THE STRUCTURE AND ORIGIN OF THE WAULSORTIAN (LOWER CARBONIFEROUS) 'REEFS' OF WEST-CENTRAL EIRE

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CONTENTS

The structures into which the Irish Waulsortian limestones are organized have been regarded as reefs. They are re-interpreted as carbonate mudbanks. Their growth mechanism has been deduced from a study of bank morphology and depositional structures.

The banks grew from Upper Tournaisian to Lower Viséan times, occupying an offshore position on a shallow water shelf. They formed a bank complex covering thousands of square miles, and many smaller masses scattered in the lagoon on its northern and eastern sides. Southwards the Waulsortian Complex was bounded by the 'Culm' mud belt.

Individual banks were detected and their internal structure mapped by studying the spatial arrangement of small-scale bedding features. The sparry masses (*Stromatactis* or 'reef tufa') proved the most useful of these because their shape and orientation were found to depend directly upon the depositional attitude of the bank bed containing them. Form lines, constructed from measurements on bedding features, were used to delineate banks incompletely exposed.

When compared with the size of the Complex the banks were not large. At any one time they may neither have risen much more than 50 ft. above the sea floor nor exceeded a few hundred yards in diameter. They are constructed from irregular, thin, lenticular limestone bodies here termed 'bank beds'. These, which are sometimes difficult to detect, apparently represent growth increments not erosional remnants. Flat-lying beds characterize the earliest stage of bank growth.

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Later, the depositional slope gradually increased. In the final 'climax form' depositional dips up to 50° are known. Bank geometry was controlled by the size, shape and arrangement of the bank beds (affected by several factors) and the relative rates of bank and off-bank sedimentation. Most banks conform to a basic 'knoll' growth pattern. 'Sheet' forms, probably highly modified knolls, are rare.

Single, isolated knoll-form banks have not been seen: the existence of one bank always seems to have promoted the formation of others. Four examples illustrate stages in the aggregation of banks to form a complex. These, taken from localities in Counties Longford, Galway, Tipperary and Limerick, show successively less intercalation of lagoonal limestone and shale until finally all the banks overlap one another directly.

Lithological variation in the Waulsortian limestones can be expressed in terms of their five main components: (i) calcite mudstone, (ii) coarsely crystalline calcite mosaics (including *Stromatactis* and 'reef tufa'), (iii) *in situ* fenestellid Bryozoa, (iv) crinoidal, shelly and bryozoan debris, and (v) entire fossils other than Bryozoa. Except at bank margins no simple pattern of lithological changes has been recognized.

Fenestellids are often common, acting as baffles trapping fine sediment. However, they did not constitute a rigid framework and cannot be regarded as the sole agents of bank growth. Depositional structures in the calcite mudstones provide the key to an understanding of bank genesis. *Stromatactis* spars, which elsewhere have attracted most attention, are less important because their form depends directly upon the depositional sequence in the mudstones. In any one sample several distinct mudstone generations are present. Most were deposited before any spar formed. Their present distribution mainly results from internal sedimentation. The earliest mud generation ($M1$) forms discrete patches or loose 'flocculent' masses often occupying less than half the total volume of mud present. It is generally surrounded by later muds ($M2$ *et seq.*) and spars. The arrangement of the generations and the structures within them suggest that (i) $M1$ behaved as lumps of sediment (compacted but not lithified) while later muds were finely particulate, (ii) both $M1$ and $M2$ arrived in their present positions together by downward movement in a gently collapsing system, and (iii) loose packing of $M1$ and $M2$ left cavities roofed by mechanical 'bridges'. Similar 'bridging' and cavities can be produced experimentally. The collapse features can be explained by decay of the organisms (perhaps plants or sponges) around and within which the mudstones of the bank accumulated. $M1$ may then represent mud trapped between the organisms and $M2$ that trapped or produced within them. A local origin for the mud is favoured. Cavities remaining after collapse were filled by geopetal muds trickling from higher parts of the bed, and by precipitated spars (thus producing *Stromatactis*). In some instances, at least, the spars were formed before deposition of the next bed. They could thus have provided an inorganic skeleton supporting the bank until the mud lithified.

It is concluded that the morphology of the banks, their steep depositional slopes, and the presence, bulk and arrangement of the calcite mudstones all point to the baffling activity of organisms (not preserved) as the mechanism of bank growth.

Details of the physical and chemical environment around the banks cannot be surely deduced from evidence available at present. The sedimentary structures give few direct clues because of extensive internal resedimentation. Further, the value of any of the mechanical structures as indicators of the state of the water around the banks is doubtful. Even if the banks grew in agitated water the presence of baffles could inhibit formation of mechanical depositional and erosional features otherwise associated with these conditions. Absence of such features may thus be misleading.

I. Introduction

The existence of structures in ancient limestones directly comparable with modern organic reefs has long been debated. Disagreement has arisen because of the absence in the fossil masses of some of the definitive criteria of organic reefs. Hence, reliance has been placed on deductions regarding conditions of deposition and on inferences concerning the capacity of the organisms for framebuilding and wave resistance. Liberal interpretation of certain criteria and ready application of the term 'reef' to many limestone bodies has led to incredible confusion in the literature. As the terminology concerning reefs and reef-like bodies is now so involved, a definition must be considered at the outset.

There is, in nature, a wide range of reefs and allied structures and any definition must be arbitrary. Thus, Lowenstam's definition of a reef (1950, p. 433) as the 'product of actively building and sediment-binding biotic constituents, which, because of their potential wave resistance, have the ability to erect rigid wave-resistant topographic structures', has been accepted by some geologists but challenged by others. For instance, Kornicker & Boyd (1962, pp. 670 and 671) concluded from a study of the Alacran reefs that Lowenstam's definition places an artificial boundary within the gradational sequence they recognize at Alacran. They regard a reef as 'a concentration of carbonate skeletons, in growth position, which significantly influences adjacent sedimentation because of its relief above the surrounding sea floor'. Doubtless this will be challenged too. However, definition apart, the acme of reef development under rigorous physical conditions is characterized by a rigid organic framework capable of maintaining itself in the surf zone. The fundamental components of such a reef are the 'frame', 'cement' and 'detrital fill' of Ginsburg & Lowenstam (1958, p. 314 and figure 3). Thus, any fossil reef should show at least a concentration of carbonate skeletons in growth position. The degree of rigidity, wave resistance, and depth of water in which the organisms grew, are features which, after investigation, can be used to qualify the term 'reef'. Ginsburg & Lowenstam differentiated sharply between structures built around a skeletal framework and those formed by the action of organic baffles and sediment binders. These two mechanisms by which mounds can be formed on the sea floor through organic action are operative today and are readily distinguishable. Both framebuilders and sediment binders undoubtedly contribute to some structures but it is still valuable to recognize their relative contributions.

The term 'bank' will be used here for all structures which formed conspicuous mounds on the sea floor. Such banks may have been built by local sedimentation or carved by erosion of once-continuous sediments. The latter are of no concern here. Those formed by local accumulation include structures as diverse as current-drifted piles of sand and *in situ* coral and algal reefs. There seems to be no reason why an organic reef should not be regarded as a special kind of bank ideally possessing the components already mentioned.

Like many other limestone bodies in the Carboniferous of the British Isles, the Waulsortian Phase* limestones of Eire have been called reefs (Turner 1937, 1938, 1939, 1948, 1952, 1962; Smyth 1939; Ashby 1939; Delépine 1951; George 1958; Nevill 1958; Shephard-Thorn 1963). As a result of the sedimentological work presented here the validity of the term 'reef' is questioned. The structures are better regarded as carbonate mudbanks. They probably grew as a result of organic activity, but the framebuilding mechanism was not important.

Fieldwork covered only part of the total Waulsortian outcrop in Eire being concentrated in areas where tectonic disturbance is small (figure 1). Further south, in the region of the main Variscan fold belt and thrust front, unravelling sedimentary structures from tectonic

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* The similarity between these Irish limestones and those of the Waulsortien Étage of Belgium (Dupont 1863, 1865; for more information see Demanet 1958, p. 77; Mennig & Vatan 1959) was noted by Douglas (1909). The name Waulsortian seems to have been first applied directly to the Irish rocks by Delépine (1940, 1949, 1951).

ones becomes increasingly difficult. It is hoped, however, that knowledge gained from the present study can be successfully applied to similar sedimentation problems in the structurally complicated areas.

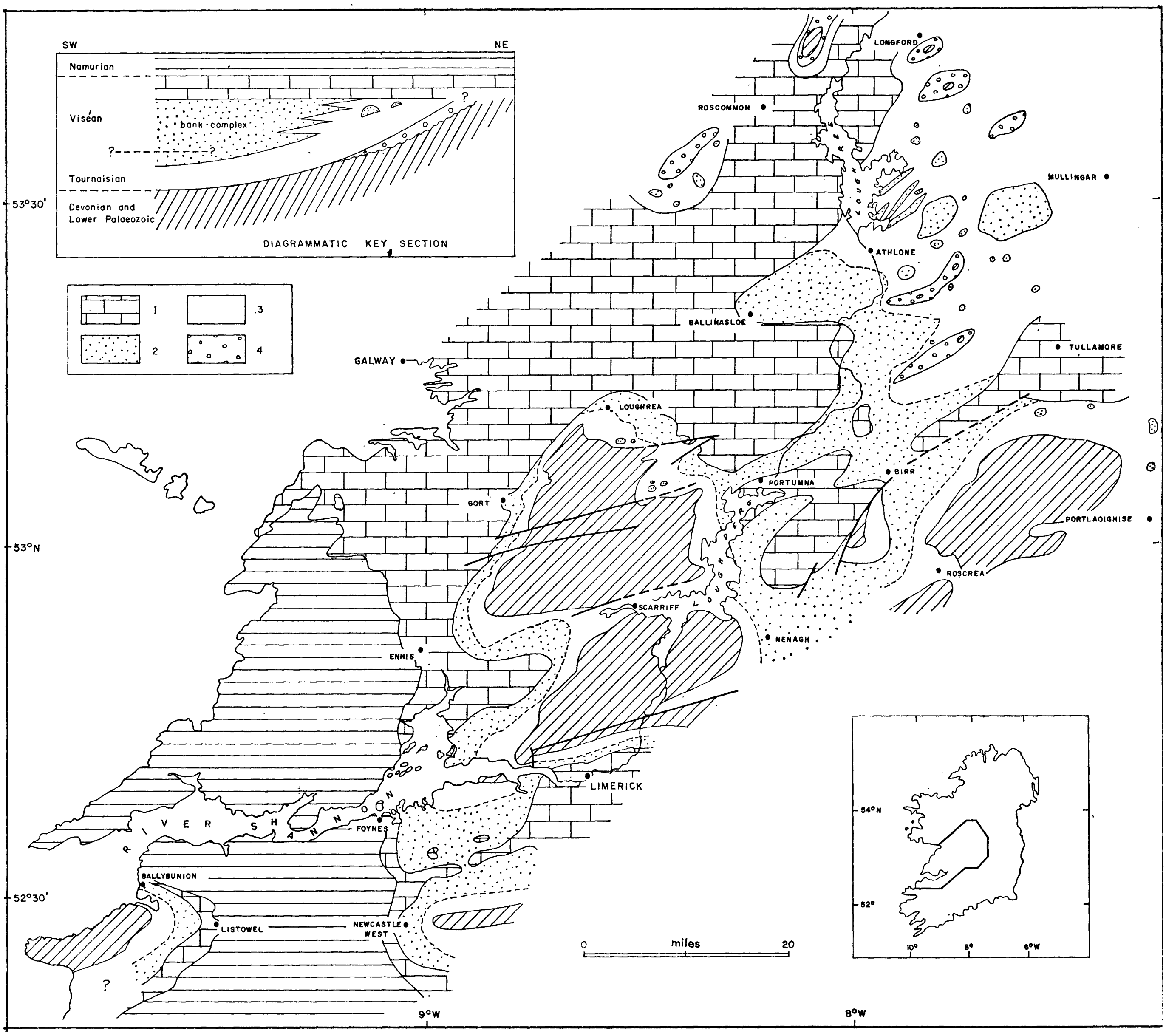

FIGURE 1. Geology of the region where the Waulsortian and associated rocks were studied.

Key to Lower Carboniferous lithofacies:

1. Upper Limestones (S_2 and D zones in some areas at least).
2. Waulsortian bank limestones.
3. Lagoonal limestones and shales (Waulsortian equivalents), and similar pre-Waulsortian rocks.
4. Offshore, and any other clastics at local base of Carboniferous.

Particularly in the north-eastern half of the map, where exposures are poor, many of the geological boundaries are uncertain. The line marking the approximate edge of the bank complex may be several miles out of position in some places.

(Continued on opposite page)

II. PALAEOGEOGRAPHIC SETTING AND THE MAJOR LITHOFACIES

Waulsortian limestones outcrop over a considerable area in Eire but exposures are scattered. As detailed correlation on faunal zones is also difficult, facies variation on all scales becomes important as the basis for analysis of palaeogeography and environment.

The main features of the palaeogeography and facies distribution have already been described (Lees 1961) and are summarized here.

During Upper Tournaisian and Lower Viséan times most of southern Ireland was occupied by a shallow water shelf, bounded to the south by the flanks of the Variscan geosyncline and to the north and east by land masses. The rocks of the geosynclinal flanks are dominantly shales, mudstones and sandstones of Mudbelt or 'Culm' facies. These terrigenous clastics were perhaps southerly derived (George 1958, pp. 279 and 280). On the shelf three major lithofacies can be distinguished:

(i) Waulsortian facies: limestones forming a large bank complex and many smaller groups of banks scattered in the lagoon on its landward side.

(ii) Lagoon facies.

(iii) Offshore clastics facies.

The distribution of these is shown in figure 2.

The Waulsortian Complex, separating the lagoon from the southern mud belt, occupied a position analogous to that of a barrier reef. It never seems to have extended close inshore but thrived farther out to sea where it eventually covered thousands of square miles. The Complex is thickest in two areas: one a few miles west of Limerick (over 2500 ft.), and the

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(Legend to figure 1 continued)

The diagrammatic key section relates to the area between Foynes and Longford. Further west, in the Listowel-Ballybunion area, the succession is similar to that at Foynes but the Waulsortian bank complex is thinner and may be 'breaking up' into smaller aggregates of banks.*

The interdigitation between bank complex and lagoon facies shown on the key section is not indicated on the map because the scale is too small and interdigitation too irregular for accurate representation. No division is made between lagoon facies and pre-Waulsortian limestones because they are lithologically similar and no faunal distinction has been attempted.

Stratigraphic correlation is based on the author's reconnaissance mapping and a number of other sources mentioned in the text (including the papers by Ashby, Delépine, Douglas, George, Nevill, Shephard-Thorn and Turner). The Carboniferous/pre-Carboniferous boundary, the faults between Limerick, Portumna and Loughrea, and the outcrops of clastics at the local base of the Carboniferous south of Athlone, are simplified from the published maps of the Geological Survey of Ireland by permission of the Minister for Industry and Commerce. The outcrops of offshore and other clastics near Longford are taken from Nevill (1958, pl. V). The base of the Namurian is from Hodson & Lewarne (1961). Geological boundaries in the area stretching from Foynes about 10 miles south and 15 miles east are from Shephard-Thorn (1963).

