CRUSTACEAN BURROWS IN THE WEALD CLAY (LOWER CRETACEOUS) OF SOUTH-EASTERN ENGLAND AND THEIR ENVIRONMENTAL SIGNIFICANCE

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ABSTRACT. The trace fossil usually known as *Ophiomorpha nodosa* Lundgren occurs at several horizons and localities in the Weald Clay (Lower Cretaceous) of Surrey and Sussex. By analogy with Recent occurrences (as described by Weimer and Hoyt 1962), all of which are marine, these structures are ascribed to the burrowing activities of decapod crustaceans (callianassids) in near-shore and littoral sands. Normally the traces are associated with a mixed assemblage of marine and brackish water fossils, and it is inferred that the Weald Clay occurrences of *Ophiomorpha* by itself indicates a marine environment, close to shore, where such an assemblage might occur.

Three variants of *Ophiomorpha* are recognizable in the Weald Clay sandstones: (1) a pellet-lined system; (2) burrows with a meniscus fill; (3) unlined burrows with scratch marks. Each represents a different type of burrowing activity by the callianassids.

THE Weald Clay (Lower Cretaceous) of southern England consists of a thick (up to 360 m.) sequence of clays, sands, silts, and limestones of Barremian age (MacDougall and Prentice 1964). It has long been realized that the Weald Clay shows marked evidence of marine conditions, although indications of fresh, brackish/marine, and perhaps near-terrestrial conditions have been recorded. Thus, as Kilenyi andAllen (1968) noted, there are two broad molluscan assemblages: a freshwater one, dominated by *Viviparus*, but also yielding unionids, and a much less common assemblage, with *Filosina* (Casey 1955), *Cassiope*, *Melanopsis*, *Nemocardium*, *Ostrea*, and other forms.

Other evidence is seen in the Isle of Wight, where the top of the Wealden Shales are undoubtedly part marine, with marine molluscs and trace fossils. Echinoid debris (again fully marine) is recorded from the Weald Clay by Casey (1961) and Allen and Keith (1965). The latter suggest extensive variation in salinities during Weald Clay times on the basis of carbon isotope ratios.

Detailed studies on the ostracods have been published; Anderson (1967) described a complex variation in the ostracod fauna of the formation, which he took as evidence of the presence of many marine phases. Kilenyi and Allen (1968) described a brackish/marine microfauna from the lower part of the Weald Clay, but in reviewing Anderson's work (op. cit. p. 162), they concluded that only three undoubted marine bands occur in the Weald Clay of Surrey and Sussex.

In this paper we describe the trace fossil *Ophiomorpha nodosa*, a marine indicator not previously recorded from the Weald Clay. It occurs in sandstones at several horizons and localities. Further detailed microfaunal work is needed to relate these sandstones to the brackish/marine bands of the ostracod workers.

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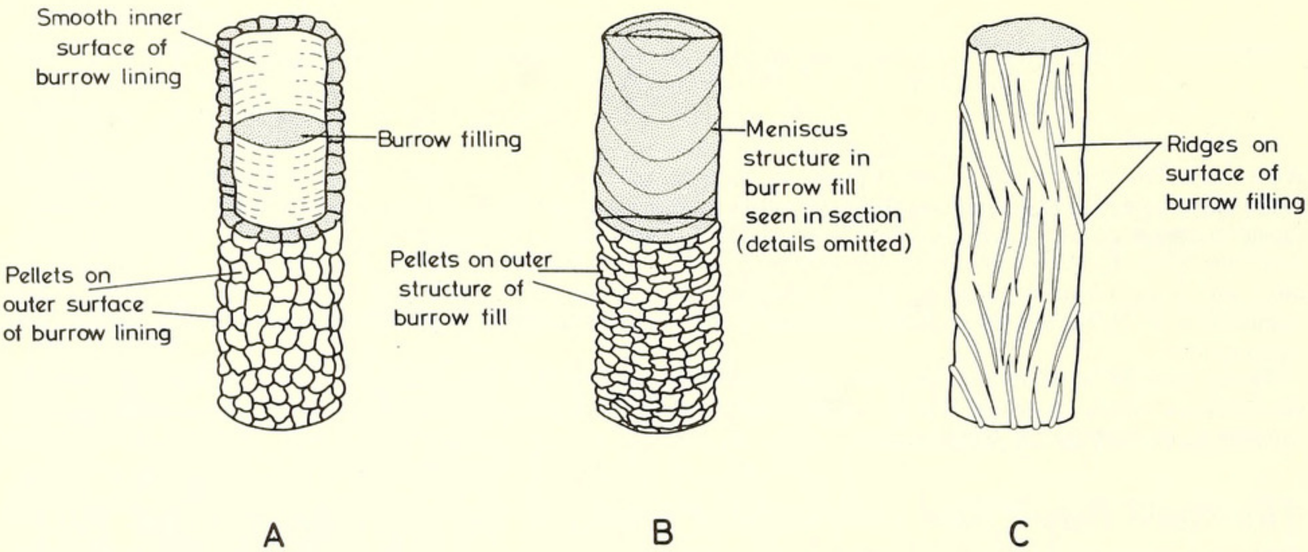
SYSTEMATIC DESCRIPTION

Ichnogenus OPHIOMORPHA Lundgren 1891 (for synonymy see Häntzschel 1962)

Type species. Ophiomorpha nodosa Lundgren (1891, p. 114) from the 'Wealden' (Lower Cretaceous) of southern Sweden, by monotypy.

