MID-DINANTIAN (CHADIAN) LIMESTONES IN GOWER

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The Chadian rocks of Gower comprise the Caswell Bay Oolite beneath and the Caswell Bay Mudstone above. The Oolite is generally a massively bedded 'pure' light-grey limestone of shallow-water origin, marking nevertheless not 'eustatic' marine 'regression' but sustained subsidence of more than 40 m. In detail it shows much variation and includes macrofossil beds, some of crinoid-brachiopod-coral limestones, that indicate proximity to open-sea environments. It gives signs of rapid lithification, including contemporary channels cut into it.

Algal wisps and fragments, and algal veneers, are not uncommon in the formation but are a very minor feature of it, so that its terminal member, the Heatherslade Bed, is in great contrast: as an algal sheet, stromatolitic and spongiostrome, the bed formed a carpet over perhaps the whole of Gower, and probably continued to east and to west for many kilometres.

A non-sequence above the Heatherslade Bed is indicated by a breccia, haematite-stained, with pseudomorphs after gypsum, interpreted as a desiccation breccia.

The Caswell Bay Mudstone, the breccia its basal member, reaches a thickness of 13 m. It is a very mixed group of rocks, greatly contrasting with the Caswell Bay Oolite in an association of calcilutites, pellet rocks, algal layers, pisolites, 'impure' oolites, and gypsiferous and sabkha-type sediments, in most of which silt-size detrital quartz grains, almost wholly absent from the Oolite, are common. A description of the rocks as 'lagoonal' is more or less appropriate, but the very rapid lithological alternations in laminar sequence imply a fluctuating multiplicity of controls needing more refined analysis of the sediments than is offered by 'lagoonal'. Fossils, although abundant in the formation, are in restricted facies; but recurrent thin layers and pockets, and more widely scattered fragments, of crinoids and brachiopods, among the laminae otherwise 'lagoonal', again point to proximate open-sea sources; and although the rocks are of very shallow-water intertidal or supertidal origin, their sustained accumulation points to an accordance of sedimentation with subsidence, and not to 'eustatic' marine 'regression'. Pre-Arundian slumping is repeated at several horizons in the formation, some of the slumped masses incorporating exotic corals carried in from neritic sources.

A palaeogeography of the stratigraphical changes is organized in terms of a fluctuating depth of sedimentation (within a narrow range) and of access to open sea in a bank or shelf environment undergoing slow subsidence. The great differences between the Oolite and the Mudstone cannot be explained simply by 'internal' differences in rock formation, but they may well reflect gentle tectonic movement hinted at by the Heatherslade Bed and the immediately succeeding non-sequence, and by the intraformational slumping in the Mudstone.

The Chadian sequence is abruptly terminated by Arundian overstep, demonstrated by pre-Arundian erosion, a basal Arundian breccia, visible unconformity, great contrasts in lithology, and the fossils. A reconstruction of the form of the overstep suggests gentle uplift to the south of Gower, in anomalous tectonic relation with the generalized palaeogeography of Dinantian sedimentation in South Wales.

I. Rock formations

The conditions of deposition of most of the Dinantian limestones of Britain have for the greater part been discussed hitherto only in general terms and have been set in a context of stratigraphical evolution with at best only generalized approximation. Certainly in the South-Western Province, of the Bristol–Mendip area and South Wales, there has been little advance in a formal sense, except incidentally in a few local studies, beyond the pioneer work of Dixon (1921) and Reynolds (1921) in giving a systematic account of the detailed petrology of the rocks and of the intrinsic evidence provided by rock type of the circumstances and processes of sedimentation in a great variety of carbonate environments. The mid-Dinantian rocks of the 'Avonian' suite, comprising in a comparatively small thickness many kinds of biogenic and bioclastic limestones and evaporitic oolites and calcilutites, are particularly informative in the evidence they provide on depositional events and on the corresponding palaeogeography that is to be interpreted from them. (See George 1972.)

The several kinds of limestones of the Chadian Stage in Gower fall into two formations, the older the Caswell Bay Oolite, the younger the Caswell Bay Mudstone. The Oolite was formerly referred and continues in general terms to belong to the *Caninia* Oolite, widely developed under a variety of names in the Carboniferous Limestone of the South-Western Province: for many years it was placed in the Lower *Caninia* (C_1) Zone of the Avonian Series. The Mudstone is the local representative of the Calcite–Mudstone Group, the lowest formation of the Upper *Caninia* (C_2S_1) Zone of the Avonian Series, recognized over much of South Wales. Despite earlier views of their being Tournaisian in age, both formations are now known by their fossils, notably the foraminifers, to be early Viséan (V_1), and in recently introduced classification their allocation to the Chadian Stage results from the terms 'Avonian' and '*Caninia* Zone' being subsumed or abandoned. (See Strahan 1907, p. 15; Dixon & Vaughan 1912, pp. 482 *et seq.*, 497 *et seq.*, 511 et seq; George 1970, pp. 63–64; Stephens 1973; Conil & George 1973; George 1974, pp. 95–99; George *et al.* 1976, pp. 17–18.)

The Caswell Bay Oolite is a lithologically prominent suite mainly of clean massive light-grey limestones, conspicuous at outcrop, reaching thicknesses of 40–45 m in Gower. It is in abrupt contrast to the darker thinner-bedded altered crinoidal limestones of the underlying Langland Dolomite (formerly the *laminosa* Dolomite of the Penmaen Burrows Limestone) its contact with which may be non-sequential.

The Caswell Bay Mudstone, locally reaching 13 m in thickness, is a mixed suite of dark thin-bedded algal-rich limestones, calcilutites, and calcareous mudstones and shales, very different in general appearance and rock type both from the underlying Oolite and from the overlying massive bioclastic High Tor Limestone, rich in a neritic fauna of crinoids, brachiopods, and corals, of Arundian age. Its characters and its inferred conditions of deposition were well summarized by Dixon (in Dixon & Vaughan 1912, pp. 513 *et seq.*). (See figure 1.)

Like many other Dinantian limestones of the province, the rocks of the Oolite and the Mudstone have suffered diagenetic changes. All aragonite is converted to calcite. The filling of voids by secondary calcite is almost universal, and coarse spar in some of the rocks obscures or wholly replaces original constituents and depositional fabrics. Dolomitization is locally highly destructive: dolomite rhombs, or an interlocking mosaic of saccharoidal crystals, may transform rocks on a large scale, so that altered Oolite cannot always be readily distinguished from Langland Dolomite. The incidence of dolomite being highly variable over short distances, the implication is that diagenesis was mainly or wholly 'subsequent' ('subsequent' to include also 'pene-contemporaneous', as taking place after sedimentation was completed within however short a time); and dolomitization receives only incidental comment in an analysis of the sequence, and of the modes and environments of deposition, of the rocks as primary sediments. Silicification, on the other hand, is uncommon: small authigenic quartz crystals may occasionally be seen in the Oolite, and there are small patches of disseminated chert in both formations, but chert nodules are absent, or at best minute.

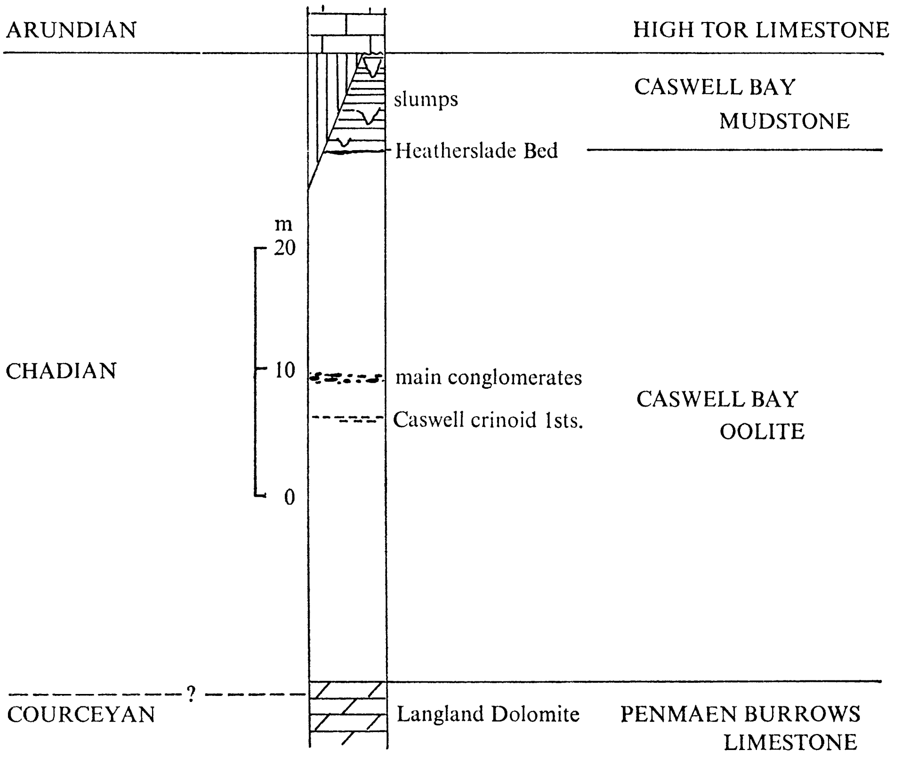

FIGURE 1. Generalized sequence of the Chadian rocks in Gower.

The Oolite and the Mudstone are repeatedly well exposed in outcrops along the south-Gower coast, notably between Worms Head and Fall, and between Three Cliffs Bay and Langland Bay; and there are outcrops of significance at Spaniard Rocks and Froglane in northwest Gower. Inland, the formations run for many kilometres in outcrops on the flanks of the Gower folds (see George 1940, pl. viii), but exposure over most of the ground is poor or nil because of a cover of glacial drift. In the westernmost outcrops the Mudstone is reduced in thickness, and locally is absent, through overstep by the High Tor Limestone. (See figure 2.)

II. THE CASWELL BAY OOLITE

1. *General characters*

(*a*) *Coarse-grained oolite*

The Caswell Bay Oolite in megascopic view gives an impression of lithological uniformity that is belied by closer inspection. In a typical coarse-grained sample (1 of plate 1) the ooliths are commonly well-formed spheres or ovoids displaying concentric and radial structures about

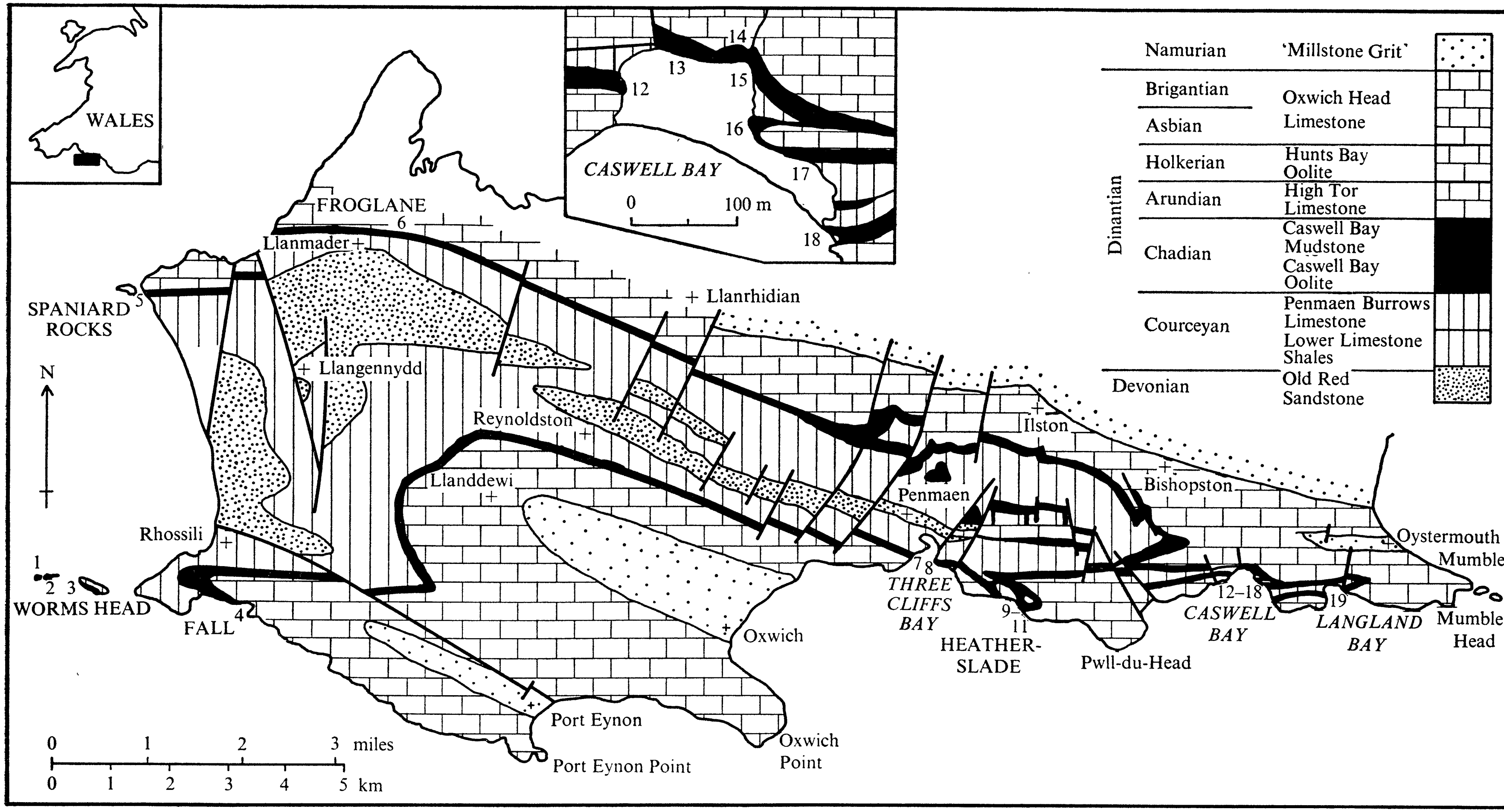

Figure 2. Outline map of the solid geology of Gower to show the distribution at outcrop of the Chadian rocks, and the location of exposures mentioned in the text. Amended after George (1940, pl. viii). The numbered localities are: 1, Outer Head; 2, Middle Head; 3, Inner Head; 4, Fall; 5, Spaniard Rocks; 6, Froglane; 7, Three Cliffs Bay, west side; 8, Three Cliffs Bay, east side; 9, mere immediately west of Heatherslade; 10, Heatherslade, west side; 11, Heatherslade, east side; 12–18, Caswell Bay (see inset map); 12, west side; 13, scarp to the west of the old engine house; 14, section behind the old engine house; 15, east side of the bay entrance; 16, near cave at west end of the Caswell syncline; 17, continuing from 16, southern flank of the Caswell syncline; 18, southernmost outcrop on the east side of the bay, on the southern flank of the Caswell (Langland) anticline; 19, Langland Bay, west side.

a core nucleus. The ooliths range up to and beyond 1 mm in diameter, occasionally exceeding 1.5 mm. Multiple growths as lumps and small grapestones are not uncommon, and, composed of three or four or five large ooliths, yet are admixed wi.h the single spheres amongst which they lie. The rock may be well sorted, ooliths of the same order of size being now preserved in a clear sparry matrix with every evidence of a 'community' or association of congeneric ooliths in any one bed or lamina. Rapid changes in modal grain size, and different degrees of grain-size selectivity, are recurrently displayed from one 'generation' of ooliths or one bed to another (see figure 3).

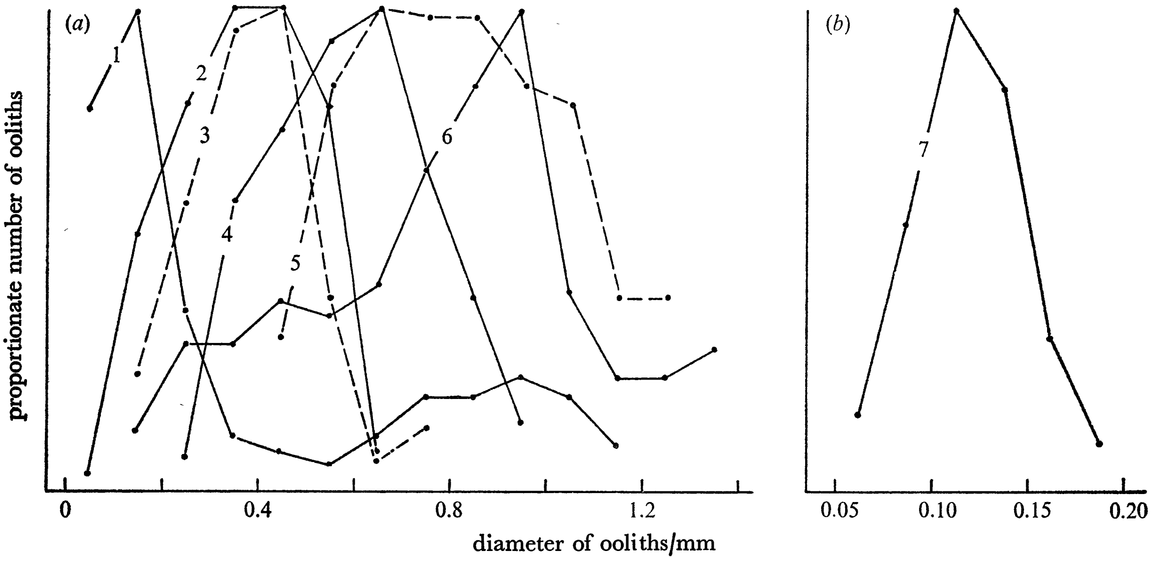

FIGURE 3. Histograms of the range of grain size in oolite samples of the Caswell Bay Oolite. Graphs 1–6 are of assemblages of relatively large ooliths; graph 7 of 'seed' ooliths. (1) About 1.8 m above the base of the formation, Caswell Bay (locality 17): the bimodal form of the graph reflects an admixture of two 'generations' of ooliths. (2) About 0.8 m below the Heatherslade Bed, Three Cliffs Bay (locality 7). (3) About 4.5 m below the Heatherslade Bed, Caswell Bay (locality 17). (4) About 1.2 m above the base, Caswell Bay (locality 17). (5) About 3.3 m above the base, Caswell Bay (locality 17). (6) About 1.8 m above the base (within a few centimetres of sample 1), Caswell Bay (locality 17). (7) About 11.8 m above the base, Caswell Bay (locality 17).

In many ooliths the nuclei are not readily identifiable, but when they are large enough they almost always appear to be of organic debris, not of terrigene grains. Crinoid plates, more or less abraded, are the main kinds, large coated specimens often comprising a notable proportion of the rock as of the ooliths. Fragments of brachiopods, echinoid spines, bryozoans, ostracods, and in some beds not uncommon foraminifers, are also oolith nuclei. A significant feature in many oolitic layers is the occurrence of fossil fragments, usually crinoid but also brachiopod and occasionally coral, much larger – they may reach 6–8 mm in length – than the ooliths of the matrix in which they lie, and lacking an oolithic veneer. They are a pointer to streaming of sufficient power to transport them, and they then suggest that the mean size of oolith in any layer is determined not solely by sorting as a function of current velocity but by the accident of available ooliths – a product of rate of growth of ooliths in a local bank of carbonate precipitation.

(*b*) *Fine-grained oolite*

In contrast to what may be regarded as a usual oolite, some of the beds are very fine-grained, laminae of contrasted grain sizes often being in sharp alternation not always in plane contact (see 2 and 5 of plate 1). These fine-grained layers may be very 'pure' both in containing few particles other than ooliths, and in being of narrowly uniform grain size (the ooliths of mean diameter of about 0.1–0.2 mm) (see figure 3). Such ooliths rarely have cores easily recognizable as of detrital origin, although many of them are not spherical but irregularly ovoid, and many of them appear to have no more than one or two enveloping films. They are regarded as 'seed' ooliths, but a graded series of ooliths transitional in mean grain size from fine to coarse is not always to be found, and the finer-grained ooliths commonly appear to be darker than the coarser-grained and to be different in kind.

(*c*) *Sorting*

Ooliths of individual layers, down to thin laminae, may be well sorted, with a unimodal distribution of narrow range in oolith diameter, and with voids between the ooliths occupied almost exclusively by secondary sparry calcite. But such 'purity' is exceptional, and most oolitic layers show an admixture of coarse and fine ooliths relatively poorly sorted with a patchily irregular distribution of varisized grains in various proportion, presumably as a product of shallow-water agitation and disturbed settling in a restless environment. (See 1 and 2 of plate 1; 2 of plate 2.)

In many rocks of medium to fine grain, large ooliths in great size contrast may be scattered through an incongruous matrix, or may form loose links of which the individuals are isolated but define a crude lamination, or may occur in such numbers as to form a layer a millimetre or two (an oolith or two) thick, intercalated between finer-grained layers. The implication of such alternating laminae is that during the steady accumulation of a self-contained 'community' of uniform ooliths, perhaps accordant in origin and history, a wash of coarse extraneous grains briefly 'contaminated' the local environment as a sign of contiguous tracts of differentiated oolith formation in the regional bank. (See 2 of plate 1; 3 of plate 3.)

Conversely, a relatively thick bed of coarse-grained oolite may include partings, each no more than a few millimetres thick, of fine-grained ooliths, wholly uncontaminated by scattered large grains; and in the change of grain size there may be developed oolith layers, some of them very thin laminae, not sharply defined by bedding planes but merging into one another, in an alternation implying differential velocities of streaming, or different 'generations' of oolith growth, or both.

In some rocks there is an admixture of coarse and fine ooliths in the one lamina, usually seen as a dominantly coarse-grained matrix of a 'community' of coarse ooliths in which the pockets are filled by finer ooliths. The texture is perhaps most often a product of contemporary incorporation, rather than of downward 'filtering', of an inwash into the openwork of the main kind of local deposit, the close definition and the 'purity' of the pocket not encouraging an inference that the grain relation is due to sea-bed churning and intermingling, unless there was a partial binding (perhaps mucilaginous) of the finer-grained material. In some beds there is a suggestion that the mixing is a bioturbid effect, and occasionally some of the pockets of fine grains show geopetal structures. (See 3 of plate 1.)

The interface between coarse and fine layers is usually precisely but not sharply delineated.

It may be plane, but it may also, without a mixing of grain sizes, be wavy or even convolute in contacts whose form was not destroyed by changes in velocity of transport or in source material; and whatever changes there were usually caused no interruption to the continuity of sedimentation.

(*d*) *Bedding*

The posts of limestone in the Caswell Bay Oolite are thick, up to tens of centimetres, sometimes up to a metre or more, and planes of parting are widely spaced and not obtrusive. Within each bed, however, the layering of the rock is well developed, manifest on a fresh face, and alternations in grain size or in constituents may recur in thicknesses of only a few millimetres. Such lamination is usually not picked out by weathering, the contacts between the laminae

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Description of plate 1†

Rocks of the Caswell Bay Oolite

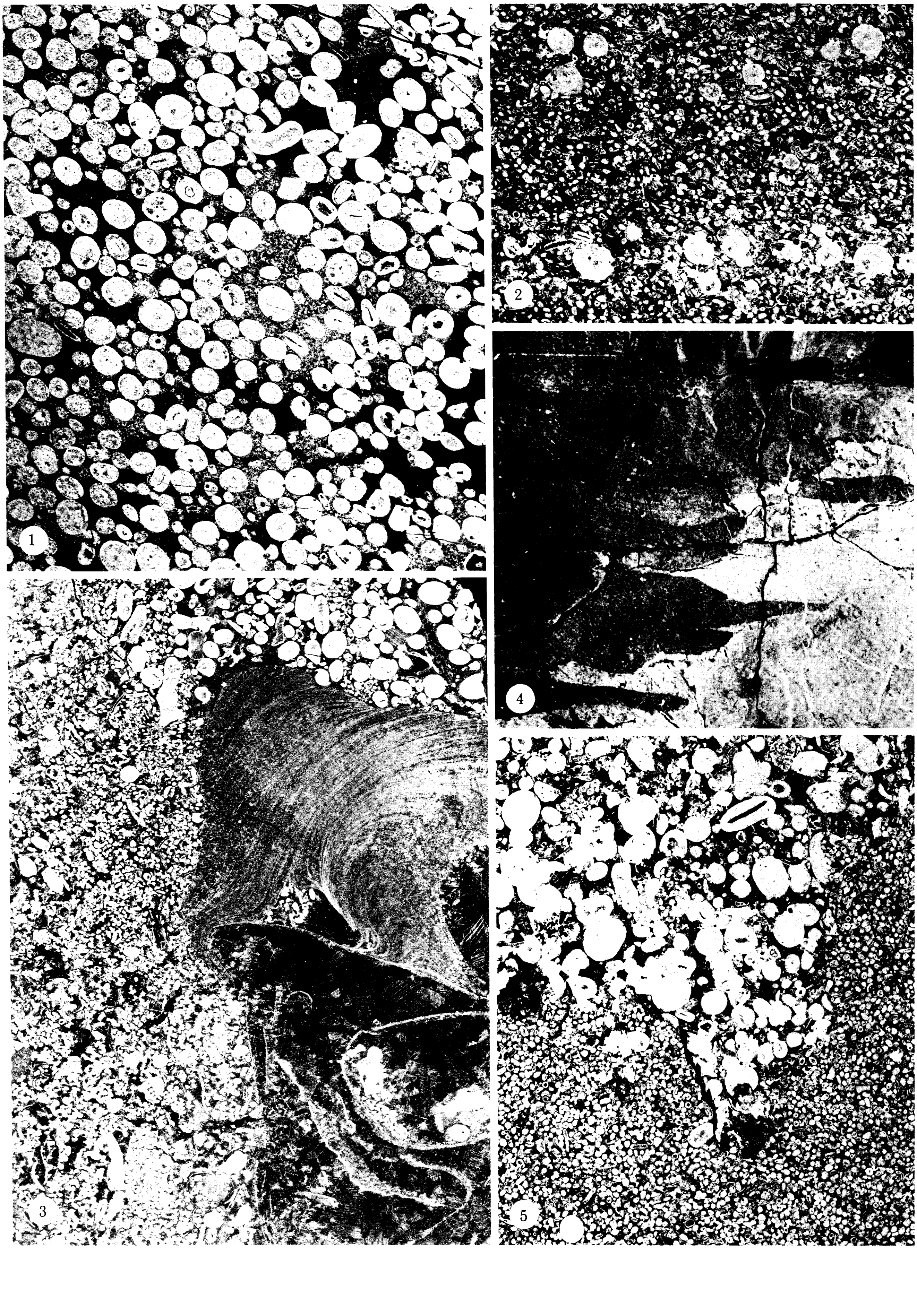
1. Clean well-sorted oolite, the oolith cores mostly small. Some of the cores are recognizably of crinoid fragments. Pockets of fine-grained detritus are not easily explained; they do not appear to be simply patchy fillings of voids in the primary oolite. About 21 m above the Langland Dolomite, Caswell Bay (locality 17). Magn. ×10.
2. Fine-grained oolite mainly of well-sorted oolith 'seeds', with laminae of scattered large ooliths. About 8 m above the Langland Dolomite, Caswell Bay (locality 17). Magn. ×10.
3. Mixed oolite with bioclastic fragments. Two main fields of ooliths are of contrasted mean grain size. The fragments include a brachiopod with a small stromatolitic growth attached. Pockets of trapped ooliths show geopetal structure. A small pebble of fine-grained oolite (bottom left) lacks obvious rim-bonding. About 5 m below the Heatherslade Bed, Caswell Bay (locality 13). Magn. ×5.
4. Interfingering of fine biomicrite (dark) and oolite (light). About 7 m below the Heatherslade Bed, Caswell Bay (locality 13).
5. Irregular contact between two layers of oolite of contrasted grain size. The relation is commonly to be seen. The upper layer, relatively poorly sorted with much bioclastic debris, is sharply distinguished from the uniformly fine-grained lower layer of 'seed' ooliths. The steep-sided small-scale channelling, and the abrupt contact with the flanking walls, suggest cementation of the lower layer before deposition of the upper. About 14 m below the Heatherslade Bed, Caswell Bay (locality 13). Magn. ×10.

† All the photomicrographs in the plates are negative prints. In the views, the scale is given by the hammer, the haft 25 cm long, the head 10 cm.

Description of plate 2

Rocks of the Caswell Bay Oolite

1. Fine-grained richly bioclastic limestone, oolitic in part, resting on a bed of coarse-grained oolite. The interface shows eroded and corroded ooliths in a compact matrix suggesting an algal bond, with depositional discontinuity in very shallow water. About 16 m below the Heatherslade Bed, Three Cliffs Bay (locality 7). Magn. ×10.
2. Conglomeratic oolite. The pebbles of oolite, derived (as their internal grain sizes show) from different sources, lie in a matrix of more or less uniformly grained ooliths. Most of the pebbles are rimmed with a dense cement, algal or evaporitic in origin. An oolite fragment near the middle of the photograph is without a bonding rim, like the flocks illustrated in figure 3. About 18 m below the Heatherslade Bed, Caswell Bay (locality 17). Magn. ×5.
3. Flocculous oolite. The very mixed rock, imperfectly sorted in multiple ways, has a dominantly biomicritic matrix, dark in the photograph, of fragments of crinoids, brachiopods, bryozoans, molluscs, ostracods, and foraminifers (notably earlandiids and endothyrids). Single ooliths 'float' in the matrix. The oolitic flocks are manifestly derived from different sources, some of large ooliths, some of fine 'seed' ooliths. The flocks, most of them without obvious cement, suggest mucilaginous agglutination at time of formation; but some have a peripheral rim, probably algal. About 4.5 m below the Heatherslade Bed, Caswell Bay (locality 14). Magn. ×10.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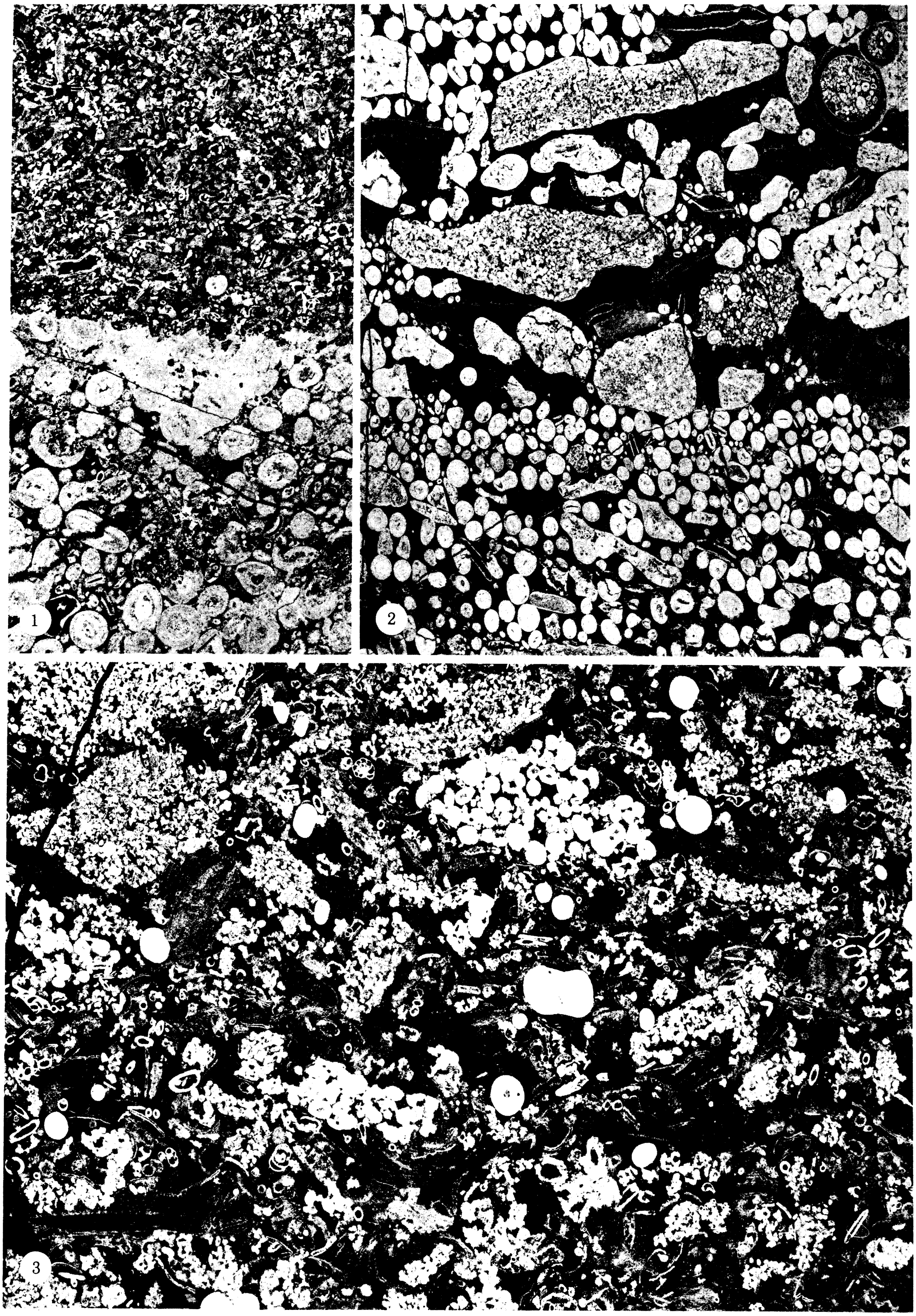
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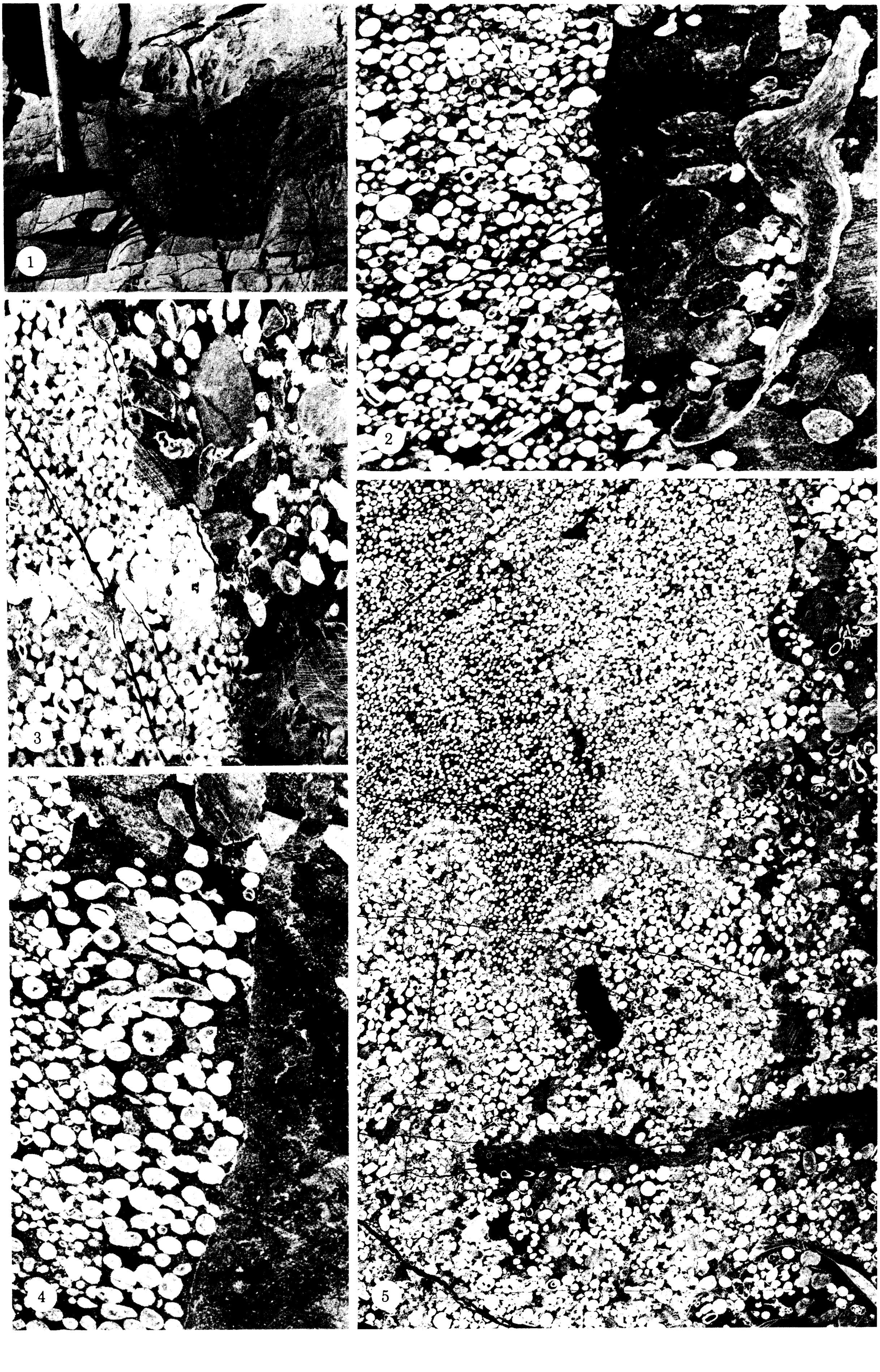
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commonly being not absolute but showing brief mergence. Some of the contacts, however, carry indications of turbulence or churned disturbance (see 3 of plate 1); and there may be abrupt junctions between one layer and the next with a suggestion of locally interrupted sedimentation to define a bedding plane. What is surprising in rock deposited under the shallow-water conditions of an oolite is the relative rarity of sharp contacts to indicate the vicissitudes of fluctuating environmental controls.