* (*Added in proof*, *5 February* 1964.) Since this was written the Ambassador Irish Oil Company has studied the microfaunas of some of the limestones from this area. The Company has kindly permitted me to record that the Foraminifera in the bank limestones exposed on the shore at Ballybunion indicate a D_1 age. On this evidence the outcrop of Waulsortian limestone shown in that position on figure 1 is incorrect. It is still possible, however, that both D zone and Waulsortian bank limestones are present.

other near Cork (4000 ft., see Nevill 1962, p. 482). As the Limerick centre, at least, is partly Tournaisian (Shephard-Thorn 1963, p. 280) these were perhaps the areas where growth started. Elsewhere, Waulsortian sedimentation may not have begun until the Lower Viséan (George 1958, p. 274; Nevill 1958, p. 288). Little is yet known about growth towards the west, but Waulsortian rocks are exposed in the western parts of Counties Cork and Kerry.

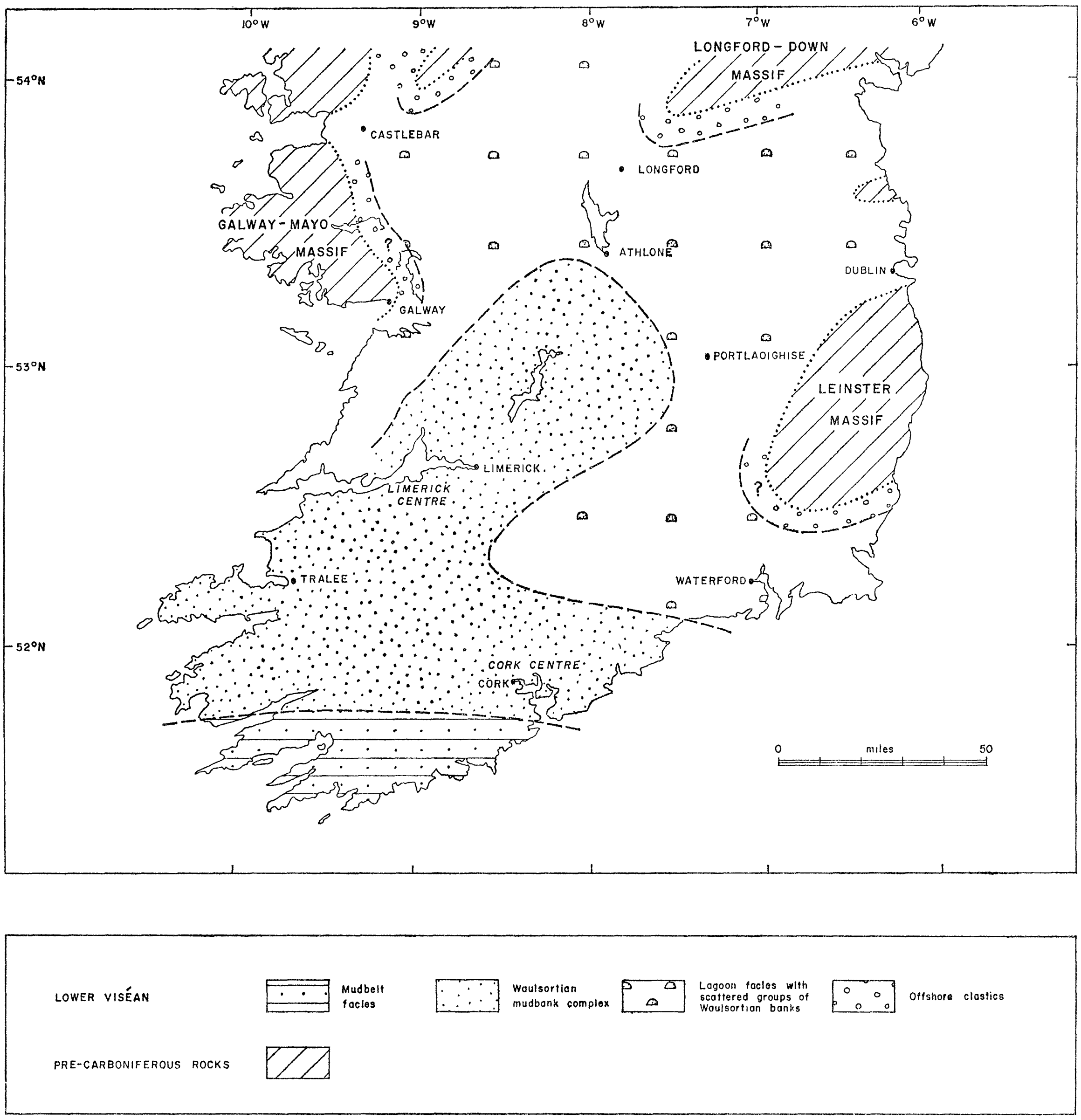

FIGURE 2. A tentative reconstruction of the palaeogeography and distribution of major lithofacies when the Waulsortian Complex was at its maximum extent. The present lack of precise stratigraphic correlation between the major facies precludes the composition of a more accurate picture. Compiled from many sources.

The Waulsortian limestones often appear unbedded in outcrop, but close examination usually reveals bedding or growth surfaces. The rocks are characteristically pale violetgrey to dark grey in colour. They are calcite mudstones with variable quantities of skeletal debris, *in situ* Bryozoa, and patches of coarser, sparry calcite.*

In contrast, the lagoonal limestones are often thinly bedded, sometimes nodular, and contain variable amounts of chert and shale. Dark grey to black in colour, they are composed of crinoidal, shelly and bryozoan debris with either a calcite cement or a matrix of calcite mudstone (more dominantly silt grade than in the banks). Oolites and dolomites are present in some areas outside the one studied.

There is generally little difficulty in distinguishing between limestones of Waulsortian and lagoon facies but intermediates can occur at bank margins.

The offshore clastics occupy restricted zones near the margins of the ancient land masses. In the study area rock types range from conglomerates and quartz-felspar sandstones to oolites and algal limestones. The sediments were predominantly terrigenous in origin, but many were deposited under conditions also favouring carbonate sedimentation. The transition to lagoonal rocks is probably gradual, carbonate sediments diluting the terrigenous clastics further offshore.

III. The Waulsortian mudbanks

(*a*) *Introduction*

Later discussion will be simplified if bank geometry and the methods by which it was studied are briefly described here.

(1) *Bank growth forms*

The Waulsortian limestones do not form a homogeneous mass but are organized into sedimentary structures. The largest of these are the banks.

It was reported (Lees 1961) that the banks accumulated in two distinct forms: as 'knolls' and 'sheets'. Detailed mapping has since shown that greater variation exists and the two types are best regarded as the end-members of a series, differing only in their relative growth rates (figure 3). However, the terminology is still useful. Bedding in the banks is sometimes obscure but it is not absent. The bank beds are irregular, thin, lenticular limestone bodies ranging up to several feet in thickness and extending laterally from tens to hundreds of feet, sometimes wedging out rapidly (figure 33, plate 6). Their shape and arrangement controlled the form of the banks.

Bank growth proceeded in a characteristic fashion. The earliest beds are generally flat-lying lenticular masses (examples in Knockadrum quarry, lat. 53° 5′ 40″, long. 8° 26′ 0″). Persistence of this flat form would result in an apparently normal, bedded sequence. Usually, however, growth became localized, the beds developing a sigmoid profile with a maximum slope of about 50° (the 'climax form'). If growth occurred about a centre the knoll form resulted; if it was linear then ridges or sheets formed. These general growth patterns are detectable even when the response of the banks to local conditions, such as sea floor irregularities, profoundly modified the simple arrangement shown in figure 3.

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* Calcite mudstone is used as a general term including both clay- and silt-grades. Sparry calcite crystals are usually much larger than those of the mudstone but do range down into silt grade. The mudstones and spars are generally distinguished by their fabrics and the clarity of the spar (cf. Folk 1959, p. 8). Throughout the paper the terms 'calcite mud', 'calcite mudstone' and 'calcite spar' are abbreviated to 'mud', 'mudstone' and 'spar'. If minerals other than calcite are present the terms are suitably qualified.

(2) *Methods of study*

The analysis of bank geometry has been based on the relationship between the orientation of (i) sparry calcite masses (*Stromatactis* or 'reef-tufa', see p. 509), and (ii) beds and growth surfaces defined by shaly partings, layers of skeletal debris, and other lithological changes (figure 4). In general terms, the sparry masses, which in vertical section usually have fairly distinct major and minor axes, are elongated almost parallel to

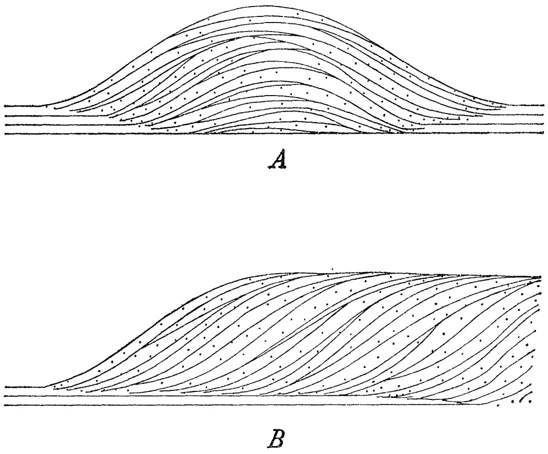

FIGURE 3. Waulsortian bank growth forms in vertical cross-section. (Diagrammatic).

A, Knoll form (growth about a centre). Banks range in diameter from less than 100 to more than 1000 ft., diameters of several hundreds of feet being common.

B, Sheet form (growth along a front). Extent of lateral growth not known but could amount to thousands of feet.

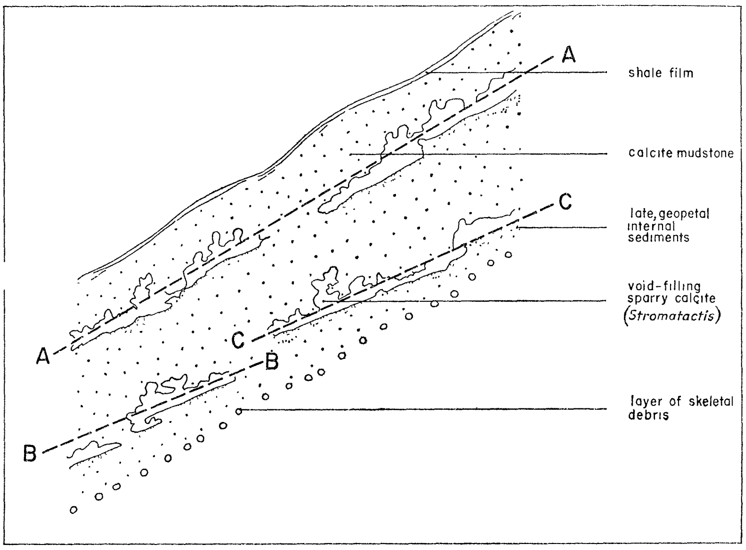

FIGURE 4. Relationship between the orientation of *Stromatactis* sparry masses and other bedding features. Diagrammatic vertical section. Two typical arrangements are shown; A–A where sparry masses are 'elongated' parallel to the depositional dip of the bed, B–B and C–C where they lie at angles less than the dip.

Scale: the sparry masses occasionally extend to more than 1 m in greatest dimension (in the plane of the bedding) but are most commonly in the 1 to 20 cm range.

the depositional dip of the bed containing them. Details are given later (pp. 512 and 514, figures 22 and 31). A similar relationship between 'tufa' layers and bedding was suspected by Dixon (1921, p. 127) and Parkinson (1935, p. 100). This 'spar orientation' has proved to be the most useful single criterion for determining the position of the depositional slope.*

The abrupt wedging of bank beds produces marked local variations in the 'spar orientation' which can be confusing. This does not invalidate the method because the beds always have much greater lateral extent than thickness. It means, however, that measurements must be checked over a distance of several yards if exposures permit.

With the exposure and topographic information normally available the construction of isopachs or strike lines on individual beds is impossible. But, form lines drawn from the pattern of strike directions of the measured features have proved useful in the analysis of bank morphology and structure. Selective erosion of the softer lagoonal rocks leaving the banks as hillocks aids the reconstruction because the comparatively thin set of beds exposed represents an approximation to a single surface. The success of the technique might be impaired if erosion normally cut across the banks because the thickness of the exposed sequence and the chance of encountering small scale irregularities in the bank cores would then be increased. Variations in the spacing of the form lines reflect either change of dip or thickness. If line spacings are chosen to correspond to a standard thickness of beds they can be used in the study of bank symmetry.

The form line pattern and the systematic dip changes known to result from the presence of the climax form make possible a three-dimensional reconstruction of banks which are incompletely exposed.

(*b*) *Simple knoll-form banks in the lagoon*

At Carrickboy, 8 miles south-east of Longford (lat. 53° 37′ 50″, long. 7° 41′ 15″) a quarry is worked in the northern end of Richmount Hill. The hill, composed largely of Waulsortian limestones organized into many banks, is surrounded by rocks of lagoon facies. In the quarry, three banks are partly exposed and their relations with the lagoonal rocks can be seen (briefly described by Nevill 1958, p. 293). Tectonic effects are fortunately slight.

The main west wall of the quarry exposes the best section of the banks (figure 5). The southern end of the section is occupied by part of a large bank (Bank 1) composed of calcite mudstone, sometimes with bryozoans, and well developed, oriented sparry masses. Crinoidal debris is common in places, particularly towards the core of the structure where it is mixed with the mudstones and spars. The outer part of the bank is relatively crinoid-free. The succeeding thinly bedded limestones and blackish shales (Lagoon I) thin and wedge out over the bank and generally dip steeply off it. Slickensiding parallel to the dip is common in the more shaly beds. Another bank (Bank 2) overlies the rocks of Lagoon I but only the edge remains, due to quarrying. Although now only intermittently exposed, the upper surface of Bank 2 is partly erosional. Truncation of the sparry masses in the bank

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* (*Added in proof*, 5 *February* 1964). Because of the irregular shapes of the sparry masses and local variations in their orientation, the measurement of 'spar orientation' cannot be precise. Each of the measurements shown on figures 7, 10, 11, 12, 15 and 17 represents the 'plane of best fit' determined visually. Where the orientation is changing rapidly and systematically over a short distance the maximum dips are given and indicated by (m).

at this surface provides important evidence on the time of spar formation (figure 6). The overlying bedded, crinoidal limestones belong to another wedge of lagoon facies (Lagoon II) although they are much less shaly than the earlier intercalation. Again, they thin and wedge out against the bank and dip off it. The succeeding limestones (3*a*) are lithologically similar to those of Lagoon II but are structurally part of another bank. They change

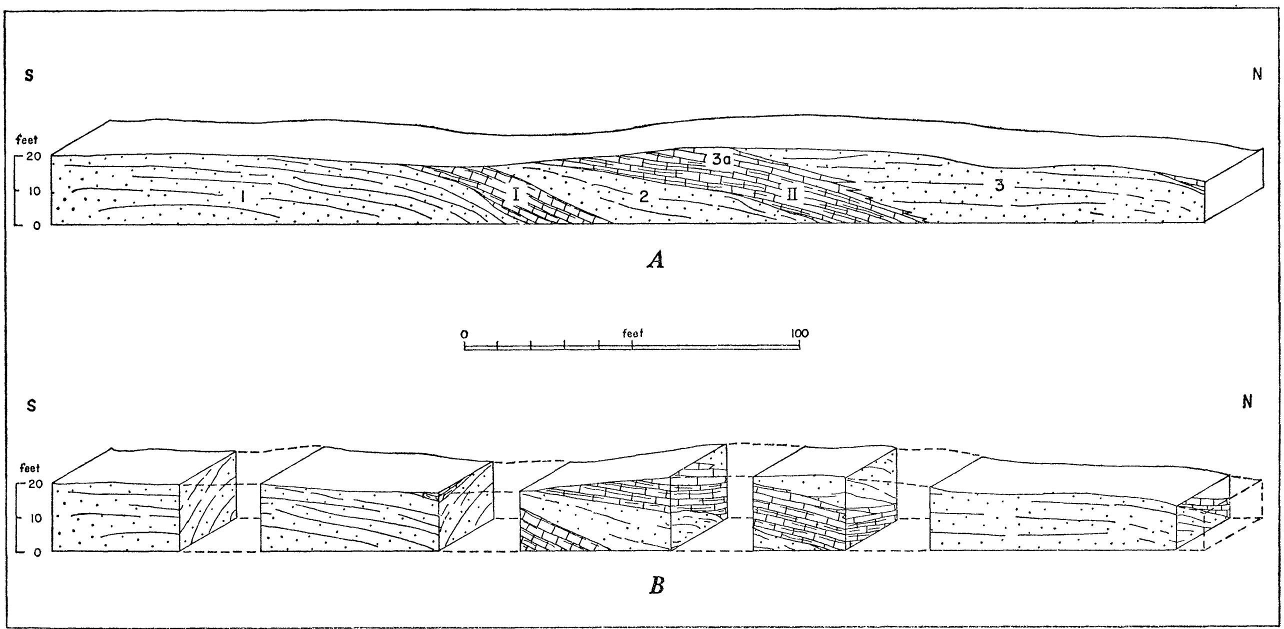

Figure 5. West wall of Carrickboy quarry, Co. Longford. Viewed from the east. Block diagrams constructed from detailed measurements and photographs.

