

---

1998

## ***Ophiomorpha nodosa* in Estuarine Sands of the Lower Miocene Calvert Formation at the Pollack Farm Site, Delaware**

Molly F. Miller  
*Vanderbilt University*

H. Allen Curran  
*Smith College, [acurran@smith.edu](mailto:acurran@smith.edu)*

Ronald L. Martino  
*Marshall University*

Follow this and additional works at: [https://scholarworks.smith.edu/geo\\_facpubs](https://scholarworks.smith.edu/geo_facpubs)

 Part of the [Geology Commons](#)

---

### **Recommended Citation**

Miller, Molly F.; Curran, H. Allen; and Martino, Ronald L., "*Ophiomorpha nodosa* in Estuarine Sands of the Lower Miocene Calvert Formation at the Pollack Farm Site, Delaware" (1998). Geosciences: Faculty Publications, Smith College, Northampton, MA.  
[https://scholarworks.smith.edu/geo\\_facpubs/66](https://scholarworks.smith.edu/geo_facpubs/66)

This Article has been accepted for inclusion in Geosciences: Faculty Publications by an authorized administrator of Smith ScholarWorks. For more information, please contact [scholarworks@smith.edu](mailto:scholarworks@smith.edu)

**GEOLOGY AND PALEONTOLOGY  
OF THE LOWER MIOCENE  
POLLACK FARM  
FOSSIL SITE  
DELAWARE**



**RICHARD N. BENSON, Editor**



# OPHIOMORPHA NODOSA IN ESTUARINE SANDS OF THE LOWER MIOCENE CALVERT FORMATION AT THE POLLACK FARM SITE, DELAWARE<sup>1</sup>

Molly F. Miller,<sup>2</sup> H. Allen Curran,<sup>3</sup> and Ronald L. Martino<sup>4</sup>

## ABSTRACT

The trace fossil *Ophiomorpha nodosa* consists of a three-dimensional network of coarsely pelleted burrows. Specimens of *Ophiomorpha*, as well as of *Skolithos linearis* and polychaete burrows, were well exposed during excavation of the Pollack Farm Site. They occur in lower Miocene sands of the Calvert Formation that were deposited in a broad tidal or estuarine channel. *Ophiomorpha* is more abundant in vertical exposures of channel-margin sands (16.5 specimens m<sup>-2</sup>; n = 11) than in channel-axis sands (0.36 specimens m<sup>-2</sup>; n = 11). This indicates that the tracemaker organism, presumably a callianassid shrimp similar to *Callichirus major*, preferred the channel-margin environment to the channel-axis environment. Environmental conditions, however, did not affect either the size of the individuals nor the thickness of the burrow walls that they constructed, as evidenced by lack of significant differences in either burrow diameter or wall thickness between *Ophiomorpha* in the channel-margin versus channel-axis facies.

At the Pollack Farm Site, *Ophiomorpha* displays the high degree of morphological variability that has been reported from other occurrences. Horizontal tunnels outnumber vertical shafts by 3 to 1. Some specimens interpenetrate, and a few have burrows within the burrows, suggesting that the burrow system was used by more than one individual.

## INTRODUCTION

The trace fossil *Ophiomorpha*, particularly the ichnospecies *O. nodosa*, is widespread and abundant in marginal marine and shallow marine sands of Cretaceous to Pleistocene age exposed along the Atlantic and Gulf Coastal Plains (e.g., Pickett et al., 1971; Curran and Frey, 1977; Frey et al., 1978; Curran, 1985; Martino and Curran, 1990; Erickson and Sanders, 1991). At the Pollack Farm Site, specimens of *O.*

*nodosa*, which closely resemble burrows of the modern callianassid shrimp *Callichirus major* (formerly *Callianassa major*), and associated trace fossils are exposed in tidal or estuarine channel sands (the cross-bedded sand unit in figure 2 of Benson, 1998). The sands, of early Miocene age, are part of the Cheswold sands, recognized in Delaware as an informal stratigraphic unit of the Calvert Formation (Benson, 1998).

The Calvert Formation at the Pollack Farm Site was well exposed in 1992 (Fig. 1), permitting detailed examination of both the physical and biogenic structures. This allowed integration of sedimentologic and stratigraphic data with information about the density and morphology of the *Ophiomorpha* burrow systems and documentation of the paleoenvironmental factors controlling *Ophiomorpha* distribution and the behavior of the tracemaker shrimp.

## Acknowledgments

We thank Kelvin Ramsey and Tom Pickett of the Delaware Geological Survey for introducing us to the Pollack Farm Site and making the logistical arrangements for our access to it. Kelvin Ramsey and Charles Savrda, Auburn University, provided helpful critical reviews of an earlier version of this paper, and Richard Benson, Delaware Geological Survey, provided editorial assistance. Heather Kelly, Smith College, assisted with the field work, and Kathy Bartus, Smith College, and Debby Juhasz, Vanderbilt University, performed word-processing for this paper with patience and care.

