandy mud clasts ≤ 20 cm in diameter, some armored with quartz pebbles embedded in a crust of hydrous iron oxide, occur near base of unit; color of sand is 10 YR 4/2 to 10 YR 6/6; grades upward into A-11b.

≤ 1.0m A-11B (fig. 7): massive slightly gravelly, muddy medium sand; mud clasts ≤ 15 cm in diameter litter lower contact; color is 10 YR 6/2; upper contact is gradational.

≤ .5m A-12 (fig. 7): massive to poorly small scale trough crossbedded highly fossiliferous sandy mud, gravelly in places; color is 10 YR 8/2, to 10 Y 8/6; upper contact is slightly gradational and unit may interfinger with lower 30 cm of A-13.

5m+ A-13: basal 30 cm is horizontally bedded sparsely fossiliferous sandy mud grading upward into massive appearing sparsely fossiliferous mud; grades upward into soil zone.

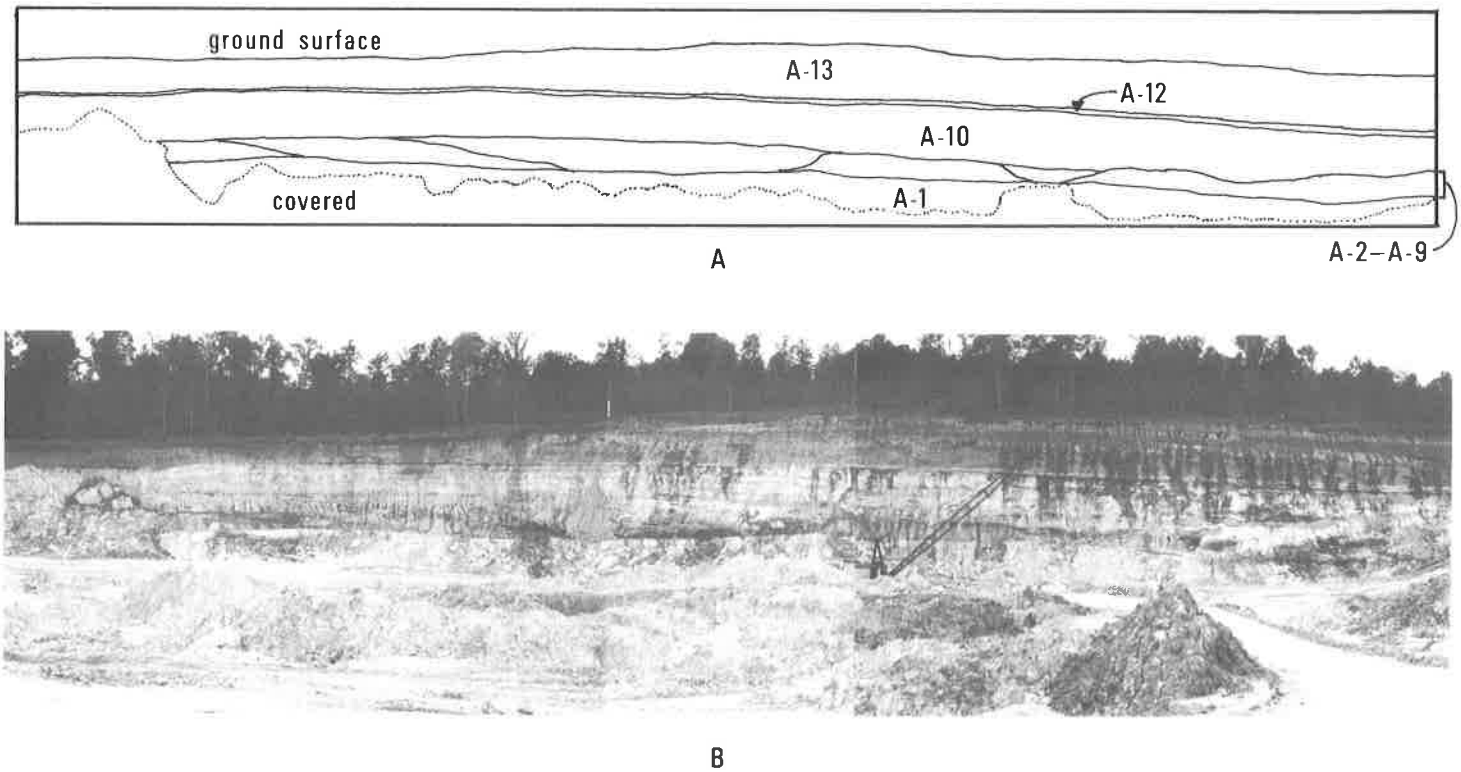


Figure 70. Portion of outcrop at Locality "A". A, after B. Contact between units A-10 and A-12 is disconformity separating Oconee Group below from Barnwell Group above. (see fig. 71).

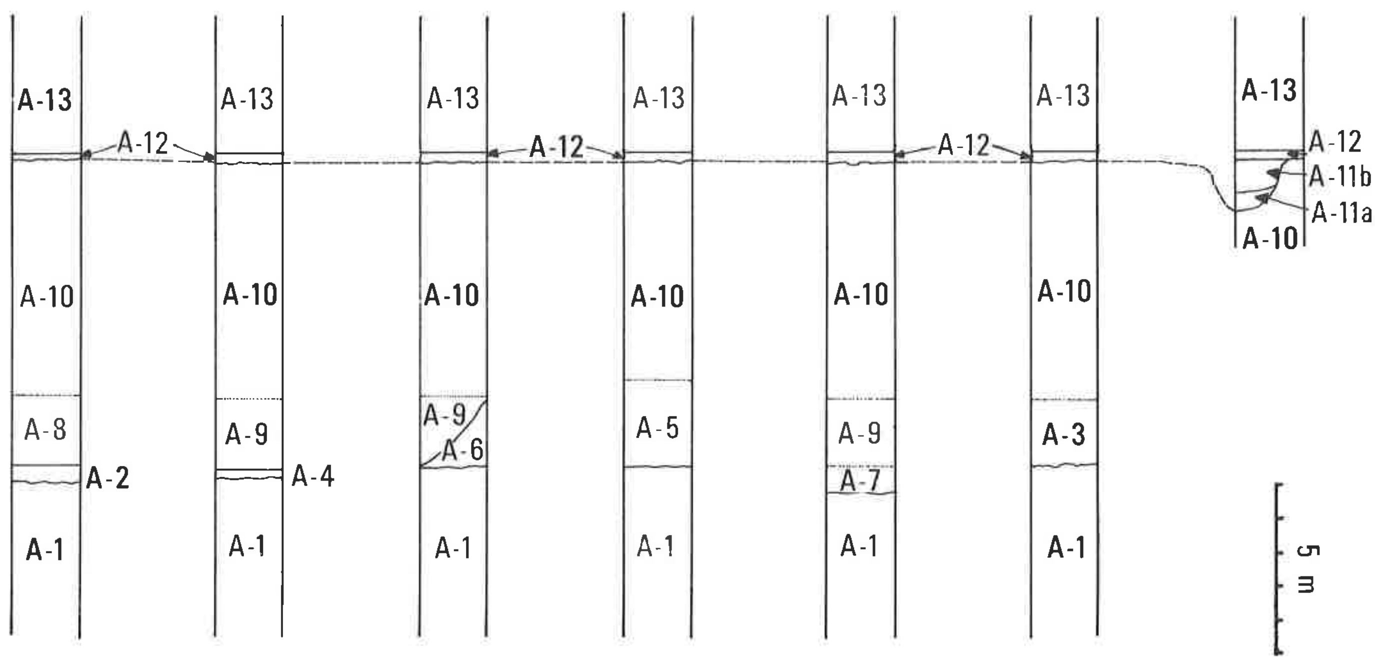


Figure 71. Representative stratigraphic sections from Locality "A". Units A-1 through A-10 are part of the Oconee Group; A-11 and A-12 are part of the Clinchfield Formation. A-13 is of the Twiggs Clay Member. Dashed line represents approximate position of Oconee-Barnwell disconformity between sections. Dotted lines represent gradational contacts.

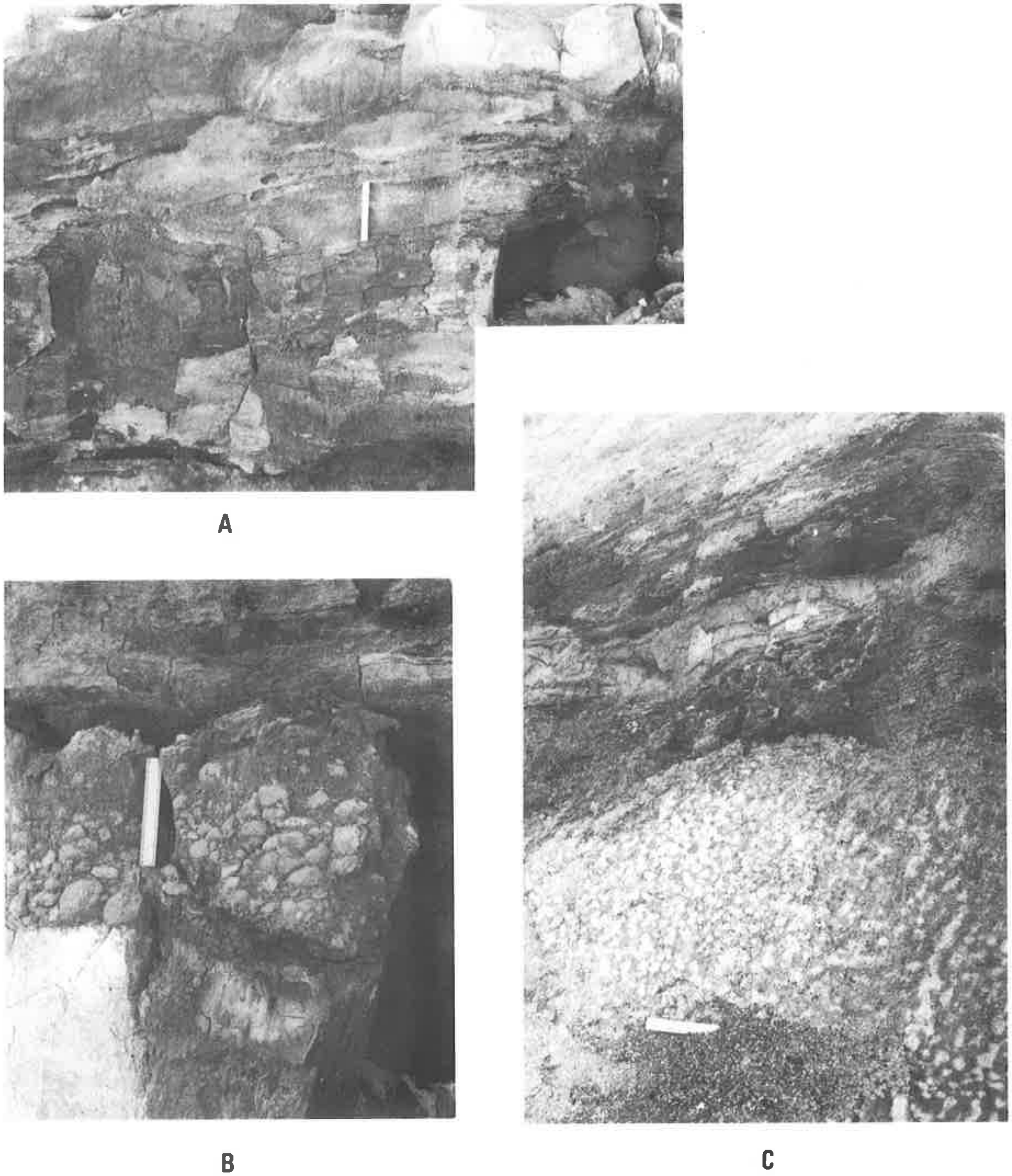


Figure 72. Sediments of Oconee Group at Locality "A". Ruler is 15 cm long. A, unit A-8, lenticular beds of sand and lignitic mud; B, unit A-1 overlain by unit A-2, overlain in turn by unit A-8; C, unit A-2, showing deformed mud clasts at lower left, overlain by unit A-8.

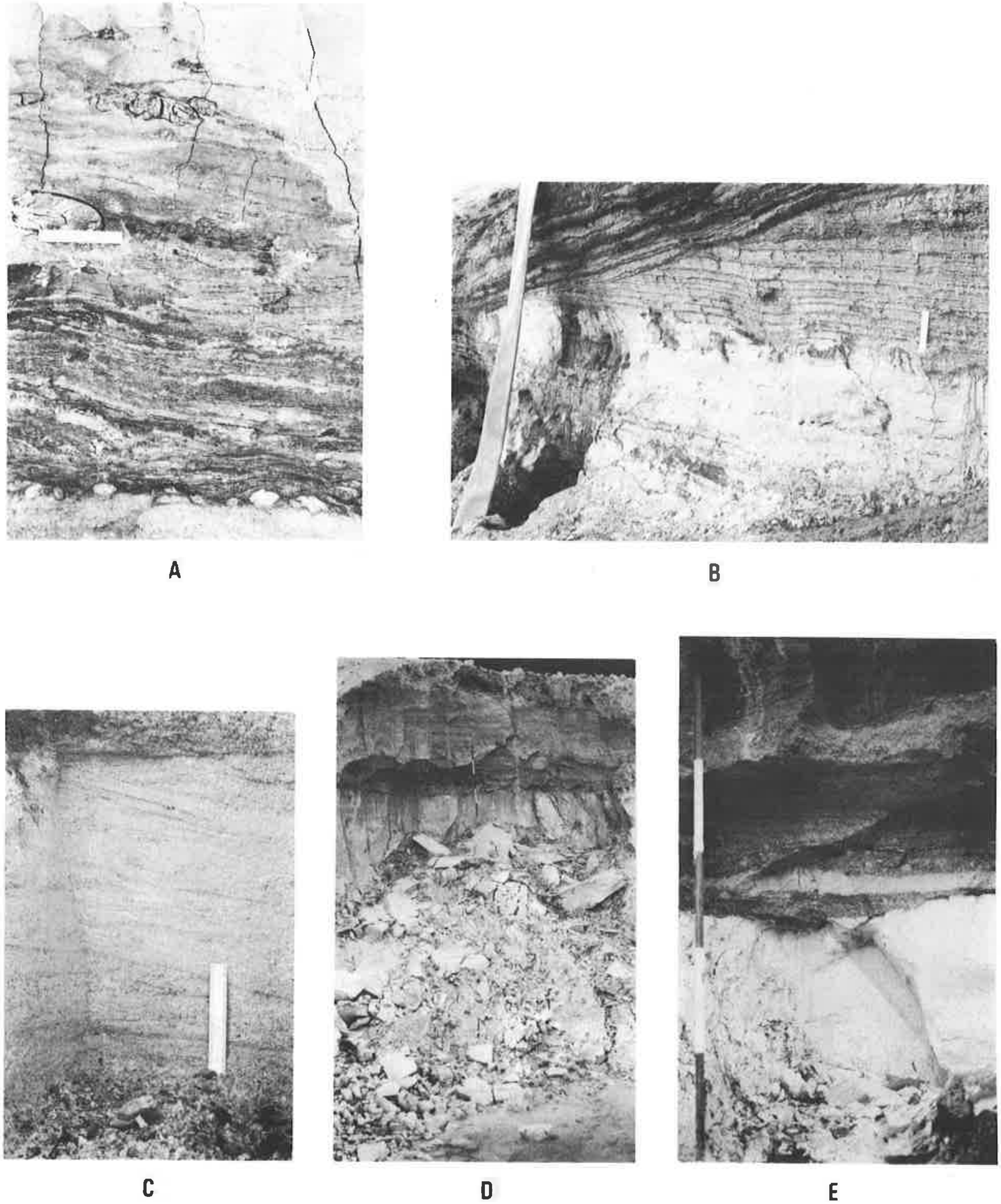


Figure 73. Sediments of Oconee Group at Locality "A". A-C, ruler is 15 cm long. A, unit A-4 at base, overlain by bedded lignitic muds of A-9; B, bedded sands and muds of unit A-6, overlain by A-9 at upper left; C, tabular cross bedded muddy sand of unit A-4; D, E, pole graduated in feet; D, massive mud of unit A-1, overlain by trough crossbedded sand of A-5; E, massive mud of unit A-1, overlain by trough crossbedded gravelly muddy sand of A-7, overlain in turn by A-9.

Locality "B": Anglo-American clay pit, Washington Co.; N33° 1′ 25″ W82° 55′ 5″.

Figures 74-76

2.5m+ B-1 (figs. 75C, D): massive mud, N9, occasionally mottled 10 YR 8/6; lower contact covered, upper contact sharp and slightly irregular, showing compaction faulting, with deformation extending into overlying sands; thin irregular hydrous iron oxide crust present on upper surface of unit.

0.5m B-2a (fig. 75C): large scale, tangentially trough crossbedded gravelly, muddy, coarse sand, containing abundant dark mineral laminae; apparent foreset width, about 1.3 m; beds typically 10 to 20 cm thick; color is N9 to N8, mottled 10 YR 8/6 to 10 YR 6/6 along some laminae; grades upward into B-2b.

