A PRELIMINARY STUDY OF THE PALAEONTOLOGY AND PALAEOENVIRONMENT OF SOME NAMURIAN LIMESTONE 'BULLIONS'

by

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Summary

'Bullions' are calcite-ferroan dolomite concretions which developed at an early diagenetic stage in the sediments constituting Namurian goniatite bands. In N.E. Staffordshire and S.W. Derbyshire, bullions are largely confined to thin goniatite bands in the E2b.1 - R1b portion of the succession. Some bullions contain no or few microfossils, but many are rich in Radiolaria. Five genera of spumelline Radiolaria are present (one new), two genera of non-spumelline Radiolaria, at least four distinct forms of small sponges and the spat shells of both lamellibranchs and gasteropods. Adult goniatites are present in practically all bullions, but adult lamellibranchs are very scarce and adult gasteropods extremely rare. Brachiopods occur abundantly at a single horizon only. The Posidonid and Myalinid lamellibranchs are shown to be probably non-pelagic. The bullions are interpreted as perfectly preserved samples of silty clay, in many cases semi-pelagic, accumulating at varying distances from land. The sediment was essentially sterile as regards fossilizable intrasediment and sediment-surface micro - and macrofaunas, though there is no evidence of anoxic conditions on the sea floor.

Introduction

The lenses of fine black limestone commonly found in the shale marine bands of the Central Province Namurian - the "Millstone Grit" of the Geological Survey of Great Britain - have long been known to palaeontologists as repositories of excellently preserved, uncrushed goniatite shells. Only recently, however, has it been recognised that many of these limestone 'bullions' also contain abundant and excellently preserved Radiolaria and sponges (Holdsworth, 1964; Holdsworth, 1966; Holdsworth, Palaeontology, in press). The bullions offer a wealth of information concerning rarely fossilized organisms, sediment texture and structure

TEXT-FIG. 1

The uppermost Viséan and Namurian succession of N.E. Staffordshire

The column is not drawn to scale and has been simplified to show the range of bullion-bearing horizons, their relationships to different lithologies - particularly sandstones, and the distribution of richly Radiolarian bullions. Only bullion horizons the positions of which are accurately known are included in the column.

Legend: Coarse stipple - Arkosic and subarkosic sandstones.

Medium stipple - Thinly-bedded, protoquartzitic sandstones and siltstones of turbidite nature.

Fine stipple - Thinly-bedded calcareous siltstones of turbidite nature.

Onecote Sandstone Formation - Calcareous and shelly sandstones and calcareous siltstones.

Diagonal lines - Shale and mudstone with sideritic ironstone.

Plain - Shale and mudstone without ironstone.

Plain horizontal line - Goniatite horizon of shale, mudstone or fissile limestone.

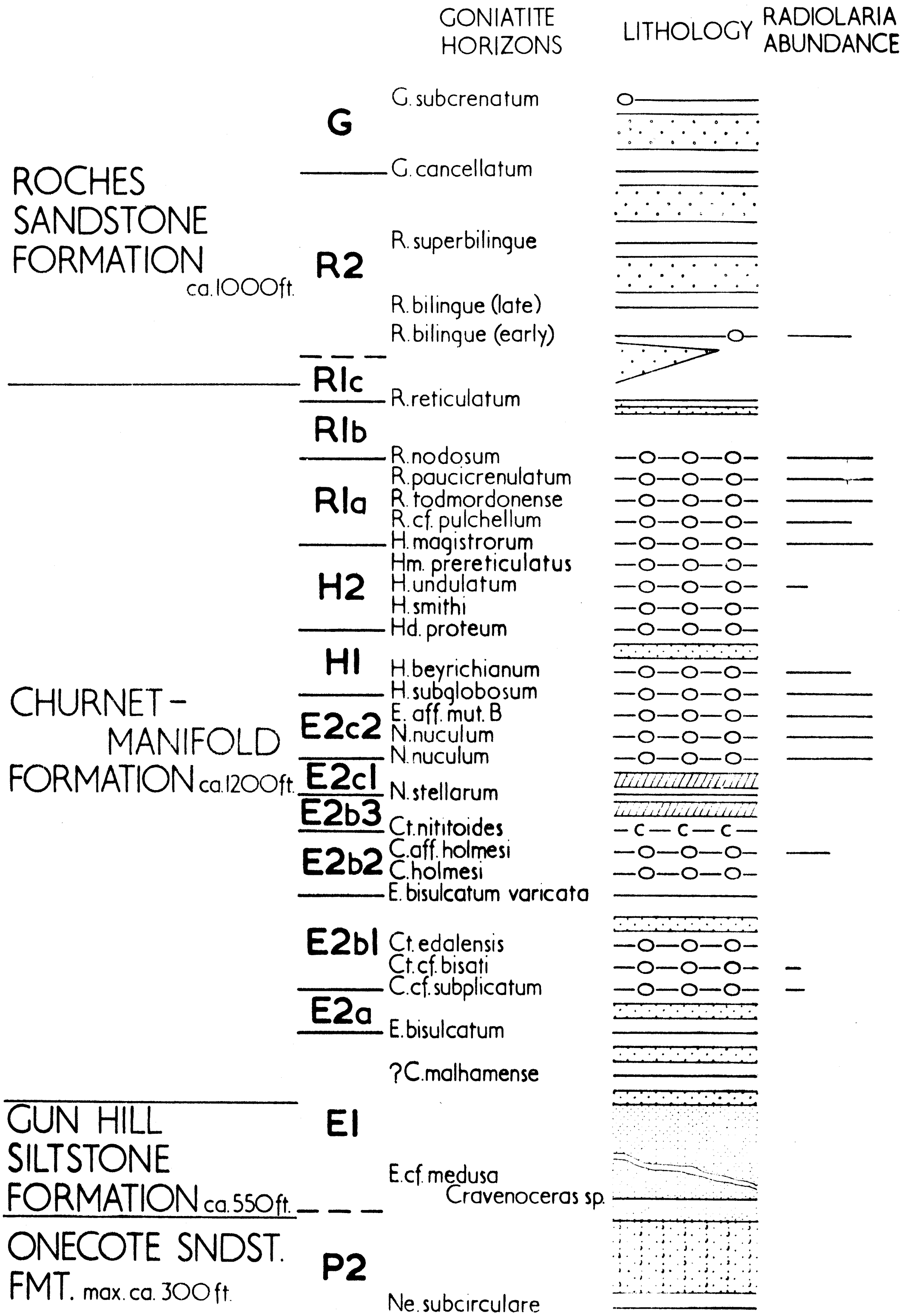
Horizontal line with single lens - Goniatite horizon with rare, local bullions.

Horizontal line with three lenses - Goniatite horizon with frequent bullions.

Horizontal line with C - Goniatite horizon with secondary chert.

Radiolaria Abundance:

Longest horizontal lines indicate horizons at which one or more bullions have yielded the maximum concentration of Radiolaria seen in the succession. Shorter lines indicate proportionally lower concentrations as visually estimated in etched preparations. See p. for comments on Radiolaria distribution.


GONIATITE HORIZONS
LITHOLOGY
RADIOLARIA ABUNDANCE
ROCHES SANDSTONE FORMATION ca.1000ft.
CHURNET-MANIFOLD FORMATION ca.1200ft.
GUN HILL SILTSTONE FORMATION ca.550ft.
ONECOTE SNDST. FMT. max. ca. 300 ft.
G
R2
R1c
R1b
R1a
H2
H1
E2c2
E2c1
E2b3
E2b2
E2b1
E2a
E1
P2
G. subcrenatum
G. cancellatum
R. superbilingue
R. bilingue (late)
R. bilingue (early)
R. reticulatum
R. nodosum
R. paucicrenulatum
R. todmordonense
R. cf. pulchellum
H. magistrorum
Hm. prereticulatus
H. undulatum
H. smithi
Hd. proteum
H. beyrichianum
H. subglobosum
E. aff. mut. B
N. nuculum
N. nuculum
N. stellarum
Ct. nititoides
C. aff. holmesi
C. holmesi
E. bisulcatum varicata
Ct. edalensis
Ct. cf. bisati
C. cf. subplicatum
E. bisulcatum
?C. malhamense
E. cf. medusa
Cravenoceras sp.
Ne. subcirculare

prior to compaction, and carbonate crystallization - much of which remains to be assessed in detail. However, in view of the recent increased interest in Namurian palaeoecology, a brief survey of the bullion evidence and discussion of its possible implications in palaeoenvironmental and sedimentological studies may serve a useful purpose.

The remarkable preservation of the originally siliceous Radiolaria and sponges is apparently due to crystallization of calcite and rapid growth of the bullions very soon after the deposition of the goniatite band sediment. The delicate fossils were thus protected from damage during compaction of the sediment - which completely crushed goniatite shells outside the bullion concretions. It is now known that the great majority of the siliceous skeletons are preserved as replacements by ferroan dolomite, and details of this remarkable replacement process and of the carbonate petrology of the bullions will be given elsewhere.

Radiolaria and sponges are detectable as common members of the marine band faunas only where bullions are present. It must not, however, be assumed that these organisms were present in the faunas of all goniatite bands. A consideration of the stratigraphical distribution of bullion bands in N.E. Staffordshire and S.W. Derbyshire suggests that bullion-rich and bullion-free bands may have accumulated under significantly different conditions. The environment of the bullion-free bands could have been unfavourable to Radiolaria and sponges, though in the absence of any lithology suited to their preservation we have no way of directly testing the matter.

