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CHAPTER 16

PROBLEMS IN INTERPRETING UNUSUALLY LARGE BURROWS

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SYNOPSIS

Although marine burrows of unusually large dimensions have long been known in certain areas, they are probably much more widespread in the rock record than is generally recognized. Such burrows constitute a heterogeneous group, having little in common other than "exceptional" size. Yet their size alone unites them in difficulty of interpretation: e.g., densely spaced ?dwelling burrows or combined dwelling-escape burrows as much as 12 cm in diameter and 5 m long; vertical dwelling burrows only 0.5 cm in diameter but up to 9 m long; possible escape structures as much as 24 cm in diameter and 3 m long, subsequently penetrated in some cases by secondary burrow-like structures.

Numerous special problems are encountered in the study and interpretation of burrows of these extreme dimensions: (1) field exposure and accessibility, so that the full extent, or a large part, of the structures can be studied; (2) preservation of the burrows in continuity, not merely in places where they pass through certain beds or within concretion horizons; (3) the "fossilization barrier"; our knowledge of comparable modern structures of similar dimensions or of the animals responsible for them is negligible; and (4) the possibility that certain of these unusual structures were formed by

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The authors are here listed alphabetically; respective parts written by each are indicated in the text, except that all collaborated on the synopsis, introduction, and conclusions.

physical rather than organic processes; again, our criteria for comparisons are limited.

The examples selected by us—from the Permian of Montana, Idaho, and Wyoming, the Cretaceous and Paleocene of northwestern Europe, and the Pleistocene of North Carolina

—are intended primarily (1) to call additional attention to such intriguing structures, and (2) to illustrate some of the problems involved in interpreting their origin and function. Hopefully, future work will solve many of these problems.

INTRODUCTION

Cross-cutting tubular sedimentary structures are in many ways difficult to interpret in the geological record, especially when their dimensions exceed those of structures usually found in modern environments. The first question that arises is: are they of organic or inorganic origin? Of course, both types are possible. Because this book is about trace fossils, we focus here on what we feel to be structures of organic origin, or physical structures that exhibit strikingly burrow-like features.

When the geologist in fact encounters a possible burrow so large that its diameter may be measured in decimeters or its length in many meters, a first thought is apt to be either "this must be artificial or inorganic," or "this was made by a fairly large vertebrate animal." The popularly known "corkscrew" burrow *Daemonelix* is a classic example of the latter (see Fig. 15.4), and other vertebrate burrows of very large size have been documented. But these occur in continental sediments. Where the structure is found in marine sediments, and bears attributes of smaller burrows made commonly by invertebrate animals, one's awe increases. And then the problems in interpretation begin to unfold.

Presence of the actual trace-making organism buried and preserved within the burrow is conclusive; however, field experience in the search for such evidence usually reveals that the organism was effectively elusive. In the absence of body fossils representing animals that may have been responsible for the structures, what is the evidence that links the structures to burrowing organisms?

The principle of uniformity adds very little in resolving the problem. Our knowledge of comparable modern structures of similar dimensions, or of the animals responsible for such structures, is negligible. In the rock record, we may even have problems in determining the size of the tracemaker. Difficulties inherent in observing such structures in situ in modern marine environments currently preclude our making comparisons of the modern analog with possible fossil examples (see Chapter 2). Furthermore, circumstances of preservation and exposure on the outcrop obscure structures of this kind; rocks are too soft or too hard, fractured, jointed, and erodable, so that complete exposure of single elongate burrows or burrow systems is unlikely. Also, only rarely may we totally discount the possibility that the large structures are physical in origin, masquerading as biogenic sedimentary structures. (See Chapter 5.)

We of course are not the first to observe structures of this kind. The "paramoudras" of Northern Ireland have been known for a century and a half; Seilacher (1964) interpreted some burrows to be 4 m long, in turbidites. But each of us has been awed by such structures, and have spent considerable time pondering their meaning. We still have many questions; but we decided to collaborate here in the hope of drawing increased interest from other quarters, thus accelerating further work on such enigmatic burrows. Our framework for discussing the structures is mainly stratigraphic, oldest specimens first.

PERMIAN BURROWS

Raymond C. Gutschick and Lee J. Suttner

Peculiar cylindrical sedimentary structures, as much as 6 m long, are common in sandstone, chert, and shale-mudstone facies of Permian rocks in southwest Montana, southeast Idaho, and northwest Wyoming. These enigmatic structures have been regarded both as organic and inorganic in origin. Similar cylindrical structures in (?)Permian siltstones of western Colorado "were probably formed by the movement of fresh or salt water or silt through the bed, because other agencies fail to explain the structures satisfactorily" (Gableman, 1955, p. 223). Based on morphology and distribution, such cylindrical columns were regarded as burrows of bottom-dwelling animals by Cressman and Swanson (1964), primarily because they could not envision a suitable inorganic process. Conversely, Yochelson (1968) did not consider the large size and regularity of the columns to be indicative of burrows, primarily because he could not find a suitable organism. Gutschick and Suttner (1972) concluded that the structures are burrows, and Peterson (1972, p. 70) referred to the large-scale, vertical, "boiler-pipe concretions" as evidence of burrowing.

Burrows or burrow-like forms such as those mentioned above are most abundant in the shelf facies of the Shedhorn Sandstone, and they occur in the platform facies of the Tosi Chert and Retort Phosphatic Shale Members of the Phosphoria Formation. All these units intertongue westward —in complicated fashion—with slope-basinal chert, phosphorite, mudstone, and carbonate sediments (Figs. 16.1 and 16.2). The Shedhorn was deposited in water less than 50 m deep, most probably less than 9 m, within 160 km (100 mi) offshore (Cressman and Swanson, 1964, p. 366). Fossil evidence suggests deposition on a firm bottom in clear water, in beach or near-beach environments (Yochelson, 1968, p. 617). Certain Shedhorn sand bodies have also been interpreted variously as sheet sands, longshore sands, and barrier island complexes (Peterson, 1972; Sheldon, 1972). Among the body fossils present, clams, snails, scaphopods, and brachiopods are the most abundant ones reported from the Shedhorn and Tosi; sponge spicules, bryozoans, and fish remains are also found (Yochelson, 1968).

A wealth of detailed stratigraphical, geochemical, and paleontological information is available for in-depth study of the relations of Permian strata in the northern Rocky Mountains: McKelvey et al. (1959), Sheldon (1963), Cressman and Swanson (1964), McKee et al. (1967a, 1967b), Yochelson (1968), Peterson (1972), and references cited by them.

BURROW CHARACTERISTICS

Observations on the Permian structures include size and shape, configuration (within and between beds), fill, and host rock composition, textures, and structures, and body fossil and trace fossil associations. The array of large structures may represent the work of more than one kind of trace-making organism. Our observations supplement those of Cressman and Swanson (1964, p. 351–354, Figs. 141A–H); however, the maximum length that they reported is only 1.5 m. Total vertical extent of a single long burrow is obscured by partial erosional destruction, so that only in exceptional, fortuitous cases does the rock exposure parallel the structure's entire length.

The large burrows are elongate, cylindrical, columnar structures having an oval, elliptical, or circular cross section. Maximum diameter ranges from 2.0 to 12.5 cm; the mean value lies between 5 and 8.5 cm.
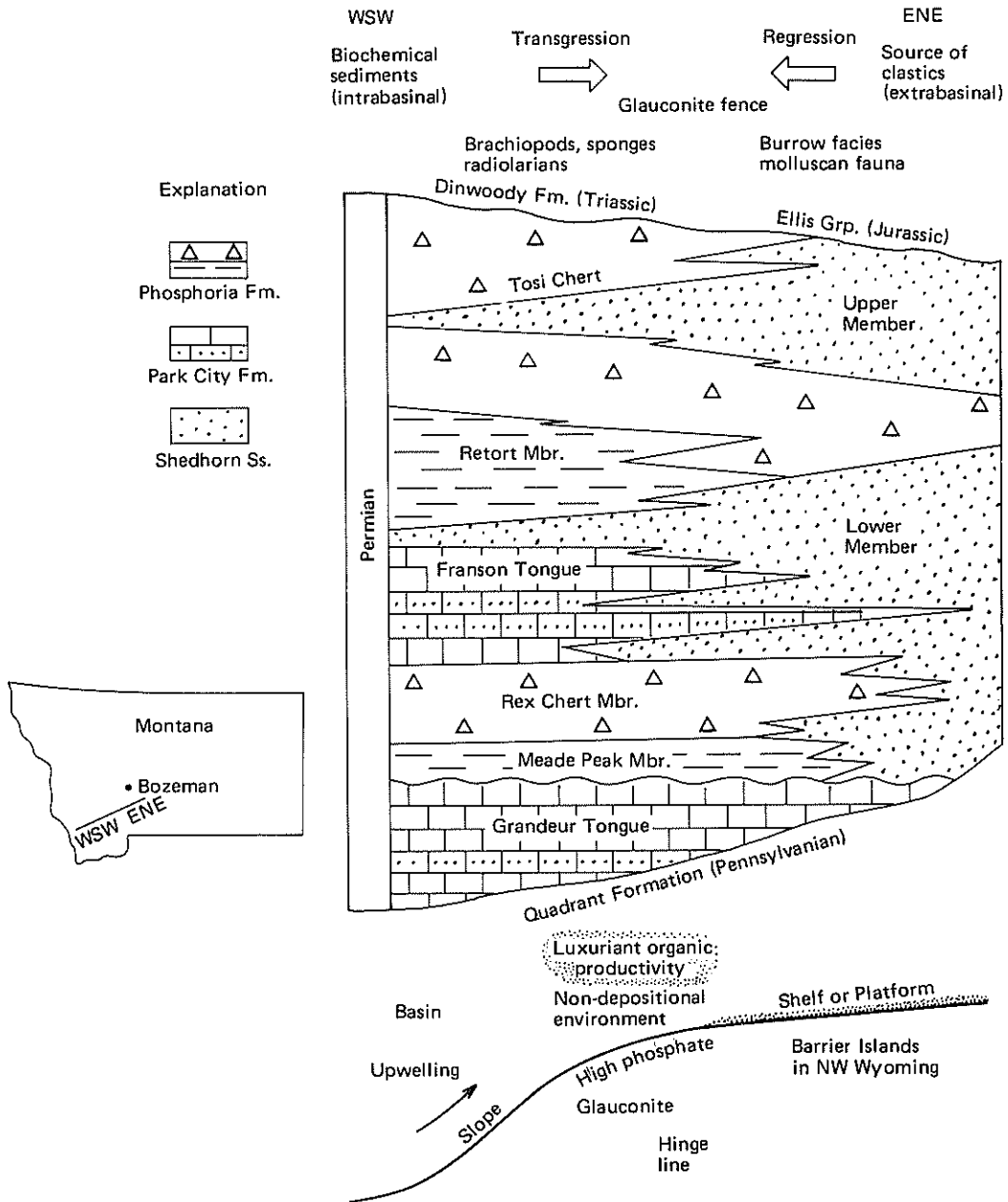
Fig. 16.1 Stratigraphic relations and general environmental interpretation of the Permian of southwest Montana.

