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PARAMOUDRAS: GIANT FLINTS,
LONG BURROWS AND THE EARLY
DIAGENESIS OF CHALKS

Det Kongelige Danske Videnskabernes Selskab
Biologiske Skrifter 20, 10



Kommissionær: Munksgaard
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Synopsis

Vertical burrows 0.5 cm in diameter and 5–9 m long are common at certain horizons from the Turonian to Maastrichtian chalk (Upper Cretaceous) of NW Europe and in Danian calcarenites in Denmark. The burrows are associated with hardening, pyritization and glauconitization of the adjacent sediment and with the development of large barrel- or pear-shaped flints known as paramoudras. The special diagenesis to which the burrows have given rise appears to have been caused by the introduction of organic matter to depths of several metres into sediment that was anaerobic and generally organic-poor. Study of these abnormal diagenetic processes associated with a special microenvironment gives further insight into the normal conditions of burial diagenesis that prevailed in the chalk sea floor sediments and particularly into the genesis of flint. The trace fossil is designated *Bathichnus paramoudrae* n. ichnogen. et ichnosp.



Fig. 1. Detail of the frontispiece to Worm's (1655) museum catalogue depicting a knobby, annular object. The form and dimensions of the object together with the Danish nationality of the collector leave little room for doubt that this was a paramoudra.

Introduction

Lying in a corner of OLE WORM's remarkable museum was a massive, ring-like object (WORM, 1655). The form and dimensions of the object were so characteristic (fig. 1) that it can be identified without question as a form of giant flint concretion which is common at several horizons in the Upper Cretaceous chalk of NW Europe. So conspicuous and locally abundant is this type of flint that it has received many colloquial names (*Paramoudra* in Ireland, *Potstone* in England, *Sassnitzer Blumentopf* in Germany and *Flintkrukke* in Denmark) and has attracted the attention of the geologist at an early date.

A re-examination of these special flints *in situ* has shown that they are associated with early diagenetic calcite cementation, glauconitization and pyritization in connection with a very large burrow. The details of morphology of the paramoudra and of the related mineralization have been known for a long time and we have been able to add little to their full description. However, the recognition of a characteristic burrow within

the flint is new and casts an entirely new light on the interpretation of the flints and related phenomena. The identification of the burrow in flintless chalk, also, stimulates a discussion of the causative organism, its environment and the special diagenesis to which it has given rise.

History

BUCKLAND (1817) described paramoudra flints *in situ* for the first time. He mentioned the core of unsilicified chalk that characteristically runs up the centre of each paramoudra and noticed their occurrence in columns, one concretion above another. TAYLOR (1824) observed that the chalk within and between the successive paramoudras in a column is relatively hardened. FITCH (1840) added significantly to the description by revealing a pencil-thick, vertical, green tube that lies centrally within the hard chalk core of the paramoudra. PUGGAARD (1851) independantly described and illustrated the central tube, with suggestions of side branches, and added the characteristic ferruginous staining and pyrite nodules to the description (fig. 2).

HAGENOW (1839, p. 293) described ring-like paramoudras from Rügen and considered them body fossils of monstrous soft animals. BRONN (1848) listed the paramoudra as a body fossil as "*Amorphozoa indeterminata, saepe Polythalamiis replete*", and in 1852 (BRONN & ROEMER) classed the flint with the Amorphozoa under the name *?Paramoudra*, while PUGGAARD (1851) considered it to be a giant sponge and named it *Spongia annula*. LYELL (1865) favoured the sponge interpretation and figured some extensive columns of paramoudras (fig. 3). ROSE (1862) also reported a column of six superimposed paramoudras. The flint received yet another binomial designation when SOLLAS (1880) placed it in a living sponge genus as *Poterion cretaceum*.

More recently, however, MANNING, ROBBIE & WILSON (1970) have regarded paramoudras as of inorganic origin. PEAKE & HANCOCK (1961; 1970) have shown that in

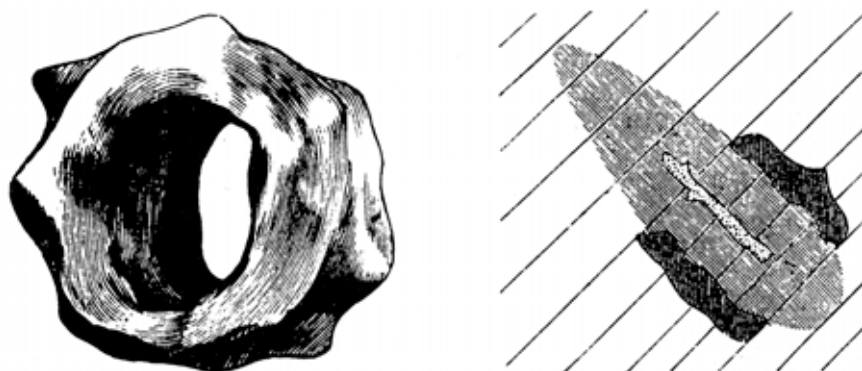


Fig. 2. Reproduction of PUGGAARD's (1851) figs 2 & 3 depicting paramoudras. To the right, a paramoudra in (oblique) section in situ in the Lower Maastrichtian chalk of Mons Klint, Denmark, with the central pyrite rod and zone of discolouration.

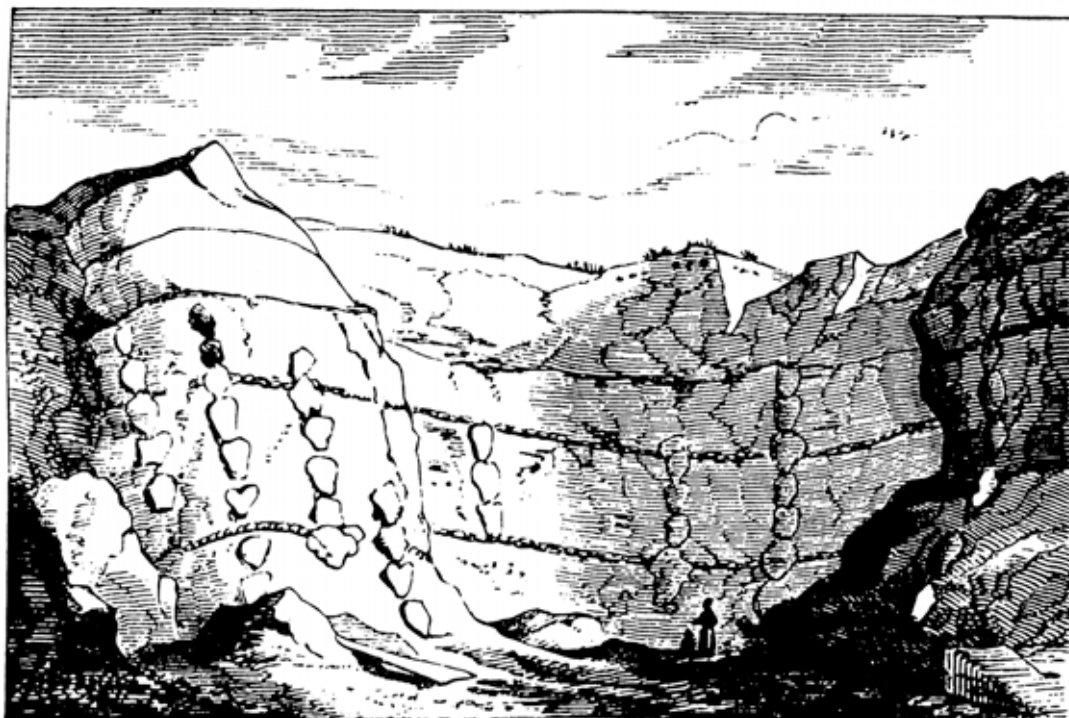


Fig. 3. Reproduction of Mrs. GUNN's drawing of paramoudra columns in Upper Campanian chalk in the quarries on the River Bure near Horstead, Norfolk (LYELL, 1865, fig. 286). The uppermost stratum is Pleistocene gravel resting on an erosion surface which truncates the columns. Lyell interpreted these structures as giant siliceous sponges which rejuvenated periodically as they became buried and thereby kept pace with sedimentation.

Norfolk, England, paramoudras are characteristic of (but by no means limited to) the uppermost part of the Upper Campanian and they established the name Paramoudra Chalk for this level. JAEKEL (1930, pl. 8), and particularly STEINICH (1972), have illustrated extensive columns from Lower Maastrichtian chalk at Rügen, Germany and KENNEDY & JUIGNET (1974) have drawn attention to similar phenomena in the Coniacian chalk of Normandie, France (see fig. 4).

However, the paramoudra has been interpreted as diagenesis associated with extensive burrows on only two occasions: by FELDER (1971) on the basis of Dutch and Belgian material and by BROMLEY et al. (in press) in a preliminary note based on the present work.

Occurrence of Paramoudras

Paramoudras and similar concretions have been reported from beds of Upper Cretaceous and Danian age (table 1). Columns are still well exposed in Northern Ireland, particularly near Moira; in the quarry at Hemmoor (Pl. 1A) and the cliffs of Rügen and of Møn, especially at Nylands Nakke, and of Normandie (fig. 4). In Nor-



Fig. 4. Part of the cliff face at Bénouville on the coast of Haute Normandie, France, showing c. 15 m flinty Coniacian chalk. The normal pattern of bedded nodular flint is crossed by at least five perpendicular flint structures. Well developed paramoudras are recognizable in these, e.g. at P, P, and a small flint cylinder is visible at X.

TABLE 1. Stratigraphical horizon of occurrences of *Bathichnus paramoudrae* and associated flint mentioned in the text.