A, The complete west wall (September 1961) showing all rock bodies described in the text. 1, 2 and 3 are Waulsortian banks, I and II intercalations of lagoonal limestone and shale, and 3*a* a near-lagoon flank of Bank 3.

B, Parts of the block omitted to show the three-dimensional relationships between the banks and lagoonal rocks.

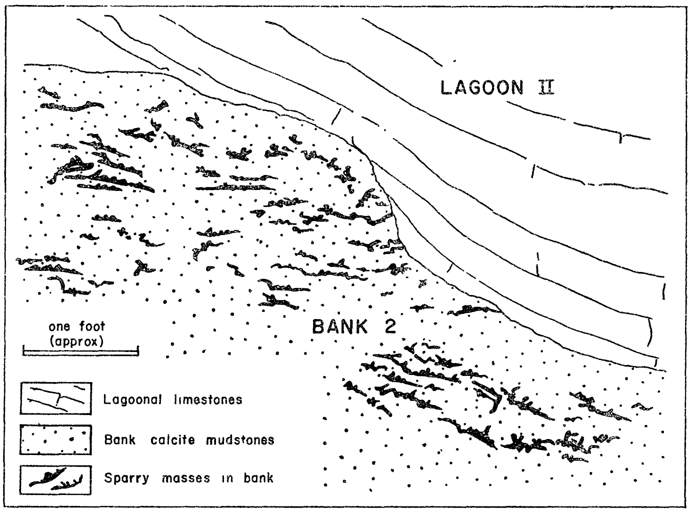

Figure 6. Detail of the contact between Bank 2 and the overlying lagoonal beds, west wall, Carrickboy quarry. Note the truncation of the sparry masses at the erosion surface. Drawn from photographs.

laterally and pass into the typical Waulsortian limestones of Bank 3, of which a segment exceeding 90° is exposed. In contrast to Bank 1 the zone of crinoid admixture here occupies a transitional flank position. Encrinites, overlapping and thinning against Bank 3 are exposed in the north-west corner of the quarry.

From measurements made on sections exposed over the past few years (figure 7) and photographs of earlier quarrying stages, form lines were plotted (figure 8). They may be analyzed in terms of the depositional sequence as follows:

(i) Deposition of Bank 1, probably from a growth centre not less than 230 ft. south-west of the south-west corner of the quarry. Although only the north-east segment of the bank is exposed, the shape of its upper surface can be clearly seen. The approximate extent of the bank's underground continuation and the position of the exposures in the structure can be estimated from the variation in dip of the sparry patches on the assumption that the climax form is developed. Towards the base of the quarry wall at the south only the flatter, upper part of the climax curve is present. Farther from the growth centre on both west and south walls the steeper, lower portions of the curve come into view and the upper, flatter parts are found high up the quarry face. A diachronous rise of the base of the bank due to considerable coeval lagoonal sedimentation may therefore be inferred (figure 9).

(ii) After the close of bank deposition sediments of lagoon facies were laid down (Lagoon I). These wedge out on to the bank and drape over it, their form lines almost paralleling those of the bank beneath (figure 8). Present dips include depositional and later components. Some of the compaction has been taken up by small shears in the shaly beds, but most of it seems simply to have emphasized original slopes. Deposition of the lagoonal sediments was clearly influenced by the mound on the sea floor.

(iii) The form lines of the early parts of Bank 2 conform to those of the underlying Lagoon I but later stages show a marked divergence. Initially, the bank grew on a sloping surface which controlled its shape. Later, this influence was overcome and the climax form established. This mode of deposition contrasts markedly with that of normal mechanical sediments like the lagoonal limestones. The bank may be said to have exerted a 'growth pressure' which overrode local conditions.

(iv) The form lines of Lagoon II parallel those of the bank surface beneath. Hence, the presence and form of a bank again influenced the disposition of the mechanical sediments.

(v) A sudden swing of about 30° in the strike of the form lines marks the change to another depositional structure hardly intimated by a change in lithology. The bedded, crinoidal limestones concerned (3*a*) represent a near-lagoon flank facies of Bank 3, being directly related to its growth structures as shown by the form lines.

(vi) Bank 3, like the previous one, seems to have grown on a sloping surface. The quarry wall shows an upward sequence of dip changes indicating a progression of climax-form beds.

(vii) Encrinites were deposited against the sloping flanks of Bank 3. They are too poorly exposed for form lines to be drawn.

In summary, the three knoll-form banks exposed in Carrickboy quarry are separated by lagoonal intercalations. The banks and lagoonal rocks show two strikingly different modes of deposition. The banks exerted a 'growth pressure' in attaining their climax form, the influence of substrate attitude soon being overcome. Bank morphology was finally controlled by the relative positions of growth centres and their respective growth vectors. The lagoonal beds, on the other hand, had no growth pressure. Their attitude was controlled by the shape of the submarine topography.

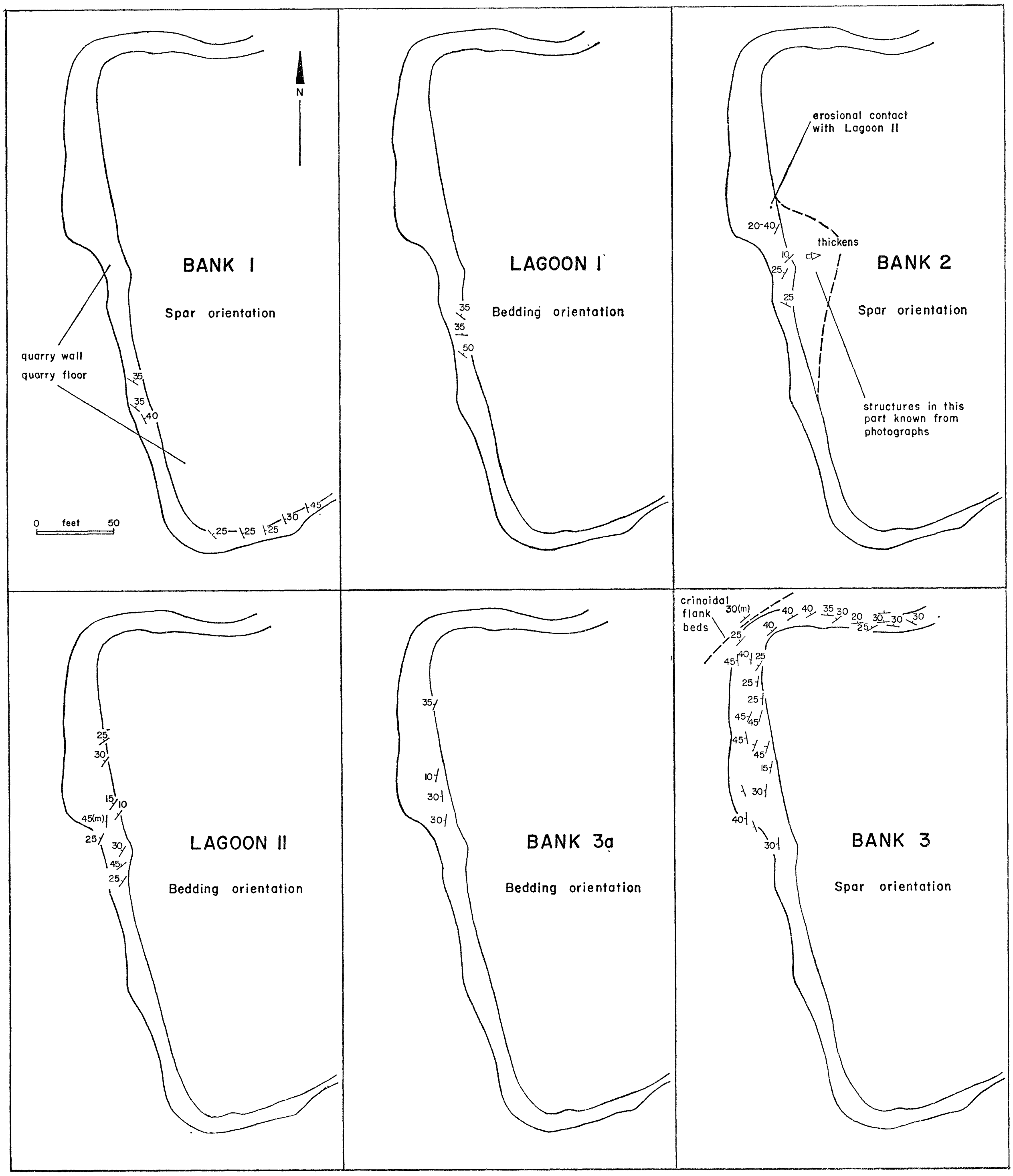

Figure 7. Plans of Carrickboy quarry with the attitudes of bedding planes or sparry masses plotted for each rock body. Dips in degrees: those followed by (m) are the maximum ones at that point. Originally mapped at a scale of 1 to 300.

(*c*) *Bank aggregation*

Several stages of aggregation can be studied at localities in and near the Complex. They can be arranged in a sequence which, while not necessarily representing the developmental pattern followed during the accumulation of Waulsortian limestones at any one place, certainly furnishes the clue to the structure of the Complex. The following localities provide the best exposures: (1) Hill 707 near Loughrea, Co. Galway; (2) Scarragh Lough, Co. Tipperary; (3) Aughinish Island, Co. Limerick.

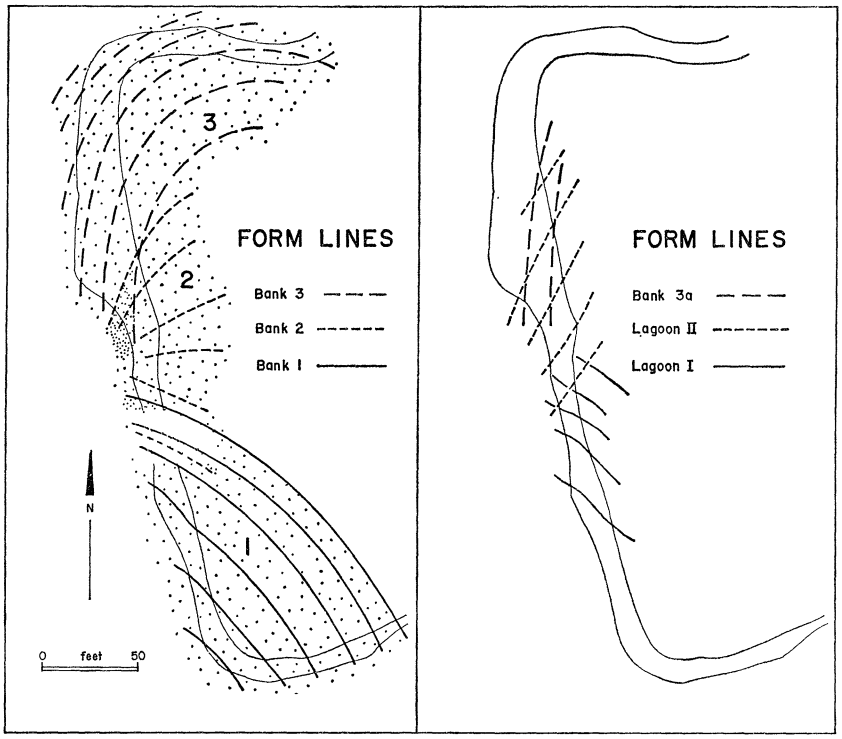

Figure 8. Form line reconstructions of the banks and bodies of lagoonal limestone exposed in Carrickboy quarry. Based on data shown in figure 7.

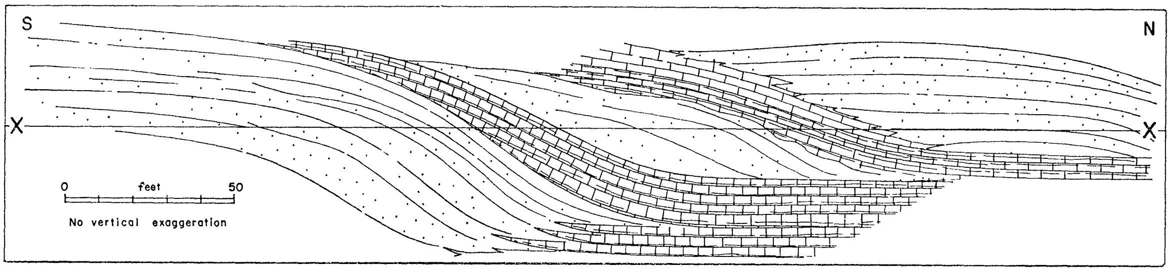

Figure 9. Vertical section showing deduced underground extensions of banks and lagoonal beds at the west side of Carrickboy quarry (cf. figure 5). X–X marks the level of the present quarry floor.

(1) *Hill* 707

This is an unnamed hill, 707 ft. high, in the townland of Knockash, 3 miles south-south-east of Loughrea, Co. Galway (figure 10, inset). It lies at the edge of the Complex.