Largest values are for burrows in chert matrix (Table 16.1A). Sample measurements made at several localities are given in Table 16.1B.

The greatest density of cylindrical burrows occurs in the upper Shedhorn of the West Fork of the Gallatin River section (Fig. 16.3A). A bed 2.5 m thick has more than 75 percent of its volume occupied by burrows. These structures are 4 m long, and some cut through other lithologies above and below. Three beds in the upper Shedhorn at Cinnabar Mountain, totaling more than 5 m in thickness, have

columnar chert-filled burrows comprising 50 to 60 percent of the rock (Fig. 16.3B) (Peterson, in Cressman and Swanson, 1964). In this same section, 195 discrete burrows were counted on 1 m² of the bedding surface! The unusually high density of burrows was seen in cross section, on such surfaces (Fig. 16.4).

The burrow structures vary in orientation and shape within beds, relative to the lithology of enclosing strata. Within cherts and fine, dark, organic shales, the burrows are typically inclined at low angles to the beds; in sandstones, they tend to be normal to bedding (Table 16.1C). All structures in any one bed generally have approximately
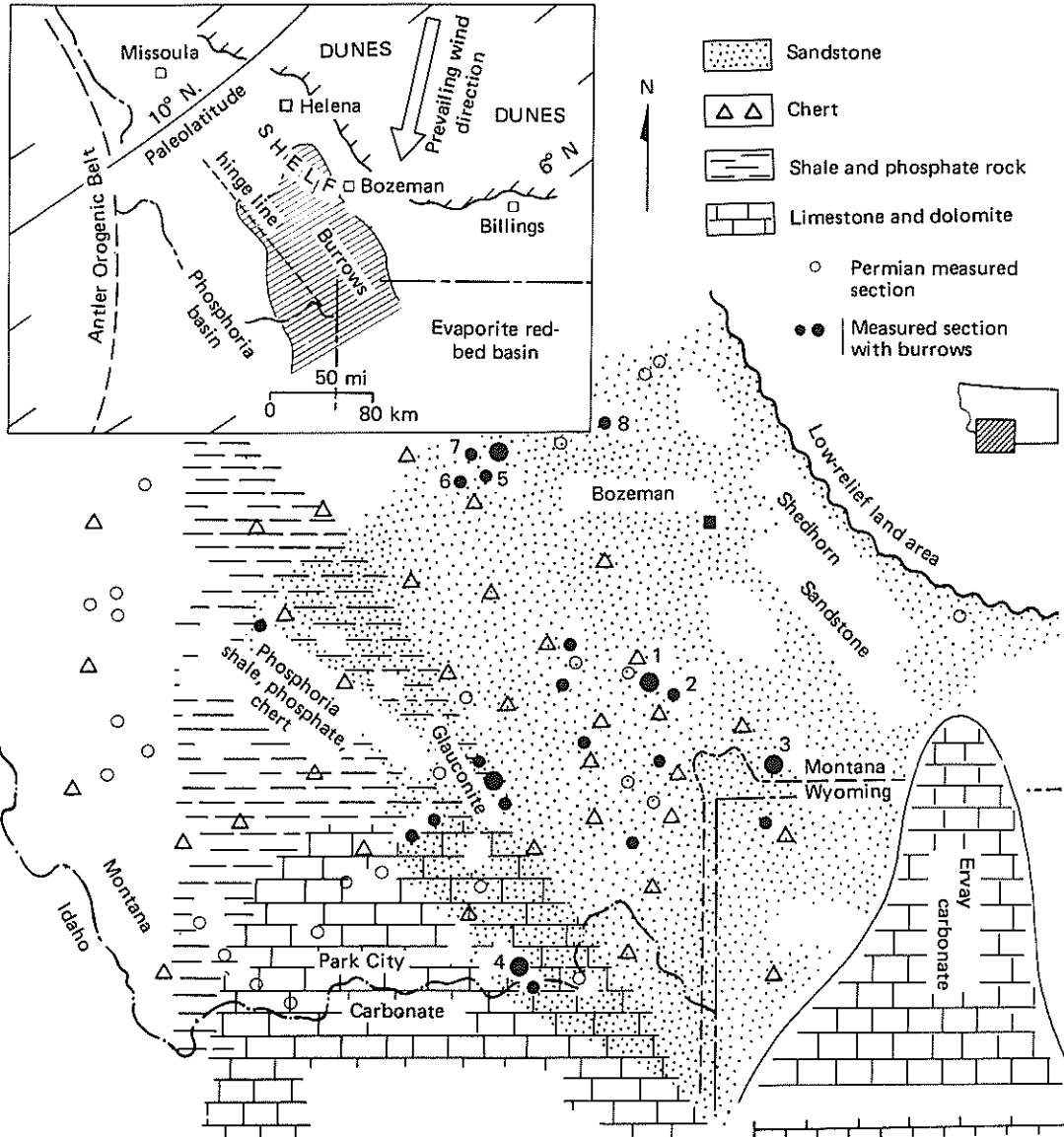

Fig. 16.2   Distribution of burrows relative to the Permian sedimentary framework in southwest Montana. (1), West Fork, Gallatin River. (2), Porcupine Mtn. (3), Cinnabar Mtn. (4), Centennial Mtns. (5), London Hills. (6), South Boulder. (7), Jefferson Canyon. (8), Logan. [After Cressman and Swanson (1964), Sheldon (1964), and Peterson (1972).]

TABLE 16.1   Major Characteristics of Permian Burrows.

A—Mean long diameter of burrows relative to matrix lithology.

Matrix Lithology	Number of Measurements	Mean Long Diameter (cm)	Standard Deviation
Dolomitic sandstone	176	3.1	1.6
Sandstone	855	3.7	2.4
Interbedded sandstone and chert	117	5.4	2.1
Chert	105	6.4	1.6

B—Representative measurements of burrow size, southwest Montana.

Number of Measurements	Cross-sectional Axes (mm)			Average Length (m)	Stratigraphic Section
	Minimum	Mean	Maximum		
100	16 x 11	40 x 31	65 x 50	5	Cinnabar Mountain
184	15 x 11	48 x 37	105 x 80	0.5	Porcupine Mountain
100	43 x 38	68 x 57	100 x 94	0.5	West Fork Gallatin River
101	45 x 40	85 x 71	135 x 105	4	West Fork Gallatin River
100	25 x 15	55 x 45	100 x 92	1 to 1.5	West Fork Gallatin River

C—Shape and orientation of burrows with respect to bedding.

Matrix Lithology (Number of Beds Containing Burrows)	Straight; Normal to Bedding	Straight; Inclined ca. 15° to Bedding	Irregularly Curved; Bulbous
Sandstone (11)	11	—	—
Mudstone (10)	4	4	2
Interbedded chert and mudstone (10)	3	3	4
Sandy dolomite (1)	1	—	—

the same orientation. Cylindrical burrows, where these can be observed, are usually singular and normal to the beds, and issue from an enlarged base (Fig. 16.5). A few such bulbous bases give rise to several parallel burrows, which extend vertically through the sediments. Branching is very uncommon, although a few, very short, stubby, lateral projections do occur. Single vertical burrows in sandstone may be traced upward into shale, where their orientation changes. Some become irregular, laterally anastomosing chambers, but continue across the bedding into the overlying sandstone unit.

Externally, the burrow is smooth in sandstone, and rugose, or wrinkled, in mudstones or cherts (Fig. 16.6A). The latter situation is undoubtedly due to differential compaction between burrow fill and host matrix. [Wrinkled, U-shaped burrows—*Diplocraterion*, several meters long—in Lower Carboniferous graywackes of the Rheinisches Schiefergebirge, Germany were used by Plessmann (1965) as evidence for 30 to 50 percent lateral compaction of sediments, while still in a horizontal position, before folding of the rocks.] Other, similar types of large Permian burrows have nodular, (?)pelleted type walls resembling *Ophiomorpha* and other crustacean burrows (Fig. 16.6B). Internally, the knobby

walled burrows have intestine-like meander structures (Fig. 16.6C). Whether or not the meander structures are primary or secondary is unknown. They suggest a foraging pattern made by a smaller sediment-feeding animal than the one that formed the larger overall structure.

The burrow fill is commonly quartz sandstone or chert, but some fills are calcareous. Chert and quartz clasts, spicules, and apatite pellets may be tightly packed or floating in a chert, quartz, or carbonate cement. This fabric does not suggest any systematic pattern of rearrangement of sediment by the burrowing organism. Overgrowths occur on some quartz grains.