Stratigraphy

Text-Fig. 1 summarizes the Namurian succession developed in N.E. Staffordshire. In the adjacent Upper Dove Valley of S.W. Derbyshire, beds below the base of E2a are cut out by the Visean-Namurian unconformity (Holdsworth, 1963a). In the same area the sandstones developed in the E2a - R1b part of the succession in Staffordshire have disappeared and the corresponding pure-shale unit of the Upper Dove has been named "Dove Shale Formation" (Holdsworth, 1963b).

It can be seen from Fig. 1 that goniatite bands with common bullions occupy the E2b.1 - R1b part of the succession in N.E. Staffordshire, and a similar distribution is seen in the Upper Dove Valley. The concentration of bullions in one portion of the succession is alone sufficient to suggest that conditions of marine band sedimentation during E2b - R1b time differed from those of E1 - E2a time and of R1c - G time. The following facts may also be significant.

(a) The E2b - R1b shale goniatite bands in which bullions are common are usually thin, seldom more than a few inches in thickness. The higher bands are commonly more than a foot in thickness and may exceed three feet.

(b) The sandstones of the bullion-rich part of the succession are thin protoquartzites of typical turbidite nature (Holdsworth, 1963a) whereas those of the highest Namurian are thickly-bedded, feldspathic sandstones, sometimes of fluvial origin.

(c) The faunal phase with the lamellibranch genus Dunbarella (see below, p. 26) occurs commonly as parts of R1c - G bands but is very uncommon lower in the succession.

(d) The iron carbonate, siderite, which is unknown in the E2b - R1b goniatite bands, begins to appear in some the higher bands. Relative abundance of iron in sediments has been taken by Krumbein and Garrells (1952) to indicate relative proximity to a shoreline. The evidence of the siderite, together with the thickening of the sandstones and of the goniatite bands themselves, might suggest that the higher Namurian marine bands accumulated rather closer to land than those in which the bullions are common. Though the explanations of the differences are still far from certain, it would be unwise to extrapolate ideas based upon the study of bullions to high Namurian, essentially bullion-free bands of the type studied by Potts (1960) and Heptonstall (1964).

Method of study of the bullion limestones

The bullions are masses of very fine black limestone, lensate in cross-section and circular in plan. They range up to three feet in diameter and somewhat more than a foot in thickness, though the majority are considerably smaller than this. The Radiolaria, sponges and molluscan spat are quite invisible on freshly cut or broken surfaces of limestone, but can quickly be revealed by simple etching with dilute hydrochloric acid. Cut or broken surfaces are immersed for about thirty seconds in acid. The fine calcite dissolves rapidly with strong effervescence, producing a marked oily scum. The much less soluble dolomite replacing the siliceous fossils is unaffected during swift etching, and, after thorough, gentle washing in water, Radiolaria and sponges stand out from the dried surface in high relief and can be studied in great detail in strong reflected light under a high-power binocular microscope. Owing to the dolomitic and sometimes silicified nature of the shells, molluscan spat is revealed during the same process and any traces of lamination in the original sediment or laminar distribution of fossils are readily apparent in the etched preparations.

Carbonates have been indentified and relative proportions roughly estimated using an X-ray diffractometer to examine whole-rock powders, and acid insoluble fractions have been investigated both optically and with X-rays. Carbonate fabrics can be studied in thin-section, but thin-section examination yields relatively little information.

Mineralogy

X-ray diffraction charts for whole rock powders of bullion limestones show the rock to be composed almost entirely of calcite (with a few mole per cent of magnesium carbonate in solid solution) and a dolomite of ferroan nature with X-ray characteristics suggesting a true ankerite. Quartz, present in the bullions, cannot be detected in whole-rock diffraction charts due to interference by the calcite diffraction pattern. During etching, calcite dissolves, leaving the dolomite in the etched surface. Thus diffraction charts of etched surfaces show the ferroan dolomite together with quartz but no calcite. During complete acid digestion of the rock both calcite and dolomite dissolve. Diffraction charts for the dark grey, very fine insoluble residue show quartz as the only crystalline constituent. The apparent complete absence of clay minerals is surprising.

Apart from very rare Radiolaria and sponge spicules still composed of silica and silicified spat shells, the acid-insoluble residue has a grain size less than 0.066 mm. and settles completely from suspension only after several hours. Thus the non-Radiolarian fraction of the sediment, free of secondary carbonate, is best described as a silty clay composed of quartz and very finely divided carbonaceous matter.

Structure of the original sediments

Study of etched surfaces enables the earliest diagenetic bullions to be divided into two important classes: (a) With abundant Radiolaria, without marked lamination and with quartz content apparently low; (b) With no or few Radiolaria, sometimes with lamination of quartz-rich and quartz-poor sediment and with total quartz content apparently high.

The weight percentage of the silty quartz-carbon clay described in the previous section was found to be 8.2% in a typical Radiolaria-rich limestone and 11.8% in a laminated limestone lacking Radiolaria. There is no evidence that crystallization of calcite in the clay has distended the original sediment structure and it is reasonable to believe that matrix calcite of the bullions occupies approximately the same space as was occupied by water at the time the calcite crystallized. Thus, taking the specific gravity of calcite as 2.71, the calcite of the non-Radiolarian bullion is equivalent to about 73.5% by weight of water in the original sediment. This figure must be taken to represent a very high porosity indeed at the time of calcite crystallization. Muds rich in organic matter are known to have porosities greater than 90% immediately after deposition (Hatch, Rastall and Greensmith, 1965) and such very high initial porosities must be envisaged for the goniatite band clays. Bullion growth must have been at very shallow depth in the accumulating sediments, before any significant water expulsion had taken place.

Thus the sediment incorporated into the non-Radiolarian bullion had about 26.5% solid matter by weight. In richly Radiolarian sediments the solid fraction consists of carbonaceous matter, quartz (apparently proportionally less than in non-Radiolarian bullions) plus the Radiolaria themselves. As the Radiolaria are dolomite-replaced and cannot be completely separated, it is impossible to determine the exact percentage by weight that they contributed to the solid fraction. An approximation can be made on the assumption that bullion growth always occurred when the sediment had attained a composition approximately 26.5% solid; 73.5% water. Thus the 8.2% insoluble residue of the Radiolarian limestone represents only 69.5% of the solid fraction presumed to be present. The 30.5% by weight deficit may approximate to the weight of Radiolaria in the solid fraction of the original sediment.

After etching, practically no two specimens of bullion limestone show identical texture and structure. However, if high-dolomite rocks - believed to represent relatively late diagenetic inception of bullion growth - are excluded from consideration, the classification into quartz-rich, Radiolaria-poor and quartz-poor, Radiolaria-rich types is realistic.

The specimen with the obviously highest detrital content was encountered at the Ct. edalensis horizon (E2b.1), etching producing a thick, porous crust with no trace of lamination. Somewhat comparable bullions, but with finer clastic material, occur at the horizon C. holmesi (E2b.2). A similar limestone but with weak, closely spaced lamination is figured (Plate 18 fig. 1) from E2b.1 of the Upper Dove. Plate 18 fig. 2 illustrates a limestone from the C. cf. subplicatum (solo) horizon (E2b.1) of the Dove, in which the total coarse detrital content is lower but segregated into definite laminae, with very weak quartz-rich laminae intercalated between the thicker layers. None of the above mentioned specimens contain Radiolaria, but limestone comparable to that of the C. cf. subplicatum band contains a few Radiolaria at the succeeding Ct. bisati horizon (E2b.1) of the Dove and in the Upper Manifold the laminated C. cf. subplicatum (solo) limestone itself contains a few Radiolaria.

It is important to note that, wherever seen, lamination shows no sign of disturbance by burrowing.

Bullions with relatively low detrital content, little or no lamination and abundant Radiolaria are first known from the C. aff. holmesi (E2b.2) horizon of the Dove. Higher, the N. nuculum - H. subglobosum interval (E2c.2 — H1a) is characterized by early diagenetic bullions all of which, as far as is known, are richly Radiolarian and usually unlaminated, with etched textures similar to the Plate 18 fig. 4 - a specimen from the R. paucicrenulatum horizon of the Dove. Plate 18 fig. 3 illustrates a specimen from the H. subglobosum horizon of the Manifold in which very weak lamination is present in the lower part.

High dolomite contents in the H. beyrichianum - H. undulatum interval complicate assessment of the original nature of the sediments, but the Hd. proteum and H. smithi levels (H2a) may have lacked Radiolaria at the time of deposition. Early diagenetic bullions in the R1a-b portion of the succession appear to be invariably unlaminated and Radiolaria-rich. Apart from the five well-located horizons shown in Text-Fig. 1, a number of loose bullions from the Dove with R1a-b faunas are of unlaminated, richly Radiolarian type.

Footnote

Abbreviations of generic names used in text, text-figures and plate captions.
A - Anthracoceras: C - Cravenoceras: Ct - Cravenoceratoides: D - Dimorphoceras: E - Eumorphoceras: G - Gastrioceras: H - Homoceras: Hd - Hudsonoceras: Hm - Homoceratoides: N - Nuculoceras: Ne - Neoglyphioceras: P - Posidonia: Pd - Posidoniella: R - Reticuloceras.

Thus the sample of bullion limestones so far obtained gives a slight suggestion of two "Radiolaria peaks" in the N.E. Staffordshire - S.W. Derbyshire succession - one in the E2c.2 - H1 interval, a second in the R1a - R1b interval. Non-Radiolarian bands appear to be concentrated in E2b.1 - lower E2b.2. The distribution may reflect a broad cyclic pattern (see Text-Fig. 1) in which Radiolaria abundance is inversely proportional to proximity to sandstone units.