Repeatedly, however, cross-bedding and truncated bedding are signs of waves and variable currents (see figure 4), and of the transgressive over-riding of one oolite sheet by another in the conditions of deposition of (notionally conceived) oolite deltas and fans. Nevertheless, sustained series of aligned foresets have not been identified, the pattern of lenticles suggesting little more than current flow variable in direction and velocity, and perhaps also wave-scalloped surfaces. The preliminary observations of James & Thomas (1966) on the lineaments of cross-bedding seem to indicate dominant current flow directed towards the south, but the direction is

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Description of plate 3

Crinoid pockets in the Caswell Bay Oolite. All about 22 m below the Heatherslade Bed, Caswell Bay (locality 17)

1. Channel of coarse-grained crinoid-brachiopod-coral limestone cut into oolite. The coral colony to the right of the hammer head is of *Syringopora*. The white spots in the dark crinoid limestone are mainly cross-sections of *Koninckophyllum praecursor*.
2. Vertical wall of a pocket of crinoid limestone cutting into lithified oolite. A brachiopod shard illustrates the coarseness of grain of some of the bioclasts. The cleanly eroded face of the wall, individual ooliths transected, points to the very early lithification of the country rock. Mag. × 10.
3. Vertical wall of a pocket of crinoid limestone cut into lithified oolite. A lamina of large ooliths defines the bedding. Magn. × 10.
4. Vertical wall of a pocket of crinoid limestone cut into lithified oolite. The interface is complex, a first stage of crinoid influx having crinoid debris 'contaminated' by numbers of 'floating' ooliths, a second stage (after lithification of the first influx) being shown by a second clean-cut wall, and by a rarity of 'floating' ooliths. Magn. × 10.
5. Vertical wall of a pocket of crinoid limestone cut into lithified oolite. Along the upper part of the interface the erosion of the oolite is well displayed in a transection of the ooliths; but in the lower part induration of the oolite was incomplete, much of the 'intrusive' crinoid limestone carrying a merging abundance of ooliths, and a brachiopod fragment running without fracture from the oolite into the crinoid limestone. Within the oolite a highly scalloped interface between coarse-grained and 'seed'-grained oolite gives a hint of rapidly variable conditions of sedimentation. Magn. × 5.

Description of plate 4

The Heatherslade Bed: transition from underlying oolites

1. Voids in a lutite-bonded oolite. Incipient growth of an algal bond is shown by the sheaths of lutite wrapped around individual ooliths: in many instances, notably surrounding the central void, the lutite completely fills the pores between the ooliths. The central void, now preserved in (black) sparry calcite, carries threads and patches of (grey) calcite taken to reflect an original frame of algal tissue that occupied and determined the form of the void. Three Cliffs Bay (locality 7). Magn. × 20.
2. Compact oolite merging upwards into compact lutute. The rock, in three stages of accumulation, shows two early stages with ooliths in contact or more or less scattered, and an upper stage, sharply separated from oolith-free lutite by rapid 'transgressive' growth of algal tissue. The waves of algal growth in the faintly defined stromatolitic layer are indicated by the small pockets and streaks of calcite-filled pustules. Caswell Bay (locality 17). Magn. × 5.
3. A pocket of algal growth in oolite. The stromatolitic periphery, in sharp contrast to the 'enclosed' oolite of its substrate, merges by the incorporation of ooliths into the surrounding matrix and expands in the heart of the pocket into a lutite mass that carries a number of 'floating' ooliths. In the lutite of the left of the photograph are voids and pustules, now filled with sparry calcite, that originally were filled with algal tissue. Spaniard Rocks (locality 5). Magn. × 10.

anomalous in a usual regional palaeogeography of the province; and an analytically separated component of an easterly long-shore drift is also surprising in a topoclinal profile of an oolite bank.

Truncated laminae, with abrupt change in oolith size and rock type, repeatedly emphasize rapid lithification, the sharp and often highly irregular contacts of upper laminae with lower, sometimes very steep-sided, strengthening the evidence (see text-figure 4; 5 of plate 1). Exposure of layers to corrosion, probably in temporary subaerial shoaling, is indicated in some coarse oolites by the etched and finely pocked surfaces of the ooliths in some laminae; and interrupted sedimentation, a small-scale non-sequence, is to be read into the surface of a lower layer, lithified and corroded, on which rests in abrupt contact an upper layer of contrasted rock-type (see 1 of plate 2): such a discontinuity receives further emphasis when an algal band, identified in a close-packed lutite veneer, is a crust on the topmost ooliths of the lower layer, and confirms both early, almost contemporaneous, lithification and appreciable breaks in sequence.

2. *Chemical composition*

The oolites are mostly very 'pure' rocks in chemical and mineralogical composition, virtually not at all contaminated by exogenous material. Apart from ubiquitous sparry calcite, and the sporadic occurrence of dolomite (which is always seen in replacement texture, and may be completely obliterative as in the basement beds at Heatherslade), there is little sign of infiltrated material in the vast bulk of the rock, although vein haematite stains the sediments near faults and joints. Cherty replacement may locally be finely disseminated, and authigenic quartz crystals are occasionally present in insignificant proportion; but detrital quartz is very rare or absent.

Partial analyses by percentage weight of random samples serve to indicate the general 'purity' of the oolites:

locality	metres below top of Oolite	CaO	MgO	calculated carbonate	SiO_2
Outer Head (1)	0.5	54.00	0.56	97.61	0.34
Middle Head (2)	13	53.24	1.83	99.54	0.06
Inner Head (3)	16	51.64	2.16	98.89	0.24
Inner Head (3)	33	53.64	1.20	98.31	0.67
Inner Head (3)	39	50.88	3.05	97.27	0.65
Three Cliffs Bay (7)	15	50.80	3.22	97.67	1.22
Heatherslade (10)	19	50.28	4.41	99.56	0.03
Heatherslade (10)	22	52.84	1.38	96.90	0.19
Heatherslade (10)	24	51.80	3.01	98.86	0.48
Heatherslade (10)	42	53.40	0.54	96.40	1.82
Caswell Bay (17)	0.5	54.92	0.61	99.38	0.12
Caswell Bay (17)	18	54.40	0.54	98.23	0.49

3. *Fossils*

Macrofossils in the Caswell Bay Oolite (see Conil & George 1973, p. 325) are usually found only thinly scattered, but at several horizons they are richly concentrated in bands or lumachelles of large bellerophontids, large schuchertellids, and tabulate corals (*Syringopora* cf. *reticulata*, *Michelinia megastoma*). It is palaeoecologically significant that the massed fossils at any one horizon tend to be of only one kind. Some of the larger shells, and the larger coral colonies, are not likely to have been transported far, and point to nearby hospitable environments not unduly saline or evaporitic. In the bulk of the rock most of the larger fossils are found randomly distributed, but there is a link between concentrations of crinoid plates, horn corals, and telotreme brachiopods pointing to open-sea neritic influence that became strong, locally and temporarily dominant, in the mid beds of the Oolite (see p. 424). Corals other than tabulates are mostly rare but include zaphrentids (with *Fasciculophyllum omaliusi* and *Hapsiphyllum konincki*) and large caniniids (‘*Siphonophyllia gigantea*’); and among the clisiophyllids *Koninckophyllum praecursor* occurs in the lowest beds in Caswell Bay (locality 17) and increases in numbers upwards, notably in the upper beds of Worms Head (locality 3). In addition to the ubiquitous crinoids, small echinoid plates and spines are not rare and contribute to a fauna that is significant in allusive comment on the possibilities of migration or thanatocene transport into oolite terrain from proximate biotas. Of the brachiopods, *Laevitusia humerosa* and linoproductids are recorded, and spirifers are not rare.

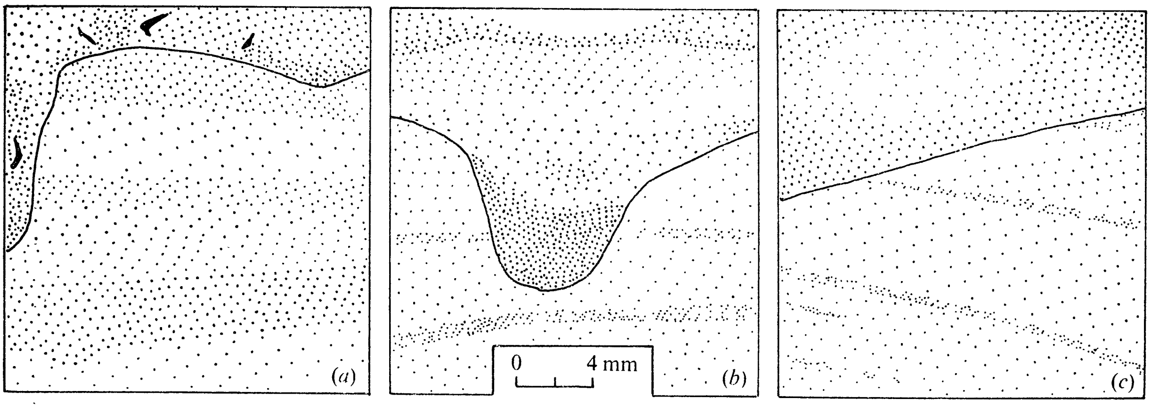

FIGURE 4. Diagrammatic illustrations of discordant bedding in the Caswell Bay Oolite of Three Cliffs Bay (locality 7), at (*a*) 12.0 m, (*b*) 7.5 m, (*c*) 12.3 m, below the Heatherslade Bed. The discontinuities (‘overstep’ and channelling) are usually accompanied by an abrupt change in lithology, coarser oolite resting on finer, and imply reactivation or realignment of oolite-fan distribution. The sharpness of the steep channel walls sometimes suggests early lithification.

The common goniatites, with *Kaypericyclus kochi*, in the topmost member of the formation in Three Cliffs Bay (locality 7) (a member, introducing the Heatherslade Bed, of other peculiarities also), are exceptional presumably as a floated-in association ‘accidentally’ concentrated in an oolitic matrix (George & Howell 1939); but they are not unique, muensteroceratid fragments being also found 6 m below the top of the formation in Heatherslade (locality 11). Nor are they a unique cephalopod occurrence in the topmost bed of the Oolite, for orthocone nautiloids, also in the only known association, occur in quite exceptional abundance in an analogous ‘accidental’ floated-in assemblage at the same horizon in the mere west of Heatherslade (locality 9).

Microfossils are very common in many beds of the Oolite. They are not obtrusively recognizable but in thin section they are seen some to occupy oolith cores, some to lie in the voids and interstices between the ooliths, and they may sometimes occur in such abundance as to separate the ooliths. The smaller kinds, calcispheres, tuberitines, earlandiids, coiled foraminifers, ostracods, are preserved as whole shells; but much of the material is not only finely fragmented as shards, probably in great part of brachiopod origin, but may be secondarily recrystallized into a calcite mosaic with a loss of detailed structure sometimes complete.

Algae are not prominent, but wisps, most of them not identifiable except as algal fragments, are recurrent from bottom to top of the Oolite, and kamaenids and other dasyclads, *Girvanella*, and occasional stromatolithic growths are found (see 3 of plate 1). *Koninckopora*, including *ducii* and *inflata*, ranges from the lowest beds, becoming in *inflata* increasingly common upwards.

While all the evidence (partly summarized in figure 5) confirms the allocation of the Oolite to the local equivalent of the Belgian V_1 and to the Chadian Stage, the fossils have further manifold significance in sedimentological analysis. Although the macrofossils are differentially

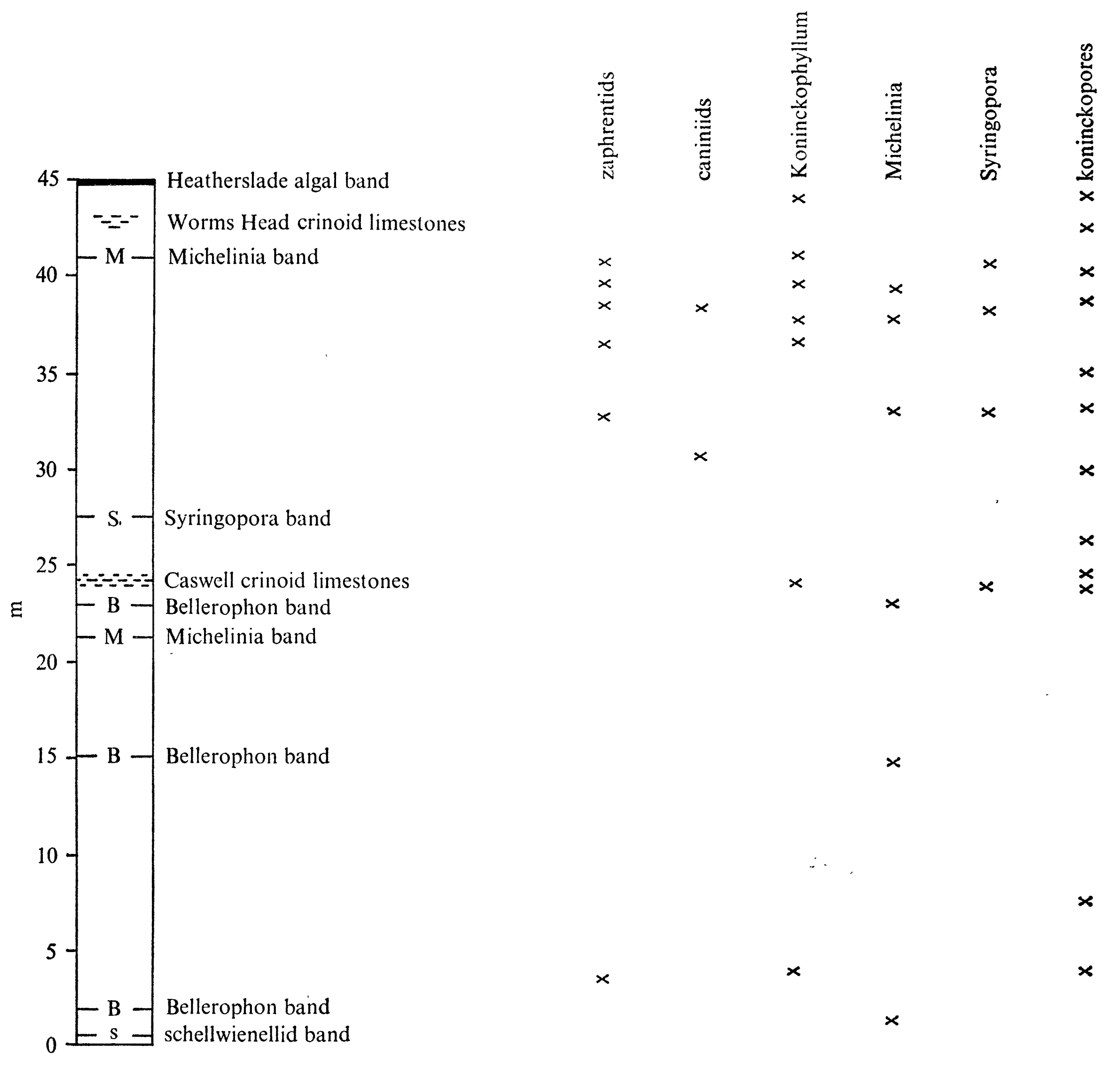

FIGURE 5. Summary generalized succession of the main fossil bands in the Caswell Bay Oolite, and of coral and koninckopore distribution. The diagram is composite, and there is notable lateral variation.

concentrated when they occur in bands (and may then be to a degree indigenous, signifying contrasted biotas), they are all of a kind typifying collateral limestones (now seen nowhere in Gower but, in Welsh development, only in southernmost Dyfed) in neritic facies; and in their forms, if not always in their species, they are members of a facies fauna characterizing the underlying bioclastic Penmaen Burrows Limestone, especially in its Tears Point Limestone, of Courceyan age, and the overlying Arundian High Tor Limestone. They point to the repeated influence of a 'normal' neritic marine environment at no great distance beyond present outcrops, from which they were derived by one process or another; and their presence in banks of oolite formation suggests that their comparative rarity in most beds, if it is not to be ascribed wholly to thanatocene influx, was due to their being as much swamped by the rapid formation and movement of abundant ooliths as discouraged by intolerable hypersaline conditions, although no doubt extensive evaporating flats and pans formed for much of the time ecologically unencouraging environments (not perhaps for some of the microfossils, which may have been persistently indigenous in the bank waters).

Analogy may be made with the distribution of fossils in many other oolites, including Recent oolites, in a demonstration that a facies contrast between biogenic and evaporitic rock type is lithologically flagrant but is without much importance in relation to depth of sedimentation.

4. *Microfossil laminae*

Microfossils, including shards, are scattered often in abundance through the Oolite, and may in local and brief concentration dominate sediment type, and in thin laminae, occasionally in beds centimetres thick, may be almost the only constituents (see 5 of plate 1). In weathered rock faces the laminae appear to be darker, buff rather than grey, and in fresh exposures more translucent, than the associated beds of 'pure' oolite; and in thin section they are seen to contain much clear calcite, their macroscopic appearance not being due to contamination by non-carbonate detritus.

The alternations of such laminae with 'normal' oolite are revealing comment on the conditions under which the Oolite as a formation was deposited, for the laminae are recurrent throughout its thickness, if more noticeably developed in its upper part. The laminae may be quite free of ooliths, or they may contain large or small ooliths scattered through the organic matrix, or they may be richly oolitic with ooliths becoming dominant. They reflect brief intervals of sedimentation each marked by a relatively abundant influx of micrograins as flotsam, carried perhaps in waters of unusual salinity as wind-driven floods, to interrupt the normal process of oolith precipitation in agitated sea.

The interlamination of oolite and biomicrite (microcoquina) is mostly planar or gently wedge-bedded; but it may be highly uneven and irregular, in swags and shallow depressions perhaps in accommodation of the finer sediments to a ripple-scalloped surface of oolite. A sharply defined interfingering of wedges of oolite and biomicrite, particularly well displayed in Caswell Bay (locality 13) through a thickness of a metre, is evidence not only of the strict contemporaneity of the two kinds of deposit in the closest but non-merging contact, but of the microenvironmental distinction of process as of sediment to be identified on a few square metres of Chadian sea-floor. (See 4 of plate 1.)

The kinds of fossils in the biomicrite are those filling the voids in a 'normal' oolite: they constitute a drifted association of planktonic calcispheres, foraminifers, and ostracods, and current-mixed benthic shards and fragments mainly of crinoids, echinoids, and brachiopods. Many of them are identifiable, earlandiids being particularly common; but much of the rock is recrystallized, original forms ghost-preserved or destroyed.

The oolith-free biomicrite laminae are thus in their 'purity' extreme members of a series ranging by proportionate increase in numbers of 'contaminant' ooliths into 'normal' oolite, and they are variant representatives of a rock-suite unitary (though composite) despite the wide differences between 'pure' biomicrite and 'pure' oolite: the ambivalence is confirmed by the rapid alternation, sometimes spanning no more than a few millimetres, of oolite and biomicrite, and by the continuity of sedimentation, without sharp bedding-plane distinction, from one lamina to the next. On the other hand, this is not to say that the two rock types in their end forms do not characterize contrasted depositional niches: it is to say that in the intimacy of their association they disclose an interplay of process that, as in Caswell Bay, may indicate fine oscillations, without change in depth, in pulsed current flow from different directions and from different immediately available sources of sediment.

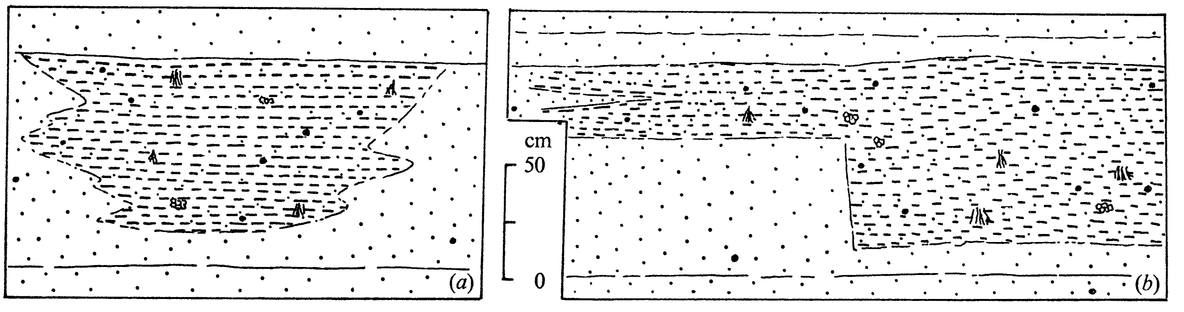

FIGURE 6. Diagrammatic representation of the development of richly crinoid-coral limestones in the Caswell Bay Oolite. (a) A pocket near the (local) top of the formation, Worms Head (locality 3). The boundary is relatively sharp, but not absolute, between bioclastic rock and surrounding oolite. (b) About 21 m below the Heatherslade Bed, Caswell Bay (locality 17). The lateral merging of almost 'pure' bioclastic rock into crinoid-rich oolite is gentle in places, but is sometimes sharply abrupt against a wall vertically cut into the oolite. The symbols are of *Koninckophyllum praecursor* (circles), *Syringopora* (threads), and *Michelinia* (polygons). Compare plate 3.

5. *Intercalations of neritic limestones*

Crinoid debris, common in the Oolite, usually occurs as the scattered plates, more or less abraded, of oolith nuclei; but in places and at certain horizons it becomes richly abundant to form the greater part of the rock. Notably in the upper beds in southwest Gower, well displayed on the Inner Head (locality 3), in which also corals (zaphrentids and *Koninckophyllum*) are relatively common, vaguely defined concentrations of such crinoid debris run for several metres laterally and descend with an uneven base for a metre or more into the surrounding oolite. They contain many ooliths and represent an admixture of the two kinds of source material.

The most spectacular of the crinoidal developments is to be seen in Caswell Bay (especially locality 13), where irregular pockets and elongate lenticles, a metre or more in thickness, lie some 20–22 m below the top of the Oolite: in their coarse grain and dark colour they stand out in scarp faces from the more smoothly weathered and lighter oolites. As on Worms Head and elsewhere, they pass laterally by admixture and a rapidly increasing proportion of ooliths into more 'normal' oolite without there being any sharply precise junction between the two kinds of rock (see figure 6). Locally, however, there is no transition and they occupy channels, excavated into a solidly bonded foundation of oolite, half a metre wide and as deep (see 1 of plate 3). The channel walls descend almost vertically, individual ooliths in the walls being smoothly planed by the cutting; and although there may be scattered derived ooliths in the channel limestones, the contrast between the bioclastic limestones and the oolitic country rock is almost absolute (see 2 and 3 of plate 3).

Grain size of the channel fragments is proportionately large, sometimes very large in coral colonies: the appearance is given of surge runnels in bedrock. Occasionally there are signs of repeated channelling, an earlier channel-fill having been cemented to the oolite walls before a second inrush cut into it to erode a second channel wall (see 4 of plate 3). The evidence is compelling of the exceedingly rapid lithification both of the oolite of the walls and of the first channel infill, and leads to an inference of very shallow depth of formation of the rocks in an environment promoting the precipitation of cement in intertidal or marginally subtidal zones.

The crinoid limestones, except for stray ooliths, may be almost wholly biogenic in their contents. They contain not only vast numbers of crinoid plates but also common corals (colonies of *Syringopora* and *Michelinia*, zaphrentids, *Koninckophyllum praecursor* in unusual richness, and caniniids on Worms Head), several kinds of brachiopods (athyrids, spirifers, chonetids, linoproductids), gastropods, bryozons, echinoid plates and spines. The association is characteristic of a mid-Dinantian neritic facies, and in aspect and in some of its species it is scarcely distinguishable from the crinoidal bioclastic contents of the Penmaen Burrows Limestone beneath or the High Toı Limestone above (although in the presence of dainellid foraminifers the beds are shown not to be Courceyan, and in the absence of permodiscid foraminifers not to be Arundian).

As open-water neritic sediments, having all the features of Dinantian crinoid-brachiopod-coral limestones hitherto taken to be the signs of a 'transgressive' sea in contrast to 'regressive' oolites, the crinoid limestones are anomalous in their depositional relations with the enveloping oolites. Without an invocation of a highly improbable and narrowly local deepening of the waters of sedimentation to accommodate a doctrinaire 'transgression' – a deepening wholly contradicted by the lateral passage within a few metres of the crinoid limestones into 'normal' oolite, and by the repeated erosion of the lithified channel walls – it must be supposed that the bioclastic rocks were deposited in no deeper water than the oolites, and that the bioclasts were available in concentrated abundance in and transported from proximate sources flanking the oolite banks in a composite regional environment characterized neither by 'regression' in the oolite phase nor by 'transgression' in the bioclastic.

6. *Conglomerates*

(*a*) *Coarse conglomerates*

Grains and small pebbles of conglomerate, up to a centimetre or so in larger diameter, are found randomly scattered through the beds of oolite. In being often larger than the ooliths in which they lie they point not only to 'contemporaneous' cementation, exposure, and erosion, but also to a 'sorting' of ooliths controlled not simply by grain size oı by 'energy' of transport, especially when in their texture they are themselves sometimes composed of coarse-grained ooliths, coarser than the ooliths of their matrix.

Pebble conglomerates, with pebbles reaching 15–20 cm in longer diameter, and closely packed in layers 10–15 cm thick, are comparatively rare: they are mainly concentrated in the mid part of the Oolite, about 20–22 m below the Heatherslade Bed; and although some are lenticular and none shows uniformity of development over many metres, so that they cannot readily be correlated from one exposure to another, they imply significant regional shallowing if only as shoaling on the crests of bars.

The pebbles are very smoothly rounded, usually as ovoids, the longer axis mostly aligned with the bedding. In any one conglomeratic bed they are usually not all of the same kind of oolite and indicate mixture from several eroded beds. Within each long lenticle of conglomerate, which may be traced continuously along the strike for several hundred metres, there is no significant change in average pebble size, but there may be some variation, not obviously systematic, between individual layers in any one lenticle.

The beds of conglomerate, signs of currents sufficiently powerful to roll the pebbles and distribute them widely, are not exposed in three-dimensional certainty to be plotted in bulk form; but they occur at about the same horizon from Langland Bay to Three Cliffs Bay, a distance of eight or more kilometres. They have many of the characters of 'beach' gravels, though they cannot well be ascribed to a regional 'beach' when they are found in thick oolite of a bank environment. An ancillary feature, concordant with such a source of gravel, is the opaque film of lutitic cement usually to be found wrapping each pebble – a film that, it is inferred, was a product of carbonate deposition by a mucilaginous coating of algal growth that swathed the pebbles and contributed to their bonding. (See 2 of plate 2.)

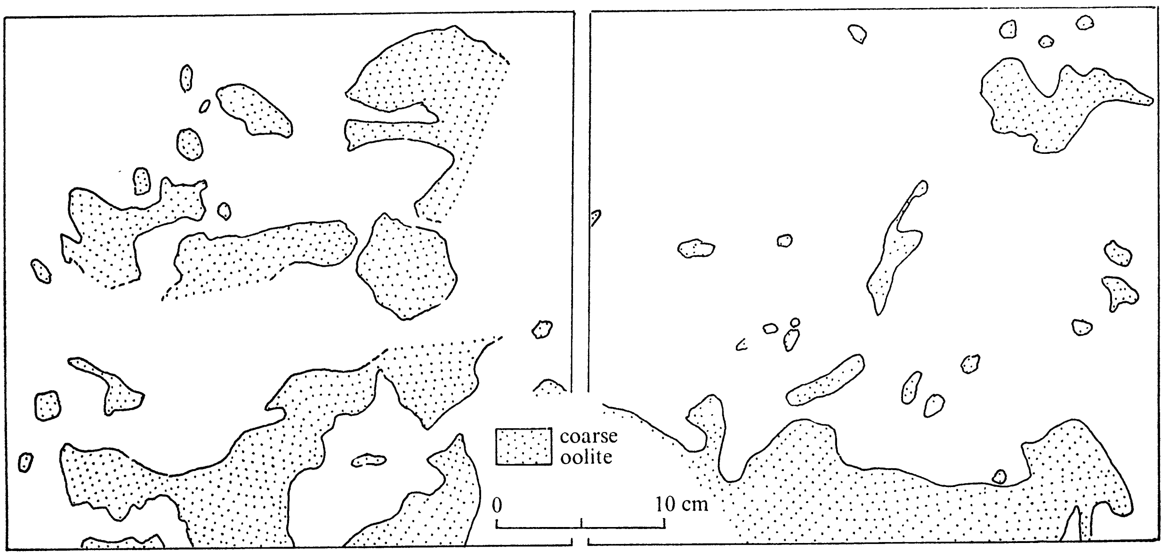

FIGURE 7. Patchy distribution and mottled appearance of 'pebbles' of coarse oolite in a matrix of finer oolite, interpreted as a sign of algal-agglutinated aggregates forming an unusual kind of conglomerate. Worms Head (Middle Head) (locality 2).

A second type of what is perhaps only with strain called a conglomerate is to be seen on Middle Head (locality 2), where about 20 m above the base of the formation irregular masses of coarse light oolite, only partially with well-defined rims, are distributed not in closely concentrated beds but patchily in a darker finer-grained oolitic matrix. The high irregularity of their shapes discourages their being called pebbles, and their wide scatter in the matrix poses problems of origin and transport that suggest a degree of mutual adhesion of the ooliths at time of formation, and of agitated and perhaps churned water in which they were deposited. (See figure 7.)

(*b*) *Flocculous microconglomerates*

Small segregated pockets of fine-grained ooliths in a matrix of coarse-grained oolite but themselves free of any 'contamination' by intermixture with large ooliths are not uncommon. They may reach several millimetres, occasionally centimetres, in dimensions and are not of particular interest as ordinary pebbles except that they appear to lack a recognizable envelope or other determinable bonding independent of the enveloping 'matrix'. They are anomalous in their 'purity', and it is not easy to imagine the manner of their erosion in a more or less distant source, and of their transport in an environment characterized by wave agitation and significant current flow, unless they were during movement held together by an algal envelope that decayed after their settling.

Even more difficult to explain are the heterogeneous associations of grains and pebbles of mixed origin that form fine conglomerates, generally in a biomicrite matrix, whose clasts under the microscope give the appearance of flocks in a recrystallized base (see 3 of plate 2). The clasts, manifestly detrital in their separate origins, are mixed in kind, some composed of large ooliths, some of 'seed' ooliths, some of solitary ooliths or lumps, some of algal wisps and fragments, some of individual foraminifers, some of finely granular constituents not readily identifiable. They are of various sizes, very poorly sorted, mostly not in mutual contact, indiscriminately set in the biomicrite matrix. Some of them give the impression, as minute pebbles, of partly rounded shapes without there being a recognizable envelope or internal bonding; but many of them are highly irregular, the marginal ooliths not corroded, despite their internal structure; and many of them having trailing threads, re-entrant angles, and a general appearance of disorganization as though they were held together during transport by weak and flexible bonds. Lacking an obvious cement, the clasts were yet carried as coherent units without disintegrating. They may then truly be regarded as clasts in being fragments of pre-existing sediments, but in their many kinds and odd shapes not as erosional remnants of lithified rock-in-place: the source sediments were still loose on the sea-floor at the moment of clast formation, or at least loose in not being held together by more than a pelogloeal veneer. It may be supposed that in other circumstances, perhaps of less washing by under-saturated waters, the precipitation of a carbonate bond would have been promoted to form crusted oolite pebbles, material for abrasive rounding; but even without the carbonate bond (and then without abrasion) the postulate of algal glutin suggests a cohesive veneer to hold ooliths and other grains together as they were transported, perhaps as flotsam or in suspension, to constitute the microconglomeratic mélange in the biomicrite base. Initially a necessity in the process, the glutin of the clasts, having served its purpose, decayed to leave the ooliths (and other detrital particles) in an association that contrived to preserve the forms of the clasts, and their distribution, in the supporting matrix.

III. The Heatherslade Bed

1. *Transition from the Caswell Bay Oolite*

A general uniformity persists through the Caswell Bay Oolite in the kind of oolitic rock found in the formation, and the lowest members are scarcely distinguishable from the uppermost in their lithology. The rock is variously sorted, and is 'contaminated' by extraneous elements of which coarse bioclasts and microfaunal laminae are pervasive and recurrent; but characteristically it is typified by the rocks illustrated in plates 1 and 2: its ooliths show well developed concentric and radial structure, small to submicroscopic nuclei, and a similarity of type in any one bed.

The top few centimetres of the Oolite, however, while also strongly oolitic, have a different association of ooliths and of accompanying particles, so that as a composite rock they tend to be readily differentiated, especially in thin section, from 'normal' beds of the Oolite. In particular, they become rich in algal growths, both in a relative abundance of unicellular oolith-like calcispheres of many kinds (see plate 13), and in a development of layered lutitic deposits impregnating and duly replacing completely the oolite rock, and then forming the terminus of the Caswell Bay Oolite as a formation. The transitional oolite, which contains a number of what appear to be abnormal ooliths that may imply organic participation in their formation, and the interlayered and overlying algal sheets, constitute the Heatherslade Bed.

The variety of constituents in the transitional oolite points to an environmental change in plankton sources; and while many of the planktonic organisms in their kind are to be found, scattered comparatively rarely, in the oolites below, their richness in the Heatherslade Bed is a sign of palaeoecological encouragement of which changes in salinity may have been a factor. The forms include calcispheres and many kinds of foraminifers: earlandiids very commonly, tuberitines, archaeosphaerids and diplosphaerids, and multichambered brunsiids, endothyrids, plectogyrids, dainellids, stacheiines, *Eotextularia diversa*, and *Palaeospiroplectammina mellina*. Small dasyclads and dasyclad fragments are not always identifiable, but they include kamaenids, coelosporellids, palaeocancellids, and koninckopores; and small fragments of codiaceans are recognizable. Of 'macrofossils' (always very small) crinoid plates and echinoid spines are common; gastropods occur; ostracods are ubiquitous; and brachiopod shards are not rare.

Lithological transition from 'normal' oolite is best seen in the bonding of the ooliths. The filling of voids of a stabilized oolite by sparry calcite was the almost-universal process of lithification in the bulk of the Caswell Bay Oolite; but in the transitional stages the spar was progressively anticipated by a filming of the ooliths by 'amorphous' algal lutite. In incipient stages

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Description of plate 5

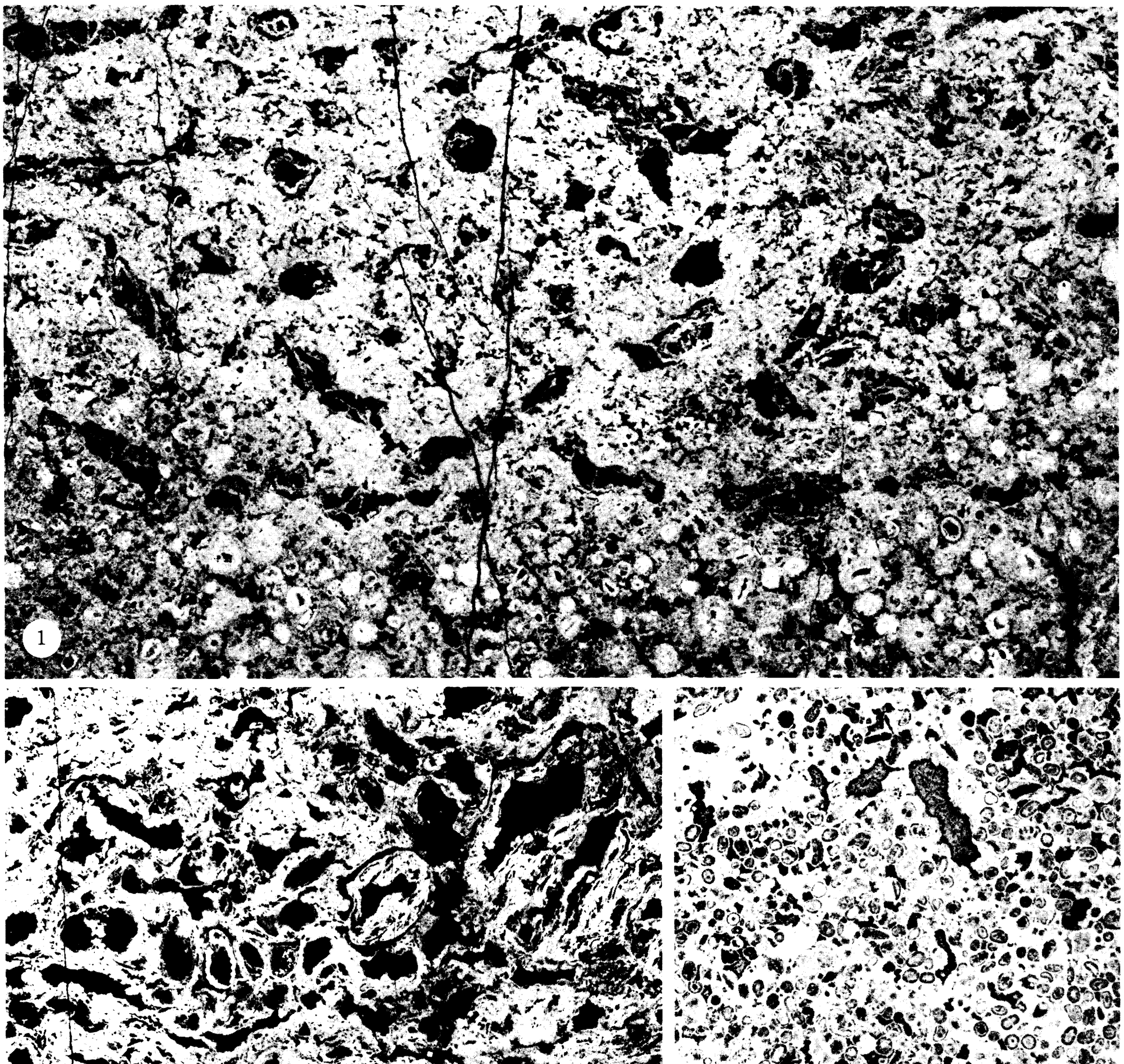
Algal growths in the Heatherslade Bed

1. Tubules in a spongioid matrix. A lower lamina of lutite-bonded oolite passes upwards into a mixed spongiostrome rock organized as integral or penetrant tubular cavities running through the minutely porous lutitic algal base. The tubules carry irregular partitions that define a 'ghost' frame of algal structure. Caswell Bay (locality 17). Magn. × 10.
2. Spongiostrome mosaic. The pattern of the spumous tissue leaves no doubt of organized structure of a kind unusual in 'normal' granular spongiostromes. There is transition to more compact algalutite in parts of the rock. Three Cliffs Bay (locality 7). Magn. × 10.
3. Nodes of algal growth in lutite-bonded oolite. The (dasyclad?) occupants of the cavities in the oolitic lutite have scalloped margins reflecting lining control. Spaniard Rocks (locality 5). Magn. × 10.
4. Spongiostrome and massive lutite with koninckopore. The faintly stromatolitic streakiness of the rock is broken by irregular lined cavities of (inferred) original algal tissue. The retention of a curved form by the koninckopore colony is a sign of the very gentle manner of incorporation of the skeleton as the lutite accreted. Pebble in the basal conglomerate of the Caswell Bay Mudstone, derived from the Heatherslade Bed, Caswell Bay (locality 17). Magn. × 10.