	DENMARK	SWEDEN	BELGIUM	GERMANY	N. IRELAND	ENGLAND	FRANCE
P = paramoudras and similar flints	Valby (København)	Thisted (Jylland)				Weybourne (Norfolk)	Yport (Haute Normandie)
C = flint cylinders	Hvide Klint (Møn)		Bolrs (Limbourg)	Rügen (DDR)	Molra (Antrim)	Ruhton (Norfolk)	Bénouville (H. Normandie)
B = burrow without flint	Kongsled (Sjælland)	Limhamn (Skåne)	Hallenbayer (Limbourg)	Kronsmoor (Holstein)	Ballysillan (Antrim)	Frettenham (Norfolk)	Étrelat (Haute Normandie)
	Møns Klint (Møn)					Castor St. Edmunds (Nfk)	
	Karstrup (Sjælland)					Whittingham (Norfolk)	
	Stevns Klint (Sjælland)					Shide (I. of Wight)	
						Roger's Whiting Pit (Hants)	
						Helhoughton (Norfolk)	
						Ashby Hill (Lincolnshire)	
						Filey (Yorkshire)	
Upper Danian.....	P	P	PC PC				
Middle Danian.....							
Lower Danian.....	P						
Upper Maastrichtian.....	PB PB			PC B			
Lower Maastrichtian.....	P PB P			B	P P	C P P PC P	
Upper Campanian.....						P P	
Lower Campanian.....						P	PC PC PC
Santonian.....							
Coniacian.....							
Turonian.....						P	
Cenomanian.....						P	

folk, the uppermost Campanian "Paramoudra Chalk" is now poorly exposed, but columns and isolated paramoudras are still accessible in the underlying "Beeston Chalk", especially at Caistor St. Edmunds (PEAKE & HANCOCK, 1970). A Turonian example is illustrated in Pl. 1 C, but the oldest reported paramoudra-like flint is Cenomanian in age (ROWE, 1904, p. 209).

Younger examples occur in the Danian of Scandinavia (table 1) in sediments ranging in texture from bryozoan micrite (Thisted) to biocalcarene (Valby).

Characteristic examples of paramoudras and other vertical flints are housed in numerous museums in NW Europe. For example, Danish material is kept in the Mineralogisk Museum, Copenhagen, Denmark and Dutch material in the Maastricht Museum, Holland; English material may be seen in the Castle Museum, Norwich, England while two of BUCKLAND's original paramoudras from Northern Ireland reside in the Museum of the University of Oxford, England.

Description of the Diagenetic Features

The burrow described here is characteristically associated with a suite of diagenetic phenomena to which it has apparently given rise. This suite consists of the following members: (1) outsized flint concretions, most typically in the form of paramoudras but (2) in many cases in other monstrous forms with vertical extensions; (3) local calcite cementation of the sediment; (4) pyrite, either in finely divided form producing discolouration of the sediment, or in nodular habit; and (5) glauconite in the immediate vicinity of the burrow itself (fig. 5).

1. *The typical paramoudra*

Size and form of paramoudras vary considerably. The essential feature is a core of unsilicified chalk usually 10–15 cm in diameter which runs centrally from top to bottom of the flint. The amount of flint enveloping this core ranges from a relatively thin ring (Pl. 2 A), through a medially thickened barrel form to heavy bomb or pear shaped flints (Pl. 1 A) which may reach a vertical length of well over 1 m, in some cases 2 m (e.g. JUKES-BROWNE, 1904).

The outer surface of paramoudras is usually gently knobbly (Pl. 2 A), showing a similar sculpture to that of nodular flints at that horizon. This irregularity is exaggerated where a paramoudra crosses a bed of nodular flint.

The internal wall of the paramoudra is usually smoother than the outer. Its form is strongly influenced by the course of the burrow. In most cases the burrow is more or less straight and is enveloped by a simple, cylindrical paramoudra (Pl. 2 A). However, in cases where the burrow describes a broad spiral the whole flint has a spiral form (fig. 6 G). And where the burrow branches within the flint, complex processes and curtains of flint project into the core of chalk (Pl. 2 B). Branches which run laterally out of the flint normally pass through holes in the paramoudra wall, and rarely does the burrow come into direct contact with the flint (fig. 5). FITCH (1840, p. 304), however, reported

that in the topmost paramoudra of a column the flint closes over the top of the chalk core.

The longest column recorded at Hemmoor was 6.5 m (truncated at both ends by the limits of the exposure) while, judging from STEINICH's (1972) figures, they reach over 8 m at Rügen. MRS. GUNN's drawing (LYELL, 1865) shows columns 9 m high in the Norfolk chalk (fig. 3), columns which, according to ROSE (1862) characteristically consisted of six or more superposed paramoudras.

Recently a complete column was temporarily exposed in "Beeston Chalk" at the quarry at Caistor St. Edmunds (F. GOFF, personal communication, 1973). In height the whole column measured c. 9 m. In the upper part the paramoudras were heavy and pear-shaped and were placed very close together. Further down, however, the flints became lighter and ring-shaped and more distant from each other, while at the



Fig. 5. Schematic longitudinal section through three paramoudra flint nodules showing the course of the central glauconite or pyrite tube enclosing the burrow and its branches, and the characteristic distribution of cementation (shaded), pyrite staining (stippled) and pyrite nodules (black).

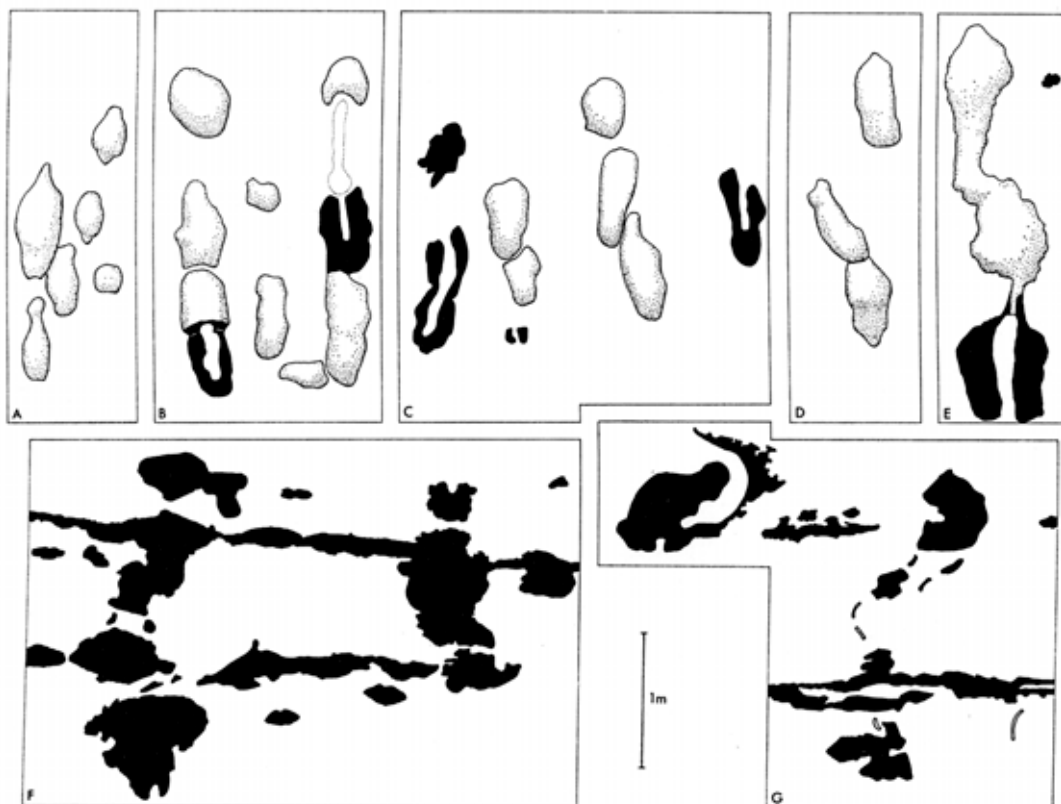


Fig. 6. Paramoudras in situ, drawn to scale from photographs. A: Upper Campanian white limestone, Ballysillan Quarry north of Belfast, Northern Ireland. B–D: Upper Campanian white limestone, Small & Hayes' Pit, Moira, Northern Ireland. The smooth outer shape of the Irish paramoudras is characteristic. The broken line in B outlines an iron stained area, possibly also silicified (specimen inaccessible). E: column in Upper Maastrichtian chalk (beds 116–120) at Hemmoor, Germany (see Pl. 1 A). F: portions of two vertical flint structures at the same horizon at Hemmoor. They are probably paramoudras but the sections are not central and the chalk core is not visible. G: unusual paramoudra-like flints with spiral form in uppermost Upper Maastrichtian chalk at Karlstrup, Denmark. The large flint to the left in reality lay 5 m further to the left. The central core of chalk in the flints is only partly visible owing to the excentric section of the flints and spiral course of the core. In four places fragments of the glauconite tube are indicated.

bottom the rings were incomplete and did not fully encircle the chalk shaft. Such a differentiation of paramoudras according to their position within the column has not been recorded previously (but compare fig. 7 B).

2. Other vertically extended flint structures

Paramoudras form a well-defined flint habit which is largely distinct from other habits of flint, but boundary cases do occur. In Coniacian chalk at Helhoughton, Norfolk, a column of four coreless flints was found (Pl. 1 B).

At Boirs, near Tongres, Belgium, the basal Craie Grossière (Upper Maastrichtian) contains columns of flints which outwardly resemble paramoudras (FELDER, 1971,