0.5m B-2b (fig. 75C): small scale, tangentially to angularly tabular crossbedded gravelly, muddy medium sand, containing mud intraclasts ≤ 3 cm in diameter; apparent foreset width, about 10 to 15 cm; beds typically 5 to 8 cm thick; color is N9, mottled 10 YR 6/6 to 10 YR 4/6 along some laminae; terminated upward by 5 cm thick bed of deformed mud intraclasts ≤ 8 cm in diameter; thin hydrous iron oxide crusts present on upper surfaces on intraclasts; color on intraclasts is 5 YR 1/8 or N9; thin bleached zones common on lower sides of 5 YR 1/8 intraclasts; grades upward into B-2c.

0.4m B-2c (figs. 75A, C): large scale, tangentially trough crossbedded muddy medium sand; apparent foreset width, about 60 cm; beds typically 15 cm thick; color is N9, mottled 10 YR 6/6 along some laminae; unit overlain in places by ≤ 20 cm of tangentially crossbedded to bedded slightly sandy mud, N9 to 10 YR 8/6 along some laminae; upper contact sharp and slightly irregular.

Compaction fault (figs. 75C, D) originating in underlying unit extends into lower 0.6 m of B-2. Thickening of affected beds, especially apparent near base of B-2, suggests fault was growing during deposition of B-2.

0.3m B-3a (fig. 75A): large-scale, tangentially crossbedded muddy medium sand, containing numerous dark mineral laminae and deformed mud intraclasts ≤ 8 cm in diameter; apparent foreset width, about 1.2 m; beds typically 8 to 15 cm thick; color is 5 Y 8/1 to 5 Y 8/4, mottled 5 Y 4/1 or rarely 10 YR 6/6 along some laminae; grades upward into B-3b.

1.2m B-3b: bedded to tangentially crossbedded slightly muddy and gravelly medium sand; mud intraclasts ≤ 8 cm in diameter concentrated along some bedding surfaces; intraclast diameter generally decreases upward; color of sands is 5 Y 8/4, mottled 10 YR 6/6; color of intraclasts typically 10 YR 8/2, with lower surface rims of 10 YR 6/6 near top of B-3b; grades upward into B-3c.

1.0m B-3c: bedded to tangentially crossbedded muddy, slightly gravelly coarse sand, N9 to N8, with 10 YR 8/2 mud intraclasts ≤ 2 cm in diameter, concentrated along some bedding surfaces; near upper contact, colors are 10 YR 8/2 to 10 YR 6/6, with 10 YR 8/2 mud intraclasts ≤ 30 cm in diameter present; upper contact gradational.

1.4m B-4: bedded to massive micaceous sandy mud, grading upward into slightly sandy mud; color is 5 YR 8/1 to 10 YR 8/2, rarely mottled 10 YR 6/6; upper contact sharp and irregular.

≲ 0.5m B-5: lens of tangentially crossbedded to bedded muddy medium sand, 10 YR 8/2; apparent foreset width, 1.2m; beds typically 15 to 20 cm thick; upper contact gradational.

≤ 1.4 m B-6 (fig. 75B): massive mud, composed of welded mud intraclasts, typically 5 to 8 cm in diameter; color is N9 to 10 YR 8/2; intraclasts vaguely separated by 10 YR 6/6 sandy mud matrix; flattened mud intraclasts ≤ 20 cm in diameter litter upper surface of unit; upper contact sharp and irregular.

≤ 0.5m B-7 (fig. 75B): bedded gravelly, slightly muddy medium sand, containing abundant flattened mud intraclasts ≤ 15 cm in diameter; color of sands 5 YR 5/6, 10 YR 7/4, and 10 YR 6/6 to 10 YR 4/6; color of intraclasts is N9 or 10 YR 8/6 to 10 YR 6/6; unit grades upward into soil zone.

≤ 0.6m+ B-8a (fig. 76C): bedded to tangentially crossbedded fining upward muddy, gravelly medium sand, containing deformed mud intraclasts ≤ 5 cm in diameter; color of sand is 10 YR 8/6 to 10 YR 6/6; color of intraclasts is N9 or 10 YR 8/2, with N9 rims; grades upward into B-8b.

0.3m B-8b (fig. 76C): bedded to tangentially crossbedded fining upward muddy, slightly gravelly medium sand, containing flattened mud intraclasts ≤ 6 cm in diameter; color of sand is 10 YR 8/2 to 10 YR 6/6; color of intraclasts typically 10 YR 8/2, some with N9 rims (fig. 76D); upper contact undulatory and slightly gradational.

0.8m B-9 (figs. 76A, C, D): alternating beds of large scale tangentially crossbedded and bedded slightly sandy mud, N9, mottled 10 YR 8/2 to 10 YR 6/6 along some laminae; apparent foreset width, defined in some cases by dark mineral laminae, is about 1.5 m; beds typically 15 cm thick; flattened mud intraclasts ≤ 60 cm embedded in upper surface of unit (fig. 76B): color of intraclasts is N9; upper contact sharp and undulatory.

3.1m B-10 (figs. 76A, B): tangentially crossbedded to bedded, fining upward sandy, slightly gravelly mud, 5 Y 8/4 to 10 YR 8/6; flattened mud intraclasts ≤ 10 cm in diameter are scattered along some bedding surfaces or occur as thin beds of welded grains; color of intraclasts is typically N9; upper contact is sharp and irregular.

≤ 0.4m B-11: massive slightly sandy mud, 5 Y 7/2; unit grades upward into soil zone.

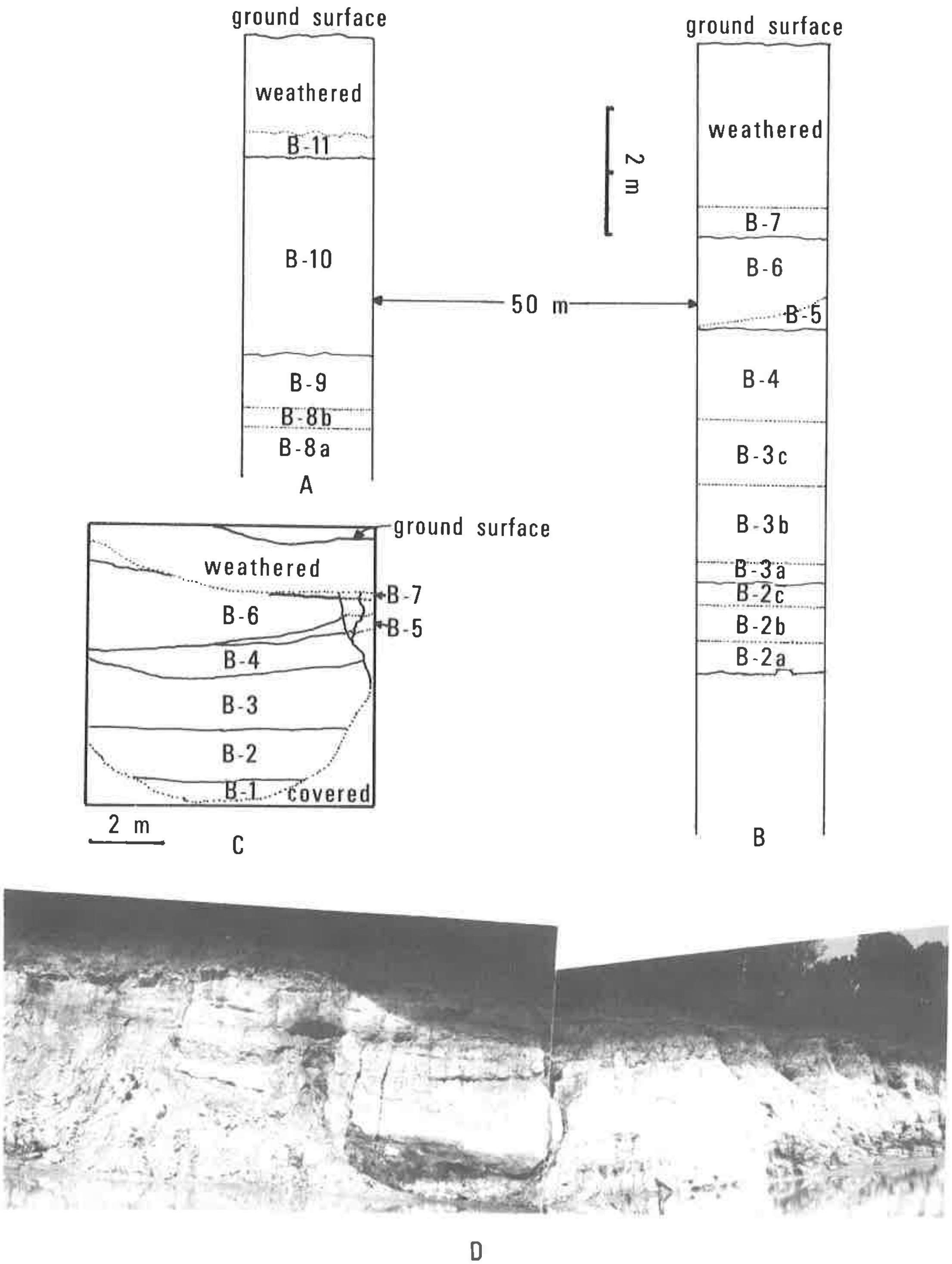


Figure 74. Representative stratigraphic sections from Locality "B". Oconee-Barnwell disconformity probably in weathered zone at tops of sections. A and B at approximately same elevation; B, from center of D; C, also from center of D; D portion of outcrop at Locality "B".

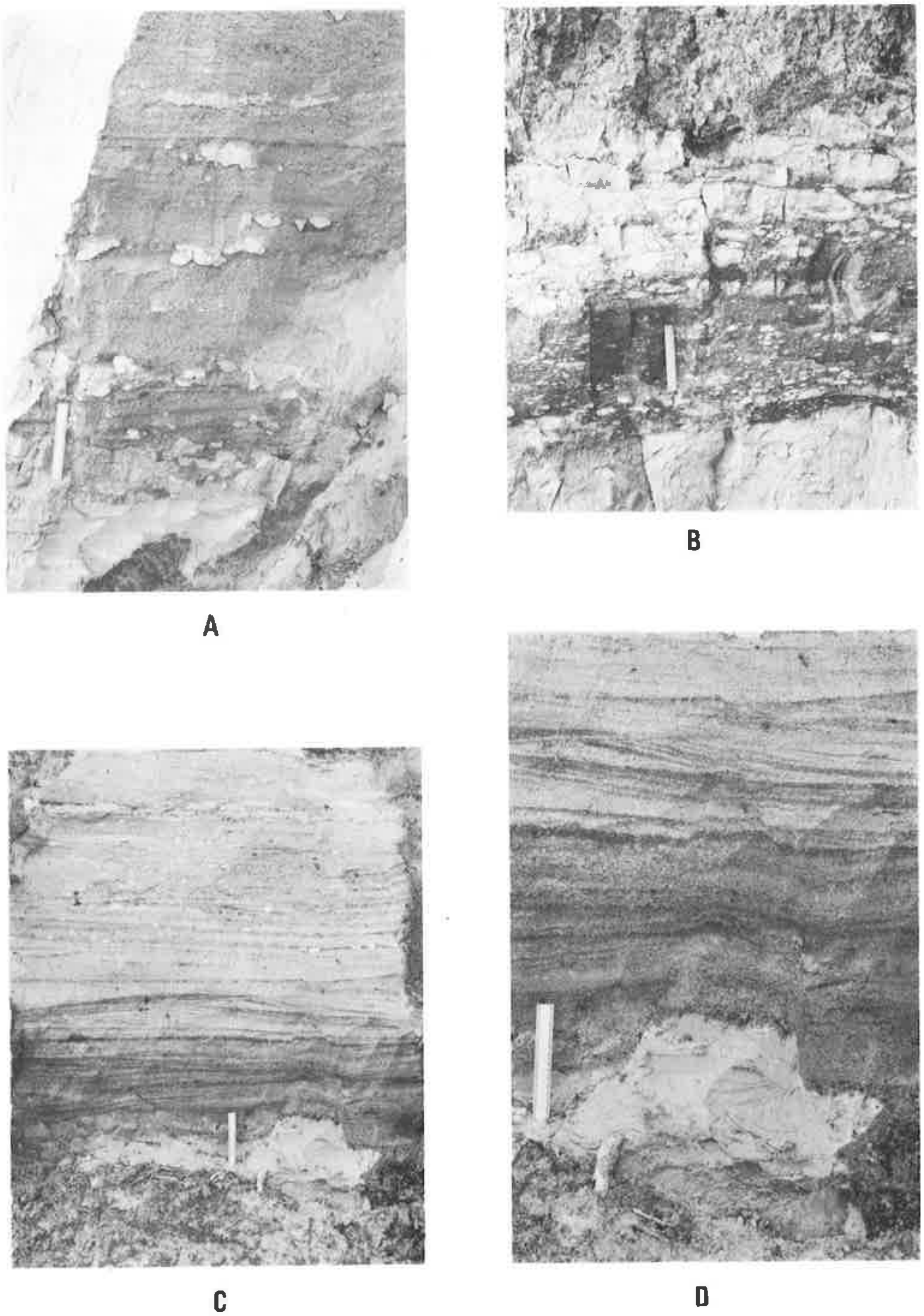


Figure 75. Sediments of Oconee Group at Locality "B". Ruler is 15 cm long. A, unit B-2 c at base, overlain by B-3a and B-3b; B, unit B-6 at base, overlain by B-7, which grades upward into weathered sediments at top; C, unit B-1 at base overlain by B-2a-c; D, detail of lower right of C, showing a small horst and compaction faults extending into overlying sands. Thickening of overlying sediments on downthrown blocks evident at left, suggesting faults were "growing" during deposition of suprajacent sediments.

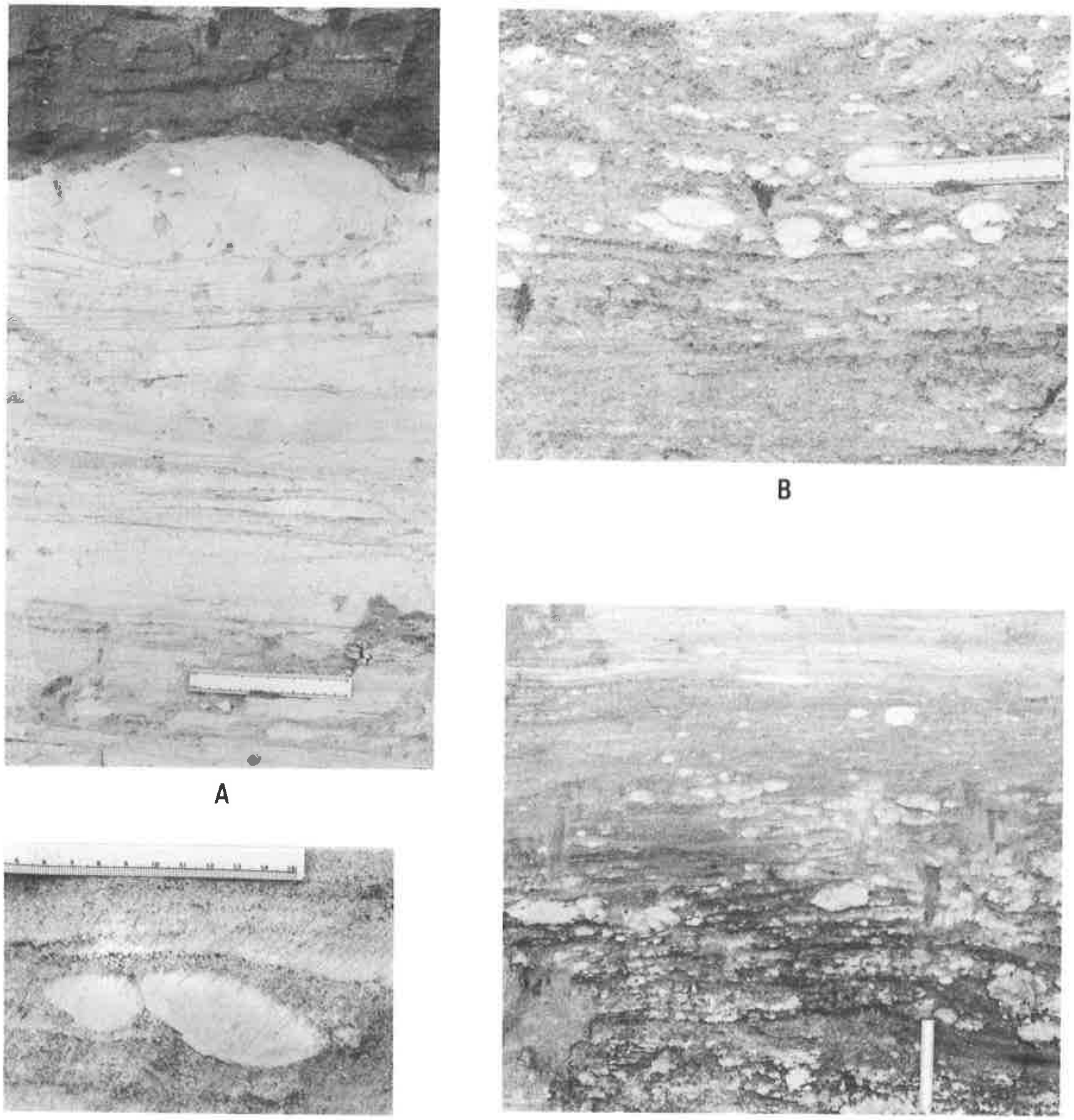


Figure 76. Sediments of Oconee Group at Locality "B". Ruler is 15 cm long. A, unit B-9, with large flattened mud clast embedded in upper surface of unit, overlain by B-10; unit B-10, containing light colored mud intraclasts and *Amphorichnus* sp. with dark fillings; C, unit B-8a in lower half, overlain by B-8b, containing *Amphorichnus* sp. at center left, overlain in turn by B-9 at top; D, mud clasts from unit B-8b, showing bleached rims. (see fig. 74A).