## DEPOSITIONAL PROCESSES AND SETTING OF THE OPHIOMORPHA-BEARING SANDS

### Description

*Ophiomorpha nodosa* is abundant in a 4-m-thick sand unit near the top of the excavation at the Pollack Farm Site (Fig. 1). The unit consists of fine to medium, well-sorted,

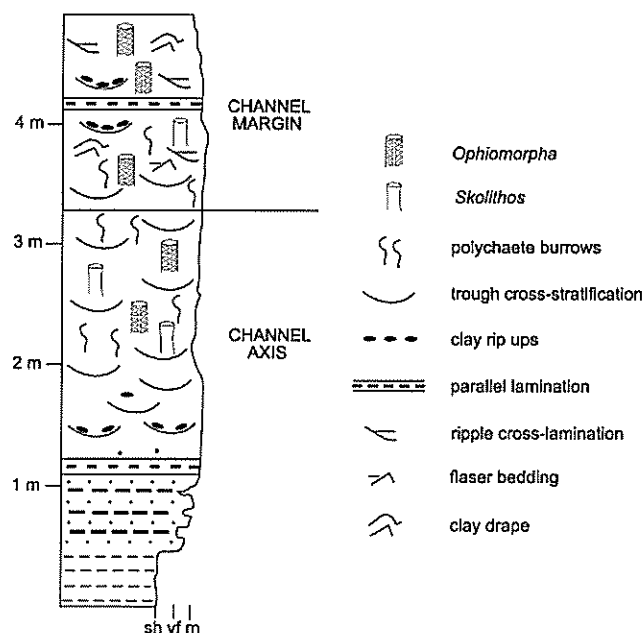


Figure 1. Stratigraphic section of *Ophiomorpha nodosa*-bearing interval (cross-bedded sand unit in Figure 2 of Benson, 1998) of the Cheswold sands of the Calvert Formation (lower Miocene) exposed during excavation of the Pollack Farm Site.

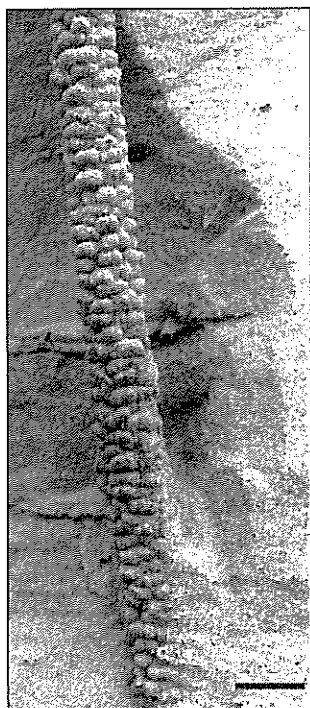
<sup>1</sup> In Benson, R.N., ed., 1998, Geology and paleontology of the lower Miocene Pollack Farm Fossil Site, Delaware: Delaware Geological Survey Special Publication No. 21, p. 41-46.

<sup>2</sup> Department of Geology, Vanderbilt University, Nashville, TN 37235

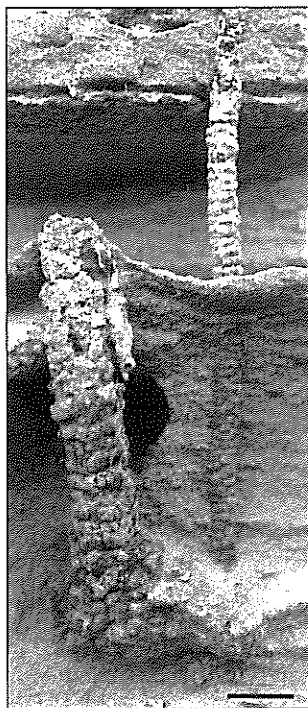
<sup>3</sup> Department of Geology, Smith College, Northampton, MA 01063

<sup>4</sup> Department of Geology, Marshall University, Huntington, WV 25755





**Figure 2.** Specimen of *Ophiomorpha nodosa* preserved in full relief. Note brick-like arrangement of pellets toward the top of the shaft; pellet arrangement becomes somewhat less uniform downward. Scale bar = 2 cm.