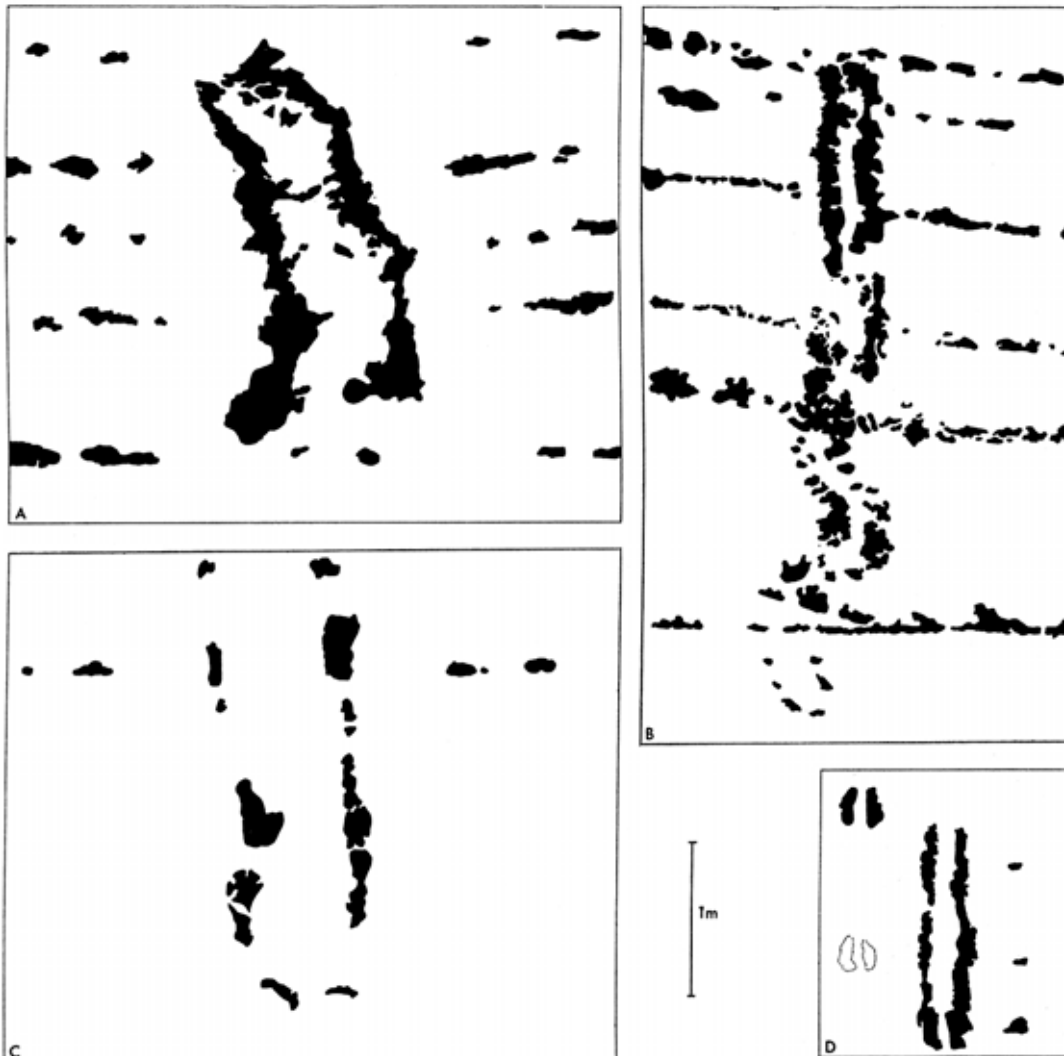


Fig. 7. Flint cylinders of various dimensions in situ, drawn to scale from photographs. A: a structure in Upper Maastrichtian chalk (beds 127–130) at Hemmoor. The nodular flint horizons die out as they approach the cylinder. B: a vertical flint structure in the Upper Maastrichtian Craie Tigrée at Boirs, Belgium. The upper half of this structure has been illustrated by FELDER (1971) but his figure is inverted. The horizontal flints fuse with but do not cross the cylinder. Below the cylinder the structure breaks into isolated nodules which indicate a spiral course to the inferred central burrow. C: a weakly developed cylinder in Upper Campanian chalk at Weybourne (see Pl. 1D). D: a cylinder in Upper Campanian chalk at Caistor St. Edmunds (see Pl. 3A). Remains of a paramoudra column were present to the left but the upper flint was shattered and the lower missing, represented by an impression in the chalk.

fig. 4) but internally are completely silicified or have only a very slender chalk core (Pl. 2C, D). Even where completely silicified, a central burrow is visible (Pl. 2D). FITCH (1840) described a similar occurrence at Norwich. The paramoudra-like flints

in the U. Danian at Thisted, Denmark, also have a narrow chalk core only 1–3 cm in diameter.

Massive, subcylindrical, vertical flints more than 4 m long occur in Upper Maastichtian (Mb) calcarenite at Marnebel, Maastricht, Holland (P. W. FELDER, pers. comm. 1973; cf. UMBGROVE, 1926, p. 305, fig. 30).

A large scale, vertical flint distribution of a rather different type occurs at several localities (fig. 7; Pl. 1 D, 3 A). In these cases a relatively thin-walled, broad cylinder of flint, or a cylindrical arrangement of discrete flint nodules, extends vertically through several metres of chalk, interrupting normal nodular flint layers which generally die out as they approach it (fig. 7 A). In one case the nodular flints were observed to fuse with but not cross the cylinder (fig. 7 B). Wide-cored cylinders of this type occur together with true paramoudras in the Santonian-Coniacian chalk at Yport, Bénouville and Étretat, Normandie (KENNEDY & JUIGNET, 1974) but their high position in the perpendicular cliffs has prevented closer examination *in situ*. At Hemmoor, also, all transitional forms from massive vertical flints to typical paramoudras occur in the Upper Maastichtian. They are most common between beds 119 and 133 where flint development reaches a maximum (SCHMID *in press*).

Flint circles are a characteristic feature of the "Paramoudra Chalk" of Norfolk (fig. 8) and are also recorded from the Campanian of Ireland (C. J. WOOD, pers. comm.). These structures consist of flint nodules arranged in a precise circle, 1–5 m in diameter, but with no greater vertical development than normal flint nodules. The inward facing sides of flints in these circles are characteristically smoother and more vertical than the other surfaces, which show the normal knobby development of flint nodules. Two concentric circles were reported by REID (1882, fig. 1) who also saw paramoudras at the centres of some circles. This combination of circles and paramoudras is in fact not uncommon and would strongly suggest that the circles are yet another manifestation of the burrow that produced the paramoudras. Both in Ireland and in Norfolk the flint circles appear at a slightly lower horizon than that in which paramoudras are common, and the occurrence of paramoudras at the centre of circles seems to be mainly confined to the horizon at which the one type of flint occurrence replaces the other.

3. *Hardening of the chalk*

The chalk contained in the open central core of the paramoudra is harder than the chalk lateral to the flint owing to the presence of a calcitic cement. As shown by TAYLOR (1824) this hardening extends in most cases vertically but patchily between neighbouring paramoudras in a column. At Caistor St. Edmunds and Whitlingham, Norfolk, empty moulds of aragonitic shells (gastropods) are present in this hard chalk (fig. 9), although they are completely absent from the normal chalk at that horizon. Thus cementation appears to have predated the dissolution of at least some aragonite, which indicates an early date for the cement.

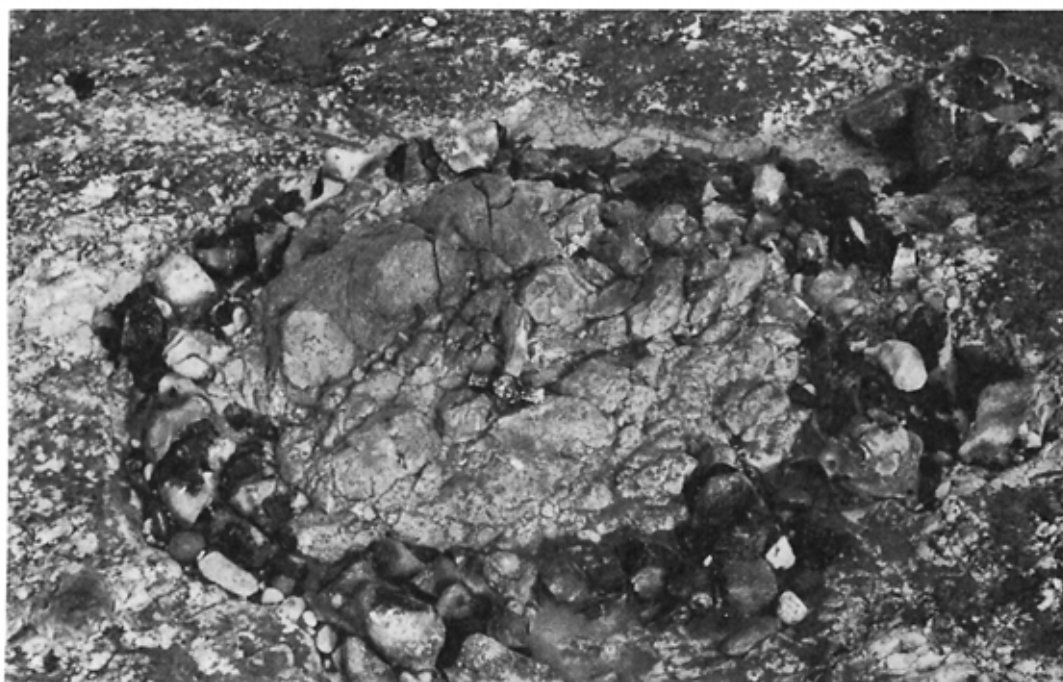


Fig. 8. Flint circle c.1.5 m in diameter in Upper Campanian chalk on the foreshore below Beeston Hill, Norfolk, England.

4. *Pyrite*

The hardening of the chalk is accompanied by a noticeable discolouration, chiefly within the core of the paramoudra but also vertically beyond it. This is a pale rusty stain in dried exposures above the water table and blue-grey in the reduced chalk below (cf. STEINICH, 1972). Nodules of pyrite (Pl. 4 C, 5 A–B) or their limonitized remains are common within this weakly ferruginized chalk (cf. FITCH, 1840; PUGGAARD, 1851).

In many cases the ferruginization of the chalk is more strongly developed, causing the chalk in the vicinity of the burrow to be strongly tinted. Such is the case for example at Græderen (Møns Klint) and at Karlstrup. The chalk is thus discoloured in a cylindrical zone from 5–10 mm to about 80 mm from the burrow shaft (fig. 4). The strongest development of this ferruginization occurs in flintless chalk at Kronsmoor, Holstein, where a zone of black chalk surrounding the burrow has a radius of about 3–5 cm (Pl. 3 B–C) but the colour fades permanently on drying. X-ray diffractometry has shown samples from Kronsmoor to be coloured by finely divided pyrite.