Internally, the burrow fills are generally structureless; however, some are vertically laminated, and in cross section thus have a discontinuous, concentric-banded pattern of annular rings. (Cf. Gableman, 1955.) The banding (Fig. 16.7A) is accentuated by alternations of (1) dark, spicular chert layers containing phosphate peloids and quartz sand grains, and (2) light-colored layers of chalcedonic chert. Spreiten-like patterns of active-fill meniscus structures (Fig. 16.7B) were observed in a few burrow fills having convex-upward laminae ("Stopfgefüge" of Valeton, 1971, Fig. 9). Another specimen has menisci convex downward. These patterns suggest that the organisms used the burrows for infaunal protection as well as paths of upward escape from sediment influx. X-radiographs of other burrows reveal a faint lamination, as
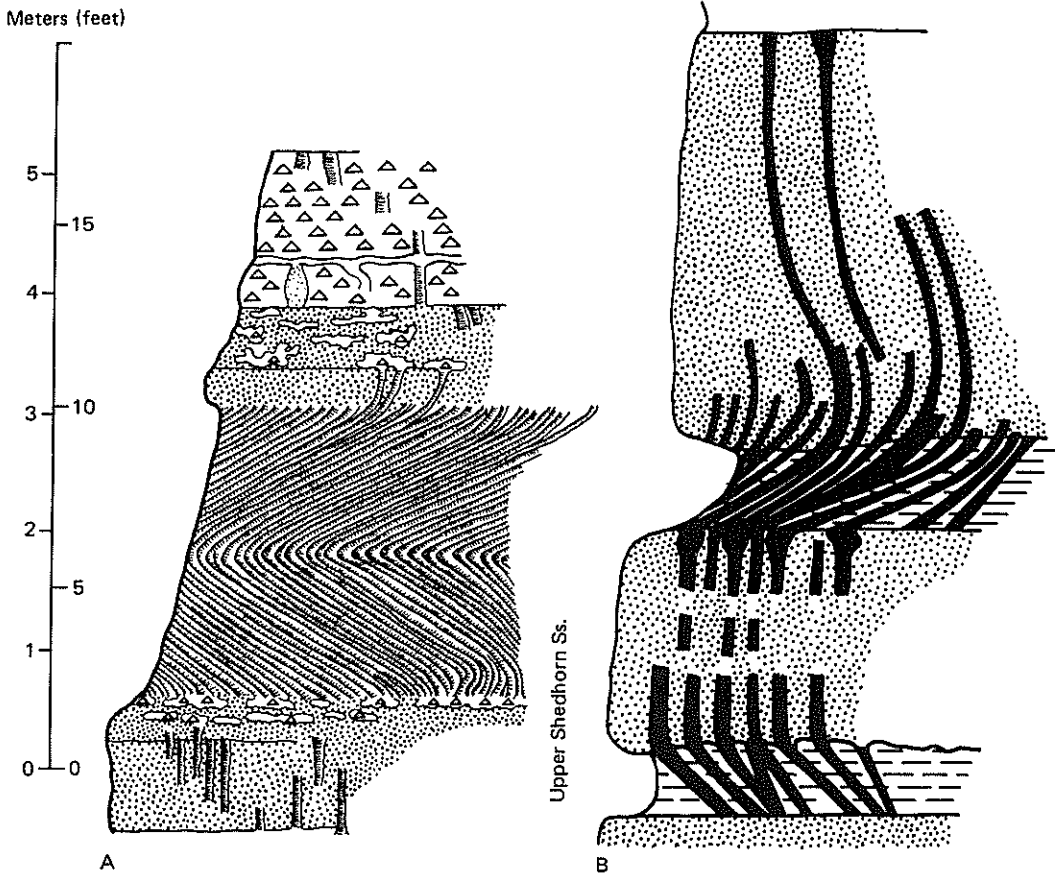

Fig. 16.3 Field sketches of burrow development, Shedhorn Sandstone. A, interpreted maximum burrow development. Chevron pattern = postulated pre-lithification collapse of unit. West Fork, Gallatin River section. B, Cinnabar Mtn. section, north of Yellowstone Park.

Fig. 16.4 Burrow cross sections on bottom of bed. Shedhorn Sandstone; South Boulder section. Scale in 0.1 ft (ca. 3 cm).

defined by oriented sponge spicules, inclined at a high angle to bedding. The laminae do not resemble minisci in that they are not curved, but they probably represent passive infilling from above. No well-preserved fossil organism, thought to be capable of producing the burrows, has been found preserved in any of them.
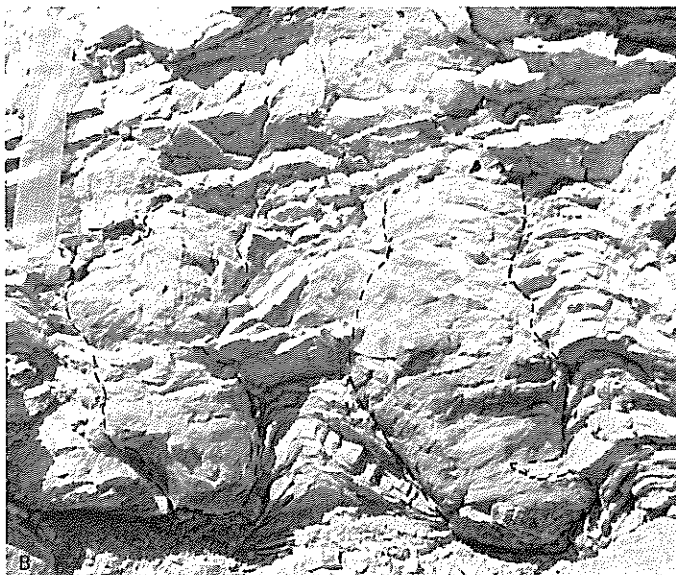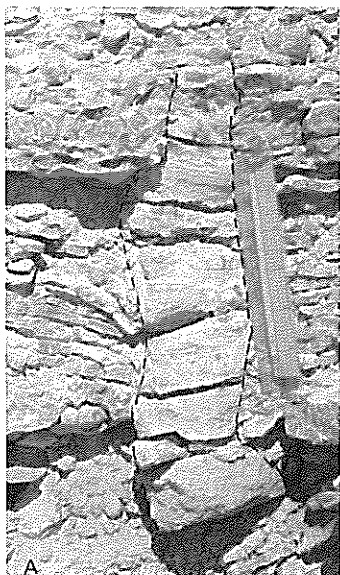

Fig. 16.5 Burrows having slightly enlarged bases, outlined in ink. A, single burrow. Logan section. B, two burrows; partially deformed bedding adjacent to burrow bases. Jefferson Canyon section.

Other trace fossils found in association with the long burrow structures include *Chondrites*, snails found within their burrows, herringbone-patterned *Cruziana*, questionable lungfish burrows, and other smaller traces. Bioturbate structures similar to those made by echinoids, and spiral, three-dimensional *Zoophycos* also occur in these rocks, but not in association with the long structures.

PROBLEMS IN INTERPRETATION

Analysis of Shedhorn burrows is made partly by comparing sandstone grain-size parameters with the dynamic properties of erosion-transport and associated feeding habits of burrowing organisms (Fig. 16.8). Deposit- and suspension-feeding organisms rely on currents for a continuous supply of organic material at the sediment–water interface; therefore, an optimum relationship exists between current velocity and sediment size. Infaunal suspension feeders thrive at velocities of about 2 cm/sec and thus occur most commonly in fine sand. Deposit feeders live in lower energy environments, where they can rework finer sediments for food (Driscoll, 1969).
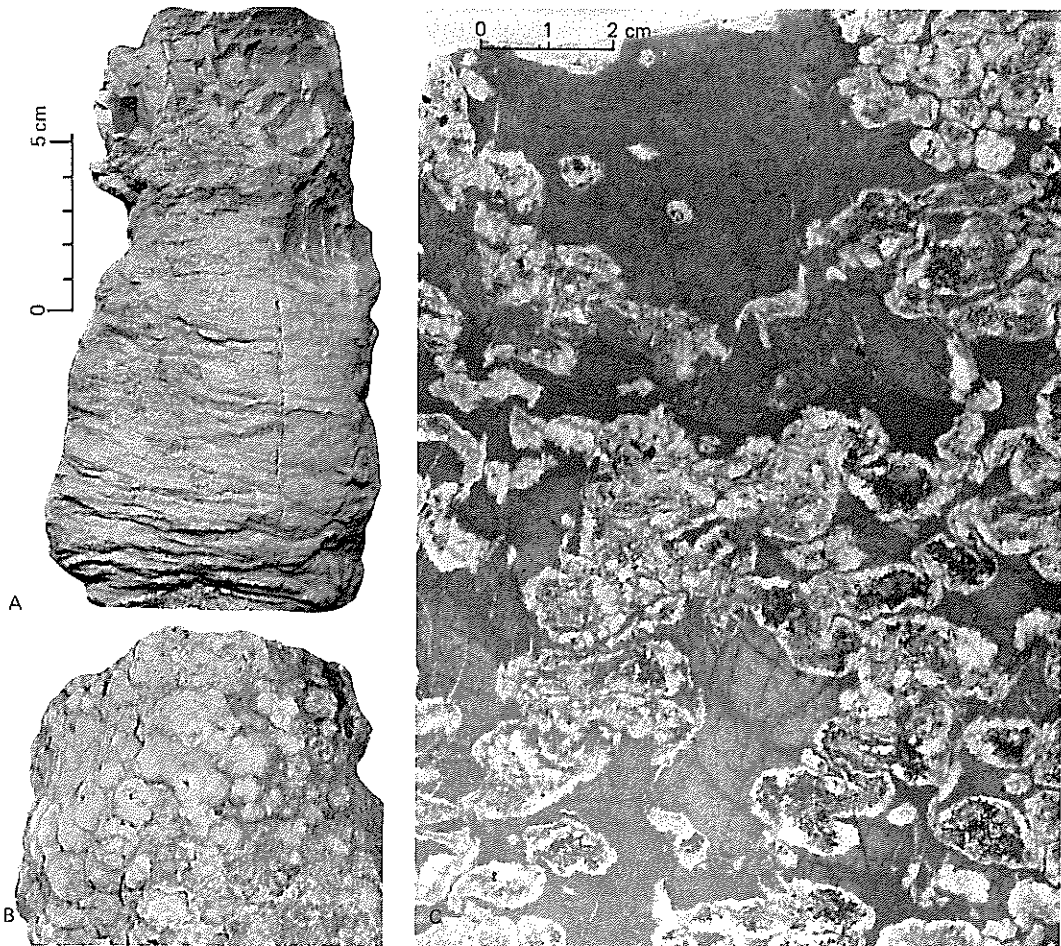
Were the Permian burrowers deposit

Fig. 16.6 Small-scale features of burrows. A, rugose or wrinkled burrow. Top unknown. B, nodular, *Ophiomopha*-type burrow; nodules are pelletal white silica. C, internal, intestine-like meander structure of burrow in B.

feeders, living in the fine sediments (clays, muds, and siliceous oozes), escaping upward with rapid sand influx? This is suggested by the concave-upward meniscus fill and by the close correlation between burrow shape and orientation with matrix lithology. Also possible is that they were suspension feeders that made their homes initially in the Shedhorn sands, keeping pace with subsequent mud deposition. Overall length and regularity of burrows, and the fact that a single burrow penetrates more than one lithology, would seem to preclude the possibility that the organisms descended far below the sediment–water interface in order to reach extranutritious sediment, and at the same time, to avoid a high-energy environment at the interface.

