

## APPLICATIONS OF TRACE FOSSILS TO INTERPRETING PALEOENVIRONMENTS AND SEQUENCE STRATIGRAPHY

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### INTRODUCTION

The main purpose of this section of the guidebook is to provide an overview of how the neoichnology of the Georgia coast may provide insights on trace fossils in former coastal and near-coastal deposits of the Barnwell Group (Eocene), using some trace fossil examples from the Irwinton Sand. As should be done with any trace fossils, these are described and interpreted on the basis of previous research on modern analogues, but are also compared with similar trace fossils reported from the geologic record. Although strict uniformitarianism is not always possible in ichnology, the morphological similarities between trace fossils of the Irwinton Sand and those of made by modern invertebrates of the Georgia coast are close enough to make preliminary hypotheses about their tracemakers and their paleoecological significance. A secondary purpose of this section is to remind geologists of the utility of trace fossils in sedimentological and stratigraphic analyses, particularly in sequence stratigraphy (*sensu* Pemberton et al., 1992, 2004; MacEachern et al., 2007b).

Trace fossils, consisting of fossil tracks, trails, burrows, and other products of organismal behavior, have been used in paleoecology, sedimentology, and stratigraphy for the past 50+ years (Seilacher, 1953, 1967; Frey, 1975; Ekdale et al. 1984; Curran, 1985; Pemberton et al., 1992; McIlroy, 2004; Miller, 2007). Most contemporary insights on trace fossils were gained originally through actualism, in which ichnologists observed modern organisms make traces in various substrates, or otherwise documented specific tracemakers and identifiable traits of their traces in the context of modern ecosystems. In this respect, Georgia is unique, having one of the best-studied suites of

modern marginal-marine traces and tracemakers in the world. Much of the neoichnology of the Georgia coast was documented during the 1960s through 1980s through the work of Robert (Bob) Frey and James Howard, formerly of the University of Georgia and Skidaway Institute of Oceanography, respectively, in addition to other collaborators (Frey and Basan, 1981; Frey and Howard, 1969, 1986; Frey and Mayou, 1971; Frey et al., 1978, 1984; Howard and Dörjes, 1972; Howard and Frey, 1975; Frey and Pemberton, 1987; Pemberton and Frey, 1985; and many other studies). Neoichnological studies on the Georgia coast lapsed temporarily with the death of Frey in 1992 and the retirement of Howard several years before then, but have resumed recently with a few focused studies on marginal-marine tracemakers and their traces (Martin, 2006; Martin and Rindsberg, 2007a,b, 2009), as well as a comprehensive volume on modern terrestrial and marine traces and tracemakers of the Georgia barrier islands (Martin, in progress). Additionally, other studies have taken more broad-sweeping overviews of bioturbation and burrowing rates of infaunal organisms of the riverine and salt-marsh estuaries of the Georgia coast (Gingras et al., 2008), or interpreted trace fossils in Pleistocene deposits by comparing these to modern traces in the same areas (Gregory et al., 2004, 2006; Martin and Rindsberg, 2009).

During the past 25 years or so, trace fossils were also applied easily to new stratigraphic paradigms, regardless of whether such models were called genetic stratigraphy, allostratigraphy, or sequence stratigraphy (MacEachern et al., 2007a). Indeed, characteristic ichnoassemblages of omission surfaces were described and recognized for their stratigraphic significance before the now-standard terminology of sequence stratigraphy