5. *Glauconite tube and burrow shaft*

The green mineral has been shown by X-ray diffraction to be a glauconite. The glauconitized chalk at first sight would appear to represent the altered wall of the burrow itself. Its inner boundary is normally sharply defined while in most cases the outer

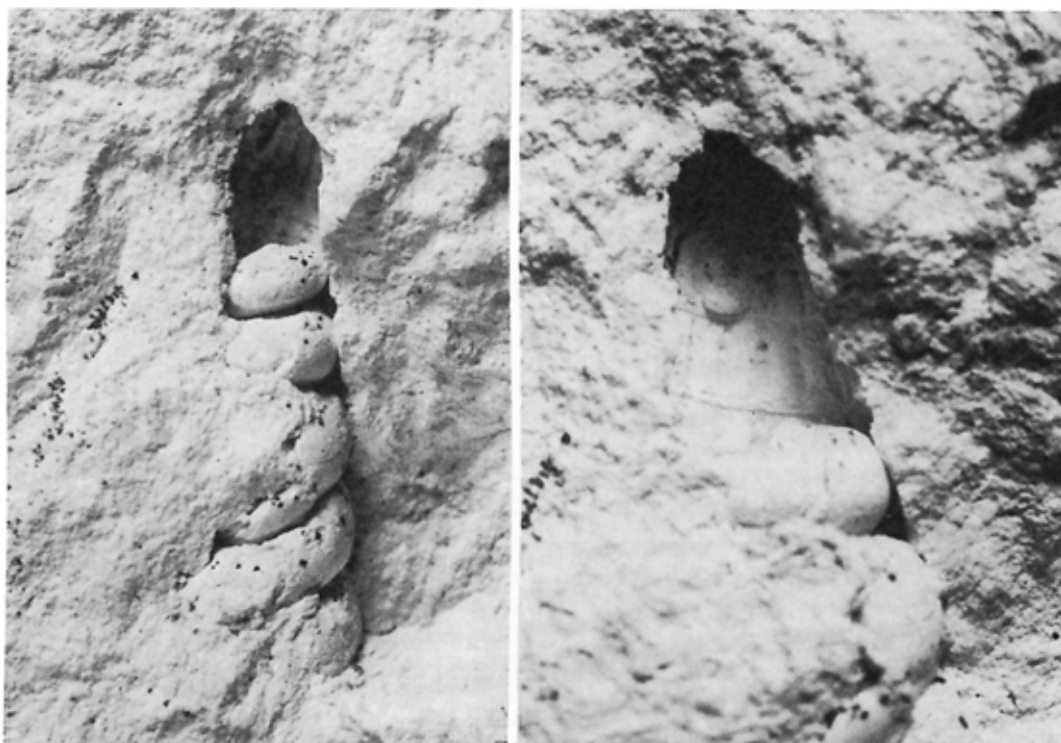


Fig. 9. Aragonitic shell of a cerithiid gastropod (3 cm high) well preserved as a cavity after loss of aragonite in the cemented chalk in the core of a paramoudra at Caistor St. Edmunds, Norfolk (Upper Campanian). MMH 13064.

fades into unaltered chalk (Pl. 5 C-E). At Krons Moor and Hemmoor the glauconite tube reaches its maximum development, with intense green-black colour and a thickness of up to 5 mm. The tube is broken and includes fragments of white chalk and appears to have suffered brittle fracture owing to subsequent slight settling of the sediment (Pl. 4 B).

A closer examination of the tubes at Krons Moor shows a slender fill of grey chalk within the white fill of the tube (Pl. 5 C-E). The grey fill has distinct boundaries and lies centrally or toward one side of the green tube. In a few cases a second, pale green tube partially encases the grey fill. Thus it would seem that the grey fill represents the burrow itself and that this has possibly wandered (since some are excentric) within the sediment enclosed by the green tube. This also explains the variation of the tube's diameter. The grey fill, where visible, has a diameter ranging from 1.9-6 mm, as does also the pyrite filament, ribbon or tube which sometimes replaces it. Thus, the green tube in the core of a paramoudra from Caistor St. Edmunds measured 8.2 mm in diameter and contained vestiges of a burrow within it in the form of a limonite tube 3.2 mm wide.

At Hemmoor, green tubes of only 3.5–3.7 mm diameter have been recorded with slightly grey fill. These tubes probably represent the burrow itself, which remained stationary. The grey fill of the burrow itself appears to be structureless.

The glauconitization of side branches fades as they are traced laterally away from the shaft. Their diameter rarely exceeds 3.8 mm, which is probably that of the burrow, but they are commonly depressed by compaction or collapse (Pl. 4A).

Morphology of the Burrow

Let us complete the description of the burrow (designated *Bathichnus paramoudrae* herein) before going on to discuss the diagenetic processes leading to the various forms of mineralization with which it is connected.

The general form of the burrow is that of a vertical shaft with subhorizontal side branches. The diameter of the shaft varies from 1.9 to 6.0 mm but is more or less constant in any one burrow. The side branches have about the same diameter but are usually depressed or completely flattened (Pl. 4A). The lateral extent of the side branches is unknown since their mineralization fades rapidly as they are traced away from the shaft. The maximum observed length is about 30 cm. Had they connected with neighbouring shafts it might be expected that they would have been glauconitized more or less throughout like the shafts. It may be conjectured therefore that they did not extend much further than they can be traced and that the shafts were not interconnected.

The distance between shafts varies considerably. In exposures more or less parallel to bedding, such as the foreshore at Weybourne, Norfolk, or in parts of the cliffs at Møns Klint, the paramoudras and their burrows are rarely closer together than 1 m and most commonly are separated by 2–3 m. At Kronsmoor also, the burrows are seen in horizontal sections to be 2–3 m apart. Sparser occurrences are common, but sections perpendicular to bedding naturally exaggerate the separation since the plane of section only passes through a few columns.

Owing to failure of the mineralization, to limits of exposure, or merely to the difficulty of following a faint tube through jointed, discoloured or sodden, unlithified chalk, individual burrows have not been traced vertically for more than 3 m.

Convincing upper terminations have not been seen. However, it is hardly to be expected that the mouth of the burrow onto the sea floor would be preserved. Shallow biogenic structures are not normally preserved in the chalk, either because the most superficial sediment was not sufficiently stable for their preservation or because later, deeper bioturbation has destroyed them (GOLDRING & STEPHENSON, 1970; HÅKANSSON, BROMLEY & PERCH-NIELSEN, 1974). Moreover, the uppermost few cm of the burrow was probably in oxygenating sediment at the depositional interface. The glauconite and pyrite diagenesis would not be expected to continue to the sea floor under these conditions, thus rendering detection of the unmineralized top of the burrow very

unlikely. The most distinct upward termination is illustrated in Pl. 4C, but it is probable that this example has been truncated by erosion.

Surprisingly, distal terminations have not been recorded either. This may be due to distal fading of the mineralization of the shaft as in the side branches. The burrow in the flint cylinder illustrated in Pl. 3A appeared to close simply at the bottom. However, as the flint structure continued a little further downwards, it is possible that this was a false observation due to an oblique section through the burrow wall caused by a sudden turn in its course.

At Krons Moor the burrows (or at least the pyrite that renders them conspicuous) are restricted to a horizon 4–4.5 m in thickness (uppermost Campanian), throughout which they are distributed equally at all levels. The upper limit of this horizon is a bed of chalk 10–20 cm thick that is tinted blue-grey by finely divided pyrite. Such horizons ("Grabganglagen") occur at several levels in the chalk of the Lägerdorf-Krons Moor region, and probably represent short interruptions or reductions of sedimentation (ERNST & SCHULZ, 1974). It is thus conceivable that slight erosion has removed the uppermost part of the burrows at this horizon (Pl. 4C). At the lower boundary of the burrow horizon the chalk is slightly more clay rich than is normal for the chalk of this locality. The impression is given of continuity of burrows throughout the 4.5 m of chalk. We have not been able to follow any burrow to its natural termination but one specimen that we succeeded in digging out turned away horizontally at the bottom (fig. 10).

Length of burrow

The burrows in the flintless chalk at Krons Moor therefore appear to be some 4.5 m in length. Paramoudra columns have been recorded with heights of 3–5 m from many localities. At Hemmoor a column, truncated above and below by loss of exposure, measured 6.5 m. There is no reason to doubt the accuracy of the carefully measured sections of the Rügen cliffs by STEINICH (1972) in which the longest columns are depicted with lengths of over 8 m. This renders much more credible the comparatively primitive drawing by MRS. GUNN (fig. 3) in which columns some 9 m high are illustrated, the tops of which are truncated by the Pleistocene erosion surface! Finally, the recent exposure at Caistor St. Edmunds of a 9 m column provides authenticity for the earlier drawing.

It is therefore not easy to avoid the conclusion that we are dealing with a burrow with a vertical length commonly of the order of 4.5 m but that in many cases extended to 9 m and possibly more. The diameter of the shaft was therefore of the order of 1/2000 of the length.

Relationship with other burrows

Most occurrences of paramoudra burrows are in chalk which contains clear signs of bioturbation, with the ichnogenera *Thalassinoides*, *Chondrites* and at some horizons *Zoophycos* recognizable among several other forms. Only rarely is glauconite associated

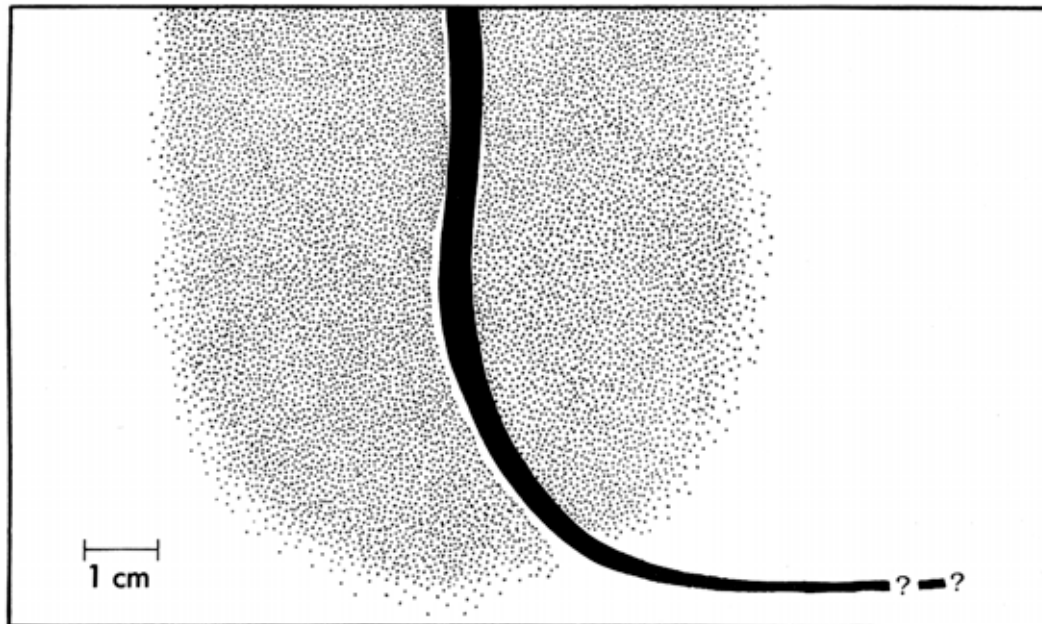


Fig. 10. Lowermost end of a burrow at Kronsnoor. The extreme termination was not recovered. The grey burrow fill (black) curved laterally and diminished in vertical diameter, thus resembling the configuration of side branches in other specimens (cf. Pl. 4 A). The main shaft lay within a zone of pyrite stained chalk (stippled).

with these burrows and then only with *Thalassinoides* and very locally and weakly. In every observed case the paramoudra burrow cut through the other burrows and clearly post-dated them. This further emphasizes that the paramoudra burrow must have descended to a far greater depth beneath the sea floor than the other burrows.

