PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

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Phil. Trans. R. Soc. Lond. B 1985 **311**, 143-153
doi: 10.1098/rstb.1985.0146

Phil. Trans. R. Soc. Lond. B **311**, 143–153 (1985) [143]
Printed in Great Britain

The role of marine cementation in the preservation of Lower Palaeozoic assemblages

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[Plates 1 and 2]

Many workers have emphasized recently the taphonomic processes involved in the preservation of fossil assemblages, and some have doubted that invertebrate assemblages have ever been preserved that reflect closely the living community. Yet there are many examples in the literature in which invertebrate assemblages have been interpreted in just such a fashion. Many of the most confident reconstructions have been based upon assemblages in early Palaeozoic limestones. What was it about some early Palaeozoic environments that led at times to such exquisite preservation?

Carbonate petrologists have stressed the importance of marine cements in some modern environments (especially reefs). Our observations in Ordovician shelf carbonates suggest that such marine cementation may have been more common in a wider range of environments in the early Palaeozoic. The reason was a sufficiently different marine water chemistry at that time.

Marine cementation effects accumulating biotic assemblages in three ways: (i) the formation of true hardgrounds with establishment of a specialized biota on the completely lithified surface; (ii) production of peculiar 'mixed' assemblages by incremental, patchy hardground formation during accumulation leading to a mixture of encrusting forms in the same bed as loose-sediment forms; and (iii) preservation of fossils in life position, or retardation of transportation and mixing, caused by early immobilization of skeletons by cement fringes.

Our thesis is that early Palaeozoic carbonate shelf communities *are* better preserved than those of other environments and other times because the fossils were more often 'locked' in place by very early, marine cements.

1. Introduction

Recently, a number of researchers have expressed doubts that fossil assemblages are ever sufficiently well preserved to allow confident interpretation in terms of the community concept (cf. Fürsich 1978). The authors of several papers in the collection edited by Scott & West (1976) expressed reservations about the quality of preservation of fossil assemblages. Some of this criticism of the use of the community concept in the study of fossil assemblages has centred on the inadequate taphonomic analysis done by some early researchers. Other criticism has been more philosophical in nature, and has resulted from an holistic view of communities. Because the fossil assemblage never contains representatives of all species present in the living community, we cannot use the community concept to interpret the assemblage. Our only argument with the latter view is that neontologists rarely collect every biotic group in a study area, and yet use the community concept as the foremost unifying concept in the study of modern

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biotas. The preservational criticism, however, is a subject upon which we hope to shed new light here. It is the thesis of this paper that some fossil assemblages preserve astonishingly well the aspect of the biotic community from which they were drawn because early marine cementation acted to retard many of those taphonomic processes which lead to poor community preservation, and that this special preservation may not have been randomly distributed with respect to geological time.

Many palaeoecologists have identified palaeocommunities in the fossil record. These studies have ranged from diagrammatic reconstruction (see, for example, Zeigler 1965; Zeigler *et al.* 1968; Bretsky 1969*a*; Walker 1972*a*) to comparisons of palaeocommunities of different ages (Walker & Laporte 1970) to attempts to analyse community change through time (Bretsky 1969*b*; Walker 1972*b*; Walker & Alberstadt 1975; Jablonski *et al.* 1983). Most of the assemblages that have been interpreted as palaeocommunities were studied in shallow marine sediments of Lower Palaeozoic or Upper Mesozoic age (see the summary by Walker 1979). We do not believe that the restriction in age of these assemblages is a mere coincidence, but, instead, may be a function of special preservation processes which were operative at those times.

2. Synsedimentary substrate modification

In a recent analysis of the effect on communities of changes in the substratum (synsedimentary substrate modification) during community establishment and elaboration, we identified several processes that lead to a gradual change in the substratum after deposition (Walker & Diehl 1985). These sediment modification processes include: (i) changes in loose-sediment consistency caused by loss of water; (ii) changes in the substratum caused by the 'paving' activity of organisms; and (iii) changes in sediment hardness caused by patchy, marine cementation. We should note that the second of these processes has recently been discussed in detail by Kidwell & Jablonski (1983). Thus, a community copes with a gradually changing substratum during its development which may lead to a confusing mix of morphotypes in the final assemblage. While studying the results of these processes in Middle Ordovician assemblages of the southern Appalachians, we found the results of one of the modification processes, marine cementation, to be more commonly represented than we had anticipated. Before discussing the effects of marine cementation on the development of marine fossil assemblages we wish to detail the process involved and how its products are recognized.

3. Recognizing marine cements

Until recently, the importance of early marine cementation was not recognized. Many workers believed that lithification required exposure to fresh waters. A seminal summary by Milliman (1966), followed by published data from many types of modern environments (among many others: Land & Goreau (1970), and MacIntyre (1977) on shallow reefs; Dravis (1979) on oolite shoals; Marshall & Davies (1981) on reef slopes; Mullins *et al.* (1981) on deeper slopes), led to recognition of the importance of the process. So far, marine cementation has only been shown to be of great importance in carbonate environments.

Longman (1980) has summarized the petrographic characteristics of cements produced in various diagenetic environments, and pointed out that many of these characteristics are usually preserved in ancient rocks (figure 1). His review was updated and amplified by James &

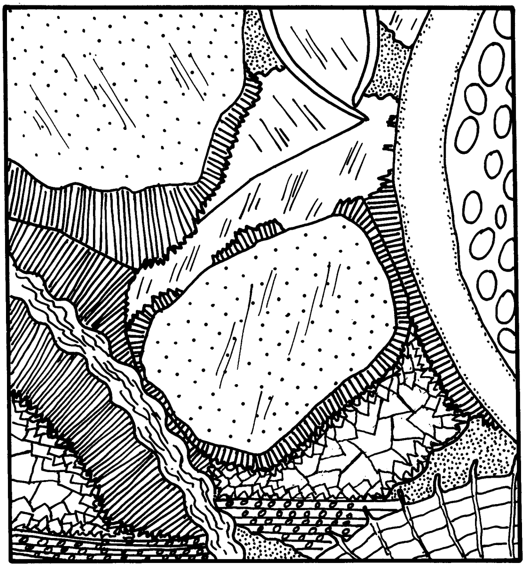

Figure 1. Diagrammatic representation of a pore showing the sites and aspects of various types of marine cements (modified after Longman 1980). Note the isopachous distribution of fibrous cement, and the concentration of micritic cement (fine stipple) at grain contacts. Grains with coarse stipple are echinoderm grains with syntaxial overgrowths (random parallel lines) which have interfered with the growth of other marine cements. Cement areas with crystal sizes that enlarge away from pore walls (lower centre and lower left) are probably of freshwater origin.