Palaeontology

The fossils composing the fauna of the bullions and sufficiently common to be detected either during collecting in the field or during the examination of etched surfaces are:- Microfossils: Radiolaria: isolated sponge spicules: spat of lamellibranchs and gasteropods. Macrofossils: Thicker-shelled goniatites: thinner-shelled goniatites (very rare): lamellibranchs (very rare): gasteropods (extremely rare); brachiopods (extremely rare): sponges: plant fragments.

Though conodonts have been described from Namurian marine horizons, they are undetected either in etched bullion samples or in acid-insoluble fractions. Endothyrid Foraminifera are known from the N.E. Staffordshire succession as allochthonous faunas in turbidite siltstones (Holdsworth, 1963b, p. 209) but do not occur in the bullions. The earlier record of bullion endothyrids (Holdsworth, 1964, p. 698) resulted from mistaken identification of sections through gasteropod spat shells.

The Radiolaria

Our knowledge of Palaeozoic Radiolaria has been very greatly increased during the last fourteen years. Advances are largely due to the discovery of Palaeozoic assemblages in phosphatic and calcareous rocks from which the fossils can be etched or completely separated. Specimens prepared in these ways reveal structures only rarely visible in the much more common chert-preserved Palaeozoic faunas and have led to the realisation that many Palaeozoic Radiolaria differ very fundamentally from those of Modern seas.

Such a conclusion may seem hardly surprising - but as Deflandre (1952) pointed out, there was for many years, since the classic work of Haeckel (1887), a common assumption that the Radiolaria had existed from Lower Palaeozoic times as a group relatively static from an evolutionary point of view. Unlikely as this state of affairs might have appeared to the biologist, there was little material of Palaeozoic age which could be cited in refutation. Specimens indistinctly seen in chert thin section certainly show gross characteristics comparable with Modern forms, and the "static" view of the Radiolaria is reflected as late as 1954 in the very long time ranges accepted for many taxa by Campbell (in *Treatise*). In view of Deflandre's (1960) strong criticism of Campbell, it should be pointed out, in fairness, that the *Treatise* was being prepared at a time when Deflandre's own discoveries in the Carboniferous were for the first time providing a serious challenge to accepted notions. It must also be pointed out that the task of revising the taxonomy of the Palaeozoic Radiolaria and reassessing the validity of earlier records has, even now, hardly begun.

The main types of skeletal organization in Palaeozoic Radiolaria so far known are illustrated, much simplified, in Text-Fig. 2. Shown also is the basic organization in Modern Spumellina and Nassellina - the two Modern suborders which appear to possess Palaeozoic ancestors. The types of organization so far recognized as being represented in the Namurian bullion faunas are also indicated in Text-Fig. 2.

The very great majority of the Namurian Radiolaria belong to the suborder Spumellina and have a basic organization such as that illustrated in Text-Fig. 2b. As pointed out by Foreman (1963) in her study of Devonian faunas, very many Palaeozoic forms differ from most Modern species in possessing a spicular system inside the spherical, perforated lattice shell. None of the Namurian forms have yet been proved to lack these spicules. Most commonly, both in the Devonian and Namurian assemblages, the spicules arise from either end of a short median bar and are continuous with the strongest set of spines originating from the shell surface. Most common are species of the genus *Entactinosphaera* Foreman, in which there are six internal

PLATE 18

Etched bullion limestones

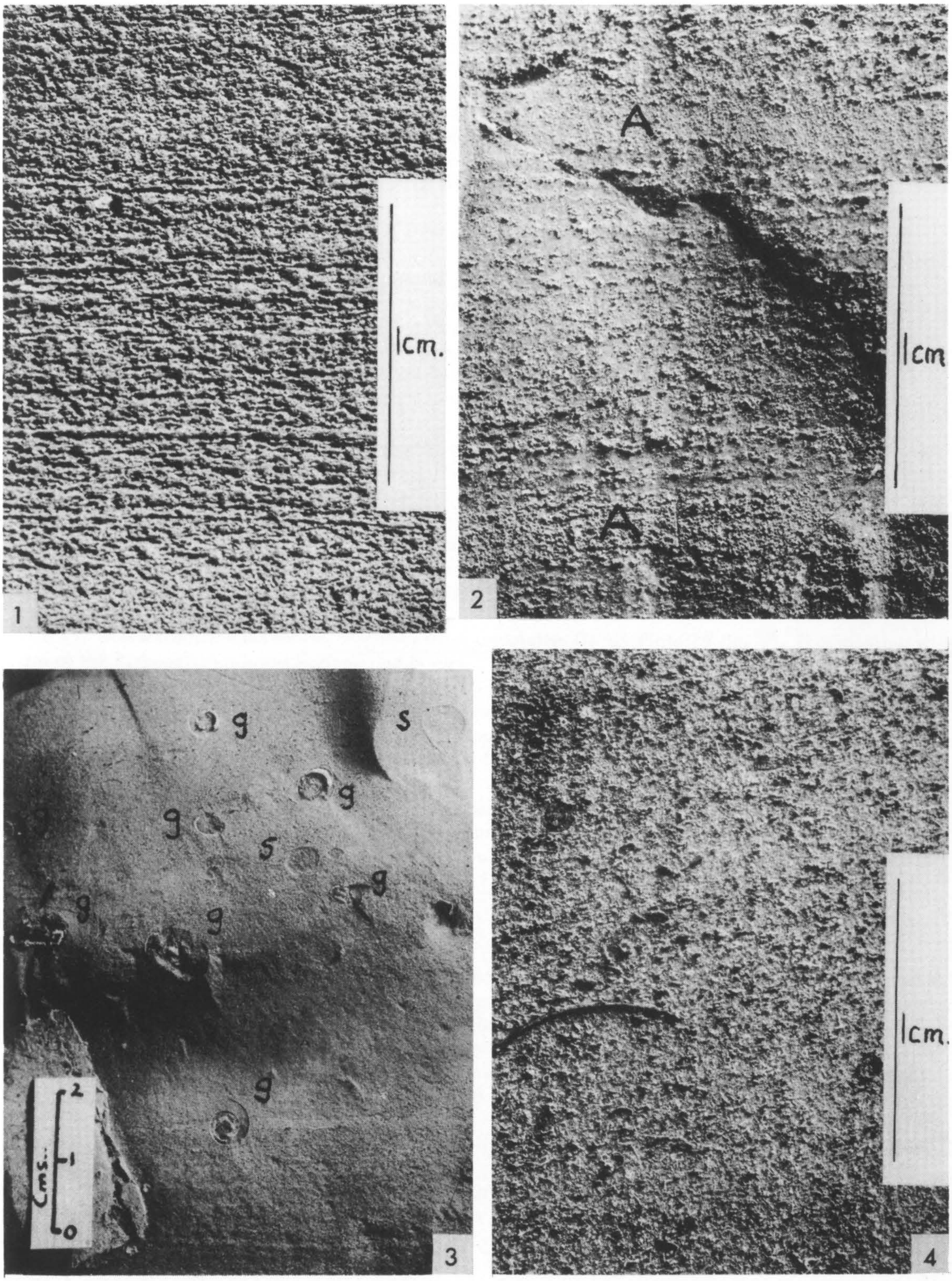
Fig. 1. Non-Radiolarian limestone with high detrital content and poorly developed lamination. Etched surface. E2b.1, Upper Dove Valley

Fig. 2. Non-Radiolarian limestone with detrital content less than that of Fig. 1 specimen and concentrated into well-defined laminae - A,A. Etched surface C. cf. subplicatum (solo) horizon, E2b.1, Upper Dove Valley.

Fig. 3. Radiolaria-rich limestone showing densities of thicker-shelled goniatites - g - and sponges of Form 2 - s. Etched surface. H. subglobosum horizon, H1a, Upper Manifold Valley.

Fig. 4. Typical texture of Radiolaria-rich limestone, low in detrital content. Etched surface. R. paucicrenulatum horizon, R1a, Upper Dove Valley.

Plate 18.



spicule rays arising from a median bar and more than one spherical lattice shell - the shells being arranged one inside the other (Plate 19 fig. 3). As demonstrated by Deflandre (1958), the number of lattice shells is frequently related to the size and stage of development of the radiolarian, and caution must be exercised in erecting species. In the genus Entactinia Foreman the spicular system is similar to that of Entactinosphaera, but there is never more than one shell. This genus is also reasonably common in the Namurian faunas (Plate 19 figs. 1, 2). One of the most beautiful Namurian species belongs to the genus Polyentactinia Foreman (Plate 19 figs. 4, 5). In this genus there are six to eight spicules which arise from a long median bar. The single lattice shell is not spherical but has flattened, polygonal faces of irregular shape.

In Tetrentactinia Foreman of the Devonian faunas the internal spicules are four in number, meeting not in a median bar but a point, and the shell is frequently more or less "spongy" (cf. Plate 19 fig. 7). Spongy shelled forms in the Namurian faunas appear to belong mainly to Tetrentactinia, but in at least one species (Plate 19 fig. 8) there are six, not four, spicules meeting at a point. This modification is of interest for it is essentially the organization met with in the Modern Centrolonchinae. A few Namurian spumellines lack a spherical lattice shell and possess a skeleton built of strong, anastomosed rods (cf. Plate 19 fig. 6). The anatomy of these species has not yet been completely determined, but by analogy with essentially similar, but somewhat simpler, Devonian forms it is probable that they are to be classified in the genus Polyentactinia.

