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Graphoglyptid Burrows in Modern Deep-Sea Sediment

Abstract. *The complex, highly patterned, invertebrate burrow systems known as "graphoglyptids" in ancient sedimentary rocks have now been recovered in box cores of modern deep-sea sediment.* Spirorape, Cosmoraphe, *and* Paleodictyon *occur as grooves in the tops of washed cores, and they apparently were produced and maintained as horizontal tunnel systems just a few millimeters below the sediment surface. These burrows, which are important as indicators of deepwater sedimentary environments in ancient strata, have been predicted in the modern deep sea but have not been found there until now.*

Complex, geometrically patterned burrow systems of benthic invertebrates are especially characteristic of deep-sea environments, and they are abundantly preserved in ancient flysch deposits all over the world (*1–4*). The most spectacular of the flysch trace fossils are those burrows belonging to the group known informally as "graphoglyptids" (*5*), highly organized systems of tunnels arranged in meandering, radiating, or anastomosing netlike patterns. Such burrow systems are very important in paleoecological and paleoenvironmental investigations as indicators of deepwater sedimentary environments. Graphoglyptid burrows have been predicted in the modern deep sea on the basis of ancient trace fossils (*5*), but heretofore they have not been found there.

I report here the first recoveries of modern graphoglyptids from the deep ocean floor. The ichnogenera *Spiroraphe*, *Cosmoraphe*, and *Paleodictyon* (*6*) were collected in deep-sea box cores on four Scripps Institution of Oceanography cruises between March 1975 and November 1978 (*7*). All the graphoglyptids occurred in pelagic calcareous ooze, and all were observed as surface features on the box core tops. None of the burrows contained the animal responsible for producing it.

Spirorape (Fig. 1, A and B) may be the most abundant graphoglyptid in modern sediment as it is one of the most common biogenic structures on deep-sea box core surfaces (*8*). Several specimens of the tightly coiled trail *S. involuta* [figure 5a in (*5*)] were collected on each of the four cruises at depths ranging from 3358 to 5119 m (Table 1). *Spirorape involuta* is distinctive in that the course of the trail spirals inward to the center, where it makes a 180° turn and spirals outward again alongside the earlier trail. In the box cores, the trail was always about 2 mm wide and the circular outline of the whole structure varied from 3 to 13 cm in diameter. In nearly every case *S. involuta* occurred in the form of rounded, spiraling furrows on the core tops. No vertical repetition of *Spirorape* specimens, such as stacked tiers of spirals, was observed in any box core.

Cosmoraphe (Fig. 1C), a uniformly meandering horizontal trail, is not as abundant in modern deep-sea sediment as *Spirorape*. Partial specimens were recovered in box cores from both the Pacific and the Atlantic at depths ranging from 4296 to 4742 m (Table 1). All occurred as regularly meandering grooves incised several millimeters into the surficial sediment on the box core tops. One specimen in core INMD 98BX (Fig. 1C) from the Gambia Abyssal Plain in the central Atlantic was particularly noteworthy in that the first- and second-order meanders that characterize the ichnogenus (*6*) were easily recognized. In this occurrence the grooved trail itself was about 2 mm wide; the amplitude of the first-order meanders was about 30 mm, and that of the second-order meanders was about 5 mm. This specimen appears to fit the diagnosis for *C. sinuosa*, which has been reported in Eocene deep-sea deposits of Spain by Seilacher [figures 3a and 4, a and b, in (*5*)] and Crimes [plate 7c in (*3*)] and in Eocene flysch of Poland by Książkiewicz [figure 2, a and b, and plate 3, a and b, in (*1*)].

Paleodictyon (Fig. 1D) is a very distinctive burrow system with horizontal tunnels anastomosing to form a regular net with hexagonal mesh. The first *Paleodictyon* specimens to be recognized in samples collected from a modern depositional environment were found in two cores from the South Atlantic, one (sample INMD 109BX) on the western flank of the Mid-Atlantic Ridge and the other (sample INMD 128BX) on the northern flank of the Rio Grande Rise (Table 1). As with the *Spirorape* and *Cosmoraphe* specimens, all the *Paleodictyon* specimens appeared as grooves in the tops of the box cores. Two specimens of different sizes occurred in core INMD 128BX (Fig. 1D). Both appeared to be *Paleodictyon* (*Glenodictyum*) *minimum*, which is common in late Cretaceous and Tertiary flysch deposits [figure 14f and plate 2a in (*5*)]. One was a patch of 1-mm-wide polygons 3 cm in diameter; the other was a patch of 2-mm-wide polygons 9 cm in diameter. In both cases the structures had been partially washed away by water trapped in the box core at the time of collection, but the hexagonal shape of several of the poly-

Table 1. Occurrences of graphoglyptid burrows in deep-sea box cores.