Diagnosis. Medium-sized three-dimensional tunnel systems branching dichotomously at acute angles, swollen at the point of branching. Tunnels internally smooth, sometimes filled or lined with ovoid pellets, when the surface of the filling is mammillated.



TEXT-FIG. 1. Diagram of types of *Ophiomorpha* occurring in the Weald Clay sandstones. Sectioned parts are stippled. × 1 approx. A, Type 1, agreeing with the typical form of *O. nodosa*. B, Type 2, with meniscus fill (detailed structure of fill omitted). C, Type 3, comparable to *Halymenites striatus*.

Discussion. Häntzschel (1962) described *Ophiomorpha* as having 'tubercle-like or wart-like ornamentation of the outer wall but smooth inside'. This description is liable to misinterpretation; Lundgren's original figures and our material shows that the tunnel is smooth, whilst the outer surface of the filling has a tubercle-like or wart-like ornament (text-fig. 1A). This is usually clear in lithified sediments, but in unconsolidated sands the distinction is usually lost.

Ophiomorpha nodosa Lundgren 1891

?1836 *Ophiomorpha mantelli* Nilsson; *in* Mantell, p. 25 (*nom. nud.*)

1842 *Spongites saxonicus* Geinitz, p. 96 (*pars*), pl. 23, fig. 2 only. (*non*. fig. 1, = lectotype of *S. saxonicus*).

1847 *Cylindrites spongioides* Goeppert; Goeppert, p. 359, pl. 35, figs. 1–2; pl. 36, figs. 2–3 (*non* Goeppert 1841, 1842 (see Häntzschel 1965)).

?1852 *Spongites saxonicus* Geinitz; von Otto, p. 20, pl. 6, fig. 1.

?1856 *Cylindrites spongiodes* Goeppert; Dunker, p. 183, pl. 25, fig. 5.

?1858 *Halymenites flexuosus* Fischer-Ooster, p. 55, pl. 13, fig. 1. (Genolectotype of *Halymenidium* Schimpner 1879, *vide* Häntzschel 1965, 42).

1865 *Cylindrites tuberosus* Eichwald, p. 8, pl. 4, fig. 13; pl. 5, figs. 1*a*, *b*.

1866 *Phymatoderma dienvalii* Watelet, p. 24, pl. 4, fig. 1.
1873 *Halymenites major* Lesquereux, pp. 373, 390.
?1873 *Halymenites minor* Fischer-Ooster; Lesquereux, p. 373.
1875 *Halymenites major* Lesquereux; Stephenson, p. 406.
1877 *Broeckia bruxellensis* Carter, pp. 382–92, pl. 18.
?1878 *Halymenites striatus* Lesquereux; Lesquereux, p. 37, pl. 1, fig. 6.
1878 *Halymenites major* Lesquereux; Lesquereux, p. 38, pl. 1, figs. 7, 8.
1878 *Halymenites minor* Fischer-Ooster; Lesquereux, p. 39, pl. 1, fig. 9.
1879 *Halymenites major* Lesquereux; Stephenson, pp. 370, 371.
1889 *Halymenites major* Lesquereux; Eldridge, p. 317.
1890 *Halymenites major* Lesquereux; Stephenson, p. 532.
1891 *Ophiomorpha nodosa* Lundgren, pp. 114–15, figs. 1, 2.
1895 *Astrophora baltica* Deecke, p. 167, pl. 1.
1900 *Halymenites major* Lesquereux; Knowlton, pp. 17, 18.
1909 *Cylindrites spongioides* Goeppert emend. Richter; Richter, pp. 8–11 (*parts*), pl. 9, fig. 7; pl. 8, fig. 6; pl. 12, fig. 3.
1916 *Halymenites major* Lesquereux; Knowlton, pp. 86, 87.
1917 *Halymenites major* Lesquereux; Lee and Knowlton, p. 242.
?1917 *Halymenites striatus* Lesquereux; Lee and Knowlton, p. 243.
1919 *Halymenites major* Lesquereux; Knowlton, pp. 313–14 (*cum. syn.*).
?1919 *Halymenites striatus* Lesquereux; Knowlton, p. 314 (*cum. syn.*).
1921 *Halymenites major* Lesquereux; Berry, pp. 55, etc.
1928 *Astrophora baltica* Deecke; Voigt, p. 104.
1931 *Halymenites major* Lesquereux; Mathias, p. 355, fig. 1.
1937 *Halymenites major* Lesquereux; Carter, pp. 256–7, pl. 43, figs. 1, 2; pl. 34, figs. 1, 2.
1938 *Halymenites major* Lesquereux; Stenzel, pp. 68–70, fig. 7.
1948 *Terebella sp.* Beets, pp. 184–7, figs. 1–5.
1952 *Ophiomorpha nodosa* Lundgren; Häntzschel, pp. 142–53, pl. 13, 14 (*cum syn.*).
1953 *Halymenites major* Lesquereux; Eargle, pp. 143, etc.
1954 *Ophiomorpha nodosa* Lundgren; Prescher, p. 59.
1956 *Ophiomorpha nodosa* Lundgren; Seidel, pp. 489–93, figs. 1, 2.
1959 *Ophiomorpha* Lundgren; Baatz, pp. 168–71.
1961 *Ophiomorpha nodosa* Lundgren; Toots, pp. 165–70.
1961 *Halymenites major* Lesquereux; Toots, pp. 165–70.
1961 *Halymenites major* Lesquereux; Weimer, pp. 88, 89, 95.
1962 *Ophiomorpha nodosa* Lundgren; Häntzschel, pp. W205–6, fig. 124 (4, 9).
1962 *Ophiomorpha* Kilpper, pp. 55, 57.
1962 *Halymenites* or *Ophiomorpha*; Weimer and Hoyt, p. 321.
1963 *Ophiomorpha* Lundgren; Hillmer, pp. 137–41, fig. 1.
1963 *Callianassa* burrows, Hoyt and Weimer, p. 530, fig. 3.
1963 *Ophiomorpha*; MacKenzie, pp. 141, 143, pl. 2*a*, *b*.
1964 *Ophiomorpha tuberosa* (Eichwald); Vialov, pp. 163–7, figs. 1–4.
1964 *Ophiomorpha, Halymenites*; Weimer and Hoyt, pp. 761–7, pl. 123, figs. 7, 8; pl. 124, figs. 1–7.
1965 *Ophiomorpha nodosa* Lundgren; Häntzschel, p. 63.
1965 *Halymenites major* Lesquereux; Häntszchel, p. 72.
1965 *Phymatoderma dienvalli* Watelet; Häntzschel, p. 71.
1965 *Astrophora baltica* Deecke; Häntzschel, p. 13.
1965 *Broeckia bruxellensis* Carter; Häntzschel, p. 18.
1965 *Ophiomorpha nodosa* Lundgren; Hoyt and Weimer, pp. 203–7, figs. 1, 2, 5–7.