Description of plate 6

The Heatherslade Bed and the Heatherslade breccia

1. Algal mat on an oolitic base. The highly contorted primary growth of stromatolitic and spongioid lutite in relation to nodes in a lutite-bonded (and therefore algal-controlled) foundations are a reflexion of the manner of accumulation of the algal mat. Heatherslade Bed, mere west of Heatherslade (locality 9). Magn. × 10.
2. Broken lutite with scattered ooliths. The partings are interpreted as desiccation cracks that demonstrate the temporary exposure of the mixed sediment above water level. Heatherslade Bed, Caswell Bay (locality 17). Magn. × 10.
3. Desiccation breccia. The highly irregular and angular fragments (with re-entrants) mostly of lutite-bonded oolites of the Heatherslade Bed, lie in a finely granular matrix that includes small detrital quartz crystals. Porpthyroblastic pseudomorphs after gypsum are common, variously concentrated; most of them terminate at fragment borders. A fragment (white in the photograph), strongly ferruginous (secondarily?), also carries gypsum pseudomorphs. Immediately above the Heatherslade Bed, mere, west of Heatherslade (locality 9). Magn. × 5.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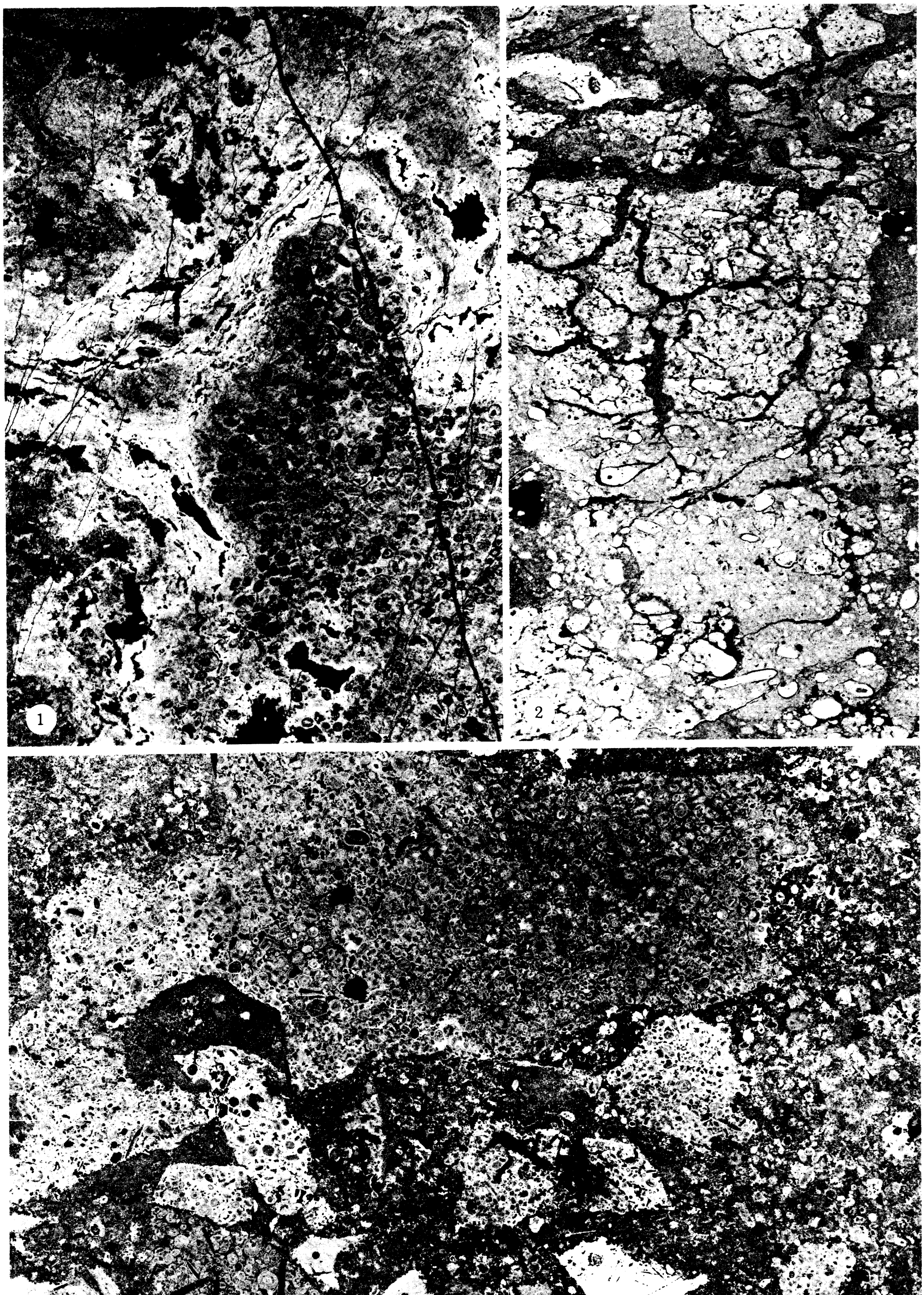
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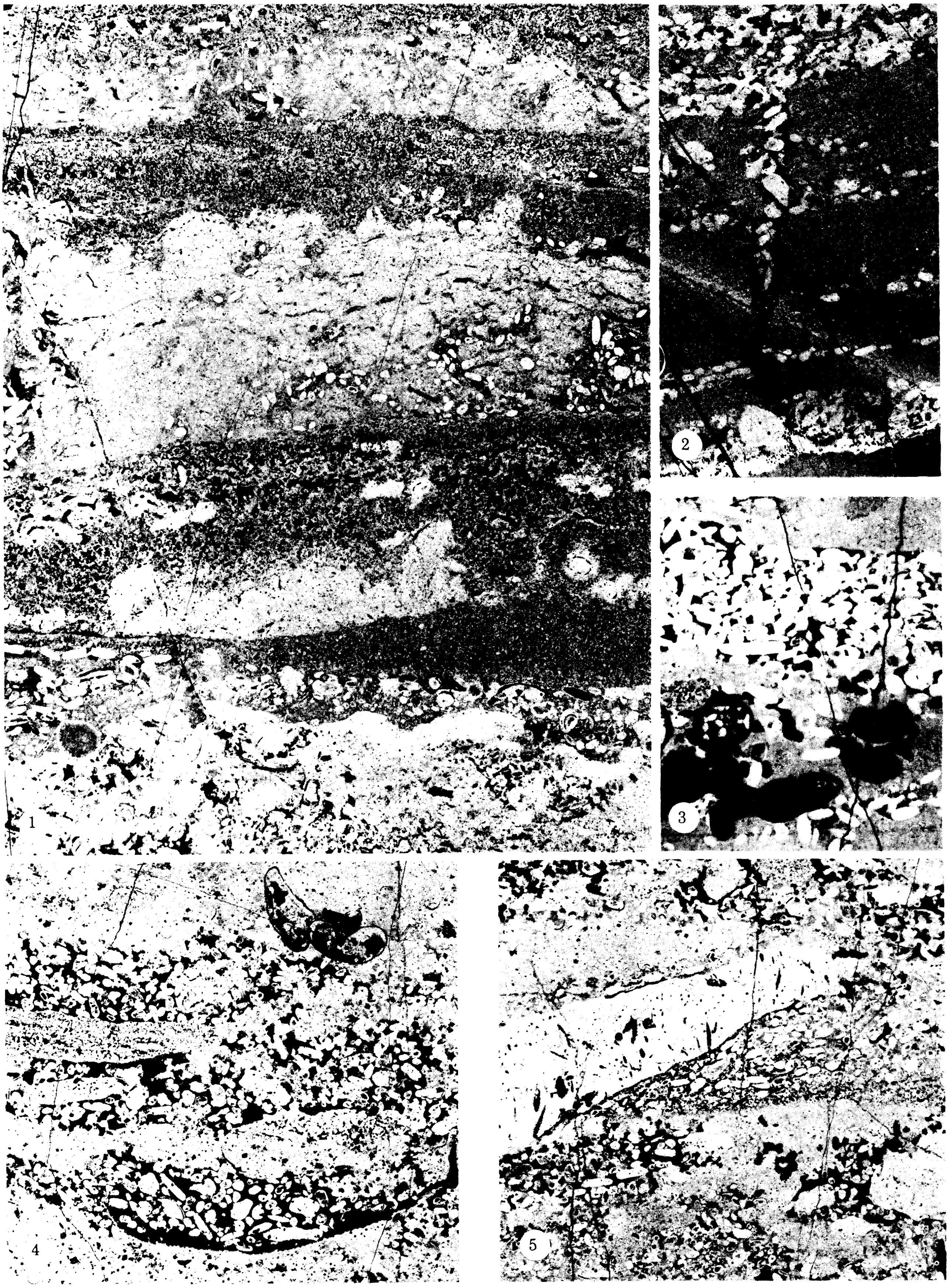
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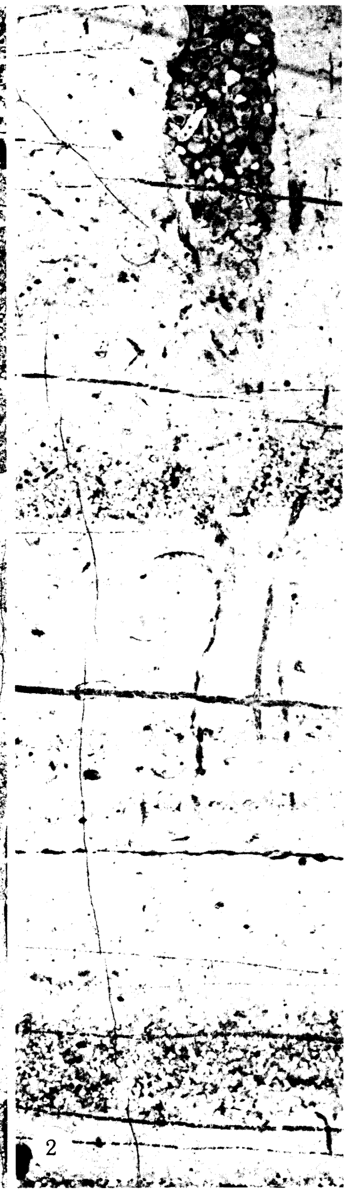

the film was very thin and the residual voids were spar-filled; but, with a thickening of the film to become a substantial wrapping, the residual voids become smaller as they were largely and then completely choked with lutite, and spar was reduced to nil, the end stage being a lutite rock whose ooliths were wholly embedded in an algalutite matrix.

The process of lithification by algal filming and algal cementation of the ooliths was strictly contemporary. In first stages no doubt films of algal growth penetrated the voids of a newly deposited loose oolite sand, to lock the grains in the process and to prevent or inhibit further grain movement; but in later stages of combined sedimentation and lithification rapidly expanding algal growth outpaced the accession of ooliths, which became 'diluted' in their distribution through the algal lutite; and in advanced stages the ooliths, no longer in the mutual contact of an oolite frame, became no more than particles trapped, as they were current-

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Description of plate 7

Pellet rocks of the Caswell Bay Mudstone

1. Rhythmic alternations in rocks with pellets. The section, spanning 14 mm, shows the multiplicity of rock types, and their irregularly bedded form, in some parts of the Caswell Bay Mudstone. Lutites with spongiostromes are the main lithological kinds, but the lamination is highly irregular, the spongiostrome masses discontinuous or highly uneven. The lutites may locally be 'worm'-bored, and may carry faecal pellets in bioturbid distribution, sometimes in scattered isolation, sometimes in tumbled masses. There are hints of minor discontinuities, the lowest laminae of an oolitic and pellet rock being abruptly floored by undulating algalutite with many ooliths. About 3.0 m above the Heatherslade Bed, Three Cliffs Bay (locality 7). Magn. ×10.
2. Lutite with pellets. The characteristic alternation of 'pure' lutite and pellet rock is interrupted by a burrow in which tumbled pellets are trapped, pointing to early lithification of both pellets and burrow-wall. About 5.8 m above the Heatherslade Bed, Caswell Bay (locality 17). Magn. ×10.
3. Alternations of pellet rock and pellet-free lutite. The variable distribution of the pellets is a sign of pulses of migration of the organisms that excreted the pellets. The absence of sediment from the empty spirorbid shells is to be noticed. The 'white bed', Caswell Bay (locality 17). Magn. ×15.
4. Faecal pellets in lutite. A mixed association of coarse and fine laminae illustrates the close links between pellets and fine lutite, hints of algal bonding, geopetal effects, and spirorbid habitat. About 1.2 m above the Heatherslade Bed, Spaniard Rocks (locality 5). Magn. ×10.
5. Faecal pellets and lutite. The eroded lutite fragment, with many 'worm' burrows, lies athwart the bedding, and formed a trap for pellets (and other grains) below, and a pavement for pellets above. About 1.2 m above the Heatherslade Bed, Spaniard Rocks (locality 5). Magn. ×10.

Description of plate 8

Sedimentary rhythms in the Caswell Bay Mudstone

1. Alternations of lutite and grain limestone. The 'amorphous' laminae of lutite are penetrated by a multitude of 'worm' burrows. The coarser intercalations, some of them showing strongly marked graded bedding, include ooliths, poorly sorted pellets, algal shards, and occasional larger fragments of 'worm'-bored lutite. A laminar stromatolite crosses the top of the section. About 1.2 m above the Heatherslade Bed, Spaniard Rocks (locality 5). Magn. ×10.
2. Alternations of lutite and laminae of grain limestone, in exemplary rhythmic sequence. A large burrow is occupied by ooliths and other coarse grains tumbled from a lamina above. About 1.2 m above the Heatherslade Bed, Spaniard Rocks (location 5). Magn. ×15.
3. Mixed lutites and grain limestones. The rapid alternation in rock type and lamination of some beds in the Mudstone is illustrated by the changes (in thicknesses of less than a millimetre) from the finer-grained limestones in the lower part of the sequence, and the coarser-grained limestones, with large ooliths, in the upper part. Small conglomeratic grains and pebbles include a fragment of lutite-bonded oolite like some of the rocks of the Heatherslade Bed, and shards of stromatolitic algal growths may (but with less certainty) have had a similar origin. A vesicular algal film is a brief intercalation; and a slipped tongue of lutite on the left contains a large and very straight 'worm' burrow. About 1.5 m above the Heatherslade Bed, Spaniard Rocks (locality 5). Magn. ×5.

transported, in algal filaments and mucilage and incorporated as incidental elements in the algal mat of tissue and lutitic 'dust' that formed the sea-floor.

The interrelations of ooliths and algal tissue are further illustrated by pockets of relatively large size running irregularly through transitional oolitic rock, that deceptively appear to be relics of voids in a consolidated oolite. They are too large to have survived without collapse if originally they were no more than voids without infilling of ooliths or other rock particles; and although they are now filled with secondary sparry calcite it is significant that they are mostly lined with dense algal lutite; and they are occupied by wraiths of a slender frame, outlined in irregularly tenuous partitions of fine-grained calcite, of what must originally have been an algal colony sufficiently massive to occupy and to sustain each cavity in the oolite rock at the time of oolite accumulation, the lithification of the rock by lutite cement being rapidly imposed to preserve the cavity before the algal tissue decayed. (See 1 of plate 4.)

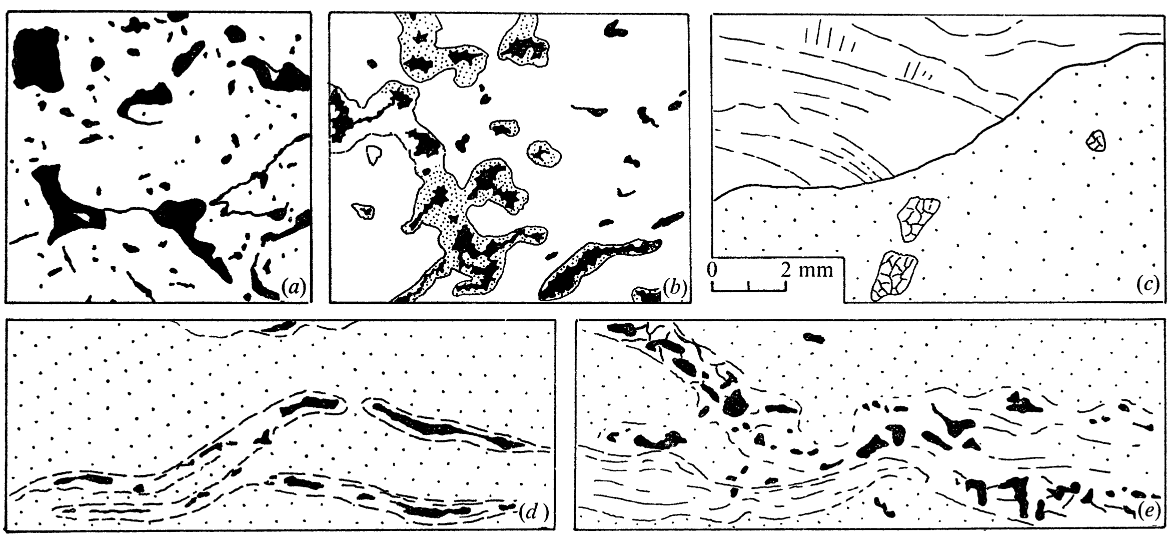

FIGURE 8. Types of algal growth in the Heatherslade Bed. (*a*) A compact lutite with an abundance of spar-filled 'vacuoles' of a variety of shapes and sizes regarded as relics of decayed soft algal tissue, Langland Bay (locality 19). (*b*) A compact lutite with vaguely formalized 'vacuoles' each lined with wraiths of algal structure having a bulbous inner surface and enclosing an inner core of secondary spar; from a derived pebble of the Heatherslade Bed in the basal conglomerate of the Caswell Bay Mudstone, Caswell Bay (locality 17). (*c*) Layered stromatolitic lutite resting with sharp 'unconformity' and 'overlap' on a floor of oolite, with incorporated small codiacean colonies (of *Ortonella*?), and (below) with small anticipatory polygonal frame structures in the oolite, Spaniard Rocks (locality 5). (*d*) Incipient films of stromatolitic growth, with cavitous central layers, as a first stage in the invasion and colonization of an oolitic environment by algal mats, Caswell Bay (locality 14). (*e*) Elaboration of an initial algal film in an oolitic context, with wraiths of partitions in the streaky lutite as signs of relatively complex algal structure, Three Cliffs Bay (locality 7).

Such intimate association between algal growth and oolite deposition is thus seen in a rock series that runs from oolite without algalutite bonding, through intermediate stages of increasing lutite between the ooliths and lutite with scattered ooliths, to lutite without ooliths in the uniformity of an algal mat. (See plates 4–6.)

Upward transition from oolite to algal mat is not smoothly continuous. Irregular partings of streaky algal growth, as lutite films a millimetre or less in thickness, may run through 'pure' oolite for short distances, as brief signs of a temporary halt in oolite accumulation that allowed a spread of algal growth to survive for a short time; and similarly, small algal-framed voids may be scattered in a 'normal' algal matrix. Locally, transition may be so abrupt that algal colonization of an irregular oolite substrate may be seen in the banking and lapping of lutite laminae against a minor rise of the oolite floor, with a hint of early consolidation of the oolite, and so of slightly interrupted sedimentation before algal transgression. (See figure 8.)

2. *Algal growths*

The upper part of the Heatherslade Bed is dominated by algal growths, mostly 'pure' and free of ooliths and other foreign contaminants (other than fine terrigenes). It is composed of algal-framed carbonate forming a sheet, less than 20 cm thick, of indefinite extension; it is found in all the Gower outcrops at the appropriate horizon. In macroscopic appearance the rock is dark and compact, fracture surfaces looking like opaque glass. Weathered, it usually shows signs of flexuous laminae, and its upper surface is mildly mammillated, but while its initial growths are sometimes pocketed in hollows in the oolite substrate, as at Spaniard Rocks (locality 5) and Caswell Bay (locality 16), it rarely has a nodular structure, and its growth did not come about by a contact fusion of enlarging nodules, still less of 'cryptozoan' or 'colleniid' pillars, but as a thickening carpet spread continuously over an uneven oolite sea-floor.

In thin section the rock displays complete transformation in texture, sometimes abrupt, from oolite with a lutitic matrix to a laminar or thrombolitic lutite in compact mass. There is then every appearance of growth or accumulation by stromatolitic trapping, and binding in place, of fine particles (compare Monty 1967; Gebelein 1969; Hofmann 1969) (with a surface penetration of the voids of a loose oolite floor by algal growth, and a cementation by algalutite, suggesting that photosynthetic precipitation of algal 'dust' may also have contributed substantially). The stromatolitic layering is commonly well expressed, but there is no spectacular development of regularly alternating dark and light laminae, or of finer and coarser laminae, and mostly there is almost no incorporation of recognizable detrital grains or plankton, and there are almost no adnate commensals; and some of the more massive rock has a singular 'purity', in uniform texture as in constitution, for such an accumulate.

The stromatolitic layers show great variation in detail. Compact laminated lutite is commonly interrupted by pustules and blisters between the laminae, that are now filled with sparry calcite. They presumably reflect pockets of soft algal tissue protected by rapidly lithified 'roof' from collapse on tissue decay; some of them incorporate faintly seen slender struts and partitions. In less obviously layered lutite the pustules may be more systematically arranged to give an impression of formal algal structure, the cavities partly occupied by differentiated calcite with inwardly facing bulbous projections (see figure 8). Sometimes ramifying threads of sparry calcite simulate the stromatactis of reef structure. The layering is rarely planar, even in contact with smooth substrate: it is commonly in waves of amplitude that may increase to develop highly convolute forms with deep re-entrants, taken to be nodes and tufts in the growing colony: a significant comment on circumstances of growth is the manner in which trapped ooliths, where they occur, follow the corrugations in the lithified mass (see 1 of plate 6).

Stromatolitic texture diminishes in some of the more extreme and internally controlled algal growths, which become spongid or spumous in organized ways and might appropriately be called spongiostrome (but they are referred only with some laxity to the comprehensive form-genus *Spongiostroma* of manifold expression). In details, however, the varieties of appearance, vaguely banded or layered, with patterns of mesh ranging from relatively large cavities with thin partitions, to tubules and branches running through a finely spumous matrix, suggest as many kinds of alga; and the stratified sheet of regional algal growth was certainly composite in the multiplicity of kinds of colony it contained. Identification of species or even genera is not possible except in a descriptive distinction between different patterns of textural habit; but although there are manifest contrasts between textures not simply attributable to density and compaction of growth, the bulk of the algal mat can most safely be ascribed to the activities of cyanophytes. Other identifiable algae, notably codiaceans, are rare in the 'purer' non-oolitic laminae, but small colonies of *Ortonella*, built into the compact or porous laminae, are occasionally to be seen while not contributing significantly to the rich mass of the algal sheet. (See plate 5.)

The Heatherslade Bed, rarely more than 20 cm thick, is recognizable from Spaniard Rocks to Langland, and, like the Caswell Bay Mudstone, is known to be absent only where outcrops disclose unconformable Arundian overstep. It thus has the form in regional extent of a persistent algal mat laterally continuous along the strike for not less than 25 km. Its dimensions across the strike are uncertain, but if the folds in Caswell Bay are unfolded, the mat must have been at least several kilometres wide. It is recognizable in its facies (although there is the possibility that it may be diachronous) 60 km to the west in Dyfed (see Sullivan 1966, pl. III B), and 30 km to the east in mid Glamorgan (see Dixey & Sibly 1918, p. 141), at its expected stratigraphical horizon. It is thus a palaeogeographical datum of high importance, for over much of South Wales it brings to a close the long season of oolite formation of early Chadian times in a deposit that, if analogy is to be read into the similar algal mats of modern seas, was formed in high inter-tidal flats of the local Dinantian environment. A confirmation of virtually nil depth of formation is provided by porphyroblastic pseudomorphs after gypsum that penetrate the ooliths of the Heatherslade Bed at Spaniard Rocks and Heatherslade.

3. *Desiccation*

The Heatherslade Bed is the uppermost member of the Caswell Bay Oolite. Resting immediately upon it are angular and subrounded fragments forming a breccia, of variable thickness (30 cm at maximum) but not everywhere present, that is a sign of non-sequence. The fragments are of a variety of sizes, reaching 3–4 cm in longer dimension, poorly sorted, large and small in haphazard contact. They are mostly derived from the Heatherslade Bed, and include algal-bonded oolite and massive stromatolite, and loose individual ooliths; but while they clearly have not been widely redistributed and have moved only short distances, they also include other rock types – bedded lutites and fine-grained limestones, and non-algal oolites, indicating a mixing of debris perhaps not all from the Heatherslade Bed. (See 2 and 3 of plate 6.)

The angularity of many of the fragments, some of which are highly irregular with re-entrant angles, and their poor sorting, suggest desiccation-fracturing of a rock exposed in a supra-tidal environment; and for a significant mid-Chadian interval the Heatherslade Bed was sufficiently uplifted to be exposed to erosion. Pervasive evidence of supra-tidal conditions is provided by a general haematite staining of the breccia: ferruginous impregnation may be no more than a superficial film on a fragment, but it may penetrate a fragment partly or completely, it may selectively stain the algal 'matrix' of a fragment while leaving the individual ooliths untouched, it may emphasize the internal structure of a fragment or may obliterate it, and it may leave parts of the breccia rock unaffected while staining neighbouring parts more or less deeply. Further signs of the contemporaneous environment is the development of gypsum (now seen as pseudomorphs) in single idiomorphic crystals, in radiating crystal sheaves, and in nodal concretions: the porphyroblasts cut through the rock matrix with indifference, but they tend to terminate at fragment margins and may in origin be both pre- and post-lithification of the breccia.

On renewed subsidence, the lithified breccia became the first member of the Caswell Bay Mudstone, an incidental mark of its stratigraphical affiliation being the occurrence of fine detrital quartz grains scattered through it.

IV. The Caswell Bay Mudstone

1. *General characters*

The Heatherslade Bed closes the cycle of sedimentation of the Caswell Bay Oolite. The succeeding Caswell Bay Mudstone as a rock group presents major contrast, its differences from the Oolite being radical in lithology and fossils, its inferred environments of sedimentation being 'lagoonal' rather than 'bank'; and Dixon had the strongest grounds for separating the one formation from the other in the zonal conventions of his time, and for his referring the one to the Lower Avonian and the other to the Upper Avonian in his views on stratigraphical relations. That the two formations are now united in the Chadian Stage is a product of novel criteria that ignore (and in principle are indifferent to) rock type and lithological sequence, and the incidental recognition of 'cycles' of change.

Nevertheless, the break between the two formations in Gower is not gross, and is not to be ascribed to marked deformational movements and transgressive unconformity: the Heatherslade Bed has a surprising continuity over the peninsula. The most direct evidence of non-sequence, above the desiccation breccia, is to be seen in a coarse pocketed conglomerate found near or at the base of the Caswell Bay Mudstone at several localities, most spectacularly in Caswell Bay (locality 17). The conglomerate, highly variable in thickness exceeding a metre at maximum, is composed of well-rolled boulders up to 15–20 cm in diameter, mostly of the Heatherslade Bed with some of a 'clean' light-grey oolite, proving contemporaneous exposure and erosion of the upper part of the Caswell Bay Oolite.

In local view the conglomerate may be looked upon as a remnant deposit of 'beach' gravels of only minor importance; but it has a wider significance when the rock relations are extrapolated to Pendine in Dyfed (20 km from Spaniard Rocks) where the Calcite-Mudstone Group (equivalent to the Caswell Bay Mudstone) is represented only by the Pendine Conglomerate (Sullivan 1965, pp. 295 *et seq.*) and rests with a pitted and channelled base on Courceyan rocks beneath, and to the north crop in Powys and Gwent (45 km from Langland) where the Calcite-Mudstone Group in the Llanelly Formation, persistently conglomeratic at its base, oversteps in extended outcrop the Courceyan Oolite Group down to the Lower Limestone Shales (see George 1954, fig. 8; George *et al.* 1976, fig. 5). The Caswell conglomerate is a witness to relative uplift followed by subsidence; and although the Caswell Bay Mudstone is persistently of very shallow-water origin and is very thin, it records a net subsidence of its floor, and thus a marine transgresssion, even if the subsidence was offset by equivalent sedimentation.

Summarized in brief description by Dixon (in Dixon & Vaughan 1912, p. 485), the rocks of the Caswell Bay Mudstone are highly varied, in contrast to the relative uniformity of the Caswell Bay Oolite (see figure 9); and on the finest scale, of the order of millimetres, they show rapid changes from one lithological kind to another. Many of them are lutitic, some of them 'porcellanous', almost 'amorphous'; but they also include coarse-grained beds of oolites and other grain limestones, and some of them are rich in algae of a number of kinds that contribute to the bulk of the rock (but there is no development of extensive algal pavements like the Heatherslade Bed). Some beds are gypseous in a sabkha-type sequence. Fossils are common in most of sediments, but of a suite called 'lagoonal' by Dixon: in addition to the algae, ostracods occur in vast numbers, calcispheres of several kinds abound and in some laminae form a great part of the rock, spirorbids are common, faecal pellets as pointers to unknown organisms are

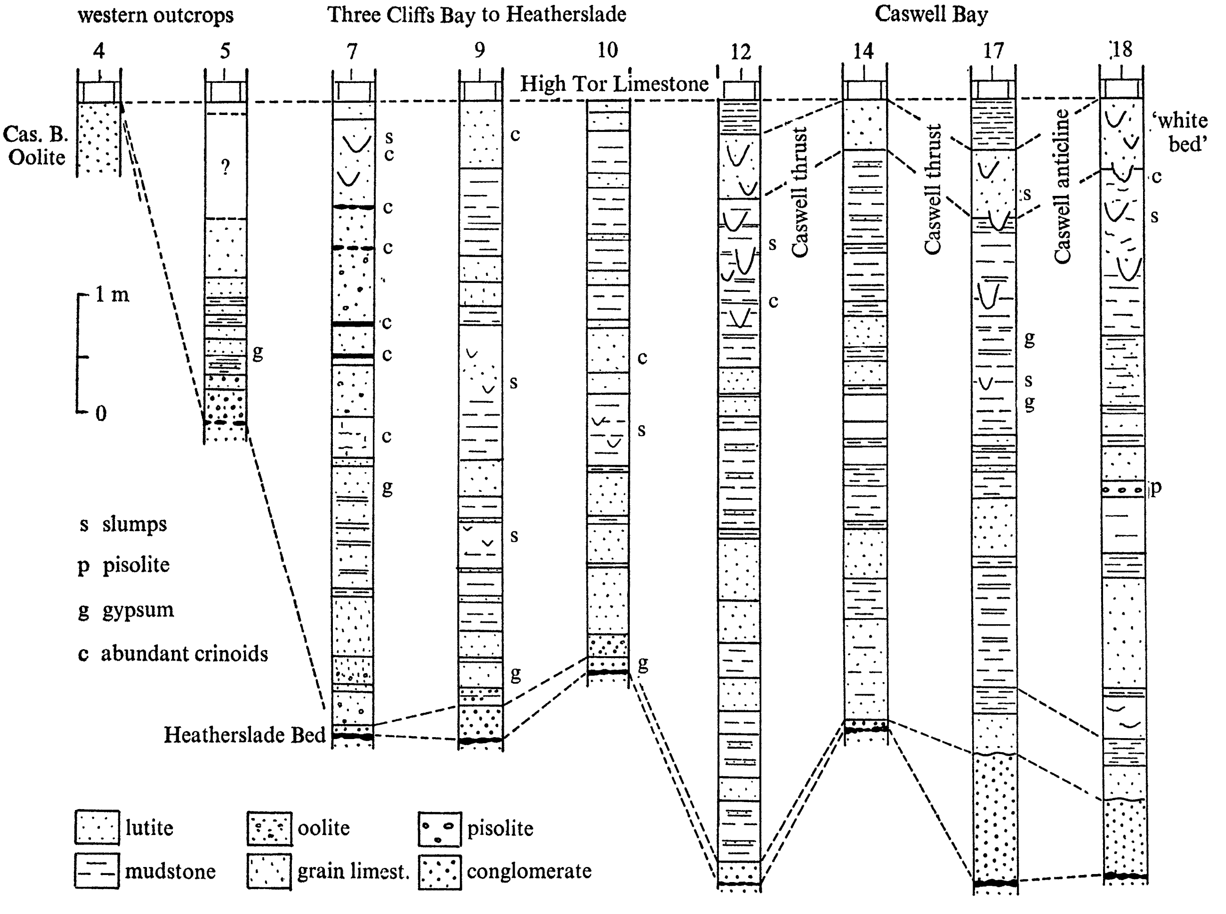

FIGURE 9. Comparative columns in the Caswell Bay Mudstone, much generalized, to show the variation in detail in a unitary rock-suite, with Arundian overstep in western Gower.

almost the only constituents of some lenticles, and burrows, slender and thick, are further signs of anonymous members of a rich biota. On the other hand, fossils of neritic facies, although rare in almost all beds, are not wholly absent: crinoid plates are scattered through some of the coarser grain limestones, shards of brachiopod shells are occasionally to be seen, and occasional corals have a limited occurrence. The name of '*Modiola* phase' for the formation – a use introduced by Dixon – is inappropriate, for although modiolids may teem on one or two bedding planes they are absent from much the greater part of the sequence.

A feature of almost all the beds is the 'contamination' of the 'depocentral' limestones by terrigenes. Even some of the 'amorphous' lutites and pellet rocks contain a fraction of non-carbonate detritus, a pervasive constituent being silt-grade angular quartz grains which may in some exceptional concentrations reach 5–10% of the rock; their wide and thinly scattered distribution suggests transport by wind. The occurrence of impurities is illustrated in sample chemical analyses:

locality	metres above Heatherslade Bed	CaO	MgO	calculated carbonate	non-carbonate residue
Spaniard Rocks (5)	0.2	54.00	0.75	98.00	2.00
Spaniard Rocks (5)	0.6	48.64	3.55	94.31	5.69
Spaniard Rocks (5)	0.8	35.16	10.94	85.76	14.14
Spaniard Rocks (5)	1.0	51.28	3.71	99.66	0.34
Heatherslade (10)	0.0	52.76	1.11	96.54	3.46
Caswell Bay (17)	6.6 ('white bed')	50.52	2.23	94.81	5.19
Caswell Bay (18)	3.0 (pisolite bed)	43.56	7.26	92.77	7.23

The formation is rarely more than 7 m thick, yet it shows great changes in detailed sequence along the strike, and it is usually difficult to trace any one bed, still less any one lamina, from one exposure to the next. Correlation, except in general terms, then becomes strained and as there are few signs of notably interrupted sedimentation it is to be supposed that the formation accumulated as a succession of alternating, inosculating, and laterally merging long and very thin lenticles, some of which may indeed be identified only on a microscopic scale.

2. *Rock types*

(*a*) *Calcilutites and pellet rocks*

The most notable of the many differences between the Caswell Bay Mudstone and the Caswell Bay Oolite is the recurrence of calcilutite as a major constituent of the Mudstone when it is almost completely absent from the bulk of the Oolite. At the same time, a mechanical measure of lutitic grain size is usually not practicable in simple application to the Gower limestones, not least because of the effects of secondary recrystallization; and 'lutite' is here used when the individual particles are not readily resolved under a medium-powered microscope. It is then a term that covers a variety of rocks contrasted in textural detail and inferentially contrasted in origin, and (as in other limestones) a genetic factor is desirably introduced into their description. Some lutites are singularly 'pure', 'amorphous' in appearance through tens of centimetres, but most contain a mixture of constituents, or are themselves merely the 'matrix' in a polygenetic rock.

The most 'pure' of the lutites, exemplified by the 'white bed' near or at the top of the formation in Caswell Bay (locality 17), are homogeneous rocks, almost without lamination. The 'purity' may on the one hand be attributed to the sustained settling of fine detritus transported by winnowing from mixed sources; but its uniformity, both laterally and vertically, with scarcely a hint of even the gentlest currents and giving the impression of deposition for relatively long periods in virtually undisturbed waters, may on the other hand suggest a provenance more convincingly located in immediate sources. As endogenes, such sediments may then be regarded perhaps as evaporitic precipitates (whitings) of hypersaline concentrates, more probably as organically formed carbonate mud in reflexion of the activities of algae and bacteria – 'dust' steadily accumulated effectively *in situ*, a drewite. An algal source is particularly preferred when the lutite contains faintly outlined palimpsests of algal form – more or less regular masses, defined by shaded patches in thin section, some of which reveal ghosts of algal structure – that are scarcely distinguishable in their texture from the matrix in which they lie. (See George 1972, p. 246.)

The uniformity of texture of a 'pure' calcite mudstone of endogenic origin may itself be disturbed by the activities of an indigenous fauna. Common direct signs of accommodation to a calcite-mud sea-floor is given by the occurrence of shoals of ostracod shells, sometimes preserved whole but most of them disarticulated (see 3 of plate 10; 6 of plate 15): they may help to emphasize a lamina, or they may lie in haphazard distribution in the lutitic matrix, or they may form small current-concentrated lumachelles, and they may act as umbrellas for trapped geopetal sediment. Spirobid shells, rarer but not uncommon, solitary or in groups of two or three, may be indifferently aligned in the rock; they are often uncrushed in reflexion of early lithification of the matrix. It is true that these several forms are not found strictly in mode-of-life position (the smaller of the vagile ostracods may well have been planktonic, and the calcispheres found in vast numbers in some of the lutites (see 1 of plate 10) were but passive immigrants) but their repeated abundance, even if they were tolerant of other environments and were members of other facies also, strongly supports their being indigenes in a hospitable carbonate-mud biotope.