Choquette (1984). The elongate (pseudofibrous) crystal habit, paragenetic position (first cement), and cloudy appearance of marine cements of larger crystal sizes, usually leave little doubt as to their marine origin even in ancient rocks. However, as noted by James & Choquette (1984), the most abundant marine cement in many modern settings is magnesian calcite precipitated as an aggregate of very fine crystals (under 4 μm) distinguishable only with some difficulty from sedimented lime mud. Often, though, the interstitial nature of this material and its occurrence at grain contacts allow its recognition as cement. Marine cement, in whatever form, is usually followed by further cementation in other diagenetic environments (for example, vadose fresh water, or deep-burial brines), and these cements have their own distinctive properties. Thus, with careful petrographic study the relative times of cementation of various parts of a fossiliferous rock can be discerned. Examples of marine cements associated with fossils are shown in figures 2–7, plate 1.

4. Effects of marine cementation on fossil accumulation

Early marine cementation has three possible effects on the nature of the accumulating fossil assemblage.

First, if marine cementation thoroughly hardens a carbonate bed, the upper surface of the bed may become a site of hard-ground community formation. The upper surface of the bed may become corroded, bored, and encrusted by a complex assemblage of organisms. A number of palaeontological studies of hardgrounds have appeared recently (see, for example, Halleck 1973; Surlyk & Christensen 1974; Palmer & Palmer 1977; Mazzulo & Cys 1979; Miller & Rehmer 1982; Wilkinson *et al.* 1982). Some of these hardgrounds are bed surfaces that are overlain by considerably younger rocks so that the hardground biota may have developed on and in a bed which had long since been lithified. Thus, the hardground biota did not usually form during the hardening by cementation of the underlying bed. None the less, the cementation of the underlying bed indirectly controlled the development of the hardground biota by providing ideal conditions for endolithic borers and surface encrusters.

If one takes a more dynamic view of marine cementation, it is clear that marine cementation may take place *during* deposition. In at least some cases, then, the biota preserved in the cemented bed beneath the hardground surface was effected by the incremental cementation of the bed in which it is preserved. This is a second way in which marine cementation may effect the preservation of a fossil assemblage. Because members of the biota did not encrust a single hardened surface, the influence of the marine cementation process would not later be as easily discerned.

We have usually found that marine cement distribution within a bed is extremely patchy. Thus, as a bed accumulated, at any one time the sediment–water interface must have consisted of small patches of marine-cemented hardground separated by larger, intervening areas of loose sediment. The scale of this patchiness was in centimetres or decimetres. Subsequent lithification produced a final rock in which relative timing of cements in different parts of the sediment is cryptic (though resolvable with careful study). The surficial microenvironments to which organisms must adapt in such a case range from loose, even soft, sediment on the one extreme to rock on the other extreme. Thus, organisms living in the environment might have widely divergent adaptive morphologies. Many palaeoecologists would include these different morphotypes in the same assemblage, and might interpret them as having belonged to the same palaeocommunity, because they occur intimately associated with one another in the same bed. Fossil examples follow.

Our examples come from the Ordovician carbonate platform sequence of the southern Appalachians. The stratigraphy and palaeoenvironments of this sequence are detailed in Walker *et al.* (1983) and Ruppel & Walker (1984). Figure 8 is a locality map showing the two localities from which samples were taken to illustrate the effect of the incremental marine cementation phenomenon. Figure 9 (plate 2) shows the top and bottom surface of a limestone lamina from the Benbolt Formation at locality A (figure 8). The lower bed surface (figure 9*a*), which is irregular because of early loading into the underlying, soft-mud substratum, is

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DESCRIPTION OF PLATE 1

FIGURES 2–7. Photomicrographs showing early Palaeozoic marine cements associated with fossils.

FIGURE 2. Curvilinear arthropod fragment underlain by void partly filled with marine fibrous cement (nearest to fragment); note micritic cements at contacts with adjacent grains.

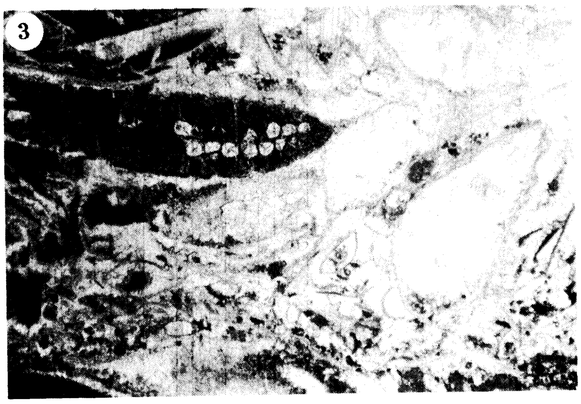
FIGURE 3. Articulated brachiopod valves, probably in life position, partly filled by fibrous marine cement and held 'in place' by both fibrous marine 'fringes', and marine micritic cement.

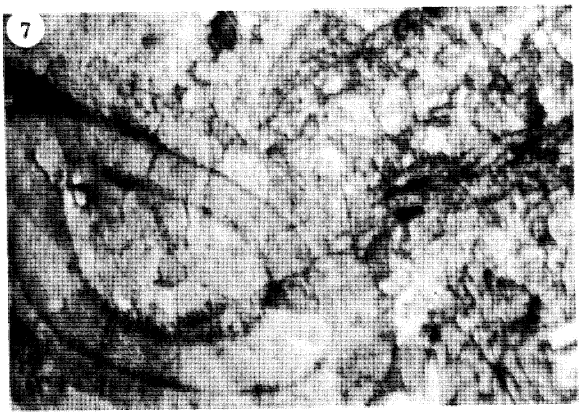
FIGURE 4. Enlargement of part of figure 3, showing cryptostome bryozoan (left) with zoecia partly filled with probably marine micritic cement; articulated brachiopod (right) partly filled with marine fibrous cement; the two are attached by both marine fibrous and micritic cement fringes.

FIGURE 5. Same as figure 4 in plane-polarized light.

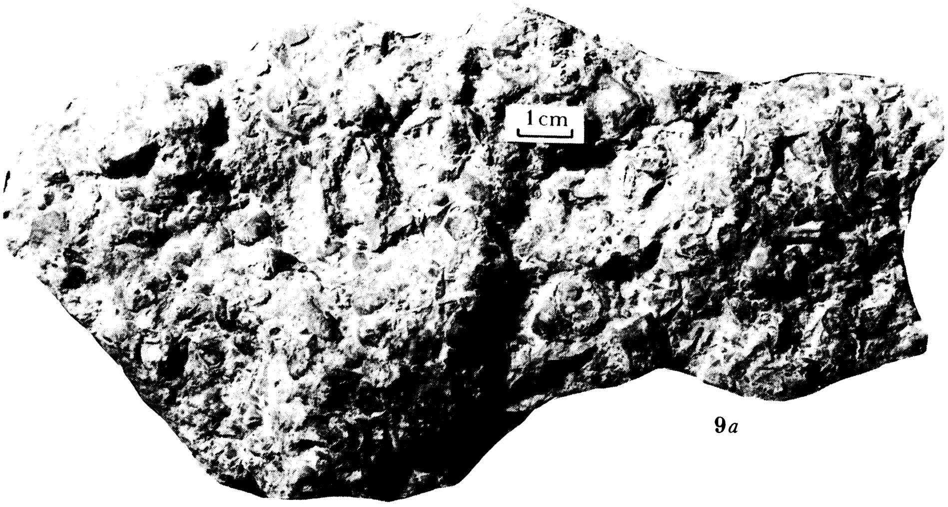
FIGURE 6. Trilobite and cryptostome bryozoan with early marine-cement fringe; probably marine, syntaxial overgrowths on echinoderm ossicles.