Material. The present description is based largely on specimens collected from the Weald Clay of Hambledon (Surrey) and Burgess Hill (Sussex). Much additional material has been examined in the field, at these and several other localities and horizons.

Diagnosis. Ophiomorpha with tunnel wall ornamented by single elliptical pellets. *O. nodosa* differs from *O. borneensis* Keij (1965, pp. 224–6, pl. 29, figs. 1–8, text-fig. 2 (1–4), text-fig. 3) by the predominance of vertical as opposed to horizontal elements in the system and the ornament of single as opposed to bilobate pellets. Neither of these criteria is particularly satisfactory.

Description. Ophiomorpha nodosa forms tunnel trails between 5 and 15 mm. diameter with a number of distinct types of surface ornament (text-fig. 1); these variations indicate the type of infillings of the tunnel; the tunnel itself is generally completely smooth. The tunnel system is extensive and ramifying both vertically and horizontally. Horizontal elements of the system predominate (though this may be an artefact of preservation) and are concentrated along sediment interfaces; with the vertical elements they form a three-dimensional network. The tunnels branch at acute angles at infrequent intervals (usually about 25 cm.), branching is dichotomous and both branch tunnels are of the same diameter as the original tunnel. The tunnel may be slightly swollen at the point of branching. The tunnelling organisms were not phobatactic, and later tunnels cut earlier tunnels indiscriminately.

There are three main variations in surface ornament, with transitional forms between; all may occur in a single tunnel. The texture of the sediment within the tunnel is variable, but always differs from that of the surrounding rock.

Type 1. (Text-fig. 1A; Pl. 87, fig. 1; Pl. 88, fig. 2). This agrees well with the typical form of *Ophiomorpha nodosa*. The surface of the tunnel infilling is mammillate, and is built up of small discoidal pellets, 2–3 mm. wide and 1 mm. thick in the largest burrows; the size decreases slightly in smaller burrows.

Type 2. (Text-fig. 1B; Pl. 87, figs. 1, 2; Pl. 88, figs. 3, 4). The surface of the tunnel infilling is ornamented by annular ridges. Sections show that these ridges are related to a well-defined fill of concavo-convex laminae (meniscus filling); these laminae may disintegrate to a honeycomb structure; the individual 'cells' of the honeycomb are clay pellets. This type is found more commonly in vertical tunnels.

Type 3. (Text-fig. 1C; Pl. 87, fig. 1; Pl. 88, fig. 1). Comparable to *Halymenites striatus* Lesquereux. The surface of the tunnel fill is covered by a longitudinal, reticulate, ridge system. Similar *trails* of ridges are present on clay/sand interfaces associated with the sandstones in which *Ophiomorpha* occurs (Pl. 88, figs. 1, 5).

Within the systems in the Weald Clay sandstones, there is little obvious distribution of types as a whole, other than a suggestion that type 1 is more abundant in the upper part of systems, type 2 in vertical elements, type 3 in the lowest, often horizontal parts of burrow systems.

Discussion. We give an extensive synonymy for this trace-fossil; other references are given by Häntzschel (1952, 1962), whom we follow in regarding *Ophiomorpha nodosa* as the most satisfactory name for these burrows.

The association of scratched burrows (type 3) with *O. nodosa* has led us to include other scratched burrows occurring associated with *Ophiomorpha* in the synonymy, i.e. *Spongites saxonicus* von Otto (*pars*, *non* Geinitz) and *Halymenites striatus* Lesquereux, but not scratched burrows not found associated with *Ophiomorpha*, e.g. *Spongeliomorpha* de Saporta 1887 (p. 299, pl. 6, figs. 2, 3).