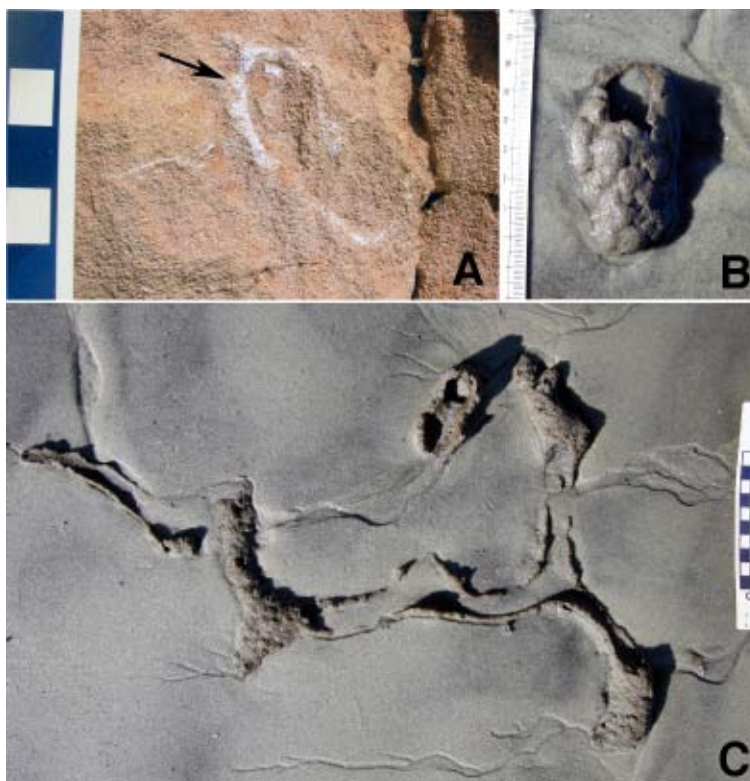
had been accepted by the mainstream geological community (Bromley, 1975; Kobluk et al., 1977; Pemberton et al., 1980; Fürsich et al., 1981; Pemberton and Frey, 1985; Savrda, 1991; Pemberton et al., 1992). Ichnofacies, which are comprised of behaviorally and ecologically consistent, recurring groupings of trace fossils (Frey and Seilacher, 1980; Pemberton et al., 1992; MacEachern et al., 2007b), have been particularly instrumental in testing identifications of: sequence boundaries (unconformities and their conformable equivalents) linked with regressions; maximum flooding surfaces associated with transgressions; and condensed sections caused by slow sedimentation rates (Pemberton et al., 1992, 2004; MacEachern et al., 2007a). Trace fossils are thus useful for sequence stratigraphy in two main respects: (1) assisting in the delineation of sequence boundaries, which are often represented by omission surfaces; and (2) helping with the correlation of laterally adjacent facies, hence better defining transgressive- and regressive-system tract sequences. More basically, most trace fossils represent in-situ behavioral interactions of organisms with their environments, thus preserving snapshots of local and more regional paleoecological conditions that typically cannot be derived from most body fossils.

### TRACE FOSSIL MODELS APPLIED TO INTERPRETING PALEOENVIRONMENTS

The outcrop at the Kamin Bracewell Mine, with its exposure of the Irwinton Sand in the Barnwell Group, provides a few examples of how trace fossils can be used for interpreting paleoenvironments. Perhaps the most commonly encountered trace fossil within the Irwinton Sand is

*Ophiomorpha nodosa*, a tubular, knobby-walled, branching burrow complex that is often observed as circular cross-sections and cylindrical, Y-shaped, or T-shaped longitudinal sections (Fig. 1A). These burrows are normally 1-2 cm in width and may be more than 50 cm long, most of which are vertically oriented (with some oblique or horizontal). Burrows also have 3-5 mm thick walls composed of clay, some hematitic and others kaolinitic. A closer examination of these walls reveals smooth burrow interiors and bumpy exteriors, with the bumps related to 1-2 mm wide, ovoid to spherical pellets composing the outer part of the burrow.