The hill exposes several masses of Waulsortian limestone and the associated cherty lagoonal limestones. Some of the Waulsortian masses comprise several banks. There seem

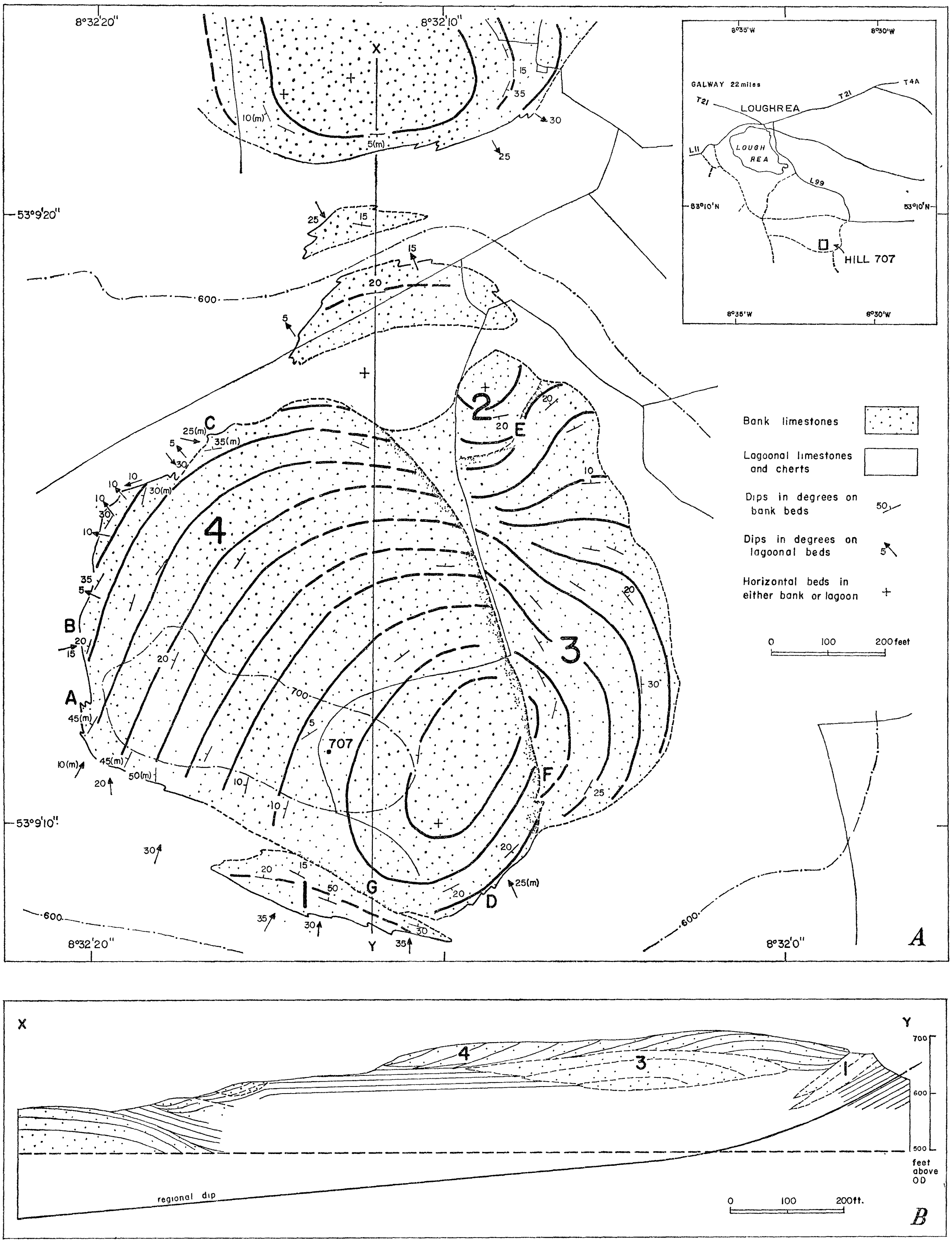

FIGURE 10. Hill 707, Co. Galway.

A, Map showing the distribution of Waulsortian limestones and lagoonal cherty limestones. Form lines, represented by thick continuous and pecked lines, have been drawn on the banks. In the main Waulsortian outcrops on the hill the banks are numbered in the order in which they are thought to have grown. For reference to points A to G, see text. Dips followed by (m) are the maximum ones at that point. Figure 33, plate 6, shows a view looking north-east from a point near the south-west corner of this map.

B, Vertical section along line X–Y on the map.

to have been local 'nodes' of growth in which the presence of one bank promoted the formation of others close by. At first sight the hilltop appears to be composed of a single bank with roughly radial dips, but detailed mapping (1:1760 scale) shows that four are present (figure 10). Here, in contrast to the arrangement at Carrickboy, the banks overlap one another directly. This can be seen at the places marked E, F and G on figure 10*A*.

The lateral passage from bank to lagoon is exposed at the points marked A, B, C and D on the figure. The simplest cases are at A and B where tectonic and compaction effects are small. Steeply inclined, climax-form beds in the bank (cf. Kinahan 1865, p. 22) flatten out when traced downwards, and pass laterally into the lagoonal limestones (figures 33 and 34, plate 6). The complete transition takes place in a few feet (elsewhere, even more abrupt changes have been found, see figure 35 plate 6). Geometrically, the bank-lagoon contact varies rapidly depending upon the relative depositional rates on and off the banks. When lagoonal sedimentation was relatively voluminous the base of the bank shows a sharp diachronous rise; when it was small, the base is almost horizontal (at A and B respectively, figure 10*A*, see also figure 33 plate 6).

These bedding relationships, coupled with evidence from sedimentary structures within the banks, show beyond doubt that many bank beds were deposited at angles exceeding 40°. As no erosional contacts are known the beds are regarded as distinct growth increments.

At the top of the hill the core of Bank 4 is exposed. Dips are low, indicating either the upper part of the climax curve or, more likely, the influence of the underlying Bank 3 on the early growth stages of Bank 4.

As at Carrickboy (p. 493) the lagoonal beds adjacent to the banks often have steep dips apparently compounded of depositional, compaction and possibly tectonic elements. However, on Hill 707 these dips vary greatly in magnitude and direction from place to place due to the presence of many closely spaced banks (some probably unexposed). Tectonic jostling of the competent Waulsortian and incompetent lagoonal masses may account for some of the irregularity, but the major tectonics appear to be relatively simple (figure 10*B*).

Bank 4 is the only one sufficiently exposed to justify any conclusions on growth vectors. Although basically of knoll-form it is markedly asymmetrical, growth being dominantly north-westwards. It is difficult to estimate the height to which the bank rose above the sea floor, particularly in the later growth stages. However, dip evidence suggests that the marked north-west spread of the bank was not accompanied by a great increase in overall bank thickness, so the height may never have greatly exceeded 50 ft.

(2) *Scarragh Lough*

The exposures lie immediately south of Scarragh Lough in the townland of Clonmakilladuff, 9 miles north of Nenagh, Co. Tipperary (figure 11, inset). In this region the Complex is probably several hundreds of feet thick, but some cherty intercalations are still present (Wynne 1862, pp. 33 and 34). Limited laterally and vertically they appear to represent local extensions of marginal lagoon conditions into the Complex.

In the small area studied in detail these cherty limestones are subordinate to Waulsortian rocks. Bank aggregation is therefore more advanced than on Hill 707 where the proportions are about equal. Mapping (1:1500 scale) has revealed four or possibly five banks (figure 11). Numbers 1 and 2 occupy low ground near the lough with only their upper parts exposed; 3 and 4 form the upper parts of two craggy hills rising sharply to the south. The cherty limestones pass laterally into all four banks, transitions being visible in several places (between A and B, C and D, and at E and F, figure 11*A*). They also undulate

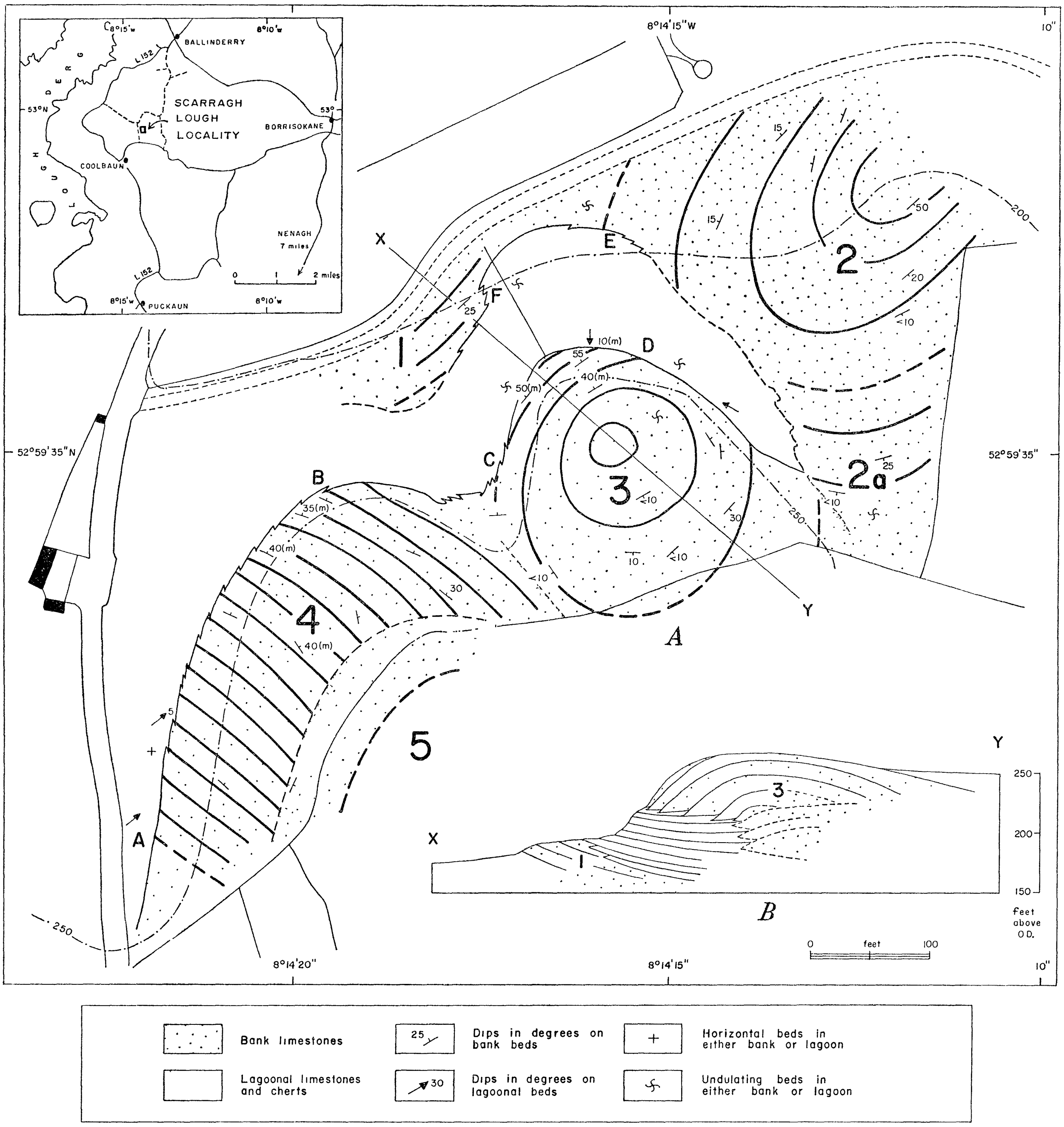

FIGURE 11. The Scarragh Lough locality. Co. Tipperary.

A, Map showing the distribution of Waulsortian and lagoonal limestones. The banks, on which form lines have been drawn, are numbered in the order in which they are thought to have grown. 2*a* may be a distinct bank, but the evidence is inconclusive. For reference to points A to F, see text. Dips followed by (m) are the maximum ones at that point.

B, Vertical section taken along X–Y on the map.

gently, probably because they drape over the exposed banks and others still uncovered. There appears to be little tectonic disturbance. In the gully between Banks 3 and 4 the cherty facies is absent, its place being taken by Waulsortian limestone presumably belonging to another (unnumbered) bank. This passage takes place abruptly (just south of C, figure 11*A*). Banks 3 and 4 thus seem to have started growing over older ones and later spread over lagoonal sediments (figure 11*B*).

Bank shapes are revealed by the form line patterns. Bank 2 might be elongated north-east–south-west but the evidence is inconclusive. Number 3 is markedly asymmetrical: the north-west face is steep, with climax-form beds and 50° dips, while the other slopes are much gentler. The centre of the bank is a region of low dips. Judging from the bedding arrangement this bank probably rose 50 ft. or more above the sea floor. Only a small part of Bank 4 is exposed so little can be said about its over-all form. However, it is probably larger than any of the others and shows a progression of climax-form beds advancing north-eastwards. This growth trend is perpendicular to that shown by the climax-form face of Bank 3.

(3) *Aughinish Island*

Aughinish Island, on the south side of the River Shannon 2 miles east of Foynes, Co. Limerick, lies in the region where the Waulsortian Complex is more than 2500 ft. thick. The island is made entirely of bank limestones except along its western side where the overlying bedded cherty limestones outcrop. The coastal sections offer good opportunities for the study of the upper surface and internal structure of the Complex.

(i) *Upper surface of the Complex.* This is best exposed in a small area on the west side of the island (figure 12). The present-day topography consists of several small hills up to 100 ft. high. These are composed of bank limestones apparently unbedded in the cores but becoming roughly bedded on the outer slopes. The intervening valleys are occupied by pale grey, cherty limestones, some contemporaneous with the banks, some younger. The bedded bank and cherty limestones generally dip radially outwards from the more massive cores, sometimes at high angles.

Detailed mapping reveals that the present topography represents an exhumed surface composed of several depositional mounds whose geometry and structures show them to be Waulsortian banks (figure 36 plate 6). The lateral passage between the cherty beds and the banks can be traced out in detail and the dips found to steepen as the banks are approached. The sequence of changes is similar to that recorded for more isolated banks (e.g. Carrickboy, p. 493; Hill 707, p. 497). Transitions can be seen in several places (A, B, C, D and E, figure 12). They are found in the normal position low down at bank margins but also occur higher up the flanks. Further, the cherty beds generally penetrate the mounds rather more than is usual in 'healthy' structures. Thus, as some of the banks also seem to have survived only a short time and never formed marked mounds, conditions were probably marginal for bank growth at that time and the Complex died slowly rather than being suddenly killed.