INTERPRETATION

There can be no doubt that *Ophiomorpha* is a crustacean burrow, a view already convincingly stated by Häntzschel (1952). Weimer and Hoyt (1962, 1964) described the burrows of the extant marine decapod *Callianassa major* Say from sand beaches of Florida and North Carolina, convincingly demonstrating their presence in Pleistocene deposits nearby, and the identity of these burrows with *Ophiomorpha nodosa*.

The material from the Weald Clay differs from that previously described, in the dominance of preservation parallel to bedding planes, a result of the occurrence of the burrows in, and on, thin, locally cemented sands in an economically exploited formation, so that the blocks of sandstone accumulate in front of the working face. Elsewhere, occurrences are in unconsolidated sands, and they are naturally seen in vertical section only.

In the Weald Clay sandstones, the density of *Ophiomorpha* systems is low, and the sediment is not burrowed intensively; depositional structures are never destroyed and there is no intense bioturbation. Characteristically the tunnels are confined to sand horizons, only passing through clays when these are thin, i.e. less than 15 cm., clearly reflecting a preference by the crustaceans for particular depositional environments.

The animals populated only recently deposited unconsolidated sediments, so that settling structures within the sand bodies, i.e. load casts and syndepositional faults (see Pl. 87, fig. 1) often affected the tunnels.

This is in strong contrast to the associated *Equisetites* (*E. burkhartii* Dunker), whose underground stem, root, and tuber systems cut the burrows (and are thus later) and are unaffected by the settling structures and compaction effects.

The three types of burrows represent different natural processes, which we interpret as follows:

Type 1. This corresponds to the generally accepted form of *Ophiomorpha nodosa*. Worked pellets of sediment, moulded and cemented by the callianassid, are pushed into the sides of the burrow and scraped flat internally (see MacGinitie *in* Häntzschel 1952, p. 150) or smoothed off by the passage of the body of the inhabitant (as described by MacGinitie 1930, p. 39, in burrows of the callianassid *Upobegia pugettensis* Dana). In the Weald Clay material the pellets can sometimes be seen to have a brown cement; in Eocene examples from Upnor, Kent, microchemical tests indicate the presence of phosphate. Weimer and Hoyt (1964, p. 763) record collophanite as the cementing agent produced by *Callianassa major* to bind the sand pellets forming the lining of its burrow.

Type 2. The meniscus-filled *Ophiomorpha* tunnels can be interpreted in several ways. According to MacGinitie (1934, p. 167), when individuals of *Callianassa californiensis* (Dana) break into adjoining burrow systems, offending tunnels are blocked off and burrowed round; a similar explanation for our filled material seems quite likely.

Alternatively, this type of burrow may represent the filling-in of early parts of the tunnel system with material from new excavations, rather than disposal by the ejection of this material at the surface. Honeycomb structure, observed in some parts of this type of filling, is a result of the deposition of loads of clay rather than sand alone. A third interpretation is that these parts of the system were never open, but represent the activities of the callianassid as it passed through the sediment, leaving a meniscus filling as the animal transferred sediment backwards.

These fills thus appear to be somewhat different from the '*Halymenites*' noted and figured by Brown (1939), which are packed with what are clearly callianassid faecal pellets.

Type 3. The surface ornament of reticulate ridges on these burrow fillings represent grooves or scratches on the inside of the burrow. These can be interpreted as scratch-marks, produced by the appendages of the inhabitant when digging or passing through the burrow system. Their preservation is the result of lack of subsequent lining or packing of the burrow, so that the marks produced during the initial excavation are preserved.

This type of burrow clearly resembles *Spongeliomorpha* [de Saporta 1887, regarded here, and by Reis (1922), Häntzschel (1962, 1965), and Kennedy (1967) as a burrow, although de Laubenfels (1955) treated it as a sponge], the scratched tube of *Rhizocorallium* (Häntzschel 1962, p. W210, fig. 129*b*), and the scratched fossil and Recent burrows figured by Weigelt (1929, pl. 1, 2).

The boring '*Terebella*' *harefieldensis* White (1923), widely distributed in the top of the Upper Chalk immediately beneath, and filled by, the Lower Tertiary deposits of southern England (Hester 1965) has a similar ornament (Kennedy 1967). In all cases these appear to be crustacean burrows or borings.

In all types of *Ophiomorpha* observed, there are occasional swollen portions, often close to, or at, the point of branching. These represent 'turn arounds' where the animals were able to change direction in the burrow (see MacGinitie 1930, 1934, for a description of similar features in Recent callianassid burrows).

The trails of ridges seen on the bottom surfaces of the sandstones containing *Ophiomorpha* (Pl. 88, figs. 1, 5) are interpreted as the surface tracks of crustaceans, produced as scratches on a mud bottom. These were almost certainly produced by the *Ophiomorpha* inhabitant. They are identical with the trails of Recent crustaceans figured by Weigelt (1929, pl. 3, figs. 1, 2).

The small rod-like objects occurring abundantly on the bottom surfaces of some of the sandstones containing *Ophiomorpha* are similar to the callianassid faecal pellets described by Moore (1932), Pohl (1946), and Weimer and Hoyt (1964).