FIGURE 7. Echinoderm ossicles and bryozoa engulfed in syntaxial cement growing from echinoderms; syntaxial cement can be seen to have been coeval with marine micritic cements.

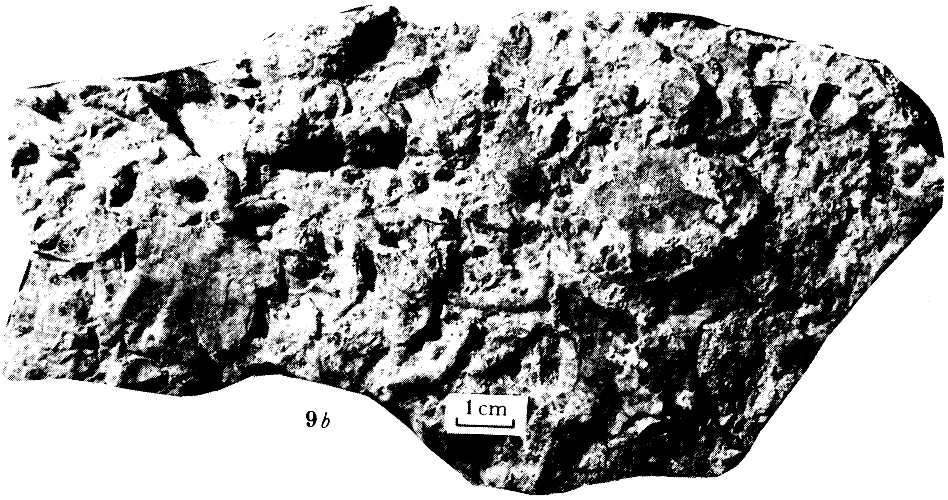




Figures 2–7. For description see opposite.



9*a*



9*b*

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FIGURES 9 AND 12. For description see opposite.

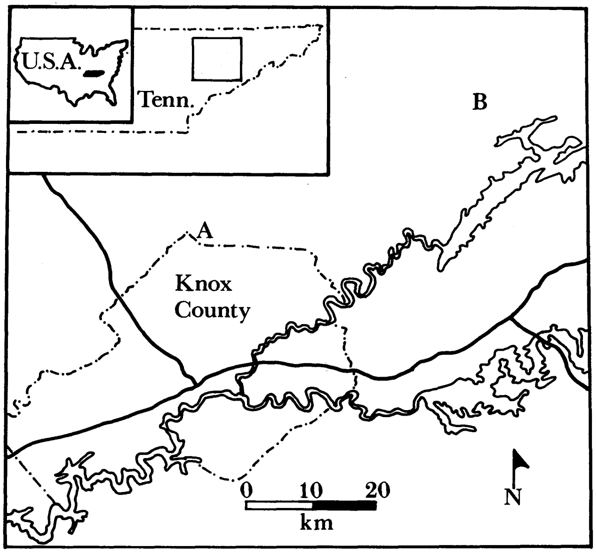

FIGURE 8. Localities of Ordovician assemblage examples given in text. A, Raccoon Valley near Interstate Highway 75 North. B, Evans Ferry along U.S. Highway 25 East.

completely covered by the small strophomenid brachiopod *Sowerbyella*. This planoconvex, lightweight brachiopod may have acted as a mud paver in a way similar to *Strophomena* in the the *Strophomena–Rostricellula* assemblage reported by Walker & Alberstadt (1975). Elsewhere in the stratigraphic sequence, *Sowerbyella* and *Strophomena* occur in monotypic shell beds without evidence of shell transportation. This sort of distributional pattern is characteristic of opportunistic species (Levinton 1970). The upper surface of the same layer (figure 9*b*) shows a diverse biota with three types of brachiopods, two trilobites, at least four bryozoa, and others. The mix of morphotypes on this surface is most striking. In addition to *Sowerbyella* and other brachiopods, three growth forms of bryozoa occur on the bed top: (i) delicate, branching cryptostomaceous forms with ribbon-like branches; (ii) robust, branching trepostomaceous forms with subcylindrical branches; and (iii) sheet-like, encrusting trepostomaceous forms which cover 20% of the slab surface. The latter form seems best adapted to a sediment-free, firm or hard substratum. Thus, even in the area of this small sample of the bed surface, several very different types of substrata must have been available. One of these was patches of hardground produced by marine cementation.

A more completely studied example of the effect of incremental marine cementation on assemblage development comes from the Wardell Formation in the same sequence (locality B, figure 8). The biota was documented by Sickafoose (1979), though we interpret the formation

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DESCRIPTION OF PLATE 2

FIGURE 9. Example of patchy hardground development in a sample from the Middle Ordovician Benbolt Formation. (*a*) Lower surface of layer showing abundant *Sowerbyella*. (*b*) Upper surface of same layer showing more diverse biota, and patches of bryozoan encrusting areas which were cemented early.

FIGURE 12. Photograph of clumps of *Rostricellula* in life position from the Middle Ordovician Witten Formation of Tennessee. These were probably 'locked' in position by early marine cementation. Largest valve is about 1 cm in width.