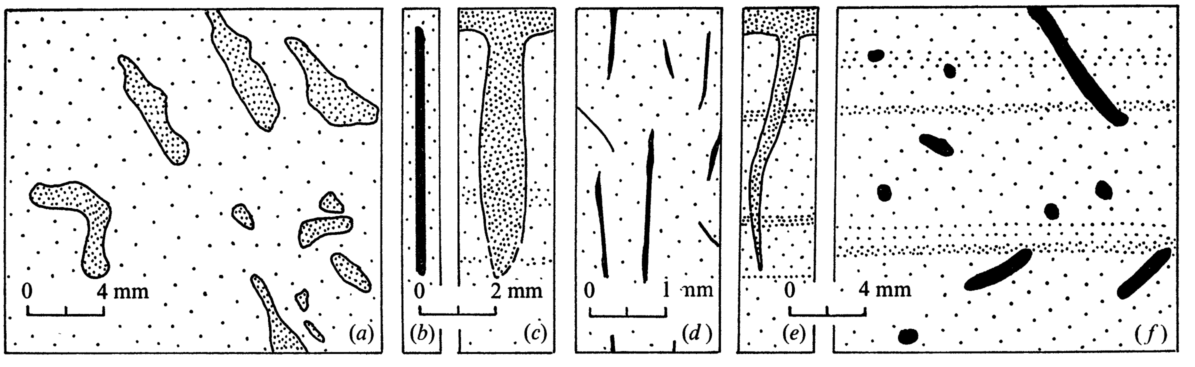

FIGURE 10. Diagrammatic illustrations of kinds of 'worm' borings and burrows in the Caswell Bay Mudstone. (*a*) Irregular borings, each filled with coarse detritus, in a lutite about 3.2 m above the Heatherslade Bed, Caswell Bay (locality 17). (*b*) A rectilinear boring, spar-filled, in fine lutite, about 1.5 m above the Heatherslade Bed, Spaniard Rocks (locality 5). (*c*) A relatively large burrow, filled with coarse detritus, in fine-banded lutite, about 0.2 m above the Heatherslade Bed, Spaniard Rocks (locality 5). (*d*) Fine spar-filled borings in fine lutite, about 3.0 m above the Heatherslade Bed, Three Cliffs Bay (locality 7). (*e*) Spar-filled burrow in pellet-rock lutite, about 5.8 m above the Heatherslade Bed, Caswell Bay (locality 17). (*f*) Spar-filled curved borings, in cross, longitudinal, and tangential section, about 0.4 m above the Heatherslade Bed, Spaniard Rocks (locality 5).

Unequivocal (although indirect) signs of a strictly local fauna are burrows and faecal pellets. Many of the 'amorphous' lutites are riddled with myriads of 'worm' tubes of the order of 0.1 mm in diameter, that, absent from interbedded coarser laminae and abruptly ending at laminar contacts, indicate bursts of repopulation in the microphases of sedimentation (see 1 of plate 8; 4 of plate 10). They are sometimes accompanied by larger ('worm'?) borings, some vertical (see 3 of plate 8), some irregular. In some instances the finer borings, and even more the calcispheres, are not evenly distributed through the matrix but are clustered or concentrated in irregular arrangement suggesting bioturbid disturbance, and sometimes they surround unstructured lutite that may be the remains of disintegrated algal tissue incorporated into the sediment. (See figure 10.)

Pellets, as undifferentiated round or oval grains in the limestones, are of widespread occurrence in 'matrix' of a variety of kinds; but segregated faecal pellets are particularly common in, and perhaps peculiar to, 'amorphous' lutite. They are elongate–oval in shape, of an order of size reaching 0.7–0.8 mm in length, 0.2 mm in diameter. In their constitution they are of the same texture and internally of the same appearance as the lutite in which they are found (and of which indeed they are little more than reorganized and shaped casts). The pellets, delicate structures held together on secretion only by mucilage, and vulnerable to distintegration in an agitated environment (the relatively still waters of deposition of the carbonate muds, to which they bear witness, being doubtless the reason for their exceptionally rich preservation), were lithified almost at the moment of formation to allow them to be incorporated as sedimentary grains and to be transported or otherwise moved (to become the infillings of burrows) as the muds accumulated. The organisms that excreted the pellets are unknown: pellet size suggests either 'worms' or molluscs, but although a single living individual may excrete many pellets, spirorbids are relatively rare in relation to the abundance of pellets, and no molluscan shells are found in the lutites. At times scavenging was thorough, 'all' the mud in the lutite being converted into a pellet-rock, a faecolite, in which the pellets are the only primary constituents and rest in a sparry matrix as a further instance of rapid lithification. (See plate 7.)

A smaller kind of pellet, not so surely faecal in origin and not so common (or not so commonly identified) is subspherical in shape and in its local abundance gives the appearance of a fine-grained oolite. It is of the order of 0.1 mm in diameter, and is found in thin laminae, evenly spread by currents, alternating with lutite. The effect, especially when there is no abrupt distinction between one lamina and the next, is of the rhythms of graded bedding (see 1 and 2 of plate 8).

Clear contrasts between 'amorphous' lutites on the one hand, and their direct derivatives on the other, are not so evident in other kinds of lutites when graining becomes obtrusive and discourages the use of the term 'lutite' except in convenient generalization. When the grains are recognizable, as detritus of one kind or another – organic-skeletal fragments are the most obvious – there is little difficulty in identifying the rock in its twofold nature as lutitic matrix incorporating immigrant exogenes, but in those kinds of limestones descriptively called grumous, sometimes vaguely clotted and flocculous, the lutite incorporates poorly differentiated material that may reflect stages in the disintegration or reconstitution of organic tissue, or conversely may reflect stages of aggregation, incipiently finely 'nodular', of constructive form. That some of the grumous clots may be of algal origin is suggested by recognizable algal forms in which structural differentiation is certainly to be identified in external shape and relations and in internal structure; but a merging of algal periphery with matrix, distinction breaking down, may add increasing doubt to interpretation, although the sedimentological significance of such limestones may not be totally lost.

(*b*) *Oolites and grain limestones*

There are no oolites in the Caswell Bay Mudstone that compare in their 'purity' and uniformity with the rocks of the Caswell Bay Oolite, and even in hand-specimen there is no likelihood of confusion between the two formations. Nevertheless, there are many oolitic beds in the Mudstone. They may be dominated by an abundance of ooliths, but most of them are poorly sorted, and almost all of them include numbers of detrital grains that may or may not be wrapped in an oolithic coat. Conversely, many grain limestones, some of them calcarenites, may include only few or isolated ooliths, or may lack ooliths altogether; and many ooliths are less signs of an immediate environment of an oolite bank than of available grains, like any other detrital grains, happening to contribute incidentally to a very mixed rock. The larger ooliths, reaching a diameter of 1 mm, have a 'normal' radial-concentric structure, and look like, some of them perhaps being derived, ooliths of the Caswell Bay Oolite. A few of them are, in groups of two or three, fused in small lumps. The cleaner oolites (and the fragmental limestones) have a sparry bond; but the burial of ooliths in fine lutite is not uncommon; and ooliths and faecal pellets may be found together in the same rock.

Even greater heterogeneity is found in the fragmental limestones. Some of them are properly called bioclastic; some contain wisps and pin-heads, occasional small nodules, of various kinds of algae; some are pellet rocks in which the nature of the pellets is not easily determined. 'Matrix' is sparry, or finely granular, or mainly lutitic. Many of the rocks appear as a confused mixture of a variety of constituents in a not clearly segregated base. The confusion, and the highly irregular churned appearance of the grain relations, indicate bioturbid structures; and although the organisms causing the churning are unknown, 'rods' several centimetres long and two or three centimetres in diameter, and chondritic burrows, are more positive signs in some beds, in which they may be abundant (see 1 of plate 15).

A common 'grain' or fragment in many of the rocks, usually larger or much larger than neighbouring grains, is algal. Algal sheets comparable with the Heatherslade Bed not being known in the Mudstone, the algal material is presumably a product of growth in immediately local waters, found in the fragmental limestones as torn-off and drifted remnants detached from

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Description of plate 9

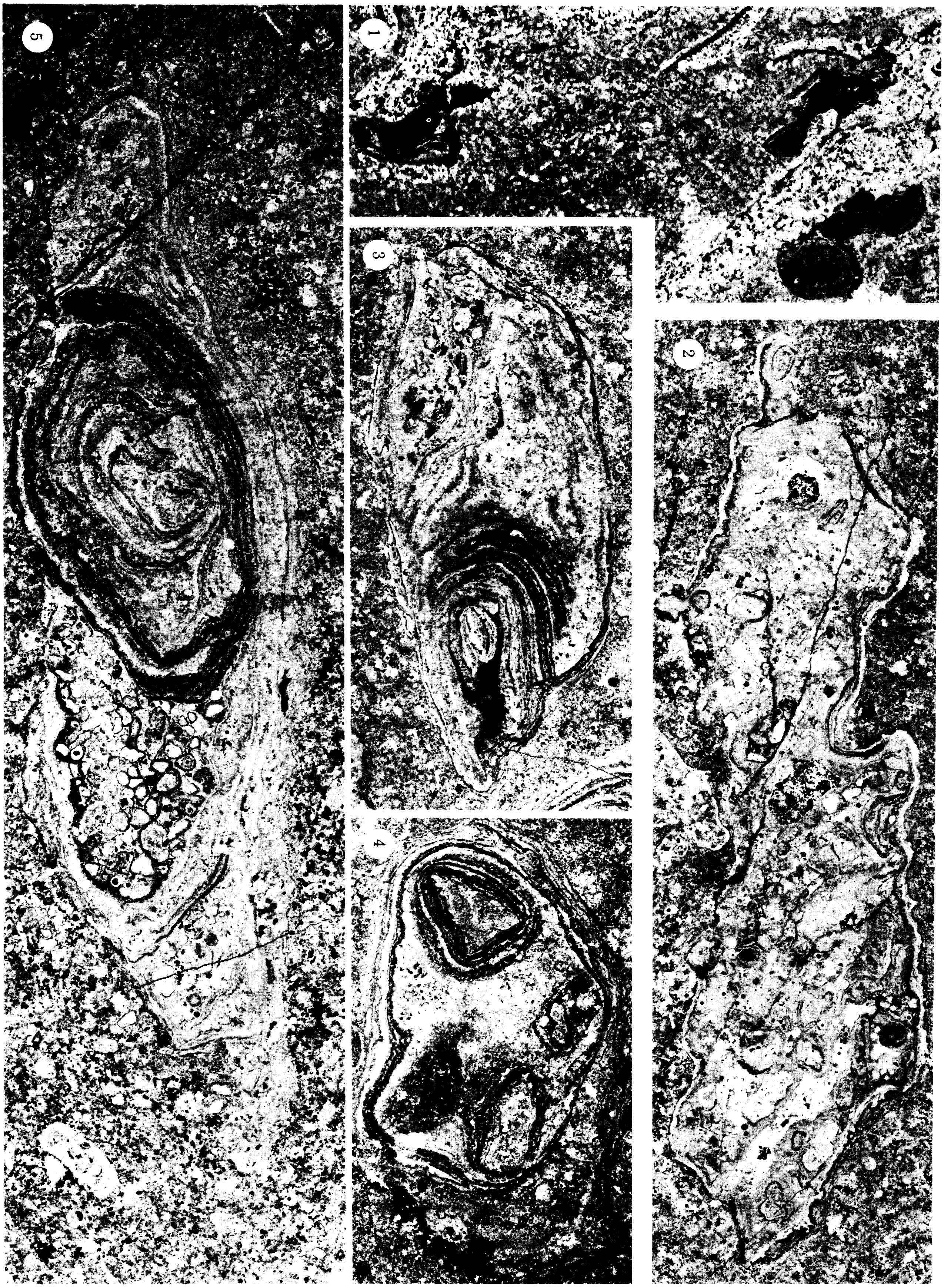
Codiacean and oncolitic growths in the pisolite bed, Caswell Bay (locality 18). All magns ×15

1. Growths mainly of ortonellids, some on ostracod bases, in random alignment, with adnate spirorbids.
2. A biscuit oncolite with well-defined margin, but with less clearly recognizable internal structure and with randomly incorporated debris.
3. A highly asymmetrical oncolite with well-defined but interrupted laminae in the earlier stages of growth, with included debris in the later stages, and with well-defined margin.
4. A composite oncolite. The incorporation, with very little debris, of four separate oncolites in the enveloping stromes of the outermost sheaths, virtually at a single 'moment' of oncolitic enlargement, is not readily explained, especially when the central 'structureless' mass of lutite is the mutual bond – unless the lutite is the 'ghost' of an algal colony whose living filaments were tapping agents to unify the whole structure.
5. Asymmetrical growth of a biscuit oncolite. Successive stages of lateral expansion are rhythmically phased, with intermittent incorporation of detritus, and indicate irregular pulses of growth. Some of the detritus is significantly different in constitution and grain size from the immediately surrounding matrix.

Description of plate 10

Rocks of the Caswell Bay Mudstone

1. Calcisphere lutite. Lowest exposed bed of the Mudstone, Froglane (locality 6). Magn. ×10.
2. Desiccation chips of a finely granular lutite in a granular matrix. About 5.9 m above the Heatherslade Bed, Caswell Bay (locality 18). Magn. ×5.
3. Ostracod limestone. The matrix is very mixed, with much lutite, small faecal pellets, scattered small ooliths, fragments of algal tissue, and clacispheres, with little sorting and poor alignment. About 2.4 m above the Heatherslade Bed, Caswell Bay (locality 18). Magn. ×20.
4. Grain limestone alternating with lutite. The particular feature of the rock is the abundance of vertical 'worm' burrows in the lutite, some of them penetrating the thin lamina of grain limestone but none of them being seen in the lower grain limestone. Immediately above the Heatherslade Bed, Spaniard Rocks (locality 5). Magn. ×10.
5. Relatively coarse-grained arenite on an 'impure' lutite. The grains, most with compact rims of a false oolite, show a multiplicity of algal(?) borings or structures in the rolled fragments (originally of lutite?). About 3.0 m above the Heatherslade Bed, Three Cliffs Bay (locality 7). Magn. ×20.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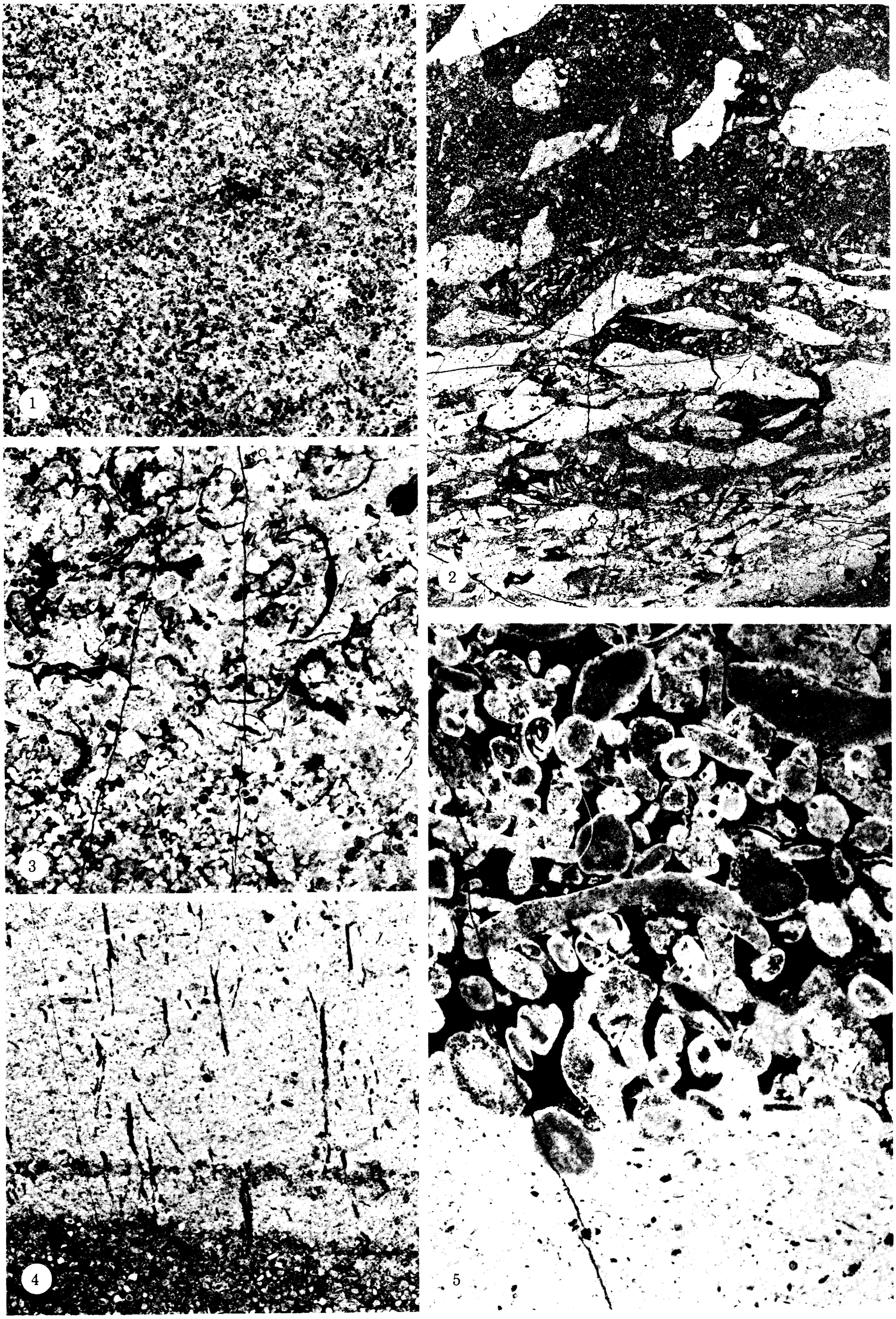
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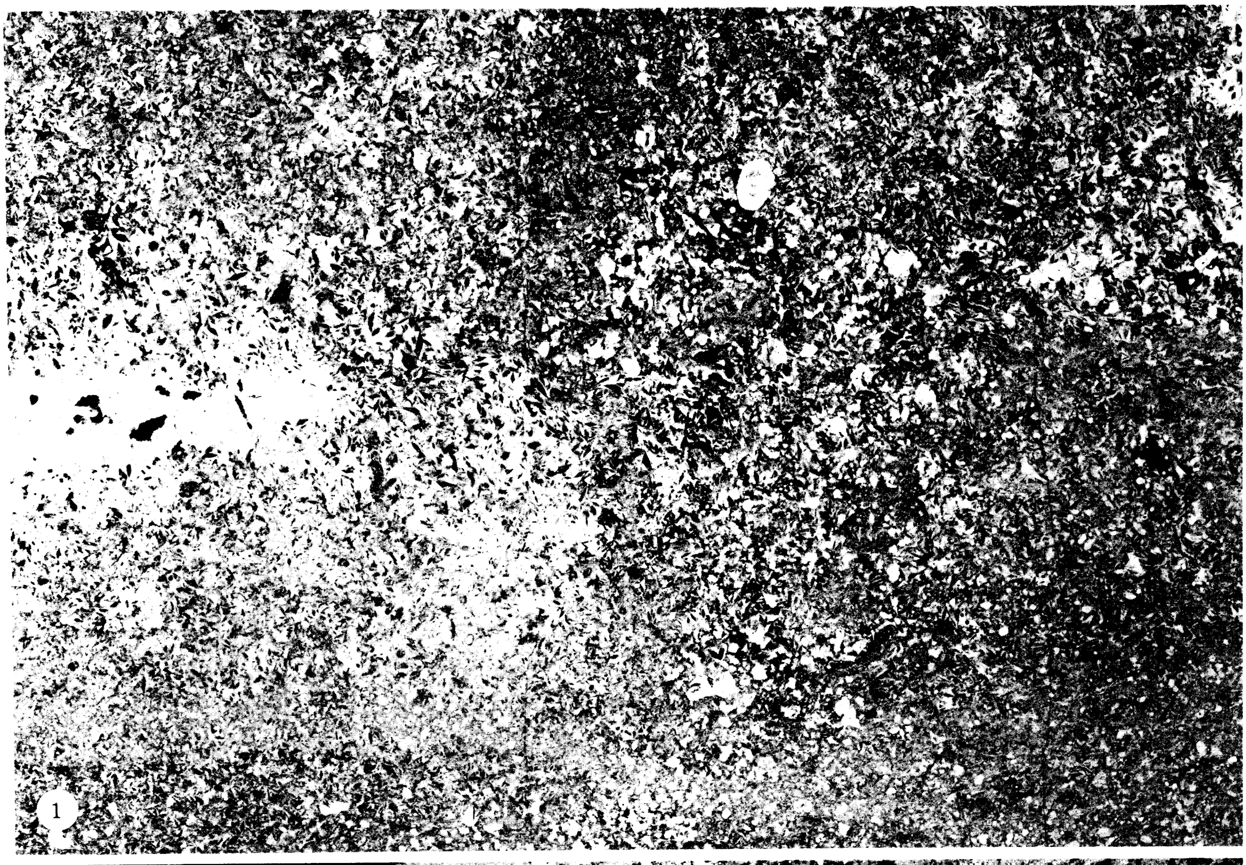
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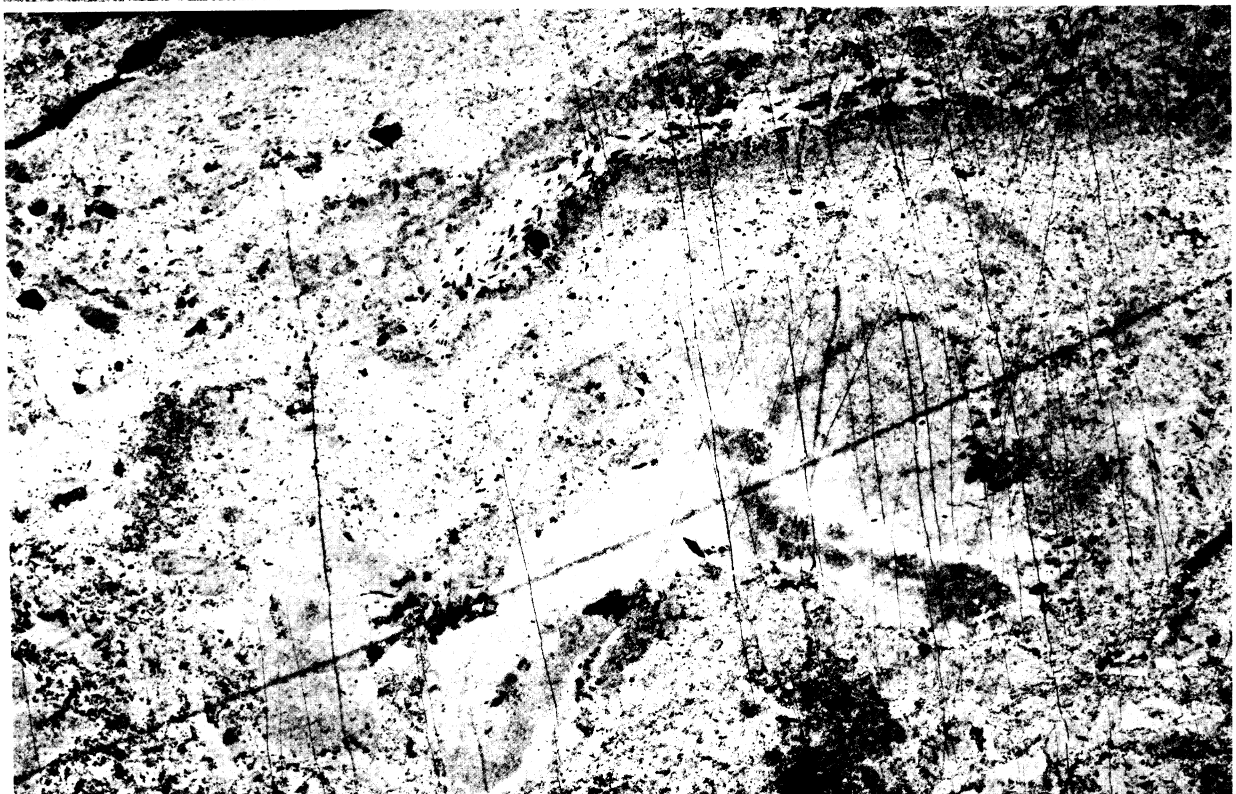
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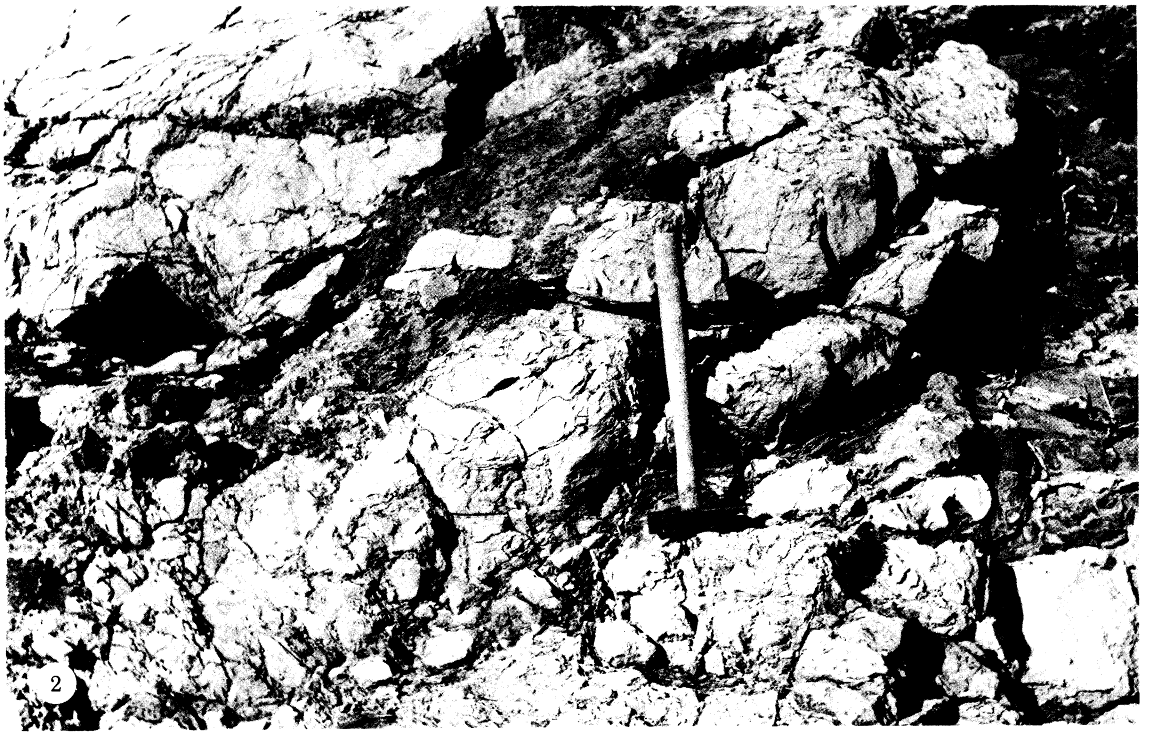

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an insecure substrate. The algal types are several: in additions to the codiaceans (*Garwoodia*, *Ortonella*), there are a number of kinds of dasyclads (including *Koninckopora inflata* and kamaenids), *Girvanella*, and *Solenopora*; and there are rather nondescript spongiostromes and ragged stromatolites. Laminated shards, and compact lutitic fragments of various sizes, often with fine 'worm' burrows, may also be relics of algal growths; and an inference is that much of the debris in the grain limestones, otherwise unidentifiable, is of algal origin.

The influx of vast numbers of calcispheres as planktonic 'grains' contributing to limestone formation was complemented by a periodic flooding of the environment by kamaenid dasyclads (see 1 of plate 14), the two fossil kinds being sometimes found together, sometimes not. The kamaenids being elongate, they tend to give the rocks a textural alignment, but a dominant current trend has not been determined. Other kinds of plankton, mainly foraminifers, also contribute, sometimes substantially, to the grain limestones, and in their different but unsorted sizes to be a further indication of the immaturity of the rocks in their polygenetic origin.

(*c*) *Pisolites*

A bed, reaching a thickness of 17 cm and lying some 3 m above the base of the Mudstone in Caswell Bay (locality 7), is exceptional in the abundance and variety of algal types it contains. Nodes, films, and tiers of algal growths, as codiacean colonies developed on shells and on older colonies, are complemented by detached stromatolitic nodules (oncolites) in a granular base. (See plate 9.)

Codiacean growths. The matrix in which the codiacean colonies lie is an ill-sorted fine-grained limestone, the angular and subangular grains, perhaps partly of algal origins, with pellets and shell fragments, ranging in longer dimension to 0.2 mm. Bedding is poor, the sediment being much disturbed by churning, with bioturbid signs. Invertebrate fossils are abundant. Ostracods are the main kinds: they appear to fall into several (unidentified) species as judged by relative

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Description of plate 11

Gypseous rocks of the Caswell Bay Mudstone

1. Mesh of pseudomorphs after gypsum, in a matrix of fine-grained limestone. A stray oolith in the mid-upper part of the photograph, and a patch of what appears to be algalutite on the left, are complementary signs of environment of sedimentation. About 0.4 m above the Heatherslade Bed, Spaniard Rocks (locality 5). Magn. $\times 15$.
2. Laminar concentrations of sphenoid pseudomorphs after gypsum in a lutitic matrix. The contortions in the laminae are interpreted as enterolithic structures. A central patchiness may reflect algal-influenced sediment. About 1.9 m below the Arundian base, Caswell Bay (locality 17). Magn. $\times 15$.

Description of plate 12

Slumping in the Caswell Bay Mudstone, Caswell Bay (locality 17)

1. Pre-Arundian movement. The massive 'white bed' against which the hammer haft rests is the same rock as that beneath the hammer head. In the wedge between, dark highly contorted dolomitic 'shales', of a rock bed no longer present in the undisturbed (but non-sequential) contact between the 'white bed' and the overlying High Tor Limestone, disclose their pre-Arundian occurrence above the 'white bed'. The relations thus reveal the pre-Arundian age of the slumping. In the uppermost part of the photograph, centre and right, the 'white bed' is seen to be followed directly by the High Tor Limestone, the dolomitic 'shales' being wedged out by overstep, although they are present in place about 20 m to the right.
2. Slump breccia – Dixon's autobreccia – in the upper part of the Mudstone. The angular blocks are mainly of the 'white bed': they lie in a matrix of dark contorted dolomitic 'shales'. The high angularity, the complete lack of sorting, and the great differences in size, of the fragments provide the evidence of slump movement.

size, shape, and ornament (seen in thin section). In patchy subparallel alignment they hint at lamination, although much of the sediment is disorganized. Spirorbid shells, some adnate, are common (see 7 of plate 15); calcispheres are scattered through the matrix, but are not abundant; larger foraminifers are present in small numbers; and broken modiolid bivalves are probably to be identified.

The codiaceans include species of *Ortonella* (*furcata*, with *kershopensis* and *tenuissima* less commonly), and *Garwoodia gregaria*. Pin-heads of algal tubules, less than 1 mm in diameter, of a variety of shapes, 'float' in the matrix, and wisps and shards are abundant. More often the algae are in small colonies attached to an ostracod base, and show a multiplicity of forms of growth: the larger ostracod shells, to 6 mm, may be overlain by compact growths little more than a veneer of insignificant thickness, or they may support radial arcuate growths that form small asymmetrical nodules scattered randomly in the matrix. Serpulids are the cores or the bases for larger colonies, some exceeding 1 cm in diameter. In some forms a core is not recognizable. Rhythms of growth are to be seen in a unitary nodule, but they are even more impressive when new colonial growth builds on an older colony: many growths are multiple, composed of alternations and interweavings of different species. Some of the algal laminae interleaved with the more obviously filamentous layers are of densely compact lutite; and there are patches of 'amorphous' lutite, incorporating fine detritus and vaguely outlining laminar structure, that may be concentrations of algal 'dust'.

The rock texture is unorganized to a degree. The algal growths are very well preserved, apparently little abraded; and the ornament of some of the ostracod shells – of sharply angular flanges and perhaps of fine pustules and spines – is quite unbroken: there is little sign of rough transport, and the rock is highly local in its concentration of the larger constituents. Yet there is confusion in the mixing of grain sizes and grain types, in the lack of sustained bedding or finer lamination, and in the random orientation of the larger particles. The appearance is of the rapid growth of algae on any convenient substrate, with sufficient turbulence or bioturbid-churning to discourage a fusion of growths into nodules of notable size, and with repeated agitation of the waters of deposition and a mixing of the sedimentary grains without much sorting, before the final settling of the heterogeneous assemblage of fossils and fragments in an unusual kind of algal limestone. (See 1 of plate 9.)

Oncolitic growths. The oncolites of a contiguous layer of the pisolite bed also lie in a matrix of poorly laminated siltstone, much of which may be algal debris, that compares generally with the matrix in which the codiacean colonies lie; but it is distinguished by being much richer in calcispheres and by being almost without ostracods and spirorbids; and although there is an abundance of nodules in the few centimetres of sediment, there is a strong contrast in microfacies between the one rock type and the other, in endogenous growths of contrasted algalithic kinds and in exogenous influx, that emphasizes the subtleties of local sedimentary controls (whatever they may have been) in determining the individual nature of deposits in a generally uniform environment.

Oncolitic growth is dominantly stromatolitic, in the usual alternating subparallel laminae of dark and light lutite. Occasional interpolations include small ortonellid colonies briefly grown between the laminae, but filamentous algae are otherwise inconspicuous or absent. The nodules of simple structure and small size are often without an obvious central core, but most of the larger ones are complex in the incorporation of detrital fragments of a variety of kinds. Calcispheres may be trapped, and with other grains (like those of the surrounding matrix) may be found scattered or pocketed within the laminated lutite. Sometimes what appear to be deformed large coated 'false' ooliths are the inclusions: they are without radial-concentric structure, they are only crudely rounded, and they may be no more than algal-veneered fragments of algal tissue in a complex association unlike any to be seen in the neighbouring rock matrix. Most pockets of detritus, core-central or interlayered, were engulfed or trapped by the enlarging oncolithic envelopes: embodied in the nodule, they are commonly differentiated, in mean grain size and proportionate contents, from the surrounding matrix, and separate grain pockets incorporated at successive stages of nodular growth may indicate in their detailed differences movement of the oncolith into different matrix contexts as it grew.

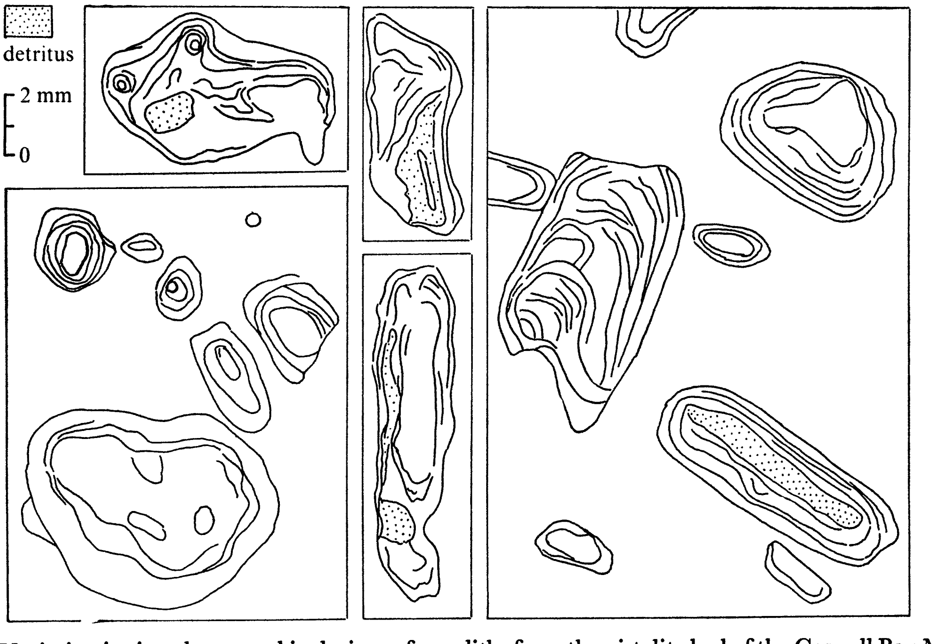


FIGURE 11. Variation in size, shape, and inclusions of oncoliths from the pistolite bed of the Caswell Bay Mudstone, Caswell Bay (locality 18), to illustrate lack of uniformity, notably in detailed mode of growth, in sorting, and in alignment.

The forms of the oncoliths are very varied. The smaller, with simple concentric layering, are subspherical or ovoid, and some of the larger ones, a centimetre in diameter, retain a more or less equi-dimensional shape; but with increasing size shapes tend to be highly asymmetrical and often multiple; some are tall and approximate to colleniids (although they are not pillared or attached to a base), but most are elongate-oval or flattened, biscuit-like, and a few display irregular pustulose and crenulate surfaces, and some show fingered extensions 'probing' into the matrix and then perhaps disclosing how matrix became pocketed in the nodule in such proportionately large bulk.

Internally, the general pattern of subconcentric layering is usually composite in the larger specimens. Each successive envelope may be complete, but commonly it is discontinuous, being abruptly transgressed by a later envelope. The truncations may be a sign of intermittent abrasion, as they are certainly a sign of interrupted and redirected growth; and in many oncoliths only the last-formed laminae may persist as complete wrappings around the inner elements. Changes in the locations of growth maxima give most oncolites a degree of asymmetry that is most convincingly related to posture in the larger and flatter forms that show upper-surface enlargement on an 'imperfect' or 'incomplete' under surface. Nevertheless, few specimens clearly display open-ended digitate extensions of laminae into flanking matrix.

The manner of oncolitic growth is not obvious. The concentric simplicity of small nodules, repeatedly tossed in agitated water by waves and currents, and the asymmetrical layering of larger nodules on the sea-floor, mostly at rest and overturned only occasionally, are readily understood as is the periodic incorporation of matrix grains in a restless environment, but the binding of several smaller oncoliths – two or three, sometimes four – into a composite larger one is not easily explained, especially when they appear to be separated by normal matrix within the outer envelope, and the growth of a peripheral film of stromatolite, as a thin lamina about a large core of what is presumably incoherent matrix (including algal 'dust') offers an analogous problem of lithification, which appears to have been almost strictly contemporary. (Compare Toomey 1974, 1975; Leeder 1975.)

The oncolites, members of a family of algal structures that usually typify deposition in intertidal or just subtidal waters (see Aitken 1967), give no sign of desiccation cracks, either radial or interlaminar. Like the matrix particles poorly sorted in grain size, they are distributed in the matrix in indiscriminate mixing of large (up to 25 mm diameter) and small individuals. They are neither clearly aligned in a recognizable bedding, nor uniform in long-axis direction, and give the strong impression of being in haphazard arrangement in unorganized matrix. The signs are thus of relatively turbulent deposition, little opportunity for differential settling, and very shallow water. (See figure 11; and 2–5 of plate 9.)