OCCURRENCE

Ophiomorpha ranges throughout the Weald Clay, but it is apparently confined to the more sandy horizons: siltstones, sandstones, and interbedded sandstones and clays. Table 1 gives the localities at which it has been found, and relates these occurrences to the divisions of the Weald Clay erected by Topley (1875), and, as far as is possible to those of Reeves (1953, 1958) and the ostracod zonation of Anderson (*in* Worssam 1963).

Hambledon, Surrey

Ophiomorpha occurs in thin, silty, largely siderite-cemented sandstones in Topley's (1875) no. 7 sand (the Fenhurst sandstone of Wooldridge (1950)), at the Nutbourne Brickworks, Vann Lane, Hambledon, Surrey (SU 973375). The beds with *Ophiomorpha* contain no calcareous fossils, but are notable for the occurrence of large numbers of well-preserved plant remains, identified as *Equisetites burkhartii* Dunker. Three containing lithologies can be recognized:

Lithology A. Thin sideritic silty sandstones in beds which vary in thickness from 40 to 120 mm., showing little lateral variation. In vertical sections these sandstones show thinly laminated low-angle cross-bedding and ripple-drift bedding in the upper part. Minor (20 mm.) textural rhythms occur within the cross-bedding. There is a general lack of biogenic disturbance, except for burrows of *Ophiomorpha* (compare with the

TABLE 1

Ophiomorpha occurrences and Weald Clay stratigraphy

Ophiomorpha *occurrence*	*Local divisions*		*Ostracod zonation* (*Anderson* in *Worssam 1963*)
	Topley (1875)	*Reeves (1953, 1958)*	
Hambledon	no. 7, sand	Group III	*Cypridea valdensis*
		newest red clay	*Cypridea clavata*
	no. 6, limestone, 'Sussex marble' (large *Paludina*)		
Capel, Burgess Hill	no. 5, sand and sandstone with calcareous grit	Group II	*Cypridea tuberculata*
	no. 4, limestone (large *Paludina*)		
	no. 3, limestone (small *Paludina*)		
	no. 2, sand and sandstone	oldest red clay	*Cypridea dorsispinata*
Southwater, Sedgewick Park	no. 1, Horsham stone	Group I	

observations of MacDougall and Prentice 1964), which pass through individual beds of sandstone and are concentrated along major bedding planes, particularly the bases of the sandstones. *Equisetites* stems pass through *Ophiomorpha* and are filled by sediment identical with the surrounding sandstone.

The bases of the sandstones are erosional, and show a variety of sole-markings, i.e. broad, poorly defined load structures, prod-marks, groove-casts, and the 'A' and 'B' trace-fossils of Prentice (1962). Dessication cracks in the underlying clay are preserved as reticulate ridges on the base of some of these sandstones.

Lithology B. Massive sideritic sandstones, up to 240 mm. thick, with indistinct bedding. The top of the sandstones is poorly defined, grading up into sandy clays. The main mass of the sandstone is penetrated by vertical and horizontal *Equisetites* stems, with tubers arising from stems at the nodes. The base of these sandstones is covered by *Ophiomorpha* tunnel systems. A syndepositional fault system cuts this surface and the *Ophiomorpha* (Pl. 87, fig. 1).

Lithology C. Micaceous sandstones, 200 mm. thick, breaking into 50-mm. slabs along clay partings, which contain abundant drifted plant remains. The bases of individual layers have load casts; other bottom structures also occur. The upper surfaces are carious, and have a honeycomb texture due to intense penetration by *Ophiomorpha*, with a lot of clay in the burrow filling, which has weathered out, leaving cavities.

Capel, Surrey

At Clock House Brickworks, 1¾ miles south of Capel Church (TQ 175385), *Ophiomorpha* occurs in Topley's (1875) no. 5 sandstone, in lithologies similar to those at Hambledon. The section in the middle face has been described by Kirkaldy and Bull (1948); it is now badly degraded, but has been confirmed by one of us (J. D. S. M.). Bed 2 of Kirkaldy and Bull includes the sandstones with *Ophiomorpha*, and two lithologies can be recognized: micaceous sandstones, similar to the Hambledon lithologies, in beds up to 200 mm. thick, sideritic, with abundant *Ophiomorpha*; and thin siltstones, (ripple-marked with an erosional base) in which basin cast structures (Prentice 1962, pl. 3, fig. 2), varying from 50 to 250 mm. thickness are developed.

The base of these siltstones is covered by groove-casts and prod-marks, which are occasionally interrupted by *Ophiomorpha* (Pl. 87, fig. 2). The siltstones are penetrated by obscure vertical tubes, similar in diameter to stems of *Equisetites burkhartii*. Apart from these, we have failed to detect the *Equisetites* recorded by Kirkaldy and Bull at this level.

An interesting feature of this section is the occurrence of *Filosina* [*Neomiodon*] in some numbers, above bed 3 of Kirkaldy and Bull (1948).

In the lower pit at Capel, a further section includes clays with *Paraglauconia strombiformis* (Schlotheim), *Filosina gregarea* Casey, oysters, and an abundant ostracod fauna including *Schuleridia*, arenaceous foraminifera, and cirripedes (Kilenyi and Allen 1968), suggesting that these beds were laid down in marine or brackish waters.