Non-spumelline Radiolaria are represented definitely in the Namurian faunas by only three species virtually confined to two goniatite horizons (Holdsworth, Palaeontology, in press). Albaillella pennata Holdsworth occurs at the horizon of Reticuloceras paucicrenulatum and A. aff. pennata (Plate 19 fig. 10) is seen as the Homoceras subglobosum horizon. The genus Albaillella Deflandre is one of two genera included in the sub-order Albaillellina - a group restricted, as far as is known, to the Carboniferous. Though they superficially resemble the latticed Nassellina they differ in possessing a marked, overall bilateral symmetry imparted by the arrangement internally of two longitudinal columellae (Text-fig 2c).

The third non-spumelline, Popofskyellum undulatum Defl. (Plate 19 fig. 9), is associated with A. pennata at the R. paucicrenulatum horizon and is rare. The genus Popofskyellum Deflandre, also unknown outside the Carboniferous, is of interest in that it appears - superficially at least - to have an organization intermediate between Albaillellina and Nassellina. The major part of the shell has a bilateral symmetry imparted by two longitudinal ribs, but the arrangement of apical spines lacks this symmetry and is superficially similar to the arrangement of apophyses in Modern latticed Nassellina (cf. Text-fig. 2 d and e).

The status of Ceratoikiscids (cf. Fig. 2h) in the Namurian faunas is still not clear. Some incomplete specimens may be comparable with the form figured but not described by Deflandre (1960, Plate 1, Fig. 30) from the Visean as "Ceratoikiscum (?) speciosum n. sp." The term "non-spumelline Radiolaria" as used in this paper refers only to forms of Albaillella and Popofsykellum.

Sponges

The sponges are all forms with skeletons composed of unfused spicules. In the bullions these sponges are most commonly represented by isolated, scattered spicules - as is usually the case with sponges of this type - the soft parts having disintegrated prior to fossilization and the released spicules having been dispersed. In relatively rare cases, however, very small sponges have been preserved intact with spicules in their original positions, and in etched preparations it is sometimes possible to determine the extent of the soft parts, which have been replaced by relatively clear calcite of distinctive appearance.

A sponge consists of megascleres - relatively large spicules making up the main skeleton - and may also contain microscleres - small spicules embedded in the flesh of the sponge. Amongst the scattered spicules of the bullions microscleres are very uncommon, but in two of the four sponge types so far recognized microscleres can be seen in association with megascleres.

TEXT-FIG. 2

Types of skeletal organization in Radiolaria

a. Type of organization in many Modern Spumellina.

b. Type of organization in Palaeozoic Spumellina.

c. Type of organization in *Albaillella* Deflandre, only known from Carboniferous.

d. Type of organization in *Popofskyellum* Deflandre, only known from Carboniferous.

e. Type of organization in Modern Nassellina. The suborder is very variable, but homologies can be demonstrated between different modifications of spicule organization. These homologies do not extend to the spicules of the Palaeozoic *Cyrtentactinia* (f) and *Pylentonema* (g), which have a superficially similar organization. Note the absence in the Nasselline organization of any strong bilateral symmetry seen in *Albaillella* (c) and *Popofskyellum* (d).

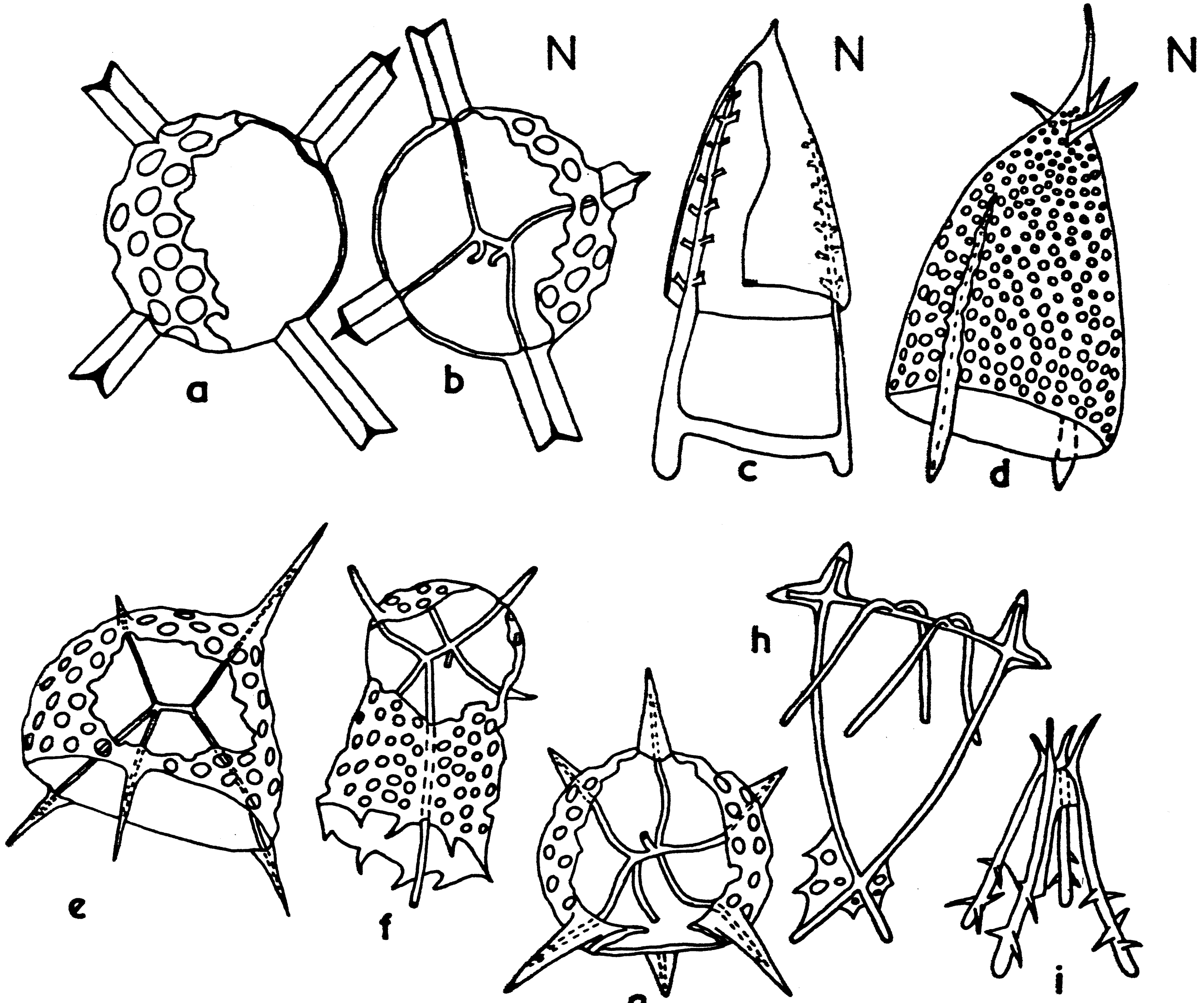
f. Type of organization in *Cyrtentactinia* Foreman, only known from Devonian.

g. Type of organization in *Pylentonema* Deflandre, only known from Lower Carboniferous and possibly synonymous with *Cyrtentactinia*.

h. Type of organization in Ceratoikiscids, Silurian to Lower Carboniferous.

i. Type of organization in *Palaeoscenidium* Deflandre, Devonian to Lower Carboniferous.

N - type of organization in Namurian faunas of bullions.



N
N
N
a
b
c
d
e
f
g
h
i

The commonest spicule type encountered amongst the bullion sponges is a pentactine megasclere approximating to a true triaxon - i.e. a relatively large, five-rayed spicule in which the rays are arranged along the three axes of a cube, one axis being represented only by an unpaired spicule. Of the four types of sponge organization recognized, in two the main skeleton is built of this type of spicule, and it is present in the other two type. Only one of the four types, found at a single horizon, contains monaxon spicules. In this respect the bullion sponge faunas seem to differ markedly from thos which contributed spicules to the Arnsbergian (E2) spongolites of Ireland (Lewarne, 1963).

The most frequent scattered spicule of the bullions is a pentact triaxon in which the five rays are thick and tapered at their ends. This spicule belongs to the first type of sponge, represented by semi-complete skeletons, a few millimetres long, at the lowest N. nuculum horizon. The shape of the sponge is apparently narrowly conical. The pentact megascleres are relatively few, lying with their four paired rays in the plane of the sponge wall, the unpaired ray being directed inwards. Forming the base of the skeleton are one or two peculiarly shaped megascleres - possibly modified pentactines - in which the rays diverge at narrow angles and are upwardly directed in the sponge wall, (Plate 20 fig. 3). Microscleres, occurring internally, are abundant hexactine triaxons in which two paired rays are sometimes elongated along the axis parallel to the long axis of the sponge skeleton. The megascleres of the first sponge type are similar to spicules to the genus Hyalostelia, but the typical rooting cords of the genus have not been found and the bullion specimens are clearly very much smaller than those which gave rise to the rooting cords recorded from the Carboniferous Limestone (Hinde, 1887).

The second sponge type, found only at the H. subglobosum horizon, lacks microscleres. The sponge is spherical or subspherical, measuring up to 5 mm. in diameter (Plate 20 fig. 1). The spicules are pentactine triaxons with thin, non-tapering rays. As in the first type, four of the rays lie in the curved plane of the sponge periphery, the fifth - often much elongated - is directed inwards (Plate 20 fig. 2). These inwardly directed rays lay in a thick fleshy layer which surrounded a small central cavity, the fleshy layer now being represented in etched cross-sections by a ring of clay - and Radiolaria-free calcite. The central cavity is filled with the same calcitized Radiolarian clay which composes the remainder of the bullion. Superficially this small spherical form resembles the Lower Palaeozoic Teganium - presumably epiplanktonic (Ruedemann 1934) - but the spicules of Teganium are tetractine, lacking the fifth, inwardly directed ray of the Namurian sponge.