(d) Sabkha-type deposits

Indications of desiccation and evaporitic mutilation are not common in the Caswell Bay Mudstone, but they are recurrent. The most obvious are the cracking and fracturing of mudstone layers, as in Caswell Bay (locality 18), where at about 2 m above the base, a layer 16 cm thick provides clear evidence of shrinking, before deposition of the layer above, in detached plates and slivers that are separated by cracks occupied by detritus spilled in as the overlying layer was deposited. Angular rock chips at other horizons have similar implication (see 2 of plate 10).

Other signs of high intertidal or supertidal sediments are provided by pseudomorphs after gypsum recognized at several horizons. Those in the Heatherslade Bed are porphyroblastic, often euhedral, embodied in coarse-grained oolite, as they are in the overlying basal breccia of the Caswell Bay Mudstone (see p. 432), without deformation of the ooliths or fragments, and comparable porphyroblasts occur in the Mudstone at higher horizons, sometimes isolated, sometimes in groups. However, a few beds in the Mudstone carry the pseudomorphs in such abundance as to replace or (recrystallized perhaps from original anhydrite) to reconstitute laminae completely. In variant expression the parental sulphate may now appear less as an intergrowth of euhedral crystals than as a mesh, crystal form not readily recognizable, that may retain a ghost frame of the original sediment. (See plate 11.)

The pseudomorphs are found at several horizons. They lie within a few centimetres of the base of the formation at Spaniard Rocks (locality 5), in two or three laminae in the mid-part of the formation, 2.5–3 m above the base, at Froglane (locality 6), in Three Cliffs Bay (locality 7), in the mere west of Heatherslade (locality 9), and in Caswell Bay (locality 17), and at 6 m above the base in Caswell Bay (locality 17). Recognizable only under the microscope, similar laminae at other localities and other horizons may well be present but have not yet been found. There is uncertainty in correlating the known occurrences: on equivalent thicknesses of strata above the Heatherslade Bed, comparison may be made of the developments near the base between Spaniard Rocks and the mere west of Heatherslade, and in the mid part of the sequence between Froglane, Three Cliffs Bay, and Caswell Bay, but there are no known links at intermediate localities.

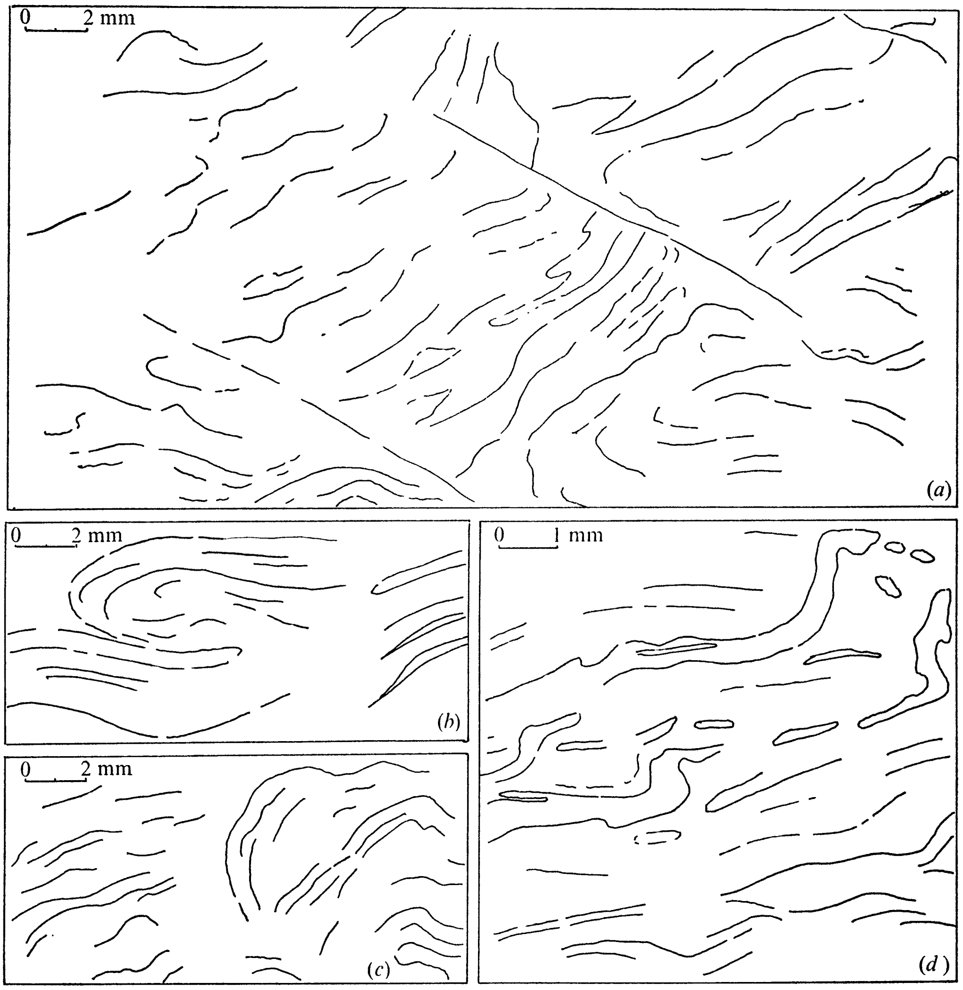


FIGURE 12. Enterolithic structures in the Caswell Bay Mudstone, attributed to evaporitic disruption. About 0.4 m above the Heatherslade Bed, Spaniard Rocks (locality 5).

The sediments in which the pseudomorphs are found are, like the original sulphates, now wholly calcitic, and any saline or evaporitic layer that may originally have been present is no longer identifiable as such; but the associated laminae are complex, sometimes highly complex, in their structure and imply a disruption and a 'plasticity' of deformation both promoted and facilitated by migrant and lubricant salines. In characteristic enterolithic fashion, many of the bedding planes (on a scale of millimetres) give the appearance of a general subparallel uniformity, but they are commonly abruptly discontinuous, the films of sediment between them having broken shallow-lenticular form with rapid and irregular inter-fingering and with multiple minor distortion in the evenness of the bedding. In less simple structure the individual lenticles become isolated or lose their coherence, the rock giving the impression of vaguely defined and churned laminar remnants in which fragments are very unevenly scattered; or a bedding pattern may be retained but the bedding 'planes' are not plane but scalloped or undulose, with their continuity broken, with raggedly edged pockets and wedges of brief extent, and with wisps and stringers of contrasted sizes embedded in the mixture. In more extreme distortion individual lenticles may display complex folding with upturned or down-turned broken ends running into neighbouring laminae or being sharply arched in small over-folds forming pustules of sediment. In the most highly distorted structures, well seen in the mere west of Heatherslade (locality 9), the broken and discontinuous laminae form steepsided and bulbous nodes, infolded and more or less isolated masses, torn and 'faulted' remnants, all in jumbled association. The structures are strictly 'internal': the laminae below and above, of fossiliferous lutites characteristic of the Caswell Bay Mudstone, being undisturbed in their even bedding in thoroughly normal fashion. (See text-figure 12; 2 of plate 11.)

Lithologically, the rocks are lutites or fine silty arenites. Some of them are relatively 'pure', very fine-grained, almost 'amorphous', with vague light-and-dark patches that may indicate original algal growths or may be a product of saline influence. A few are penetrated by borings, subparallel and running across the lamination, of the order of 0.4 mm in diameter, and some larger tubules, about 1 mm in diameter, have an internal frame that suggests algal growth. The walls of the borings and tubules seemingly were lithified before disturbance by saline penetration. A number of the beds contain flotsam, drifted plankton, of calcispheres, ostracods, occasional foraminifers, lying in a 'normal' matrix of mixed particles including pellets and grumous grains, the organic fragments sometimes being in the closest contact with gypsum crystals.

Porphyroblasts after gypsum, randomly scattered in some of the beds, are selectively concentrated in laminae themselves deformed in enterolithic structures, and their sphenoid crystals, elongated in laminar orientation, imply crystallization before the structures were imposed. In yet other laminae, pseudomorphs are almost the only constituents, occurring in such abundance that the crystal fabric is an interlocking mesh; sulphate then appears to have been primary in lamina formation (if not necessarily as gypsum). Associated finely granular aggregates may reflect an initial anhydrite deposit, and an accompaniment of equally fine-grained dolomite may also be primary – a rare development contrasting in crystal form with the usual rhomboidal and saccharoidal crystals of most replacement dolomite. (See plate 11.)

The several rock types of the suite compare with the mixed association of sediments found in Recent high-intertidal and supertidal crusts of arid and semi-arid coastal flats, in an association of transported fine detritus and endogene salts of cognate origin; they confirm an ascription of the rocks to a sabkha-type environment recurrent during Chadian times. (Compare Kendall & Skipwith 1969; Evans, Schmidt, Bush & Nelson 1969; Friedmann, Amiel, Braun & Miller 1973.)

(e) Neritic intercalations

Macrofaunal detritus in the Caswell Bay Mudstone includes most abundantly small crinoid plates, which are not uncommon in many of the coarser-grained rocks, notably in oolith cores. Less common are brachiopod shards, bryozoan fragments, and small echinoid spines. Usually the fossils form a very small proportion of the rock, but they are not without significance in demonstrating their availability. Locally, however, the detritus becomes more concentrated in truly bioclastic limestones, each a few centimetres or less in thickness, at a few horizons, especially in the upper part of the sequence in Three Cliffs Bay (locality 7), where chonetids are common and occasionally zaphrentid corals are to be found (see figure 14).

The importance of such intercalations lies less in the place they occupy in the sequence of the Caswell Bay Mudstone, which is minor, than in the contrasted facies they offer to the dominant lithological types of the formation; for, like the crinoid pockets in the Caswell Bay Oolite (see p. 424), they indicate the accession, however brief, of a neritic fauna during a major 'lagoonal' interlude (in Dixon's Avonian terms) – or at least an accession into a 'lagoonal' environment of an assemblage of organisms, perhaps washed-in rather than indigenous, in unhindered derivation from 'off-shore' sources (although a 'shore' cannot be identified).

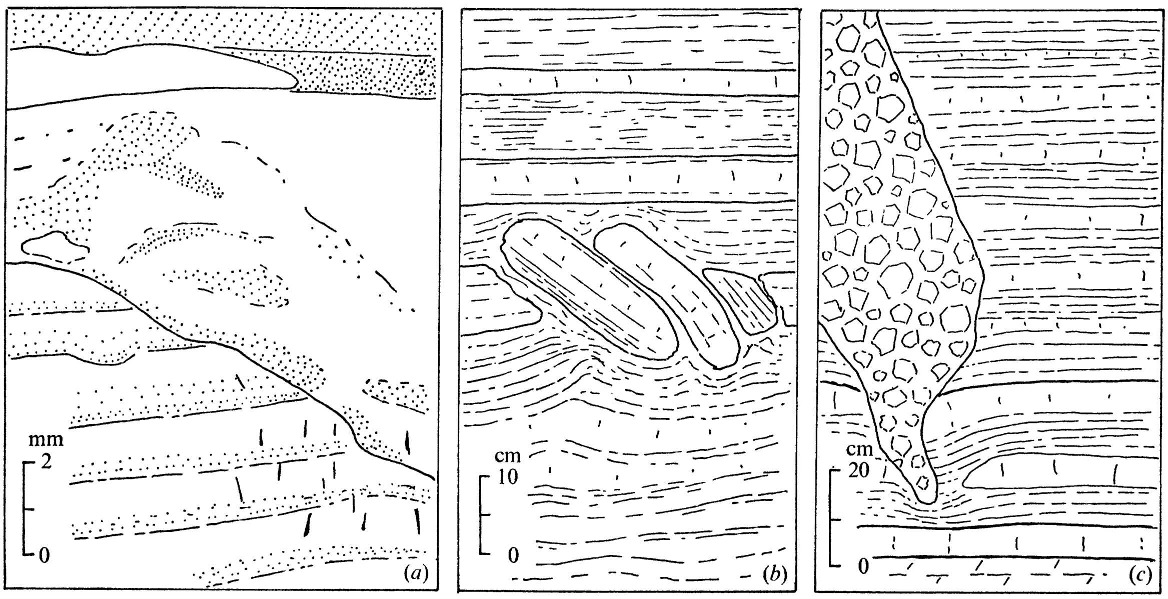


FIGURE 13. Scales of slumping in the Caswell Bay Mudstone. (*a*) About 0.6 m above the Heatherslade Bed, Spaniard Rocks (locality 5). (*b*) In the lower part of the sequence, Caswell Bay (locality 17). (*c*) In the greater part of the sequence, Caswell Bay (locality 12).

(*f*) *Slumping and brecciation*

Minor adjustments and slumps are not uncommon in the Caswell Bay Mudstone. Local swelling and thinning of beds differing in competence are widespread, in part perhaps in post-Chadian movement. More spectacular, and strictly intra-Chadian, are the cracking and fracturing of the more competent limestones, lubricated on more thinly bedded layers to contribute to slump breccias that cut through several metres of underlying beds, by a process that Dixon called 'autobrecciation' and attributed to the permeation of water along desiccation cracks. Some of the broken beds show structures small in scale, of about 40 cm and restricted to a few beds (see figure 13); but in crushed rock and in the rotation of fragments they are clearly the result of internal stresses and not of simple downward movement along opening cracks. The structures on a larger scale, repeatedly seen along the strike for some 12 km, are far too extensive to be a product of desiccation, and in their internal deformation are clearly the result of slumping no doubt facilitated by interbedded salines. (See plate 12.)

The breccias were recurrent in the sequence. An early movement is indicated by local fracture, affecting no more than a metre or so of sediment, of a brittle lutitic limestone near the

Description of plate 13

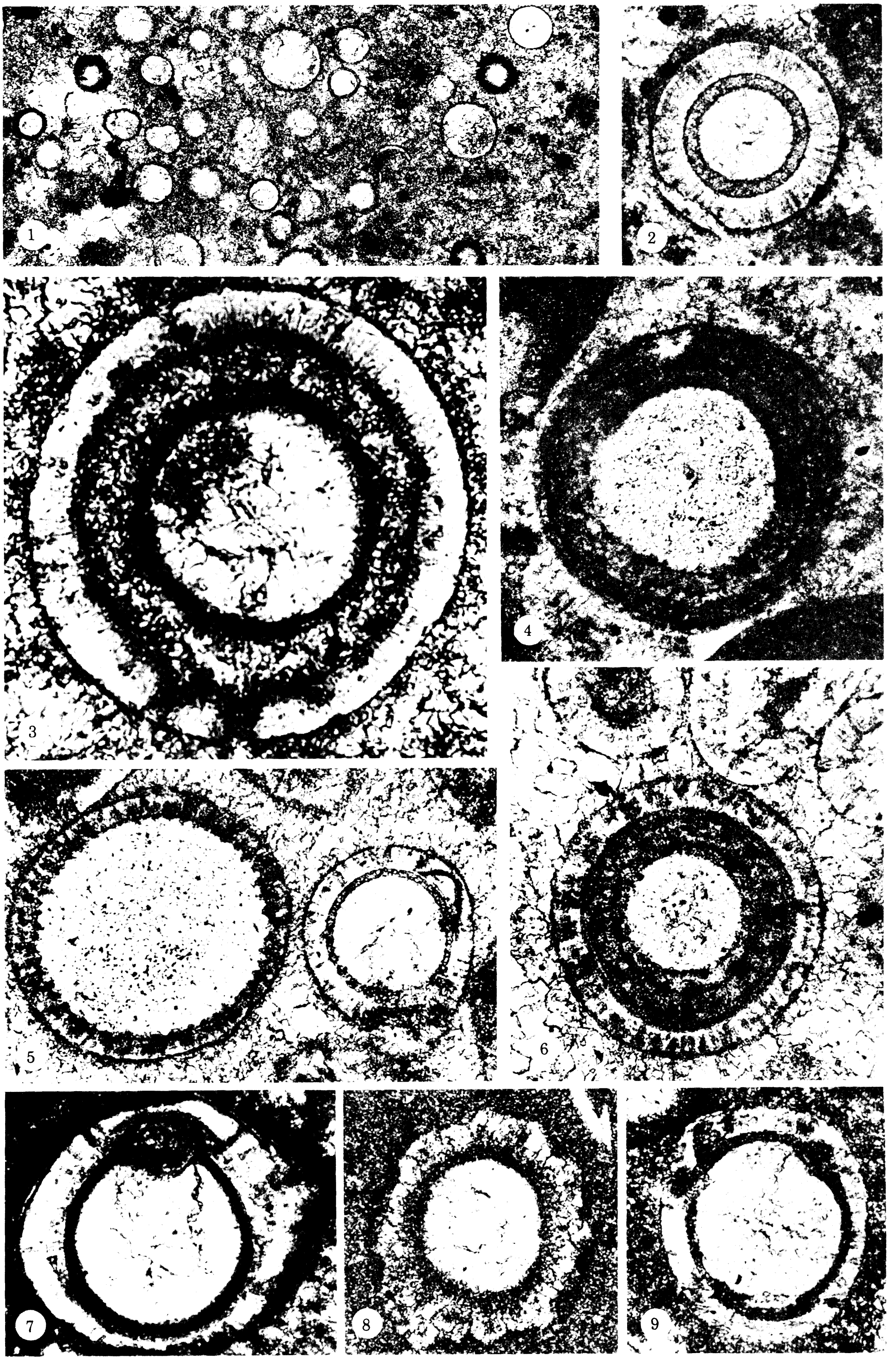
Calcispheres and calcispherids

1. A calcisphere limestone, to show the abundance of many kinds of calcispheres and calcispherids occurring in a single assemblage. About 5 m above the base of the Caswell Bay Mudstone, Froglane (locality 6). Magn. × 75.
2. A polyderm calcisphere. The outermost dark irregular layer is doubtfully an integral part of the calcisphere. A thick outer shell is strongly radial, enveloping a darker granular shell. The calcite of the crystalline core appears to be secondary. Heatherslade Bed, Heatherslade (locality 11). Magn. × 200.
3. Detailed structure of the successive shells of a polyderm calcisphere. The strongly radial outer envelope (itself with a dark margin that may be secondary), wraps a shell, granular or meandrine in texture, with dark inner and outer margins. The core appears to be secondary crystalline infilling. Heatherslade Bed, Spaniard Rocks (locality 5). Magn. × 400.
4. A two-layered calcisphere. In the pattern of its shells the dark outer layer is perhaps oolitic (but this may be deceptive, for its inner margin is denticulate). It surrounds a partly recrystallized granular core not readily envisaged as independent without a containing shell. From a fragment in a slump breccia, Caswell Bay (locality 17). Magn. × 200.
5. Contrasted calcispheres. The larger specimen, having a narrow envelope with an internal radial-denticulate margin about a granular core, is markedly different from the smaller, which, with four or five shells, may in its apparent asymmetry be a tuberitine. Heatherslade Bed, Spaniard Rocks (locality 5). Magn. × 200.
6. Calcisphere with ooliths. A thick dark middle shell separates an outer shell of strongly marked irregular radial structure from the granular core. Parts of two ooliths offer contrasts in structure. The secondary matrix, as in all the specimens, shows characteristic drusy growth. Heatherslade Bed, Spaniard Rocks (locality 5). Magn. × 200.
7. Calcisphere with flare. The simplicity of the spherical element is in contrast with the complexity of structure in many calcispheres, but the enveloping 'flare' (a corrugated wrapping) is rare. Immediately above the Heatherslade Bed, Three Cliffs Bay (locality 7). Magn. × 200.
8. Diplosphaerid calcispherid. The form has a strongly developed small polar cell encased in a thick wall. Other forms in the Chadian rocks display variations in the development of the polar cell from insignificant protuberances to hemispheres to detached peripheral elements. Oolite transitional to the Heatherslade Bed, Three Cliffs Bay (locality 7). Magn. × 200.
9. Calcispherid of unknown affinity. The form is conceivably an incipient diplosphaerid, but the multiple projections not symmetrically disposed on its periphery are unusual. About 0.2 m above the Heatherslade Bed, Spaniard Rocks (locality 5). Magn. × 200.

Description of plate 14

Algae of the Chadian rocks

1. Kamaenid limestone. The tubular kamaenids, internal structure partly obscured by recrystallization, lie in a finely grumous matrix with ostracods. About 10 cm below the top of the Caswell Bay Mudstone, Three Cliffs Bay (locality 7). Magn. × 100.
2. *Kamaena* sp., in illustration of camerate form. About 1.6 m below the top of the Caswell Bay Mudstone, Heatherslade (locality 10). Magn. × 200.
3. A kamaenid(?) wrapped in an oolithic envelope. The wrinkled appearance is seen in many specimens and may be original; the kamaenid allusion is then based only on the hints of partitions and a camerate structure. About 4.3 m above the base of the Caswell Bay Oolite, Caswell Bay (locality 17). Magn. × 50.
4. Denticulate dasyclad. *Anchicodium*-like denticulate forms, their appearance in thin section depending on the accident of cross-cuts, are found in several kinds in both the Caswell Bay Oolite and the Caswell Bay Mudstone. About 0.7 m above the Langland Dolomite, Caswell Bay Oolite, Caswell Bay (locality 14). Magn. × 150.
5. Reticulate dasyclad. A random section, of a kind seen commonly throughout the Chadian rocks, preserved as a core of a well-developed oolith. About 7.8 m above the Langland Dolomite, Caswell Bay Oolite, Caswell Bay (locality 17). Magn. × 120.
6. Elongate reticulate dasyclad. About 0.8 m below the local top of the Caswell Bay Oolite, Fall (locality 4). Magn. × 75.
7. Reticulate dasyclad. A subsymmetrical cross-cut of a specimen forming the core of an oolith. Heatherslade Bed, Heatherslade (locality 10). Magn. × 150.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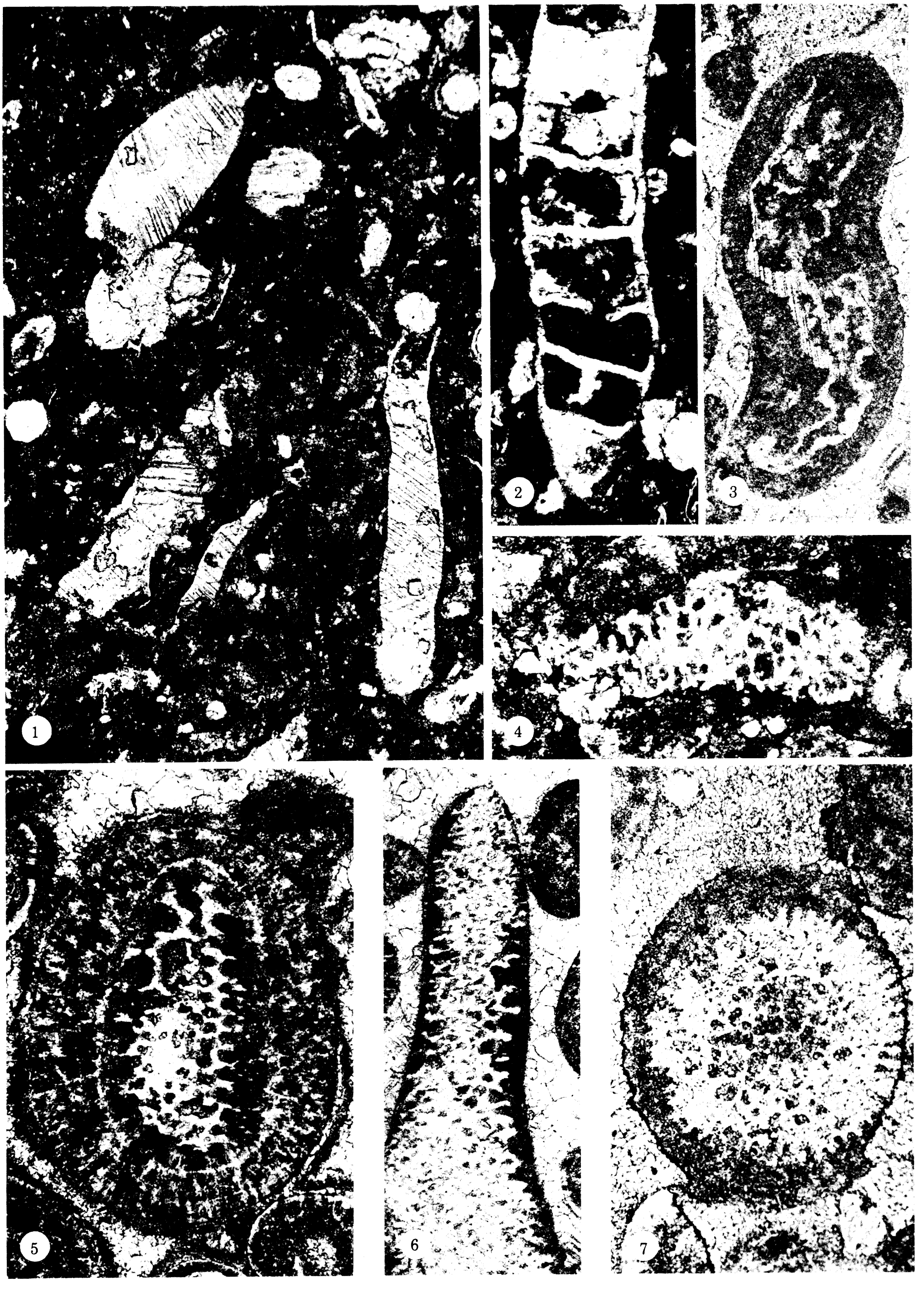
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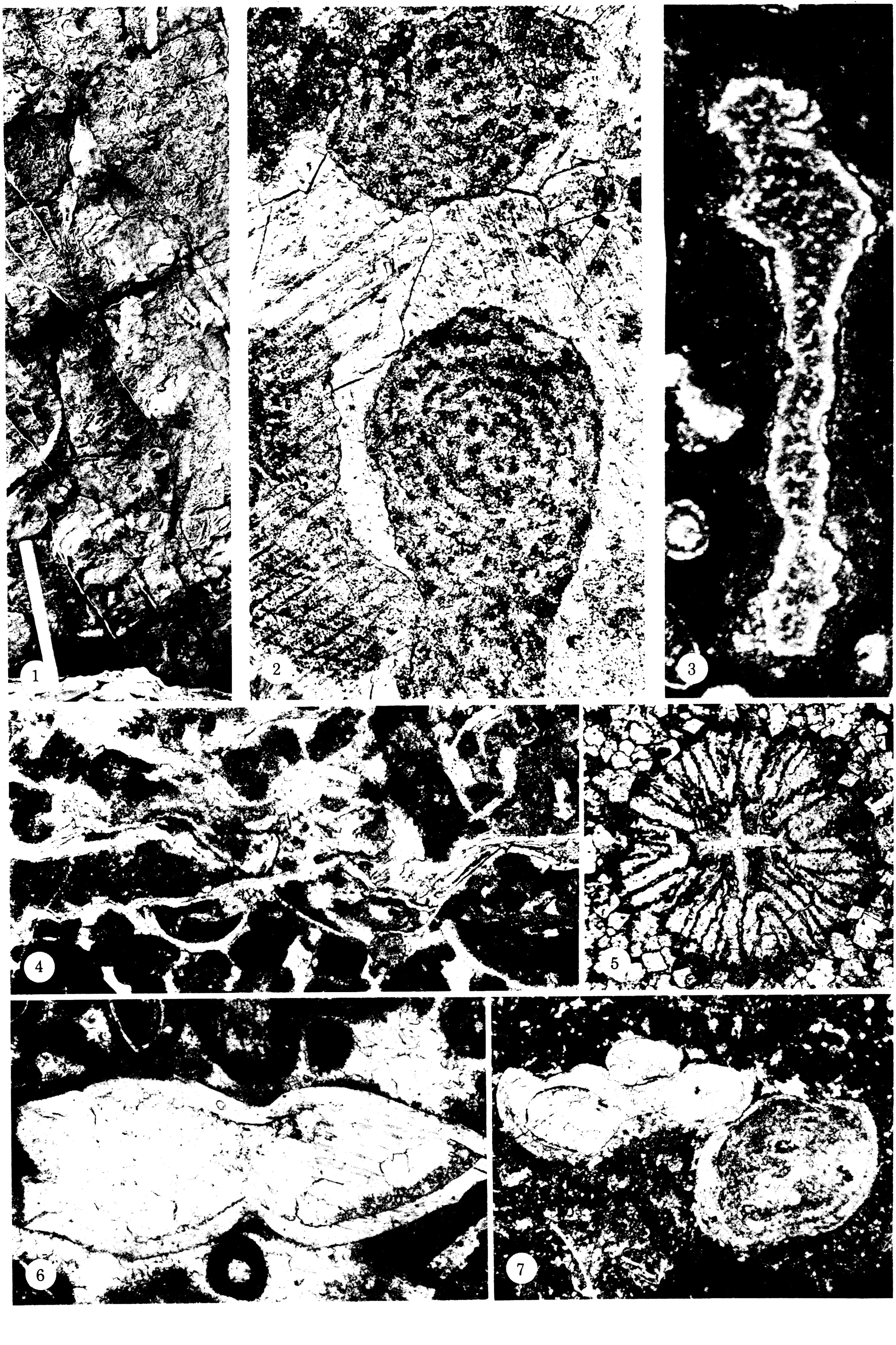
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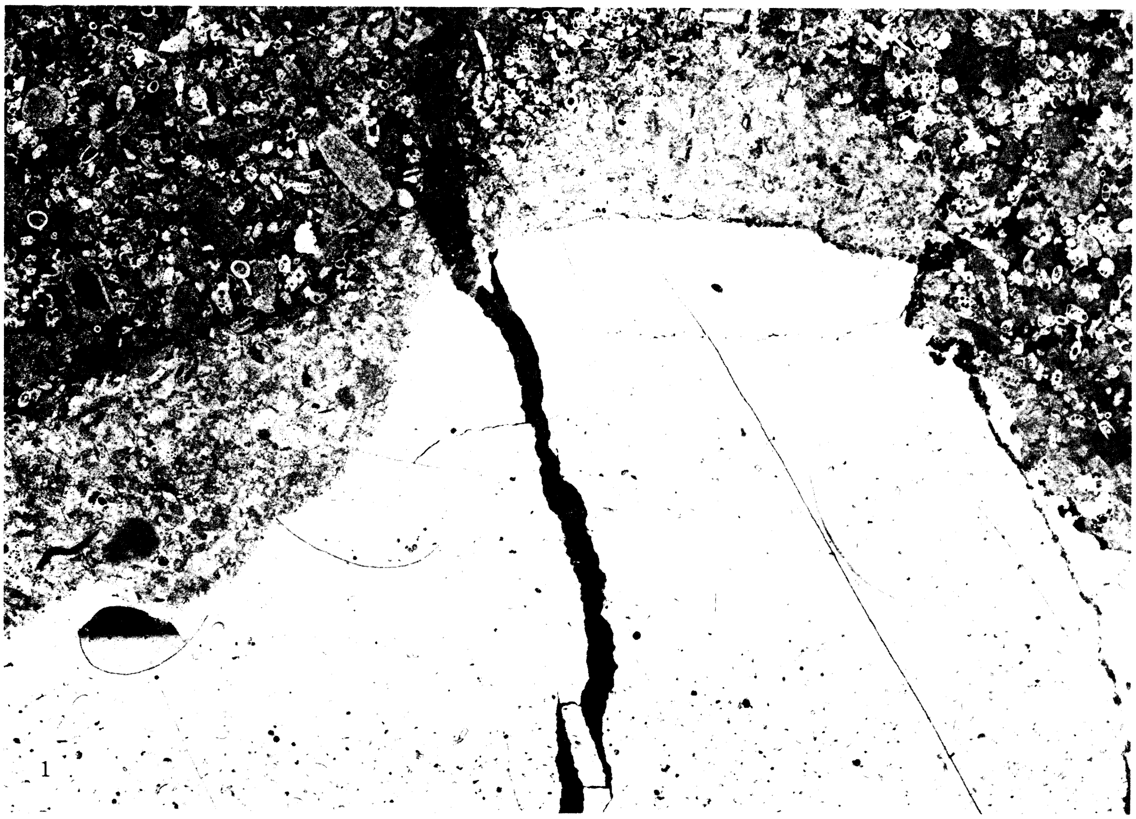
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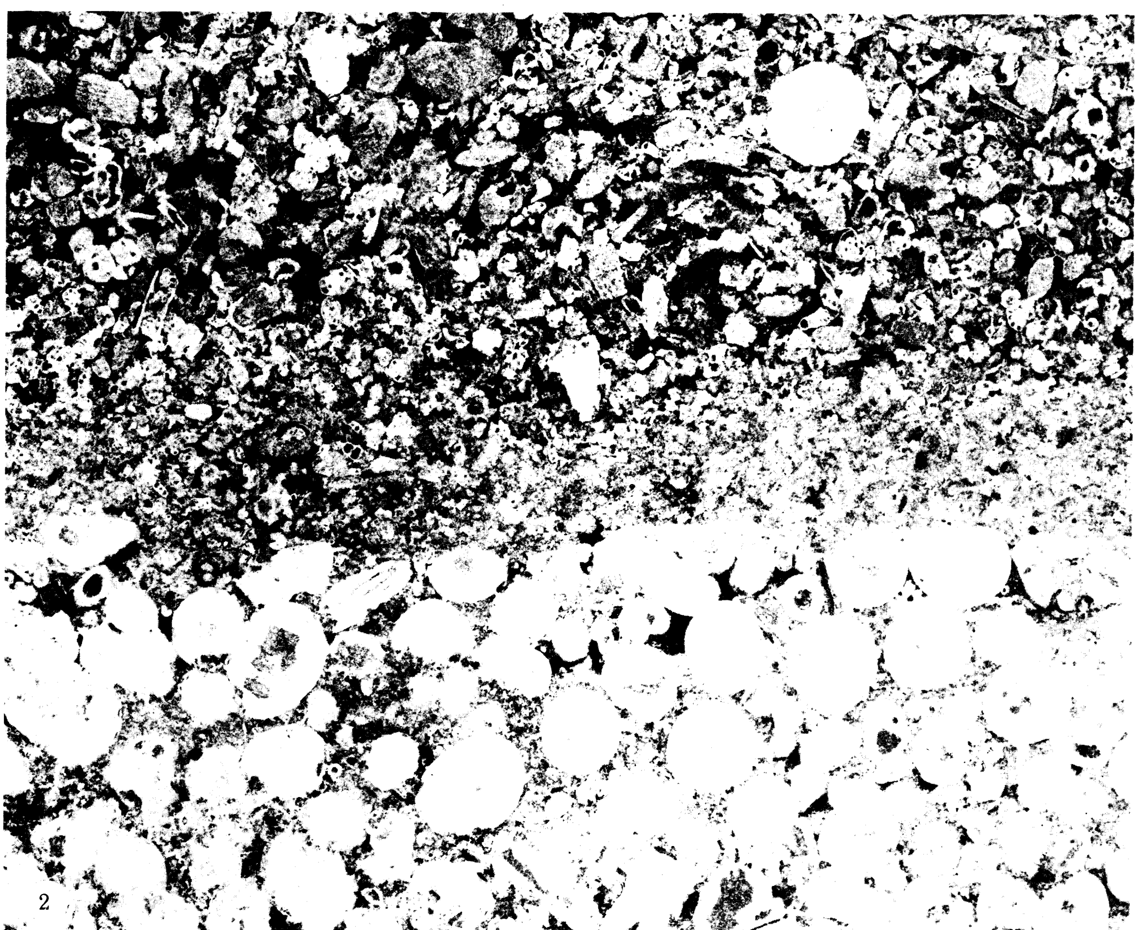
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base of the sequence in Caswell Bay (locality 17), where associated thin layers of dolomitic 'shales' are moulded above and below the detached limestone blocks but fade in their deformation both downwards and upwards, reaching neither the top nor the base of the formation. A much later movement, far more destructive in its effects, is repeatedly shown along the strike at the same Caswell locality, where the prominent 'white bed' near or at the top of the formation is indurated and very brittle as a compact lutite, and is overlain and underlain by more thinly bedded 'plastic' layers. In the slumped pockets, which penetrate deeply into the beds beneath, the 'white bed' is broken into an unsorted breccia of fragments lying in greatly contorted dolomitic 'shales' that form the 'matrix' of the slumped mass. Movement at this horizon took place after the latest (local) beds of the Mudstone were deposited, but before the deposition of the unconformably overlying Arundian High Tor Limestone, in direct proof of the stratigraphical break.

The large masses of slump breccia (see 2 of plate 12), the details of which are delineated by the fragments of the 'white bed', are wholly unsorted, great blocks of lutite, metres in length, lying in contact with small chips in a matrix containing pieces of all sizes. The fragments are

Description of plate 15

Algae, 'worms', an ostracod, and a spirorbid of the Chadian rocks

1. Chondritids. Bedding-plane of the underside of the uppermost bed of the Caswell Bay Mudstone, showing abundant chondritids of perhaps two species of 'worm', and more massive short 'rods'. Heatherslade (locality 10).
2. Rhodophyte(?) alga. The mottled (grumous) appearance of the alga suggests rhodophyte affinities only at a remove, but the kind is recurrent in both the Caswell Bay Oolite and the Caswell Bay Mudstone. About 12 m below the Heatherslade Bed in the Caswell Bay Oolite, Caswell Bay (locality 14). Magn. $\times 100$.
3. Mottled alga of unknown affinity: a type not uncommon in the Caswell Bay Mudstone. Heatherslade Bed, Spaniard Rocks (locality 5). Magn. $\times 80$.
4. Stromatactis-like structure. The lutitic base carries an abundance of organic fragments and many calcispheres, with an apparent development of algal binding-threads like those of reef-framing stromatactis. Caswell Bay Mudstone, about 2.2 m above the Heatherslade Bed, Three Cliffs Bay (locality 7). Magn. $\times 75$.
5. Cruciform dasyclad. An alga of unknown affinities that is recurrent, if never abundant, in the Chadian rocks. About 0.3 m below the top of the Caswell Bay Mudstone, Heatherslade (locality 11). Magn. $\times 100$.
6. A beyrichiid ostracod in cross-section, of a kind not uncommon in the Caswell Bay Mudstone. About 1.9 m above the Heatherslade Bed, Three Cliffs Bay (locality 7). Magn. $\times 50$.
7. An unusually well preserved spirorbid, typifying the abundant specimens found in the Caswell Bay Mudstone. The pisolite bed, Caswell Bay (locality 18). Magn. $\times 40$.