If one consults the published fossil record of the Shedhorn and Tosi, few—if any—known organisms were capable of producing these burrows (Yochelson, 1968). Perhaps clams-are the most likely possibility among the organisms reported. Infaunal, siphon-feeding clams are among the deepest burrowers (Stanley, 1968) and have the greatest escape potential (Kranz, 1970). Unfortunately, not much is known about their late Paleozoic history (according to Stanley, siphonate clams having fused mantles had not evolved yet), and no clam body fossils were found within the burrow structures.

Sponge spicules are the immediate source of silica in Phosphoria chert, constituting perhaps as much as two-thirds of the silica in this large volume of rock. The spicules probably underwent some transportation, as suggested by the fact that most are broken; yet a large population of benthic animals somewhere furnished this large volume of spicules. The single sponge
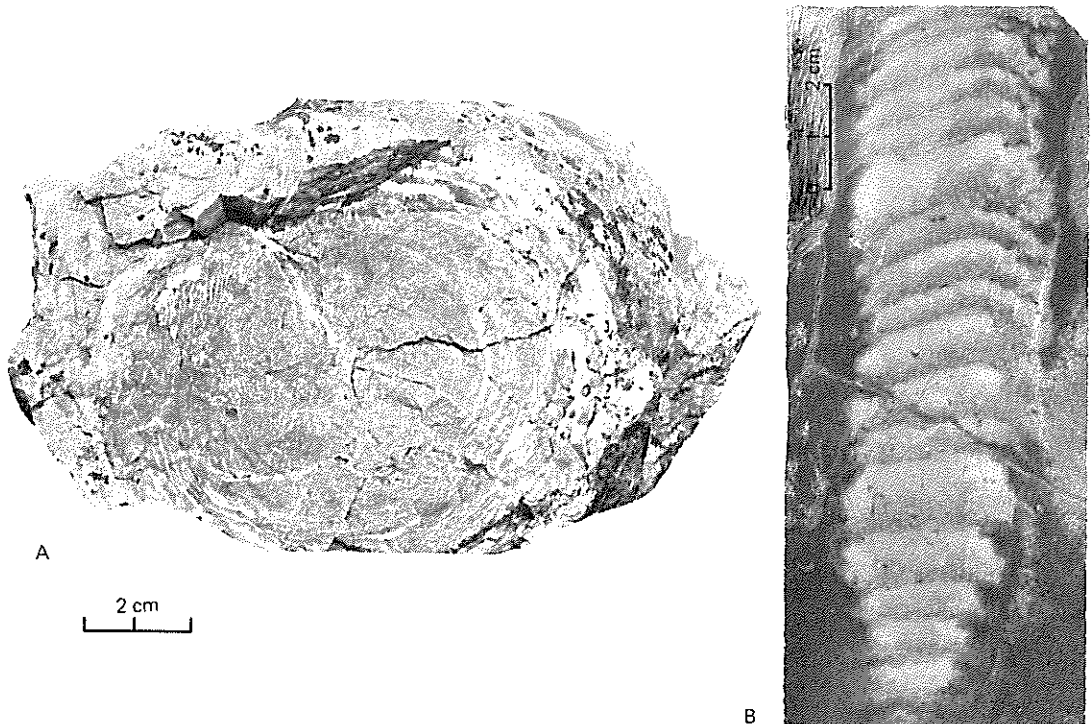

Fig. 16.7   Internal structure of selected burrows. A, discontinuous, concentric-banded cross section of burrow. B, longitudinal section of burrow exhibiting well-developed spreite-like meniscus fill. Shedhorn Sandstone; Centennial Mountain, Montana.
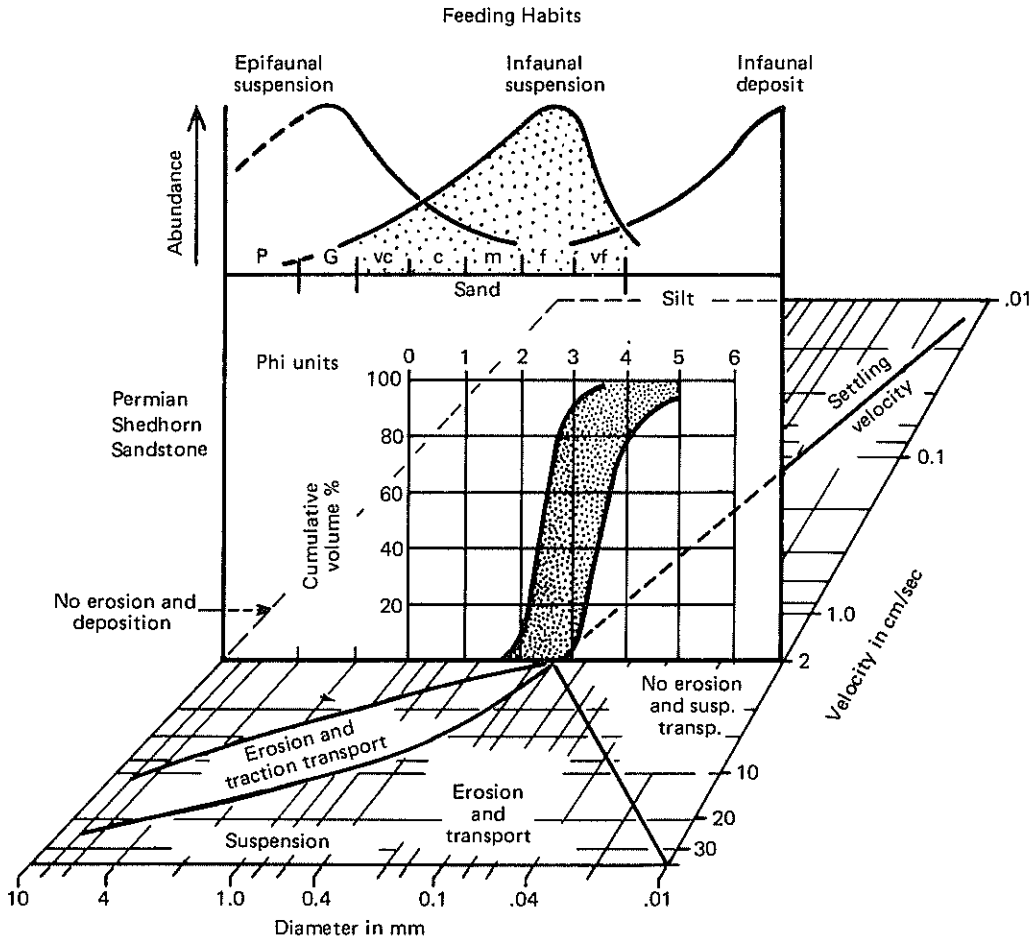
Fig. 16.8 Diagram showing relationship between infaunal feeders, water velocity, and sediment size for the Shedhorn Sandstone. [Interpretation from Driscoll (1969). Data for Shedhorn from Cressman and Swanson (1964).]

Actinocoelia maeandrina occurs in carbonates of the Franson in Wyoming and is common in chert nodules of the Permian Kaibab Limestone of Arizona. R. P. Sheldon and R. M. Finks (1972, personal communication) reported that the sponges are responsible for the long columnar "burrows," but no information has been published. How such organisms would have fared in the environment represented by the Shedhorn is not clear.

Other prime suspects of burrow making are the decapod crustaceans. No fossil remains of arthropods, other than trilobites and ostracods, have been reported from the

Phosphoria and Shedhorn of Montana, and none were found by us. Evidence for *Ophiomorpha* from Permian strata of Utah is known (Chamberlain and Baer, 1973), and a pelleted wall structure is indicated —by geopetal matrix and supported quartz-grain fabric—for some burrow walls in Montana (W. A. Pryor, 1972, personal communication). The characteristic long, fairly straight, smooth, columnar, unbranched burrows of the Permian of Montana are unlike modern callianassid and related burrows; at this time, however, the evidence is inconclusive as to the organism(s) responsible for these unusual burrows.

CRETACEOUS AND PALEOCENE BURROWS

Richard G. Bromley

At most horizons, the chalks and fine-grained calcarenites of the Upper Cretaceous and Danian of northwestern Europe are thoroughly bioturbated. Development of flint nodules in these sediments provided a well-preserved record of burrow types involved in the bioturbation. Genera thus preserved include *Thalassinoides*, *Zoophycos*, *Chondrites*, rare *Gyrolithes*, and others (Bromley, 1967; Kennedy, 1970). (See also Chapter 17.) Spectacularly large flint nodules draw attention to the presence of unusually long burrows, which are otherwise inconspicuous where unsilicified. Felder (1971, Fig. 6), for example, recorded a horizontal burrow in the Senonian chalk at Fécamp, Normandie, France, that—because of an enveloping flint concretion—was traceable for 11 m, although having a diameter of only a few centimeters.

One type of giant flint nodule, having a particularly characteristic orientation and shape, is widespread at several horizons within the flint-bearing Upper Cretaceous chalk of northwest Europe. These nodules were first described under the name "paramoudra" by Buckland (1817) from the Campanian White Limestone of Northern Ireland, but have since been reported from chalk of the same age in Norfolk, England (Peake and Hancock, 1961, p. 318; see references); they are also common in Maastrichtian chalk of Denmark and Germany.

The environmental setting for these paramoudras is generally that of a restricted energy, marine shelf seafloor. Water depth probably ranged between 100 and 300 m, and the sedimentation rate was slow to moderately slow. Minor omission surfaces are visible in some regions (Fig. 18.2) and indicate a cyclicity of sedimentation. Additional details may be found among references cited herein.

BURROW CHARACTERISTICS

Paramoudras are vertically extended ring-, barrel-, or pear-shaped to cylindrical flints, variably massive, having a central core of unsilicified chalk that is typically open at each end. The concretions are characteristically stacked in columns (Fig. 16.9), although they may occur alone. Related phenomena include vertical cylinders of flint having wider cores, thinner walls, and greater length than do typical paramoudras (Fig. 16.10; see Felder, 1971, Fig. 5).

Within the central core a burrow shaft can be detected, having a diameter of about 0.4 cm. The shaft is generally vertical but sinuous in detail (Fig. 16.11). In some cases, as it passes through a particular bed, the shaft describes a broad spiral 1 m or more in diameter.