The third sponge type is represented at the R. paucicrenulatum horizon by dense clusters of hexactine and pentactine triaxons with non-tapered rays. The overall form of this sponge is uncertain. Microscleres are absent. The fourth and largest type of sponge skeleton detected occurs only at one horizon with R. nodosum, where it is sufficiently abundant to mottle the limestone even in unetched specimens. The skeletons have the form of very much flattened and almost certainly collapsed sacs. The sac walls are composed of flat-lying sheets of slightly tapered monaxon spicules, a few spicules deep. Viewed in oblique cross section it can be seen that the sheets consist of mutually parallel monaxons, but abrupt changes in spicule direction around the periphery of the skeleton suggest that the wall is composed of a patchwork of monaxon sheets meeting edge to edge. The interior of the sponge is now represented by pure calcite - suggesting replacement of soft tissue - with abundant poorly preserved polyactine microscleres and a few pentactine triaxon megascleres.

Mollusc spat

One third of the bullion limestones examined contain minute shells recognizable as molluscan spat. Most common is the spat of lamellibranchs. Gasteropod spat was noted in only five out of twelve spat-containing limestones and, somewhat surprisingly, goniatite shells of comparable size were not definitely identified in any of the limestones examined.

The lamellibranch shells are sub-circular to ovate in shape with the umbo placed slightly to one side of the hinge-line centre. The maximum length is about 0.5 mm. The difficulty of identifying lamellibranchs in these very early growth stages has been discussed by Ramsbottom et. al. (1962) and these authors figured three forms of lamellibranch spat from Namurian shales at Ashover (Plate VI, Figs. 5, 8, 9) which they considered might represent either Posidonia, Caneyella or Nuculids. The range of shape seen in the three figured specimens is very similar to that observed in the bullion lamellibranch spat. Gasteropod spat shells, similar in size to the lamellibranchs, fall into two distinct shape classes - shells with a flat coiling and shells with a spire, variable in height but always relatively shallow. The flat-coiled shells appear to be comparable with examples figured from the Ashover Namurian (Ramsbottom et.al. 1962, Plate VI, Figs. 1, 3) and tentatively identified as Bellerophontids. Probably more than one species is represented amongst the spired shells.

In view of the distinct rarity of adult lamellibranchs in the bullions and the virtual absence of adult gasteropods (below, p.329) the presence of the spat shells is somewhat puzzling and is discussed below (p. 333).

Goniatites

The Namurian goniatites are of two broad types - the "thicker-shelled" and the "thinner-shelled" goniatites. Several authors have noted the distribution of the two types to be broadly antipathetic. The thicker-shelled group includes all the genera important in zonal classification. The thinner-shelled group includes the two genera Anthracoceras and Dimorphoceras, in which the shell wall is relatively thin and shell shape narrowly discoid. Included in the thicker-shelled class are the genera Cravenoceras and Homoceras, though in many species shell thickness is not appreciably greater than in Anthracoceras and Dimorphoceras. Shell shapes, however, are comparable with those of more typical thicker-shelled genera such as Cravenoceratoides and Reticuloceras, and at many horizons they are associated intimately with typical thicker-shelled species of these genera.

Thinner-shelled goniatites are uncommon in bullions examined. Very occasional specimens are restricted to only seven horizons - three E2b. 1-2, three E2c. 2, one R1a. At four of these seven horizons lamellibranchs were also present - a significantly high correlation in view of the rarity of lamellibranch-bearing bullion horizons (see below).

Thicker-shelled goniatites are the only macrofossils which have been found to be almost invariably present in bullions. Of all bullions examined two only failed to yield a single specimen. Nevertheless, at many horizons density of shells is low. Owing to the difficulty of collecting from bullions, reliable estimates of number of shells per unit volume of limestone are impossible to make and there is difficulty even in expressing relative abundance from horizon to horizon. In order to give some impression of abundance, Plate 18 fig. 3 illustrates the density of H. subglobosum as seen on a surface broken perpendicularly across the bullion lamination. This density is approximately twice the average encountered where shells are randomly distributed through the whole volume of a bullion. At a number of horizons laminar concentrations of goniatites have been noticed, two to three shells deep, with individuals in contact or almost so. In such cases almost the entire goniatite content of a bullion is concentrated in a single thin layer.

In a few case, bitumen or fluid oil may represent the original soft-parts of the goniatite, but in most cases the shells seem to have been empty at the time of calcite crystallization. The gas-chambers are filled (sometimes incompletely) with sparry calcite and in etched preparations the enclosing sediment, often Radiolarian, can be seen to extend into the living chamber as far as the last-formed septum.

Lamellibranchs, gasteropods and brachiopods

(a) Lamellibranchs: The commonest lamellibranch of the succession is Posidonia corrugata, but, like all other lamellibranchs, it is very scarce in bullions. Sparse individuals, never more than 5 mm.

PLATE 19

Radiolaria

Fig. 1. Entactinia Foreman species A. Broken specimen showing internal spicular system. Short median bar and four of six spicules visible. Homoceras subglobosum horizon; Upper Dove Valley. x 160.

Fig. 2. Entactinia Foreman species B. Broken specimen showing internal spicular system. Very short median bar and four of six spicules visible. Reticuloceras paucicrenulatum horizon: Upper Dove Valley. x. 100

Fig. 3. Entactinosphaera Foreman species. Broken specimen showing internal spicular system. Very short median bar and four of six spicules visible. Note concentric lattice shells. Reticuloceras nodosum horizon. Upper Manifold Valley. x 227

Fig. 4. Polyentactinia Foreman species nova. Slightly broken specimen showing details of lattice pores, lattice meshes, main and subsidiary spines. Homoceras subglobosum horizon: Upper Dove Valley. x 126

Fig. 5. Polyentactinia Foreman species nova. Broken specimen showing internal spicular system. Long median bar and six spicules visible. The species has six to eight spicules. Homoceras subglobosum horizon: Upper Dove Valley. x 170.

Fig. 6. ? Polyentactinia Foreman species. Specimen showing lattice of strong fused bars and one main spine. Reticuloceras paucicrenulatum horizon: Upper Dove Valley. x 150.

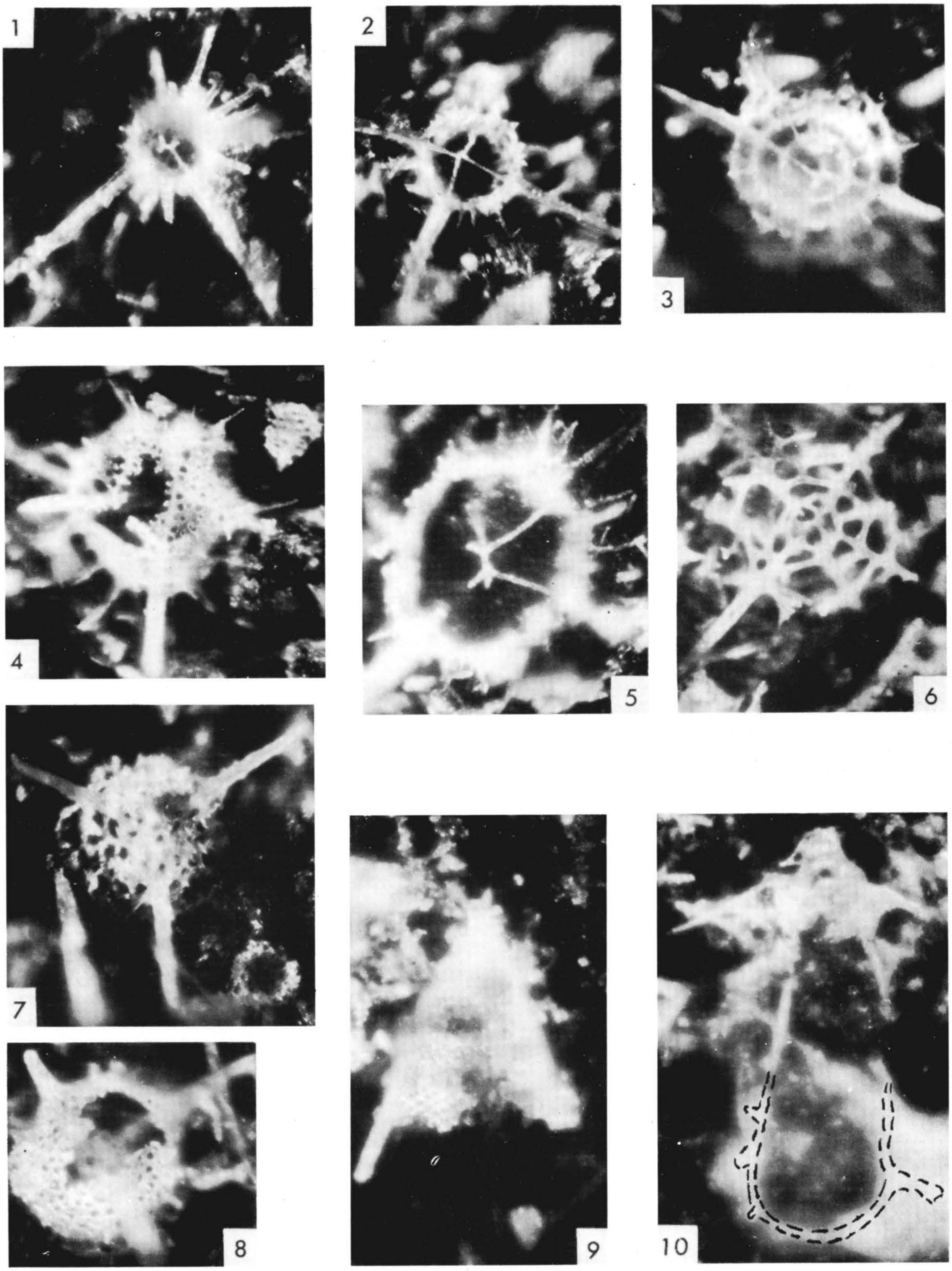
Fig. 7. Tetrentactinia Foreman species nova. Specimen showing spongy lattice and three of four main spines. Reticuloceras paucicrenulatum horizon: Upper Dove Valley. x 134