Description of plate 16

Arundian overstep

1. Arundian discontinuity with the Caswell Bay Mudstone. The irregular top of the 'white bed' (the overlying dark dolomitic 'shales' of neighbouring exposures being absent beneath fossiliferous High Tor Limestone) may be discerned in the discordant lineation of inclusions in the lutitic 'white bed', with the upper surface of the 'white bed' being minutely corroded and pocked. Ostracod shells are scattered in the lutite, one of which displays geopetal structure. The faint basal-Arundian film on the lutite surface is interpreted as a relic of a mucilaginous algal veneer that trapped the great number of small foraminifers forming much of the first few millimetres of the High Tor Limestone. Caswell Bay (locality 17). Magn. $\times 10$.
2. Richly fossiliferous Arundian limestone welded to the Caswell Bay Oolite. The smoothly planed surface of the Oolite (the Caswell Bay Mudstone absent) demonstrates the unconformity, the interface cutting through the planed individual ooliths. The basal-Arundian pelogloeal film is again well developed, although only a millimetre or two thick, and is charged with abundant microfossils. Fall (locality 4). Magn. $\times 10$.

highly irregular, angular, with no sign of the abrasive effects seen in products of water transport. The breccia penetrates several metres into the beds below, disturbing the collateral strata, but it does not reach the lowest layers of the formation, which presumably were sufficiently indurated to serve as a rigid platform on which forward sliding took place. The dolomitic 'shales' above the 'white bed', highly plastic, flowed as lubricant between the limestone blocks, and in complex rippling and overturning movement now form much of the interstitial packing of the breccia.

It is clear that while some of the 'purer' carbonate layers, mainly closely compact calcilutites, were rapidly indurated almost as fast as they accumulated, the thinner beds, mainly 'shales' (thin-bedded dolomitic limestones with a significant terrigenous content), remained to a degree waterlogged, presumably by unexpelled cognate hypersaline fluids, until movement took place. It is also evident that the surface of sedimentation had an appreciable slope, which remained or was renewed as a slope through much of the interval of Mudstone formation, and therefore that, the sediments being almost all deposited within or not much beyond tidal range, there may well have been repeated movements of gentle tilting to disturb the tranquillity of sedimentation. The evidence being seen only in linear scarp faces, it is not possible to determine the direction of movement of the slumping: a short cross-profile on the nose of the Caswell syncline (locality 16) gives an impression of southward movement, but this may be deceptive and be due to later internal tectonic sliding.

Slump breccias in Caswell Bay are anomalously macrofossiliferous. Notably on the west side of the bay (locality 12) a coarse breccia cuts through underlying strata with abrupt contact against a wall of tuncated beds, lateral collapse and contortions of bedding being relatively minor and induration of the wall rocks being virtually complete at moment of slump flow. The particular feature of the exposure is the occurrence in the matrix of the slump of fossils alien to a rock otherwise composed only of fragments of highly local lutites of the Caswell Bay Mudstone. The fossils in their large size are without counterpart elsewhere in the formation in Gower, as an assemblage including zaphrentids, *Koninckophyllum*, athyrids, spirifers, and large crinoid plates. The assemblage, unique as an association more especially in the presence of corals with large brachiopods, is in faunal facies precisely like that of the crinoid pockets in the Caswell Bay Oolite beneath, and of the crinoid beds of the High Tor Limestone above, and is out of phase in the breccia (although macrofossil fragments are found in other Mudstone beds).

Difficulties of interpretation are twofold, in the source of the fossils, and in the manner of their transport. If analogy may be made with southern Dyfed – the only practicable analogy on a basis of the place of Gower in a regional geology of South Wales (see George 1969, fig. 8; 1970, fig. 21) – neritic developments of Chadian age, with a crinoid-brachiopod-coral fauna, lay south of Gower in a belt running eastwards from the Linney – Boshertson rocks towards the Mendips, which, although only a postulated belt, appears to be the only likely source of the fauna. There is implied a northward movement of the slumps, bringing with it the fossils in evidence – a direction unexpected in the structural context, but suggesting a slight upfold to the south of Gower down the northern slopes of which movement took place.

Whatever the direction of movement may have been, the occurrence of the macrofossils in the body of the breccia is more difficult to explain. They are isolated fossils, not in their own matrix, set among angular fragments that are dominantly of calcilutite in a contorted dolomitic-'shale' milieu. As in the slumped masses on the east side of the bay, the rocks give every appearance, apart from the fossils, of local origin, although the sharpness of cut of the slump trench in the flanking sediments suggests relatively high velocity and high momentum of slump flow. The fossil assemblage, not otherwise found in the Mudstone of the Caswell Bay area (crinoids in a slump breccia on the east side of Caswell Bay (locality 18) are allusive), must be regarded as exotic: what is then puzzling is an absence of included blocks of neritic sediments in the breccia, derived from the same sources as the fossils. A notional surge of open-sea water which brought in the fossils, and may have been linked with a triggering of the slump, is gratuitous on the evidence available, but it accords with a reconstruction that places the 'lagoonal' sediments in an environment contiguous with, or at least at no great distance from, biotas of 'standard' Dinantian type.

3. *Microfossils*

(*a*) *Foraminifers*

Foraminifers are not very common in the Caswell Bay Oolite, but they are sufficiently known to justify their allocation to the earliest Viséan stage (V_1) (see Conil & George 1973). They are rather more abundant in some of the beds of the Caswell Bay Mudstone, in which the smaller forms include earlandiids of several species, the 'calcisphaerids' *Pachysphaerina, Archaeosphaerina, Bisphaera, Diplosphaera,* and *Umbella*(?), and the tuberitines *Eotuberitina* and *Tuberitina*; and the larger forms include *Brunsia, Endothyra, Endothyranopsis, Plectogyra, Textularia, Dainella,* and *Palaeosphiroplectammina* (*mellina*). They indicate a V_1 age, probably V_{1a}, the early part of the *Eoparastaffella* (Molinacian) Stage of Conil and Pirlet. Significant absentees are archaediscids – forms in *Permodiscus* common in the immediately overlying Arundian High Tor Limestone. (See 8 and 9 of plate 13.)

(*b*) *Algae*

The calcispheres (in a descriptive rather than classificatory sense) are heterogeneous. Those more or less spherical, with an aperture, are commonly regarded as foraminifers because of their implied complex structure; they are the 'calcisphaerids' of the previous section. Much the greater number of forms in the Caswell Bay Mudstone (and some in the Oolite beneath) are, however, without an aperture and are almost always strictly spherical, and they lack established taxonomic allocation; they have been looked upon as foraminifers, as the 'resting' stages of algal spores, as hystrichospheres, as unicellular algae (which is here what they are conveniently accepted to be) but it is not a present purpose to discuss their affinities. Since the first studies of Williamson (1880) they have been divided and subdivided into 'genera' and 'species' merely on the basis of wall structure and peripheral excrescences (flares, spines, wrappings). The larger number of the Gower specimens appear to have a simple wall, but many are complex in the number and relative thickness of the concentric spheres composing them – a feature of ontogenetic development, sphere within sphere, that is not readily understood, for each internal spherical wall, presumably secreted by encysted tissue, wholly contained the tissue and inhibited secretion of a next outer embracing wall – the pattern of the spheres being expressed in the number of spheres, in the apparent density of the calcite in successive spheres, and in the granular or crystalline texture of the (present) calcitic layers and core (see plate 13). (See Derville 1931.)

Some of the ooliths in beds low in the Mudstone, as even more commonly in the Heatherslade Bed, are unusual in their cores and in their emphasis on radial structure, and they are associated with undoubted calcispheres: they promote a suspicion that they also may be partly of organic origin (see Zabrodin 1972).

Rhodophyte algae are represented, not commonly, by *Solenopora* in the Mudstone: it is accompanied by an uncertainly identified *Parachaetetes*.

Cyanophytes are found abundantly in several kinds of stromatolites and spongiostromes, whose genera as at present identified have dubious validity. Tubes of the porostrome *Girvanella* (identified as *ducii*) are rare.

Chlorophyte algae are abundant in some Mudstone beds. Codiaceans referable to *Garwoodia* and *Ortonella* are the most common: they form small nodules not always well defined when the tubules are enmeshed in other algal tissue, or relieve the uniformity of compact 'stromatolitic' lutite. Denticulate fragments, the spinous denticulations sometimes forming a mesh, are signs of *Anchicodium*-like forms (if *Anchicodium* is truly a codiacean), and reticulate forms may be affiliated. (See 4–7 of plate 14.)

Dasyclads are common and varied, although usually preserved only in small to very small fragments. *Koninckopora* (mainly as *inflata*) runs through most beds of the Mudstone, and the related *Koninckoporoides* may also be present. Coelosporellids and anatolisporellids, not surely identified in random cross-section, are repeatedly to be seen, and reticulate wisps (some preserved in oolith cores) are to be recognized in many beds (see 5 and 6 of plate 14). The floods of septate tubes found in laminae at several horizons in the Mudstone (the forms known also in the Oolite) are identified as kamaenids, *Kamaena* being regarded as a dasyclad by Antropov (1967, p. 123) and by Petryk & Mamet (1972, p. 777), although it might be a nodosinellid foraminifer, the preservation of the recrystallized walls in the Gower specimens not contributing informatively to a distinction between the two phyla (if wall structure is an adequate basis) (see 1 and 2 of plate 14). Some of the kamaenid forms, with thick walls showing rhythmical contractions, may be referable to *Pseudokamaena*, and some that hint at branching give the appearance of *Donetzella* or *Dvinella* (see Rich 1967). Other stacheiine dasyclads are new and need much further study: they include aoujgalliids of doubtful affirmities (see Termier & Termier 1950; Termier, Termier & Vachard 1977; Mamet & Roux 1977).

V. Rhythms of sedimentation

It has long been recognized that the Dinantian rocks display rhythms of sedimentation in alternating facies of relatively shallow-water rocks, identified in algal and pellet limestones, oolites, and 'lagoonal' mudstones, on the one hand, and relatively deep-water rocks, mainly crinoid-brachiopod-coral neritic limestones, on the other. In imposed 'eustatic' interpretation, the rhythmical contrasts have been ascribed to changes of sea-level, in a 'regression' of the sea in the one facies, and a 'transgression' of the sea in the other. The terms in further hypothesis have been extended to reflect 'eustatic' fluctuations in world-wide sea-level, each fluctuation useful as in isochron and thus an absolute datum in correlation (see Ramsbottom 1973, 1977).

That truly eustatic fluctuations have this universality resides in their very nature, and eustatic control was continuously operative during Chadian (as all other) times, but there is a cyclicity of argument in imposing the hypothesis in facies correlation, and then in using facies correlation to support the hypothesis. Even when assumptions of the significance of facies are set aside (that, for instance, an oolite facies implies marine 'regression' and not merely marine recession along a prograding coast without change in sea-level), the influence of local tectonic activity, in promoting differential movements of neighbouring sea-floor segments in a series of flanking swells and downwarps, is no less applicable to regional interpretations of changing sea-levels, and may locally obscure or reverse or generally overprint the changes constantly brought about by eustatic fluctuations.

Thus the Caswell Bay Oolite is pre-eminently a shallow-water deposit. At any time during its formation the depth of sedimentation was likely to have been (on analogy with present-day oolites) not more than a few metres – say, in the wide shoals and flats of an oolite bank of rapid induration and periodic erosion and corrosion, two or three metres at most. It is in its lithology a characteristic and emphatically thick example of an orthodox 'regressive' deposit, and should illustrate a corresponding hypothesis of eustatic control. Yet it is in gross of the order of 40–45 m thick. As it was never deposited in water 40 m deep, filling a depression in the sea-floor until it reached surface level, its thickness, in the general uniformity of its lithology, can be explained only if, during the whole period of its deposition, its interface with the sea was always at insignificant depth. That is, its base, resting on the Langland Dolomite, subsided 40–45 m as the sediments accumulated. The obvious inference is that as a thick formation it represents not a 'regressive' but a 'transgressive' sea whose surface level rose in relation to the Dolomite datum as sedimentation continued. Moreover, there was constantly a nice balance between potentially increasing depth of water and accumulation of sediment, so that the sea always remained very shallow no matter how fast the base subsided, and in relation to eustasy an interpretation of the Oolite as a rock of shallow-water facies implies little more than that the rate of subsidence was never so rapid that deposition could not keep pace with it. A bank environment on a regional carbonate shelf (perhaps extending from southern Ireland to Belgium) is typified in such a relationship, and was responsive less to subsuming eustatic controls than to immediate tectonic controls.

An incidental comment on the significance of facies is provided by the neritic intercalations in the Oolite, particularly in the mid part of the formation in Caswell Bay. As rocks, the crinoid-brachiopod-coral calcarenites compare closely with the overlying strongly 'transgressive' Arundian High Tor Limestone, and in petrographic isolation they no less invite the adjective 'transgressive', at least in the sense that they invaded the oolite bank from some external source; but they interfinger with and within a few metres pass laterally into massive oolite, and 'transgressive' as meaning an advance and a deepening of the sea by a eustatic change in sea-level is altogether an inappropriate word to apply to their occurrence, or at least 'transgressive' is no more an appropriate word in application to them than it is to the oolites with which they are closely associated.

The Heatherslade Bed in such a context certainly reflects a 'regression' of the sea in terminating the major 'rhythm' of the Oolite, as a rock formed at nil depth when subsidence was insufficient or too slow to sustain continued deposition; but the overlying breccia and conglomerate, and the signs of non-sequence with the Caswell Bay Mudstone above, imply that the terminus of the 'rhythm' was due to tectonic warping. The direct evidence of what formerly was called the 'mid-Avonian break' is not spectacular in Gower, where both of the Chadian formations fall into the earliest (V_1) Viséan stage, but the tectonic interruption, as major unconformity, to the Chadian rhythms of sedimentation elsewhere in South Wales – along the north crop at the base of the Pendine Conglomerate and of the Llanelly Formation – is spectacular.

The Caswell Bay Mudstone is as shallow-water a rock as the Caswell Bay Oolite, in its gypseous layers even more so. Yet its structural relation is clearly 'transgressive' even if it was deposited at insignificant depth. Although its residual thickness in Gower is not great, a mere 13 m at maximum, its basal beds were not deposited in 13 m of water, and there was no equivalently rapid subsidence to a depth of 13 m to initiate deposition: rather, all the sediments being 'intertidal' in generalized designation, its formation, like the formation of the Oolite if not so impressively sustained, gives proof of a close matching of sediment thickness with rate of subsidence, and the minor rhythmic peaks of the gypseous beds can be looked on as signs of brief intervals when sedimentation rate exceeded subsidence rate.

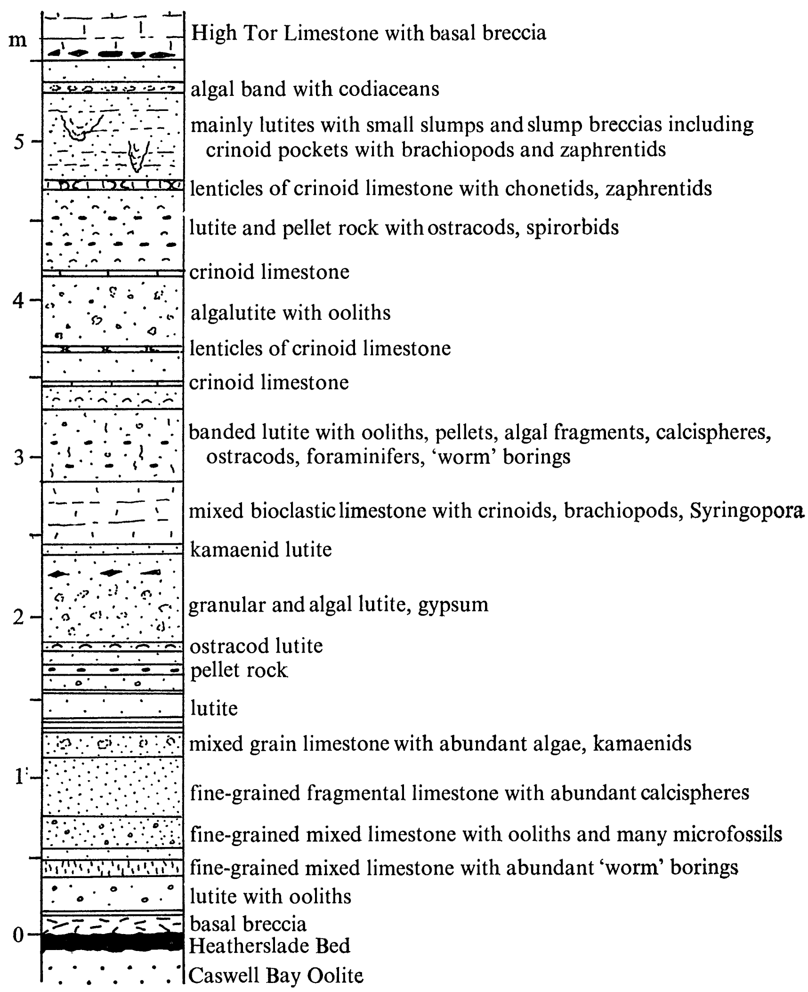

Figure 14. Generalized column of the Caswell Bay Mudstone in Three Cliffs Bay (locality 7), to illustrate the repetition of rock types in the unitary formation.

In short, the Chadian rocks are in composite suite the products of deposition in a fully transgressive sea, the transgression being due to tectonic warping superposed on whatever (positive and negative) eustatic movements may have taken place. They reflect in their contrasted facies tectonically induced palaeogeographical changes in the regional carbonate shelf and are not suitable criteria for more extensive Dinantian correlation beyond South Wales. (See figure 14.)

The abrupt ending of the Chadian rhythms in Gower is even more obviously a product of tectonic deformation. Pre-Arundian uplift (see p. 458), with tilting, differential erosion, and locally complete erosion of the Caswell Bay Mudstone, was self-evidently a result of the regression of the sea through a local lowering of sea-level, and of later subsidence; and the deposition of the High Tor Limestone (a result of transgression and a deepening of the sea) was a major tectonically induced cyclical turnover. The change was only insignificantly 'eustatic', for beyond Gower in the Ffwrwm gorge in Gwent (see Dixey & Sibly 1918, p. 155; George 1954, p. 308) the Arundian sediments, containing *Permodiscus*, are in 'lagoonal' facies, and even in Gower itself the Arundian beds, at about 25 m above the base, contain lutitic and 'worm'-bored layers, with dolomitic 'shales', like those of the Caswell Bay Mudstone and are themselves internally cyclical.

The minor rhythms within the Mudstone, which at any one locality are many and varied, are thus not to be attributed to wide fluctuations in depth of sedimentation that followed from rapidly repetitious 'regressions' and 'transgressions'. The alternations of lutites and oolites, pellet rocks and ostracod limestones, calcisphere floods and kamaenid floods, neritic films and gypseous layers, recurrent in thicknesses of a few centimetres, sometimes a few millimetres, are to be explained – in their detail they cannot yet be explained – by trivial changes in depth, or variable salinity, or current direction, or subtly responsive biotas. And although the lithological differences between one lamina and another are in a descriptive sense enormous, they do not vitiate the generalization that they belong to sediments all intimately congeneric in the particular environment of the Chadian shelf.

It may be added that several factors control what appears to be 'regression' or 'transgression', beyond simple 'eustatic' change. These include an advancing sediment front, with a migrating 'strand' and with lateral change in sediment facies as progradation continues, a relation truly described as a marine recession, although there may be no change in local sea-level. Conversely, a receding coast, the sea undercutting its mud banks and eating into its hinterland, or perhaps affected only by diminishing sedimentation as channels of sediment-transport migrate or mud-flats become very wide and water-filmed, may be attributed to a marine transgression, also without change in sea-level. In such very shallow-water rocks, heavy rains, or exceptionally high tides or occasional storms, may be far more influential in controlling lithofacies (and attendant biofacies) than what at most must have been very minor eustatic effects.

VI. Depositional environments of the Chadian rocks

1. *An oolite bank*

The *Caninia* Oolite of the South-Western province, as the regional formation of which the Caswell Bay Oolite is the local representative, has a distributional range in present outcrop from Dyfed to the Mendips for some 180 km along the strike and in places for not less than 60 km across the strike. It thus formed a large oolite bank in the Dinantian sea. Unfortunately its lateral relations with other rock types are unknown in South Wales, northwards because of unconformable overstep at the multiple 'mid-Avonian break', southwards because of a Mesozoic cover and of erosion over the crests of anticlinal folds. Reconstructed relations in Dyfed between the Pembroke–Tenby and Bullslaughter folds (see Dixon 1921, pp. 88, 100, 126; George 1970, fig. 21), and again in the Mendips (if the Vallis Limestone is correlative at least in part with the Gully Oolite: see George *et al.* 1976, fig. 4), suggest a passage southwards from oolites into highly fossiliferous crinoid-brachiopod-coral limestones of a neritic open-sea environment.

Equivalent southward passage in Glamorgan, including Gower, is not known, the *Caninia* Oolite being well developed in southernmost outcrops. It is then only analogy, but not unconvincing analogy, to see the intercalations of neritic limestones in the Caswell Bay Oolite, notably on Worms Head and in Caswell Bay, to be incipient signs of transition like that in Dyfed and the Mendips, and to postulate that a belt of bioclastic limestones formed the lower Chadian rocks to the south of Gower. The sea-floor slope between the oolite bank and the 'off-shore' neritic limestones may well have been relatively steep, for subsidence in Dyfed, judged by corresponding thicknesses of sediment, was certainly greater to the south than it was to the north; and the bank, a geomorphic as a tectonic shelf, was a uniform area of lively waters fed by unimpeded constant net flow of the sea into a widely extensive evaporating pan of brines and variably saline deposits.

It required only insignificant uplift, of only a metre or two, to encourage the algal growths of the Heatherslade Bed – or if not a positive uplift a relative change in sea-level perhaps by decelerated subsidence. The bed offers analogy with the algal mats of many present-day tropical and subtropical intertidal zones where stromatolotic and spongiostrome growths are widespread (see for example Logan *et al.* 1974; Friedman *et al.* 1973). A feature of the Gower growths is that they are more or less continuously and uniformly sheet-like and were not built up or controlled in their growth into separate colleniid mounds or other pillared structures (although they may be nodular and are commonly noded), and they did not provide niche environments for enveloping sediments or habitats for niche biotas.

Like its oolite foundation, the Heatherslade Bed in the distributional persistence of the algal mat is witness to a singularly unchanging beach-flat topography, for not only is it to be found almost everywhere in Gower (except where it is overstepped), but the outcrop at West Williamson in Dyfed, 45 km to the west of Spaniard Rocks (see Sullivan 1966, pl. IIIB), and the section near Miskin in the Vale of Glamorgan, 40 km to the east of Langland (see Dixey & Sibly 1918, p. 153), are even more impressive as signs of its range. Its transition from the oolites below rather than to the Mudstone above is strengthened in a negative way by its absence beneath the Pendine Conglomerate, only 22 km from Spaniard Rocks in a traverse towards West Williamston (see George *et al.* 1976, figure 5).

2. *'Lagoonal' sediments*

The intimate association of a great variety of limestones in the Caswell Bay Mudstone, and the rapid alternation of kinds, demonstrate the fluctuation in process that brought about the contrats as formations between the Mudstone and the Oolite. This is obvious in the general sequence (see figure 14), but even in a rock column of the Mudstone a mere 10 cm high (see figure 15; compare 4 of plate 10, and 8 of plate 3), twenty or so separately distinguishable laminae of about six major kinds of limestone, from compact calcilutites to algal films to oolites and mixed calcararenites, indicate correspondingly rapid changes in detailed sedimentary process, and only in a few instances, notably of the 'white bed' in Caswell Bay, is there indication of a continuity of unchanged process through thicknesses approximating to a metre. Yet the association of limestones is so intricate, and the recurrence of types so repetitive, that the formation is properly generalized as a unity, and an emphasis on details of contrasting lithology should not obscure the reciprocal facies relations of the several kinds of sediment.

Although all factors cannot now be known (for some were ephemeral, not preserved in

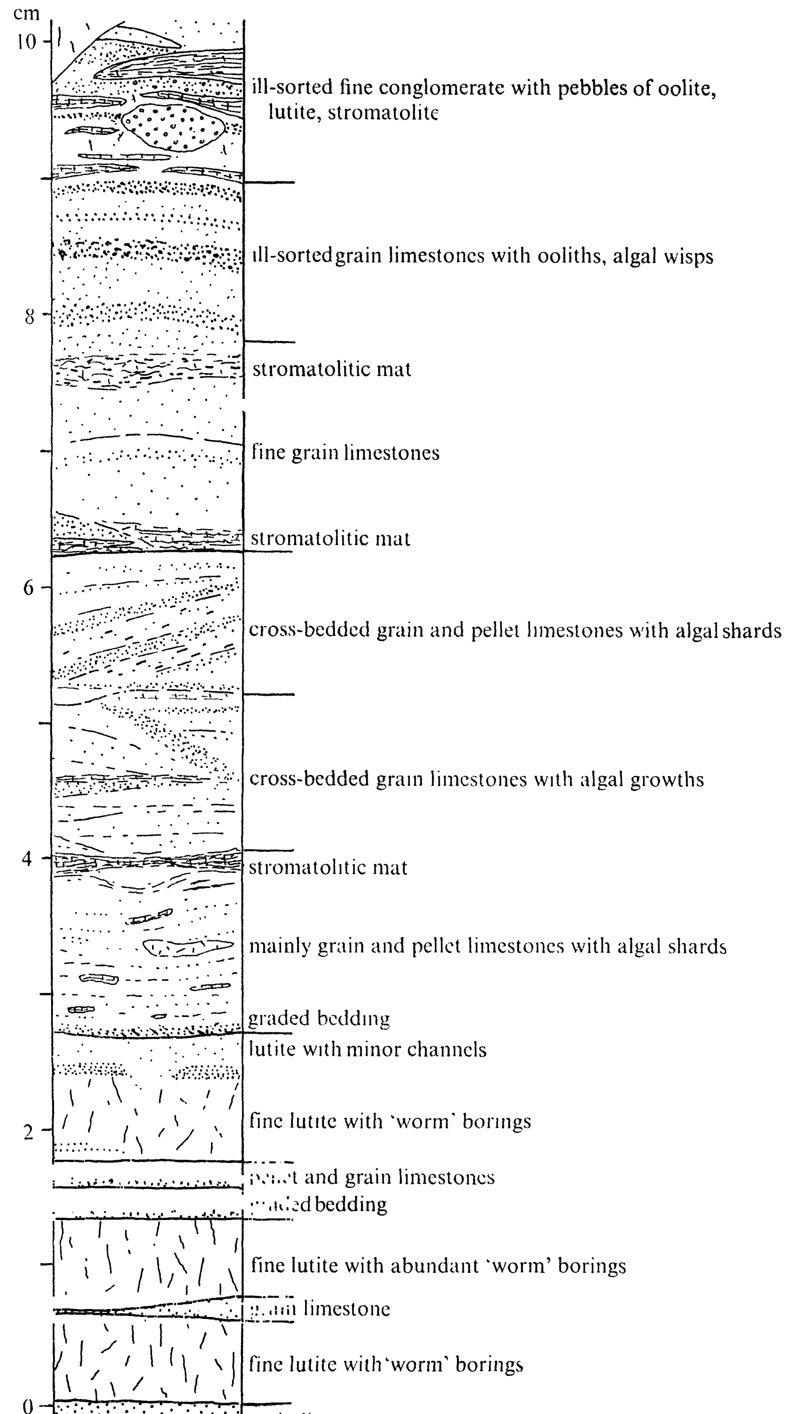

Figure 15. An illustrative column, to show the rapid alternation of sedimentary types in a short (10 cm) section of the Caswell Bay Mudstone, about 0.6–0.7 m above the Heatherslade Bed, Spaniard Rocks (locality 5).

permanent effects on the sediments), the controls on process and on abrupt changes in process need not be wholly cryptic. The differences between a compact lutite of gentle algal-filtered origin and a mixed current-bedded oolite–calcarenite of agitated-water origin may at least in part be attributed to contrasts between back-water and main-stream, or between bonded substrate and loose substrate, or between immediately endogene or partly exogene sources, or simply between tidal-flat quiescence and wind-driven wave-driven swash; and further inference

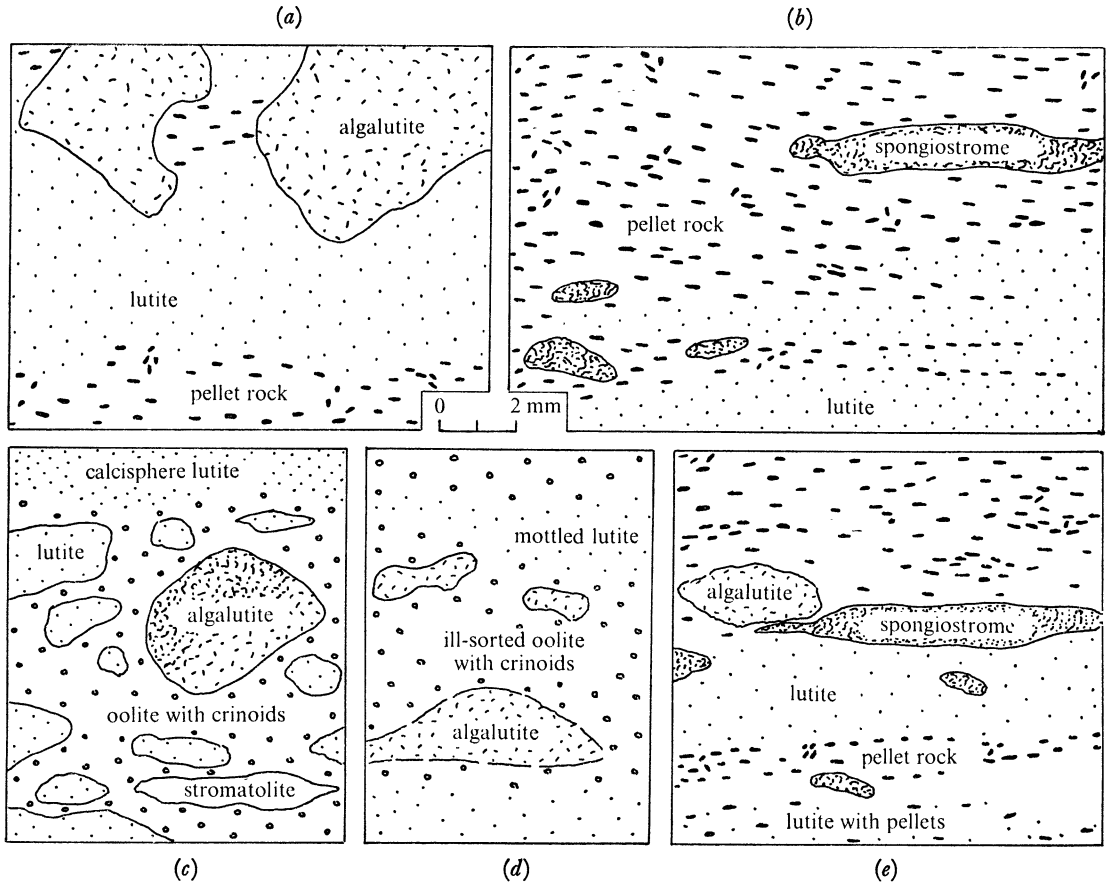

FIGURE 16. The lithology of illustrative rock types in the Caswell Bay Mudstone. (*a*) The 'white bed', about 6.0 m above the Heatherslade Bed, Caswell Bay (locality 17). (*b*) About 3.3 m above the Heatherslade Bed, Spaniard Rocks (locality 5). (*c*) About 4.8 m above the Heatherslade Bed, Heatherslade (locality 10). (*d*) About 0.6 m above the Heatherslade Bed, Spaniard Rocks (locality 5). (*e*) About 1.1 m above the Heatherslade Bed, Spaniard Rocks (locality 5).

of the dependence of lithology on water régime in a very narrow depth-range is convincing to the point of being obvious. Moreover, the individual rock unit, commonly a lamina of small thickness, is rarely persistent over long distances, and while regional subsidence during Mudstone formation may have been uniform in Gower (as judged by uniformity of facies thickness) it did not ensure uniformity of sedimentation type from one locality to the next. There was no general carpeting of the sea-floor by a lutite-depositing algal film at any one 'moment', to be followed by a sweeping-in of coarse-grained arenite at a 'moment' later: rather, the sequence at any one locality rarely matches precisely the sequence at the next, so that close correlation is difficult. At best, there is only a suggestion that a few of the more prominent beds, like the kamaenid limestones and the mid-formation gypeous laminae, may be identified in relatively extensive development. More often it appears that there were localized tracts of sedimentation and sediment dispersal that gave the sea-floor a patterned variability of sediment types at any one moment (compare Heckel 1972).

To call the sediments 'lagoonal' is to use the term negatively, as meaning not open-sea marine. The geography of the 'lagoon' is not easily made out. Control of sedimentation by such definable geomorphic features as embayments, inlets, channels, or barriers is unknown, and it may be that little more than distance across wide but persistently very shallow flats was needed to keep out the sea or to diminish its effects, with perhaps the most gentle of shoals, a metre or less in height, to give some containment to mud pockets separated from coarser detritus. Within the flats, very minor changes in current-flow direction or intensity had major effect on a lateral shifting of sediment type, and in very shallow water of fluctuating salinity (to hypersaline) variability was relatively great (see figure 16).

The margins of the 'lagoon' are difficult to discern when southward passage into non-lagoonal rocks is not to be seen in the Gower outcrops. Even in Dyfed the similar 'lagoonal' rocks of West Williamston and Tenby are not to be seen in the folds to the south until their equivalents appear in the Pembroke and Bosherston synclines, where the Chadian beds are neritic bioclastic limestones (see Sullivan 1965, pp. 289 *et seq.*); and in the Bristol–Mendip country also the Clifton Down Mudstone (which includes both Chadian and Arundian strata) is not traceable across the intervening ground southwards into the Vallis Limestone. Nevertheless, the southward disappearance of the 'lagoonal' sediments is in simplest interpretation to be ascribed to lateral passage into neritic bioclastics best represented by the Berry Slade Formation in southernmost Dyfed, in which the Hanging Tar reefs may conceivably have been a local barrier between 'lagoon' and open sea (see George *et al.* 1976, fig. 5).

Along the north crop in South Wales the Calcite-Mudstone Group, to which the Caswell Bay Mudstone belongs, becomes richer in algal nodules and sheets and much more terrigenous (with cacareous sandstones, quartzites, and conglomerates) at West Williamston and Pendine in Dyfed, and in the Llanelly Formation (which contains gypseous layers) in Powys. The evidence is now widely scattered, fragmented, and residual, with a wide gap between north and south crops, but generally it confirms, and finds its place in, an inference of a Viséan landward approach to the north (where lay the hinterland of St George's Land), a seaward approach to the south. A Chadian thickening northwards from Glamorgan into Powys is then anomalous: like the northward thickening in the residual sediments of Gower, it may be a sign of pre-Arundian warping.

The derivative palaeogeographical reconstruction confirms and amplifies much earlier work (see George 1958, fig. 8). It departs widely from the model recently proposed by Bhatt (1976, fig. 8), in which an extensive but static reef and back-reef complex with east-and-west strike, persisting through late-Couceyan, Chadian, Arundian, and Holkerian strata, is postulated in southern Powys and Glamorgan and runs into Gwent. There is in fact no sign in the field of any such complex, or indeed of any kind of reef, at any horizon in the area, despite comprehensive outcrops of bioclastic limestones and oolites.

VII. Arundian overstep

Evidence of overstep by the Arundian High Tor Limestone is multiple. The lithological contacts with the Caswell Bay Mudstone are marked by an overt sign of discordance when at most localities the uppermost lutites of the Mudstone are eroded to produce flakes, up to 12–15 cm in length, incorporated in a breccia bed, sometimes 12–15 cm thick, forming the basal member of the overlying coarsely crinoidal limestones of Arundian age. The high angularity of the flakes, and the lack of any signs of rolling, imply subaerial cracking and fracturing, with little abrasive transport at the first influx of the Arundian sea. Correspondingly, the topmost surface of the Mudstone shows in local detail high irregularity of profile, truncated laminae at the erosional contact, and minute pock marks as corrosive etching. (See 1 of plate 16.)

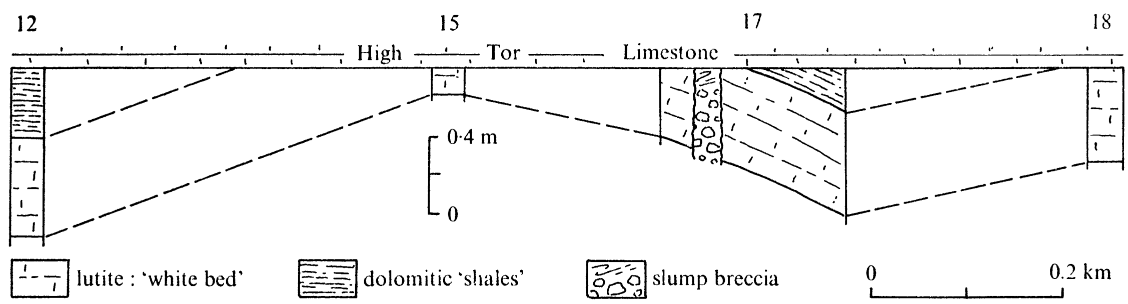

Figure 17. Diagrammatic representation of Arundian overstep in Caswell Bay. The linear relations in present outcrop are misleading, for acute structures, folds and thrusts, lie between each exposure and the next.

Angular discordance is visible in Caswell Bay (locality 17), where the base of the High Tor Limestone rests on dark dolomitic 'shales', ½ m thick, well seen along the eastern cliffs of the exposure, but descends, with a wedging-out of the 'shales', onto the prominent lutite of the 'white bed' as it is followed to the western cliffs of the exposure. An insight into the structural relations is given by the pre-Arundian slumping spectacular in the western cliffs, where the richly crinoidal Arundian base is welded to the 'white bed' along the greater part of the cliff face, except over the slumped masses which incorporate highly contorted dolomitic 'shales' as matrix for the lutite blocks in the breccia, to demonstrate that the 'shales' were in place above the 'white bed' at the moment of slumping (see plate 12). The 'shales' are absent at other points in the bay (localities 14, 15, 18) and in Langland Bay (locality 19), but they reappear, underlain by the 'white bed', in the westernmost Caswell exposure (locality 12). (See figure 17.)