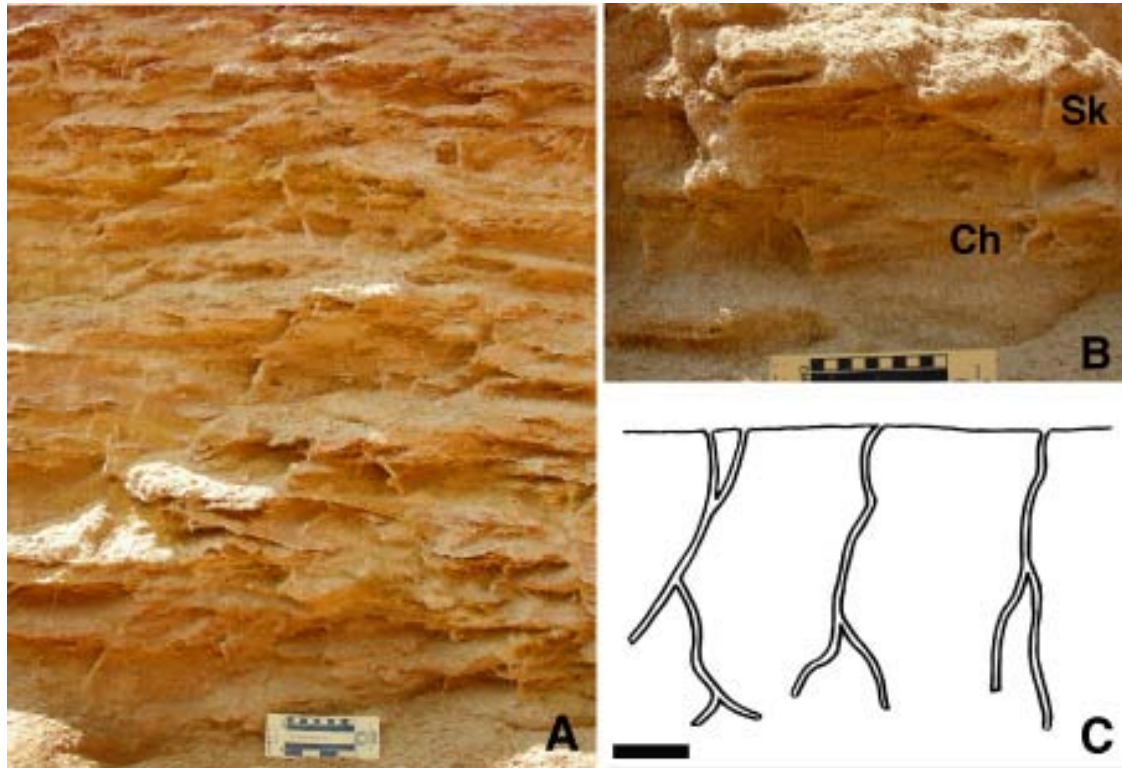
*Ophiomorpha* is interpreted as the work of callianassid shrimp or similar burrowing decapods in marine-influence environments (Weimer and Hoyt, 1964; Frey et al., 1978,



**Figure 1.** *Ophiomorpha nodosa* in the Irwinton Sand (Barnwell Group) and its modern analogues from the Georgia coast. A – Oblique section of *Ophiomorpha nodosa* in the Irwinton Sand, showing diagnostic pelletal lining (arrow) and smooth interior. B – Vertical section of modern callianassid shrimp burrow (probably from *Callinectes major*) showing similar pelletal lining and size; Sapelo Island, Georgia. C – Horizontal, branching network of callianassid shrimp burrow; Sapelo Island, Georgia. Scales in centimeters.

1984; Goldring et al., 2007). Beautiful analogues for this trace fossil are on the Georgia coast, represented by burrows of the Carolinian ghost shrimp (*Callichirus major*) and the biform ghost shrimp (*Biffarius biformis*), which are exceedingly abundant in lower intertidal and subtidal foreshore sands (Bishop and Brannen, 1993). The overall architecture of these burrow, from the sediment-water interface downward, is: (1) a narrow opening, through which the shrimp

Ghost shrimp form the knobby exteriors of the burrows by rolling sand and mud into spherical pellets (which are not of fecal origin, though) and cementing these with mucous into the burrow wall: the ghost-shrimp equivalent of bricks and mortar. Similarly, the burrow walls serve a structural function, strengthening the burrow so that it is more resistant to erosion in environments subject to constant movement of sand (Frey et al., 1978, 1984).