Core	Burrow type	No. of specimens	Ocean	Latitude	Longitude	Water depth (m)	Sediment type	$CaCo_3$ content of surface sediment (%)
ERDC 108BX	*Spiroraphe*	2	Pacific	1°45′S	160°48′E	3383	Nannofossil ooze	83.0
ERDC 125BX	*?Spiroraphe*	2	Pacific	0°0′	161°0′E	3668	Nannofossil ooze	82.8
ERDC 128BX	*?Spiroraphe*	2	Pacific	0°0′	161°26′E	3732	Nannofossil ooze	81.6
ERDC 129BX	*Spiroraphe*	1	Pacific	0°0′	161°59′E	4169	Nannofossil ooze	78.7
PLDS 90BX	*Spiroraphe*	1	Pacific	0°59′N	135°5′W	4296	Nannofossil ooze	79.1
PLDS 90BX	*Cosmoraphe*	1	Pacific	0°59′N	135°5′W	4296	Nannofossil ooze	79.1
INMD 59BX	*Spiroraphe*	1	Atlantic	33°29′N	32°18′W	3358	Nannofossil ooze	89.2
INMD 70BX	*?Spiroraphe*	1	Atlantic	34°58′N	24°19′W	5119	Nannofossil ooze	75.0
INMD 94BX	*Spiroraphe*	1	Atlantic	16°43′N	51°35′W	4391	Nannofossil ooze	64.5
INMD 98BX	*Cosmoraphe*	1	Atlantic	15°31′N	42°57′W	4742	Nannofossil ooze	65.3
INMD 106BX	*?Spiroraphe*	1	Atlantic	2°44′N	20°56′W	4702	Foraminferal ooze	72.4
INMD 109BX	*Paleodictyon*	1	Atlantic	5°28′S	15°58′W	3895	Foraminferal ooze	89.1
INMD 121BX	*Spiroraphe*	2	Atlantic	28°59′S	32°1′W	3908	Nannofossil ooze	81.1
INMD 123BX	*Spiroraphe*	1	Atlantic	29°31′S	33°14′W	3361	Nannofossil ooze	91.4
INMD 125BX	*Spiroraphe*	2	Atlantic	29°44′S	33°52′W	3535	Nannofossil ooze	85.8
INMD 128BX	*Paleodictyon*	2	Atlantic	29°55′S	34°21′W	1436	Pteropod ooze	