The overstep is emphasized in southerwestern Gower, where the Caswell Bay Mudstone is absent and where the discordance is impressively visible in truncation of the Caswell Bay Oolite by the basal bed of the High Tor Limestone. The junction, exposed for many metres on Worms Head (localities 1, 2, 3) and particularly in Fall (locality 4), is firmly welded to and shows gentle swags and some channelling in the Oolite, with *Syringopora* colonies neatly truncated at the Arundian base. Under the microscope, ooliths *in situ* are seen to be smoothly planed at the junction, and other derived ooliths, mostly corroded, some isolated and 'floating', some in pebbles of oolite, are incorporated in the bioclastic limestones above (see 2 of plate 16). The perfect welding of the formations at the junction, without a suggestion of bedding-plane parting between the two, is surprising. On the other hand, a persistent feature, to be seen also in the

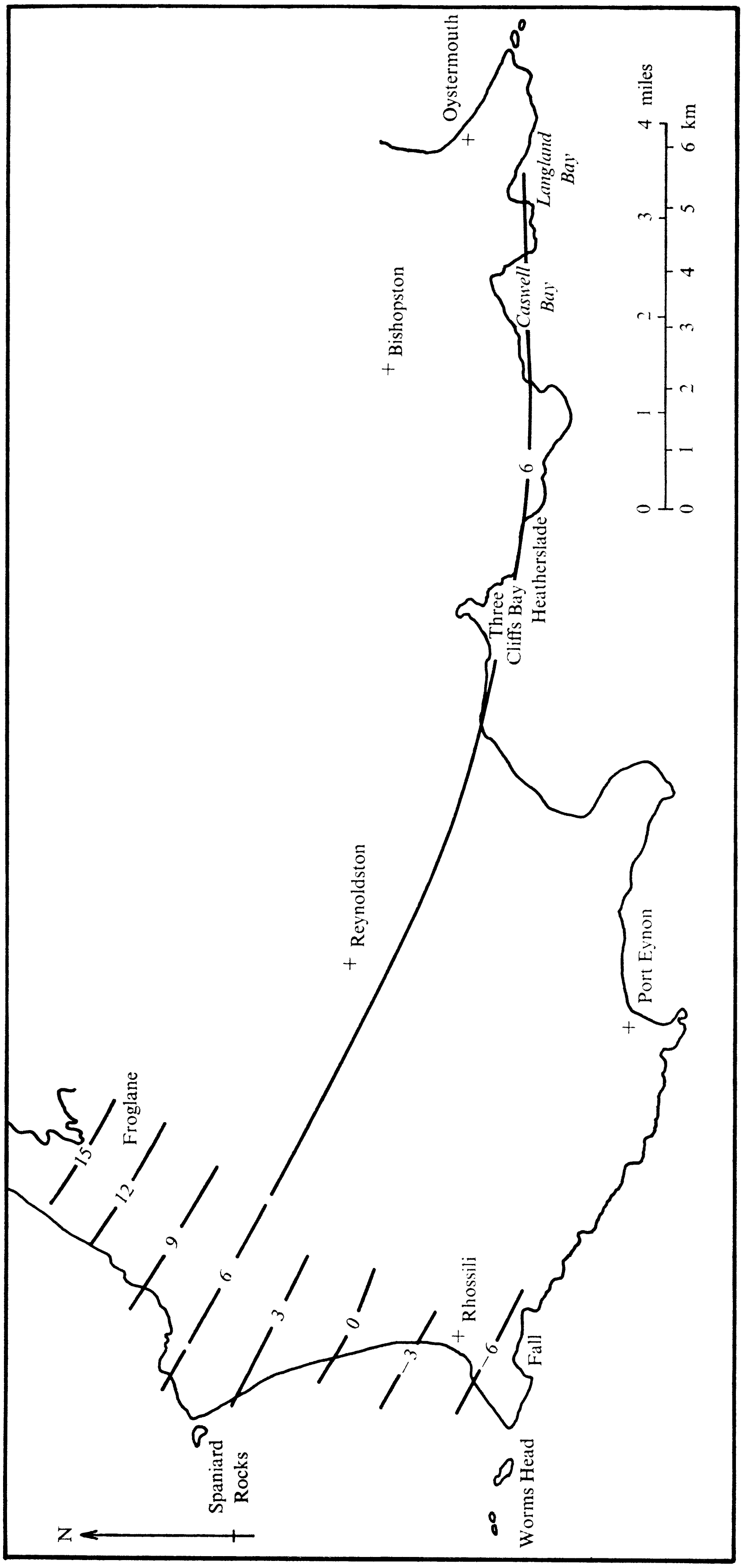

FIGURE 18. Generalized isopach map of the Caswell Bay Mudstone in Gower, structural complications discounted. Isopachs in metres.

outcrops of eastern Gower, is the occurrence of a film, 2–3 mm thick, developed on the eroded Chadian surface of whatever kind of rock, oolite or lutite, as the first sediment of the Arundian limestones: it contains an abundance of foraminifers, together with large macrofossils – crinoids, corals, brachiopods, bryozoans – and suggests a mucilaginous pelogloeal growth on a newly invaded 'shore' platform.

The overstep is confirmed by the foraminifers. The Mudstone contains forms characteristic of early V_1, probably V_{1a}, in Belgium, while the High Tor Limestone, within a millimetre of its base, contains large specimens of *Permodiscus*, characteristic of V_2.

The form of the Arundian overstep may be determined, at least approximately, by the pattern of isopachs in the Caswell Bay Mudstone. A Mudstone thickness of the order of 6 m is fairly uniform from Langland Bay to Three Cliffs Bay. Although the thickness cannot now be measured at Froglane (locality 6), it shows an increase there to about 13 m (see Dixon & Vaughan 1912, table I); and it is reduced to rather less than 3 m at Spaniard Rocks (locality 5). The degree of overstep is not known in the southwestern outcrops of Worms Head and Fall, where not only is the Mudstone missing but the Heatherslade Bed also, and although the Caswell Bay Oolite preserved is about 40 km thick (not greatly different from its thickness in eastern outcrops) its original thickness is unknown; but if the effects of the overstep are notionally maintained in a postulated isopach gradient of about 4 m per km, some 5–6 m of Oolite are extinguished in southerwestern outcrops. A zero isopach in a Mudstone feather-edge may then be located a little north of Rhossili, and a generalized isopach map may be constructed (see figure 18).

The map is certainly grossly over-simple – it wholly neglects the redistribution of rock-loci by post-Arundian (Hercynian) folding, and is quite without evidence in the empty ground between the eastern and the north-western outcrops – but it gives some indication of the rate of overstep, and in its essence it is to be accepted. The overstep is not exceptional in South Wales – similar breaks are to be identified at other Dinantian horizons – and might be regarded as implied in the great lithological contrasts between the neritic Arundian rocks and the 'lagoonal' and oolitic Chadian rocks. It is a lithological comment, however, on Dixon's misapplied zonal linking of the Caswell Bay Mudstone with the High Tor Limestone in the Avonian Upper *Caninia* (C_2S_1) Zone, the link now being shown to be broken on the basis of Dixon's own measure of stratal grouping in relation to rhythmic pulses of sedimentation and of tectonic warping (see George 1955, p. 332).

The map also brings out the high importance of the pattern of overstep in its comment on regional palaeogeography in South Wales, for it indicates a pre-Arundian upwarp to the south-west of Gower in a position unexpected and anomalous, and although the upwarp was relatively mild and is known only locally in its Dinantian context, it has tectonic significance in discouraging a naive interpretation of Chadian–Arundian stratigraphy that, as in Dyfed, attributes a southward disappearance of the facies of the Calcite-Mudstone Group (and of the *Caninia* Oolite) to simple lateral change by passage from very shallow-water into 'off-shore' neritic sediments. It may also have significance in anticipating upwarps in the region of the Bristol Channel that (on sedimentological evidence) are surmised to have controlled deposition during Silesian times. It may also incidentally offer a reason for the occurrence of exotic well-preserved neritic fossils in the slump breccias in Caswell Bay if gentle warping had incipiently begun during Mudstone times to promote a sliding of the sediments northwards.

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References

Aitken, J. D. 1967 Classification and environmental significance of cryptalgal limestones and dolomites. *J. sedim. Petrol.* **37**, 1163–1178.

Antropov, I. A. 1967 In *Fossil algae of the U.S.S.R.* (ed. T. F. Vozhennikova) Moscow.

Bhatt, J. J. 1975 Evidence of evaporite deposition in the Lower Carboniferous Main Limestone Series in South Wales, U.K. *Sedim. Geol.* **13**, 65–70.

Bhatt, J. J. 1976 Geochemistry and petrology of the Main Limestone Series (Lower Carboniferous), South Wales, U.K. *Sedim. Geol.* **15**, 55–86.

Conil, R. & George, T. N. 1973 The age of the *Caninia* Oolite in Gower. *C. R. 7me Congr. intern. Strat. Géol. Carb. Krefeld 1971*, **2**, 323–330.

Derville, P. H. 1931 *Les marbres du Calcaire Carbonifère en Bas-Boulonnais*. Strasbourg.

Dixey, F. & Sibly, T. F. 1918 The Carboniferous Limestone Series in the south-eastern part of the South Wales coalfield. *Q. J. geol. Soc. Lond.* **73**, 111–164.

Dixon, E. E. L. 1921 The country around Pembroke and Tenby. *Mem. geol. Surv. U.K.*

Dixon, E. E. L. & Vaughan, A. 1912 The Carboniferous succession in Gower (Glamorganshire). *Q. J. geol. Soc. Lond.* **67**, 477–571.

Evans, G., Schmidt, V., Bush, P., & Nelson, H. 1969 Stratigraphy and geological history of the sabkha, Abu Dhabi, Persian Gulf. *Sedimentol.* **12**, 145–199.

Friedman, G. M., Amiel, A. J., Braun, M., & Miller, D. S. 1973 Generation of carbonate particles and laminites in algal mats: example from sea-marginal saline pool, Gulf of Aqaba, Red Sea. *Bull. Am. Assoc. Petrol. Geol.* **57**, 541–557.

Gebelein, C. D. 1969 Distribution, morphology, and accretion rate of Recent subtidal stromatolites in Bermuda. *J. sedim. Petrol.*, **39**, 49–69.

George, T. N. 1940 The structure of Gower. *Q. J. geol. Soc. Lond.* **96**, 131–198.

George, T. N. 1954 Pre-Seminulan Main Limestone of the Avonian Series in Breconshire. *Q. J. geol. Soc. Lond.* **110**, 283–322.

George, T. N. 1955 In field meeting in South Wales (ed. B. Simpson). *Proc. Geol. Assoc.* **65**, 328–337.

George, T. N. 1958 Lower Carboniferous palaeogeography of the British Isles. *Proc. Yorks. geol. Soc.* **31**, 227–318.

George, T. N. 1969 British Dinantian stratigraphy. *C. R. 6me Congr. intern. Strat. Géol. Carb. Sheffield 1967*, **1**, 193–218.

George, T. N. 1970 British regional geology: South Wales. *Inst. geol. Sci.*

George, T. N. 1972 The classification of Avonian limestones. *J. geol. Soc. Lond.* **128**, 221–256.

George, T. N. 1974 Lower Carboniferous rocks in Wales. In *The Upper Palaeozoic and post-Palaeozoic rocks of Wales* (ed. T. R. Owen), pp. 85–115. Cardiff.

George, T. N. & Howell, E. J. 1939 Goniatites from the Caninia Oolite of Gower. *A. Mag. nat. Hist.* **(11)** 4, 545–561.

George, T. N., Johnson, G. A. L., Mitchell, M., Prentice, J. E., Ramsbottom, W. H. C., Sevastopulo, G. D. & Wilson, R. B. 1976 A correlation of the Dinantian rocks of the British Isles. *Spec. Publ. geol. Soc. Lond.* 7.

Heckel, P. H. 1972 Recognition of ancient shelly marine environments. *Spec. Publ. Soc. econ. Paleontol. Mineral.* **16**, 226–285.

Hofmann, H. J. 1969 Attributes of stromatolites. *Pap. geol. Surv. Can.* 69–39, 1–58.

James, M. D. & Thomas, L. P. 1966 Palaeocurrents in some Gower oolites. *Geol. Soc. J. Univ. Coll. Swansea* **4**, 5.

Kendall, C. G. & Skipwith, F. A. 1969 Holocene shallow-water carbonate and evaporite sediments of Khor al Baxam, Abu Dhabi, south-west Persian Gulf. *Bull. Am. Assoc. Petrol. Geol.* **53**, 841–869.

Leeder, M. 1975 Lower Border Group (Tournaisian) stromatolites from the Northumberland basin. *Scott. J. Geol.* **11**, 207–226.

Llewellyn, P. G. & Stebbins, R. 1970 The Hathern Anhydrite Series, Lower Carboniferous, Leicestershire, England. *Trans. Inst. Min. Metall.* **79B**, B1–15.

Logan, B. W., Read, J. F., Hagan, G. M., Hoffman, P., Brown, R. G., Woods, P. L. & Goebelein, G. D. 1974 Evolution and diagenesis of Quaternary carbonate sequences, Shark Bay, Western Australia. *Mem. Am. Assoc. Petrol. Geol.* 22.

Mamet, B. & Roux, A. 1977 Alques Rouges Dévoniennes et Carbonifères de la Tethys occidentale. *Rev. Micropaléontol.* **19**, 215–256.

Monty, C. L. V. 1967 Distribution and structure of recent stromatolitic algal mats, Andros Island, Bahamas. *Ann. Soc. géol. Belg.* **90**, 55–102.

Petryk, A. A. & Mamet, B. 1972 Lower Carboniferous alga flora, south-western Alberta. *Can. J. Earth Sci.* **9**, 767–802.

Ramsbottom, W. H. C. 1973 Transgressions and regressions in the Dinantian: a new synthesis of British Dinantian stratigraphy. *Proc. Yorks. geol. Soc.* **39**, 567–607.

Ramsbottom, W. H. C. 1977 Major cycles of transgression and regression (mesothems) in the Namurian. *Proc. Yorks. geol. Soc.* **41**, 261–291.

Reynolds, S. H. 1921 The lithological succession of the Carboniferous Limestone (Avonian) of the Avon section at Clifton. *Q. J. geol. Soc. Lond.* **77**, 213–245.

Rich, M. 1967 *Donetzella* and *Dvinella*, widespread algae in Lower and Middle Pennsylvanian rocks in east-central Nevada and west-central Utah. *J. Paleontol.* **41**, 973–980.

Stephens, J. V. 1973 Geol. Surv. 1-inch map 247 (Swansea). Revised edit. *Inst. geol. Sci.*

Strahan, A. 1907 West Gower and the country around Pembrey. *Mem. geol. Surv.*

Sullivan, R. 1965 The mid-Dinantian stratigraphy of a portion of central Pembrokeshire. *Proc. Geol. Assoc.* **76**, 283–300.

Sullivan, R. 1966 The stratigraphical effects of the mid-Dinantian movements in south-west Wales. *Palaeogeogr. Palaeoclimatol. Palaeocol.* **2**, 213–244.

Termier, H. & Termier, G. 1950 Paléontologie marocaine. 2. Invertèbres de l'Ere Primaire. *Notes Méms Serv. Mines Maroc* 73.

Termier, H., Termier, G. & Vachard, D. 1977 Moravamminida and Aoujgalliida (Porifera, Ichthyospongia). In *Fossil Algae* (ed. E. Flugel). Berlin and New York.

Toomey, D. F. 1974 Algally coated grains from the Leavenworth Limestone (Upper Pennsylvanian, mid-central region, U.S.A.) *N. J. Geol. Paläontol.* 1974–73, 175–191.

Toomey, D. F. 1975 Rhabdoliths from the Upper Palaeozoic of Kansas and the Recent – a comparison. *N. J. Geol. Paläontol.* 1974–75, 242–255.

West, I. M., Brandon, A. & Smith, M. 1968 A tidal flat evaporitic facies in the Viséan of Ireland. *J. sedim. Petrol.* **38**, 1079–1093.

Williamson, W. C. 1880 On the organisation of the fossil plants of the Coal Measures: X. *Trans. R. Soc. Edinb.* **17**, 493–519.

Wolf, K. H. 1965 Littoral environment indicated by open-space structures in algal limestones. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **1**, 183–233.

Zabrodin, V. K. 1972 Upper Riphaean oncolites of the Urals and Spitsbergen. *Trans. Acad. Sci. U.S.S.R. geol. Inst.* **217**, 52–105.

[Plates 1–16 have been printed at the University Press, Oxford.]