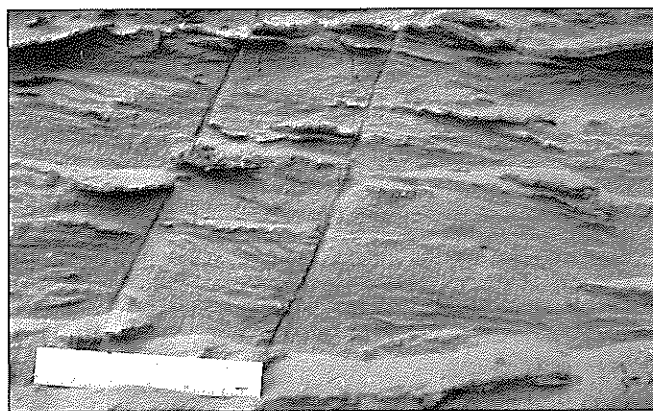


**Figure 3.** Two sizes of *Ophiomorpha*. Pellets are less uniformly packed than in Figure 2. Note enlargement where shaft merges with tunnel at base of specimen at left. Scale bar = 2 cm.

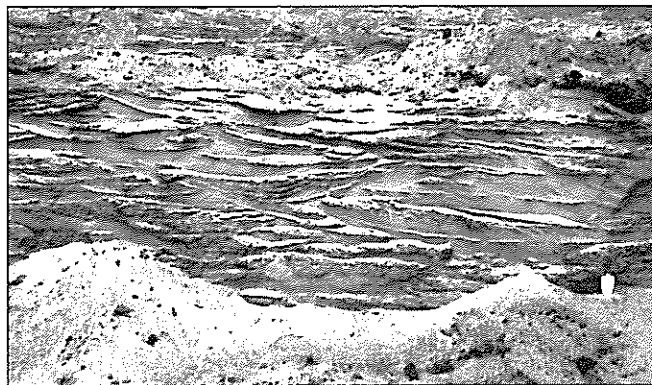
mostly quartz sand. The vertical exposure had been gently sandblasted by the wind, revealing many specimens of the relatively resistant *Ophiomorpha* in full relief (Figs. 2, 3).

Sedimentary structures within the sands include trough cross-stratification in sets up to 20 cm thick, ripple cross-lamination, and flaser bedding. Clay drapes on ripple forms are common, as are accumulations of clay clasts in the troughs of some sets of cross-stratification.

Vertical trends in the distribution of sedimentary structures within the *Ophiomorpha*-bearing unit are well defined (Fig. 1); no significant lateral changes in the 100-m-long exposure were identified. A test pit beneath the sand indicated that a 50-cm-thick clay layer is overlain by 40 cm of



**Figure 5.** Ripple cross-lamination and flaser bedding, channel-margin facies (Fig. 1). Clay drapes stand in relief. Ruler at bottom left is 15 cm.



**Figure 4.** Trough cross-stratified sands of channel-axis facies (Fig. 1); white trowel at right is 15 cm.

interbedded clay, sand, and silt. This interval coarsens upward to the *Ophiomorpha*-bearing sand by addition of sand layers. The contact between the sand and the underlying clay is therefore gradational rather than abrupt. The lowermost 60 cm of the sand is composed of ripple-laminated and trough cross-stratified sands with abundant clay clasts along the foresets. This is overlain by a 1.7-m-thick zone dominated by sets of large-scale trough cross-stratification that range from 10 to 20 cm thick and 1.0 to 1.25 m wide (Figs. 1, 4). Current direction was approximately north to south or northwest to southeast. The upper 1.6 m of the unit grades upward from large-scale, trough cross-stratified sands to flaser-bedded and ripple cross-laminated sands with clay drapes (Figs. 1, 5).

### Interpretation

Sedimentary structures in the *Ophiomorpha*-bearing unit suggest that deposition was dominated by unidirectional flow. A reasonable interpretation is that deposition occurred in a broad (> 100 m wide) tidal or estuarine channel in which the dominant flow was to the south or southeast. Large-scale, three-dimensional bedforms migrated in the central part of the channel, as recorded by the large-scale trough cross-stratified sands in the lower part of the sequence. In areas marginal to the channel, reduced flow and periods of slack water produced current ripples, flaser bedding, and clay drapes; material from the clay drapes was subsequently reworked and redeposited as rip-up clasts. Conditions of channel-margin deposition are recorded by the upper 1.6 m of the *Ophiomorpha*-bearing zone. The fine sediments at the base of the section also record channel-margin deposition; a channel interpretation is not precluded by absence of a basal scour surface.

The features of these deposits that indicate deposition in a tidal or estuarine setting versus a shoreface setting include (1) evidence of fluctuating energy conditions (clay drapes, rip-up clasts, flaser bedding), (2) unidirectional current indicators reflecting either unidirectional flow or strong domination by either ebb or flood tidal flow, and (3) absence of features formed by wave or storm activity (e.g., oscillation ripples, hummocky cross-stratification, and laminated to burrowed sequences).