Since this was tectonically a more active region than those previously discussed, the possible influence of earth movements on the exhumed topography must be considered. The regional dip can be readily estimated because this area lies close to the axis of a major

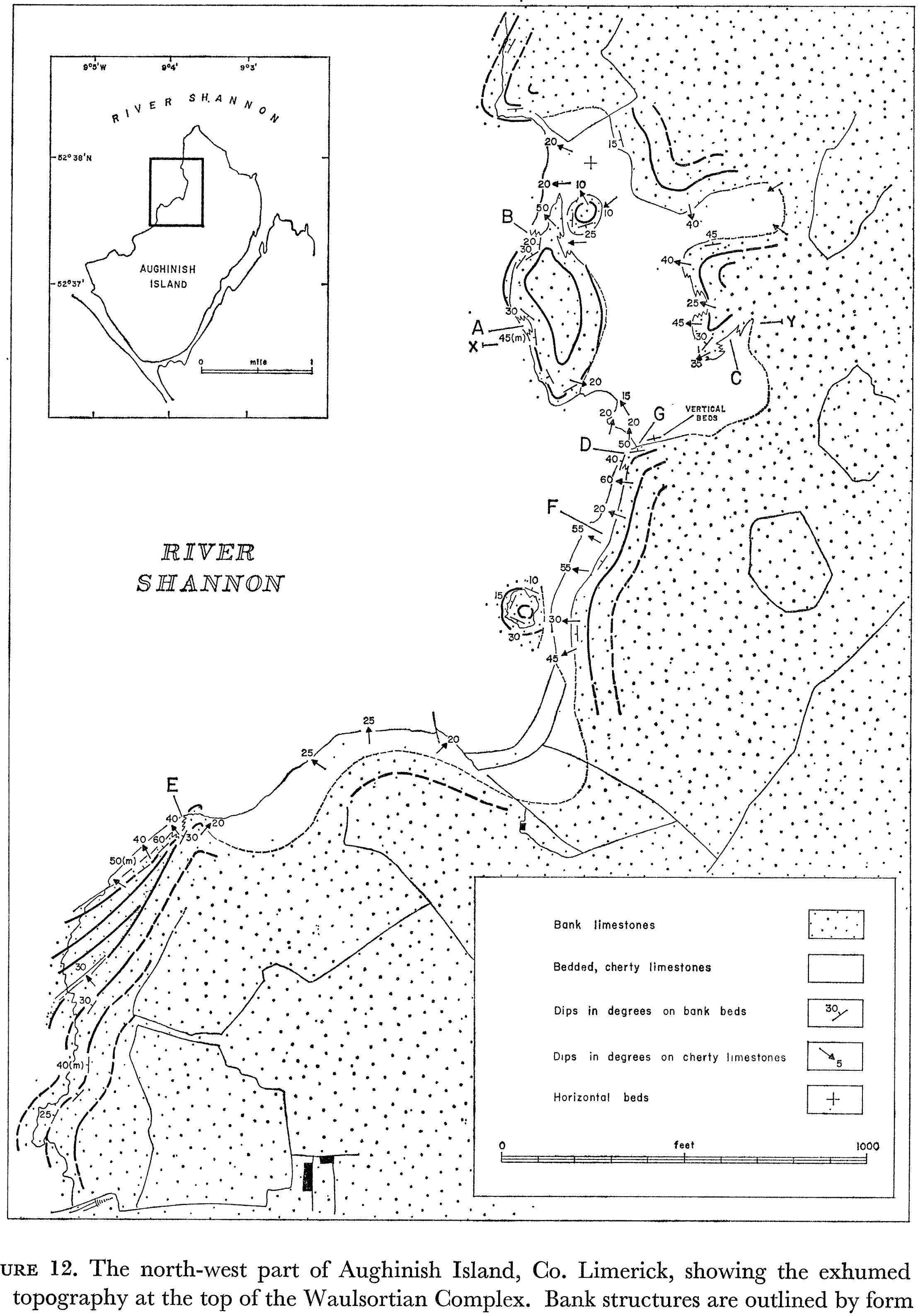

Figure 12. The north-west part of Aughinish Island, Co. Limerick, showing the exhumed knoll topography at the top of the Waulsortian Complex. Bank structures are outlined by form lines. Dips followed by (m) are the maximum ones at that point. For reference to points A to G see text. The line X–Y marks the position of the section shown in figure 13. Critical coastal exposures were originally mapped (jointly with Dr E. R. Shephard-Thorn) at a scale of 1 to 720.

anticline crossing the River Shannon and passing north-eastwards through Slieve Bernagh (figure 1). The plunge, calculated stereographically from all available dip data in north Co. Limerick and south Co. Clare, is approximately 10° towards 252°. This can be taken as the regional dip at Aughinish. By correcting for it the original symmetry of the banks is restored (figure 13). Small-scale undulatory structures, if any, are more difficult to detect. They are known in the sub-Waulsortian limestones 3 miles to the east (Mantlehill, east bank of Deel River: lat. 52° 37′ 40″, long. 8° 59′ 25″). However, the bank limestones probably resisted this type of folding. Their internal structure must permit few continuous planes of movement and these, where known, form an interlocking pattern (figure 3).

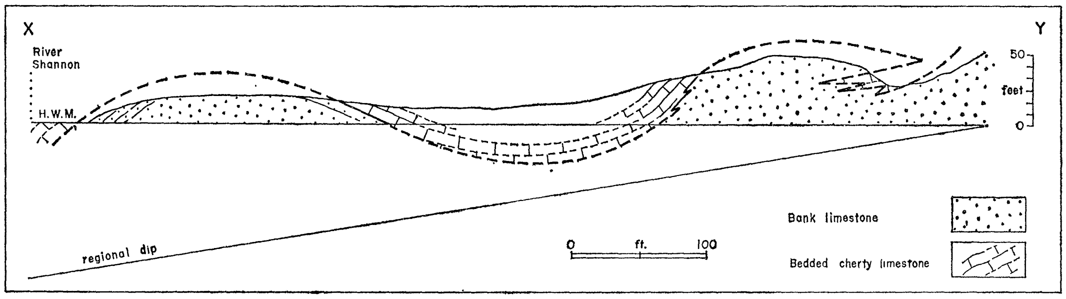

FIGURE 13. Diagrammatic vertical section across the upper surface of the Complex along the line X–Y on figure 12. Note the interdigitation of the Waulsortian and bedded, cherty limestones, and the effect of regional tilt. The thick pecked line shows the probable original form of the upper surface of the Complex. If the regional dip is subtracted, present-day dips in the banks of up to 45° westerly and 20° easterly are equalized.

Tectonic forces were apparently relieved by shearing around and between banks separated by marked discontinuities. The banks themselves acted as resistant bodies, responding by rolling rather than folding. Evidence for local shear and over-steepening is visible on Aughinish (F and G, figure 12). Most likely, therefore, folds as small as the banks are not developed and only regional dip and local shear need be considered. For all practical purposes the topography can be regarded as depositional, modified only by tilting and compaction.

This small area on Aughinish Island thus shows the closing stages of Complex formation. Individual banks are recognizable; some attained a knoll form, while others, much flatter structures, probably represent abortive efforts to reach the normal form. As conditions deteriorated the banks grew farther apart, permitting skeletal debris of the succeeding sedimentary phase to accumulate between, and eventually to overlap and bury them.

Other examples of knoll-form growth at the top of the Complex are exposed inland in Ballynamona townland (lat. 52° 34′ 50″, long. 8° 53′ 20″) and Ballinvirick townland (lat. 52° 34′ 30″, long. 8° 54′ 20″), Co. Limerick.

(ii) *Internal structure of the Complex.* Because the top of the Complex is composed of overlapping banks it is tempting to infer that the remainder of the enormous volume of Waulsortian limestone in the area is similarly organized. However, no obvious evidence supports this inference. Bank growth forms are relatively easy to detect where they adjoin rocks of different facies since these outline them and act as controls for estimating tectonics. Within the Complex no contrasting rock type is present, so the 'spar orientation' technique was used.

Much of the section along the north-east coast of Aughinish is virtually useless for orientation analysis since exposure is interrupted by small inlets. To prove the existence of banks within the Complex, exposures showing actual overlap between them are needed. Otherwise the structures may be practically indistinguishable from folds (figure 14).

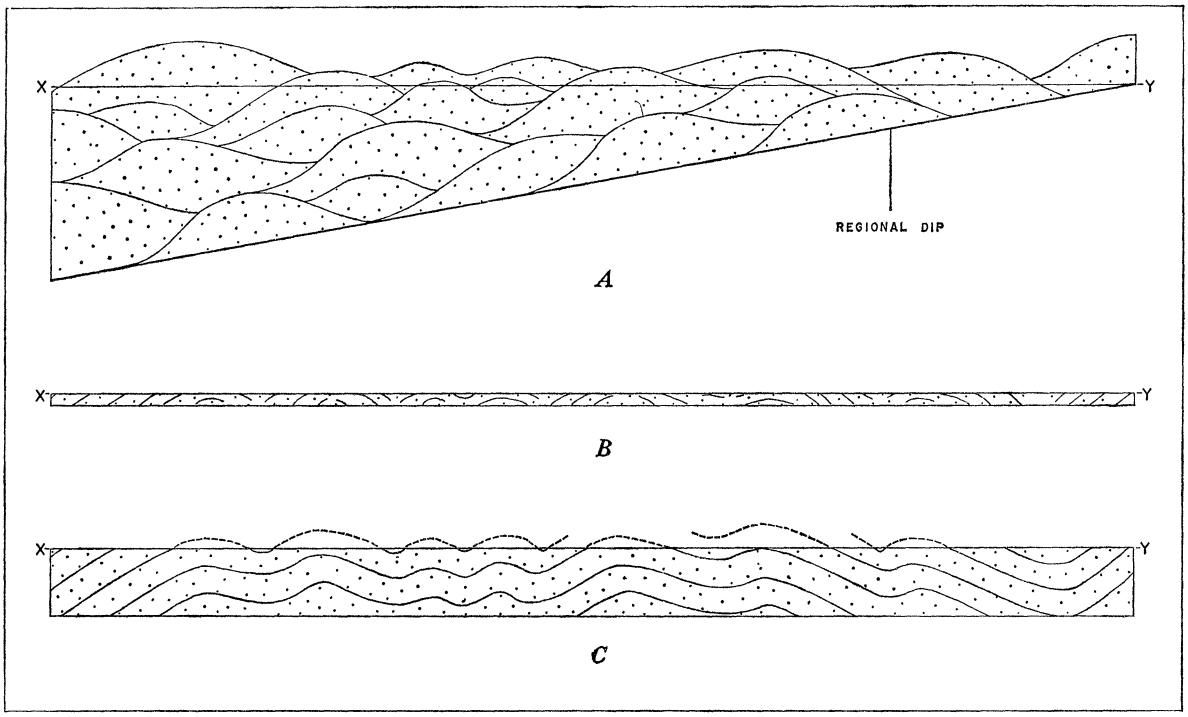

FIGURE 14. Possible interpretations of the internal structure of the Waulsortian Complex. Diagrammatic vertical sections based on measurements made on the north-east coast of Aughinish Island, Co. Limerick. X–Y is the present ground level. Length of section about $\frac{1}{2}$ mile.

A, Interpretation favoured here. The Complex is composed of overlapping banks and is inclined at the regional dip of about 10°.

B, The extent of information normally available on the ground.

C, False tectonic interpretation of this information. Even the regional dip is incorrect.

Depending on the internal symmetry of the banks, these 'folds' may also appear to be superimposed on a spurious regional dip (figure 14*C*).

Suitable exposures have been found on a small promontory, here called Poularone Point. Parts of four banks are exposed (figure 15). The contact between Banks 2 and 3 is visible (between A, B and C), exhibiting features predicted from previous hypotheses of bank geometry. Along part of the contact (from A to B) the difference in the two banks' growth directions is considerable and their relationship is clear. Nearby (from B to C), however, the beds in both banks dip in similar directions and the contact could be easily overlooked* (figure 16). Fortunately, a lithological distinction is possible here. The contacts

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* This illustrates a general point mentioned concerning Hill 707. When, in a system of overlapping banks, one bank climbs over another, there must often be a stage at which the beds in both dip in similar directions. If this section alone is exposed the presence of more than one bank may be difficult to detect. Small angular discrepancies sometimes provide a clue but these must be consistent or they are indistinguishable from ordinary wedge-bedding.

between Banks 1 and 4, and 3 and 4 are not exposed, but their positions can be deduced from the form lines.

No proper estimate of the size of the banks can be made as none of them are sufficiently exposed, but both 3 and 4 probably exceeded 500 ft. in diameter.

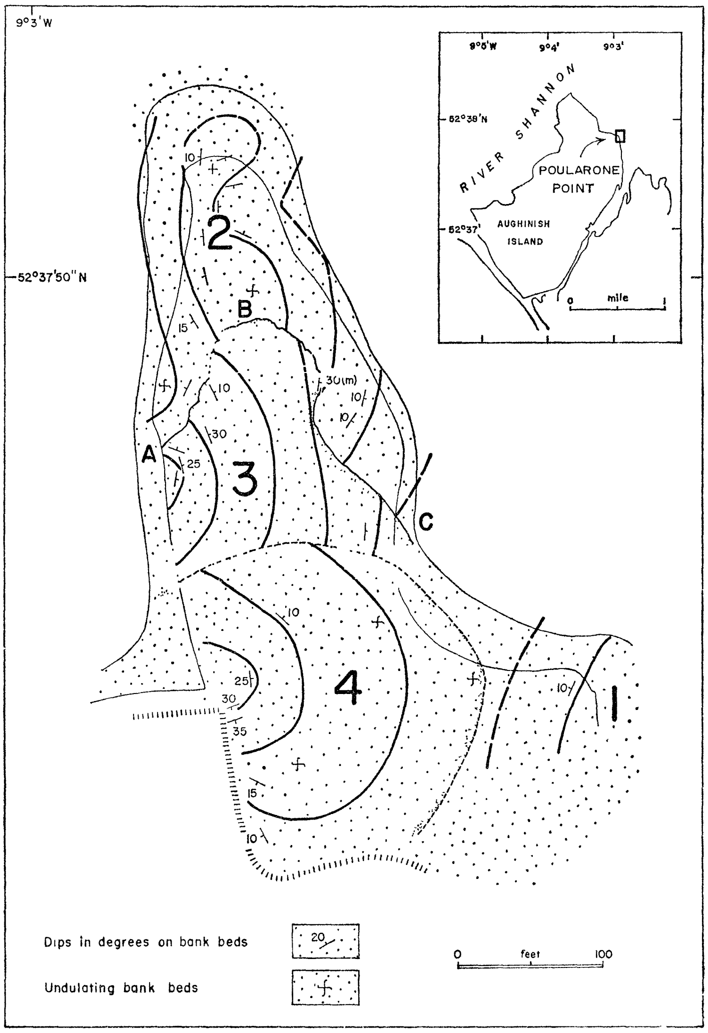

Figure 15. Poularone Point, Aughinish Island, Co. Limerick. The map shows the depositional structure of a small part of the Waulsortian Complex. Form lines reveal the shapes of the banks which are numbered in their probable order of growth. Along line A–B–C the contact between Banks 2 and 3 is visible (see figure 16). Dips followed by (m) are the maximum ones at that point. Simplified from a plane-table survey at a scale of 1 to 350.

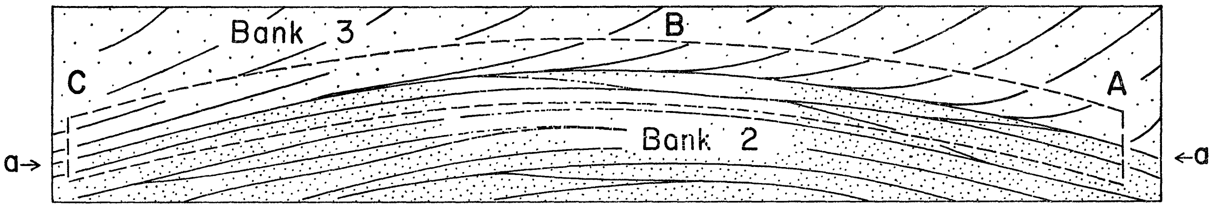

Figure 16. Diagrammatic vertical section along line A–B–C on figure 15 showing contact relationships between Banks 2 and 3. The line of contact is indicated by *a–a*. Pecked lines enclose the exposed section. Length of section about 250 ft.