Locality "C": American Industrial Clays claypit, Washington Co.; N33° 1' 26" W 82° 55' 22".

Figures 77-80

3.0m+ C-1 (fig. 79C, 80C): massive slightly sandy mud, containing scattered mud intraclasts (?) ≤ 1 cm in diameter; color of mud is 10 YR 8/2; color of intraclasts is 10 YR 8/6 or N9; irregular hydrous iron oxide stains 10 YR 6/6 to 5 YR 4/4 and associated aggregates of small hydrous iron oxide spheroids occur sparsely in upper 0.5 m of unit; an irregular discontinuous hydrous iron oxide crust ≤ 5 mm thick is present on upper surface of unit; lower contact is not exposed; upper contact is sharp and slightly irregular.

0.6m C-2a (fig. 79B): tangentially tabular crossbedded to bedded muddy slightly gravelly coarse to medium sand, fining upward and containing flattened mud intraclasts ≤ 15 cm in diameter; some intraclasts occur as lenses of welded grains; apparent foreset width, where present, is typically 1.5 m; beds are 5 to 25 thick; hydrous iron oxide is concentrated in lower few cm; color of sand is 5 YR 5/6 or 10 YR 6/6 to 10 YR 8/6 near base of unit to 10 YR 8/6 near top; color of intraclasts is 10 YR 8/2 to N9, with some showing 10 YR 8/2 cores and N9 rims; grades upward into C-2b.

0.3m C-2b (figs. 79A, B): bedded to tangentially crossbedded muddy medium sand, fining upward in places to muddy fine sand; mud intraclasts ≤ 1 cm in diameter are sparsely abundant; apparent foreset width, where present, is 15 to 50 cm long; beds are typically 5 to 10 cm thick; color of muddy medium sand is 10 YR 8/2; color of muddy fine sand is N8 to N9; upper contact with C-2c is gradational to sharp and slightly irregular.

0.3 to 0.5 m C-2c (figs. 79A, B): trough crossbedded gravelly muddy sand to gravelly sandy mud, grading upward slightly gravelly muddy sand; mud intraclasts ≤ 5 cm diameter decrease in abundance upward; apparent foreset width, typically 2 m; beds are typically 30 cm thick; color of sands is 10 YR 8/6, mottled 10 YR 6/6 or rarely 5 YR 5/6; color of muds is N9; color of intraclasts is typically 10 YR 8/2, some showing N9 rims; upper contact with C-2d is sharp and slightly irregular.

0.8 to 1.0m C-2d (fig. 79A, B): interbedded trough crossbedded muddy fine sand, sandy mud, and muddy, slightly gravelly medium sand, containing scattered mud intraclasts ≤ 7 cm in diameter; apparent foreset width, 10 to 60 cm; grades upward into bedded to tangentially crossbedded slightly gravelly, sandy mud, containing scattered mud intraclasts ≤ 5 cm in diameter; apparent foreset width where present, about 1.5 m; throughout unit, beds are typically 10 to 15 cm thick and color is N8 to 5 Y 8/1. Upper contact is sharp and slightly irregular.

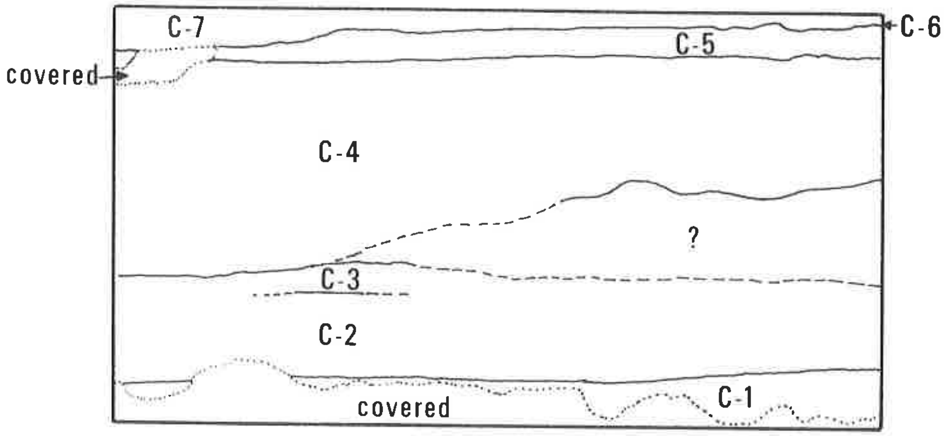
1.0m C-3 (fig. 80A): bed of slightly sandy gravel, about 30 cm thick, consisting mostly of mud intraclasts ≤ 5 cm in diameter, grades up into bedded to tangentially crossbedded muddy medium sand to sandy mud, slightly gravelly in places due to scattered presence of mud intraclasts ≤ 5 cm in diameter; color is N8 to 5 Y 8/1; upper contact is sharp and slightly irregular.

4.5m C-4 (figs. 80A, B, D, E): bed of slightly sandy gravel, ≤ 15 cm thick, consisting mostly of mud intraclasts ≤ 15 cm in diameter, grades upward into bedded muddy, sandy gravel to gravelly muddy sand, containing abundant deformed mud intraclasts ≤ 5 cm in diameter, concentrated along bedding surfaces; individual lamine are 1 to 2 cm thick; grades upward into poorly bedded gravelly, muddy sand and gravelly sandy mud; color is 10 YR 8/2 to N9, mottled 10 YR 8/6; upper contact is gradational.

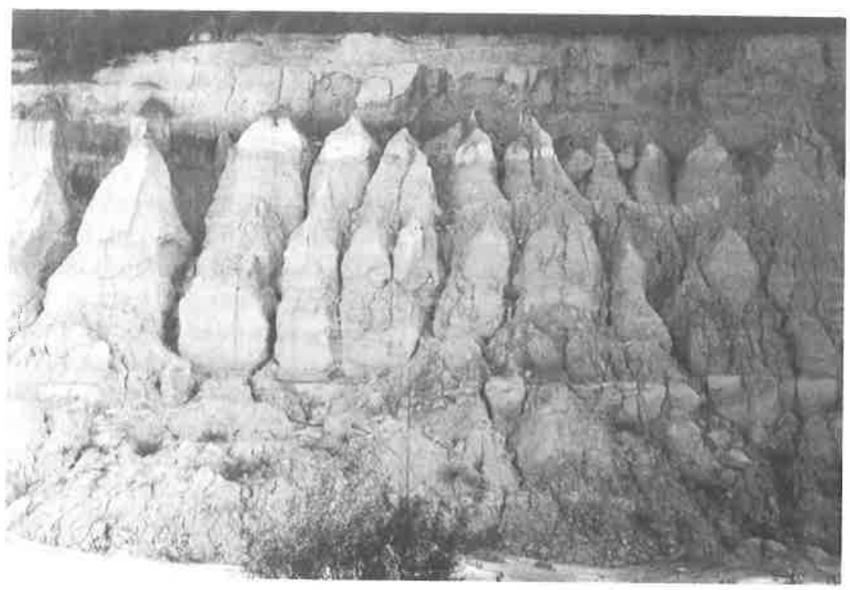
1.5 to 4m C-5 (fig. 80C): massive sandy to slightly sandy mud; in places, pisolitic spheroids are present 1 to 2 m below upper contact; vertical fluting (fig. 68C) occurs in upper 1 to 2 m of unit in places and is associated with observed occurrence of pisolitic spheroids; upper contact is sharp and irregular to highly irregular.

≤ 20cm C-6: bedded to massive fossiliferous muddy to slightly muddy medium to coarse sand.

2.0m+ C-7: bedded to massive-appearing sparsely fossiliferous mud.



A



B

Figure 77. Portion of outcrop at Locality "C". A after B. Contact between units C-5 and C-6 is disconformity between Oconee Group below and Barnwell Group above. (see fig. 78).

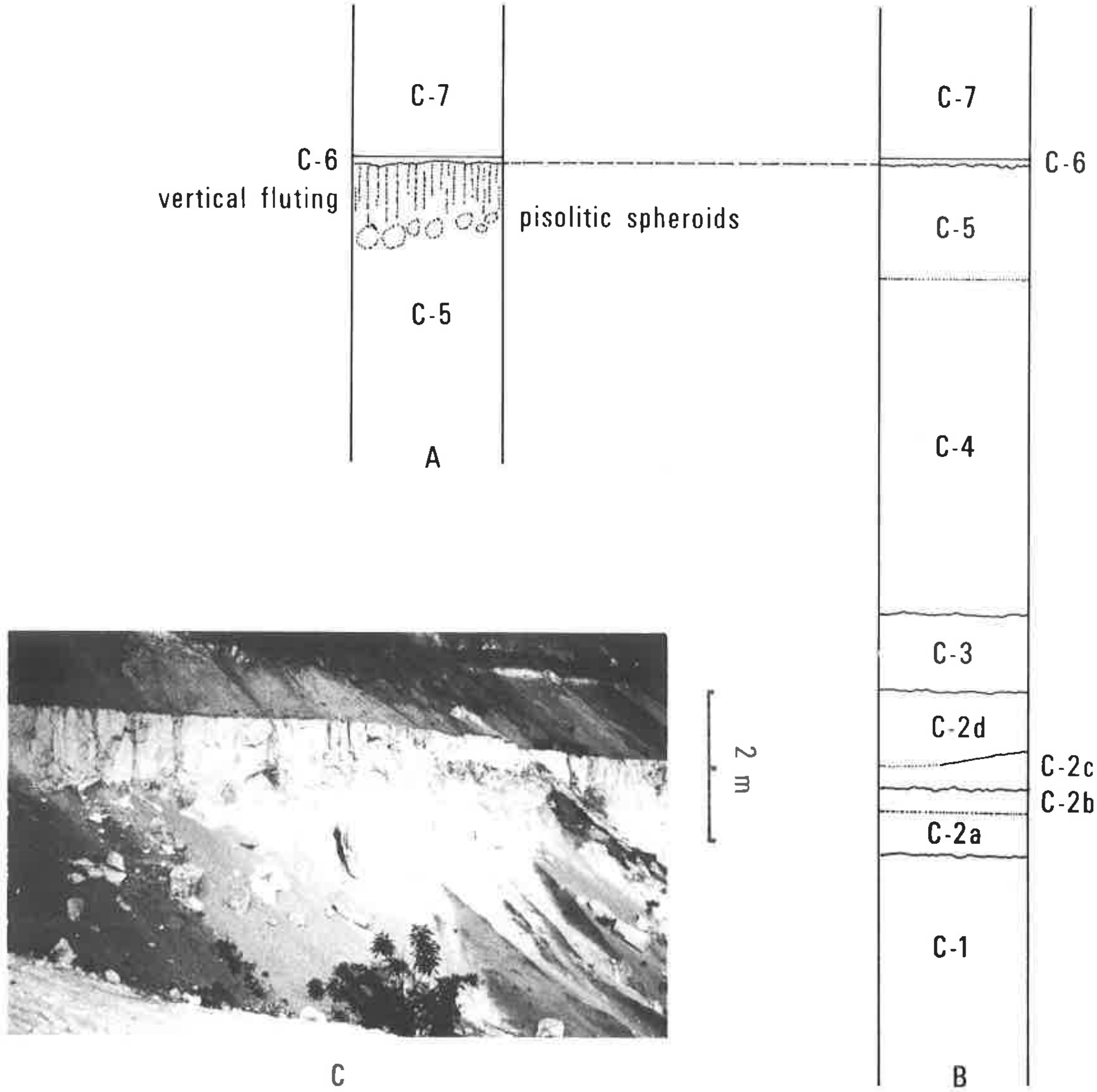


Figure 78. Representative stratigraphic sections from Locality "C". A, B, units C-1 through C-5 belong to Oconee Group; C-6 belongs to Clinchfield Formation; C-7 belongs to Twiggs Clay Member. Dashed line represents approximate position of Oconee-Barnwell disconformity between sections. Dotted lines represent gradational contacts. (see fig. 77); A, after C; B, after figure 77 B; C, portion of outcrop, showing lighter colored Oconee, overlain by darker Barnwell. Vertical fluting evident subjacent to disconformity, underlain by zone of pisolitic spheroids.

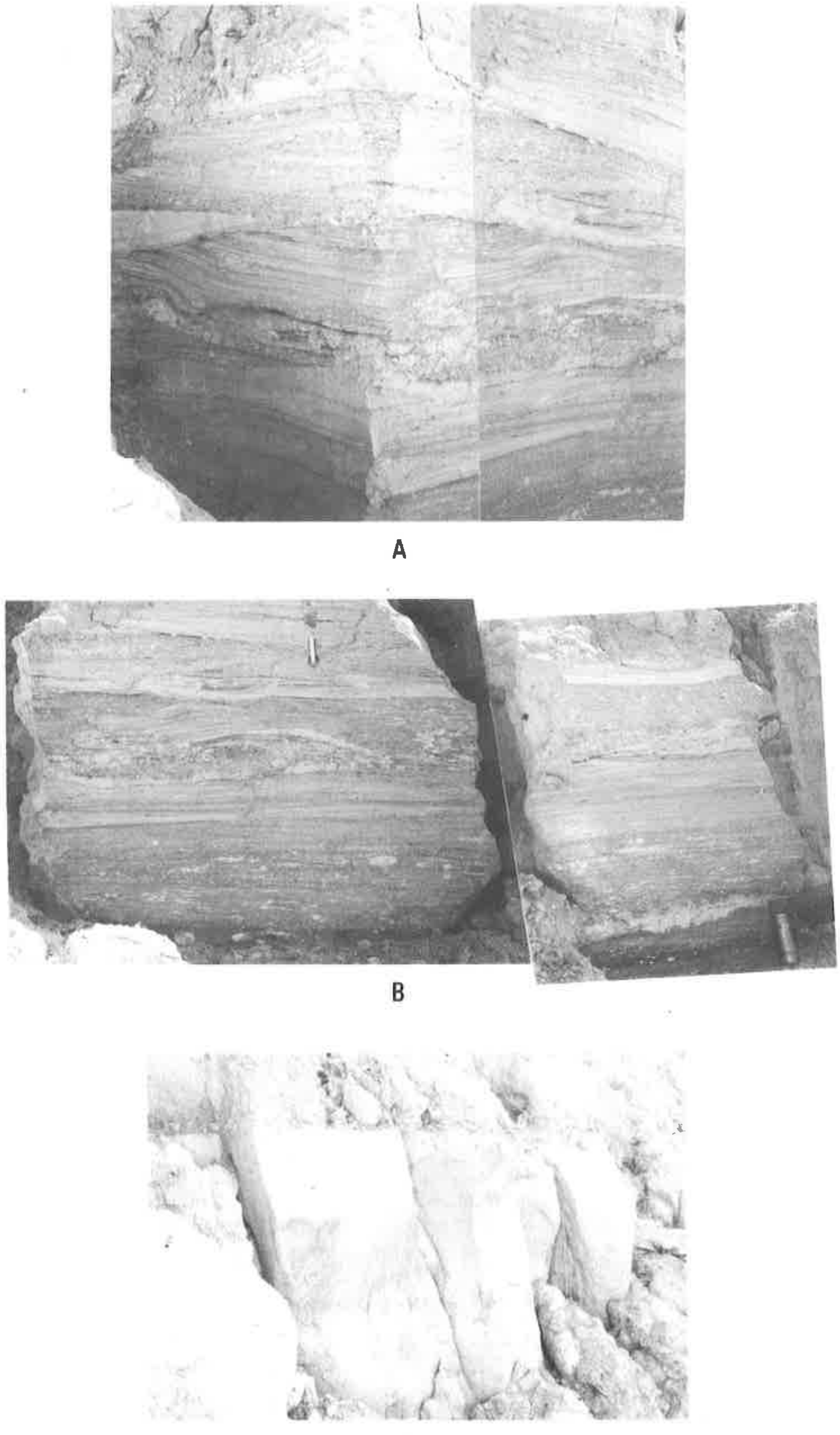


Figure 79. Sediments of Oconee Group at Locality "C". Ruler is 15 cm long. A, corner view of a portion of unit C-2 from left end of B; B, fining upward sequence of unit C-2a through C-2d. Thermos bottle rests on upper surface of C-1. C, massive mud of unit C-1.