Discussion

Burrower and sediment

The nature of the burrowing organism and its relationship to the sediment are among the most difficult problems posed by the paramoudra burrows. Few clues emerge from a study of the ichnological literature since only two fossil burrows approaching the extreme dimensions of those of the paramoudra burrows appear to have been described, and the likelihood of such structures being discovered with our present techniques in the modern seafloors is somewhat remote.

Vertical fossil burrows described by BROMLEY (1968) from a hardground in Belgian Campanian chalk were over 2 m long and only 2 mm in diameter, but their mode of branching, dissimilar mineralization and smaller absolute size prohibit closer comparison with the paramoudra burrows. From the Upper Cretaceous deep water flysch of Italy, SCHOLLE (1971) described a burrow with even more extreme dimensions than paramoudra burrows, being a single, unbranched, vertical shaft 6 m long and

only 0.3 mm in diameter. It was filled with pyrite and had an auriole of haematite, but the lack of branches and extreme slenderness distinguish it from paramoudra burrows.

Owing to the extraordinary nature of the paramoudra burrow and its diagenesis, it is worth considering the physico-chemical environment of the burrow in some detail. An examination of this environment will provide a basis for discussion of the diagenetic processes to which the presence of the burrowing organism has given rise, and also of the reasons that an animal might have had for delving to such extraordinary depths beneath the seafloor.

Eh and organic matter. The decrease of *Eh* with depth in sediments is a very complicated problem and it is doubtful if more than an enlightened guess can be made of the depth of the redox barrier below the chalk seafloor. It is clear, however, that this depth must have varied at different times (from horizon to horizon) as the depositional environment fluctuated. In a sea such as the chalk sea, where the bottom waters were well oxygenated (witness the active benthos), the two factors which largely controlled the *Eh* of the sub-bottom sediment must have been the amount of organic matter in the sediment and the rate of its bacterial decomposition.

Benthic faunas were present at all levels of the flinty chalk and even at horizons where preserved skeletons of benthic organisms are rare, the bioturbation of the sediment indicates an active infauna. Organic matter introduced into the substratum by the benthos must have been considerable, and was augmented by the rain of pelagic detritus, consisting of both dead organisms and excrement of the plankton and nekton.

Exhaustion of free O_2 in the sediment by aerobic bacterial decomposition of organic matter would have been offset by diffusion of dissolved oxygen downwards from the seafloor and presumably also outwards from open burrow systems within the sediment. The slower the rate of deposition, the more organic matter can be oxidized near the surface and the less can be expected to be preserved by burial (EMERY & RITTENBERG, 1952).

The chalks in which paramoudra burrows are found are in general very free of clay and their porosity is high. Downward diffusion of oxygen from the sea floor therefore must have been relatively rapid. Rate of deposition was also relatively slow and marked by frequent halts, allowing much organic matter to be oxidized near the surface. Most horizons furthermore are characterized by 100% bioturbation of the sediment; this thorough mixing of the upper layers returned buried sediment to the surface several times before final burial. Finally, the sea floor always contained networks of *Thalassinoides* burrow systems that were open to the sea floor, descended 1–2 m below it and through which their crustacean inhabitants pumped a continuous stream of oxygenated, fresh sea water. These facts strongly suggest that the sea floor sediment was generally oxidizing to a depth of several cm and possibly to 1 m or more during much of the deposition of the flinty chalk.

The form and preservation of the burrows themselves support this. The burrows

are chiefly *Thalassinoides*, *Zoophycos*, *Chondrites* and "*Planolites*" and are purely the work of sediment eaters (KENNEDY, 1970; HÅKANSSON *et al.*, 1974). Where the colour of its fill renders it visible, *Thalassinoides* can be seen commonly to descend vertically 1–1.5 m, while *Zoophycos*, *Chondrites* and "*Planolites*" characteristically post-date the *Thalassinoides*, reworking its walls and fill or merely cutting through them. Consequently, these other burrows were clearly excavated at a similar depth below the depositional interface, up to 1.5 m.

The sediment eating animals that produced these trace fossils must themselves have introduced organic matter into the sediment by their life activities. For example, the crustaceans that dug the *Thalassinoides* must have deliberately applied mucous cement to the walls (e.g. BROMLEY, 1967) and the fill may have contained faecal matter (compare KENNEDY, JAKOBSON & JOHNSON, 1969). This is indicated by the common restriction of the fodinichnion *Chondrites* within the walls or fill of these burrows.

Had these burrows been produced in strongly reducing sediment, then it is probable that the relatively high organic content of the fill and wall would have led to local pyritization (BERNER, 1969) and the walls of the open *Thalassinoides* systems, flushed with a constant supply of sea water, would have been glauconitized. Such mineralization of these trace fossils is found, but it is the exception, not the rule. This would suggest, therefore, that these burrows were formed in oxygenous or only weakly reducing sediment and that the level of about 1–1.5 m where these burrowers ceased to operate may represent very approximately the redox barrier.

Nevertheless, we may assume that organic matter was present to much greater depths in the sediment than this. EMERY (1960, p. 179, 229) found that in the basins off southern California only one third of the organic matter was decomposed at the redox barrier. In the reducing environment below this, bacterial activity is considerably diminished.

Most authors agree that the most rapid regeneration of nutrients, concerning the organic matter least resistant to breakdown, takes place close to the sea floor (OPPENHEIMER, 1960, p. 249; BORDOVSKIY, 1965, p. 85). However, in some shelf sediments, negligible decrease in the more resistant organic matter with depth beneath the redox barrier has been recorded (e.g. TRASK, PATNODE, STIMSON & GAY, 1942). Furthermore, it should be added that while bacterial activity declines with depth, the numbers of dormant spores of bacteria increase in proportion.

Thus it would seem probable that below the level of *Thalassinoides* the chalk still contained some organic matter but that, bearing in mind the slow deposition, high porosity, complete bioturbation and apparently extensive oxidizing zone, the quantity is not likely to have been significant. That which remained will have been that which was most resistant to decomposition, together with quantities of bacterial spores. With so little organic matter available, bacterial activity would be correspondingly low, and since most sediment eaters are as much concerned with bacteria as with the organic matter itself (MACGINITIE, 1932; 1937), it would seem unlikely that the chalk beneath the redox barrier would offer a niche suitable for a sediment eating organism. Certainly

the *Thalassinoides* producing organism does not seem to have exploited it. An alternative way of life must be sought for the inhabitant of the paramoudra burrow.

Nature of the burrower. The reason for an animal to descend vertically to such a great distance below the sea floor while apparently maintaining communication with it remains something of a mystery. Having excluded the role of sediment eater, two other life habits remain possible—predator and filter feeder.

There would be little or nothing for a predator to prey on at distances of 3–9 m below the sea bed, nor do the vertical shaft and short side branches suggest the work of an infaunal predator. However, a stationary mode of life may be considered, with the animal waiting at the mouth of the burrow for prey passing by on the sea floor, but this does not explain the great depth of the structure.

Vertical burrows are commonly produced by filter feeders in shallow water, high energy environments (*Scolithos* facies, SEILACHER, 1967). The chalk sea floor did not at all resemble such environments and simple vertical burrows of this type are absent. This does not rule out the possibility, however, that a niche existed for a specialized filter feeder in the chalk environment, but this again offers no explanation for the extraordinary length of the structure. But we know next to nothing about the deeper burrows of organisms on the outer shelf today.

Thus it would seem most plausible that the producer of *Bathichnus paramoudrae* was either a stationary predator or a filter feeder.

The functional nature of the side branches remains unexplained. Since their mineralization fades away from the shaft they are interpreted to have been open passages, yet not leading anywhere, nor containing as much organic material as the shaft, if any. Sanitary tubes can be discounted since these would be especially rich in organic matter and correspondingly well mineralized. Nurseries for eggs or young also seem unlikely since branches arise irregularly throughout the length of the shaft. And as suggested above, there is little likelihood that they are traces of hunting sorties of a predatory worm (cf. MICHAELIS, 1971) considering their depth below the sea floor. Their lack of distal mineralization and their ubiquitous presence also discourages an interpretation as burrows of other animals living commensally with the animal in the shaft.

The lower end of a burrow dissected at Krons Moor bent off horizontally for a few centimetres (fig. 10). It is possible, therefore, that the side branches represent successive abandoned lower ends as the burrow was extended deeper into the sediment. The configuration of many branching points (e.g. Pl. 4 A, fig. 4) supports this possibility, the shaft making a bend that is aligned with the side-branch rather than the distal continuation of the shaft.

Another approach to the problem is that of finding an animal of suitable dimensions to fit the hole. It is first necessary to decide whether a single animal occupied each burrow, or whether they were produced by several generations of organisms keeping pace with sedimentation and closing off the distal end progressively. No structures

in the burrow have been seen to suggest a compound mode of origin by a succession of organisms. Furthermore, the rate of deposition (c. 15 cm/1000 years on average for the Danish Maastrichtian chalk; HÅKANSSON, BROMLEY & PERCH-NIELSEN, 1974) would imply tens of thousands of years' activity at the same site in most burrows, and evidence of succession of generations over such a period would surely be preserved. Thus it is considered that a single individual constructed each burrow. On the other hand, that each burrow was occupied for a considerable period of time is indicated by the glauconite, which is known to be a mineral that develops slowly (HOWER, 1961).

Few groups of animals can offer us a predator or filter feeder approaching the dimensions we are looking for. (The vermiform burrower may nevertheless have been considerably shorter than its burrow and have been capable of moving actively up and down it.) In our search among extant groups we verge upon the ludicrous. Barring typographical errors (e.g. STRESEMANN, 1970, p. 247, cites a polychaete 800 m long), there are many records of exceptionally attenuated vermiform animals. However, it has to be borne in mind that very long animals are exceptions and that we are concerned with a burrow of no ordinary length. Three extant groups—the polychaete annelids, pogonophores and nemertineans—offer extremely long, free-living, marine worms; no other group possesses the slenderness required.

The longest polychaete today is the 3 m palolo worm, *Eunice* sp. It is a burrowing form but is far too stout for our burrow requirements. It must be emphasized, however, that this size is exceptional and that an average length for polychaetes is 5–10 cm and large ones do not normally exceed 15–30 cm (FAUVEL, 1959, p. 14).

Most pogonophores have relative dimensions of length to diameter which approach those of paramoudra burrows. However, two important facts oppose their candidature. Their absolute dimensions are far smaller than we require, and they do not branch. The largest known species today does not exceed 1 m in length, though its tube reaches 1.5 m (IVANOV, 1960, p. 1606). This discrepancy is hard to accept, especially since at least half the length of the animal and its tube extends up into the overlying water.