The vertical succession records an episode of channel migration. The lower sands, characterized by large-scale trough cross-stratification, reflect deposition toward the cen-

ter of the channel, whereas the upper, rippled and flaser-bedded sands record deposition closer to the channel margin; however, lack of exposure of the actual channel margins and of the adjacent facies precludes detailed reconstruction of the shoreline setting of which this broad, migrating channel was a part.

### DISTRIBUTION OF *OPHIOMORPHA* WITHIN CHANNEL DEPOSITS

Cursory comparison of the number of specimens of *Ophiomorpha nodosa* in the upper channel-margin and lower channel-axis sands suggests that *Ophiomorpha* was more abundant in the channel-margin than channel-axis deposits. This observation was tested by counting the number of burrows (noting burrow orientation) in 11 one-meter square grids on vertical exposures in both the channel-margin and channel-axis deposits. The results confirmed the preliminary observation; mean densities of *Ophiomorpha* are  $16.5\text{m}^{-2}$  in the channel margin deposits vs.  $0.36\text{m}^{-2}$  in the channel axis sands. Based on a Student's t-test modified for inhomogeneity of variances, this difference is significant ( $t = 5.81$ ;  $df = 11$ ;  $p < 0.05$ ; Dixon and Massey, 1969). Channel-margin density is sufficient to impart an ichnofabric of 2 to 3, whereas ichnofabric index in the channel axis is 1 to 2 (scale of Droser and Bottjer, 1989).

The results indicate that the *Ophiomorpha*-producers, presumably callianassid shrimp, preferred the channel margin as opposed to the center of the channel, probably because of lower current velocity, more stable substrates for burrowing, and related factors. The alternative interpretation, that the observed difference in density results from differences in preservation, is not supported. In this scenario, as many *Ophiomorpha* were produced in the channel axis as in the channel-margin facies, but they were subsequently eroded. Because callianassids burrow deeply ( $>50$  cm), complete removal of their burrows by erosion would require multiple large erosional events that left no record (e.g., major scours, discontinuities) in the sedimentary sequence and that are not consistent with the in-channel accretion reflected by the trough-cross-laminated sands. Finally, if *Ophiomorpha* were formed and subsequently eroded in the channel axis, short shafts of truncated, partially eroded *Ophiomorpha* would be predicted to be common, but they are not.

Higher density of *Ophiomorpha* in facies deposited in protected or marginal environments than in those deposited in higher energy environments has been reported elsewhere from Mesozoic and Cenozoic deposits (e.g., Carter, 1978; Pollard et al., 1993). Pollard et al. (1993) presented evidence that *Ophiomorpha* producers colonized the sediment during low energy conditions in fluctuating hydraulic regimes. Their caution against interpreting a "high energy" environment based on the presence of *Ophiomorpha* is supported by our observations of facies-controlled abundances of *Ophiomorpha* at the Pollack Farm Site.

The distribution pattern of *Ophiomorpha* in the sands at the Pollack Farm Site also bears close resemblance to that of modern *Callianassa californiensis* in Mugu Lagoon, southern California. *C. californiensis* is abundant on the margins of the main tidal channel but absent from the center of the channel (Miller and Myrick, 1992). As sediment is transported during ebb and flood tidal flow in the channel axis, a significant amount of sand enters the burrows (M.F.

Miller, personal observation). Removing the passively deposited sand from the burrows requires burrower energy, probably explaining why the center of the channel is not the preferred habitat. In the transition zone in Mugu Lagoon between where its burrows are abundant and where they are absent, *C. californiensis* occurs in small, dense patches, a distribution pattern that differs from the apparently widely spaced distribution of *Ophiomorpha* (as seen in vertical section) in the channel-axis deposits at the Pollack Farm Site.

To test for differences in size and thickness of the burrow walls between *Ophiomorpha* in channel-margin versus channel-axis deposits, the internal and external diameters of specimens from the two facies were measured and compared. Mean inside diameter of specimens of *Ophiomorpha* from the channel margin sands ( $n = 97$ ) is 1.68 cm versus 1.49 cm ( $n = 7$ ) for those from the channel-axis sands. This difference is not significant ( $t = 0.913$ ;  $df = 100$ ;  $p < 0.01$ ). Mean external diameter in the channel-margin specimens is 2.40 cm ( $n = 126$ ) compared to 2.29 cm ( $n = 14$ ) for the channel-axis specimens; again, the difference is not significant ( $t = 0.162$ ;  $df = 100$ ;  $p < 0.01$ ). The mean external diameter is close to the mean external diameter of *Ophiomorpha* from the Pleistocene of South Carolina (Erickson and Sanders, 1991). There is no significant difference in burrow wall thickness between the channel axis and channel margin deposits at the Pollack Farm Site. [Channel margin mean is 0.755 cm ( $n = 97$ ) compared to a channel-axis-mean of 0.628 cm ( $n = 7$ );  $t = 0.858$ ;  $df = 100$ ;  $p < 0.01$ .]