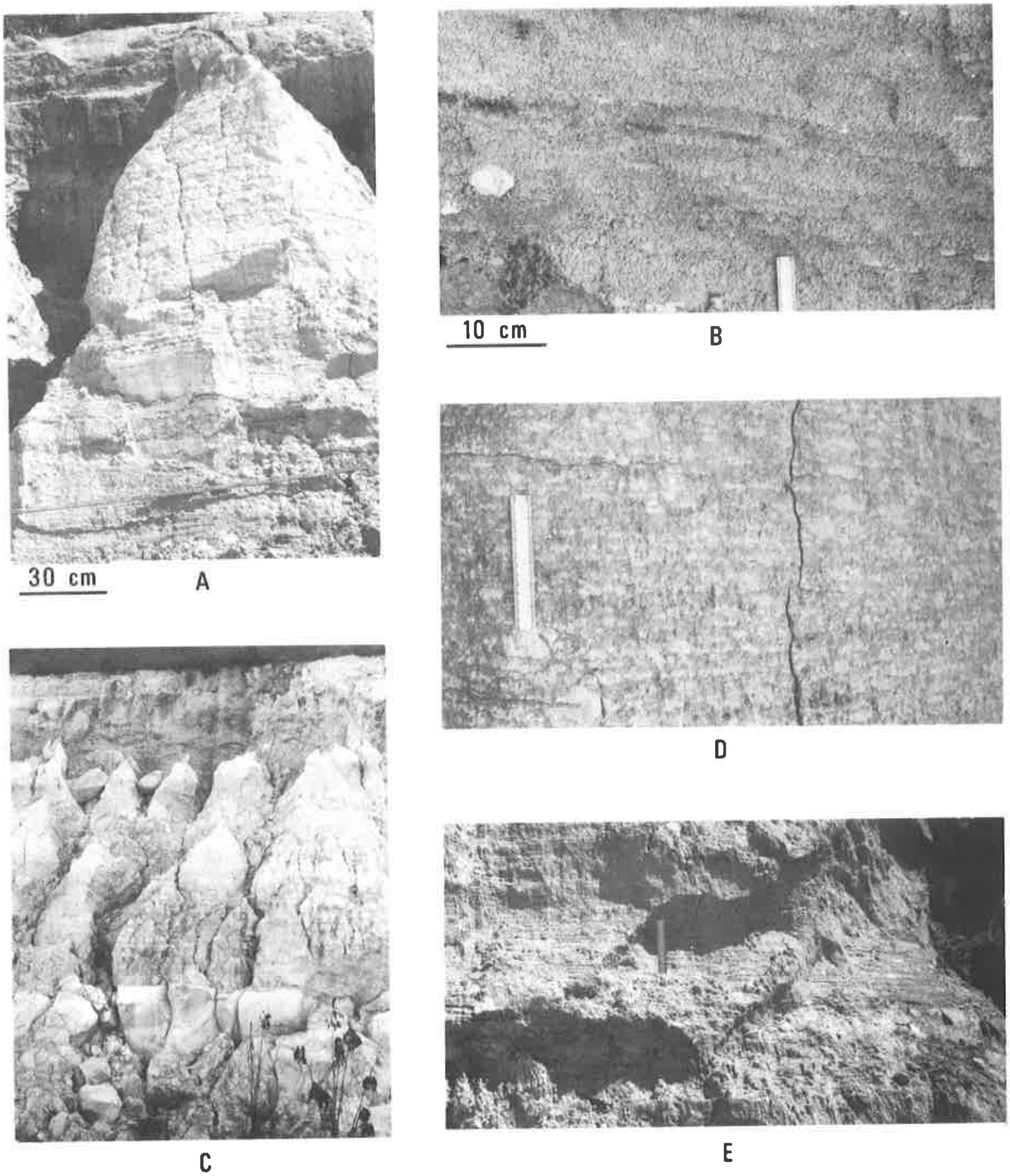


Figure 80. Sediments of Oconee Group at Locality "C". A, unit C-3 at base, overlain by C-4, overlain in turn by C-5 (ledge at top); B, transition between units C-4 and C-5; C, complete section depicted in figure 78B; D, E, ruler is 15 cm long; D, unit C-4, showing mud intraclasts with highly irregular outlines; E, contact between units C-3 and C-4. Large mud intraclasts visible at contact.

Locality "D": Washington Co.; N33° 1' 33' W82° 55' 50".

Figures 21, 22, 27-29, 81-84

6.7m+ D-1 (figs. 83C, D): massive mud, grading upward into massive slightly sandy mud in upper 60 cm of unit; color is typically N9 to 10 YR 8/2; muddy fine sand intraclasts (?) occur between 3.5 m depth and upper contact, showing a gradual increase in abundance upward to a maximum of 20 percent of sediment volume, 1 m below upper contact, above which abundance drops sharply; color of intraclasts (?) is 5 Y 8/2, with some showing 10 YR 6/6 rims; intraclasts (?) may stand out in negative relief on erosion surfaces (fig. 83C). Upper contact sharp and undulatory, with an irregular hydrous iron oxide crust ≤ 6 mm thick present in some places.

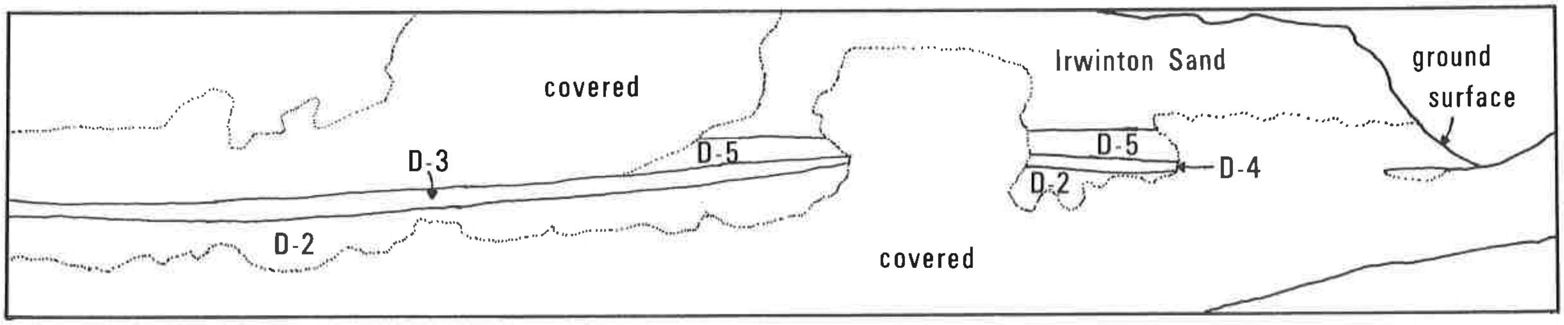
3.0m D-2 (figs. 21, 83A, B): massive muddy fine sand-/sandy mud, fining upward to sandy mud; color is 5 Y 8/2 to 10 YR 8/2, rarely mottled 10 YR 6/6; color to depths of 1 m below reduced Barnwell sediments is N7; planar vertical jointing (fig. 21) well developed in some places; slickensides common in places near top of unit, but not associated with vertical jointing; mud may have hackly appearance in places where dessication has occurred; upper contact sharp and variably irregular.

1.5m D-3a (figs. 84B, C): intercalated bedded mud and small scale trough crossbedded sandy gravelly mud, the later containing variable quantities of mud intraclasts ≤ 10 cm in diameter; color of muds is 5 Y 8/1 to 5 Y 4/1; color of sandy gravelly muds is 5 Y 6/1, mottled 10 R 6/6 to 5 YR 5/6; color of intraclasts is N9; beds are ≤ 10 cm thick and are typically 1 to 2 cm thick; laminae in mud beds typically ≤ 1 mm thick; grades upward into D-3b; grades laterally into D-4.

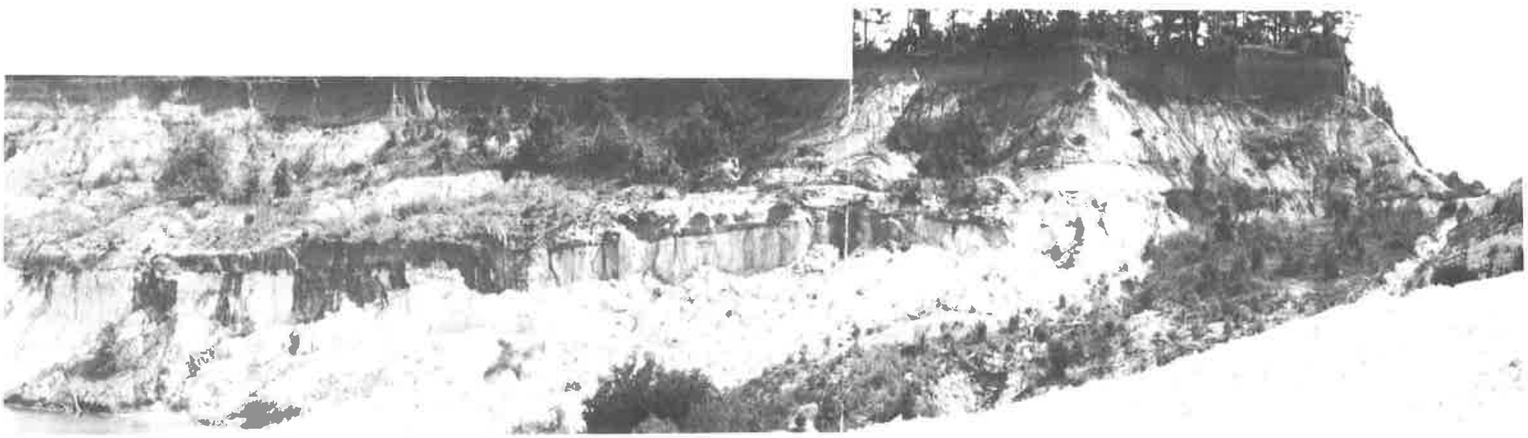
1.5m D-3b (figs. 27, 28, 84A): massive to lenticularly bedded, abundantly fossiliferous sandy mud, 5 G 6/1, mottled 5 Y 6/1; upper contact slightly gradational and nearly flat; grades laterally into D-4.

1.0m D-4 (fig. 29): generally massive, bioturbated sandy mud, showing patches of unbioturbated trough (?) crossbedded material in lower 0.5 m (fig. 29); color of unbioturbated areas is N9 to 5 Y 8/1; color of bioturbated areas is 5 Y 8/4, mottled 10 YR 6/6 to 10 R 4/6; layer of mud intraclasts ≤18 cm in diameter occurs 50 cm above base of unit. Upper contact slightly gradational and nearly flat.

2.0m+ D-5 (fig. 29): laminated, sparsely fossiliferous mud; thin lenses of fine sand and decalcified fossil shells occur sporadically.



A



B

Figure 81. Portion of outcrop at Locality "D". A, after B. Contact between unit D-2 and suprajacent units is disconformity separating lighter colored Oconee Group sediments below from darker Barnwell sediments above. Units D-3 and D-4 belong to Clinchfield Formation. Unit D-5 belongs to Twiggs Clay Member, which is overlain by Irwinton Sand Member, both of the Dry Branch Formation.

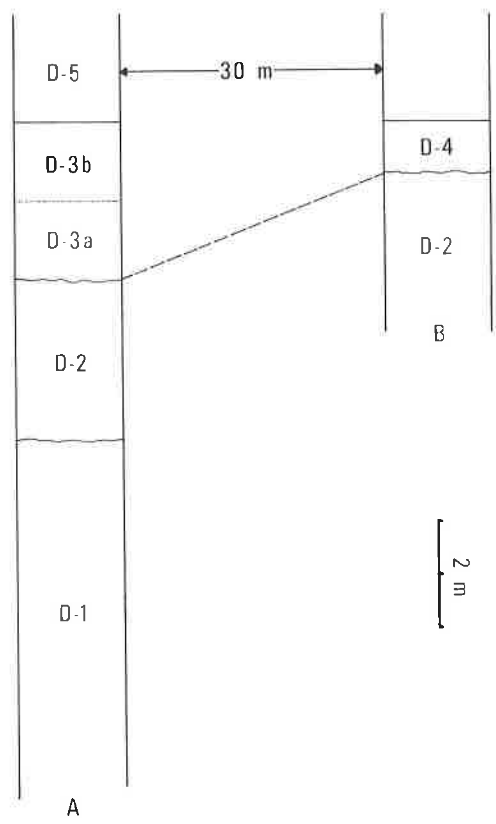
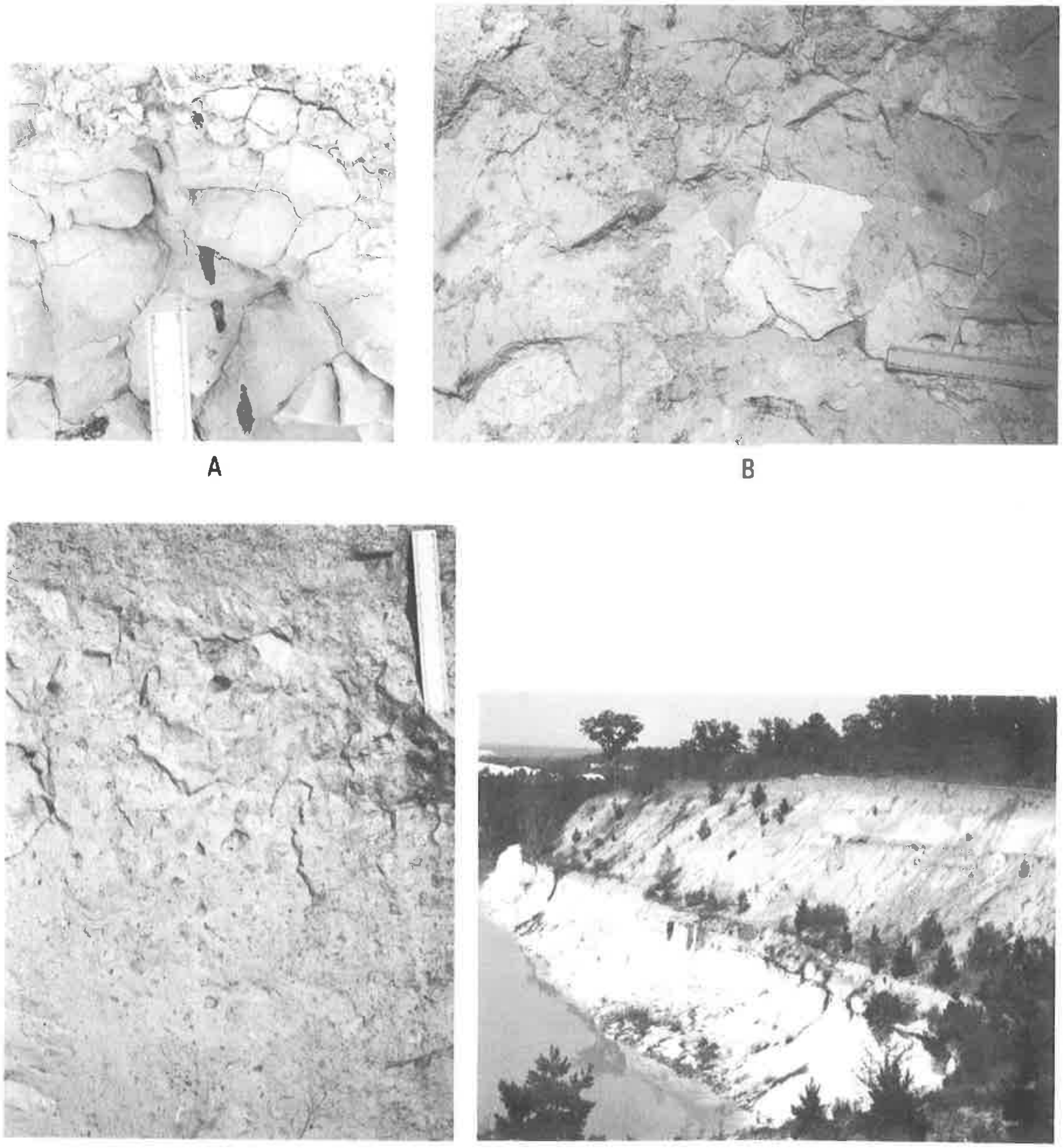


Figure 82. Representative stratigraphic sections from Locality "D". Oconee-Barnwell disconformity at top of unit D-2. Heavy dashed line indicates approximate position of disconformity between sections. Dotted lines indicate gradational contact.



A B C D

Figure 83. Sediments of Oconee and Barnwell Groups at Locality "D". A, massive mud of unit D-2, showing hackly appearance and segment of *Thalassinoides* sp. B1 at center; B, unit D-2; C, massive mud of unit D-1, showing pisolites weathering out in negative relief; A-C, from Oconee Group. Ruler graduated in centimeters and inches; D, portion of outcrop at Locality "D", showing lighter colored Oconee Group overlain by darker Barnwell Group.