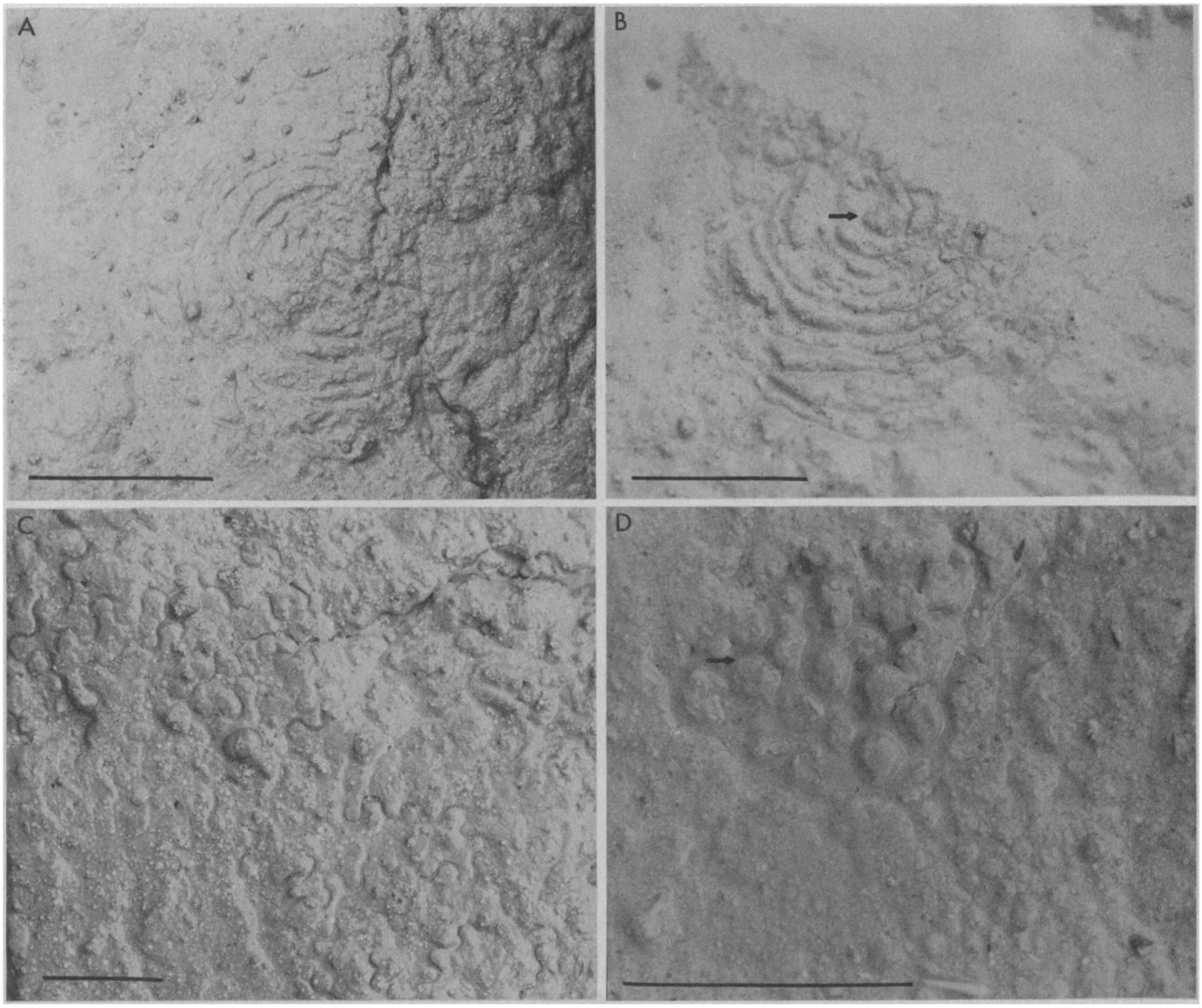

Fig. 1. Graphoglyptid burrows recovered in deep-sea box cores. (A) *Spiroraphe involuta* in calcareous ooze (core INMD 94BX) from 4391 m of water in the North Atlantic; (B) *Spiroraphe involuta* in calcareous ooze (core INMD 123BX) from 3361 m of water in the South Atlantic (arrow indicates 180° turn in the center of the spiral); (C) *Cosmoraphe sinuosa* in calcareous ooze (core INMD 98BX) from 4742 m of water in the North Atlantic; and (D) *Paleodictyon minimum* in calcareous ooze (core INMD 128BX) from 1436 m of water in the South Atlantic (arrow indicates hexagonal mesh). Scale bar equals 2 cm.

gons was still discernible. Another partially washed specimen of *P. minimum* was recovered in core INMD 109BX; it was about the same size as the smaller one in core INMD 128BX.

The mode of preservation of the three kinds of graphoglyptids listed here raises a question about whether they represent traces of vagrant epifaunal organisms or shallow-burrowing infauna. Seilacher (5) has demonstrated convincingly that most graphoglyptids in the ancient record were produced in (as opposed to on) the sediment, yet the modern ones reported here have been observed only on box core surfaces. Although the box-cored sediment at all sites was heavily burrowed by infaunal organisms (8), no graphoglyptid burrows were recognized deep within the sediment. On the other hand, the distinctive horizontal geometries of *Spiroraphe*, *Cosmoraphe*, and *Paleodictyon* have not been reported from the thousands of deep-sea bottom photographs that have been investigated for surficial biogenic sedimentary structures by many workers (8-10).