The banks in the Complex are geometrically similar to the others described, but, because no other facies is present, they show one special feature. The change in depositional slope at the base of the banks is abrupt and the bank beds wedge out sharply, there being no other deposit into which they can pass laterally (see base of Bank 3 in figure 16). In the area mapped, the eastern flanks of the banks are more prominent than the western, exemplifying the situation (p. 502) where dips in the Waulsortian limestones can give a wrong impression of the regional dip, here about 10° westerly. If this regional tilt is corrected, the measured maximum dips are increased to about 40° which is normal for the climax form.

The conclusions drawn from this local study of the internal structure of the Complex are thought to be generally applicable. They may, for instance, be used in interpreting the remainder of the section on the north-east Aughinish coast. Probably, the long succession of promontories and embayments forming this coast results from erosion along weaknesses determined by prominent north-east–south-west joints and the edges of individual banks. Certainly the embayments are not due to erosion of other, softer sediments between the banks for the inland exposures show continuous Waulsortian limestones. Preliminary examination of exposures on the promontories shows that the attitudes of the bank beds are consistent with their being isolated exposures of a continuous set of overlapping banks (figure 14*A*).

The Waulsortian banks of Aughinish seem to be simple and of knoll form, each having a growth centre. Although varying much in shape and size they show no obvious tendency to develop as sheets growing along linear fronts.

(*d*) *Sheet-form banks*

These have not yet been described because their occurrence is restricted and they apparently do not enter into the normal growth sequence of the Complex. Sheet forms have only been found in areas where the Complex is probably not more than a few hundreds of feet thick, and in the lagoon where they are asssociated with the more usual knoll-form banks. The series of four sheets in the Athlone–Ballymahon area (Counties Westmeath and Longford: figure 17) is an example of the lagoonal development. These sheets sometimes form marked 'escarpments' over 50 ft. high, having steep slopes to the north-west and gentle ones to the south-east. They extend along the strike for several miles and then die out. Only Waulsortian limestones, dipping north-westerly at angles up to 45°, are exposed on the steep north-western slopes of the 'escarpments', while on the south-eastern ones only south-easterly dipping lagoonal limestones are found. The attitude of the latter represents the regional dip, being verified by the alinement of cavity fillings in the Waulsortian rocks. The relationship between the sheets is doubtful because of insufficient exposure. Theoretically, repeated strike faulting of a single sheet could explain the distribution of Waulsortian rocks, but there is no other evidence that this has occurred. An alternative interpretation regards the sheets as off-shoots from the large aggregates of knoll-form banks lying east and west of Ballymore (figure 17). The consistency of the dips in the Waulsortian limestones makes it unlikely that the outcrops are parts of long ridge-shaped banks.

The other possible sheet forms are poorly exposed. One of them occurs well within the

Complex, between Carrigahorig and Terryglass, Co. Tipperary (lat. 53° 4′ 0″, long. 8° 8′ 30″, to lat. 53° 3′ 20″, long. 8° 11′ 30″), where it is exposed in an irregular, discontinuous 3-mile-long ridge overlooking Lough Derg. The ridge, which has a steep north-west slope, exposes Waulsortian limestones dipping at between 35° and 50° towards north-west and north.

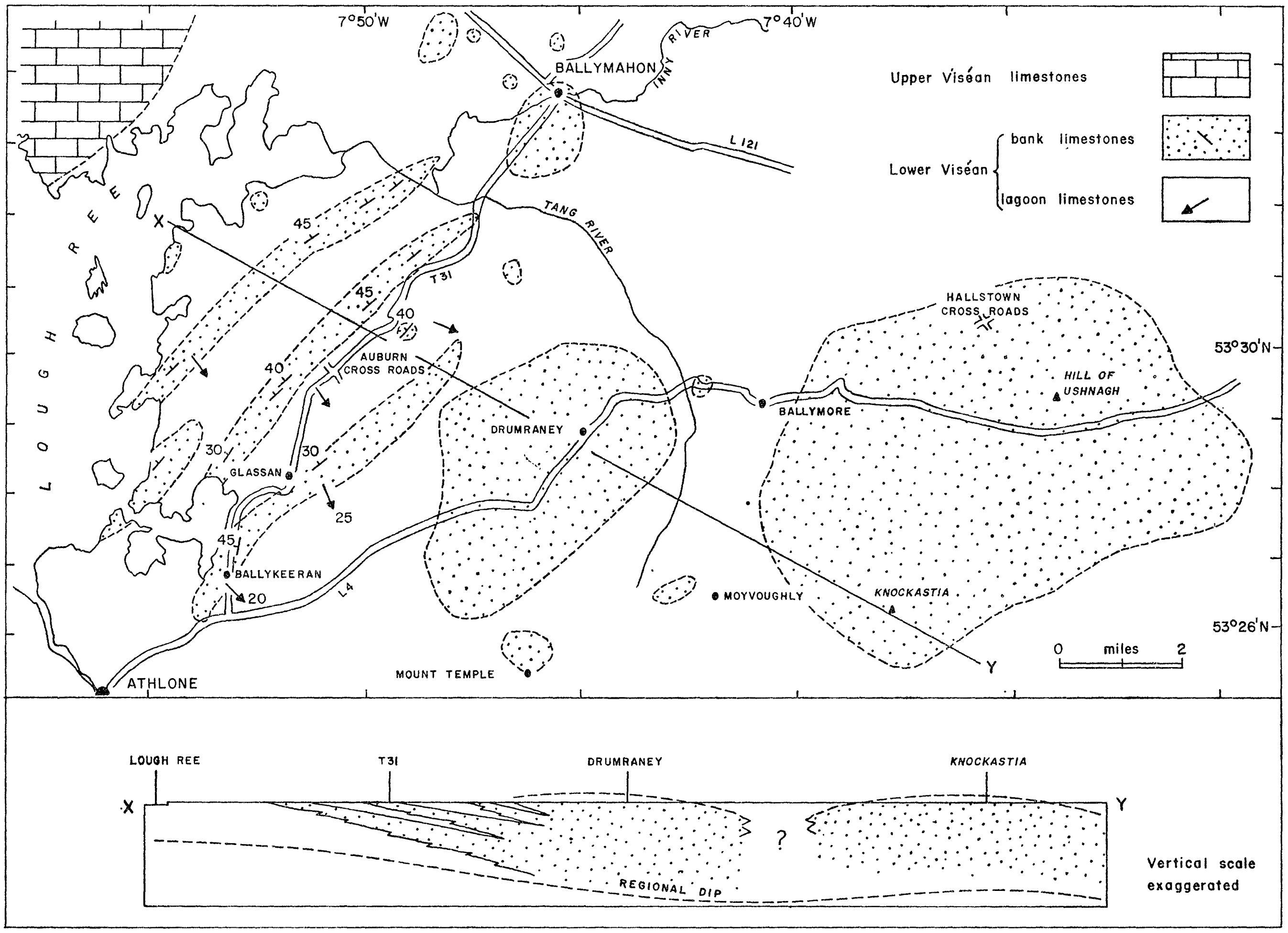

FIGURE 17. Geological sketch map of the Athlone–Ballymahon–Ballymore area, Co. Westmeath and Co. Longford. The elongated outcrops of Waulsortian limestone correspond to four sheet forms. A possible interpretation is shown in the diagrammatic vertical section taken along the line X–Y on the map. Here the sheets are regarded as extensions of the dominantly knoll-form masses lying east and west of Ballymore.

Exposures of the sheets so far examined are restricted so that only sections of the steep depositional slopes can be seen. Thus, there is no direct information regarding the form of their bases and tops, and their over-all geometry can only be surmised. Perhaps some of the structures mapped as sheets with continuous flanks really comprise long lines of highly asymmetrical knoll-form banks, the chance exposures showing only north-westerly flanks. However, although the strike of the beds does vary laterally to some extent, this interpretation seems untenable. Growth may well have started from a number of closely spaced knoll-form banks. Coalescence of these, followed by uni-directional flank growth (figure 18 *A*), could explain the present geometry since most sections through the final form would show beds dipping in roughly the same direction (figure 18*B*). Asymmetrical knoll forms (for example Bank 4 on Hill 707; figure 10) may show an early phase of this type of growth. Extensive sheets may represent the response of groups of banks to pauses in subsidence restricting vertical growth but allowing lateral spread.

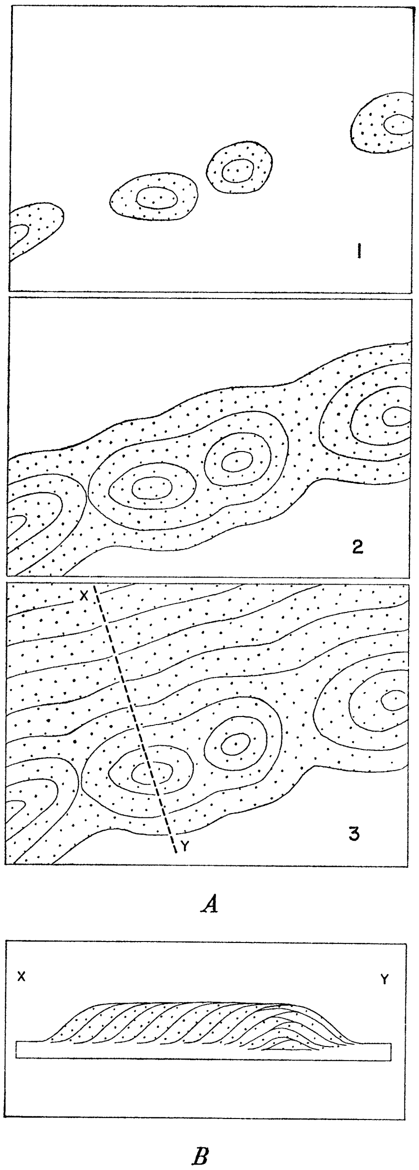

FIGURE 18. A possible growth sequence leading to the development of a sheet form from a line of knolls. Diagrammatic.

A, Three stages in the sequence viewed in plan and outlined by form lines.

B, Vertical section along X–Y on *A*, stage 3.

Scale: X–Y could be of the order of 1500 ft.

Obviously it is doubtful if the consistency of the northerly to westerly dip directions in all the sheet forms arose by chance. Combined with the information from Scarragh Lough (p. 499) and Hill 707 (p. 497) it points instead to real alinement of sedimentary features. This may indicate some mechanical current influence on bank morphology.

(*e*) *Summary*

(1) The Waulsortian limestones accumulated as banks showing considerable variation in external morphology.

(2) The knoll and sheet forms are the end-members of this morphological sequence.

(3) Bank geometry was controlled by (i) the shape of the surface on which growth started, (ii) the relative positions of growth centres, (iii) their respective growth vectors, and (iv) the relative rates of bank and off-bank sedimentation.

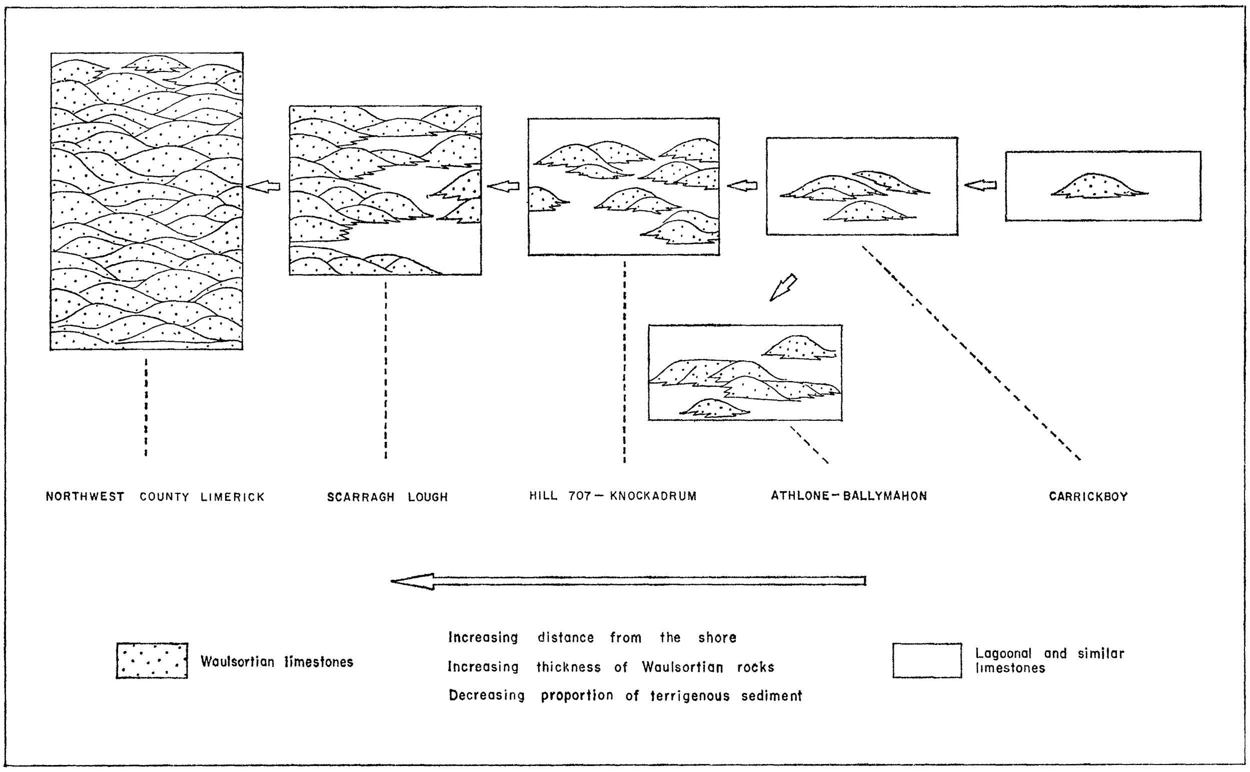

FIGURE 19. Stages in the aggregation of Waulsortian mudbanks as traced from the landward side of the lagoon to the centre of the Complex illustrated by localities described in the text. The sequence is started from a single, knoll-form bank, the commonest basic growth form. Diagrammatic.

(4) The Complex did not grow as a uniform layer of sediment but by the aggregation of banks.

(5) These banks, mainly of knoll form, were individually little different from those found isolated in the lagoon.

(6) Several aggregation stages have been recognized and illustrated with examples taken from the lagoon and various parts of the Complex. They are shown diagrammatically in figure 19.

(7) Further study of bank growth vectors may reveal the extent of external mechanical controls on bank morphology.

IV. THE WAULSORTIAN LIMESTONES

The limestones forming the Waulsortian banks are lithologically varied, ranging from calcite mudstones to coarse encrinites. Most of the variation results either from original sedimentary differentiation or from early resedimentation. Later textural and mineralogical changes are relatively minor and will not be discussed in detail.

(*a*) *Components of the limestones*

The sedimentary variation may be expressed in terms of the arrangement and relative proportions of five major carbonate components: (i) calcite mudstone, (ii) coarser calcite mosaics, (iii) *in situ* bryozoan meshworks, (iv) skeletal debris, and (v) entire fossils other than *in situ* Bryozoa.

(i) *Calcite mudstone* (clay grade and silt grade material) is the basic constituent of most Waulsortian limestones but rarely occurs alone. It comprises a mosaic of grains ranging in largest diameter from about 2 to 30 μm (microns) or more (cf. Bathurst 1959, p. 509; S 10001 B 1 and B 2, S 10049 B 1, S 10050 B 1).* Grain size distribution is often patchy due to clotting (S 10022 B 1, S 10048 B 1, S 10050 B 1), and probably to the diverse origin of grains falling into the size range.