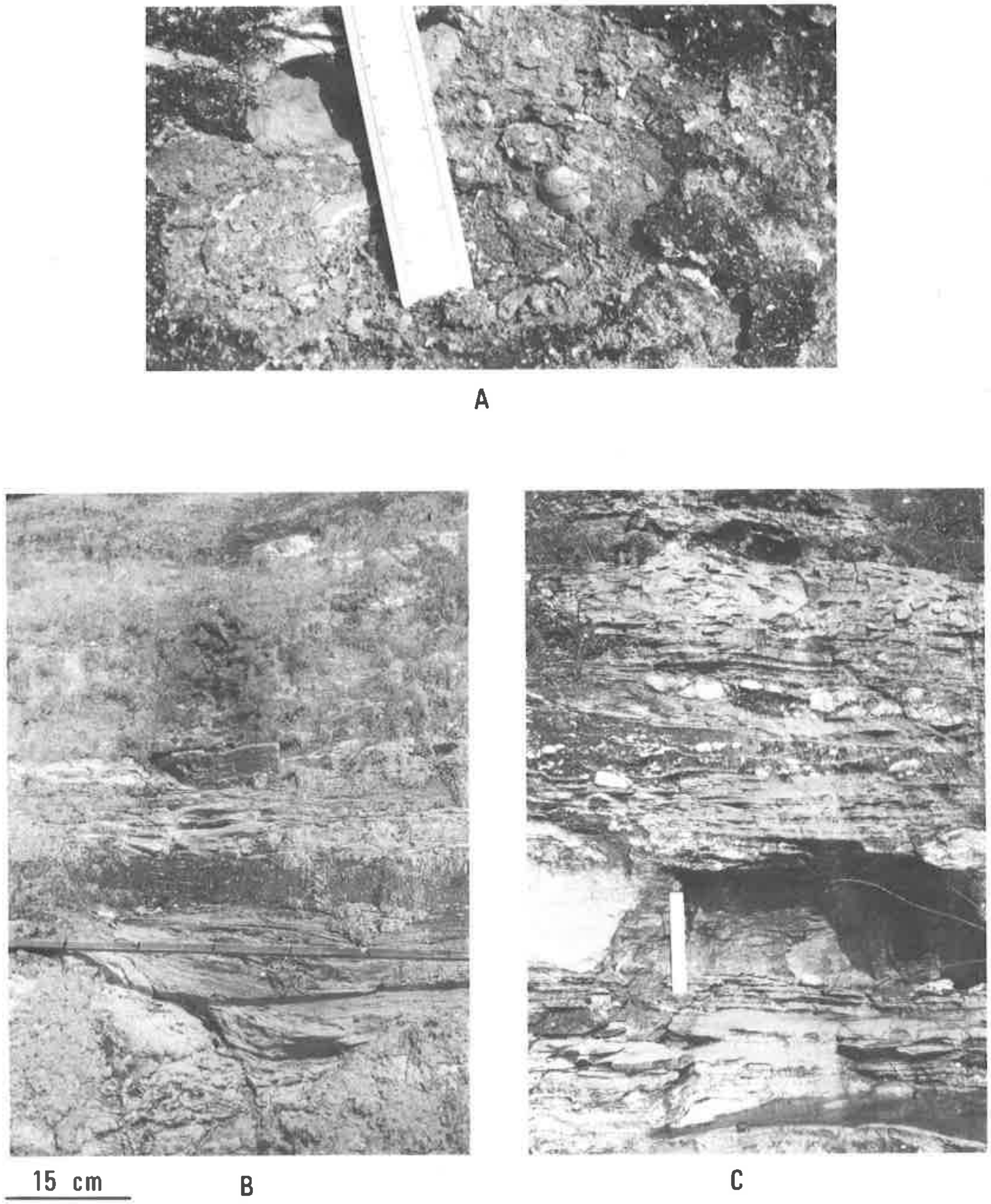


Figure 84. Sediments of Clinchfield Formation at Locality "D". A, fossiliferous sandy mud of unit D-3b. Scale graduated in centimeters and inches. B, irregular surface of Oconee-Barnwell disconformity beneath rod. Below is unit D-2, above is unit D-3a, overlain by D-3b in upper half of figure; C, interbedded mud and sandy mud of unit D-3a, showing light-colored mud clast probably derived from underlying Oconee Group sediments. Ruler is 15 cm long.

Locality "E": Deepstep Sanitary Landfill, Washington Co.; N33° 1' 31" W82° 58' 32".

Figures 85, 86

2m+ E-1: massive, bioturbated mud; color in unbioturbated areas is 10 YR 8/2; color in obviously bioturbated areas is N10; upper contact sharp and slightly irregular.

3.5m E-2: sandy mud at base; physical structures and other details unknown due to outcrop cover.

0.6m+ E-3 (fig. 86A): large scale tangentially to angularly tabular crossbedded muddy sand to sandy mud; color of sandy mud is N9; color of muddy sand is 10 YR 8/2, stained 10 YR 8/6 to 10 YR 6/6 along some foreset laminae; foresets are 0.3 to 1.0 m long; beds typically 15 to 20 cm thick; lower contact may be covered (see E-2); upper contact sharp and irregular.

≤ 0.6m E-4a (fig. 86A): lenticular bed of welded mud intraclasts ≤ 20 cm in diameter, grading upward in places into bedded muddy, gravelly sand, containing mud intraclasts ≤ 5 cm in diameter; color of intraclasts is typically N9; color of sand is N9 to 5 Y 8/1, mottled 10 YR 8/2 to 10 YR 6/6 in upper portion; grades upward into E-4b.

1.4m E-4b (fig. 86A): small to intermediate scale angularly to tangentially trough crossbedded muddy coarse sand, with sparse, flattened mud intraclasts ≤ 4 cm in diameter scattered along some bedding surfaces; apparent foreset width, 8 to 30 cm long; beds typically 5 to 20 cm thick; color of sand is 10 YR 8/2 to 10 YR 6/6, stained 5 YR 5/6 along some bedding laminae; color of intraclasts is N9 to 10 YR 8/2; irregular, concave up "bleached" zone 10 YR 8/2 occurs at top of unit (fig. 85B): upper contact sharp and slightly irregular.

≤ 2.0m E-5 (fig. 86B, C): small to intermediate scale angularly to tangentially crossbedded to bedded muddy coarse sand; mud intraclasts ≤ 13 cm in diameter abundant in lower 60 cm of unit and tend to be concentrated along certain bedding surfaces; petroleum-like material concentrated along some bedding surfaces and on underside of mud intraclasts (fig. 86C): apparent foreset width, 10 to 30 cm long; beds typically 10 to 30 cm thick; color of sand is N9 to 10 YR 8/2, mottled 10 YR 6/6 or 5 YR 5/6; color of intraclasts is N9 to 10 YR 8/6, mottled 10 YR 6/6, with bleached rims present in some cases; color of petroleum-like organic material is N1; upper contact is gradational to sharp and highly irregular (fig. 86C)

1.2 to 1.4m E-6 (fig. 86B, C): massive gravelly, sandy mud, color is 10 YR 8/2, stained 10 YR 6/6 along burrows; upper contact is sharp and highly irregular.

4m E-7 (fig. 86D): massive bioturbated (?) slightly gravelly, coarse to medium sand; color is N9 to N8, mottled extensively 10 YR 6/6.

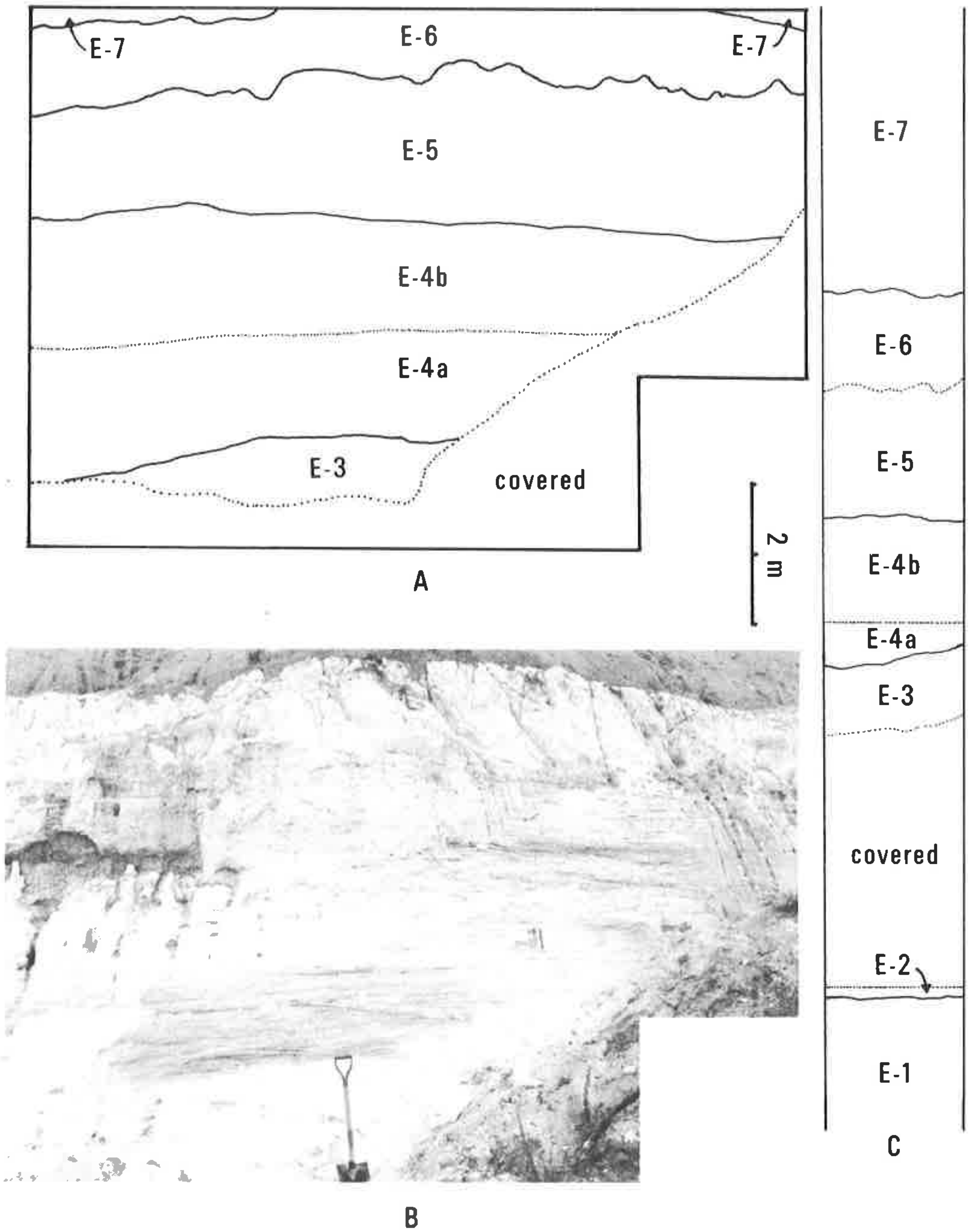


Figure 85. Representative stratigraphic section from Locality "E". Contact between units E-6 and E-7 is disconformity separating Oconee Group below from Clinchfield Formation above. A, after B; portion of outcrop at Locality "E".

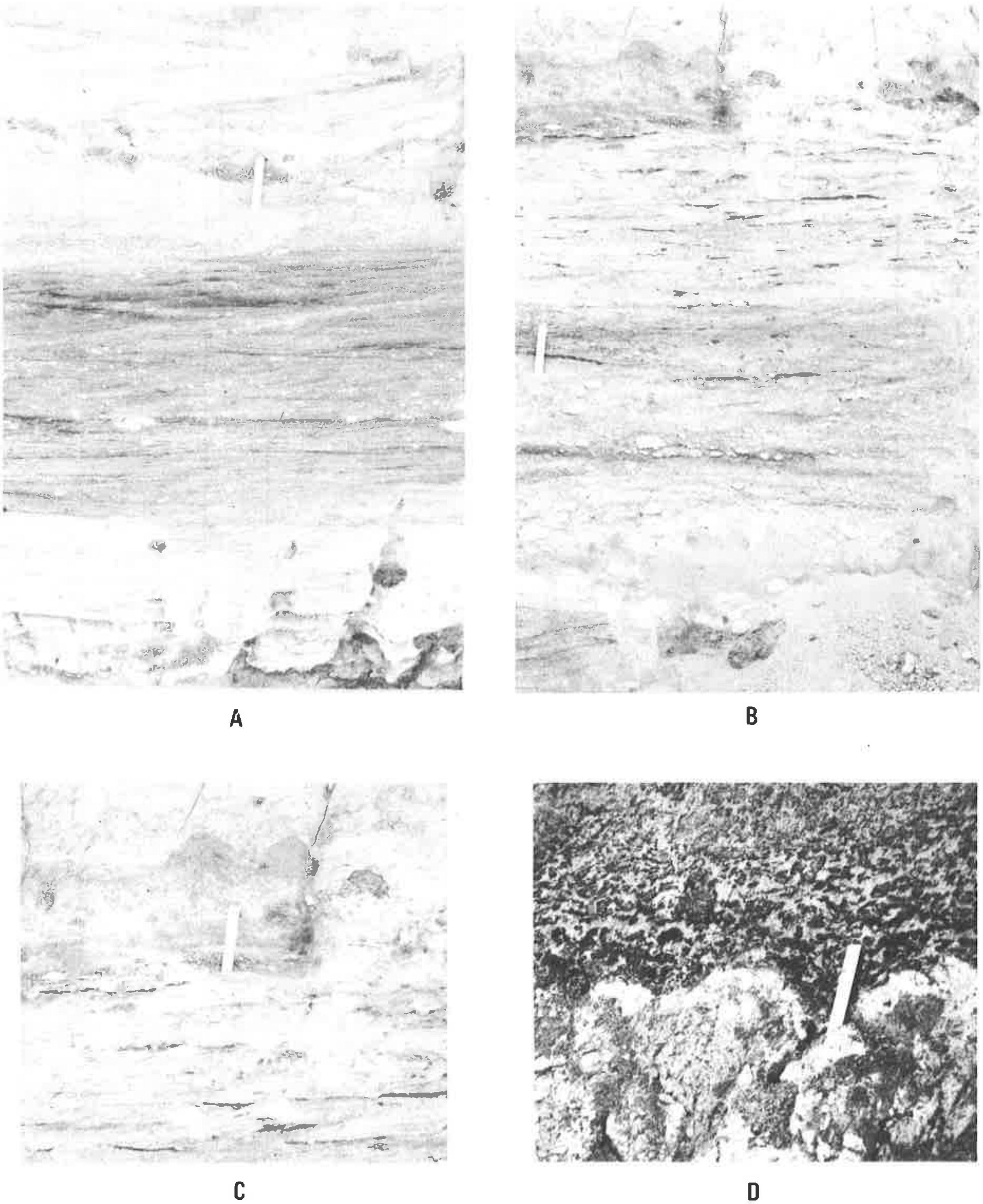


Figure 86. Sediments of Oconee Group at Locality "E". Ruler is 15 cm long. A, unit E-3 at base, overlain by E-4a, overlain in turn by E-4b; B, unit E-4b at base, overlain by E-5, overlain in turn by E-6 at top; C, detail of top left portion of B, showing dark streaks of petroleum-like residue in unit E-5 and gradational transition between E-5 and E-6 above; D, irregular surface of Oconee-Barnwell disconformity, showing unit D-6 below and burrow (?) mottled Clinchfield sands of D-7 above.

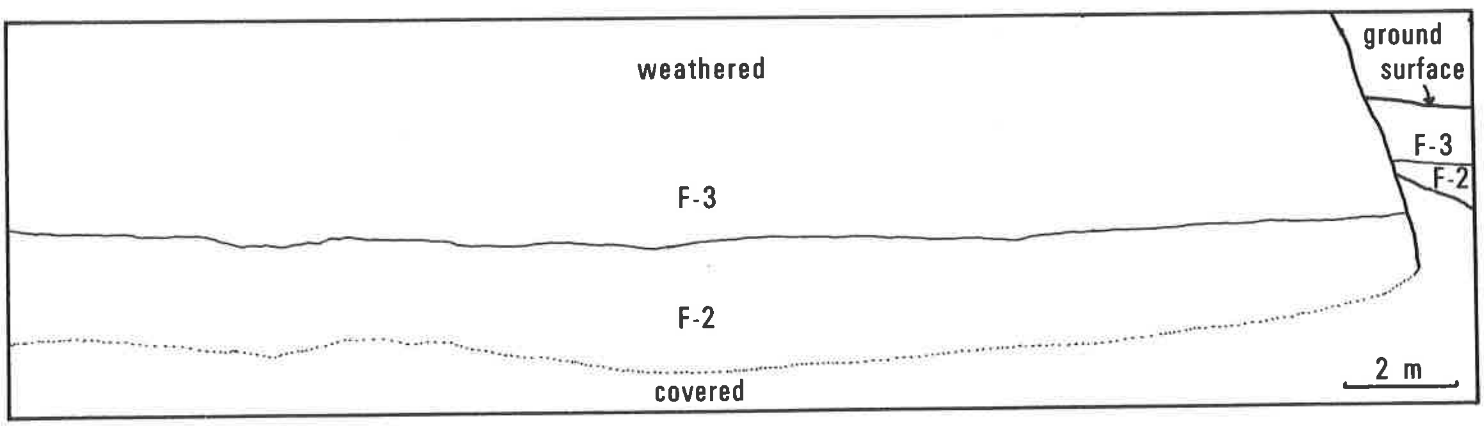
Locality "F": American Industrial Clays claypit, Washington Co.; N33° 1' 15" W 82° 59' 53".