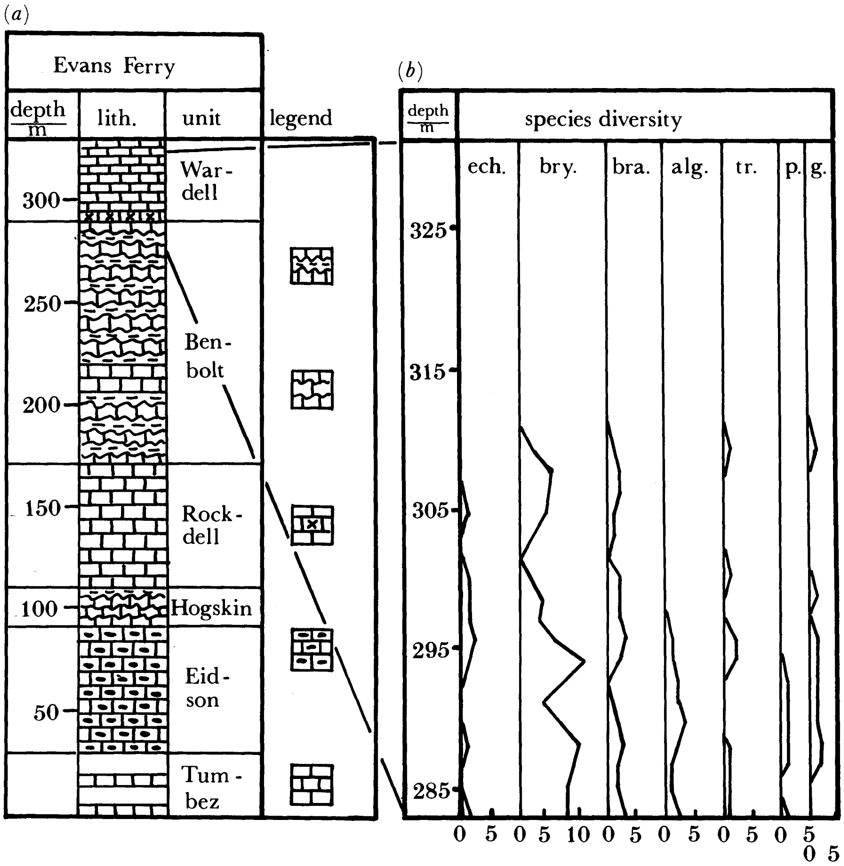

FIGURE 10. (*a*) Columnar section of the lower Middle Ordovician sequence at Evans Ferry, Tennessee. Limestone lithological symbols in legend (top to bottom) are wavy bedded with shale, nodular, oncolitic, cherty, and massive. The example of incremental marine cementation discussed in text is from the Wardell Formation. (*b*) Species diversity in ecological units in the Wardell Formation; groups are: ech., echinoderms; bry., bryozoans; bra., brachiopods; alg., algae; tr., trilobites; p., pelecypods; g., gastropods; note especially the unusual diversity at about the 294 and 307 m levels. (Both (*a*) and (*b*) modified from Sickafoose (1979).)

of the assemblage differently. Figure 10*a* is a columnar section of the Middle Ordovician succession at that locality (Evans Ferry), and figure 10*b* shows the diversity within higher taxa for the Wardell Formation. Notice the unusually high diversities of the assemblages at the 294 and 307 m level. Increases at those levels are largely in the bryozoans, corals, sponges, and algae. In all four groups, the added taxa are mostly laminate encrusting forms. Based on thin-section observation, these added fossils are associated with patchy areas of more abundant early marine cement. Subsequent precipitation of other types of cement to produce the final rock has made recognition of the early hardground areas difficult, and careful petrographic analysis was required to discern the subtle relationships. The development of this biota is summarized in the reconstruction shown in figure 11. At a fine scale, two distinct assemblages are resolvable, one which lived on loose sediment, and one which inhabited coeval areas of hardground. At a coarser scale, these might easily be misinterpreted as a single palaeoecologically coherent biota. Any attempt at analysis of the composite biota would lead to peculiar results.

The third effect of marine cementation on assemblage preservation is a more generalized one. As early cements precipitate they serve to hold fossils in place and to protect them from

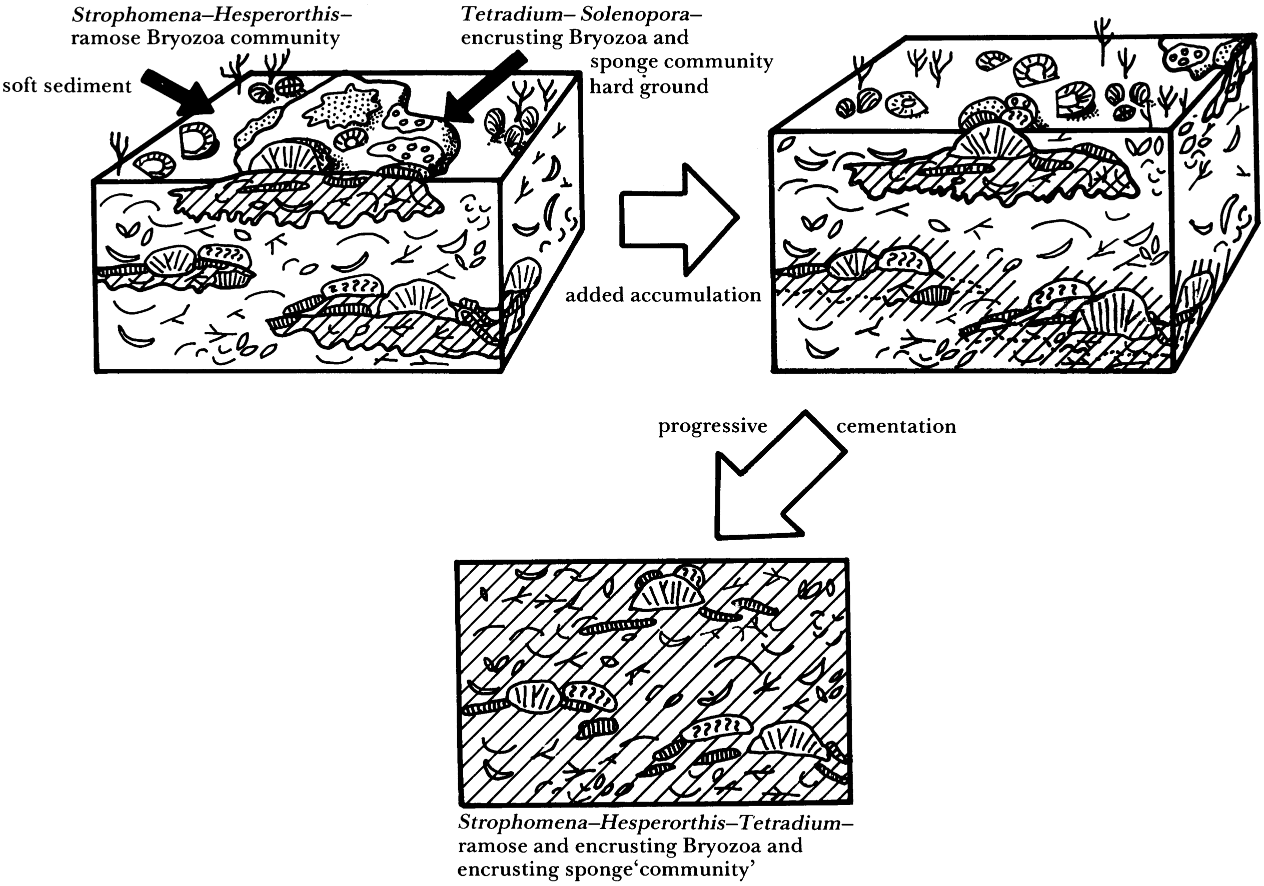

FIGURE 11. Reconstruction showing the sequence of events during assemblage development at Evans Ferry.

removal from their living environment, and even from life position. As noted by Dravis (1979), only a small volume percentage of marine cement is required to give carbonate sediments considerable coherence. This is primarily because cementation begins at points of grain contact. The result in an environment where early marine cementation was common would be the much more faithful preservation of the skeletonized biota than in the absence of cementation. Figure 12 shows a bed surface from the Middle Ordovician Witten Formation of the southern Appalachians. The bed contains the *Strophomena–Rostricellula* assemblage discussed by Walker & Alberstadt (1975) in which they could perceive the results of ecological succession encompassing a very short time interval (perhaps as little as a few years). Note the range of sizes of the articulated *Rostricellula* shells shown, and that the population still retains its clumpy distribution and individuals their probable (gravitationally unstable) life position. They must have been cemented permanently in place very early. Although this specimen shows an unusually well preserved example of this effect of marine cementation, the thin section photographs of figures 2–7 (all derived from Middle Ordovician carbonates) clearly show the various manifestations of the process. The potential for special preservation of a biota is obvious. Whether such special preservation is an abundant phenomenon in the fossil record remains to be seen, because the detailed petrographic analysis required for its recognition has rarely been done by palaeontologists.