No individual burrow has been traced uninterrupted over its full length. However, associated diagenetic phenomena, particularly columns of cylindrical flints, indicate that the burrows commonly have a length of 5 m and that examples more than 8 m long do occur. Paramoudra columns described in the literature suggest burrow lengths of 8 to 9 m (Lyell, 1865, Fig. 286; Steinich, 1972, "Anlage" 6). The diameter of the shaft is thus characteristically 1/1,000 of its length, and in some cases may reach 1/2,000!

The upper end of the shaft has no special aperture structure, and at the lower end the burrow also ends simply, without a swelling or special chamber. Side branches, having the same diameter as the central shaft, emerge irregularly at most levels and radiate from the shaft more or less horizontally and straight (Fig. 16.11).

The shaft is rendered visible by complex mineralization of its wall and sur-
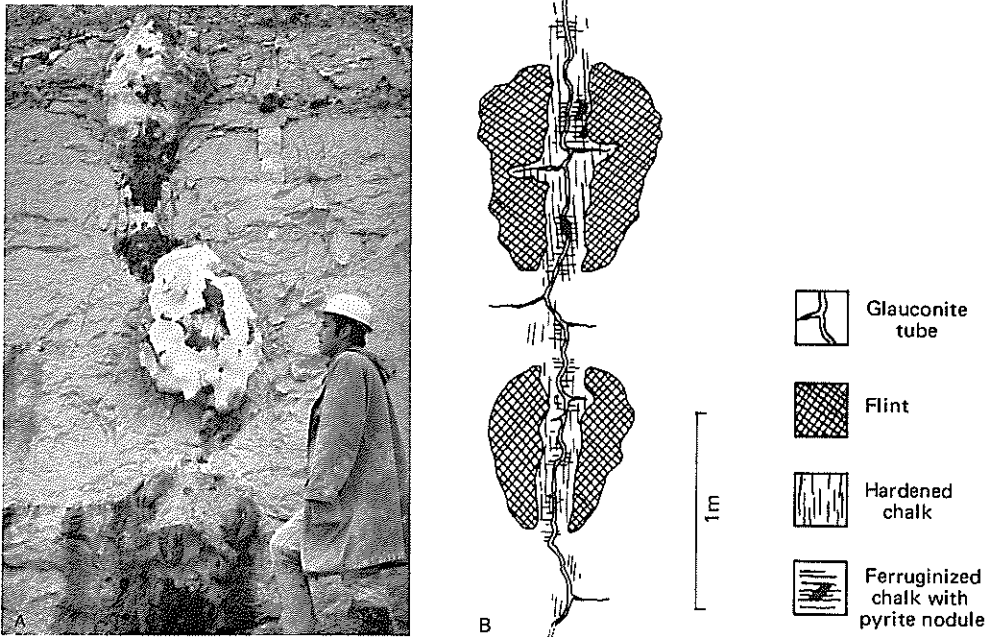
Glauconite
tube

Flint

Hardened
chalk

Ferruginized
chalk with
pyrite nodule

1m

B

Fig. 16.9 Paramoudras. A, part of column of paramoudras in chalk. Paramoudra at knee level is broken, but its central core is not visible. The cylinder of flint connecting successive paramoudras is unusual. Upper Maastrichtian; Hemmoor, Niedersachsen, Germany. B, composite sketch of section through two paramoudras in a column, showing relationship of burrow to associated diagenetic phenomena.

rounding chalk. Because of incomplete mineralization, one cannot follow the shaft through its complete length (maximum distance, ca. 3 m). Another problem is logistics—tracing a faint, pencil-thick tube in jointed, dirty, often soft and sludgy chalk! Although the shaft is more or less vertical, faces of exposures usually slope irregularly, truncating the burrows at various levels.

The side branches are mineralized only near the shaft; the tinting of the chalk fades progressively as the branches are traced away from the shaft (Fig. 16.11), thus they are rarely visible for more than 20 cm. The side branches therefore appear to have been culs-de-sac and not to have interconnected with neighboring paramoudra burrows.

No structure can be detected in the fill, which lithologically resembles the surrounding sediment.

The shaft is usually extensively lined with a film of glauconite or pyrite, or both; in other cases, the chalk immediately surrounding the burrow wall is slightly glauconitized for a distance of a few millimeters from the burrow. In rare cases the green tube has a complex wall structure (Fig. 16.11), which possibly represents fracture crumpling of the brittle glauconite skin due to compaction. The chalk surrounding the burrow, at a distance of 5 to 10 cm from its wall, is typically iron stained; in some examples it is darkly discolored (Fig. 16.11). Chalk in the vicinity of the burrow is patchily cemented with calcite (Fig. 16.9B).

Beyond this zone of hardened and stained chalk, a zone of flint replacement resulted—at stratigraphic horizons rich in flint layers—in the production of monstrous flints. In their minimum development, the flints are massive rings 20 to 30 cm high, but at many localities they are extended

Fig. 16.10 Flint cylinder (ca. 0.6 m diameter) sectioned in chalk. Upper Campanian; Weybourne, Norfolk, England.

vertically along the shaft as pear-shaped or barrel-like concretions as much as 2 m high (Fig. 16.9A). A central core of unsilicified chalk 10 to 20 cm in diameter invariably runs up the flint and corresponds to the mineralized chalk around the burrow shaft. Paramoudras occur wherever the burrow shaft passes down through the horizon of a normal flint-nodule bed, and also between these horizons, so that a vertical chain or column of paramoudras marks the position of each burrow. In flint-poor chalk, the paramoudras are separated by several meters of chalk, or are completely isolated and occur only at flint-nodule horizons. Paramoudras are absent where all other flint is lacking. Thus, at several localities, only the staining and hardening help one to find the slender green tubes.

PROBLEMS IN INTERPRETATION

The chief difficulties in interpretation of paramoudra burrows lie in the unusual dimensions of the burrows and in their apparent (although not proved) isolation from neighboring shafts. Discussion of these difficulties amounts to little more than speculation until similar structures are described in recent seas.

The burrow was presumably produced either by an animal that had dimensions similar to those of the shaft, or by shorter animals that moved up and down within the shaft. In the first case, the shaft would have been largely filled by a long, worm-like animal that was capable of living in reducing conditions, its respiratory organs exposed at the sea floor.
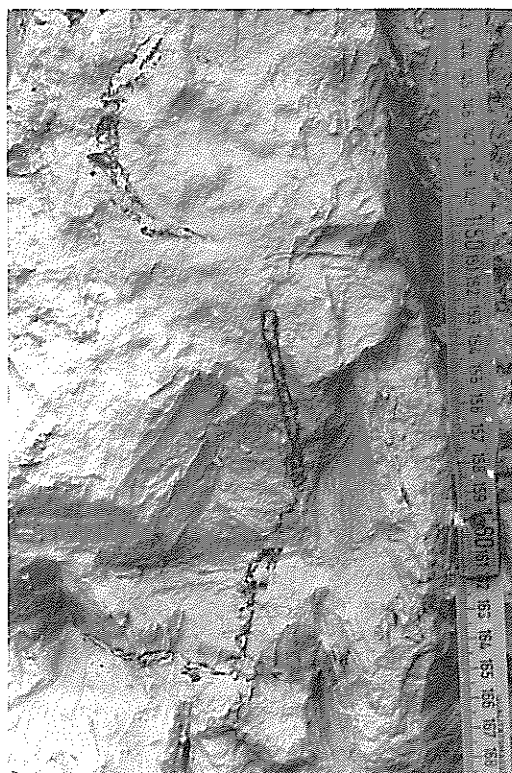

Fig. 16.11 Section of burrow in chalk. Shaft curves in upper part of picture; complexly "broken" glauconite wall is clearly visible. Basal section includes two side branches. Lower Maastrichtian; Hemmoor, Niedersachsen, Germany.

Few living animal groups have dimensions suitable to fulfill this role. Pogonophores, nemertines, and polychaetes have long, thin, endofaunal representatives. Certain pogonophores are remarkably slender and long (Ivanov, 1960, p. 1541), the most extreme showing a width 1/600 of their length. But the absolute length of these forms is too small, a matter of decimeters. Possibly some species, known only from their upper end as truncated by the dredge, may eventually prove to be much longer. Pogonophores are largely deep-sea forms today, and are immobile, dwelling in unbranched tubes. Attribution of the paramoudra burrow to this group produces problems of interpretation of the side branches, which do not correspond to any structures in known pogonophore tubes.

The more active nemertines include several extremely elongated burrowing forms, some of which reach a length of 2 m (Barnes, 1968, p. 157). The problem here is that most of these worms are active carnivores, unlikely to construct permanent, vertical shafts.

The other possibility, a short animal that shuttled actively up and down the shaft, widens the field of possible tracemakers. But the reason for the descent of a "shorter worm" to such a distance beneath the sea floor remains unexplained. The tendency to spiral, seen in a few examples, may suggest a crustacean architect, but again the diameter of the shaft restricts the great task of excavation to very small crustaceans.

The shaft is almost certainly a dwelling burrow. But no special evidence indicates the particular function of the side branches, whether as feeding structures, egg incubators, burrows of commensal or other cohabitors, etc. Clearly, much more information is needed before these problems can be solved. A more detailed examination, documentation, and discussion of these burrows is given in Bromley et al. (in press).

PLEISTOCENE STRUCTURES

H. Allen Curran and Robert W. Frey

Strip-mining operations near Aurora, North Carolina, on the Atlantic Coastal Plain, reveal a stratigraphic section of beds ranging from middle Miocene to Holocene in age. The upper part of this section contains poorly consolidated marine Pleistocene (?Sangamon) sediments that bear distinctive associations of biogenic and physical sedimentary structures (Welch et al., 1972). Trace fossils commonly found in these units include *Ophiomorpha*, *Planolites*, *Skolithos*, and *Thalassinoides* (Curran and Frey, 1973; Curran et al., 1973). One of the Pleistocene units contains possible escape burrows of very distinctive form and unusually large size, as much as 3 m in length and 24 cm in diameter. This unit also contains some large, vertical, cylindrical structures of uncertain origin; at least one of these cylindrical structures resembles a reburrowed escape structure.