Fig. 8. Radiolaria genus nova. Specimen showing outer lattice shell, semi-spongy inner lattice and three of six main spines. Homoceras subglobosum horizon: Upper Dove Valley. x 160

Fig. 9. Popofskyellum undulatum Deflandre. Broken specimen showing bell-shaped lattice of muslin-like texture and one of two longitudinal rods. Reticuloceras paucicrenulatum horizon: Upper Dove Valley. x 184

Fig. 10. Albaillella aff. pennata Holdsworth. Much broken specimen showing the two wings set closer to the apex than in typical A. pennata and the H-frame. (Out of focus continuation of H-frame indicated by dashed ink lines). Homoceras subglobosum horizon: Upper Dove Valley. x 197

Plate 19.



long, were noted at four bullion horizons, the highest being that of C. holmesi (E2b.2). It may be significant that this range is coincident with that of the poorly Radiolarian or Radiolaria-free bullions (above, p. 319).

Posidoniella cf. variabilis was found only in a bullion from the middle N. nuculum horizon (E2c.2), where a great concentration of shells appeared to lie on the surface of a thin sheet of calcitized vegetable material. This bullion was unique also in containing specimens of Aviculopecten s.l. sp..

A Homoceras - containing R1a bullion contained a single specimen of Dunbarella sp..

(b) Gasteropods: One bullion only - that of Ct. bisati (E2b.1) - yielded very sparse gasteropods, a few millimetres in diameter, with low spires. The specimens are unidentified but in coiling closely resemble some of the gasteropod spat at other horizons.

(c) Brachiopods: The Ct. bisati bullions (E2b.1) yielded a single specimen of a Productid. The only bullion horizon with a significant brachiopod population is one low in R1b, where Crurithyris sp. is only slightly less frequent than R. nodosum.

Plant fragments

An apparent anomaly regarding the fossil content of the bullions is the presence of large plant fragments buried in the Radiolarian clays. The largest and most perfectly preserved specimen was found at the lowest N. nuculum horizon. The fossil is "stem-like", two inches wide, originally seven inches long but was bent into a weak S-shape prior to bullion growth. The thickness of the fragment (measured perpendicularly to the bedding planes of the enclosing shale) is only about 0.7 inch. The fossil gives the appearance of a bent and compressed cylinder, but there can be no certainty that the "stem" was originally cylindrical. The fossil appears to be an internal cast composed of sparry carbonate, the only ornament on the surface consisting of weak and rather irregular longitudinal striations. The fragment has not been broken open, but plant fragments at other horizons prove to contain coalified organic matter mixed with coarsely crystalline calcite. Aragonite was detected in one filling. In some cases interiors are partly hollow.

The nature of the fragments remains uncertain. Recognizable terrestrial plant remains can be found in some goniatite-containing shales and platy limestones, but the bullion specimens differ in their greater size and absence of any surface or internal structures preserved in detail. If they are of terrestrial origin, it is strange that all specimens known come from the richly Radiolarian type of bullions. In view of the early diagenetic nature of the bullion carbonates, the very poor fossilization seems best accounted for by assuming the fragments to have been in an advanced state of decomposition when they entered the sediments. Decay could have created the internal spaces in which the sparry carbonate crystallized and the completeness with which the internal structure appears to have been destroyed suggests that the tissues could have been soft, lacking woody elements. This raises the possibility that the fragments originated not from terrestrial plants but from massive algal thallae of the kind possessed by Modern Sargassum.

Ruedemann (1934), who described graptolite-sponge-alga associations from North American black shale lithofacies, stated that Modern, floating mats undergo decay at the surface and it might be expected that only the more massive portions of thallae would reach the accumulating sediments in recognizable form. If indeed the fragments do reflect a contemporaneous planktonic flora in the Radiolarian part of the bullion environment the algal layer could have provided the habitat for the small sponges (below, p 333) and contributed all or part of the finely divided organic matter encountered in the limestones.

Interpretations

Apart from the purely palaeontological interest of the Radiolaria and sponge faunas, the bullions are of importance in that they provide us with perfectly preserved, undistorted samples of goniatite band sediment. From these samples a much clearer picture can be gained of goniatite band sedimentation and ecology than from the highly compressed sediments now constituting the goniatite band shales. Provisional interpretations can be summarized under four headings.

(a) Density of goniatite populations

The two most immediately striking features are the fine grain and extreme delicacy of the uncompacted sediment and the comparitive scarcity of the goniatite shells distributed through it. The thin seams of black shale, rich in crushed goniatites, are the result not of relatively rapid concentration of goniatites in a small amount of sediment, but rather of the slow addition of shells to a large volume of extremely compressible clay, often richly Radiolarian. Thus the shale bands give a somewhat misleading impression of the actual density of goniatite populations in the Namurian seas.

Not only was the addition of a goniatite shell to a unit volume of sediment often a rare event, but the accumulation of that sediment may have been extremely slow. Though detrital quartz is present in all bullions, E2c, H1 and R1 bullions indicate the accumulation of clays with an appreciable Radiolaria fraction. No figures are available for the rate of accumulation of Modern Radiolaria-rich sediments, but for pelagic globigerina oozes figures of 0.59 to 1.2 cms. per 1,000 years have been estimated (Schott, 1955). In spite of the very different setting of the Namurian seas compared with the Modern oceans, there is at least the possibility that the rate of pelagic sediment accumulation was approximately comparable. If so, the commonly low concentration of goniatites in bullions may reflect populations of very low density indeed. Occasional increases in population density seem to be indicated by the thin seams of shells within certain bullions, but in some other bullion samples goniatites are so rare as to suggest that the shells are no more than exceptional, drifted inclusions rather than representatives of a population living above the accumulating semi-pelagic clay.

(b) Mode of life of Namurian lamellibranchs

The faunas of the shale-sandstone facies of the upper Visean and Namurian are commonly spoken of as constituting a major Carboniferous faunal assemblage - the "goniatite-thin-shelled lamellibranch" assemblage. In fact, the writer's experience of the North Staffordshire Visean-Namurian succession indicates that the intimate association of thin-shelled lamellibranchs _Posidonia_, _Caneyella_ and _Posidoniella_ with thicker-shelled goniatites is far less common than the general concept of a "goniatite-lamellibranch" assemblage might suggest. Though lamellibranchs and thicker-shelled goniatites do occur in the same thin beds of shale and fissile limestone, nevertheless, levels rich in _Caneyella_ and _Posidonia_ often fail to yield a single goniatite and _vice-versa_. The extreme scarcity of lamellibranchs in the bullion sediment samples tends to confirm the view that the distribution of lamellibranchs - both Posidonids and Myalinids - and thicker-shelled goniatites is largely antipathetic.

The evidence of the bullions may throw a little extra light on the controversial question of the mode of life of the Carboniferous thin-shelled lamellibranchs. Hind (1896) pointed to the common colonial occurrence of _Posidoniella laevis_ and figured a colony "attached" to fossil wood. He concluded that the organisms were byssally fixed - whether to floating or sunken wood he did not specify. Hudson and Cotton (1943) wrote that the thin-shelled lamellibranchs "are usually accepted as either floating or seaweed-attached organisms". Craig (1954) believed that the adult _P. corrugata_ - the commonest lamellibranch of goniatite bands studied by the writer - was benthonic. Jefferies and Minton (1965) questioned this conclusion and showed a high probability that the two closely related Jurassic species, _Bositra buchi_ and _Posidonia radiata_, were truly planktonic forms. Ramsbottom _et. al._ (1962) considered the Namurian Posidonids - _Posidonia_ and _Caneyella_ - to be free-living benthos and the Myalinids - _Posidoniella_ and _Promytilus_ - to be byssally fixed and probably benthonic organisms.

As Jefferies and Minton (1965) pointed out, pelagic organisms - being independent of bottom conditions - will appear in a variety of lithologies and in association with a wide range of non-pelagic fossils. Thus a marine fossil species showing a marked antipathetic distribution with respect to one or more other, broadly contemporaneous marine species is unlikely to be pelagic (i.e. planktonic or epiplanktonic). If the Posidonids and Myalinids were pelagic organisms, it is surprising that their fossils are not more widely associated with those of the free-swimming thicker-shelled goniatites and particularly surprising that they are so very rare in the semi-pelagic, almost certainly open sea sediments represented by the Radiolarian bullions.

If it is argued that the thin-shelled lamellibranchs were epiplanktonic - i.e. attached to floating plant material - then it might be that their appearance was controlled by infrequent development of "Sargasso Sea"-like conditions, restricted in space and time and inimical to the goniatites. Against this view is the failure to find concentrations of plant remains in lamellibranch-rich shales and the absence of lamellibranchs (except in one instance) associated with vegetable fragments in the bullions.