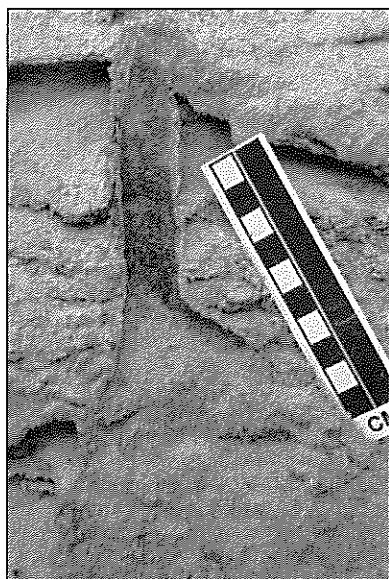
The lack of a significant difference in burrow diameter indicates that the size distributions, and presumably the age distributions, of the callianassids inhabiting the channel-margin environment were similar to those of the callianassids living in the channel-axis environment. This suggests that shrimp larvae were not excluded from the more favorable channel-margin environment, and that individuals in the less favorable channel-axis environment were able to reach full maturity.

### *OPHIOMORPHA*: MORPHOLOGIC CHARACTERISTICS AND BEHAVIORAL IMPLICATIONS

#### Description

*Ophiomorpha nodosa* at the Pollack Farm Site resembles *O. nodosa* described from Cretaceous and Tertiary deposits elsewhere (e.g. Kern and Warme, 1974; Curran and Frey, 1977; Kamola, 1984; Merrill, 1984; Curran, 1985; Barrick, 1987; Martino and Curran, 1990; Erickson and Sanders, 1991; Anderson and Droser, 1993; Pollard et al., 1993). These burrows generally are well-lined and consist of branching, three-dimensional structures with shafts, tunnels, and oblique components that sometimes interpenetrate (Figs. 6, 7). The external wall commonly is distinctively pelleted, and bulbous enlargements are common at shaft-tunnel junctions (Figs. 2, 3). At the Pollack Farm Site, outside burrow diameters range from 1.3 to 4.0 cm; internal diameters range from 0.7 to 3.5 cm.

The pellet shape and packing is variable, but pellets are exclusively in a single layer rather than double layer. Some burrows have pellets that are brick-like (Fig. 2), but typically the pellet arrangement is less well organized (Fig. 3). In some parts of the burrow systems, usually along segments of tunnels, pellets are lacking altogether.

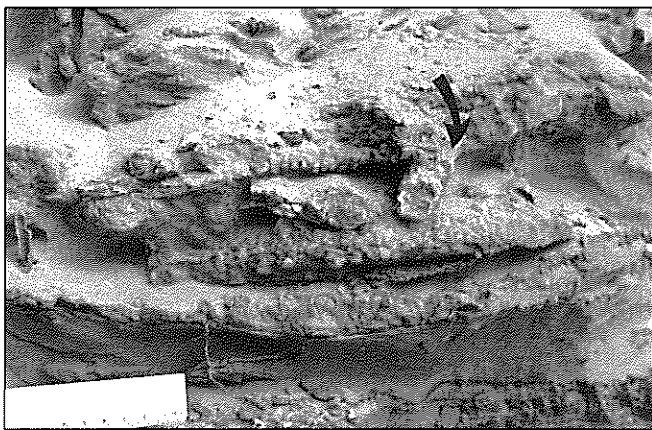


**Figure 6.** Axial section of shaft showing smooth interior and branching.

The burrow systems are dominated by their horizontal (tunnel) components (Figs. 7, 8). In the channel-margin deposits, with particularly abundant specimens of *Ophiomorpha*, horizontal components outnumber vertical components by a ratio of 3:1 ( $n = 182$ ). In the lower channel-axis deposits, the horizontal to vertical ratio is 1:3, but this observation is based on a small number of burrows ( $n = 4$ ). Tunnels are not clustered tightly around shafts, nor are they

consistently connected by shafts to form a boxwork pattern. Rather, several tunnels typically appear to branch off from vertical to oblique components at different levels.