The clots are irregular to rounded in outline and range up to about 400 μm in diameter. Sometimes, particularly in the later mud generations (see pp. 515 and 518), the clots have sharp boundaries, are often roughly ellipsoidal in form, and could justifiably be called pellets. The grains forming the clots are generally smaller than those in the matrix between. In many cases, however, merging has occurred. The clots are then barely detectable (cf. Beales 1956, pp. 864 and 865) and no grain size distinction is possible. The arrangement of the pellets shows that they were deposited as such and are not post-depositional aggregations. Similarly, most of the clotting is probably primary or early diagenetic (cf. Maxwell 1962, p. 224, and plate 3, figure 7; Schwarzacher 1961, pp. 1486 and 1487). Some mudstones are relatively homogeneous, either through absence of clots or their complete merging.

Other grain size variation is due to diagenetic grain enlargement (evidence from embayment of skeletal debris) and perhaps to the presence of comminuted, unidentifiable skeletal debris (cf. Emery, Tracey & Ladd 1954, p. 88).

(ii) *The coarser mosaics* formed either by diagenetic grain enlargment of mudstone or organic debris, or by primary sparry growth. The forms assumed by the sparry masses are bewildering in their variety, but fall into three main groups:

(*a*) Gash and vein fillings (S 10030, S 10043, S 10044) cutting across depositional structures.

(*b*) Cements, and cavity fillings in shells. Cements are developed only where the ratio of mudstone matrix to larger grains is low. As mudstone is ubiquitous they are rare. They may be either granular or syntaxial depending upon the nature of the host grain. Shells are sometimes entirely spar-filled but more often are partly mud-filled and only capped with spar. They then may act as useful 'spirit levels'.

(*c*) Sparry masses directly associated with sedimentary structures in the mudstones.

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* The numbers refer to specimens, thin slices and peels housed in the collections of the Sedimentology Research Laboratory, Department of Geology, The University, Reading.

These spars have many morphological and fabric features in common with (1) the 'reef-tufa' as first described by Tiddeman (1892, quoted in Kendall & Wroot 1924, pp. 95 and 96) and later used by Hudson (1933, p. 244), Parkinson (e.g. 1935, p. 100; 1950, p. 273; 1957, pp. 516–518), Bond (1950, p. 165), Black (1952), and others; (2) the 'blue and black veins' of Delépine (1951, p. 141); (3) the 'crystalline laminae' of Dixon (1921, p. 69); (4) the 'bands of crystalline calcite' of Prentice (1951, p. 179); (5) the 'sparry calcite' of Pray (1958, p. 265); (6) the 'patches of coarse crystalline calcite' of Schwarzacher (1961, p. 1492); (7) the *Stromatactis* of Dupont (1881, p. 268), Lecompte (1937, pp. 4–11), Bathurst (1959), Pareyn (1959, p. 352) and others; and (8) the *Ptylostroma* of Dupont (1883), Dorlodot (1911) and Pareyn (1959, p. 352). Such spars are widespread in the Waulsortian limestones, forming patches and sheets ranging in size from tiny microscopic flecks to aggregate masses more than a metre across. Their fabric characters* (S10001 B1 and B2, S10019 B1, S10022 B1, S10041 B1) are typical of, but not necessarily restricted to, crystals formed by chemical precipitation on to a free surface. The crystals, which may exceed 1 mm in length, vary in their physical and optical characters. They may be blocky, elongated, even fibrous in form. Many conform to the radiaxial fibrous extinction pattern described by Bathurst (1959, p. 511; e.g. S10001 B1 and B2, S10019 B1, S10041 B1, S10048 B1), but some exhibit unit extinction (S10040 B1, S10050 B1). The factors controlling the formation of these types are unknown.†

(iii) *Bryozoa*, particularly fenestellids, are often common. They are the only organisms preserved which could conceivably have provided a framework for the 'reefs' (Parkinson 1957, p. 519). When plentiful, their fronds formed loose meshworks which trapped other sediment and provided open surfaces for sparry growth (S10019). Frequently, the fronds lie roughly parallel to the depositional surface (S10006), but there is no simple preferred orientation (cf. Schwarzacher 1961, p. 1489). Such bryozoans are uncommon in the coeval lagoonal limestones.

(iv) *Skeletal debris* is widely but unevenly distributed in the Waulsortian limestones (S10001 B1 and B2, S10012 B1, S10031 B1, S 10033 B1, S10039 B1 and B2). It mainly comprises fragments of brachiopods, molluscs, crinoids and bryozoans. Calcareous spicules of doubtful origin are occasionally present. The debris ranges in size from unbroken crinoid columnals to comminuted silt-grade shell fragments. Some of the skeletal material is so little damaged that it is regarded as a distinct component.

(v) *Fossils* are patchily distributed, there being a marked tendency for local concentrations ('pockets' or 'nests') to occur. The fauna is fairly well known (Davidson 1858–63;

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* (*a*) Crystals are elongated perpendicular to the wall on which they rest. The wall may be a bryozoan frond, piece of skeletal debris, or calcite mudstone. (*b*) Crystal size generally increases away from the wall. (*c*) Change in crystal size at the wall is abrupt. (*d*) Crystals growing from opposite walls may meet in the centre at a compromise boundary. Otherwise the central area is occupied by anhedral crystals or is empty. (*e*) True crystal terminal facies are occasionally developed, pointing away from the wall. (*f*) Crystals often have curved cleavage.

† (*Added in proof*, 5 *February* 1964.) Since this was written G. R. Orme and W. W. M. Brown have shown (1963, *Proc. Yorks. Geol.* (*Polyt.*) *Soc.* **34**, 51–66) that fibrous calcite may develop as a replacement fabric. This may well explain the radiaxial fibrous arrangement so common in the crystals forming the sparry masses. However, the crystals which have this *internal* structure have the *external* morphology and arrangement of primary precipitates and are associated with geopetal sediments. Thus, the fibrous structure, if of replacement origin, apparently represents an alteration of a cavity-filling drusy mosaic.

Foord 1897–1903; Turner 1937, 1948, 1952, 1962; Delépine 1940, 1949; Shephard-Thorn 1963). Commonly occurring groups are brachiopods—including productids and spiriferids; molluscs—many pelecypods, gastropods and cephalopods, including some large nautiloids; crinoids—mainly disarticulated columnals or longer lengths of stem but a few calyces have been found; corals—usually only *Amplexus*; and the bryozoans already mentioned. Trilobites are uncommon.

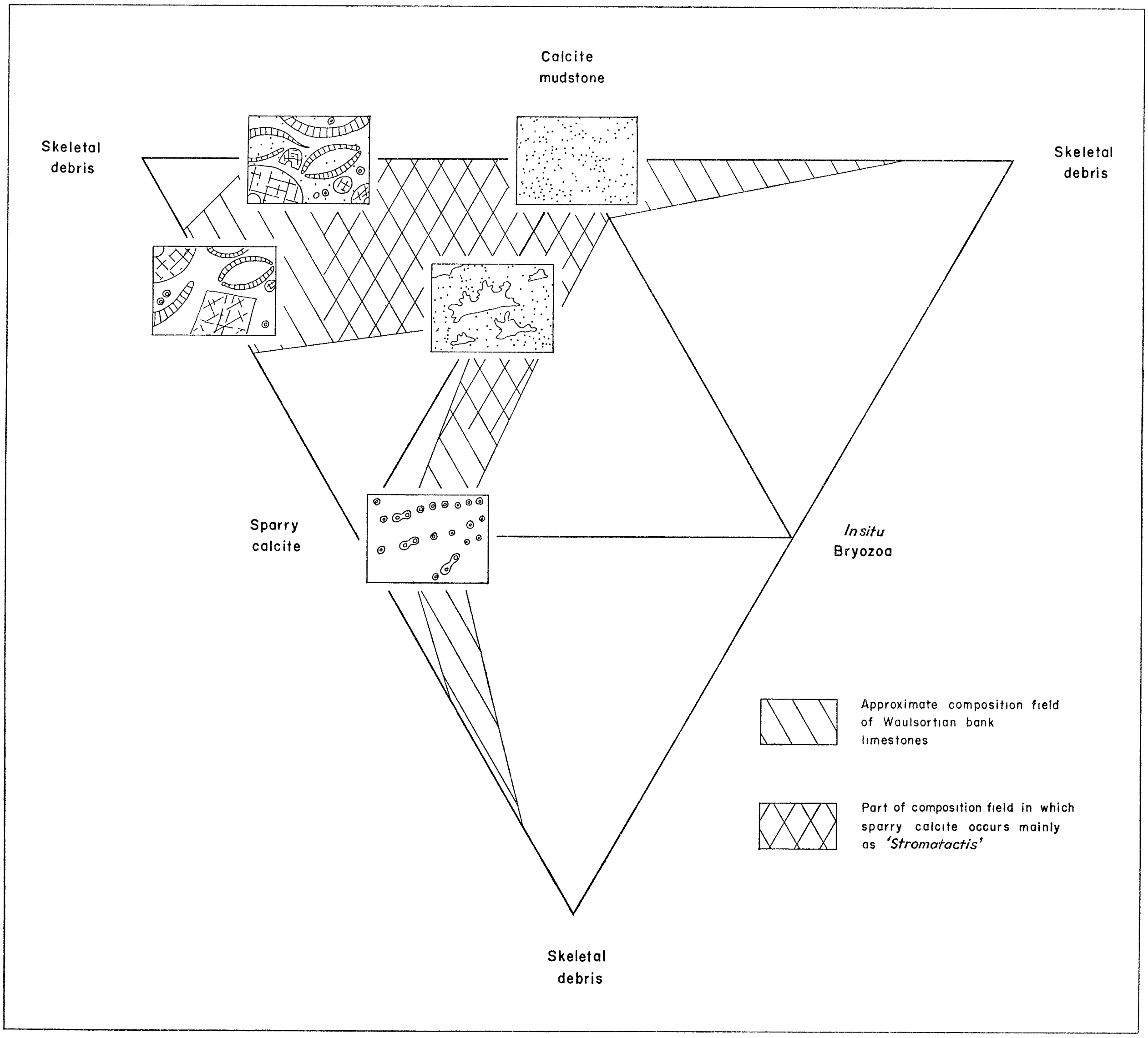

Figure 20. The approximate composition field of the Waulsortian limestones considered in terms of 4 components, with diagrams of some of the rock types in vertical section. Sparry calcite other than that occurring in *Stromatactis* or sheet sparry masses is found as granular cements or syntaxial rims. Key to lithologies as in figure 21.

Little is known of the microfossils. Foraminifera and problematical organisms, possibly calcareous algae, have been noted but are rare.

(*b*) *Limestone types and their relation to bank structure*

Certain combinations of components are more common than others and some do not occur at all (figure 20). The end-members of the variation range are easily distinguished but, because so many intermediates exist, no simple division into lithological types has been attempted. Many superficially distinct rock types can be seen in the field, but investigation shows this is often due to differences in the arrangement of the components. A minor change in the ratio of one component to another can result in a striking difference in appearance. For the present study the most valuable analysis of lithology has been found to be that based on sedimentary structures.

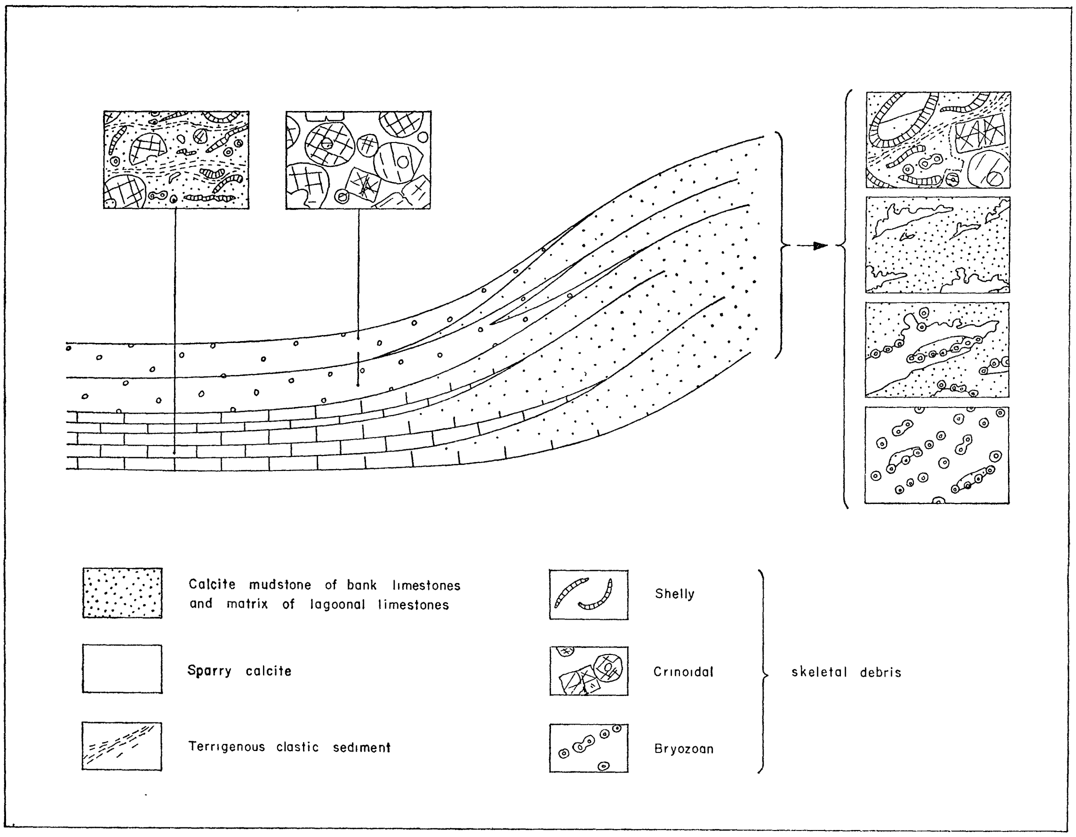

Figure 21. The relationship between lithology and bedding characteristics at the bank margins. Diagrammatic vertical sections. Only the main rock types are shown. These could occur anywhere in the beds indicated, the orientation of their components varying with the depositional dip. Key relates only to small drawings of rock types.

The most marked and consistent compositional changes occur at the margins of banks in the lagoonal area, when the bank beds pass into or are overlapped by encrinites* or other limestones composed dominantly of skeletal debris (figure 21). The coincidence of these changes with a drastic alteration in bedding characteristics confirms that the edge of the bank marked a sharp change in depositional environment. The inclined bank beds

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* A good example of crinoidal flank beds passing into a bank is exposed in a quarry at Hallstown, Co. Westmeath (lat. 53° 30′ 40″, long. 7° 35′ 10″; figure 17). On the whole, however, flank beds of this type are less common associates of the Irish Waulsortian banks than of similar structures in northern England and New Mexico. The encrinites may have either a mud matrix or spar cement.

with their high proportion of calcite mudstone must have formed under some control which overrode the mechanical processes dominating off-bank sedimentation. Within the banks the gross lithology often changes in an apparently random fashion. Sometimes adjacent beds are of distinctly different composition, but in other instances the lateral or vertical variation within each bed is equally marked. Doubtless, part of the present variation (e.g. presence or absence of Bryozoa) is due to original sedimentary differences on the bank surface, but some of it results from processes operating in the beds after their initial formation.