A current-bedded unit in the Pleistocene sequence (Belt et al., in press) has a maximum thickness of 4.7 m and consists of a planar, tabular cross-bedded member overlain by a wavy- and flaser-bedded[1] member. The tabular cross beds are composed of fine to very coarse quartz sand. Coarse and very coarse sands are irregularly interbedded with finer sands of the foreset beds. Ripples outlined by heavy-mineral and silt-clay laminae are common in fine sands. The tabular cross-bed sets are separated by thin, horizontal-bedded, rippled sequences of fine to medium sand. This member contains

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[1] Terms as defined by Reineck and Wunderlich (1968).

the burrows *Ophiomorpha nodosa* and *Skolithos*, and also the large structures described below. Burrows are sparse in the medium to very-coarse-grained basal cross-bedded sands of the member. Density of burrows, particularly *Skolithos*, greatly increases in the fine to medium sands of sets in the upper part of the member.

Physical and biogenic structures found in this member suggest conditions of rapid deposition in a shallow sublittoral, shoaling environment having strong currents. Welch et al. (1972) interpreted the beds as a possible tidal-delta deposit, or a laterally accreting large bar or spit.

The wavy- and flaser-bedded upper member of the current unit is composed of fine to medium quartz sand and clay. This member is moderately bioturbated, containing *Ophiomorpha nodosa*, *Skolithos*, and *Planolites*. The increased clay content and the flaser and wavy bedding indicate lower energy depositional conditions, and suggest a protected, shallow subtidal or intertidal environment (Welch et al., 1972), such as a tidal flat, shoal, or large bar.

BURROW–LIKE CHARACTERISTICS

"Escape" Structures

In longitudinal section, the large "escape burrows" are marked by V- to U-shaped, in echelon laminae of coarse to very coarse quartz sand layers interbedded with fine to medium quartz sands (Fig. 16.12A). Coarse
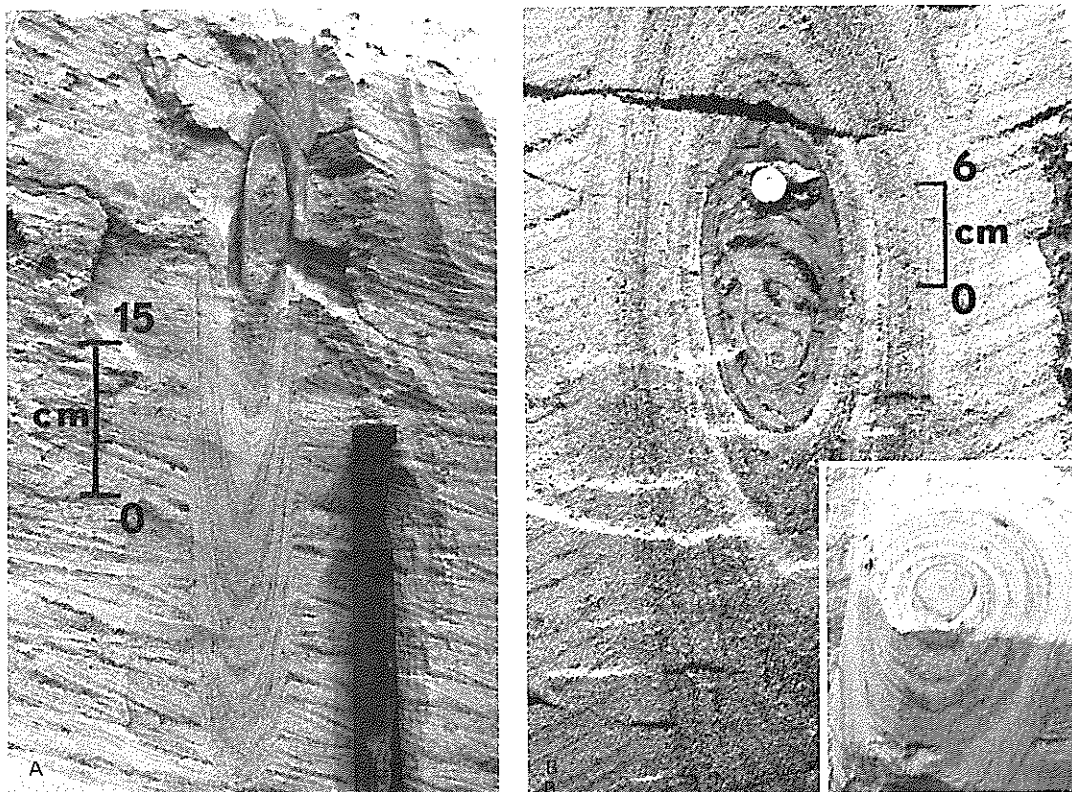

Fig. 16.12 "Escape burrows" in tabular cross-bedded quartz sands. A, sediment core at top of structure, weathered out naturally from mine wall; remainder of surface has been scraped smooth. Core is conical in shape and composed of unlaminated sand. B, close up of oblique section through "escape burrow." Core of structure filled with unlaminated fine sand, rich in organic detritus, from overlying flaser-bedded member. *Inset*: three-dimensional block view of structure. (Minimum overall length of structure, 2 m.)

sand layers in the tabular cross-bedded sets containing these structures can be traced to the margin of the overall structure, where they dip sharply downward. Numerous laminae can then be followed continuously across the structure, in distinctive V- to U-shaped patterns, and then traced back into the cross-bedded set on the opposite side. In transverse sections, a pattern of concentric circles is revealed, also formed by alternating layers of coarse and finer sand. A distinct central core of unlayered fine to medium sand, containing clay blebs and woody organic fragments, is well defined toward the top of some of the structures (Fig. 16.12B). In three dimensions, these structures consist of a set of nested, cone-in-cone laminations, many having an unlaminated core at the top.

Six such structures were found, all of unusually large size, ranging from 1.2 to 3 m in length and 10 to 24 cm in diameter. All lengths reported here are minimal because the structures were recognized by the protrusion of their weathered, truncated tops out of the friable, poorly consolidated sediments of the mine walls (Fig. 16.12A). The structures maintain a constant diameter through much of their length, e.g., the one shown in Figure 16.13 has a diameter of 9 to 10 cm through a length of 1.2 m. The structures taper inward abruptly toward their base, but the actual characteristics of the base could not be determined with certainty because all terminated at the contact of the current unit with an underlying, wet, sandy clay unit.

Laminae that could be traced continuously across the structures were deflected downward as much as 50 cm from their original position in the cross-bedded sets. The laminae were separated across the structures by a distance averaging 10 to 14 cm, reaching a maximum of 24 cm.

Vertical Cylindrical Structures

In general form and size, the large cylindrical structures resemble those de-
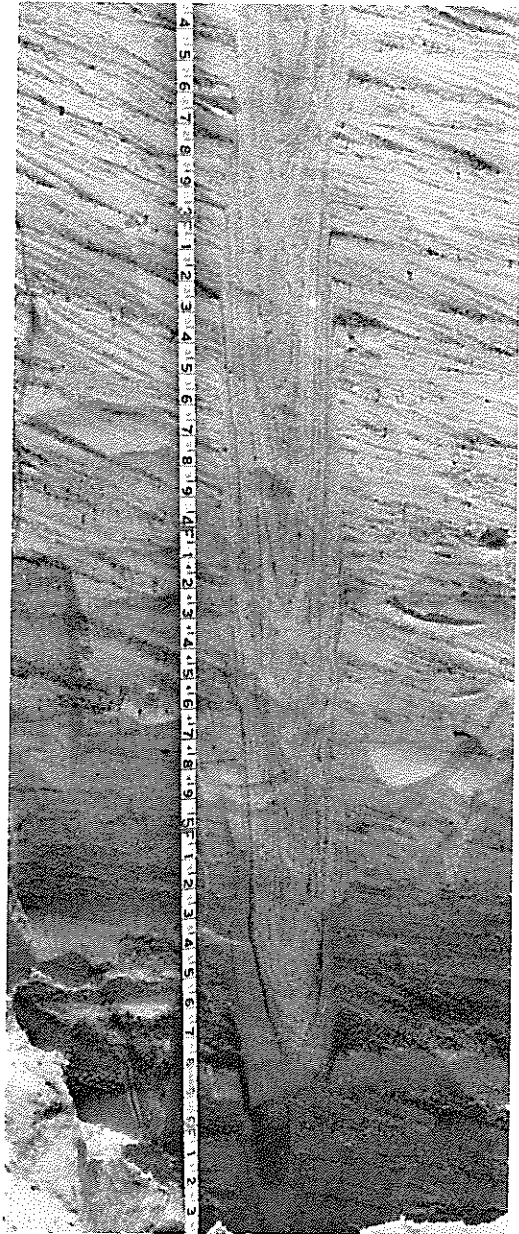

Fig. 16.13 Continuous section (1.2 m) of an "escape burrow." Laminae of dark sand, many of which can be traced continuously across the structure, form U- to V-shaped patterns.

scribed previously. They differ in that the pattern of V- to U-shaped, in echelon laminae is largely obliterated. All occur in the tabular cross-bedded member of the current unit, and they are filled with fine

quartz sand containing numerous clay blebs and organic fragments from the overlying flaser- and wavy-bedded member.

In one case, features that appear to be cone-in-cone laminations of a large "escape structure" have a secondary structure super-imposed on them (Fig. 16.14A). This struc-ture is evocative of reburrowing activity; the path of this "reburrowing" is marked by a thin but continuous dark gray clay layer that lines the inner surface of the shaft, an irregular vertical path having a minimum length of 1.65 m. The diameter of the clay-lined shaft is 7.5 cm in its central part, and gradually narrows toward the top.

At its base, the clay-lined shaft opens up abruptly into an irregularly shaped, thinly clay-lined chamber having a maximum diameter of 15 cm and variable height of 15 to 20 cm.