Burgess Hill, Surrey

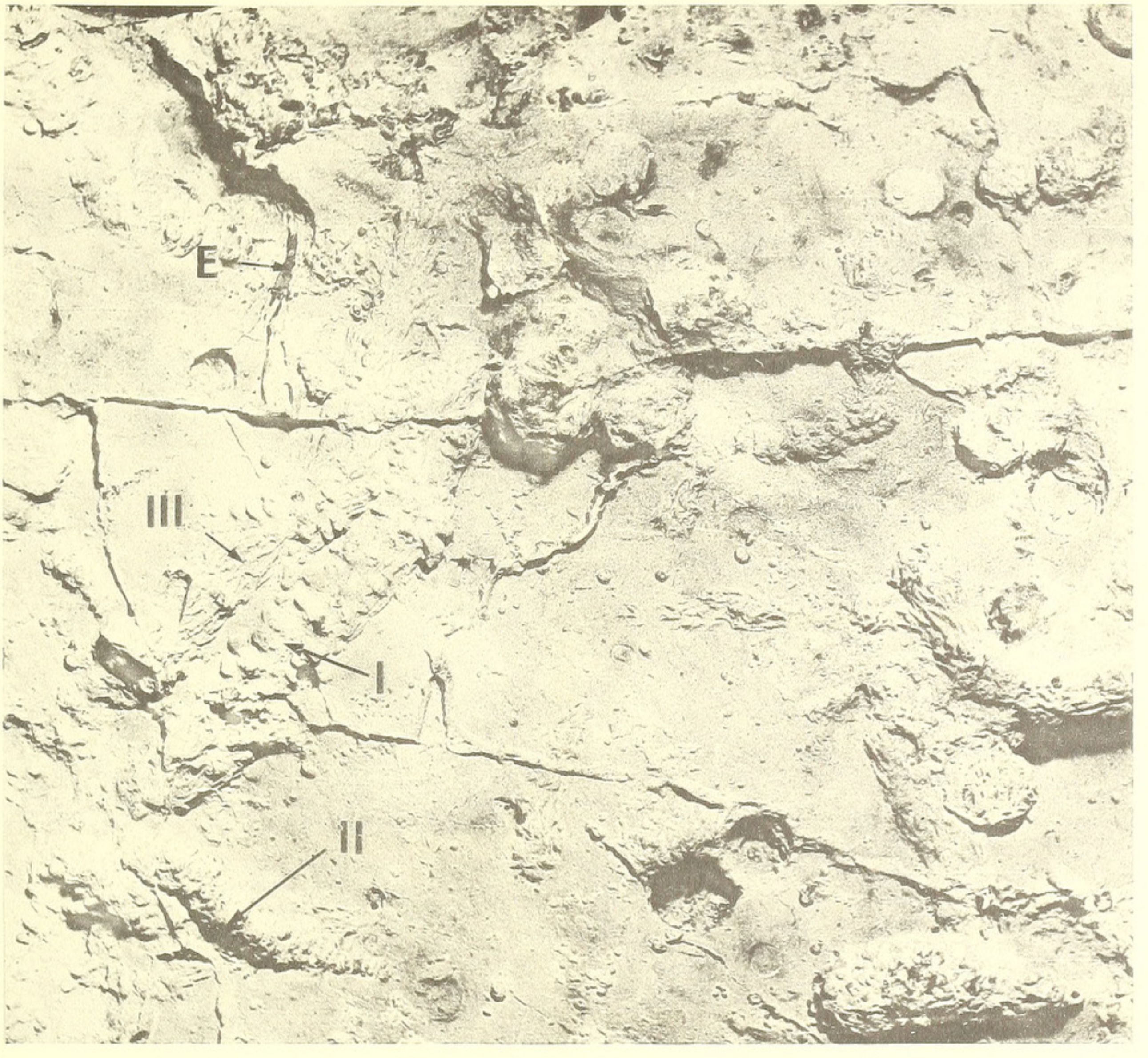
Ophiomorpha occurs at Keymer Brickworks, near Wivelsfield station, Burgess Hill, Surrey (TQ 324193), in massive, micaceous sandstones up to 200 mm. thick, ripple-drift bedded in the upper part. These sandstones appear to have been dredged up from the lower part of the succession, where silty clays and shaly clays with ostracods, passing up into red clays and sandstones, are seen; the succession is rather like that at Capel. The beds with *Ophiomorpha* appear to be Topley's (1875) no. 5 sandstones.

EXPLANATION OF PLATE 87

Figs. 1, 2. *Ophiomorpha nodosa*. 1, Bottom surface of a sandstone block from Hambledon, Surrey, showing all three forms of *Ophiomorpha* (as indicated), load casts, syndepositional faults, and *Equisetites burkhartii* (E); ×1. 2, Bottom surface of a basin cast from Clockhouse brickworks, Capel, Surrey, showing a specimen of Type 2 *Ophiomorpha*, with prominent pelletal fill, cutting a surface covered with aligned groove- and prod-marks; ×1.