No living pogonophores to our knowledge have branched tubes (WEBB, 1971). In the only known apparent exception to this (WEBB, 1964) the branches of the tube were abandoned attempts to penetrate vertically into the sediment and do not greatly resemble the branches of the paramoudra burrows. However, the possibility discussed above that the side branches of *Bathichnus paramoudrae* may represent abortive or abandoned lower ends of the extending burrow still permits consideration of the unbranched pogonophores as architects.

In the North Sea today, the Nemertinea provides an animal, *Heterolineus longissimus* (GUNNERUS), which more than adequately fulfills the size requirements of *Bathichnus paramoudrae*. This species is a burrower and has a width of 2–9 mm and a length (when extended) of up to 30 m (HYMAN, 1951, p. 463; STRESEMANN, 1970). Furthermore, several members of this group of predatory worms construct semi-permanent burrows and some have such a stationary mode of life as to even allow secretion of a tube (BARNES, 1969, p. 157). Certain nemertineans thus also appear to possess the

characters required to provide an architect for *B. paramoudrae*. Once again it must be emphasized, however, that *H. longissimus* is an outstanding exception. As HYMAN (1951) stresses, most nemertineans are less than 20 cm and few reach 0.5 m or more.

On the basis of our limited knowledge of extant forms, therefore, we are only in a position to suggest that the exceptional burrow *Bathichnus paramoudrae* seems most probably to be the work of an exceptional pogonophore or nemertinean, or possibly an exceptional annelid. However, our knowledge of Cretaceous life forms is so minute in comparison with their living representatives or replacements that no attempt to identify the burrower more closely will be made until more positive evidence is available.

Diagenesis around the burrow

The conspicuous and unusual diagenesis which has taken place in the immediate vicinity of the burrow must be accounted for by anomalous conditions created in the sediment by the presence of the burrowing organism. The shafts appear to be isolated, so it is unlikely that a microenvironment of oxygenating conditions was introduced into the deep sediment. Rather it is considered that the most significant consequence of the animal's presence was the introduction of quantities of unstable organic matter at levels at which this had generally been removed by bacterial activity. Organic phases will have diffused into the sediment as a result of both the animal's metabolic processes during life and the decomposition of its body after death. The chemical gradients set up by this local and extreme inequality in distribution of organic matter in the anaerobic environment provide the basis for a model to explain the diagenetic alteration of the chalk around the burrow.

Pyrite. Laboratory experiments led BERNER (1969) to suggest that sharp variation of organic matter in an otherwise homogeneous anaerobic sediment with a very low iron content could bring about migration of iron and sulphur. Bacterial generation of H_2S in the organic-rich region would lead to iron sulphide formation in the surrounding organic-poor sediment in a volume much greater in size than the organic region. This model accounts very well for the finely divided pyrite that darkens the chalk as an auriole around the burrow. It may be speculated that this extensive and evenly distributed auriole was the result of the breakdown of the metabolic products of the live animal while the local development of framboidal nodules immediately adjacent to the burrow occurred after the animal's death owing to decomposition of the body as the general chemical gradients set up by the metabolic processes were collapsing.

KAPLAN, EMERY & RITTENBERG (1963) considered that sulphur released from decaying organic matter played a small role in the sulphur cycle and that, for the precipitation of pyrite in sediments, large amounts of sulphate S are extracted from the overlying sea water. In the present case, however, no downward decrease in pyritization along the long shaft has been seen and it appears rather that the S was exclusively derived from the burrower and its metabolism.

Glauconite. Authors are generally agreed that glauconite requires reducing conditions for its development (CLOUD, 1955). In the present case, the pyrite confirms that the sediment was generally reducing. The appropriate source materials for the development of glauconite were presumably present in the pore water of the sediment since, as in the case of the pyrite, there is no noticeable increase in mineralization towards the top of the burrow to suggest downward migration of ingredients from the overlying sea water.

The glauconite appears to have replaced the calcium carbonate of the chalk, but a detailed petrographic study of the replacement has not been made. Glauconitization is assumed to have been triggered by the sudden appearance of organic matter in the anaerobic sediment. The presence of an organic phase for glauconite formation has been found necessary by several authors (TAKAHASHI, 1938; CLOUD, 1955; BURST, 1958; PRATT, 1963).

Cementation. The precipitation of calcite cement irregularly in the vicinity of paramoudra burrows, in chalks that are normally poorly cemented, was probably also triggered by the appearance of local concentrations of organic matter. TAYLOR & ILLING (1969) considered that the presence of organic matter was responsible for cementation of a carbonate sediment around burrows, but this was in a well oxygenated intertidal environment. In the present case, organic decay possibly locally lowered pH sufficiently to increase the solubility of carbonates, thus causing a gradient producing migration of HCO_3^- and Ca^{++} away into the immediately surrounding sediment, where CO_2 pressure was normal and reprecipitation could occur.

Another, apparently obvious and copious source of CaCO_3 deserves consideration: that of the chalk massively replaced by the enormous paramoudra flints. However, two circumstances oppose this as the source of the cement. Firstly, the date of the cementation appears to be early, as indicated by the preservation by it of aragonite skeletons which have later dissolved to leave voids. The formation of flint, on the other hand, was almost entirely a late diagenetic process (see below) that post-dated the dissolution of aragonite. Secondly, it is a remarkable fact that the emplacement of flint in the chalk, although a replacive process, has not given rise in other instances to cementation of the surrounding sediment. On the contrary, chalk immediately adjacent to flint nodules in many cases is unusually soft. Also in the case of the paramoudras, the chalk adjacent to their external surfaces shows no cementation; only that within their core, between the flint and the burrow, is hardened. The extension of this hardening in the chalk near the burrow above and below the horizon of the paramoudra strongly suggests that the cement was derived from the burrow and not from CaCO_3 displaced during flint formation.

Flint

In a recent paper, HÅKANSSON, BROMLEY & PERCH-NIELSEN (1974) outlined a model for the formation of flint in the Upper Cretaceous chalk of Europe. This model

may now be extended in an attempt to explain the genesis of paramoudra columns and related anomalous flint structures. Here again, the introduction of organic matter to unusual depths within the sediment seems to be the key factor.

RITTENBERG, EMERY & ORR (1955, p. 43) found that the content of dissolved silica of the interstitial water increased regularly with depth below sea floor until, at about 2 m, it was some ten times more concentrated than in sea water. This silica was derived chiefly from dissolution of opaline organic skeleta. SIEVER (1962) demonstrated that silica solubility was lowered at sites of organic decay by adsorption on organic matter. The concentration gradient so produced would cause further dissolved silica to migrate into the organically rich region where it in turn would be immobilized by the production of insoluble organic silica complexes.

With deeper burial, the slow breakdown of organic matter released the adsorbed silica, producing local supersaturation and precipitation as minute lepispheres of cristobalite. In the flintless, clayey Cenomanian Lower Chalk of England these lepispheres are widely distributed through the sediment (KENNEDY & GARRISON, in prep.). In the flinty chalk, however, their clustered distribution at sites previously rich in organic matter appears to have led to further migration of silica towards them and their recrystallization to quartz during late diagenesis.

Nodular flint of the chalk. Before considering the abnormal occurrence of flint in the form of paramoudras it is necessary to discuss the normal situation.

Flint occurs in the chalk both as bedded horizons of nodules more or less fused together as continuous layers depending on the degree of silicification, and also as isolated nodules randomly distributed throughout the sediment. (The much later sheet flint along joint and fault planes does not concern the present discussion.) The isolated nodules show a close connection with organic remains, particularly those of siliceous sponges and calcareous fossils (brachiopods, oysters and especially echinoids, see HÅKANSSON, BROMLEY & PERCH-NIELSEN, 1974). However, it is doubtful if these isolated nodules owe their origin to sites of organic decomposition connected with these organisms along the lines of SIEVER's (1962) model.

In the case of the sponges, these represent original sites of silica concentration in the form of the opaline skeleton of the organism. It should be pointed out, however, that the vast majority of siliceous sponges in the chalk are poorly preserved as empty or ferruginous casts after loss of silica and without any associated flint development. The exceptions preserved in flint may represent examples of rapid burial where organic decay has played a role; indeed, many can be shown to be preserved within *Thalassinoides* fills, and may have fallen into the burrow and thereby escaped the rapid oxidation processes operating in the uppermost sediment.

The case of the isolated echinoid (or brachiopod or oyster) with a fill of flint is rather different. As elsewhere, the flint has replaced CaCO_3 —chiefly the chalk fill but in some cases also parts of the skeleton. Only complete echinoids or two-valved oysters and brachiopods are involved, where the silicified chalk is isolated and surrounded by

the skeleton. The urchins are almost invariably spineless and encrusted by epizoans and this and the chalk fill suggest that they have been long or repeatedly exposed at the sea floor with loss of all decomposable organic parts before final burial. It appears, however, that the physically and chemically isolated microenvironment within the echinoid test and between oyster or brachiopod shells in certain conditions has favoured the development of flint.

Nearly all chalk flint, on the other hand, is represented by the nodular layers, and these appear to have had a very different origin from the isolated flints. Nodular layers of flint show a close connection with fills of *Thalassinoides* systems (BROMLEY, 1967; KENNEDY & JUIGNET, 1974), usually lying within the fill but in some cases around it, leaving the fill unsilicified. Further silicification normally extends beyond the boundaries of the burrow walls and neighbouring branches may fuse together, but the characteristic knobs, finger-like processes and cavities remain to betray the origins of the layer. SIEVER'S (1962) model offers a convincing basis for an explanation of the mode of genesis of this type of flint (HÅKANSSON, BROMLEY & PERCH-NIELSEN, 1974).

While most of the organic matter in the original sediment, including that of the macrobenthos, had been exhausted by aerobic bacterial activity within the uppermost sediment of the sea floor, the *Thalassinoides* burrow systems were constructed to depths of 1–1.5 or even 2 m within this sediment. These burrows were semi-permanent, and during their long habitation the organisms will have introduced much organic matter into the surrounding sediment. In particular the cementation of the walls with mucus and the final filling of galleries with detritus-rich and faecal-rich sediment will have added greatly to the local concentration of organic matter in and immediately around the burrows. The horizontal basal network of these systems, lying so deeply beneath the sea floor, was probably constructed at or a little below the redox barrier, beneath which, it has been argued above, little organic matter remained in the general environment. Thus the *Thalassinoides* systems produced an acute heterogeneity in the distribution of organic matter within the sediment which may be expected to have led to a concomitant local concentration of silica around the basal networks. A cyclic sedimentation of the chalk (KENNEDY & GARRISON, in prep.) would have caused alternating levels of greater and lesser burrowing activity and concentrations of organic matter, leading to the rhythmic repetition of nodular flint horizons (fig. 4).