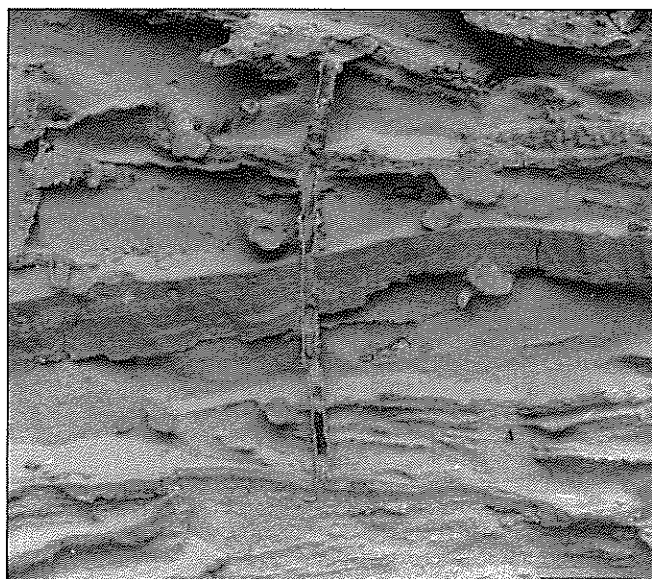
Whereas most shafts and oblique components of the burrow systems are pelleted, some tunnels connect to vertically to obliquely oriented "disorganized zones" of variable diameter (6 cm maximum) characterized by swirled sediment, commonly with clearly meniscate structure. These "disorganized zones" lack well-defined margins and pelleted burrow walls, although pellets could be found scattered in the sediment (Fig. 9).



**Figure 7.** Closely stacked *Ophiomorpha* tunnels. Arrow points to intersection. Ruler at bottom left is 10 cm.

### Behavioral Implications

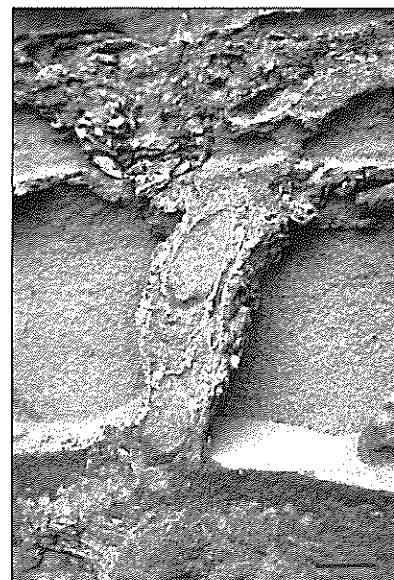
Considerable variability has been documented in *Ophiomorpha*, particularly with respect to pellet shape and packing and to arrangement of the shafts and tunnels of the burrow system. Morphology of shafts and tunnels comprising the burrow network has been found to range from predominantly vertical shafts to tiered mazes to regular and irregular boxworks to spiralled structures (Frey et al., 1978) and has been observed to change vertically within a single burrow system (Curran, 1985). Pellets may be bilobed, dis-



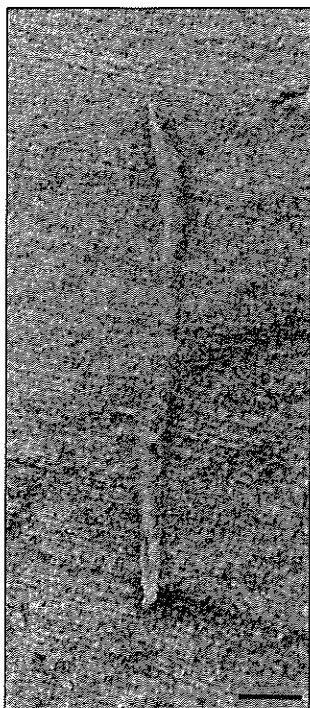
**Figure 8.** Axial section of *Ophiomorpha* shaft and cross-sections of many tunnels, channel-margin deposits. Scale bar = 5 cm.

coid, oval, or round, and burrow walls may be composed of one or two layers of pellets. Frey et al. (1978) considered the characteristics of the burrow wall and its pellets to be less variable than morphology of the burrow system and used the former as a criterion for discriminating between several ichnospecies.

Although there have been few suggestions regarding the behavioral factors controlling the morphology of *Ophiomorpha* burrow systems, it is inferred that non-pelleted burrow segments served a different function from pelleted sections (Asgaard and Bromley, 1974). The influence of substrate consistency on the abundance of pellets in the burrow wall has been well established. In sequences of alternating siliciclastic sandstones and mudstones, pellets commonly have been restricted to the sandstones, presumably because wall reinforcement was required in the sands but not in the more cohesive muds (Ager and Wallace, 1970; Kennedy and Sellwood, 1970; Kern and Warme, 1974). In this study, there was no significant difference found in thickness of burrow wall between specimens from the channel-axis and channel margin facies, implying that any differences in substrate consistency between the two environments were too subtle to have caused the *Ophiomorpha*-producers to alter



**Figure 9.** Association of meniscate-filled *Ophiomorpha nodosa* burrow with disorganized zone in upper left center. Note pelleted walls within burrow, suggesting a "burrow within a burrow." Scale bar = 1 cm.