EXPLANATION OF PLATE 88

Figs. 1–5. *Ophiomorpha nodosa* and associated trace fossils. 1, Type 3 *Ophiomorpha* running parallel to bedding, with a trail of ridges to the left. 2, Type 1 *Ophiomorpha*, showing characteristic pelletal surface; a tuber of *Equisetites burkhartii* is visible at the top right of the photograph. 3, Type 2 *Ophiomorpha*, showing ornament of burrow fill. 4, The same, vertical longitudinal section, showing meniscus fill. 5, Trail of ridges from bottom surface of *Ophiomorpha*—bearing sandstone. All photographs (except 4, a section) are the lower surfaces of sandstones from Hambledon, Surrey; figs. 1–3, 5 are ×2; fig. 4 is ×4.



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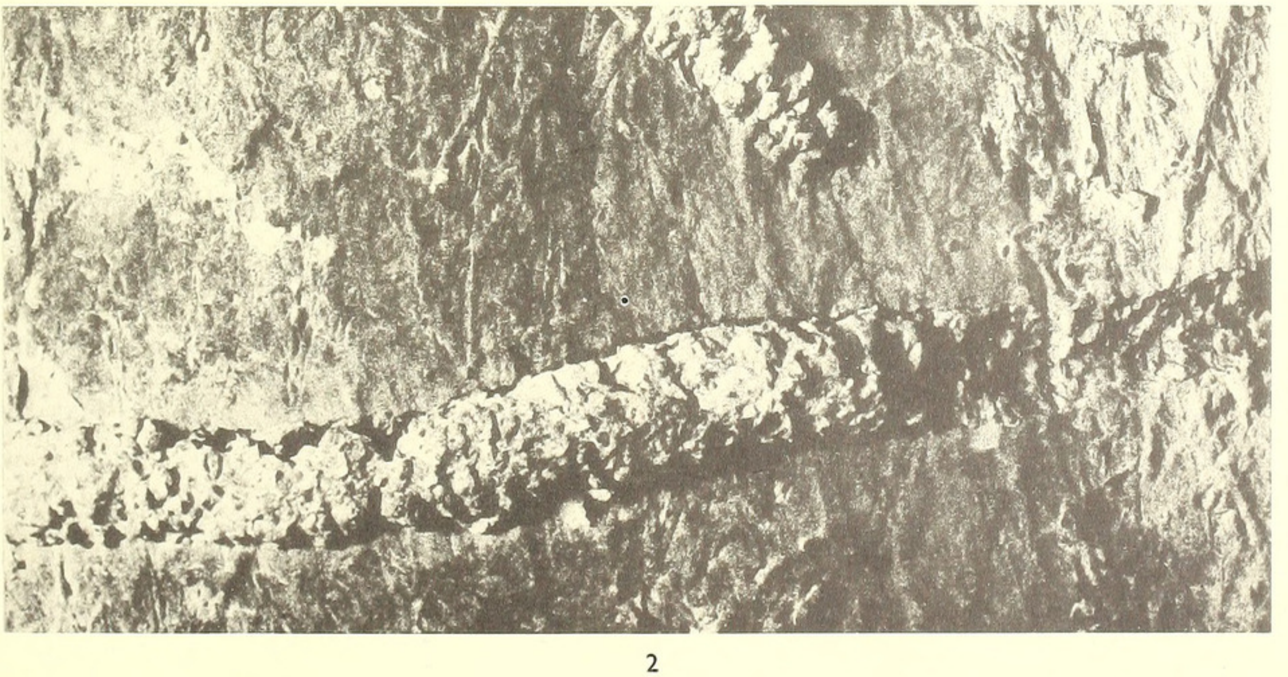