Figures 16.14B and 16.15 illustrate a similar vertical structure of even larger size, having a minimum length of 2.5 m and maximum diameter of 37 cm. The thin (2 to 4 mm) clayey sand lining is less con-tinuous than that of the structure shown in Figure 16.14A, but this lining can be traced for the length of the structure and shows up clearly in transverse sections (Fig. 16.14B). At its base, the structure gradually
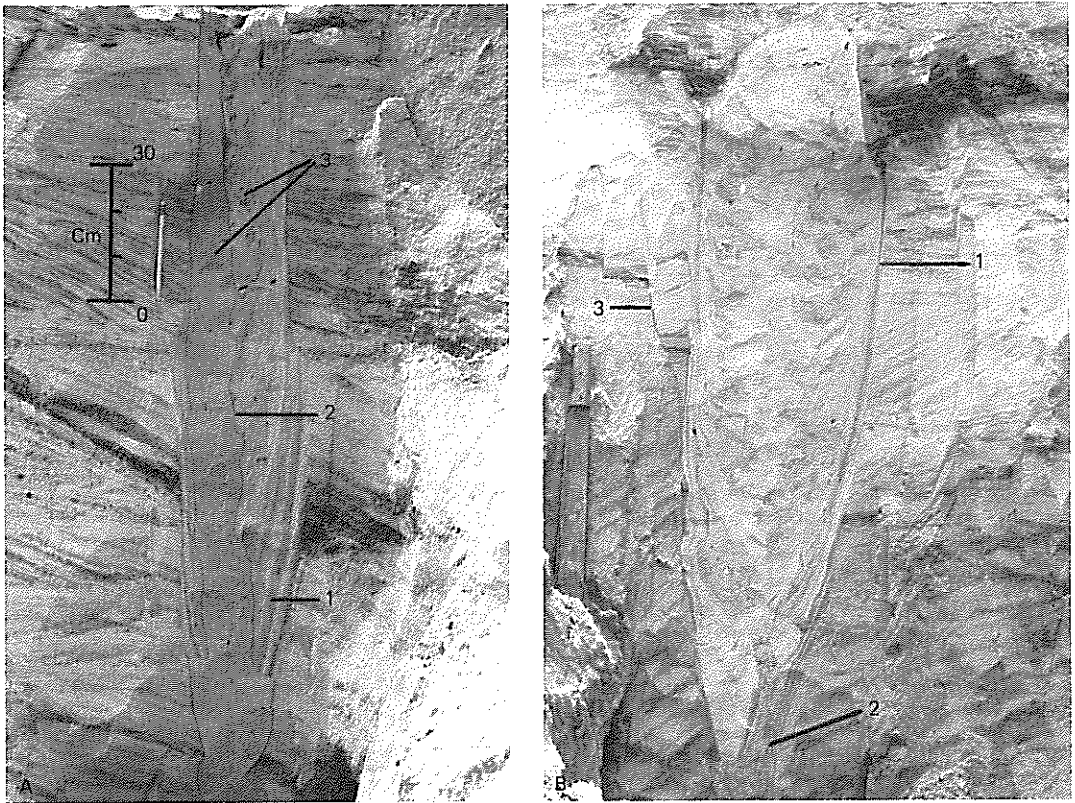

Fig. 16.14   Problematical "burrow" structures. A, ?reburrowed "escape structure" in tabular cross-bedded sand. Laminations of the original "escape burrow" (1) are distinct toward base of structure. Thin clay lining (2) marks the bounds of the "reburrowed" structure. Much of the structure is filled with unlaminated fine sand rich in organic detritus (3), from overlying flaser-bedded member. B, large vertical cylindrical structure. Lining (1) is a thin, continuous, sandy clay layer. Sand fill-ing the structure is from overlying flaser-bedded member. Laminations (2) tend to be deflected downward at base. Small-displacement normal faults (3) adjacent to the structure probably orig-inated during its formation. Machete 68 cm long.

tapers inward to a blunt terminus having a U-shaped profile. A well-defined chamber, such as that in the "reburrowed" structure described previously, is lacking. Numerous normal faults involving small displacement (as much as 25 cm) disrupt layers adjacent to the margins of this structure (Figs. 16.14B and 16.16). In general the fault planes dip toward the structure's margins; most likely, this faulting occurred during formation of the structure.

PROBLEMS IN INTERPRETATION

"Escape" Structures

The Pleistocene structures superficially resemble burrows characterized by downward deflected laminae described by Boyd (1966, p. 45–46) from the Middle Cambrian Flathead Sandstone of Wyoming. Hallam and Swett (1966, p. 103–106) described similar

trace fossils from the Lower Cambrian Pipe Rock of Scotland, which they assigned to *Monocraterion*. Features of this type were classified by Hanor and Marshall (1971, p. 128, Fig. 1b) as structures formed by shearing. Experiments conducted by Boyd (1966, p. 46–50) indicated that the downwarping and truncation of laminae in the Flathead burrows probably resulted from subsurface removal of sediment, although the mechanism of subsurface sediment removal was not satisfactorily explained. Schäfer (1972, p. 288, Fig. 165) noted that the modern cerianthid anemone *Cerianthus* deflects sediment downward and truncates laminae during both upward and downward burrowing activity. (See Chapter 22.)

The North Carolina "burrows" differ from those mentioned previously in that numerous deflected laminae can be traced continuously across longitudinal sections of the structure (Figs. 16.12 and 16.13) and were not truncated by downward "burrow-
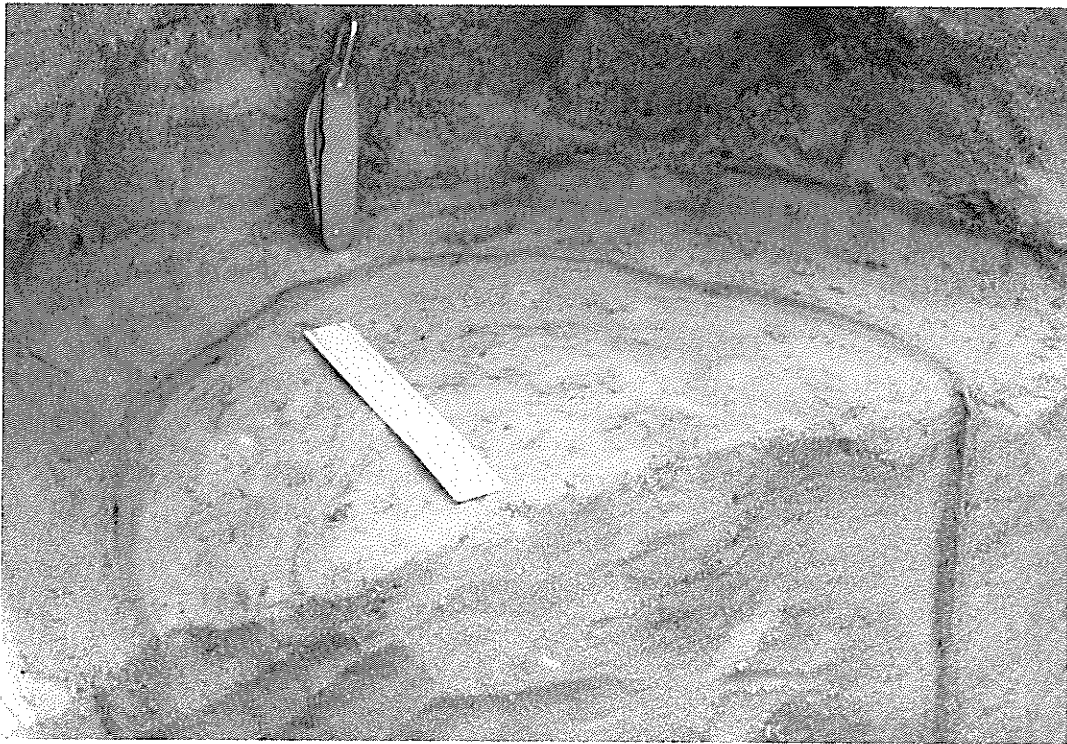

Fig. 16.15 Cross-sectional view of structure shown in Figure 16.14B. The structure is circular in section and has a thin, sandy clay lining. Scale 15 cm long.

Fig. 16.16 Two vertical cylindrical structures in close proximity, showing characteristic fills. Offsets in thin dark beds reveal small faults.

ing" activity. This configuration of laminae seemingly argues for an inorganic origin for the structures, as by collapse of sediment, e.g., structures strikingly resembling escape burrows are produced by the collapse of sediment into open vertical burrows of *Callianassa major* (Howard, 1971, p. 200, Fig. 9). Some of these collapse structures attain very large sizes. However, we have found no evidence of a cavity into which the Pleistocene sediments might have collapsed. We thus note the similarity of these to dwelling structures formed by an organism forced to move upward periodically in order to escape burial and maintain a constant position relative to the sediment-water interface during rapidly shoaling conditions.

The depth of deflection of laminae (as much as 50 cm) and width of separation of laminae across the structures (as much as 24 cm) would provide absolute maximum-size dimensions for the "burrower." However, the "burrower" probably would have considerably smaller body dimensions. Penetration experiments by Boyd (1966, p. 48) produced deformed sediment zones having twice the diameter of the penetrating object. (See also Schäfer, 1956.) The unlaminated, cone-shaped, central cores found in the upper part of some of the Pleistocene structures would more accurately reflect the diameter of a burrower's body, because these cores probably would represent fillings formed after the burrower evacuated the burrow site. The core zone shown in Figure 16.12B has a diameter of 8 cm, but laminae are deflected downward across a diameter of 20 cm.

A possible ethological analog for these "escape burrows" are the structures formed by burrowing actinian sea anemones. Shinn (1968) studied burrows of *Phyllactis conguilegia*, an anemone living on the Bahama Banks in cross-bedded oolitic sands, where large migrating megaripples are common. When covered by oolitic and skeletal sand in an aquarium, specimens of this anemone burrowed upward by peristaltic action and resumed their normal position at the sediment–water interface. The resulting burrow recorded by Shinn (1968, Pl. 112, figs. 1 and 2) consisted of cone-in-cone laminae formed by sand trickling down from above as the animal moved upward. Shinn (p. 889, Pl. 112, figs. 3 and 4) reported similar structures from the cross-bedded Pleistocene Miami Oolite and Pleistocene oolites in the Bahamas. Frey (1970a, p. 308–309) studied burrows of the actinian *Paranthus rapiformis* near Beaufort, North Carolina, and found that these burrows are very similar to those of *Phyllactis conguilegia*. The North Carolina Pleistocene structures are strikingly similar in form to those described by Shinn and Frey, including deflected laminae that may be traced across the structure. They differ primarily in their much larger size, having a maximum diameter of

as much as 24 cm, as compared to approximately 3.5 cm for the modern anemone burrows.

A matter more problematical than mere size itself, however, is the respective thicknesses of sediment involved. Recorded dimensions for escape structures created by these recent actinians involve only a few centimeters of sediment, whereas the Pleistocene structures involve as much as 3 m of sediment in a given, continuous trace. Such traces, if indeed biogenic, suggest remarkable prowess by the tracemakers in combatting prolonged, unstable conditions in the depositional environment. Little is known about the possible tenacity of anemones under such conditions, but certain of them are at least sufficiently long-lived (as discussed subsequently), and actinians exhibit the requisite behavior on a small scale. Anemones thus remain our best biogenic analog for the Pleistocene tracemakers. But could any ancient anemones (or indeed *any* infaunal invertebrates) have attained the size necessary to produce these huge structures? [One group of animals that warrants further attention in this regard are the marine eels (see Clark, 1972).]