**Figure 2.** *Skolithos* and “Chondrites” in the Irwinton Sand (Barnwell Group) and comparison to the forms of modern polychaete worm traces from the Georgia coast. A – Vertical section of Irwinton Sand, showing numerous vertical and oblique burrows (*Ophiomorpha* and *Skolithos*) in a medium-coarse cross-bedded sandstone. B – Close-up showing vertical burrows, and *Skolithos* (Sk) interconnected with “Chondrites” (Ch). C – Sketches of burrow forms made by the polychaete worm *Heteromastus filiformis*; after Howard and Frey (1975) and Hertweck et al. (2007); scale = 2 cm.

pumps out water containing sand, mud, and its feces, seen as 5-mm long cylinders (and looking much like “chocolate sprinkles” but far less tasty), forming a low-profile mound; (2) a widened vertical burrow shaft (slightly wider than the shrimp) with a smooth-walled interior and a knobby exterior (Fig. 1B), which leads to; (3) horizontal, branching (interconnected) mazes (Fig. 1C). These burrow systems can be quite deep, with vertical shafts penetrating 2-4 m of sand before branching into horizontal networks.

These well-documented modern analogues of *Ophiomorpha* from the Georgia coast have allowed ichnologists and geologists to use this ichnogenus as a reliable indicator of shallow-marine environments (lower intertidal to shallow shelf) with actively reworked sandy bottoms. More simply, it has been applied successfully as an indicator of shoreline proximity in ancient deposits (Weimer and Hoyt, 1964; Frey et al., 1978, 1984; Goldring et al., 2007). The uppermost parts of such burrow systems are

rarely preserved, presumably because of active erosion of the top 20-30 cm at the sediment-water interface (Bishop and Brannen, 1993), but the lower parts (the vertical shafts and horizontal networks with reinforced walls) were buried deeply enough that these made it into the fossil record. Furthermore, *Ophiomorpha* does not normally occur in mud-dominated environments, nor is it in freshwater-dominated systems, with very few exceptions (Loope and Dingus, 1999). Thus any presence of *Ophiomorpha* can be used to infer broad paleoecological conditions in the Irwinton Sand, such as whether a given deposit and its stratigraphic equivalents represent marine or marine-influenced environments.

Other trace fossils in the Irwinton Sand include 3-7 mm wide and 5-10 cm long *Skolithos*, and a few forms that defy easy ichnotaxonomic labels (Fig. 2A). *Skolithos* is a simple (unbranched), straight, small-diameter, vertical burrow that has been attributed to a wide variety of tracemakers, from arachnids to marine polychaetes. Some ichnologists have even pointed out how *Skolithos*-like tubes in the fossil record could have formed as molds around plant stems or roots (Gregory et al., 2006). Nevertheless, if numerous specimens of *Skolithos* are found in close association with *Ophiomorpha* and other clearly marine-related trace fossils, it is likely attributable to marine polychaetes. On the Georgia coast, possible analogues for makers of *Skolithos* include parchment worms (*Onuphis microcephala*), palp worms (*Scololepsis squamata*), and caprellid thread worms (*Heteromastus filiformis*). All of these polychaetes make narrow, vertical burrows with thin linings of mucous, which help to support these burrows in shifting, sandy substrates of shallow-marine environments (Howard and Frey, 1975).

In some instances, however, specimens of “*Skolithos*” within the Irwinton Sand are slightly curved to semi-helical; others have some downward branching into 2-3 connected, obliquely oriented shafts (Fig. 2B). In the latter examples, the ichnogenus is different (recall the “nonbranching” part in the diagnosis for *Skolithos*), thus it must be given another name. The closest applicable name to the branched forms is *Chondrites*, as this ichnogenus consists of a single vertical shaft branching downward.

Ichnotaxonomy aside, the close proximities, similar diameters, lengths, and interconnections of *Skolithos* specimens with these *Chondrites*-like forms imply that they were probably made by the same or similar species of tracemaker. The concept that the same tracemaker can be responsible for a variety of trace fossil forms is a basic principle in neoichnology, but is uncommonly affirmed from the fossil record (Rindsberg and Martin, 2003). Fortunately, neoichnological examples from the Georgia coast clearly provide forms comparable to the Irwinton trace fossils; analogous burrows are thin, vertical shafts succeeded downward by 2-3 obliquely oriented branches, made by the aforementioned caprellid thread worm *Heteromastus filiformis* (Fig. 2C). Indeed, burrows of these and other polychaete species have been proposed as possible analogues for makers of *Chondrites* (Hertweck et al., 2007). Modern thread worms also live in slightly muddy and oxygen-depleted sediments (Frey and Howard, 1975; Bromley, 1996; Hertweck et al., 2007). Otherwise these burrows overlap well with callianassid burrows in their ecological range, as do those of other possible polychaete tracemakers, such as parchment worms (*Onuphis microcephala*) and palp worms (*Scololepsis squamata*).