The distribution of lamellibranchs can be most satisfactorily explained by supposing them to have been benthonic in the adult stage and to have occupied a depth range overlapping slightly with that favouring the thicker-shelled goniatites. Their failure to colonize the pelagic muds of the bullions was not due to anoxic bottom conditions (see below) but probably due either to excessive depth _per se_ or to some factor or factors commonly associated with increased depth and distance from shore line. Lack of an adequate food supply seems unlikely in view of the high organic carbon content of the bullions (above, p. 319). Bottom conditions may have been the crucial factor. If estimates of original sediment porosity are valid (above, p.   ) the sediment-water interface could have been so ill-defined as to preclude sediment-surface faunas. At the same time - in view of the apparent sterility of the bullion muds (see below) - it must be assumed that the same "soupiness" of the sediments also inhibited intra-sediment faunas which would have recorded their presence by burrow-mottling and disturbed lamination.

(c) Sea floor conditions of the 'bullion environment'

The predominantly unlaminated, Radiolaria-rich sediments encountered in E2c, H1 and R1 appear to have accumulated slowly, uninfluenced by any fluctuation in supply of detrital material. The E2b, 1-2 bullion sediments, with microlamination of quartz-rich and quartz-poor sediment and with Radiolaria sparse or absent, may represent accumulation rather closer to a land surface, though the cause and periodicity of fluctuation in supply of detrital material remains uncertain. In neither case is any evidence to be found that the fine clays were disturbed after deposition by organisms living on or in the sediment. With the single exception of the _R. nodosum_ horizon (above, pp. 326-29) with its _Crurithyris_-large sponge fauna, there is little evidence that the floors of the goniatite band seas supported either fossilizable macro- or microfaunas.

The goniatites were almost unquestionably free-swimming organisms in view of the mode of life of the Modern _Nautilus._ The probably benthonic lamellibranchs (see above) are extremely rare and the molluscan spat, including both lamellibranchs and gasteropods, is most probably plankton which settled into an environment where continued adult life was impossible (cf. Ramsbottom _et. al._ 1962). All Modern Radiolaria are planktonic and there is no reason to suppose that the Namurian spumellines - closely comparable in gross morphology with Modern forms - had any but a free-floating mode of life. The non-spumelline genera _Albaillella_ and _Popofskyellum_ may have lived at greater depth than the spumellines (Holdsworth, _Palaeontology_, in press), and could conceivably have been benthonic, but the only common group of organisms in the bullions for which a benthonic habit might seriously be postulated is the sponges.

In this respect it has already been pointed out (above, p. 326) that at least one of the bullion sponges is superficially similar to Lower Palaeozoic forms for which an epiplanktonic mode of life has been suggested, and the very small size of all forms detected, together with the rarity of complete skeletons suggests that all may well have been added to the sediment from a plankton-epiplankton layer. The single exception occurs at the _R. nodosum_ horizon where the sponges are considerably larger than usual,

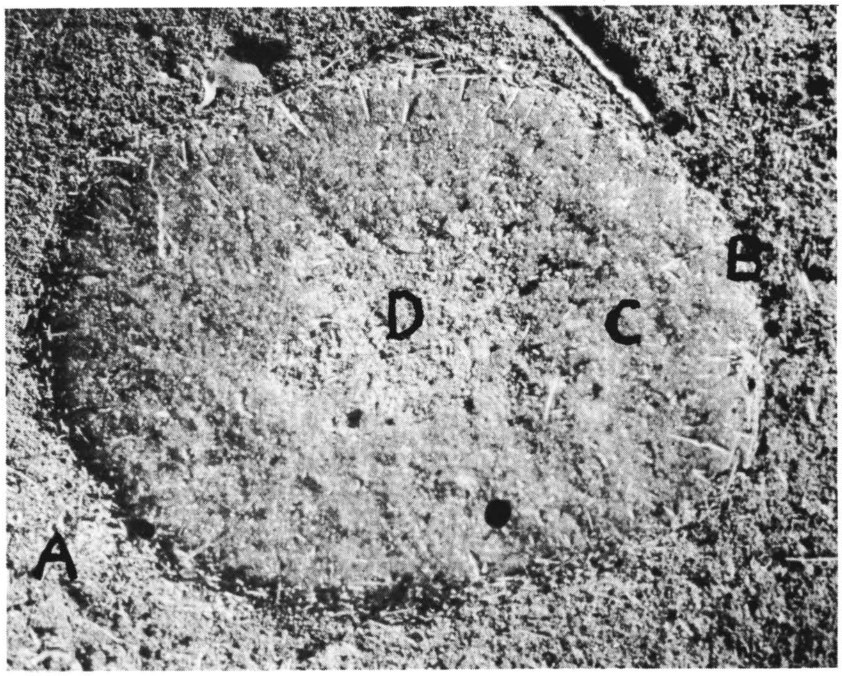
PLATE 20

Sponges

Fig. 1. Sponge form 2 (p. 326). Cross-section of complete specimen on etched surface showing thin, spicular wall (B) surrounded by Radiolarian matrix (A), thick, calcite-replaced fleshy layer (C) and internal cavity filled with Radiolarian matrix (D). Homoceras subglobosum horizon: Upper Manifold Valley. x 20

Fig. 2. Sponge form 2. Detail of specimen illustrated in Fig. 1 showing portion of spicular wall with unpaired spicules directed inwardly through calcite-replaced fleshy layer. x 45

Fig. 3. Sponge form 1 (p. 326). Base of skeleton showing strong, forking megascleres and microscleres internally. Lowest Nuculoceras nuculum horizon : Upper Dove Valley. x 55



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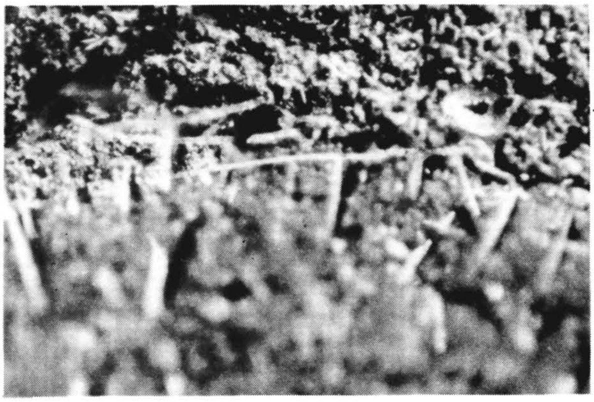

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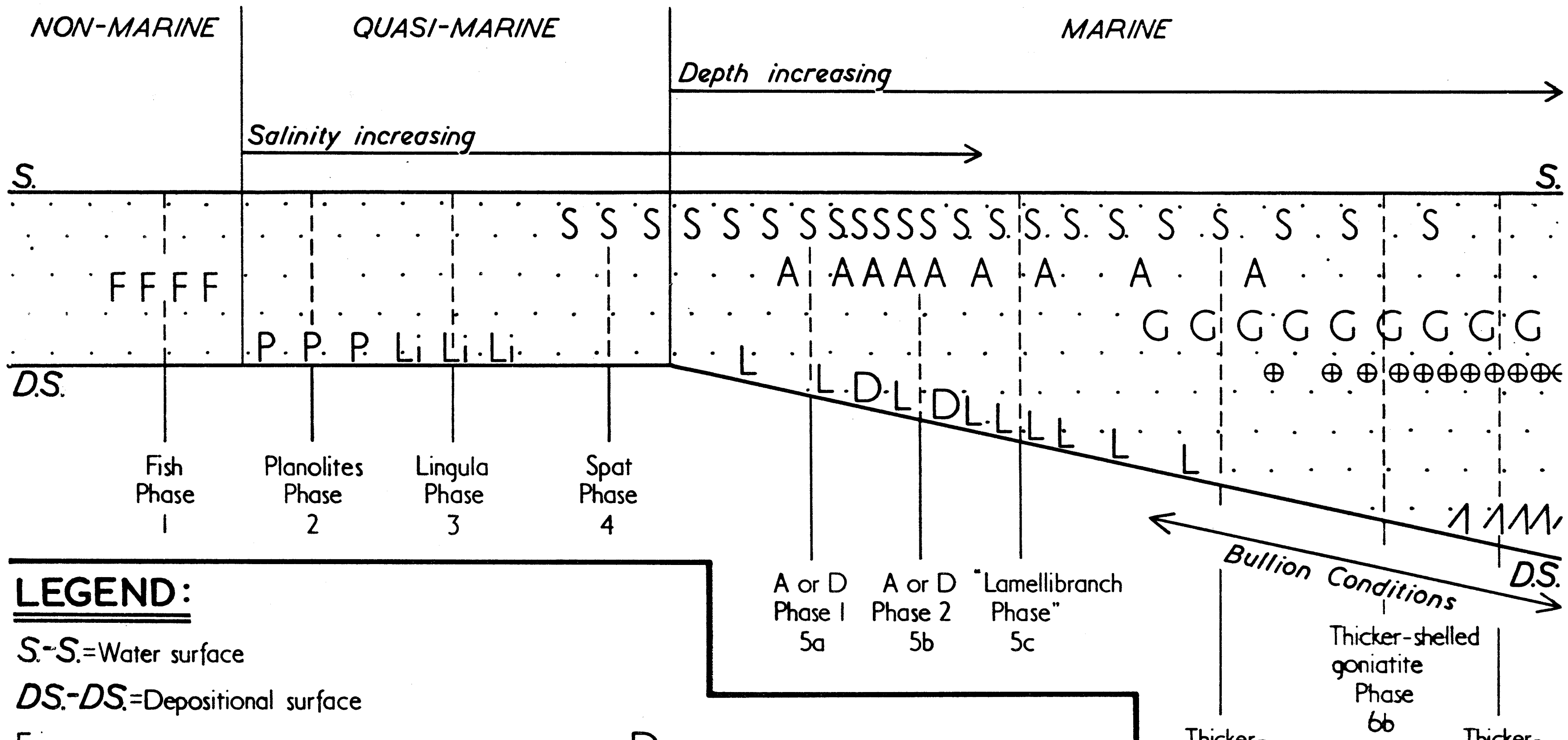
3

Simple Environment Model for Faunal Phases



LEGEND:

S.-S.=Water surface

DS.-DS.=Depositional surface

F=Fish

P=Planolites

Li=Lingula

S=Lamellibranch and gasteropod spat

L=Caneyella, Posidonia and Posidoniella adults

D=Dunbarella adults

A=Anthracoceras or Dimorphoceras

G=Thicker shelled goniatites

⊕=Spumelline Radiolaria

Λ=Non-spumelline Radiolaria

Fig.3

Full explanation in text

preserved as unscattered skeletons more frequently and very much more abundant. As they are here associated with the thick-shelled and almost certainly benthonic Crurithyris it seems highly probable that this particular sponge was a bottom dweller.