Kitchell *et al.*, who studied surficial traces in bottom photographs from high latitudes, discovered (10, p. 178) that "those trace types identified in the fossil record as most efficient, i.e., spirals and meanders, were conspicuously absent at all depths in the Arctic and present at all depths in the Antarctic." They concluded that paleoenvironmental reconstructions based upon supposed deep-water trace fossils in ancient rocks may be erroneous. However, they apparently overlooked the fact that graphoglyptids, which are among the most abundant and characteristic of deep-sea trace fossils in the rock record, actually are burrows and therefore not normally discernible in sea floor photographs. Thus, especially in light of the discovery of modern graphoglyptids reported here, the conclusions of Kitchell *et al.* (10) are inconclusive.

Rona and Merrill (11) have presented several photographs of the abyssal sea bottom near the Mid-Atlantic Ridge which contained regular arrays of evenly spaced black dots arranged in a rhombic pattern. These dots could be holes representing the surface expression of infaunal burrow systems resembling *Paleodictyon*. The photographs were taken in 3200 to 3700 m of water about 26° north of the equator. Although Rona and Merrill allowed for the possibility that these geometric structures might be "worm burrows" (11, p. 373), they concluded that the structures most likely were the collapsed or compressed bodies of unidentified hexactinellid sponges. Interestingly, however, Seilacher [figure 14h and plate 2, b through d, of (5)] illustrated several Eocene examples of the trace fossil *Paleodictyon* (*Ramidictyon*) *nodosum* with vertical outlets arranged in exactly the same pattern and with approximately the same dimensions as the black dots in the deep-sea photographs.

A similar array of holes was recovered by McMillen (12) in a deep-sea box core from 1849 m in the Cayman Trough in the northwestern Caribbean Sea, but he observed no infaunal burrow system associated with the holes. The rhombic arrangement of McMillen's holes differed slightly from that in the bottom photographs and in fact more closely resembled some Cretaceous specimens of *Paleodictyon* (*Ramidictyon*) *tripatens* illustrated by Seilacher [figure 14g and plate 2e of (2)]. In *P. tripatens* there are three vertical outlets per hexagon located at every other branching point, whereas in *P. nodosum* there are six vertical outlets per hexagon located in the center of each straight limb of the mesh.

No vertical components were observed in the *Paleodictyon* specimens in box cores INMD 128BX and INMD 109BX, described earlier in this report. The near-surface position of these burrows implies that the vertical outlets were very short and therefore easily eroded away by the agitation of water trapped inside the box cores as the cores were being retrieved, a process which typically takes several hours.

Seilacher (5) envisions graphoglyptid burrows not as deposit-feeding trails like the well-known *Helminthoida* of the European flysch nor as mere dwelling structures like the very common *Ophiomorpha*. Rather, he suggests that graphoglyptid tunnel systems represent nets constructed by infaunal invertebrates for the specific purpose of trapping (or perhaps even farming) a mobile food supply of meiobenthic or microbenthic organisms such as protists or microscopic arthropods and worms, which live and travel around between the sand-sized sedimentary particles. Such a trap or farm would not have to be deep within the mud to be effective; indeed, because of the very shallow burrowing habits of most meiobenthos and microbenthos, the trap may be most effective when positioned as close to the sediment surface as possible without being exposed. The graphoglyptids in the box cores bear a striking resemblance to the burrows of the living polychaete *Paraonis*, which do serve as traps or farms (13) and which were used by Seilacher (5) as the basis of his ethologic model for graphoglyptids.

The modern graphoglyptid burrows reported here were observed as grooves incised 2 or 3 mm into the surficial sediment of the box cores. None possessed ostensible burrow linings composed of mucus or any other substance, although the tunnel walls were sufficiently durable to survive core recovery without being destroyed entirely. Moreover, in the best-preserved specimens the tunnel walls were smooth and uniform in diameter; this result suggests that these were not burrows of deposit feeders. Very watery, fine-grained material apparently caps the abyssal sea bottom, and this soupy surface layer (no more than 1 or 2 mm thick) commonly is washed away when the water is drained from the box core prior to opening onboard ship. Thus, *Spiroraphe*, *Cosmoraphe*, and *Paleodictyon* very likely are infaunal burrow systems positioned just beneath the veneer of sediment at the deep-sea floor.

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