The paramoudra anomaly. The animal which produced the paramoudra burrows entered sediment in which, at 3–9 m below the sea floor, the future sites of flint horizons had already been determined, but in which the silica was still in a dispersible form, either as organic complexes or as cristobalite lepispheres. The creation of the micro-environment around the burrow by the introduction of highly reactive organic matter and concentrated products of decay completely reorientated the chemical gradients. Where the burrow passed through the incipient flint horizons the silica was remobilized and redeployed around the burrow along the new chemical front.

This disturbance of the pattern of development of flint nodule horizons shows

that the locations of these horizons were already determined, but that they offered no resistance to the passage of the burrower. Thus, the model presented by HÅKANSSON, BROMLEY & PERCH-NIELSEN (1974) for the mode of formation of flint in the European Chalk receives considerable support from the evidence provided by the remarkable columns of paramoudras.

Conclusions

Vertical burrows with the remarkable dimensions of 0.5 cm diameter and 5–9 m length occur at many horizons in the Upper Cretaceous chalk and Danian calcarenites in NW Europe. The burrows have given rise to the formation of glauconite and pyrite in the adjacent sediment, to irregular CaCO_3 cementation and to spectacular redistribution of silica where they pass through nodular flint horizons. The special nature of this diagenesis is explained by the unique depths to which the burrow extended beneath the sea floor, thus exposing sediment that had already passed through the early phases of burial diagenesis to a second phase of early diagenesis locally around the burrow.

The study of this abnormal condition reveals valuable clues as to the normal burial environment of the chalk sea floor. Thus, the contrast in preservation of the paramoudra burrows with the other burrows in the chalk suggests that (1) the redox barrier was generally about 1–2 m below the sea floor; (2) there was little organic matter in the general sedimentary environment below 1 m except where introduced in *Thalassinoides* systems; and (3) local concentration of organic matter in the generally organic-poor, anaerobic sediment caused local pyritization, glauconitization, carbonate cementation and silica redistribution and concentration.

The chronological order of events appears to have been as follows:

(1) Deposition of biomicritic nannochalk on a well oxygenated shelf sea floor with an active benthos.

(2) Owing to the high porosity and total bioturbation of the sediment, most of the organic matter probably was oxidized within the uppermost metre.

(3) Enough organic matter remained to nourish a community of crustaceans that produced networks of *Thalassinoides* at 1–1.5 m below the sea floor.

(4) *Chondrites* and *Zoophycos* were constructed at similar depths and in many cases with preferential reworking of walls and fill of *Thalassinoides*. This indicates that additional organic matter had been locally emplaced in and around the *Thalassinoides* systems rendering these relatively organic-rich in sediment that had generally lost most of its organic matter and probably was just below the redox barrier.

(5) The organic-rich fills and walls of the basal networks of *Thalassinoides* caused the migration and fixation of silica and laid the foundations for the future horizons of nodular flint.

(6) Paramoudra burrows were probably domicinia and possibly the work of a predatory or filter-feeding nemertinean worm or pogonophore. Penetration of these burrows many metres into the sea floor caused the local appearance of quantities of unstable organic matter in an otherwise anaerobic organic-poor sediment. Metabolism

of the living burrower and decomposition of its body after death established steep chemical gradients within the sediment.

(7) An auriole of finely divided pyrite developed in the sediment surrounding the burrow, and framboidal nodules of pyrite crystallized close to the shaft or within it. The sulphur appears to have derived solely from the organic matter introduced by the burrower.

(8) Glauconite developed in the chalk adjacent to the burrow shaft.

(9) Patchy CaCO_3 cementation of the sediment occurred in the near vicinity of the burrow.

(10) Where the burrow passed through an incipient flint horizon the silica was redeployed to form a massive cylindrical paramoudra around the burrow at a distance of a few centimetres. In other cases a thin cylinder of nodular flint developed around but at some distance out from the burrow. The remobilization of silica supports the hypothesis that early diagenetic processes determined the location of nodular flint layers but that their completion as quartz-flint horizons is a product of much later diagenesis.

Naming the Trace Fossil

The burrow appears to be new and for further reference it is desirable that it be designated a trace fossil name.

Bathichnus ichnogen. nov.

Type ichnospecies: *B. paramoudrae* ichnosp. nov.

Derivatio nominis: from *bathus* Greek: deep and *ikhnos* Greek: trace.

Diagnosis: as for type ichnospecies.

Bathichnus paramoudrae ichnosp. nov.

Synonymy: names have previously been applied to the paramoudra flint associated with the burrow, but not to the burrow itself.

Holotype: MMH 13058. Housed in the Mineralogical Museum, Copenhagen, Denmark. The specimen is shown in situ in Pl. 4A. The specimen contains 60 cm of the shaft with side branches.

Locus typicus: Hemmoor, Niedersachsen, Germany.

Statum typicum: *Belemnella occidentalis* zone, Lower Maastrichtian, Upper Cretaceous.

Diagnosis: burrows comprising a vertical shaft 0.2–0.6 cm in diameter and 5–9 m long. Side branches radiate irregularly from all parts of the shaft and have the same diameter as the shaft but are rarely traceable for more than 10 cm sub-horizontally.

Derivatio nominis: the obscure origins of the name "paramoudra" have been discussed by PEAKE & HANCOCK (1961) and MANNING, ROBBIE & WILSON (1970).

Range: ?Turonian, Coniacian, Santonian, Campanian and Maastrichtian chalk and Danian chalk and calcarenite of NW Europe (table 1).

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PLATE 1

Flint columns

A: three paramoudras in a column in Upper Maastrichtian chalk at Hemmoor, Niedersachsen, Germany. The lowest paramoudra is shattered; it was seen to have a chalk core 10 cm in diameter. This column is unusual in that there is a tubular flinty connection between successive paramoudras. See also fig. 6E.

B: column of four giant flints in Santonian chalk at Helhoughton, Norfolk, England. The top flint and third flint down lie at horizons of scattered flint nodules; the second and bottom flints are at levels otherwise devoid of flint. None of these flints had the central core characteristic of a paramoudra.

C: unusual, paramoudra-like flint in uppermost Turonian chalk at Ashby Hill, Lincolnshire, England. It has not been dissected, so it is not known if it possesses an axial chalk core. A flint tube extends from it to the top and bottom of the picture.

D: flint cylinder in Upper Campanian chalk at Weybourne, Norfolk. The projecting chalk within the upper part of the cylinder was well lithified.

All scale-bars represent 50 cm.

PLATE 1



PLATE 2

Morphology of paramoudras

A: a small, ring-shaped paramoudra from Upper Campanian chalk ("Beeston Chalk" of PEAKE & HANCOCK, 1961) at Caistor St. Edmunds, Norfolk, England. A₁: axial view showing the irregular external outline in contrast to that of the smooth, cylindrical core. The central burrow is visible within the chalk core. A₂ and A₃: two parts of the paramoudra split longitudinally along the crack visible in A₁. A₄: the chalk core sliced longitudinally to show the central burrow, which is invariably straight in simple paramoudras such as this.

B: longitudinally split paramoudra from Lower Maastrichtian chalk at Kongsted, Denmark, chosen to illustrate a complex, irregular paramoudra. Owing to sinuities and branches in the burrow, the flint extends as irregular processes into the unsilicified core. Mineralogisk Museum, Copenhagen: MMH 13059.

C: barrel-shaped paramoudra-like flint from low Craie Grossière (Upper Maastrichtian) chalk of Boirs, Belgium. C₁: oblique lateral view of the flint; originally the long axis of the flint stood vertically. C₂: transverse fracture surface showing grey, silicified fills of *Thalassinoides* in the body of the flint, cut by a slender core of unsilicified white chalk approximately corresponding to *Bathichnus paramoudrae*.

D: transverse fracture surface of similar flint from the same horizon and locality as C. The central core here is completely silicified, but the burrow within it (*B. paramoudrae*) is still distinctly visible.

All scale-bars represent 10 cm.