It seems unlikely that the comparitive sterility of the bullion band clays resulted from anoxic bottom conditions. Had such conditions prevailed, the activities of sulphate reducing bacteria would be expected to have produced pyrite, probably in framboidal form, at, or very closely beneath, the sediment surface. In fact pyrite is extremely rare in the bullions and unpublished petrological work seems to suggest that pyrite began to form only at a comparatively late stage in diagenesis. The absence of an intra-sediment or sediment-surface fauna remains largely unexplained, though as suggested above the highly water-charged nature of the clays may have been an important factor.

(d) Bullion faunas and the "faunal phase" concept.

One of the most important contributions to understanding of the Namurian shale environments was the demonstration by Ramsbottom and his co-workers (1962) that in a condensed shale succession over a massif-controlled submarine high (cf. Holdsworth, 1963), the continuous fossil record can be analysed in terms of six distinctive kinds of fossil assemblages or "phases" which occur in a broadly cyclic pattern. The development of the different phases was explained largely in terms of cyclically fluctuating salinity, though variation in water depth was suggested as a further factor involved. "Maximum marine" conditions were supposed to be indicated by the thicker-shelled goniatite phase - i.e the phase containing the zonally important genera Eumorphoceras, Homoceras, Reticuloceras etc.

The bullion faunas belong exclusively to the thicker-shelled goniatite phase, and the evidence of the bullions suggests that Radiolaria-rich and Radiolaria-poor subphases may be distinguished, perhaps indicating relatively "near shore" and "open sea" conditions respectively. There is also some indication that the Radiolarian-rich subphase may contain two distinctive kinds of fauna - one containing only spumelline Radiolaria, a second with both spumellines and the non-spumelline genera Albaillella and Popofskyellum. This latter "microphase" may mark the maximum depths attained by Namurian goniatite band seas (see discussion in Holdsworth, Palaeontology, in press).

Text-fig. 3 presents a simple tentative interpretation of Ramsbottom et al's. faunal phase analysis in terms of the two variables, salinity and depth. No attempt has been made to estimate absolute values for either parameter. The diagram is drawn to show the supposed slightly overlapping depth ranges of the lamellibranchs Posidonia, Caneyella and Posidoniella (L) and of the thicker-shelled goniatites (G) (see above, p. 331). The tentative subdivision of the thicker-shelled goniatite phase is also indicated. Closeness of horizontal spacing of the symbol for a particular faunal element expresses relative density of population. Vertical lines 1-4; 5a-c; 6a-c indicate the approximate relative positions on the profile of the depositional surface (D.S. - D.S.) at which the phases will accumulate, and faunal elements lying adjacent to the dashed upward continuations of these lines are the elements which will occur in the different phase faunas.

An interesting point is the dual appearance of lamellibranch spat unassociated with adult lamellibranchs. In the spat phase (4) this is due to the planktonic spat shells drifting into a zone of unfavourably low salinity (Ramsbottom et. al., 1962); in the thicker-shelled goniatite phase (6b, 6c) the shells sank into water of excessive depth (above, p. 331).

The complete phase cycle 1-6 has so far been demonstrated only in the condensed shale succession of the Ashover bore-holes. As stressed earlier (Holdsworth, 1963) the "massif" area of the Ashover succession contrasts with the adjacent "basin" or "autogeosynclinal" area of thicker deposits from which come the bullions. One of the most urgent problems of Namurian research is to determine whether the full cyclical range of environments extended into the basin, and if so, how the phases relate to the intercalations of coarser clastic sediments - the turbidite siltstones and sandstones. In fact it seems likely that in the bullion-bearing portions of the basin succession the cycles cover a more restricted range of environment than in the massif succession. Lamellibranchs of the genus Dunbarella, characteristic of Ramsbottom et. al's. Anthracoceras or Dimorphoceras phase 2 (5b, Text-fig. 2) - and common usually at top and bottom of thick R1c - R2 goniatite bands - make only very infrequent appearances in the E2c - H1 and R1a shale successions where bullions occur in the thicker-shelled goniatite phase. Thus, in terms of Text-fig. 2, it may be that in the basin during these intervals the maximum range of cyclical fluctuation was between the environments represented by the 6c and 5c phases.

The kind of model presented in Text- fig. 3 is a useful approach to interpretation of the complicated faunal-lithological situation encountered in the Namurian, but there can be little doubt that a two dimensional model involving only the variables depth and salinity will prove too simple to describe fully the features of the basin succession. For instance, it has been suggested that nature of the sediment-water interface may determine the appearance of the thin-shelled lamellibranchs and that the interface was unfavourable in the bullion environment. If the nature of this surface is accepted as the main control on the lamellibranch density, the Text-fig. 3 implies that favourability of interface is a direct function of decreasing depth. In fact nature of interface and ability to support bottom faunas may well vary independently of both depth and salinity. Conditions favouring both goniatites and crinoids are recorded by the E. bisulcatum s.s. band in Staffordshire and Derbyshire and as far away as Ireland (Yates, 1962). Goniatites, some brachiopods (Chonetes, Productus), and trilobites occur very widely in the British Isles at the Ct. nititoides horizon and in Staffordshire and E. Derbyshire brachiopods appear at one horizon with R. nodosum.

Though the Staffordshire-Derbyshire basin succession seems to show a restricted range of faunal phases (see above) it must be remembered that considerable thicknesses of argillaceous rock occur between the goniatite bands and the lamellibranch bands and yield no macrofauna. These "barren intervals" have still to be examined for microfaunas, but in view of the general absence of faunal phases indicative of reduced salinity it seems most unlikely that they can represent conditions as far to the left on the Text- fig. 3 model as the spat phase. More probably they record periods of depth reduction such as to inhibit the thicker-shelled goniatites, but without decrease in salinity sufficient to favour Anthracoceras and Dimorphoceras and without the establishment of bottom environments able to be colonized by the thin-shelled lamellibranchs.

Conclusions

Bullions are largely confined to goniatite bands of the E2b.1 to R1b portion of the N.E. Staffordshire - S.W. Derbyshire Namurian succession. Where found they yield valuable information regarding the sedimentation, fauna and environment of the goniatite bands. On the basis of bullion study, post-E2b goniatite bands are interpreted as the results of deposition of semi-pelagic silty clays, rich in Radiolaria and organic carbon. Initial porosities were very high and, though the sediments were probably oxygenated, the extremely tenuous nature of the sediment-water interface may have been an important factor in preventing colonization by the benthonic thin-shelled lamellibranchs or by any other intra-sediment or sediment-surface fauna. Small sponges are thought to have been contributed to the sediment from a plankton-epiplankton layer, which probably provided much of the finely divided organic carbon and may even have contributed the large vegetable fragments often found in an advanced state of decomposition. Of all sediments examined in the succession, these Radiolarian silty clays are believed to have accumulated at the greatest distance from a shoreline. Within this class of Radiolarian sediments it is possible that those containing Albaillella and Popofskyellum indicate maximum depth.

Sediments of E2b.1 goniatite bands are believed to have accumulated slightly closer to land. Radiolaria are infrequent or absent in the sediments and the increased detrital quartz fraction often shows lamination suggestive of fluctuating supply. However, initial porosities were at least as high as those of the richly Radiolarian deeper water sediments, and conditions appear to have been equally inimical to benthonic faunas.

Acknowledgements

The material used in the present study was collected during a stratigraphical-sedimentological survey carried out while the writer held a D.S.I.R. Research Studentship. For invaluable help with palaeontology during this stage the writer is indebted to Dr. W.H.C. Ramsbottom. X-ray work on the bullions was made possible by a grant to purchase equipment from the Scientific Research Council: a full account of work carried out under this grant will appear elsewhere. For assistance in Radiolaria studies the writer is indebted to Mrs. Helen Foreman, Oberlin College, Ohio; Prof. G. Deflandre, Laboratoire de Micropaleontologie, Paris; W.R. Riedel, Scripps Institution of Oceanography, California; and Mrs. Catherine Nigrini, Northwestern University, Illinois. Throughout work in Staffordshire the writer has been greatly helped by Prof. F.W. Cope's knowledge of the upper Namurian succession; and knowledge of the lowest Namurian and uppermost Visean derives from field work being carried out in collaboration with P.C.D. Cazalet, Bedord College. Final drafts of text-figures were made by M.J. Wright, Dept. of Geology, Keele University.

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Manuscript received 18th April, 1966