## TRACE FOSSILS APPLIED TO INTERPRETING SEQUENCE STRATIGRAPHY

The preceding example from the Irwinton Sand demonstrates how neoichnology and trace fossils provide some hints for interpreting paleoenvironments, even on a small scale. On a wide scale, however, the denoting sequence boundaries or genetic packages through trace fossil assemblages must be tested over longer distances and in vertical sequences (i.e., using Walther’s Law). The most useful ichnofacies in sequence stratigraphy are substrate-controlled, in which the available substrate limited the types of tracemakers and their modes of tracemaking. These substrate-dependent ichnofacies include the: (1) *Trypanites* ichnofacies; (2) *Teredolites* ichnofacies; and (3) *Glossifungites* ichnofacies (Pemberton et al., 1992, 2004; MacEachern et al., 2007b). All three of these ichnofacies are normally associated with non-depositional or

erosional breaks, and hence may be considered as indicators of stratigraphic discontinuities. Discontinuities may be also discerned through disjunct softground ichnofacies successions, such a continental, insect-dominated assemblages (*Coprinisphaera* ichnofacies) vertically succeeded by a deeper-water marine assemblage (*Zoophycos* ichnofacies), with no clear transitions.

The *Trypanites* ichnofacies is an assemblage of marine lithic borings, which represents a hardground community in an area with laterally continuous rocky surfaces, such as reefs, beach rock, or rocky coastlines (Frey and Seilacher, 1980; Pemberton et al., 1980). In contrast, the *Teredolites* ichnofacies, although also considered as a hardground, is associated specifically with woodgrounds in marine settings, in which wood-boring bivalves or other organisms drill into xylic accumulations (Bromley et al., 1984; Savrda, 1991). The *Glossifungites* ichnofacies is a firmground trace assemblage, in which traces reflect organisms adapted to excavating dewatered (but not quite lithified) sediments (Frey and Seilacher, 1980; Pemberton and Frey, 1985). Of these three, the *Glossifungites* ichnofacies is best related to work done on the Georgia coast, as modern examples were recognized in relic salt-marsh deposits of St. Catherines and Cabretta Islands (Morris and Rollins, 1977; Frey and Basan, 1981; Pemberton and Frey, 1985). In these firmgrounds, two species of modern bivalves (*Petricola pholadiformis* and *Barnea truncata*) have bored into these 500-1,000 year old firmgrounds once these were exposed in intertidal zones.

Detailed explanations of how these ichnofacies have been used for defining sequence boundaries are beyond the scope of this study, let alone for their applications toward interpreting autocyclic processes (within-basin sedimentary dynamics) versus allocyclic processes (outside-basin changes, such as eustasy or tectonics) in a given stratigraphic sequence. For a thorough review, I recommend beginning with some of the older literature dealing with trace fossils and discontinuities (Bromley, 1975; Kobluk et al., 1977; Pemberton et al., 1980; Fürsich et al., 1981; Pemberton and Frey, 1985; Savrda, 1991; Pemberton et al., 1992), followed by the most recent summary

provided by MacEachern and others (2007b). The latter work in particular gives case examples of how trace fossils were key to interpreting sequence boundaries, regressive surfaces of erosion, correlative conformities, marine-flooding surfaces, and so on.

If laterally continuous, substrate-dependent ichnofacies or disjunct softground ichnofacies were found in the Barnwell Group, these would likely serve as excellent indicators of sequence boundaries, representing sea-level stillstands, marine flooding surfaces, and other such genetic stratigraphic surfaces and sequences. Of course, the absence of such ichnofacies in the Barnwell Group at any given outcrop does not mean sequence boundaries are correspondingly absent. Nonetheless, ichnofacies and other aspects of ichnology are additional tools to consider when undertaking a stratigraphic analysis that can test preliminary identifications of sequences boundaries and intervening sequences.

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