Figures 87-89

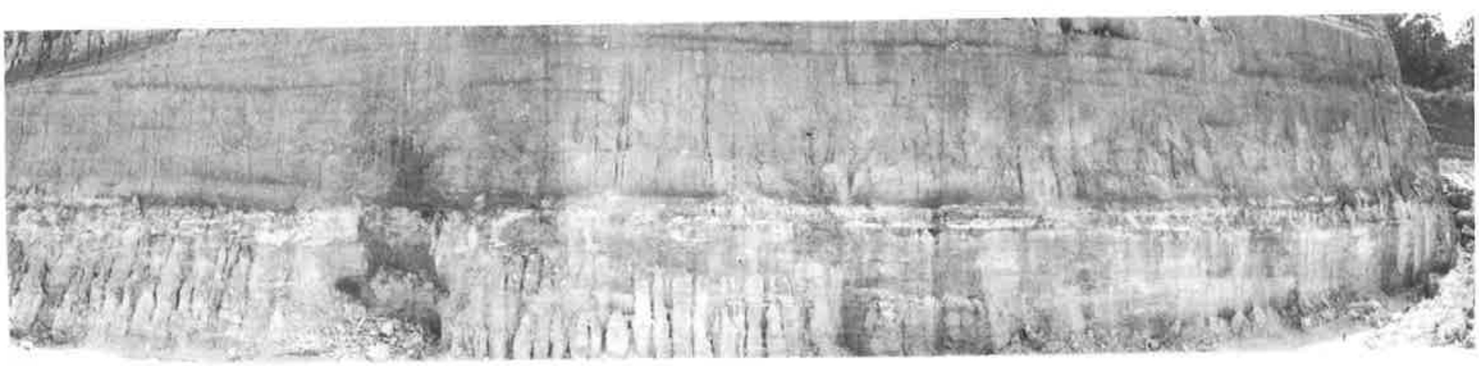
3m+ F-1 (figs. 89A, B): massive slightly sandy mud, grading upward into mud and back into slightly sandy mud; mud contains iron oxide and hydrous iron oxide liesegang bands and a few deformed, discontinuous horizontal laminae 5 to 10 mm thick; slightly sandy muds are highly micaceous; color of sandy mud and mud is 5 YR 9/1, mottled 10 YR 8/4 or 5 RP 8/2 to 5 RP 7/2 along *Planolites* sp. B (?), in small spots, and along liesegang bands; color of discontinuous laminae is N10; upper contact is gradational.

2.0m+ F-2 (figs. 89, 79C): bedded or tangentially to angularly trough crossbedded sandy mud, containing mud intraclasts ≤ 15 cm in diameter; intraclasts commonly occur as welded lenses; beds are 5 to 30 cm thick; upper contact is sharp to slightly gradational.

3.5 to 4.5m F-3 (fig. 87, 79C): bedded gravelly muddy sand, containing mud clasts ≤ 20 cm in diameter concentrated in basal few cm of unit along bedding surfaces elsewhere grading upward into massive, finer grained material of soil zone; color is 10 YR 8/6 to 10 YR 6/6.

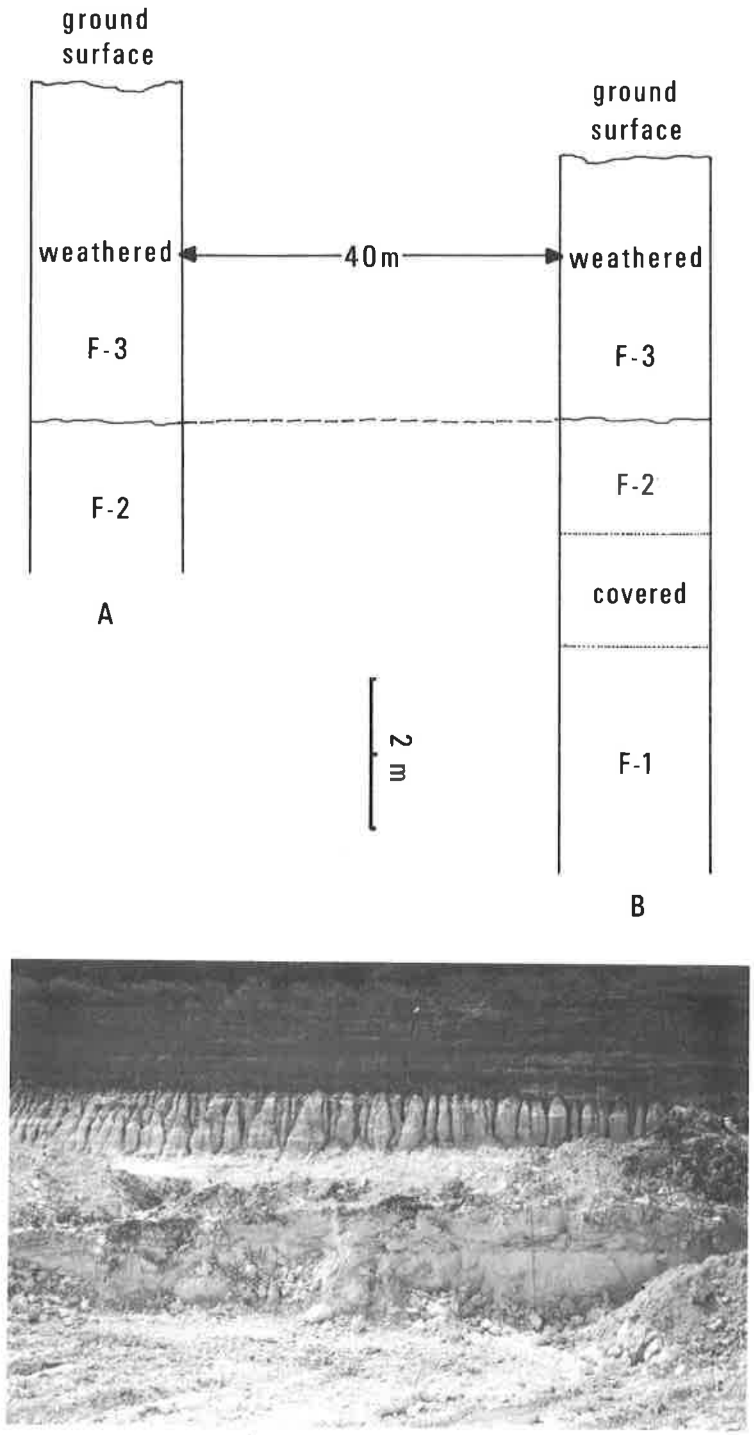


A



B

Figure 87. Portion of outcrop at Locality "F". A, after B. Contact between units F-2 and F-3 is disconformity separating Oconee Group sediments below from undifferentiated Barnwell Group sediments above (see fig. 88).



C

Figure 88. Representative stratigraphic sections from Locality "F". A, after center portion of figure 87 B; B, after C. C, portion of outcrop, showing unit F-1 at base of vertical face. Contact with F-2 covered. Light colored sediments of F-2 in upper central portion overlain by dark F-3 sediments. Rod is ≈ 3 m long. Dashed line between A and B represents approximate position of Oconee-Barnwell disconformity.

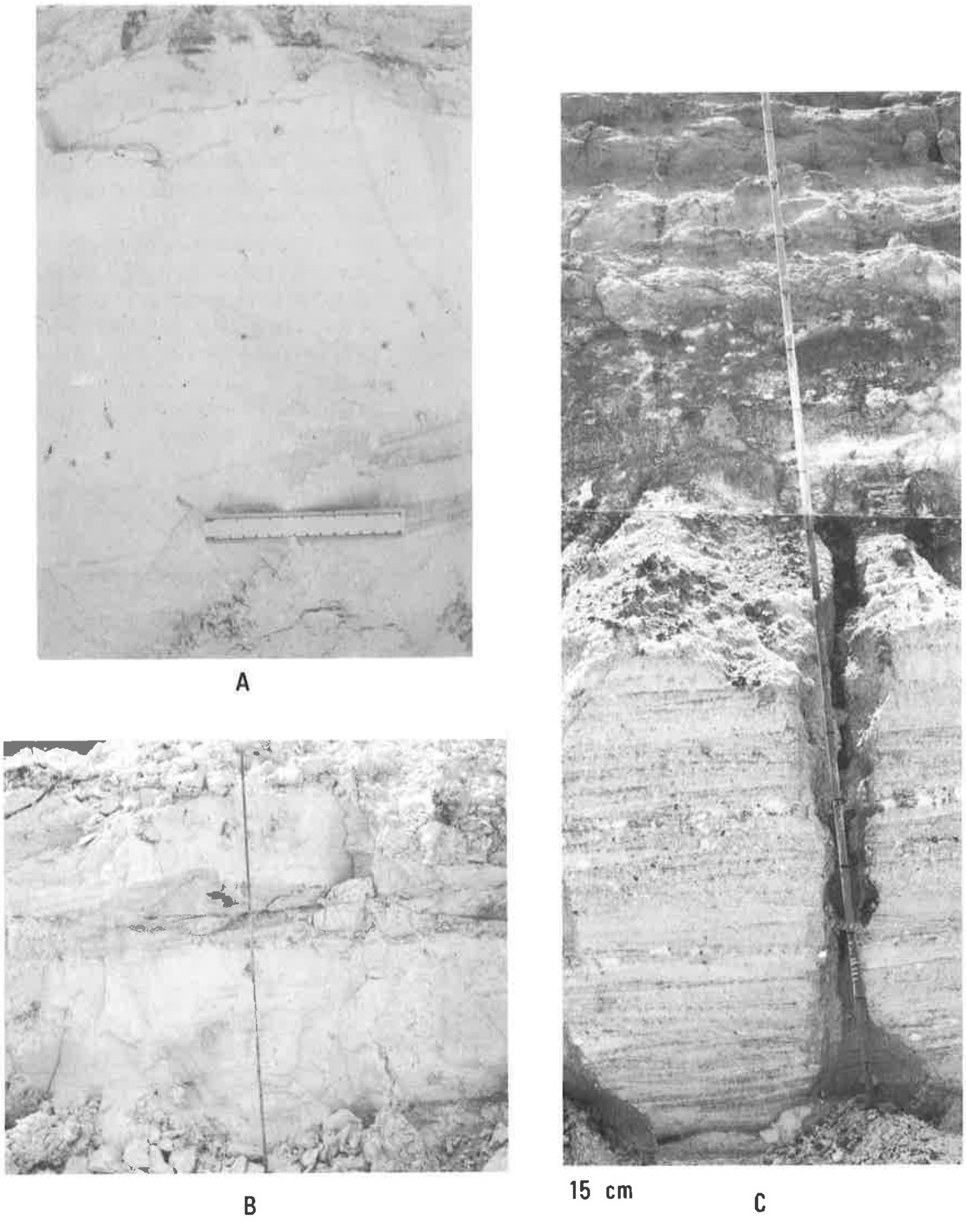


Figure 89. Sediments of Oconee Group at Locality "F". A, massive mud of unit F-2, showing poorly defined bioturbate textures and iron oxide/hydrous iron oxide liesegang bands above ruler. Ruler is 15 cm long. Detail of B, center left; B, portion of outcrop showing unit F-1 and multidirectional liesegang bands. Rod ≈ 3 m; C, detail of central portion of figure 87B, showing lighter sediments of F-2, overlain by darker Barnwell Group sediments of F-3.

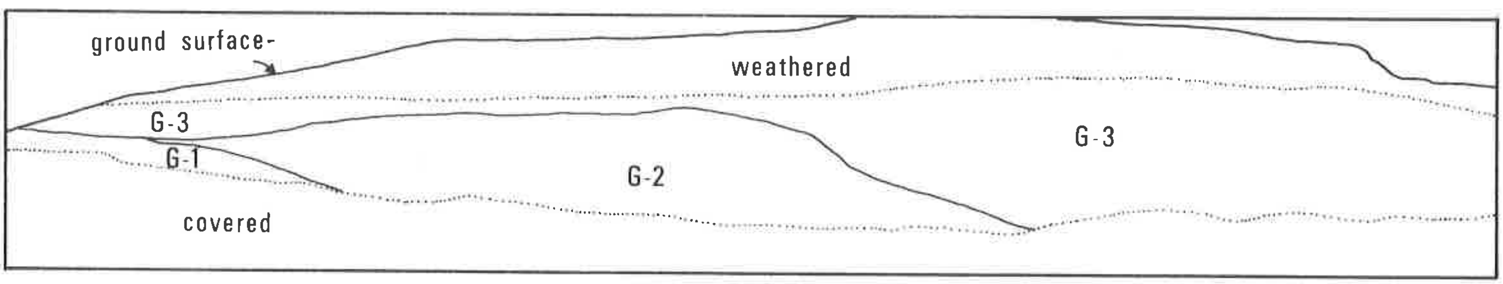
Locality "G": roadcut about 0.2 mi. E of Cowper Creek, Wilkinson Co.; N32° 48' 2" W83° 14' 20".

Figure 90

2.5m+ G-1: crossbedded (?) muddy medium sand/sandy mud; color is N9, mottled 5 YR 5/6 or 5 R 5/4 to 5 R 3/4; irregular iron oxide concretions, some vaguely resembling tubular burrows, occur in upper 0.5 m of unit and are especially abundant at upper contact; upper contact sharp, irregular, and broadly undulatory.

≤ 2.7m G-2: lens of partially weathered, slightly pisolitic, massive mud; color is N8, 5 YR 5/4, or 5 R 6/6, mottled 10 R 6/6 to 10 R 4/6 along some joints; irregular to tubular iron oxide concretions, some resembling "parallel ferruginous tunnels", occur sporadically at upper contact; upper contact is sparsely littered with pisolitic boulders ≤ 0.5 m in diameter; upper contact is sharp, highly irregular, and undulatory.

1.0-3.7m G-3: crossbedded (?) sandy mud to muddy medium sand, containing a few pisolitic boulders ≤ 0.5 m in diameter at lower contact; color is 5 YR 5/4 to 5 YR 6/4, 5 YR 5/6 to 10 YR 6/6, or N9. Sporadically abundant "parallel ferruginous tunnels", *Phycodes* sp. and irregular hydrous iron oxide concretions occur throughout unit; grades upward into soil zone.



A

B

Figure 90. Portion of outcrop at Locality "G". A, after B. Contact between unit G-3 and subjacent units is probably disconformity between Oconee Group below and Barnwell Group above. Occurrence of "parallel ferruginous tunnels" and *Phycodes* sp. at center right.

Locality "H": M and M Clays claypit, Wilkinson Co.; N32° 47' 30" W83° 17' 30".

Figures 34, 49, 55-58, 91-98

0.7m+ H-1* (fig. 94A): massive mud, similar in color and shrinkage properties to H-12; upper contact sharp and slightly irregular.

≤ 1.5m H-2* (fig. 94): bedded muddy sand, grading upward into small-scale angularly trough crossbedded muddy to slightly muddy sand and finally into bedded sandy mud; upper contact gradational.

1.5to 5.2m H-3 (figs. 94A, 95B, C): massive to poorly bedded, pisolitic, sandy to slightly sandy mud; irregular iron oxide concretions and pisolitic spheroids (fig. 95A) ≤ 50 cm in diameter are common, especially toward top of unit; spheroids show liesegang bands which roughly parallel upper surface of unit; color of mud is 10 YR 9/2 to 10 YR 8/2, mottled 10 YR 6/6 or 10 R 7/4; color of pisolites is 10 YR 8/2 to 10 YR 7/2 and diameter is 0.5 cm to 2.0 cm; color of iron oxide concretions is 5 R 2/6 to 10 R 2/2; slickensides common in some places; upper contact is sharp, highly irregular and undulatory, with a thin crust of iron oxide present.

0.5 to 2.5m H-4a* (94A, 95B, C, 96C): poorly crossbedded slightly muddy, gravelly sand, containing pisolitic boulders and cobbles ≤ 2 m in maximum diameter (fig. 94A); iron oxide liesegang banding is present in some boulders and cobbles show no preferred orientation; color of sand is 5 YR 8/4, mottled 5 YR 5/6 or 10 R 4/6; several broad, diffuse hydrous iron oxide liesegang bands are present in sand, ranging upward in color from 10 R 4/6 and 5 YR 5/6, through 10 YR 6/6, 5 YR 4/4, and 5 YR 5/6, to 10 R 4/6.

3.1 to 1.6m H-4b (figs. 34, 95B): tangentially to mainly angularly tabular or trough crossbedded, slightly muddy medium sand, containing dark mineral laminae along some foresets; apparent foreset width, about 1.0 to 1.5 m; beds are 0.5 to 1.0 m thick and laterally continuous up to at least 10 m; sand-sized white spots of mud are suggestive of in situ weathered feldspar; color of sand is mainly 10 R 7/4 or N9 to 10 YR 6/6. Upper 1 m grades laterally into H-4c and H-4d.

1.0m H-4c (figs. 96A, B): small scale trough crossbedded (festoons) slightly gravelly medium sand, mainly N9 to 10 YR 6/6 or 10 R 7/4 in color; apparent foreset width, 20 to 30 cm; beds are typically 10 to 20 cm thick; hydrous iron oxide concentrations, 10 YR 6/6 in color, commonly occur along bottom sets, where adjacent sands show evidence of "bleaching" (fig. 96B): pelecypod resting traces (?) penetrate some bottom sets (fig. 96B) (see Curran and Frey, 1977, pls. 3b, 4b, d): multidirectional iron oxide/hydrous iron oxide liesegang bands present.

≤ 0.6m H-4d: bedded to tangentially crossbedded slightly muddy medium sand, similar in color and iron oxide/hydrous iron oxide distribution, including liesegang bands, to H-4c.

Contact between H-4 and H-5 or H-6 is slightly gradational and irregular and relatively flat.

0.7 to 0.3m H-5 (fig. 96A): lens of interbedded muddy fine sand to sandy mud, grading laterally into fine sand; beds are ≤ 2 cm thick; color is typically N9 to N8; upper contact is sharp and irregular.

0.6 to 0.3m H-6a (fig. 96D): graded bedded gravelly, slightly muddy coarse sand, containing abundant mud boulders and cobbles ≤ 0.5 m in diameter and typically 2 to 5 cm in diameter; color is 10 R 4/6 to 10 YR 6/6, due to concentration of iron oxide/hydrous iron oxide atop relatively impermeable H-5; color of boulders and cobbles is typically 5 YR 8/1; grades up into H-6b.