**Figure 10.**  
*Skolithos linearis* in channel-margin sands. Scale bar = 2 cm.

rowers abandoned the burrows. In other examples, it appears that the shrimp that made the penetrating burrow subsequently used the original as well as the new burrow, thus efficiently increasing the size of the burrow network. The burrow system may have been inhabited by more than one individual simultaneously or by more than one individual at different times. Alternatively, it may have been burrowed, abandoned, and reburrowed by the same individual.

### ASSOCIATED TRACE FOSSILS

Some trace fossils other than *Ophiomorpha nodosa* are common in the Miocene sands of the Pollack Farm Site. These include *Skolithos linearis* burrows approximately 0.5 cm in diameter and thread-like vertical burrows that closely resemble previously described burrows attributed to polychaetes (Figs. 10, 11; Curran, 1985). *Skolithos linearis* and the polychaete burrows occur in both the channel-axis and channel-margin deposits, but they are particularly abundant in the latter. We found no clusters of polychaete burrows in and adjacent to the walls of *Ophiomorpha*, as reported from the Cretaceous of Delaware by Curran (1985).

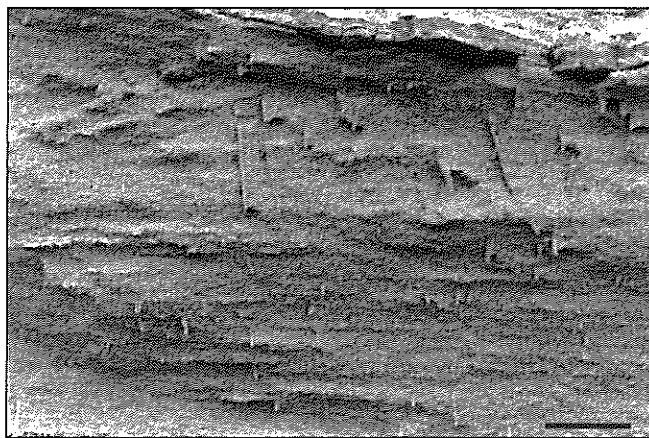
### CONCLUSIONS

(1) The 4-m-thick sand unit of the Cheswold sand section of the Calvert Formation near the top of the lower Miocene sequence formerly exposed at the Pollack Farm Site was deposited in the axial and marginal portions of a broad, migrating tidal or estuarine channel, in which the dominant flow was toward the south or southeast. Common trace fossils in the channel sands include *Ophiomorpha nodosa*, as well as *Skolithos linearis* and small-diameter burrows attributed to polychaetes.

(2) *Ophiomorpha nodosa* is significantly more abundant in sands deposited in the channel margin (mean density  $16.5 \text{ m}^{-2}$ ) than in sands deposited in the more axial portion

their method of burrow construction.

A notable characteristic of the specimens of *Ophiomorpha nodosa* at the Pollack Farm Site is that they interpenetrate (Figs. 7, 9), a phenomenon that has been illustrated previously (Curran, 1985; Pollard et al., 1993). Given the relatively low density of burrows at the Pollack Farm Site, penetration of one burrow by another could easily have been avoided by the producers. Thus, the fact that they do interpenetrate suggests that some advantage is conferred by burrowing into a pre-existing burrow. Several repenetrated specimens record the following sequence of events: (1) filling of initial burrow, (2) reburrowing, (3) filling of the second burrow. This sequence implies that both the first and second bur-



**Figure 11.** Burrows likely formed by polychaetes that occur in association with *Ophiomorpha*. Scale bar = 1 cm.

of the channel (mean density  $0.36 \text{ m}^{-2}$ ). This implies that the channel margin was a preferred habitat of the tracemaker organism, which is inferred to have been a callinassid shrimp similar to *Callichirus major*.

(3) Burrow diameter does not vary significantly between the channel-margin and channel-axis deposits, suggesting that size and age distributions of the two shrimp populations were similar. This implies that larval-adult interactions did not control the distribution of individuals and that individuals in the channel axis thrived sufficiently to reach maturity.

(4) *Ophiomorpha nodosa* at the Pollack Farm Site displays the wide range in morphology that is typical for the ichnospecies. Tunnels outnumber shafts by almost 3 to 1.

(5) Some specimens of *Ophiomorpha* interpenetrate, whereas a few others have burrows within the burrows. This suggests that these burrow systems were inhabited by more than one tracemaker, or that they were abandoned and subsequently re-occupied by the same trace maker.