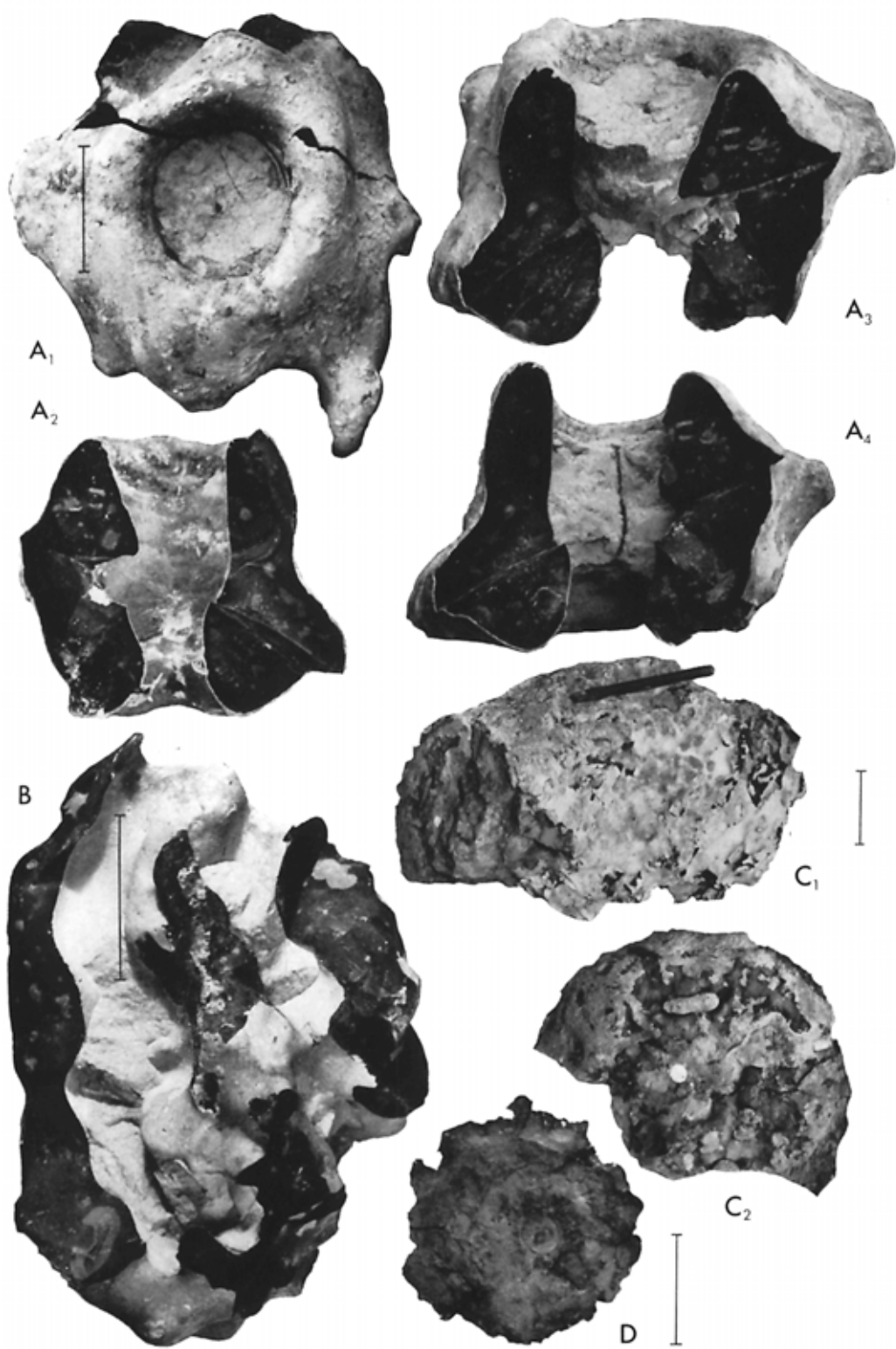


PLATE 3

A: vertical flint cylinder in Upper Campanian chalk at Caistor St. Edmunds. A length of the shaft and a side branch of the central burrow are visible, preserved here as a rusty tube. Scale-bar: 30 cm.

B: fresh section of *Bathichnus paramoudrae* in Upper Campanian chalk at Krons Moor. The very dark auriole of pyrite-rich chalk fades rapidly on exposure. Scale-bar: 5 cm.

C: transverse fracture surface across the same burrow as in B. Scale-bar: 5 cm.

PLATE 3

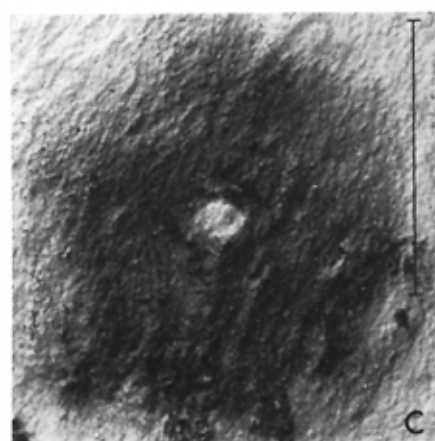


PLATE 4

A: *Bathichnus paramoudrae* in Lower Maastrichtian flintless chalk, 30–35 m below the marl band at Hemmoor. The subvertical shaft makes a sudden bend near the top. A side branch at (a) has been flattened by compaction while another at (b) is uncrushed. This specimen was extracted and chosen as Holotype, MMH 13058.

B: enlargement of part of A, showing the fragmentation of the glauconite tube. Width of tube: 1 cm.

C: upper termination of a burrow at Krons Moor, apparently truncated by erosion (a). The burrow is represented by a thin pyrite tube, and is surrounded by an aureole of dark grey, pyrite-stained chalk. Two pyrite concretions lie close to the burrow (b, b).

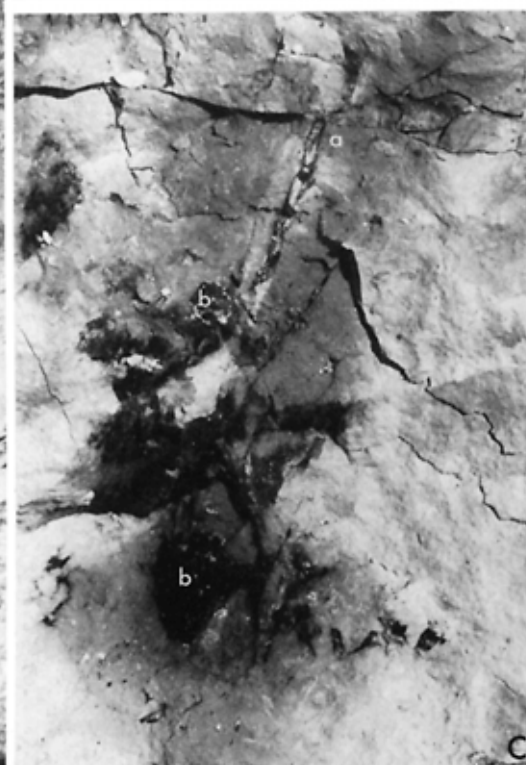
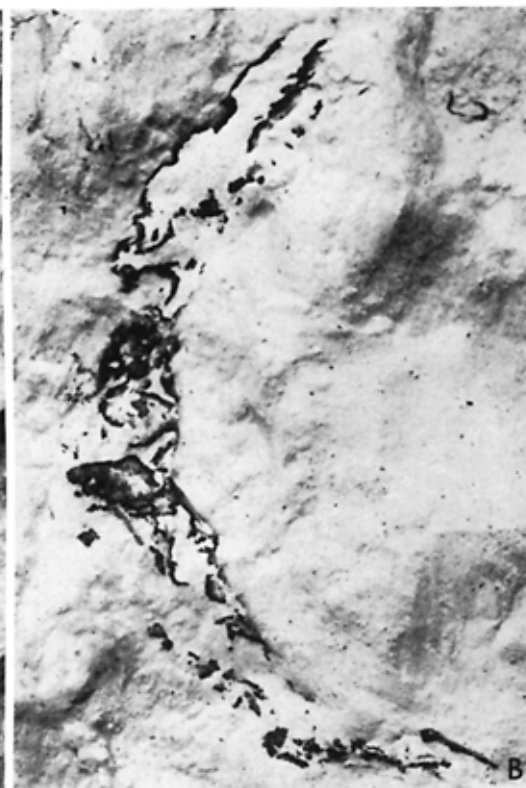
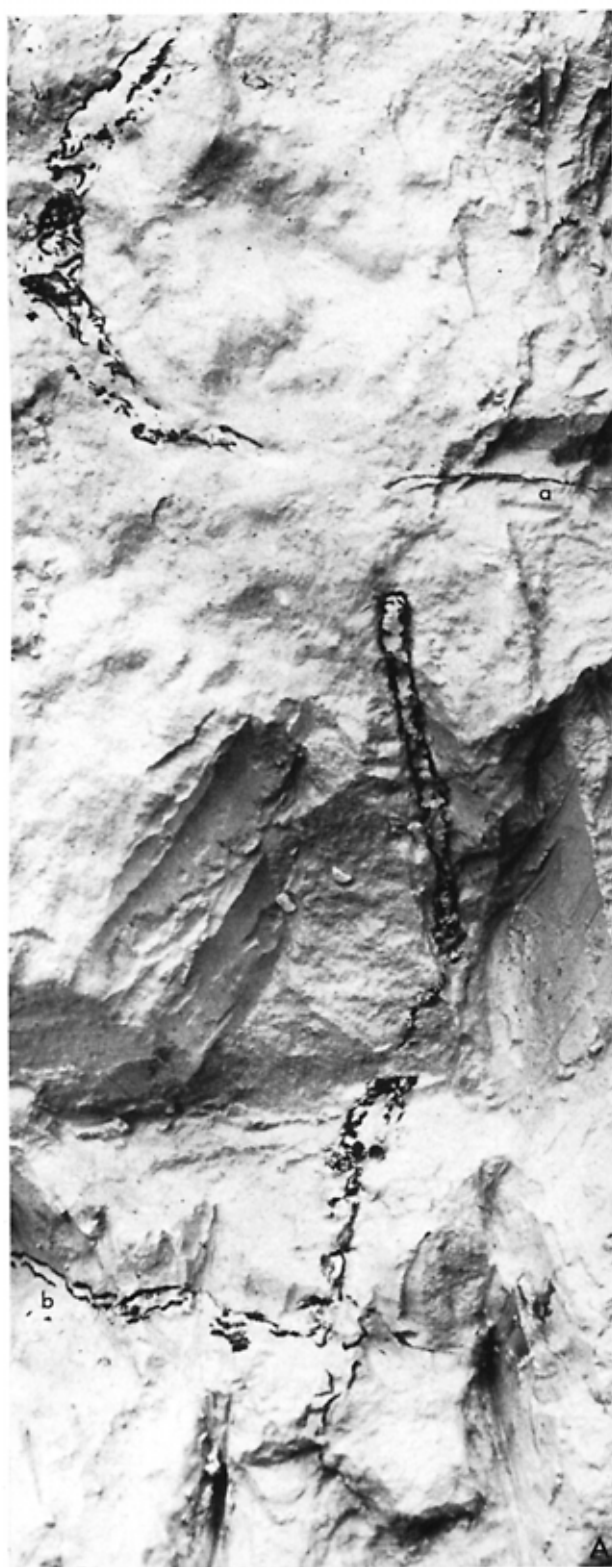


PLATE 5

Aspects of diagenesis associated with *Bathichnus paramoudrae* in *Belemnitella langeti* zone, Upper Campanian chalk at Krons Moor, Holstein, Germany.

A: the burrow is represented by a slender pyrite tube, outside which is a narrow zone of white chalk. Beyond this the chalk is tinted grey (black when fresh) by finely divided pyrite. The burrow passes through a small concretion of pyrite. MMH 13060. Scale-bar: 1 cm.

B: three pyrite concretions from the same situation as in A. The burrow is largely enveloped by the elongate nodule while it runs within a furrow in the two rounded ones. MMH 13061. Scale-bar: 1 cm.

C and D: transverse sections of the burrow itself. The outer grey ring is tinted dark green with glauconite; the inner limit is seen to be sharper than the outer. Within this is white chalk containing more-or-less centrally a complex burrow fill of grey chalk: in these cases a pale grey fill lies within a darker grey one. In D there is a partial development of a pyrite tube (black) around the grey fill. MMH 13062. Scale-bar: 5 mm.

E: longitudinal slice of a similarly preserved burrow to C and D. The green tube here is rather faint, while the chalk within it is distinctly whiter than the pyrite-stained chalk outside it. Centrally lies the complex grey chalk fill. MMH 13063. Scale-bar: 1 cm.