2.8 to 2.4m H-6b (fig. 96D): angularly tabular crossbedded slightly muddy fine sand, containing sparsely scattered mud boulders and cobbles ≤0.4 m in diameter; apparent foreset width, 0.5 to 1.0 m long; beds are typically 0.3 to 0.5 m thick and some are laterally continuous in excess of 20 m; color is 10 YR 7/4 to 10 YR 8/6 or N8 to N9, mottled 5 YR 5/6 to 5 YR 3/4 or 10 YR 7/4; color of mud boulders and cobbles is 5 Y 9/1; upper contact is sharp, slightly irregular and broadly undulatory.

3.6 to 5.6m H-7 (fig. 95B): angularly to tangentially tabular crossbedded slightly muddy medium sand; apparent foreset of angularly planar foresets is 0.3 to 0.5m; apparent foreset width, of tangentially planar foresets is ≤ 2m; beds are typically 0.2 to 0.4 m thick and some are laterally continuous in excess of 20 m; color is 5 R 5/4 to 5 R 7/4 or 10 YR 8/6 to 10 YR 6/6 or 10 YR 7/4 in places, mottled 5 YR 5/6; upper contact sharp and slightly irregular where unit is overlain by channel fillings; otherwise, unit grades up into soil horizon.

H-8 (fig. 91): large scale angularly tabular crossbedded sandy material, light in color, probably representing laterally accreted channel fillings; upper contact sharp and slightly irregular.

H-9 (fig. 91): same as above

H-10 (figs. 91, 97): large scale angularly tabular crossbedded muddy sandy, containing abundant mud cobbles and pebbles on bottom set and lower portion of foresets (fig. 97A); unit cut by several closely related normal faults, which die out about 7 m below basal contact (figs. 97 A-C); grades upward into soil zone.

3.4m+ H-11 (figs. 49, 55-58, 98 C-E): massive, faintly pisolitic mud, containing a few deformed, thin, discontinuous, horizontal mud laminae (figs. 49, 98C) and iron oxide liesegang bands; color of mud is N9; color of pisolites is 10 YR 7/4 10 YR 8/2; color of horizontal mud laminae is N10; color of liesegang bands and irregular mottling is 10 YR 8/6 to 10 YR 6/6 or 5 R 7/4 to 5 R 3/4; nearly horizontal faults present at several levels, cutting "large conical structures" and pisolites (figs. 54, 56-58): where unit is overlain by H-12, upper contact is gradational and irregular (for example, fig. 52); otherwise, upper contact is sharp and irregular.

0.2 to 1.4m H-12 (figs. 51, 53, 55, 92): massive, pyritic (?) mud; color is 10 YR 6/2, mottled 5 YR 7/2 and 5 R 5/4; unit interfingers laterally with or grades abruptly into H-11; upper contact is slightly gradational and irregular.

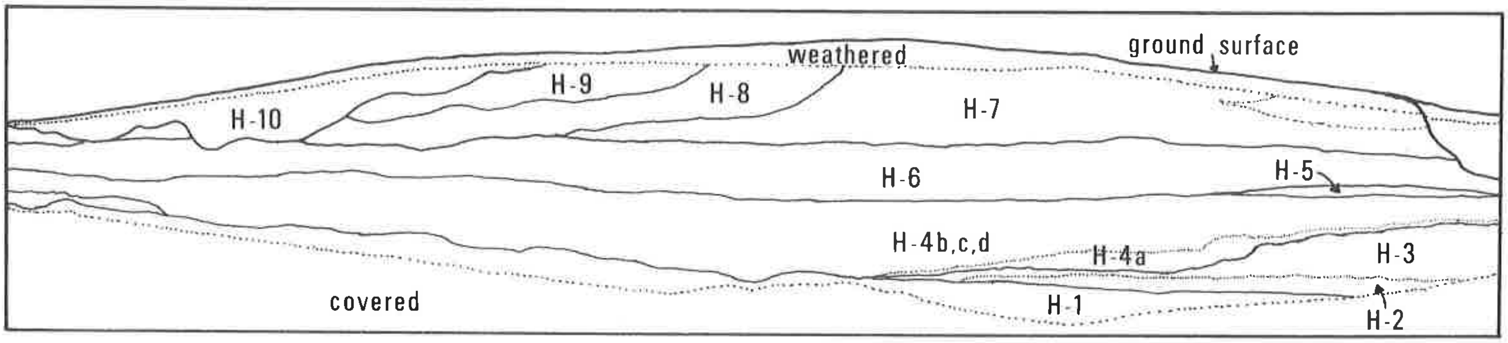
≤ 1.8m H-13 (figs. 92, 98B): interbedded medium sand and sandy mud, with a few mud beds similar to H-12 material in lower portion; many beds show signs of soft sediment deformation due to loading; mud and sandy mud beds are typically ≤ 1 cm thick; sand beds are typically 4 cm thick; color of mud beds is 10 YR 6/2; color of sandy mud beds is N8 to N9; color of sand beds is N7 to N8, mottled 10 YR 7/4 or 10 YR 6/6 to 10 YR 8/6 toward upper contact; upper contact is sharp and highly irregular.

2.5m H-14 (figs. 92, 98B): bedded to tangentially crossbedded slightly gravelly coarse sand; large mud clasts ≤ 0.4 m in diameter and typically 5 to 10 cm in diameter are concentrated at lower contact; mud clasts typically ≤ 5 cm in diameter are scattered throughout unit and tend to be concentrated along certain bedding surfaces; color of sand is 10 YR 6/6 to 10 YR 8/6 or 10 R 4/6; color of mud clasts is typically 10 YR 8/6 to 10 YR 7/6; grades upward into topsoil (?); lower contact about 7 m below ground surface.

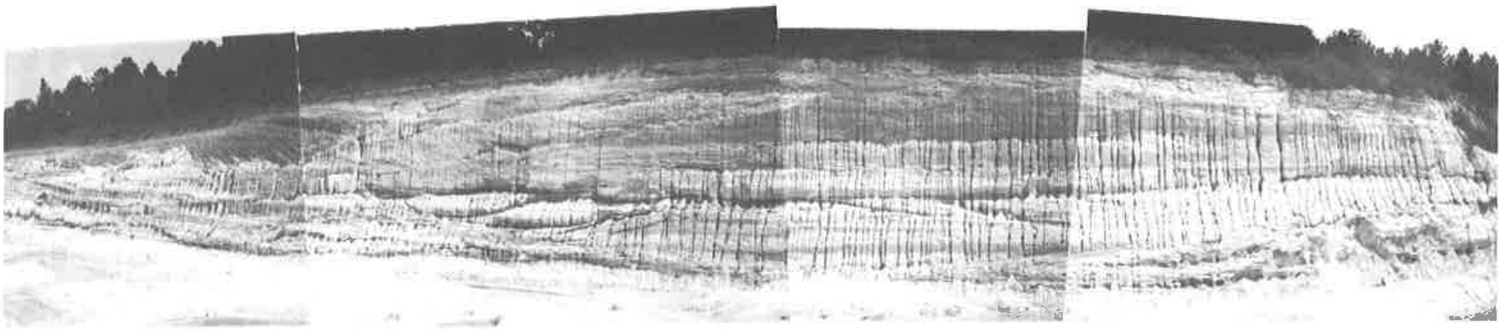
3m+ H-15*: massive faintly pisolitic mud; same as H-11, with upper contact covered.

1.5m+ H-16 (fig. 98A): tangentially to large scale angularly tabular crossbedded to bedded muddy, slightly gravelly sand, containing sparsely scattered mud intraclasts ≤ 3 cm in diameter; apparent foreset width, where present, is typically 2.5 m; observed bed thickness is 0.5 to 1.5 m; color of muddy sand is N7 to N8, mottled 10 YR 8/6 to 10 YR 4/6 or 5 YR 5/6 near upper contact; color of intraclasts is N9 to N10; upper contact is sharp and slightly irregular.

2m+ H-17 (fig. 98A): weathered bedded to small scale trough crossbedded muddy, slightly gravelly sand; bedding is poorly defined, apparently due to partial homoginization of primary structure by soil-forming processes; color is 10 YR 7/2 to 10 YR 6/2, mottled 10 YR 6/6 to 5 YR 5/6 or 10 R 4/6; grades upward into soil zone.

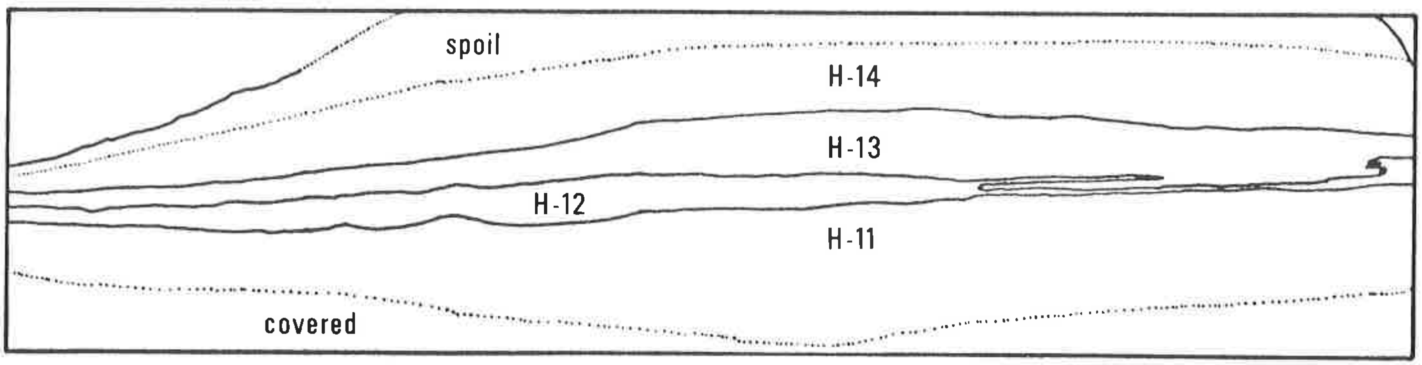


A



B

Figure 91. Portion of outcrop along eastern margin of surface mine at Locality "H". A, after B. Contact between unit H-4 and subjacent units is disconformity separating Oconee Group below from undifferentiated Barnwell Group sands above (see fig. 93A).



A

B

Figure 92. Portion of outcrop along northern margin of surface mine at Locality "H". A, after B. Contact between units H-13 and H-14 is disconformity separating Oconee Group below from undifferentiated Barnwell Group sediments above. (see fig. 93B).

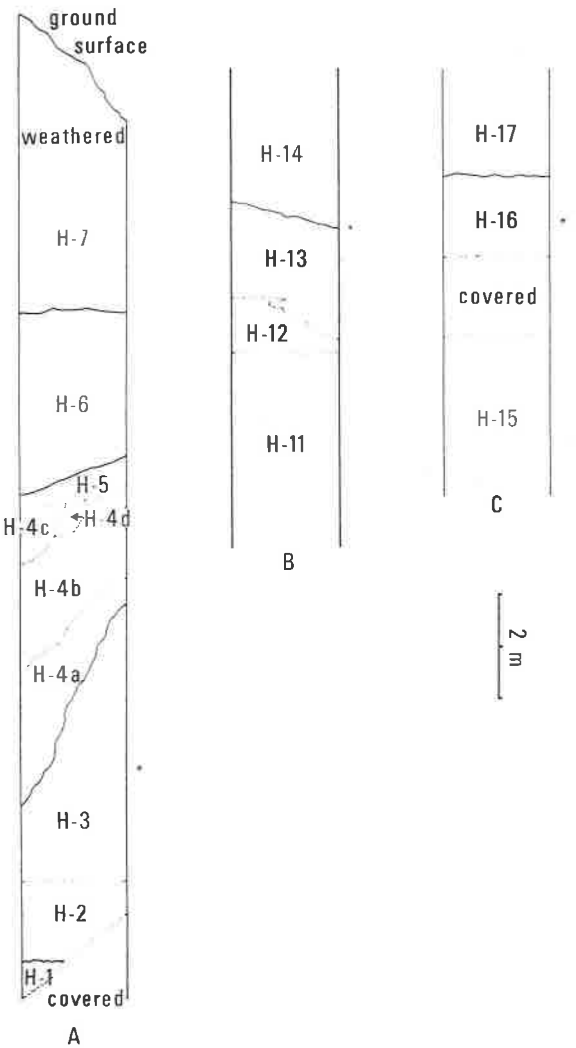


Figure 93. Representative stratigraphic sections from Locality "H". Asterisk (*) indicate points of approximately equal elevation. A, after right end of figure 91B. Contact between units H-3 and H-4a is disconformity separating Oconee Group below from undifferentiated Barnwell Group Sands above; B, after right end of figure 92B. Contact between units H-13 and H-14 is disconformity separating Oconee from undifferentiated Barnwell sediments above; C, from western margin of surface mine at Locality "H".

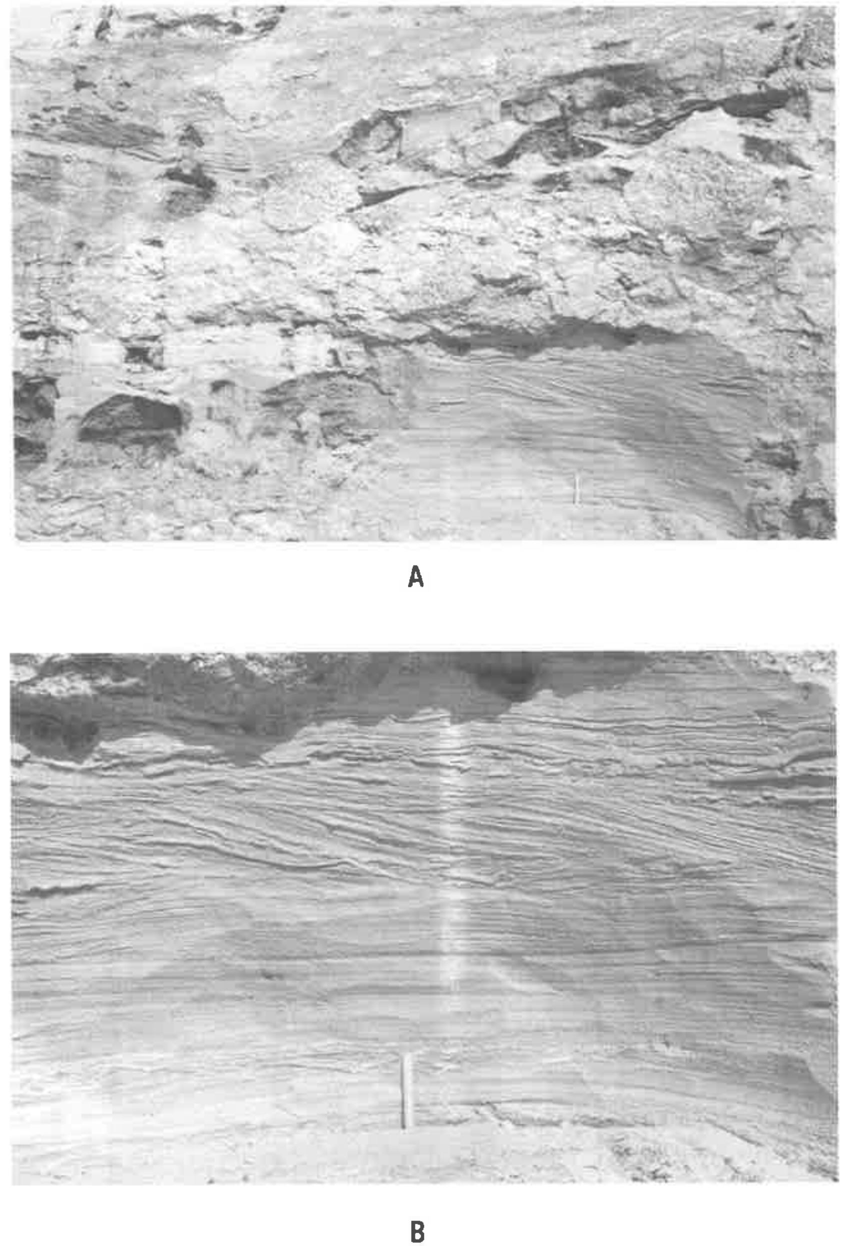
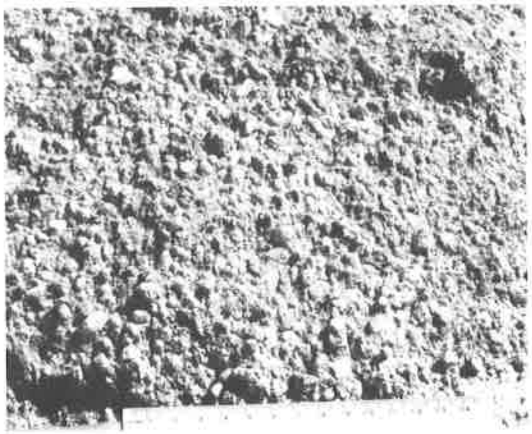
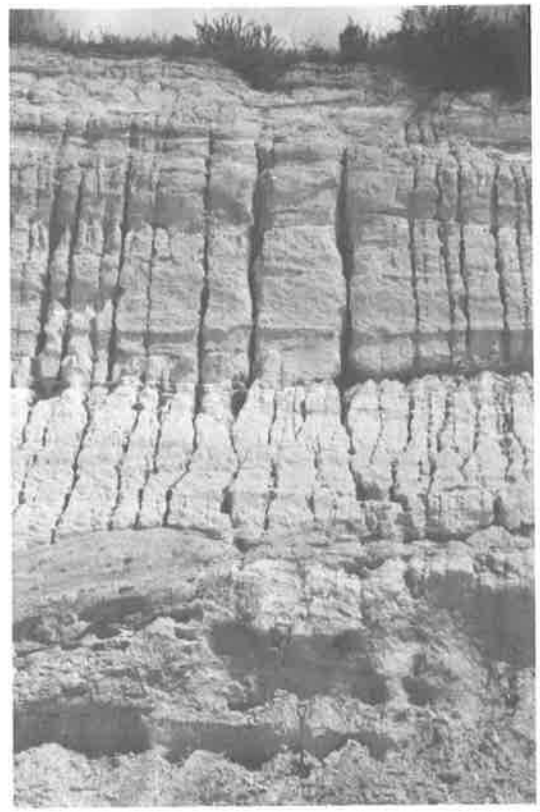


Figure 94. Sediments from Locality "H", taken from lower right of figure 91B. (see also fig. 93A). Ruler is 15 cm long and rests on upper surface of unit H-1. A, unit H-1 at base overlain by muddy sands of H-2, overlain in turn by lighter massive mud of H-3 containing pisolitic spheroids and iron concretions, overlain in turn by slightly darker sands of H-4a, containing pisolitic boulders at base of bed. H-1 through H-3 are of Oconee group. H-4a is of undifferentiated Barnwell Group; B, detail of lower right of A, showing bedding in unit H-2. H-1 at base, H-2 at top.