5. Enhanced marine cementation during parts of geological time?

Marine cementation is common today in certain carbonate environments; in particular in reefs and other shelf marginal facies, and in shoreline environments such as beaches (James & Choquette 1984). However, the distribution and abundance of marine cements could have been different at times in the past because marine geochemistry has varied with time. Sandberg (1975) was among the first to hypothesize that at times in geological history calcite was the preferred physiochemical precipitate from tropical and subtropical shallow sea water (rather than aragonite as is true today). He believed that temporal variations in the Mg:Ca ratio in sea water was the underlying cause of changes in the preferred carbonate phase (lower Mg in sea water tends to facilitate calcite, and inhibit aragonite, precipitation). Sandberg based his thesis on study of ooids of various ages (these are widely accepted as of dominantly physiochemical origin). Sandberg (1983) recently updated his earlier work, based on study of many more samples, and extended his conclusions to encompass marine cements as well. In this later analysis, Sandberg follows MacKenzie & Pigot (1981) in attributing the shifts between aragonite facilitation and calcite facilitation to temporal changes in p_{CO_2} in sea water. In this case, higher p_{CO_2} tends to facilitate calcite precipitation relative to aragonite precipitation.

Figure 13 shows the distribution in geological time of these changes in the 'preferred' carbonate phase along with changes in processes believed to affect atmospheric and oceanic p_{CO_2} balance. Note especially the two calcite-facilitating spans of time: a longer one in the Lower Palaeozoic, and a shorter one in the Upper Mesozoic. The Lower Palaeozoic calcite interval is initiated during and following the removal of large quantities of magnesium in the form of dolomite from sea water in the late Cambrian and early Ordovician (for example, the Beekmantown and Knox Groups in the Appalachians and the Ellenburger Group in the Ouachitas). Such a time must have seen a profound decrease in the Mg:Ca ratio of worldwide

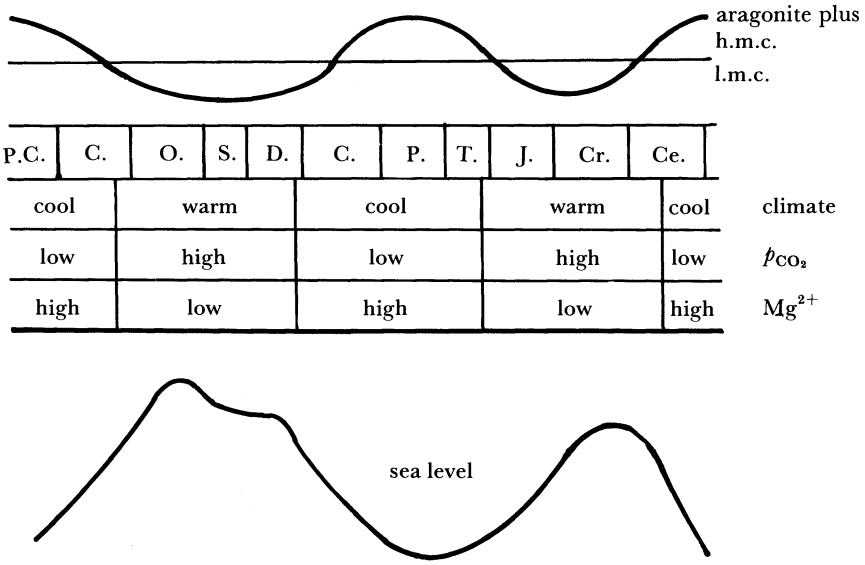

Figure 13. Distribution in geological time of periods of facilitated low Mg calcite precipitation and aragonite precipitation, probably controlled by changes in p_{CO_2} in atmosphere and oceans which controlled carbonate precipitation. Changes in Mg:Ca ratio in sea water may also have been involved. Sea level and climatic cycles are also shown. Abbreviations: l.m.c., low magnesium calcite; h.m.c., high magnesium calcite. (Substantially modified from Sandberg 1983.)

sea water, and a consequent increase in calcite facilitation. So the Lower Palaeozoic period of calcite preference may have involved changes in both p_{CO_2} and Mg:Ca ratio operating at the same time.

But how might changes in the 'preferred' physiochemical carbonate phase result in increases and decreases in the prevalence of marine cementation with time?

The answer to this question involves the influence of pore walls on cement precipitation. Although the influence of substrate on cement precipitation is poorly understood, there is little question that nucleation of cement with the same crystallographic structure as the pore wall would be thermodynamically preferred. The biota of the early Palaeozoic was overwhelmingly dominated by calcitic forms (brachiopods, bryozoans, echinoderms, trilobites, red algae, among others). Thus, most pore walls in fossiliferous deposits consisted of calcite and would have more readily acted as a substratum for calcite cement precipitation than for aragonite precipitation. Because that was a period of calcite facilitation in sea water, I submit that this would have led to increased marine cementation. In addition, evidence is now accumulating that the abundant syntaxial cements on echinoderm ossicles in early Palaeozoic rocks was probably precipitated in the marine realm. The growth of this cement can often be seen to have interfered with the growth of other types of cement of probable marine origin. Interestingly, in parts of the modern ocean below the thermocline but above the calcite-compensation depth (dissolution becomes the norm below this), syntaxial overgrowths occur on echinoderm plates. This modern zone is a calcite facilitative area, and probably similar geochemically to warm shallow waters of the early Palaeozoic.

Thus, both syntaxial echinoderm cements and other types of early cements in the early Palaeozoic were probably calcitic when precipitated and originated in the marine realm. Because of the dominance of calcitic fossils in that span of earth history, marine cements may have been more common than at later times. Though this conclusion is speculative at this time because of the rarity of careful petrographic analysis of the sediments which accompany biotas, it suggests that preservation in Lower Palaeozoic rocks may be at times much better than we might otherwise anticipate.

6. Conclusions

The early Palaeozoic was a time of calcite-precipitation facilitation in marine waters. Because the biota of that time was dominated by forms with calcitic skeletons, calcitic pore walls were the norm in fossiliferous deposits. This coincidence of pore-wall mineralogy and preferred physiochemical precipitate may have led to increased marine cementation at that time. Marine cementation leads to three effects which tend to preserve better the skeletonized portion of marine assemblages, though some of the effects may confuse interpretation in community terms.