### REFERENCES CITED

- 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: Liverpool, Seel House Press, Geological Journal Special Issue No. 3, p. 1-18.
- Anderson, B.G. and Droser, M.L., 1993, Variation in the geometric configurations of *Ophiomorpha nodosa*: An indicator of physical energy levels [abs.]: Geological Society of America Abstracts with Programs, v. 25, p. 269.
- Asgaard, U., and Bromley, R.G., 1974, Sporfossiler fra den Mellem Miocene transgression i Soby-Fasterhot området: Geological Survey of Denmark, Arsskrift, 1973, p. 11-19.
- Barrick R.E., 1987, Trace fossils of the San Clemente deep-sea fan, California, in Bottjer, D.J., ed., New concepts in the use of biogenic sedimentary structures for paleoenvironmental interpretation: Los Angeles, Pacific Section SEPM, p. 43-47.
- Benson, R.N., 1998, Radiolarians and diatoms from the Pollack Farm Site, Delaware: Marine-terrestrial correlation of Miocene vertebrate assemblages of the middle Atlantic Coastal Plain, in Benson, R.N., ed., Geology and paleontology of the lower Miocene Pollack Farm Fossil Site, Delaware: Delaware Geological Survey Special Publication No. 21, p. 5-19.
- Carter, C.H., 1978, A regressive barrier and barrier-protected deposit: Depositional environments and geographic setting of



- the late Tertiary Cohansey Sand: *Journal of Sedimentary Petrology*, v. 48, p. 933–950.
- Curran, H.A., 1985, The trace fossil assemblage of a Cretaceous nearshore environment: Englishtown Formation of Delaware, U.S.A., in Curran, H.A., ed., *Biogenic structures: Their use in interpreting depositional environments*: SEPM Special Publication 35, p. 261–276.
- Curran, H.A., and Frey, R.W., 1977, Pleistocene trace fossils from North Carolina (U.S.A.), and their Holocene analogues, in Crimes, T.P., and Harper, J.C., eds., *Trace fossils 2*: Liverpool, Seel House Press, Geological Journal Special Issue No. 9, p. 139–162.
- Dixon, W.J., and Massey, F.J., Jr., 1969, *Introduction to statistical analysis*: New York, McGraw Hill Book Co., 638 p.
- Droser, M.L., and Bottjer, D.J., 1989, Ichnofabric in high energy near-shore environments: measurement and utilization: *Palaaios*, v. 4, p. 598–604.
- Erickson, B.R., and Sanders, A.E., 1991, Bioturbation structures in Pleistocene coastal plain sediments of South Carolina, North America: *Scientific Publications of the Science Museum of Minnesota*, v. 7, p. 5–14.
- Frey, R.W., Howard, J.D., and Pryor, W.A., 1978, *Ophiomorpha*: its morphologic, taxonomic, and environmental significance: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 23, p. 199–229.
- Kamola, D.L., 1984, Trace fossils from marginal-marine facies of the Spring Canyon Member, Blackhawk Formation (Upper Cretaceous), east-central Utah: *Journal of Paleontology*, v. 58, p. 529–541.
- Kennedy, W.J., and Sellwood, B.W., 1970, *Ophiomorpha nodosa* Lundgren, a marine indicator from the Sparnacian of south-east England: *Geological Association Proceedings*, v. 81, p. 99–110.
- Kern, J.P., and Warne, J.E., 1974, Trace fossils and bathymetry of the Upper Cretaceous Point Loma Formation, San Diego, California: *Geological Society of America Bulletin*, v. 85, p. 893–900.
- Martino, R.L., and Curran, H.A., 1990, Sedimentology, ichnology, and paleoenvironments of the Upper Cretaceous Wenonah and Mt. Laurel Formations, New Jersey: *Journal of Sedimentary Petrology*, v. 60, p. 125–144.
- Merrill, R.D., 1984, *Ophiomorpha* and other nonmarine trace fossils from the Eocene Ione Formation, California: *Journal of Paleontology*, v. 58, p. 542–549.
- Miller, M.F., and Myrick, J.L., 1992, Population fluctuations and distributional controls of *Callianassa californiensis*: effect on the sedimentary record: *Palaaios*, v. 7, p. 621–625.
- Pickett, T.E., Kraft, J.C., and Smith, K., 1971, Cretaceous burrows—Chesapeake and Delaware Canal, Delaware: *Journal of Paleontology*, v. 45, p. 209–211.
- Pollard, J.E., Goldring, R., and Buck, S.G., 1993, Ichnofabrics containing *Ophiomorpha*: significance in shallow-water facies interpretation: London, *Journal of the Geological Society*, v. 150, p. 149–164.