Several modern species of burrowing actinians and cerianthids are known from shallow-marine, sandy-substrate environments along the middle and north Atlantic coast of the United States (Gosner, 1971, p. 150–151, 153, 160; Kirby-Smith and Gray, 1971, p. 8), and others may be present. Individuals of one or more of these latter species conceivably may have formed the Pleistocene escape burrows. Unfortunately, the burrow characteristics of most modern burrowing sea anemones have not been studied. A possible candidate for construction of the Pleistocene burrows might be the large, tube-dwelling cerianthid *Ceriantheopsis brasiliensis*, living offshore near Beaufort (Frey, 1970a, p. 311). However, according to Arai (1972, p. 314), the musculature of cerianthids is such that they may not be capable of the strenuous burrowing represented by long escape structures. The observations of Schäfer (1972, p. 288, Fig. 165) indicate that cerianthids tend to truncate laminae during burrowing rather than to form the cone-in-cone structure that characterizes the Pleistocene "escape burrows."

If these are escape structures, their exceptional length (at least 3 m) indicates that the organism continuously occupied a single geographic position on the sea floor and moved progressively upward with sediment accretion. The unlaminated, conical sediment-core that fills the upper part of some of the structures would represent filling that occurred after the organism moved from the burrow site or died and decayed in place. Individuals of certain species of actinian and cerianthid anemones are known to have life-spans greater than 50 years (Annandale, 1912, p. 607; Cutress, in Frey, 1970a, p. 311). If the "escape" structures were produced by anemones, and assuming a possible life-span for the anemones of as much as approximately 50 years, this is a maximum time for accumulation of the 4-m thickness of tabular cross-bedded Pleistocene sands at this locality; of course, the sediments could have been deposited much more rapidly.

Vertical Cylindrical Structures

The structures shown in Figures 16.14–16.16 occur in sands of the current unit and are filled with unlaminated sand, clay blebs, and organic fragments from the overlying wavy- and flaser-bedded member. Figure 16.14A illustrates a structure that apparently is superimposed on a previously formed "escape burrow"; the cylindrical structure seems to have been excavated from above and to have followed the general path of the preexisting "burrow." The structure is characterized by a nearly continuous, thin clay lining, which is notable evidence for a biogenic origin; conceiving of a physical mechanism that could form this

lining is difficult. The lining was traced to a large, irregular chamber at the base.

Could this distinctive structure represent burrowing from above by an animal seeking to form a dwelling chamber? The phenomenon of selective burrowing on the site of previously formed burrows is not uncommon (e.g., Frey, 1970b, p. 26), although the large size of this Pleistocene structure is exceptional. The clay lining of the structure is too thin to have functioned as a strong, protective wall, but it might mark the path followed by the animal. This lining, if biogenic, could have formed during initial penetration of the sediment, after occupancy of the burrow, or after partial filling of the burrow while the animal burrowed upward through sediment fill in the process of exiting the dwelling chamber. The last event seems to be most plausible for the upper part of the structure, where fill material is found both inside and outside of the clay lining. Inorganic mechanisms also must be considered for the origin of this structure, of course, as discussed below.

Figure 16.14B illustrates a structure that has a thin, discontinuous, sandy clay lining, somewhat similar to that of the structure shown in Figure 16.14A; but this structure does not terminate with a chamber at its base. Its form is essentially that of a large inverted cone, filled with unlaminated sediment from above (Fig. 16.15). The process of formation apparently triggered small displacements through normal faulting in the sediments adjacent to the structure's margin (cf. Fig. 16.16). Similar faults were found in other places not in direct association with the large structures, however, thus the two phenomena are not uniquely interdependent.

Two structures of this last type were found in the North Carolina deposits. In size and overall appearance, they closely resemble a large structure described by Dionne and Laverdière (1972) from a Quaternary sand and silt deposit in Quebec Province, Canada.

A variety of origins—physical and biogenic, summarized by Dionne and Laverdière (1972, p. 532–533)—have been postulated for vertical structures of this general type. Dionne and Laverdière suggested that the Canadian structure was formed by the action of a whirlpool eroding a cylindrical hole in unconsolidated sediments, or by the action of spring waters rising through the sediments. Of these two suggestions, the whirlpool mechanism seems most plausible for the North Carolina structures, because they definitely are filled with sediment from the overlying wavy- and flaser-bedded member. Yet the sediments of this member are interpreted as having been deposited on an intertidal sand flat or in a shallow subtidal environment, and to assess the probability of whirlpools or springs being active in either environment is difficult.

The possibility that these structures were formed by a vertebrate animal cannot be ruled out. When startled, some marine snake eels (Ophichthidae) and worm eels (Echelidae) burrow very quickly to depths of 1 m, the approximate length of the animal (Lagler et al., 1962, p. 198). The morays (Muraenidae) are even larger; modern ones are predominantly crevice-nestlers in reefs or rubble, but some ancient ones or little-known modern ones conceivably may burrow in sediments. However, no modern analog for these Pleistocene structures is known, and if biogenic, the identity of the tracemaker(s) remains a mystery—made all the more perplexing by the close correspondence between associated trace fossils and their recent counterparts: e.g., burrows of *Callianassa major* and *Upogebia affinis* for the *Ophiomorpha* and *Thalassinoides*, respectively, and dwelling tubes of *Onuphis microcephala* for the *Skolithos* (Curran and Frey, 1973; Curran et al., 1973).

Other structures of similar form, occurring in generally similar environmental settings, have been reported to us: in Pleistocene oolitic sands from the Bahamas (A. C. Neumann, 1973, personal communication) and Upper Cretaceous quartz sands

of Utah (J. D. Howard, 1973, personal communication). We suspect that these kinds of huge structures are more common than is now generally known, and their origins—whether physical or biogenic—certainly warrant further investigation.

DISCUSSION AND CONCLUSIONS

The foregoing examples should illustrate some of the variations, peculiarities, and complexities of unusually large burrows or burrow-like structures. Of course, the interpretation of large burrows in general must be tempered somewhat by the actual function of the structure, as well as by its overall size and probable maker. The length of an escape structure, for example, is more a matter of sedimentation rate and survivorship or longevity of the tracemaker than of body length. The rate of lithification of the substrate is also very important in determining burrow characteristics (e.g., Chapter 18). Similarly, well-integrated burrow systems are theoretically endless; the interconnected shafts and tunnels are in effect a giant commune maintained by many individual animals. The shrimp *Callianassa major* constructs such burrow networks in Georgia beaches (Frey and Mayou, 1971), and certain ancient examples are equally striking; one of us (RGB) has traced *Thalassinoides* systems continuously along the Chalk Rock hardground (see Bromley, 1967), in one enormous quarry, for the entire 2-km extent of the exposure, and suggests that the system is, in fact, continuous through the 200-km extent of the hardground itself!

Nevertheless, the diameter of exceptionally large escape structures may be impressive, important, and problematical, as is the length of the structure when considered in terms of the actual tenacity and adaptations of the tracemaker. And the paramoudras are striking in their singular occurrences: individual burrows that are extremely small in diameter relative to their length.

One of the main problems in interpreting the latter, as well as the Permian forms, is whether the animal(s)—individually or through successive generations—occupied the entire structure at any given time, or whether basal parts were abandoned gradually as the tracemakers kept pace with sediment accumulation. In neither case were the entire burrows likely to have been inhabited simultaneously, throughout their length: the Permian ones because little or no evidence indicates that the burrow walls were structurally reinforced—as is generally seen in durable dwelling structures; and the Cretaceous–Paleocene ones because of the sheer length of time involved—the walls may well have been reinforced, but the rate of deposition of the sediments containing the burrows was so slow that vertical extension with time, as the animals kept pace with sediment accumulation, would require that the burrows be inhabited continuously for millions of years. "Cut-offs" and abandoned burrow components are common among shrimp domiciles (e.g., Weimer and Hoyt, 1964); but such evidence is lacking for the Permian and Cretaceous–Paleocene burrows studied by us. If the animals inhabited the total structure, how did they aerate the lower part? Irrigation is not difficult in burrows having more than one aperture (e.g., Vogel and Bretz, 1972), or even in small vertical burrows (Mangum, 1964); but how so in a single large burrow that is tremendously longer than wide?

The density of large burrows is also important, especially in cases such as those illustrated in Figures 16.3 and 16.4. The ultimate density of trace fossils is as much a matter of depositional rates and function and "preservability" of the original traces as it is of initial animal density (see Chapters 8, 9, and 20). In fact, the dense Permian burrows argue against high animal density; considering the engineering properties of the host sediments, how could the substrate retain its integrity if 80 percent of its volume consisted of open burrows several

meters long? Nevertheless, we cannot imagine a very small number of organisms building such large numbers of extensive, geometrically regular structures.

Overall, the problem of interpreting ancient burrows of such size is a matter of understanding the tracemaker's food requirements, need for domicile or protection, and manner of escape from pressures imposed by predation or physiochemical conditions of the environment. In the absence of body fossils attributable to the tracemaker preserved within the burrow, however, the evidence for the tracemaker remains circumstantial and speculative. Evolutionary changes must also be considered; for example, although the general behavioral patterns of tracemakers have remained more or less constant for hundreds of millions of years (Seilacher, 1964), we have no direct assurance that the Permian burrower has a close counterpart today. The uniformitarian principle is hampered further by a dearth of information on recent tracemakers that construct unusually large burrows, or on their limits of escape through rapidly accumulating sediments.

Finally, in some cases at least, we must also consider the possibility that the "burrows" are, in fact, inorganic in origin. Indeed, the situation here can be paradoxical: we may concede that the structures are inorganic simply because we cannot envision a suitable biogenic process, or that they are biogenic because we cannot conceive of a suitable physical process! Such problematical structures require meticulous study (e.g., Allen, 1961; Walter, 1972; Asgaard and Bromley, 1974); the evidence can be much more subtle than we might expect, and in many cases we probably fail to recognize the significance of the evidence itself (see Chapter 5).

The numerous difficulties notwithstanding, we suspect that unusually large burrows and burrow-like structures are much more abundant in recent and ancient sediments than the literature would suggest. Future work will hopefully reveal more of them and more criteria for their recognition and interpretation.

ACKNOWLEDGMENTS

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