First, hardgrounds may be produced which become populated by encrusting and boring forms which clearly are immune to transportational effects. Second, the incremental cementation of sediment as it is deposited may lead to a patchy preservation of soft-substratum forms with hard-substratum forms within the same sedimentation unit. This may complicate the interpretation of the biota in community terms. Finally, early marine cementation served to 'lock' biotic elements 'in place' and at times even 'in life position'. When this happened, spatial relationships between biotic elements were exquisitely preserved.

All of these effects acting together may have led to overall better preservation of assemblages during the early Palaeozoic than at many later times in the geological record.

We thank Stephen C. Ruppel for critically reading an earlier draft of parts of the manuscript, and John C. B. Simonson for preparation of some of the illustrations. The first author's research was partly supported by grants from the National Science Foundation, and by the Faculty Development Grant Fund of the University of Tennessee. The second author thanks The Society of Sigma Xi for a grant in support of his research. Presentation of the results of this research was partly supported by the Royal Society of London.

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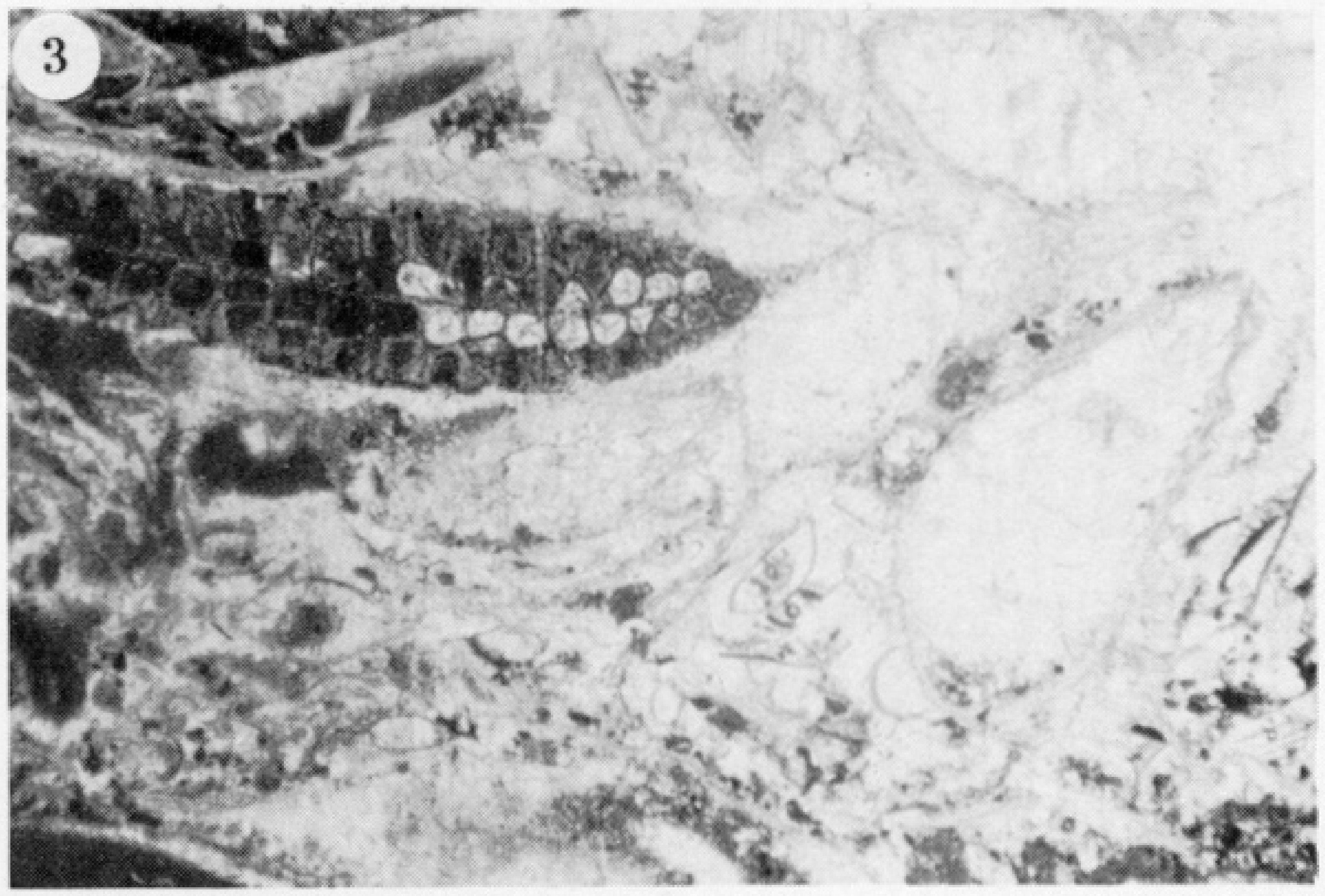
2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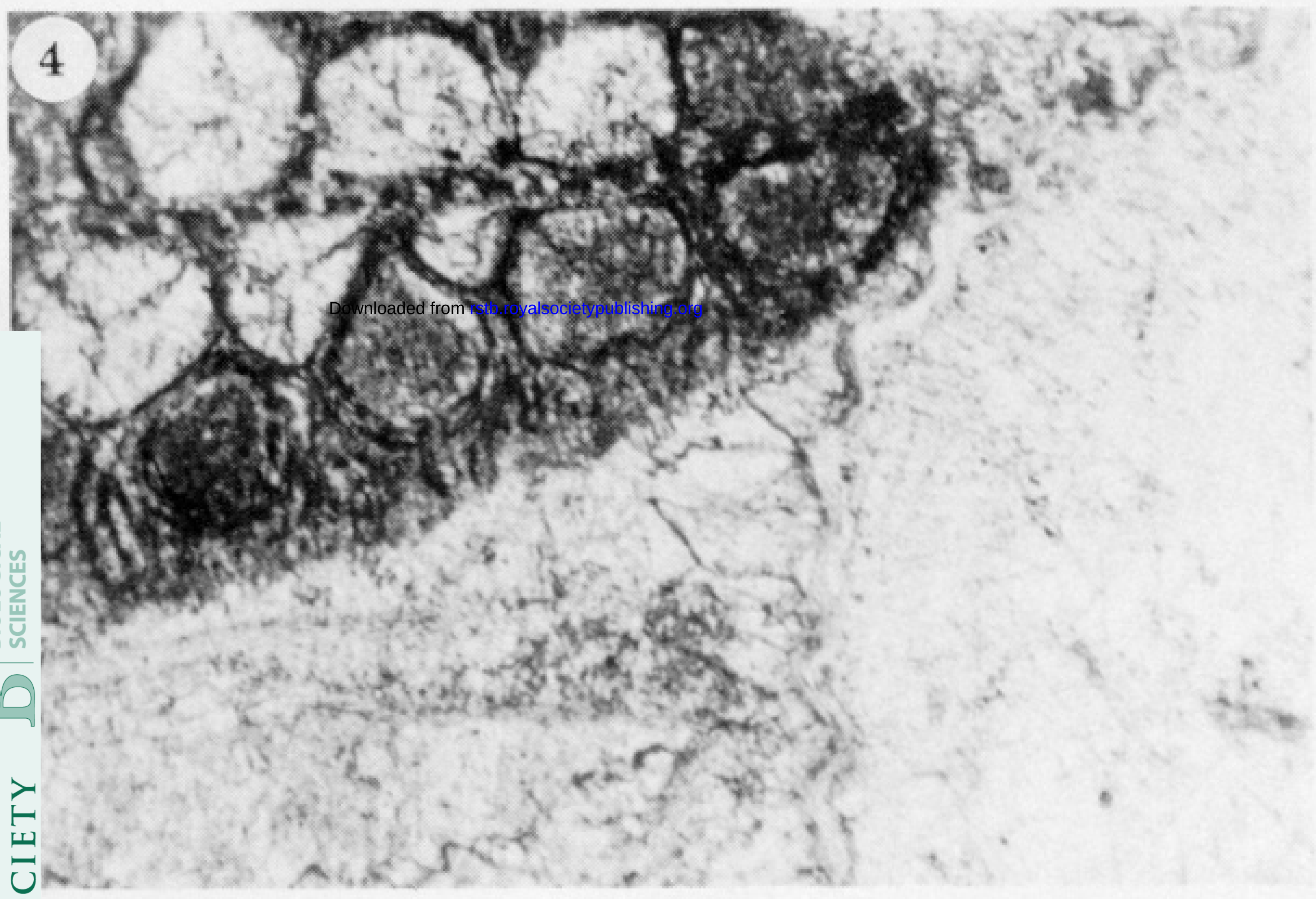
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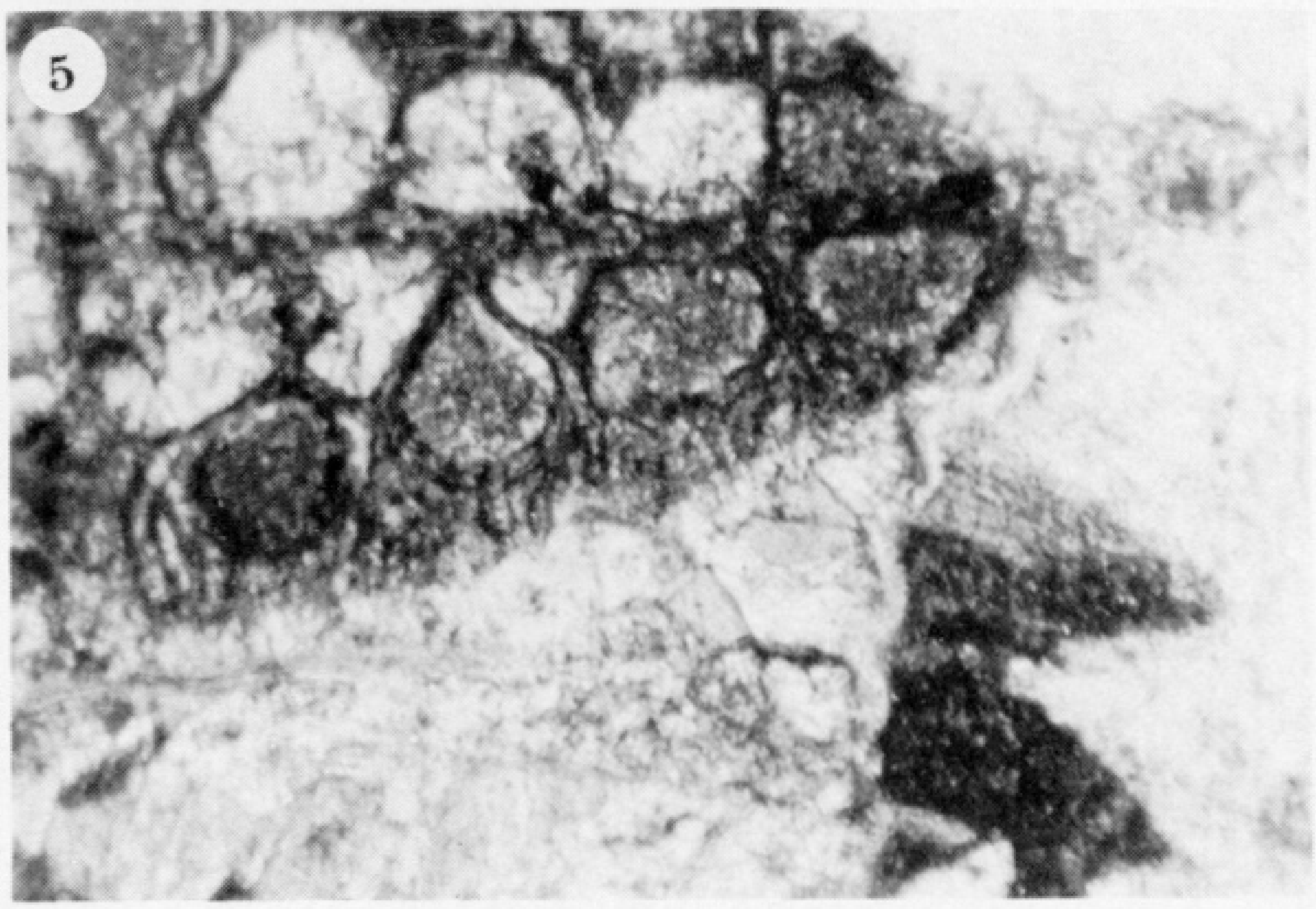
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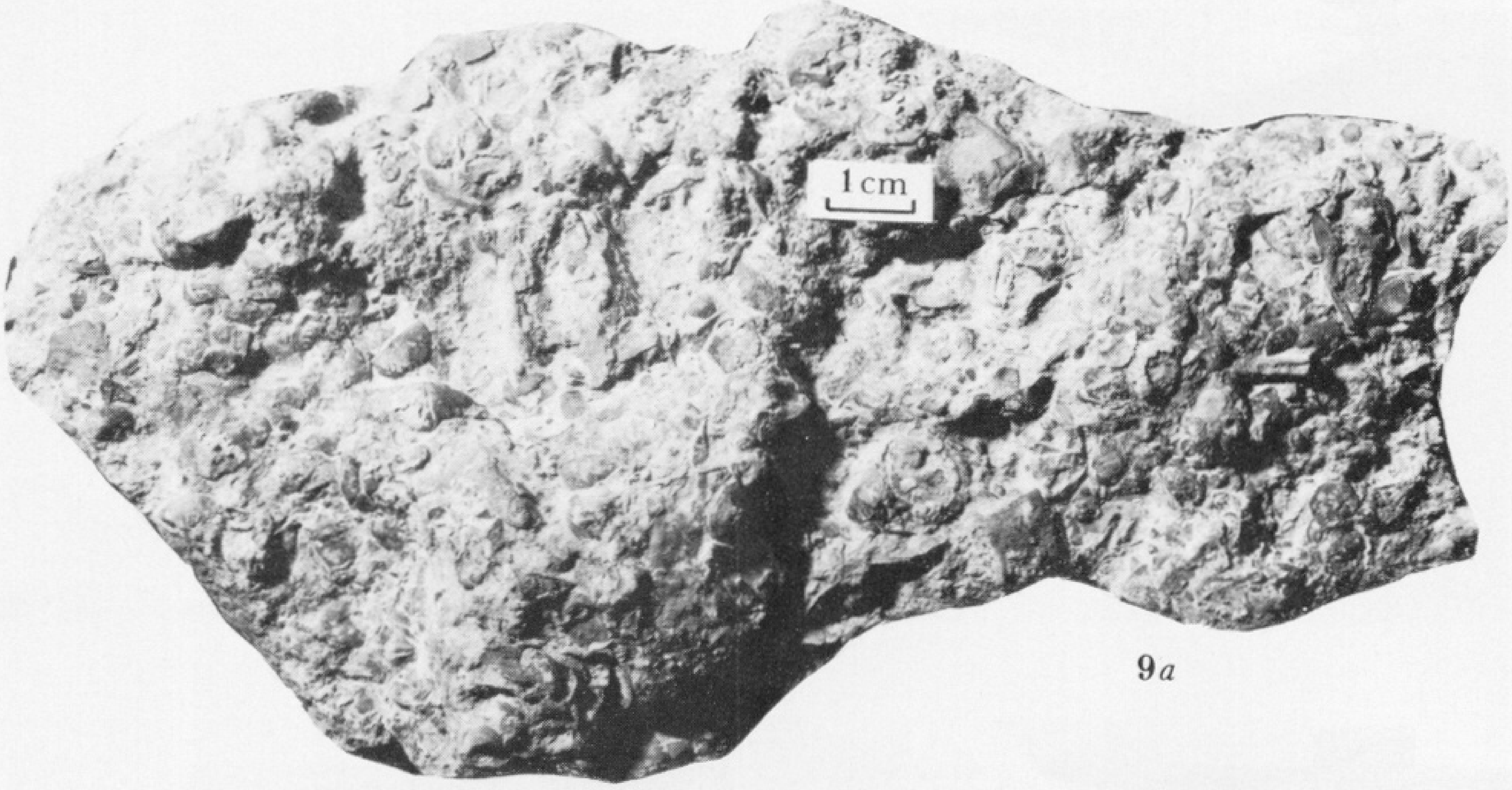
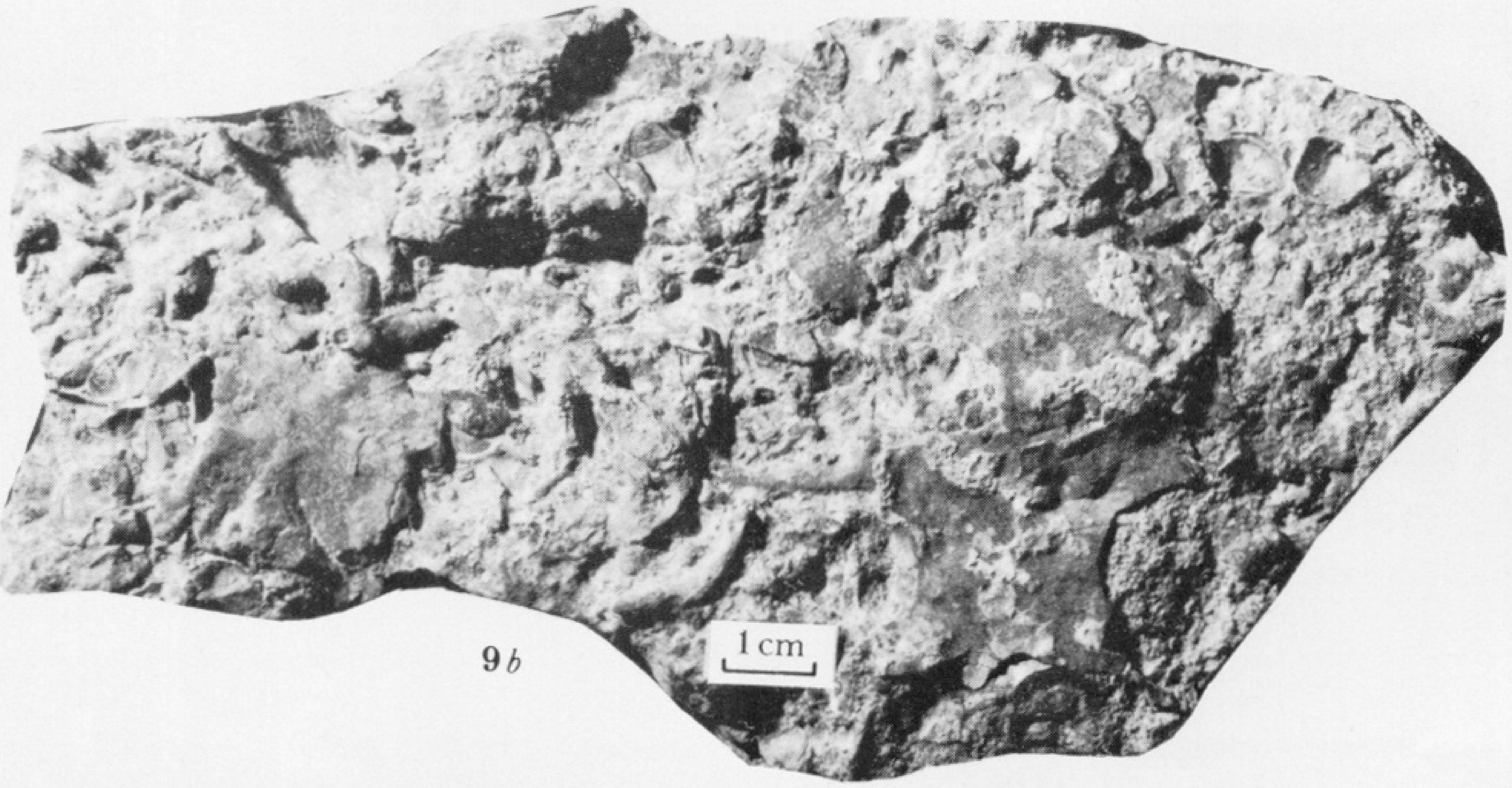
6


7

FIGURES 2–7. For description see opposite.



9 *a*



9 *b*

12

FIGURES 9 AND 12. For description see opposite.