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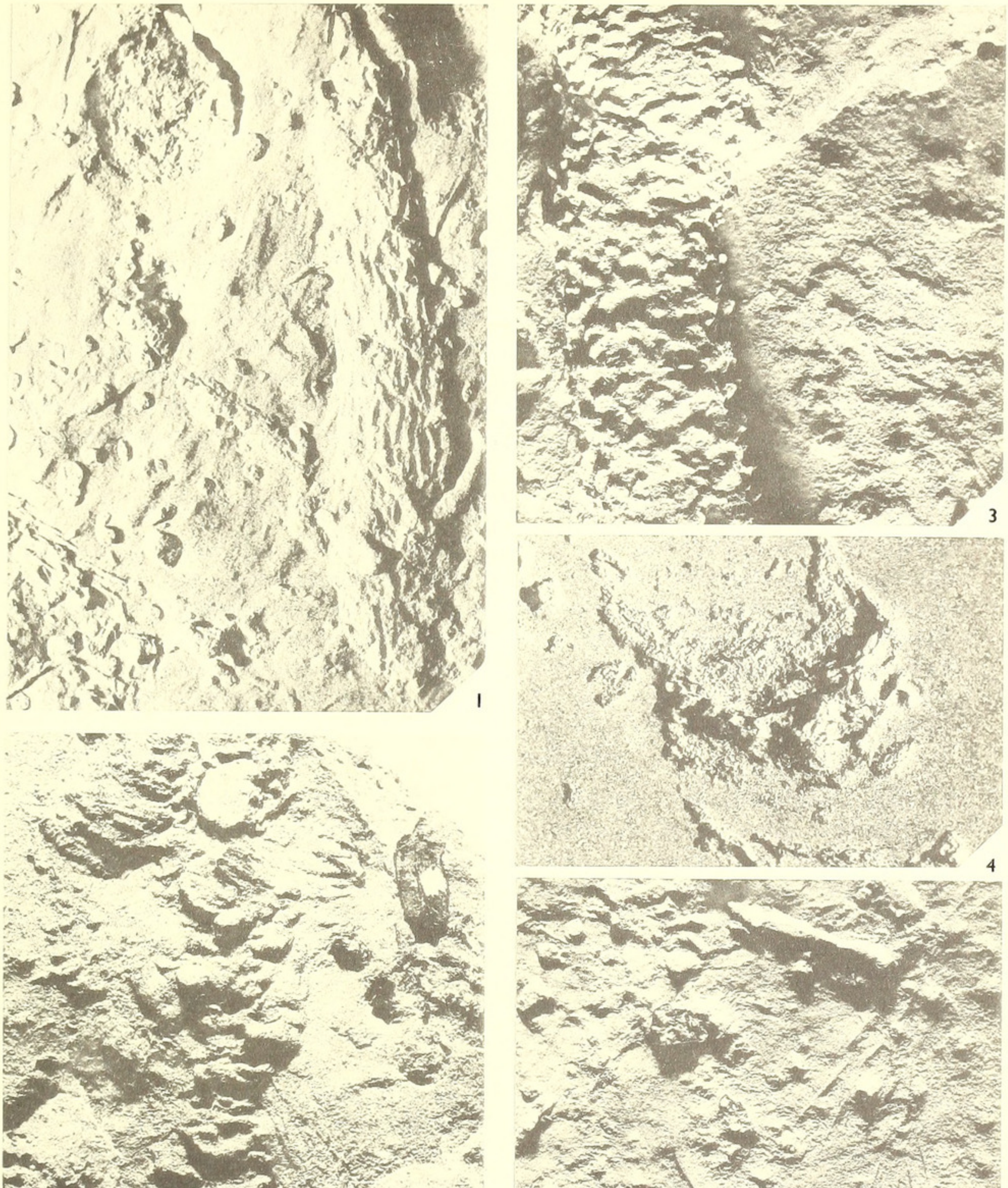
KENNEDY and MacDOUGALL, Crustacean burrows in Weald Clay



KENNEDY and MacDOUGALL, Crustacean burrows in Weald Clay

Southwater, Surrey

The topmost bed of the Horsham Stone (Topley 1875, no. 1 sandstone) in Southwater no. 2 Brickpit, Castle Wood, Southwater, is intensely penetrated by *Ophiomorpha*. Fragments of crustacean carapaces and rootlets of *Equisetites* are occasionally found in both sandstone and clay.

Sedgewick Park and Slinfold, Surrey

Ferguson (1926) recorded three types of sandstone in the Horsham Stone, very similar to those recognized by us at Hambledon. At a quarry (now filled in) 800 m. west of Southwater Church (TQ 152263) he recorded (p. 408) what may be *Ophiomorpha*: 'peculiar cylindrical bodies, possibly animal tracks or burrows, are observed, and carbonaceous fragments are not uncommon'.

Ophiomorpha also occurs in Ferguson's type A sandstone in the Upper Horsham Stone at a natural exposure at Sedgewick Park, Surrey (TQ 179271).

OPHIOMORPHA AS AN ENVIRONMENTAL INDICATOR

Ophiomorpha *structures in Recent sediments*. Weimer and Hoyt (1962, 1964) have shown beyond doubt that *Ophiomorpha*-like structures are being produced in present day sediments by callianassids (marine decapod crustaceans), particularly *Callianassa major* Say. They recorded this animal primarily from the low littoral zone, between mean sea-level and low tide on beaches that face the open ocean (1964, fig. 2), in well-sorted sand in strongly wave-agitated waters. They also noted some occurrences just above mean sea-level, and in the shallow neritic zone, up to 1·5 m. below mean low water, and suggested that the burrows extend to greater depths.

Fossil occurrences. Extending their observations to adjacent Pleistocene sands, Weimer and Hoyt successfully demonstrated that the occurrence of *Ophiomorpha* in these indicated their deposition in shallow neritic and/or littoral conditions. They suggested that Tertiary and Cretaceous occurrences indicated a similar environment; burrows in well-sorted massive-bedded sandstones indicated littoral or shallow neritic conditions; burrows in poorly sorted, well-bedded silty sandstone suggested deeper neritic conditions.

In spite of this definitive view of the environment indicated by *Ophiomorpha*, i.e. wholly marine, littoral/sub-littoral, there is a range of suggested environments in the very extensive literature on this trace fossil (Baatz 1959, Hillmer 1963, Mathias 1931, Ortmann 1925, Seidel 1956, etc.)

Ophiomorpha is recorded in sequences which contain lignites, marine fossils (including ammonites), freshwater fossils (including unionids), quasimarine or brackish-water forms, and mixed assemblages in the same bed. Other authors have recorded faunas suggesting varying salinities in the same sequence, features which require explanation.

Considering the occurrence of a trace-fossil of this type, the environment indicated by the burrow is not that of the sediment the burrows occur in, nor of the sediment above the surface whence the burrows originate, nor any fauna these sediments may contain. The environment indicated is that existing during part, or all, of the period represented by the surface from which the burrows originate.

If this is borne in mind, it is readily understood how *Ophiomorpha* can occur associated