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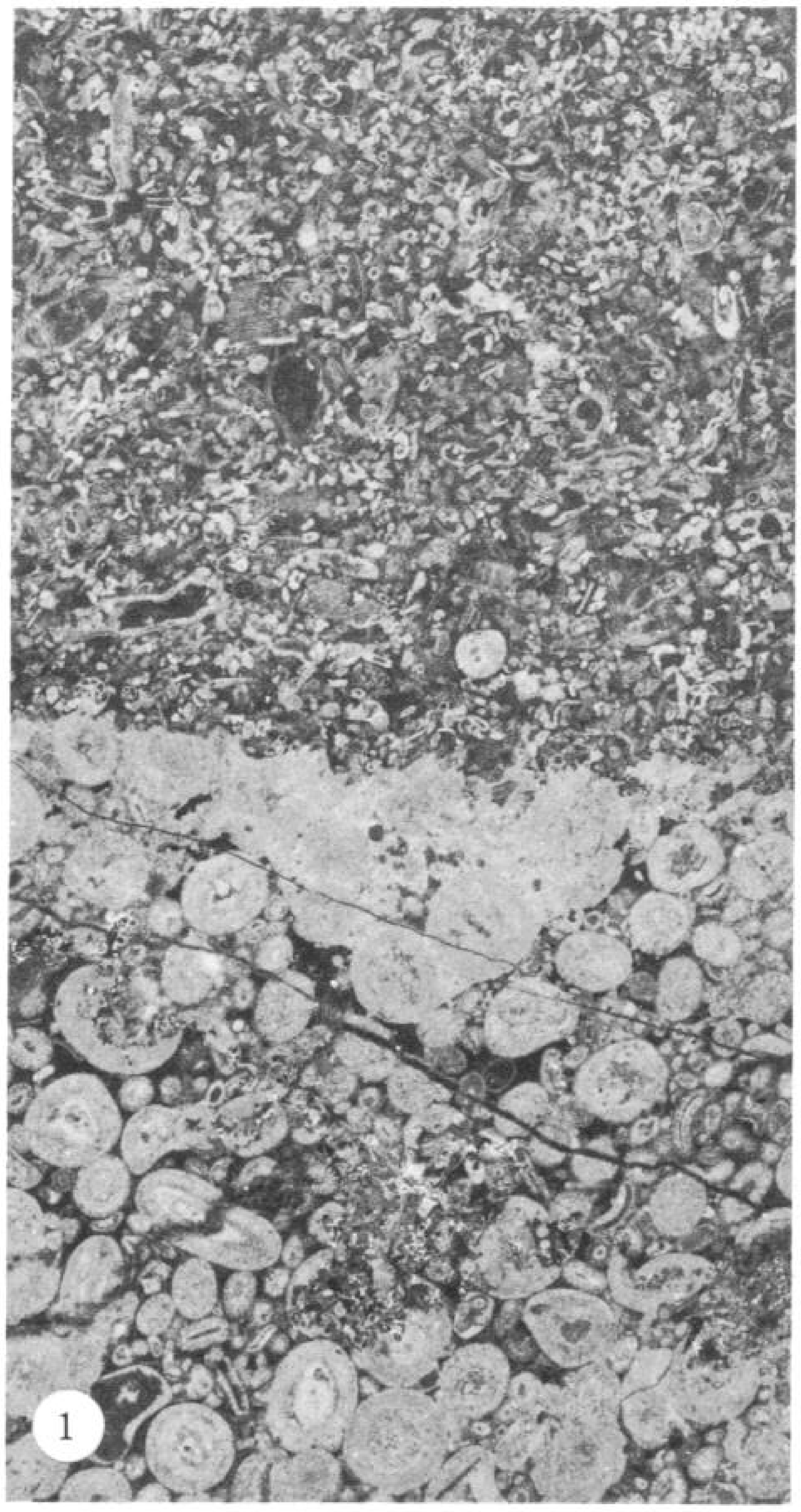
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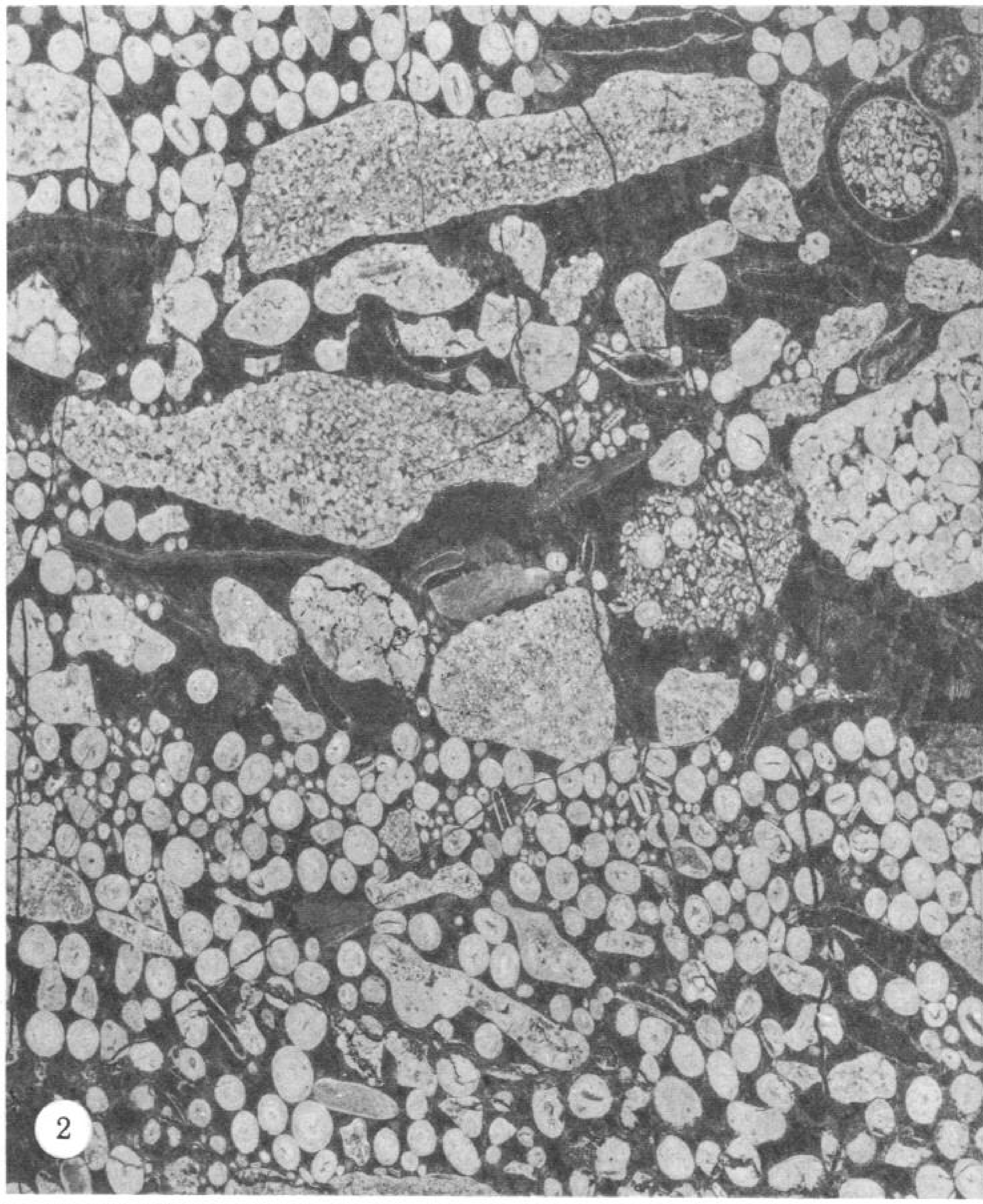
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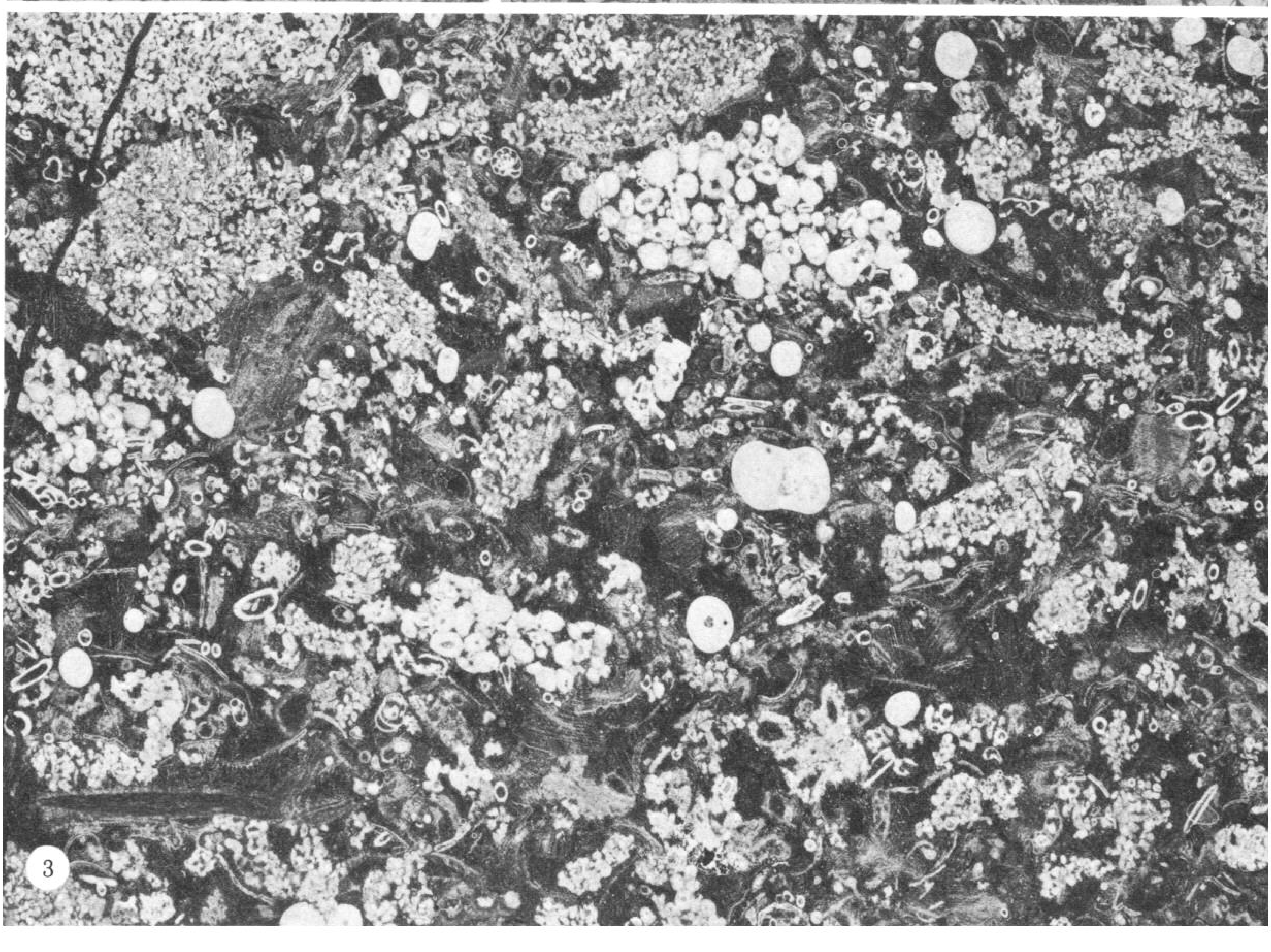
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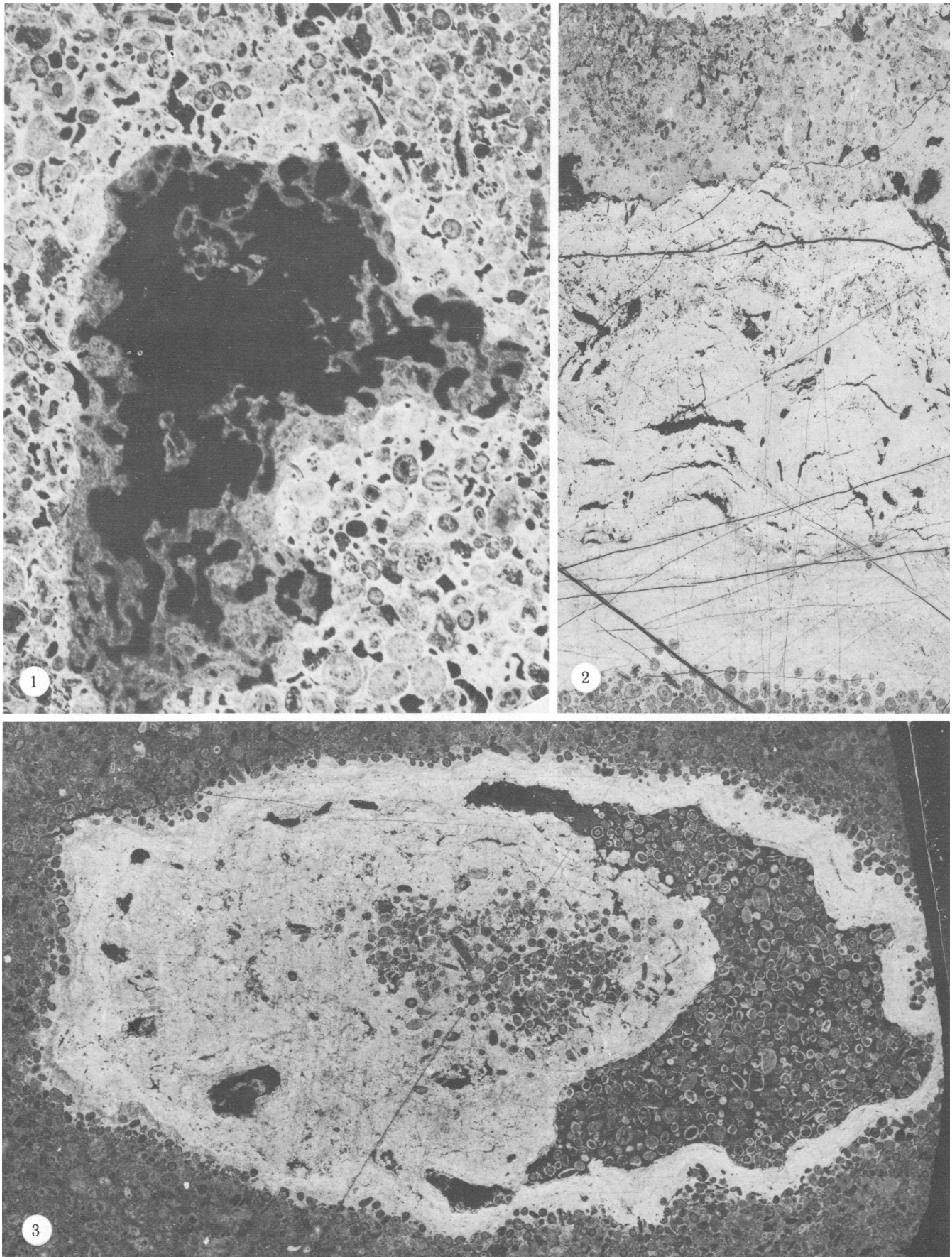
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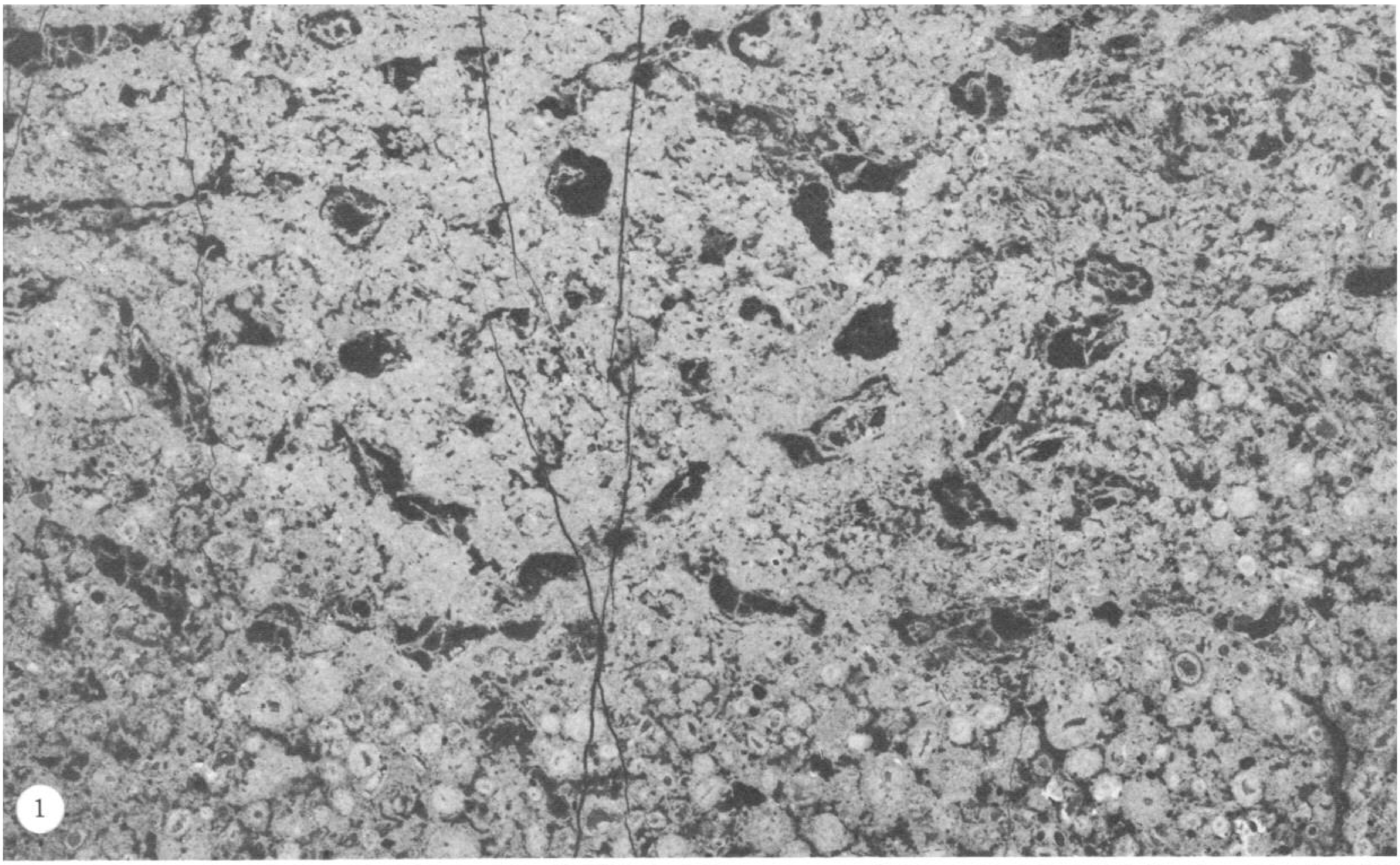
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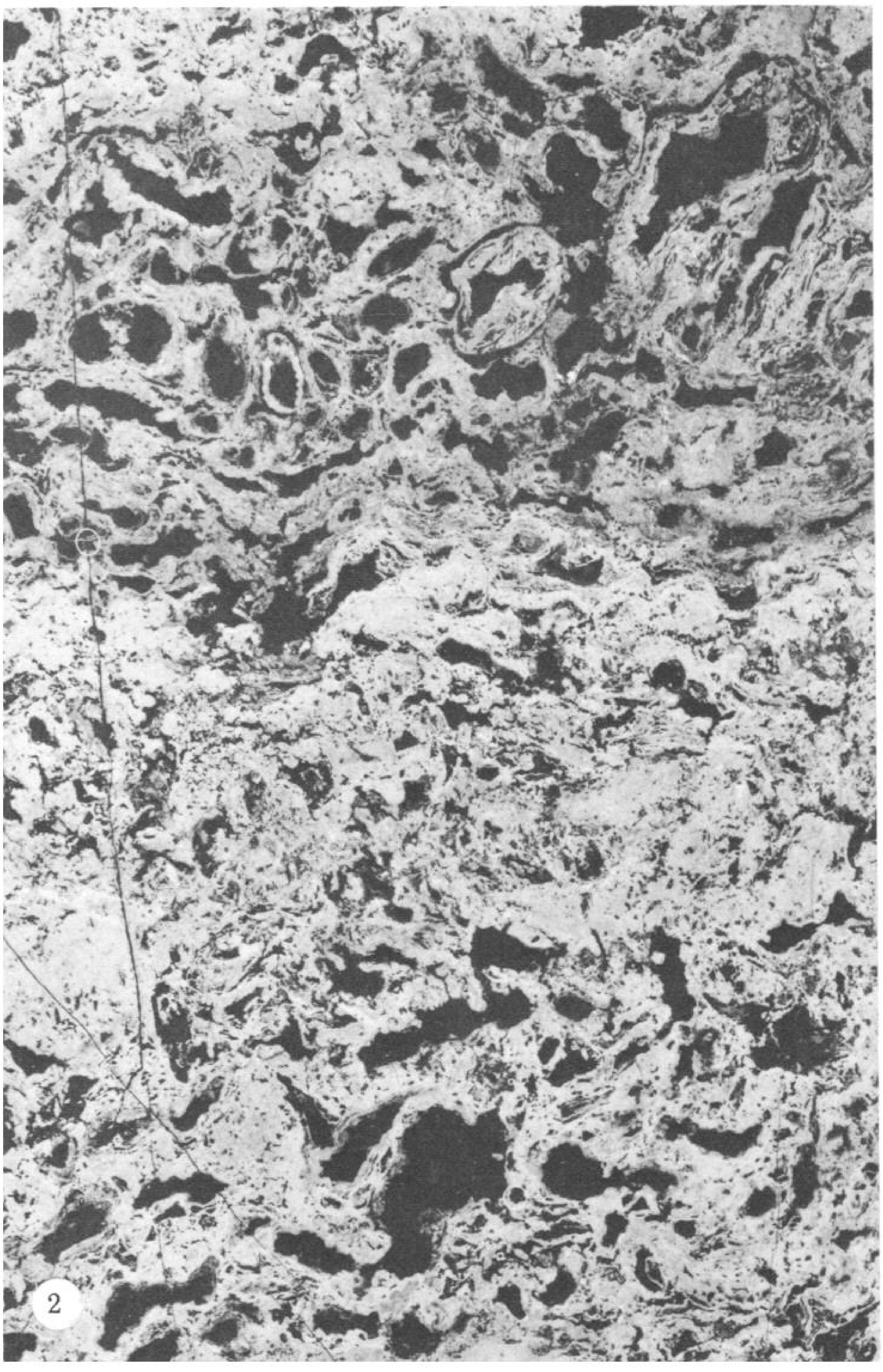
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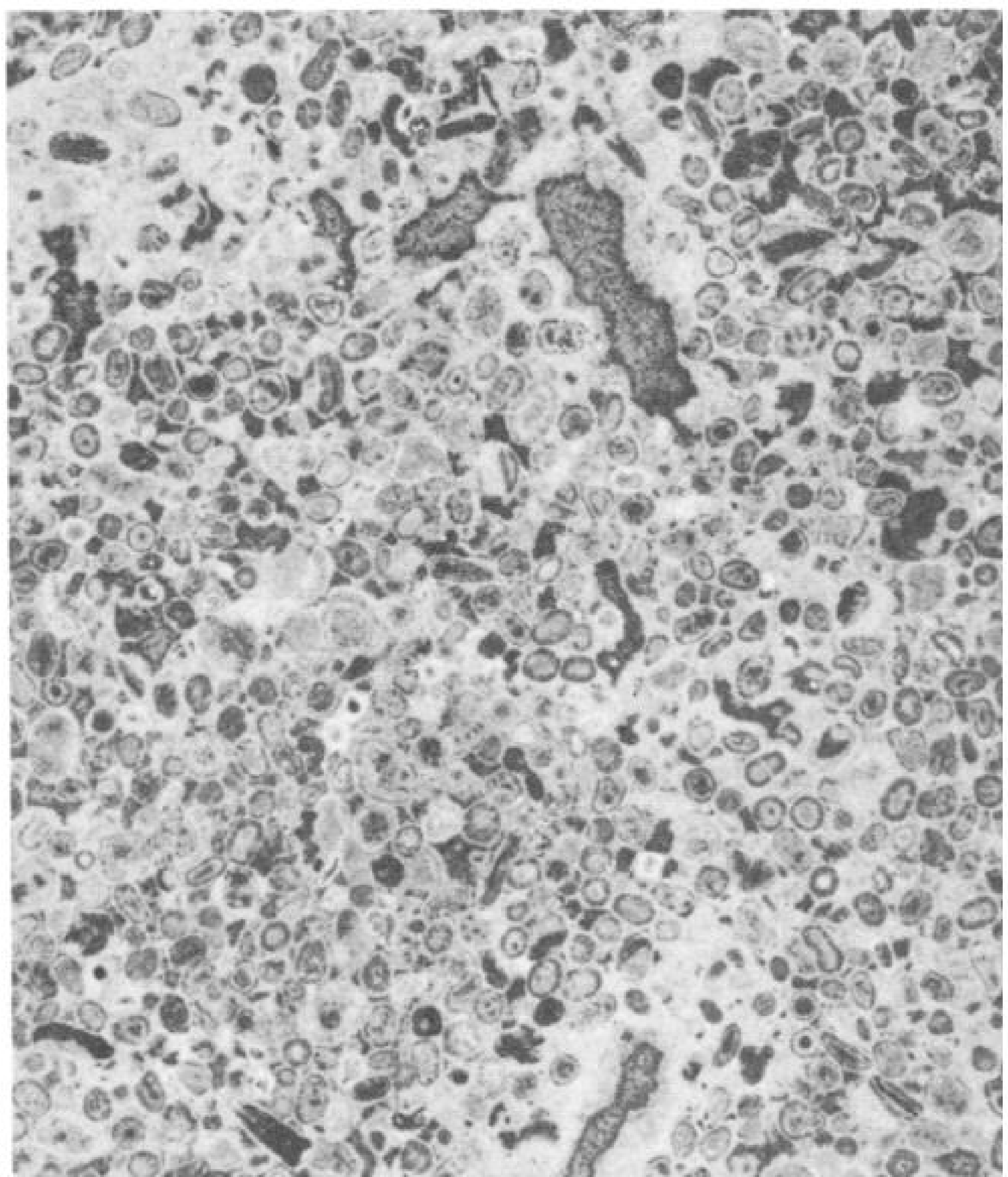
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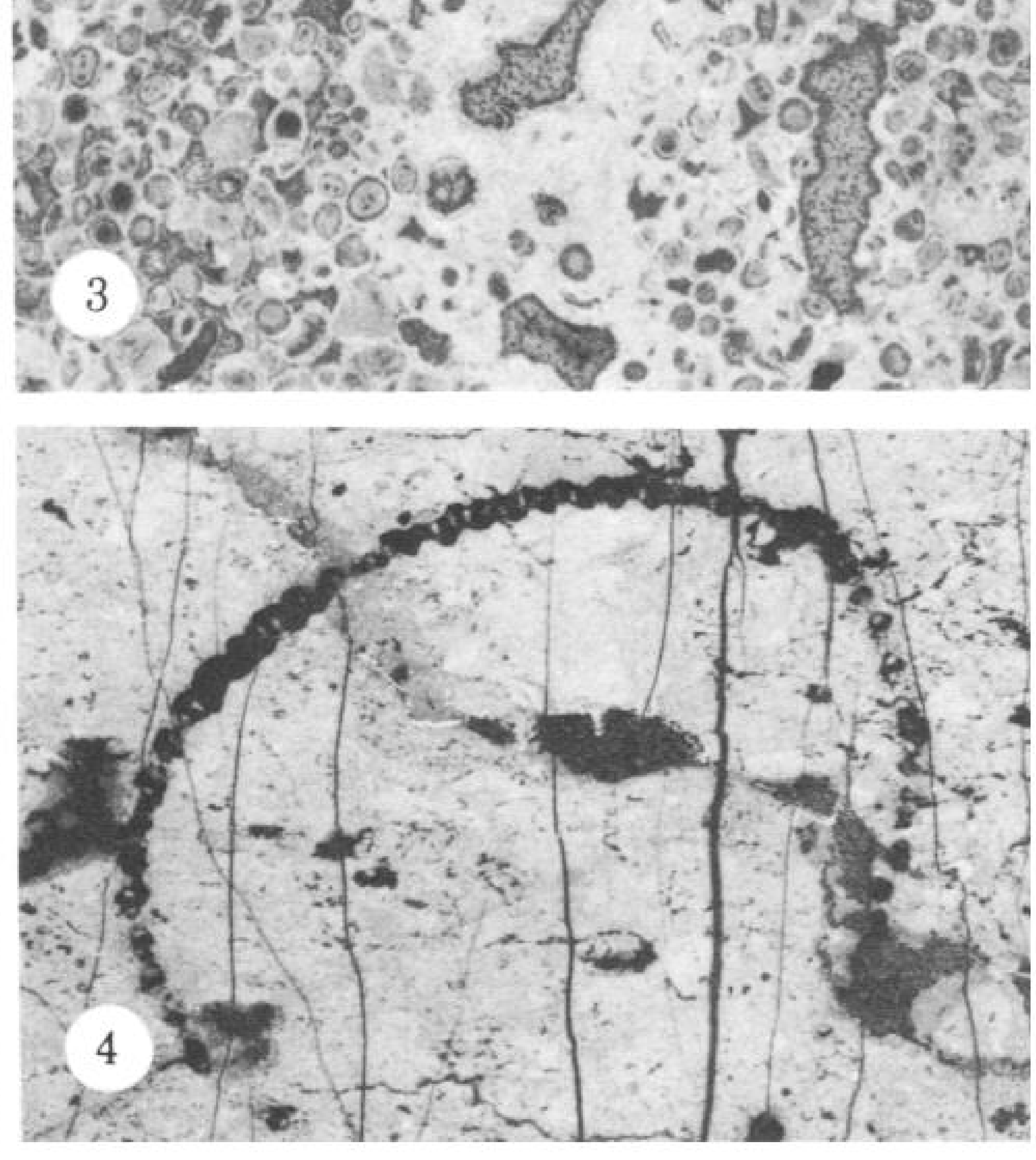
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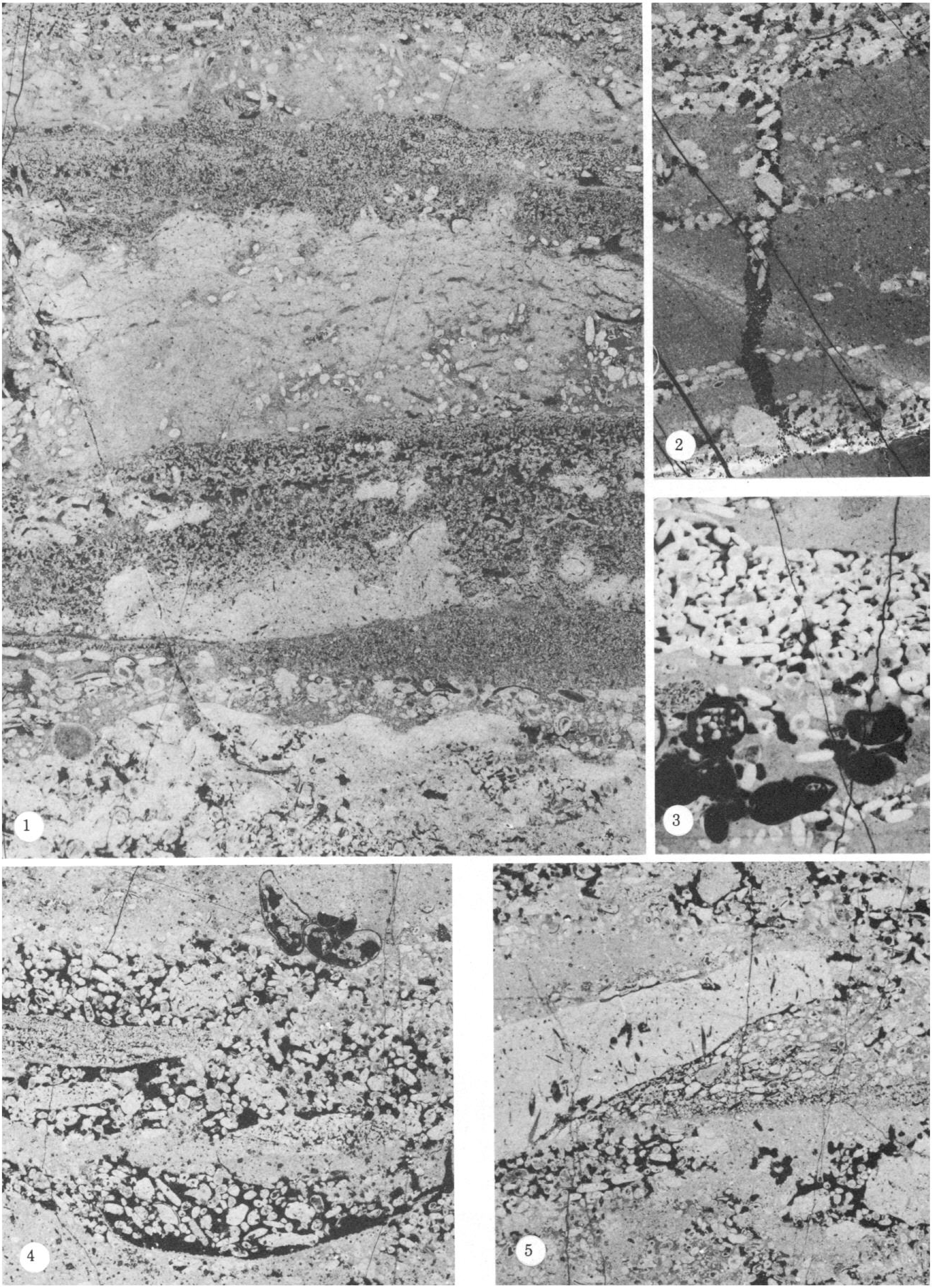
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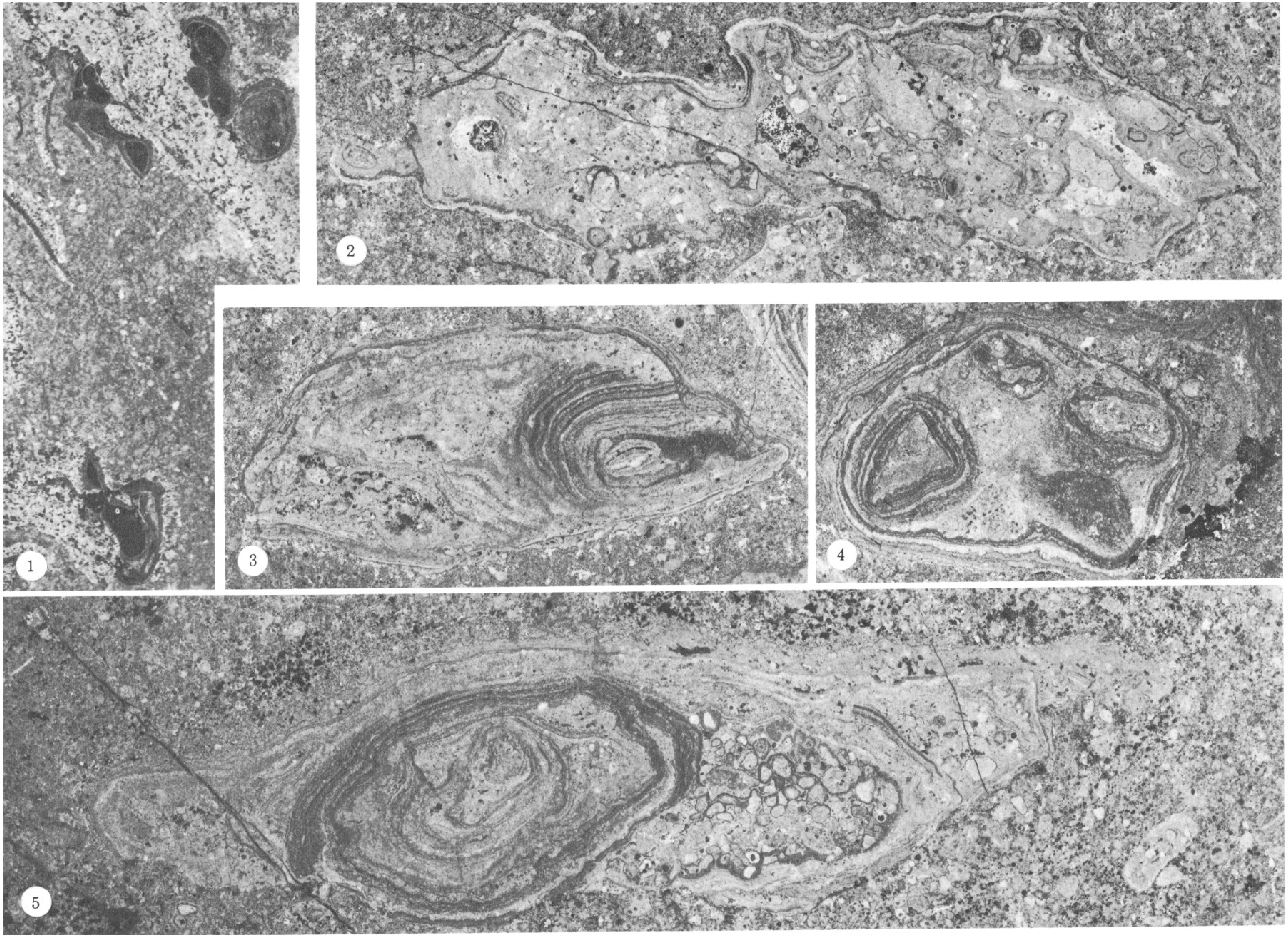
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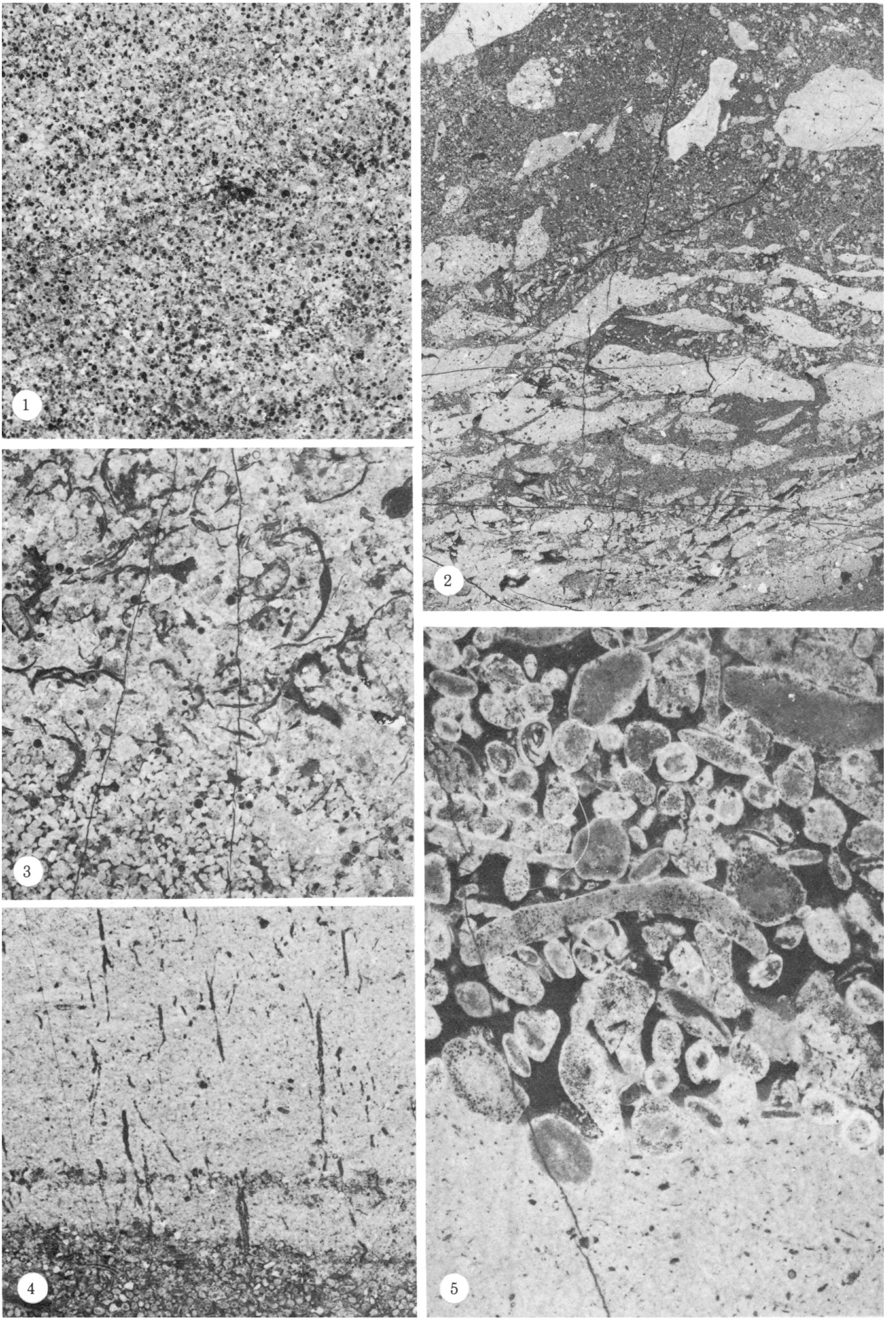
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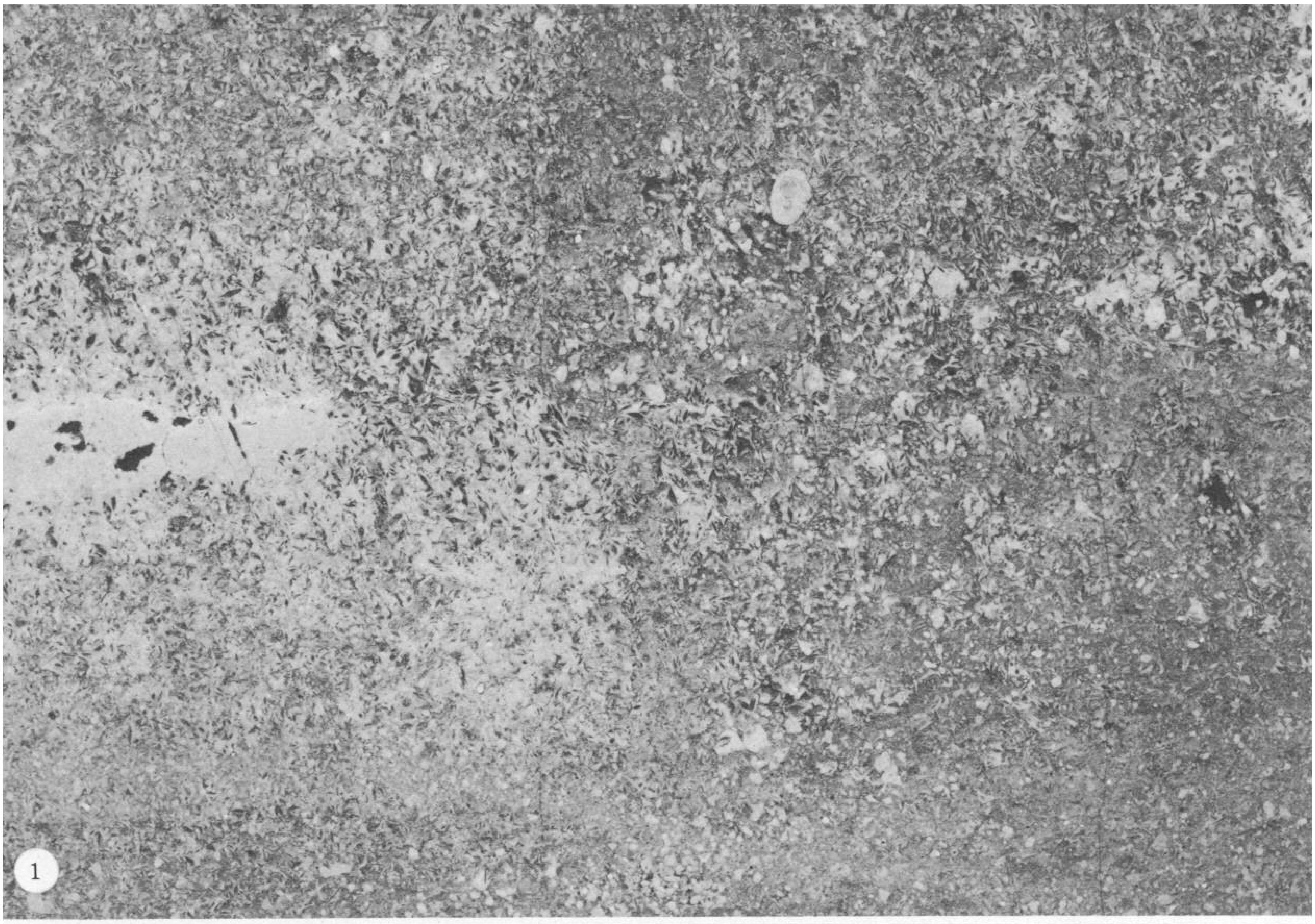

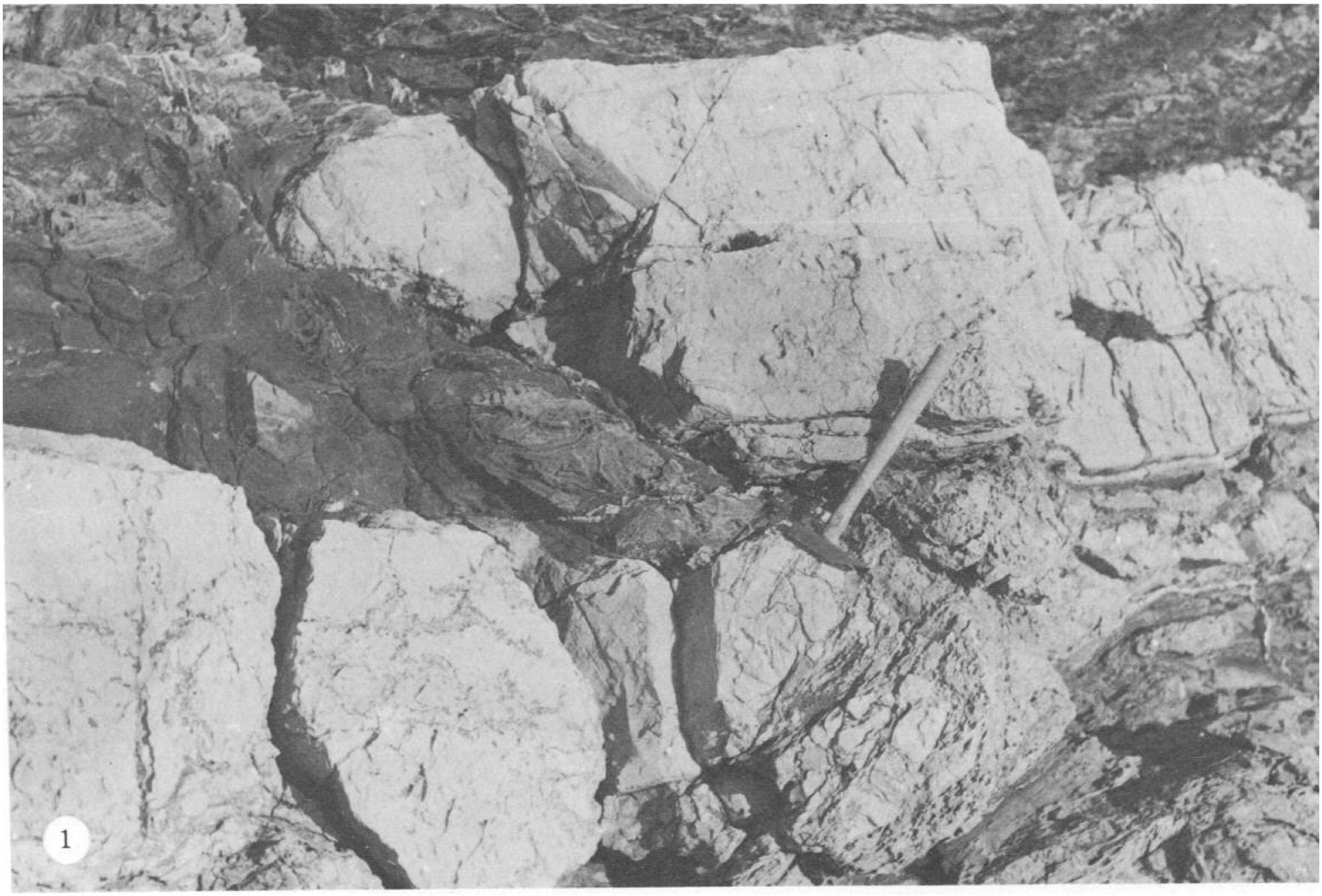

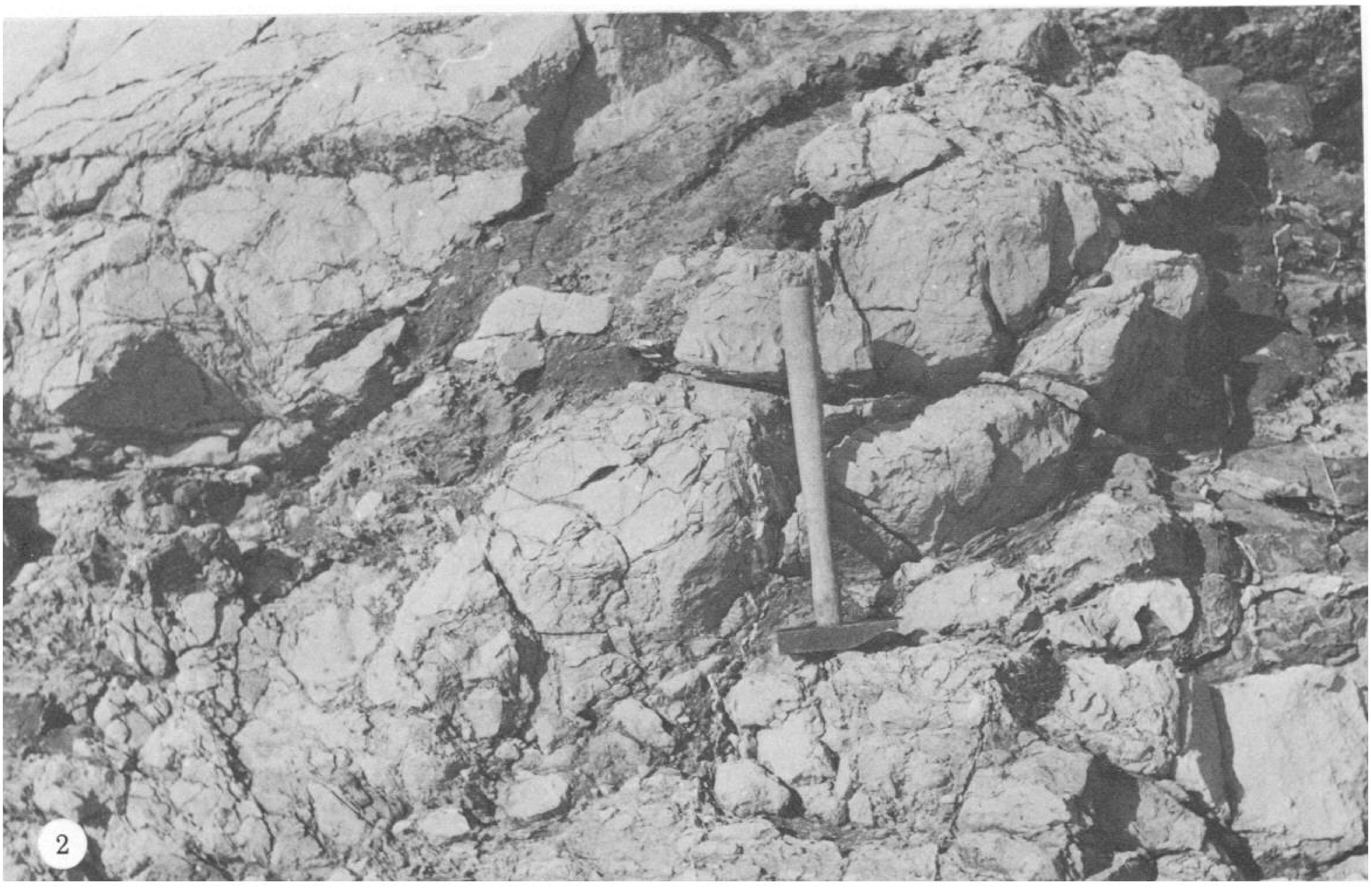


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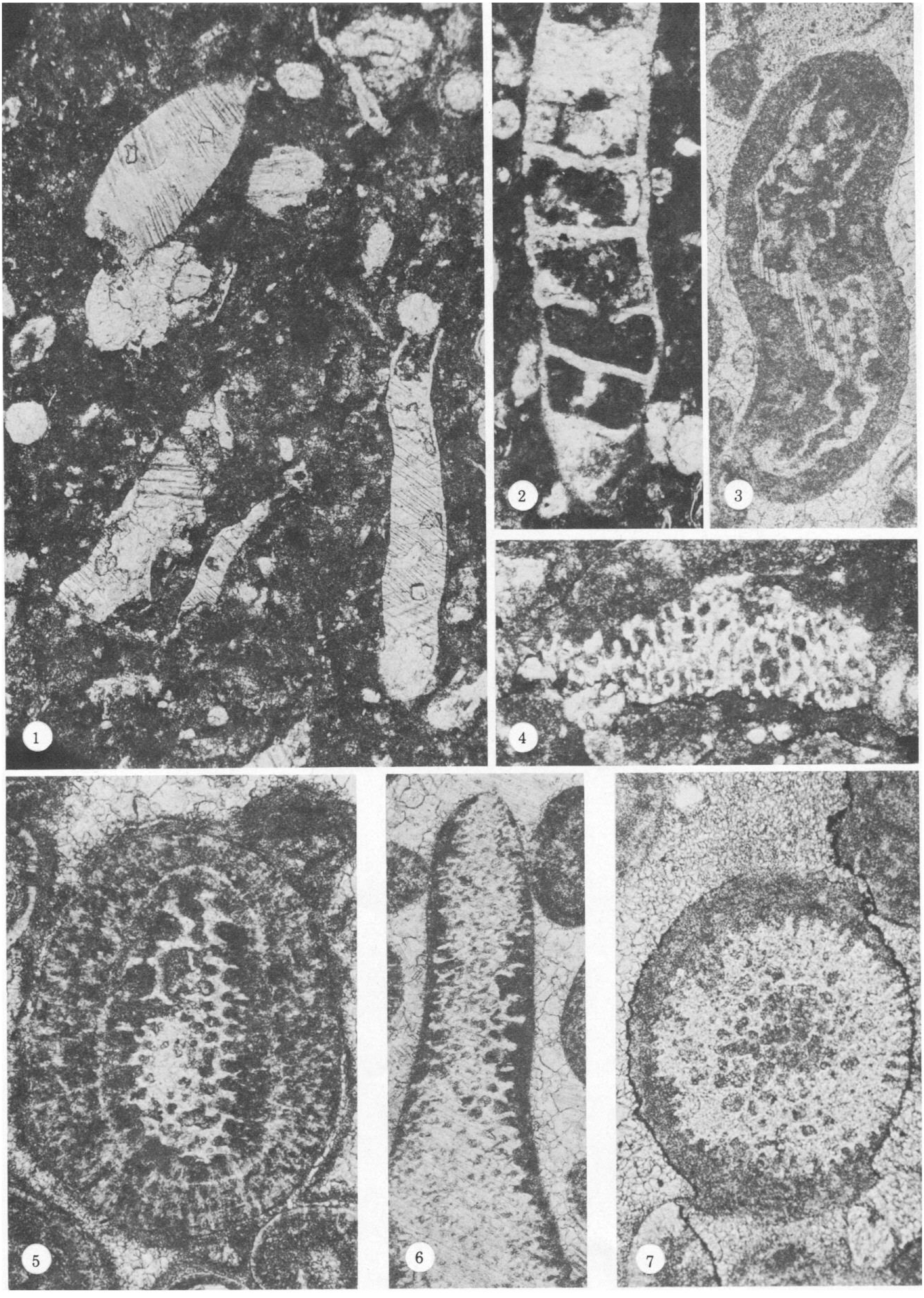
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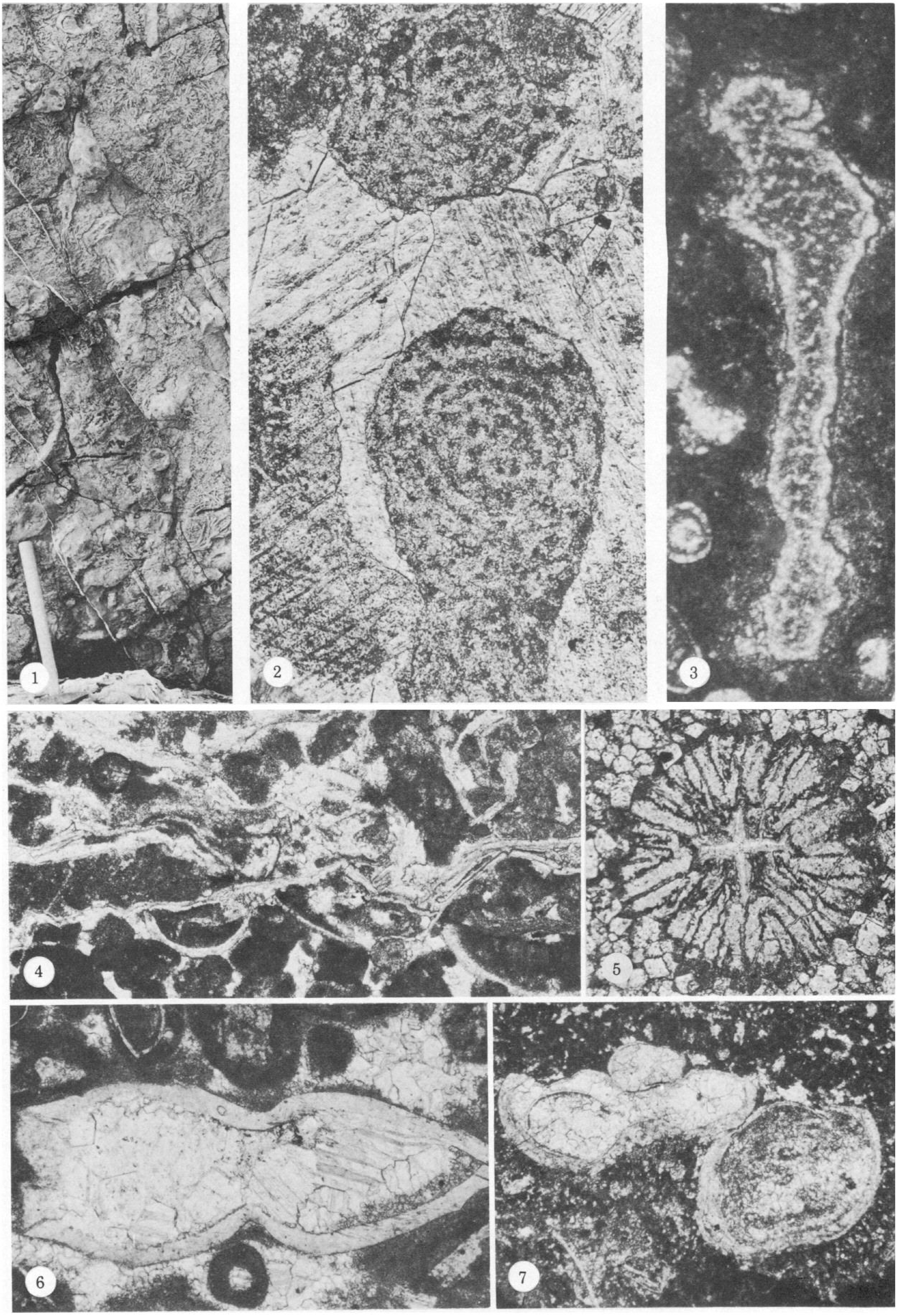
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