A



B

C

D

Figure 95. Sediments from Locality "H", taken from right end of figure 91B. (see also fig. 93A). A, detail of pisolitic spheroid from base of unit H-4a; B, stratigraphic section, showing Oconee-Barnwell disconformity in lower part, sloping irregularly to left. Shovel is 95 cm long; C, detail of disconformity, showing lighter colored sediments of unit H-3 overlain by darker sediments of H-4a. Ruler is 15 cm long; D, slickensides in massive mud from unit H-3. Scale in centimeters.

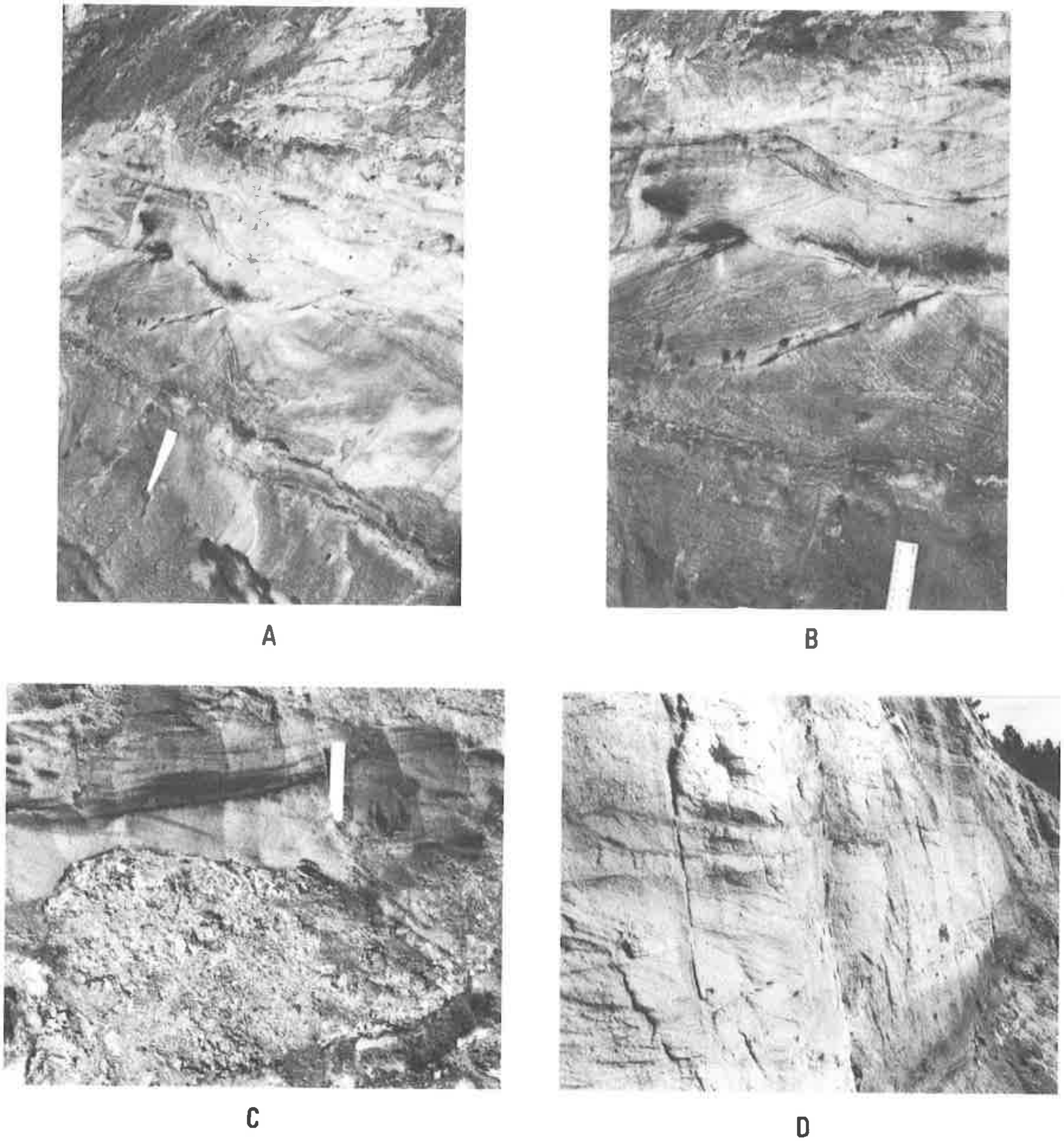
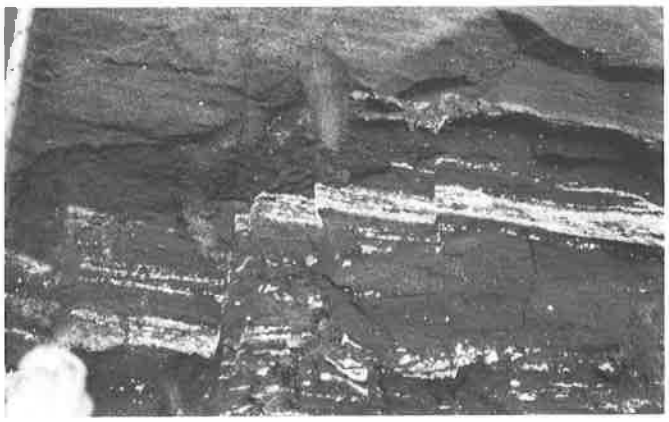


Figure 96. Undifferentiated Barnwell Group sediments from Locality "H", taken from right end of figure 91B. (see also fig. 93A). A, trough crossbedded sands of unit H-4C, overlain by interbedded muddy sand/sandy mud of unit H-5 at top. Ruler is 15 cm long. B, detail of left central portion of A. Iron oxide/hydrous iron oxide concentrated in darker areas, as along bottomsets and in liesegang bands. Probable pelecypod resting traces at center right. Scale in centimeters and inches; C, unit H-3 at extreme lower right, overlain by H-4a containing pisolitic boulder. Ruler is 15 cm; D, tabular crossbedded sands of unit H-6B.

A



B

C

Figure 97. Conspicuous channel filling (unit H-10) in undifferentiated Barnwell Group sediments at Locality "H", taken from left end of figure 91B. A, light colored bottom sets and lower foresets composed of gravel and pebble sized mud clasts. Normal faults at left center; B, C, details of faults near base of channel. Photos courtesy of Tony Atkins.

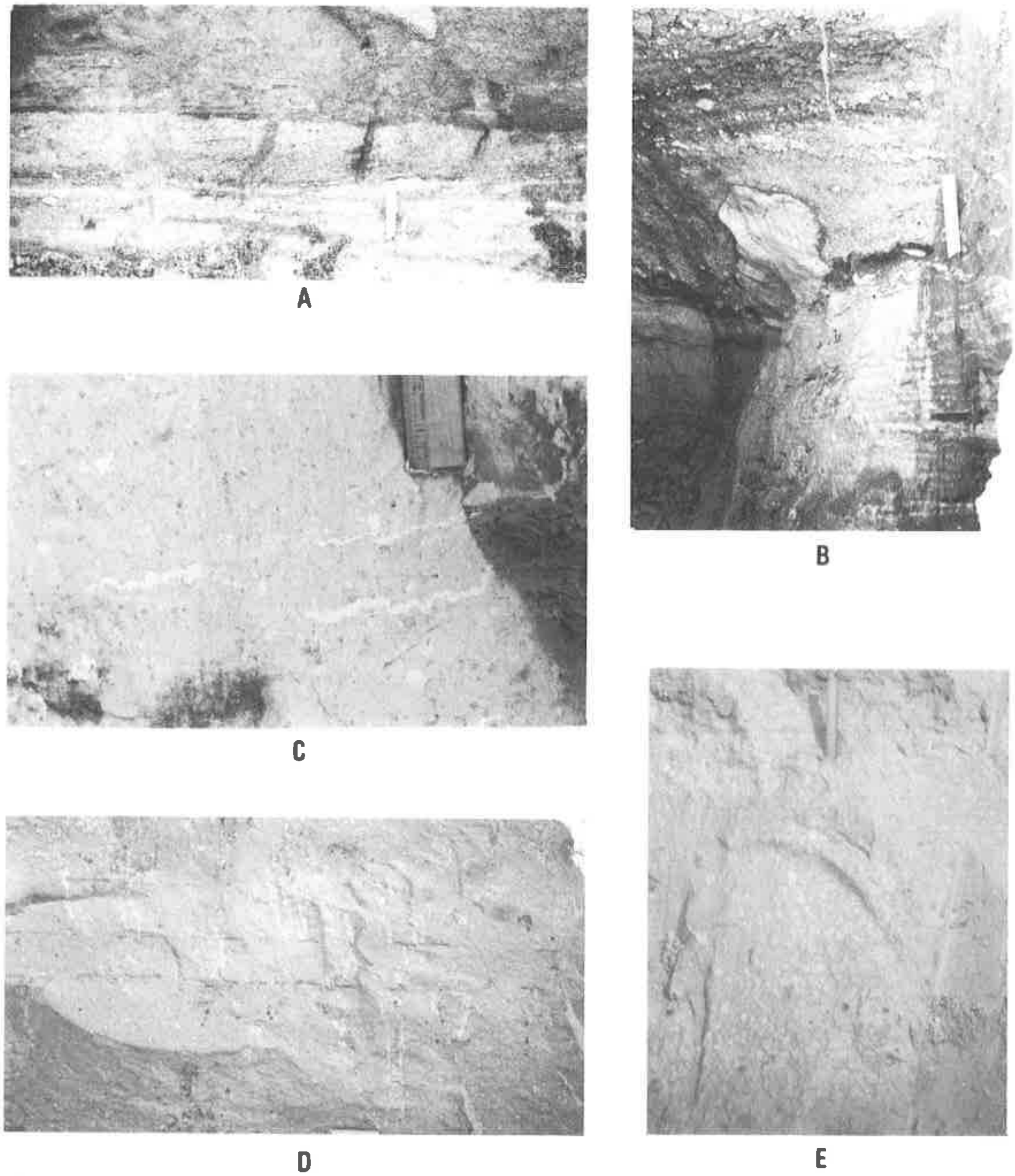


Figure 98. Sediments from Locality "H". Ruler in A, B, D, E is 15 cm long. Scale in C is graduated in inches. A, from western margin of surface mine, showing contact between lighter colored unit H-16 of Oconee Group below and darker Barnwell Group sediments above "Large sinuous shafts at center right; B, from northern margin of surface mine, showing contact between deformed bedded sediments of lighter colored unit H-13 of Oconee below and darker Barnwell above. Mud boulder rests on disconformity; C, pisolitic texture and deformed white laminae of unit H-1; D, "large conical structures" truncated by horizontal faults, unit H-11; E, breccia-like pisolitic texture, unit H-11.

APPENDIX B

Grain Size Distributions

Samples from most units described in appendix A were returned to the laboratory where grain size distributions were visually estimated using a 32x binocular microscope (see pages 1, 3). The results are presented below. Grain size distributions of a few units described in appendix A were estimated by inspection at the outcrop. These latter units are listed in appendix B as "not sampled".

Grain Size Distribution

Unit	Remarks	mud	fine sand	med. sand	coarse sand	gravel
A-1	1 m below upper contact	90	10	1		
	Rhizocorallium-like burrow fill, upper portion	10	70	15	5	
A-2	15 cm below upper contact	30	3	2	5	60
A-3	30 cm above lower contact	60	20	5	10	5
	1 m above lower contact	40	5	25	25	5
A-4		5	50	40	5	
A-5		not sampled				
A-6	sand beds	5	95			
	muddy beds	35	65			
A-7		not sampled				
A-8	15 cm above lower contact	65	10	20	5	
A-9	60 cm above lower contact, mostly lignite	100	TR			
A-10	1 m below upper contact	92	5	2	1	
	undifferentiated Thalassinoides fill, 30 cm below upper contact	highly variable				
	Trypanites sp. fill	55	5	20	10	10
	Planolites sp. A fill.	100				
A-11a	unburrowed sediment	1	1	30	65	5
	Ophiomorpha sp. fill. boulder from lower contact	55	25	20		
A-11b		20	15	40	20	5
A-12	at lower contact	70	7	10	7	5
	intercalation with A-13	50	5	35	10	
A-13	intercalation with A-12	85	5	7	3	
	30 cm above lower contact	100				
B-1	30 cm below upper contact	97	2	1		
B-2a	lower 0.5 m	20	10	15	45	10
B-2b	middle 0.5 m	40	5	30	15	10
B-2c	upper 0.4 m	30	5	40	25	1
B-3a	lower 0.3 m	10	10	60	20	1
B-3b	middle 1.2 m	5	3	60	30	2
B-3c	upper 1 m	25	1	25	45	5
B-4	lower 1.3 m	60	25	15		
	upper 0.8 m	95	5			
B-5		25	25	45	5	
B-6		98		2		
B-7		7	30	30	4	30
B-8a	upper 0.3 m	20	25	35	1	20
B-8b	15 cm below upper contact	45	5	20	25	5
	Amphorichnus sp. fill. upper portion only	1	5	15	70	10
B-9		90	10			
B-10		65	3	15	7	10
B-11		not sampled				

Grain Size Distribution

continued

Unit	Remarks	mud	fine sand	med. sand	coarse sand	gravel
C-1		not sampled				
C-2a		not sampled				
C-2b		not sampled				
C-2c		not sampled				
C-2d		not sampled				
C-3		not sampled				
C-4		not sampled				
C-5		not sampled				
C-6		not sampled				
C-7		not sampled				
D-1	50 cm below upper contact	90	8	2		
	internal grain size of intraclasts (?)	30	65	5		
	15 cm below upper contact	95	3	1		
D-2	lower portion	50	40	10		
	30 cm below upper contact	75	20	5	2	
D-3a	laminated mud beds	98	2			
	sandy mud beds	60	35	5	1	
D-3b	highly fossiliferous	65	5	30	1	1
	undifferentiated Thalassinoides fill	55	5	20	15	5
D-4		60	15	25	1	
D-5		100	TR			
E-1	upper 1.4 m	100	TR			
E-2	covered	not sampled				
E-3		not sampled				
E-4a		not sampled				
E-4b		25	3	25	45	2
E-5		25	5	25	45	
E-6	grain size distribution highly	55	TR	2	18	25
	variable	55	5	30	10	
E-6	*Thalassinoides* sp. B_2 fill	3	15	65	15	
E-7		1	5	30	65	1
F-1	central portion of unit	100	TR			
F-2		65	2	25	10	TR
F-3		not sampled				
G-1		45	10	40	5	
G-2		100	TR			
G-3	muddy beds	60	35	5		
	sandy beds	15	35	55	2	
	pisolitic spheroid	98	1	1		
	"parallel ferruginous tunnels" fill					
H-3		60	5	30	5	
H-4a		not sampled				
H-4b		5	30	65		
H-4c		1	10	55	30	5
H-4d	30 cm below upper contact	5	10	55	30	
	"parallel ferruginous tunnels" fill, hydrous iron oxide in mud fraction	40	55	5		
H-5	30 cm above base	45	50	5		
H-6a	30 cm below upper contact	10	5	15	65	5
H-6b		5	50	40	5	
H-7		5	5	50	40	
H-8		not sampled				
H-9		not sampled				
H-10	dark portions only	not sampled				
H-11	3m below upper contact	100	TR			
	1.5m below upper contact	97	3			
	"large conical structures,"	100	TR			
	discontinuous laminae	100				
	pisolites	100				
H-12						
H-13	sand beds	1	20	75	5	
	mud beds	60	40			
H-14		1	10	40	45	5
H-15		not sampled				
H-16	30 cm below upper contact	40	10	20	25	5
	"large sinuous shafts" fill	35	10	25	30	TR
H-17	20 cm above lower contact	40	5	15	35	5