(*c*) *Sedimentary structures*

(1) *General*

Some workers on Waulsortian and similar Carboniferous 'knoll-reef' limestones have emphasized that certain lithological components are typical, characteristic or unique (e.g. 'meshwork of blue or black 'veins' with fenestellids', Delépine 1951, p. 141; 'calcite mudstone', Black 1954, p. 278). Others have stressed the characteristic association of particular features (e.g. Parkinson 1957, p. 535). The present study shows that apart, perhaps, from some faunal elements, none of the components is unique, and supports the contention that the association is important. It also reveals, however, that the arrangement of components is significant.

(2) *Structures composed of spar*

The sparry structures ((*c*), p. 508) have received more attention than any of the others. Many of them have a fancied resemblance to organisms (hence *Stromatactis* and *Ptylostroma*) and present problems which are immediately intriguing. Both organic and inorganic origins have been suggested.

There is ample fabric and other evidence in the Irish Waulsortian banks to conclude that most, if not all of these crystalline masses are cavity fillings. The small isolated ones, less than about 1 cm across, are generally filled with clear, anhedral spar tending to show increasing grain size away from the wall (S10009, S10039 B2, S10040 B1, S10056). The larger ones, ranging up to a metre or more across, are mainly lined with distinct layers of oriented calcite crystals (the 'drusy mosaic' of Bathurst 1958, p. 14; see footnote p. 509), but often have a final central filling of anhedral calcite (S 10009, S10049, S10051, S10056) or occasionally of dolomite (S10042, S10045). The shapes of the sparry masses are less predictable but, excluding those simply filling voids in bryozoan meshworks, there seem to be two main forms:

(i) The commoner type varies in gross morphology from tiny isolated patches to simple branching masses and finally to irregular reticulate systems (figure 22*A* and *B*; S10022, S10047, S10052, S10056). In more detail, the upper surfaces of the masses are irregularly embayed, undulating or digitate, while the floors are generally flattish though often stepped (figure 37, plate 7; S10000, S10009, S10056). Frequently, patches of mudstone appear to be 'floating' in the spars, but serial peeling (S10022 Ca 1–Ca 8) shows that these are cross-sections of projections from the mudstone wall and are not surrounded by spar. These characters are typical of the structure elsewhere called *Stromatactis* (illustrations in Lecompte 1937; Bathurst 1959). For convenience this term will be retained here.

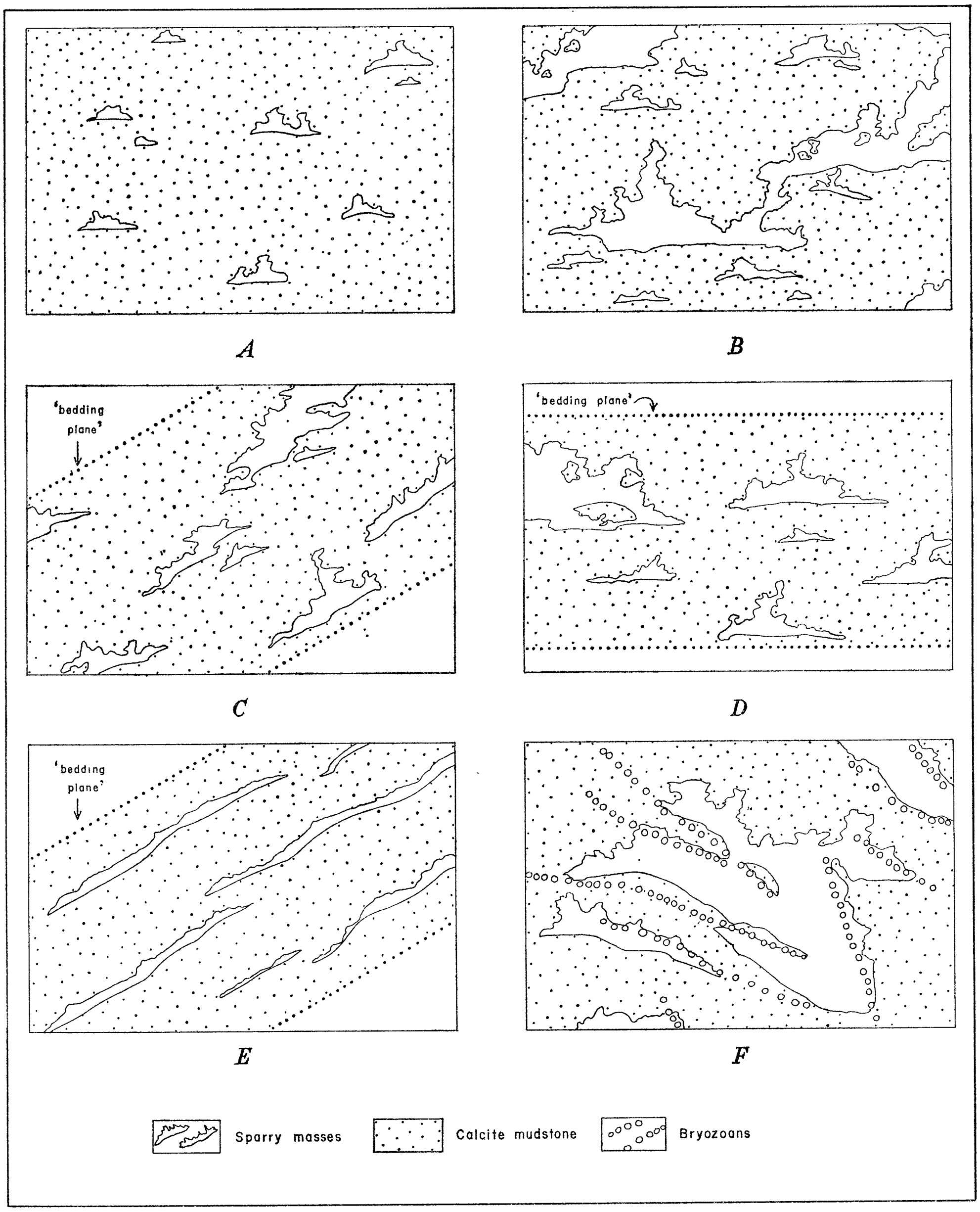

FIGURE 22. Shape, size and distribution of sparry masses in the bank beds. Diagrammatic vertical sections.

A and *B*, *Stromatactis* spars. All size gradations between these two extremes are known. The bank bed is assumed to be horizontal. Scale: the sparry masses in *A* range up to about 1 cm across in the plane of the bedding; the larger ones shown in *B* may extend to 1 m but are most commonly in the 10 to 20 cm range.

C and *D*, *Stromatactis* spars. Variation in arrangement depending upon bed attitude. Scale: as for *B*.

E, Sheet spars and their typical arrangement. Scale: the sparry masses occasionally extend to several metres, and commonly to several decimetres in the plane of the bedding. Their thickness rarely exceeds 1 cm.

F, The effect of Bryozoa on the shape of *Stromatactis*. Size of sparry masses as for *B*.

The shape and arrangement of the *Stromatactis* masses are clearly related to bed attitude (figure 22*C* and *D*). Bryozoan fronds are often but not invariably found in the spars and surrounding mudstones (present: S10000, S10049, S10051; absent: S10009, S10052, S10053). They may make *Stromatactis* angular in outline (figure 22*F*, S10037, S10049) but, as many of the fronds lie roughly parallel to the bedding, there is little change in over-all orientation (S10006).

(ii) The other, less common form comprises undulating sheet-like masses rarely more than 1 cm thick but sometimes extending laterally up to several metres (S10002, S10003, S10046, S10054). These are arranged as shown in figure 22*E*. Their upper surfaces are irregularly lobate, or digitate on a small scale, their floors gently undulating or sometimes irregular (figure 38, plate 7). Bryozoa are not found in these spars.

'Sheet spars' and *Stromatactis* differ in so many respects that they are best discussed separately.

(3) *Mudstone structures associated with* Stromatactis *spars*

The calcite mudstones of the banks are rarely homogeneous. Variation in colour, grain size distribution, skeletal debris content, and insoluble residue is often rapid. It may be expressed as lamination or irregular patchiness, sometimes displaying depositional dips of more than 30° (figure 40, plate 7; seen well at Mullawornia quarry, lat. 53° 34′ 50″, long. 7° 48′ 10″). The scale of the structures ranges from the 100 μm pellet and clot level to over-all bed to bed differentiation. In rocks containing *Stromatactis*, however, the mudstones vary in a systematic fashion. They are multicomponent, being composed of several distinct generations resulting from multiple internal sedimentation. These mudstone structures are perhaps the most characteristic features of the bank beds.

Description of plate 6

Figure 33. A Waulsortian bank advancing over and passing into lagoonal, cherty limestones. Note (i) the bank beds, (ii) the increase in their depositional dip when traced upwards from the base of the bank, and (iii) the shape of the base of the bank, reflecting the relative rates of bank and off-bank sedimentation (the sharp rise of this contact towards the left of the photograph corresponds to point *A* on figure 10). South-west face of Hill 707, Co. Galway. Scale: height of the exposed bank section in the centre of the photograph is about 20 ft.

Figure 34. Typical lateral passage from the toe of the bank beds (right) into thinly bedded, cherty lagoonal limestones (lower left). The head of the hammer rests on the passage zone. The bank was growing towards the left. Base of Bank 4, south-west face of Hill 707, near point *B* on figure 10.

Figure 35. Unusually rapid lateral passage from bank (right) to lagoonal limestones (left). The hammer is lying along the bedding in the lagoonal rocks. Note the sparry masses (*Stromatactis* and gash fillings) in the bank limestones. Knockadrum quarry, Co. Galway; lat. 53° 5′ 40″, long. 8° 26′ 0″.

Figure 36. Small knoll-form bank at the top of the Waulsortian Complex, north-west coast of Aughinish Island, Co. Limerick. The transition from 'unbedded' bank limestones (centre) into well bedded, cherty limestones (right) is completely exposed here. The photograph was taken looking north from point A on figure 12.

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PLATE 7

All figures are arranged so that the depositional tops of the specimens are uppermost. All specimens were cut perpendicular to bedding.

FIGURE 37. *Stromatactis* sparry masses and multicomponent calcite mudstone. The early mudstone generations are generally darker in colour than later ones: all are pre-spar. Spar is white.

Waulsortian bank limestone, S 10009, polished surface. (Magn. × 2.)

FIGURE 38. Sheet sparry masses and associated calcite mudstone. Note (i) the absence of distinct generations in the pre-spar mudstone (cf. figure 37), (ii) the several generations of later geopetal muds and their time relationships with the spars, and (iii) the spar layers coating the roofs of the sheet cavities are thicker than those on the floors—a useful way-up criterion.

Waulsortian bank limestone, S 10003, polished surface. (Magn. × 1·25.)

FIGURE 39. Part of the surface shown in figure 38 but etched with dilute acetic acid, not polished. Sparry layers now appear dark and the mudstone light in colour. Note that the pale mudstones immediately below the spars in figure 38 do not correspond with the true pre-spar geopetal sediments revealed by etching. S 10003. (Magn. × 1·25.)

FIGURE 40. Small-scale bedding features in calcite mudstone, showing a depositional dip of over 30°. Some of the muds were evidently deposited in cavities since they rest on other, geopetal, sediments (indicating the depositional horizontal) and are capped by spar. The local disturbance of the muds is probably due to collapse or slumping.

Waulsortian bank limestone, S 10005, polished surface. (Natural size).

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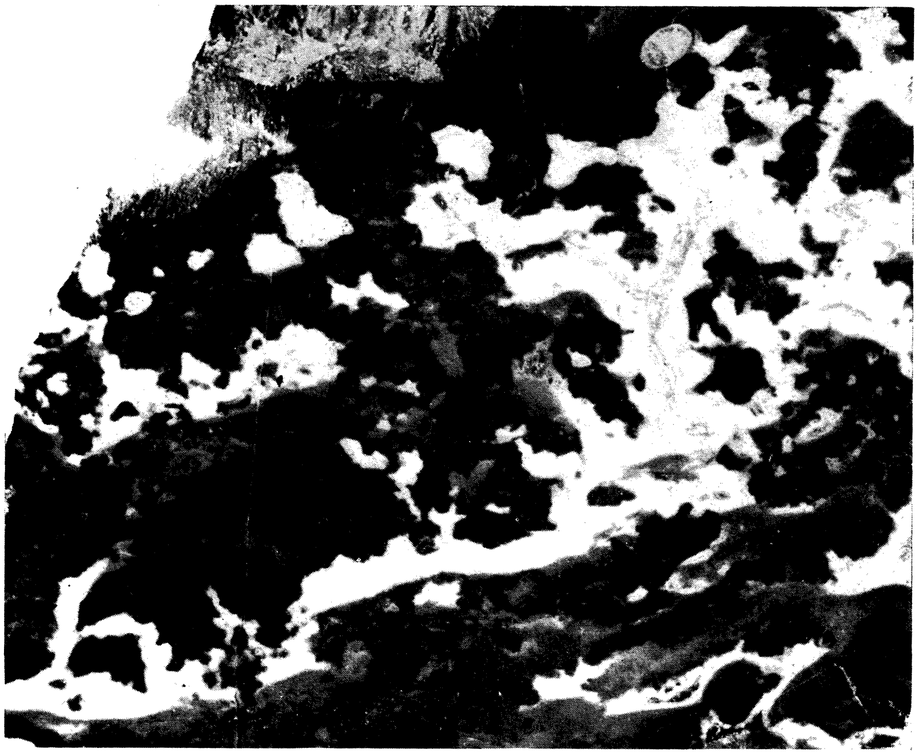

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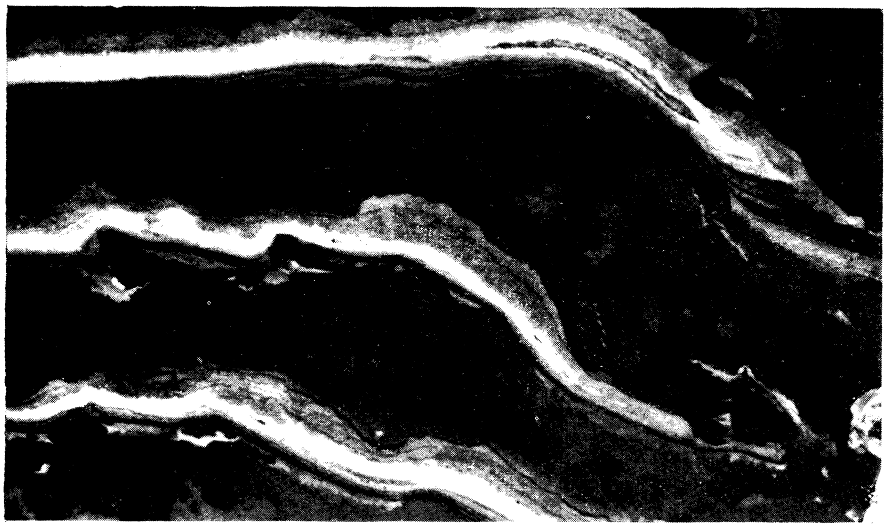

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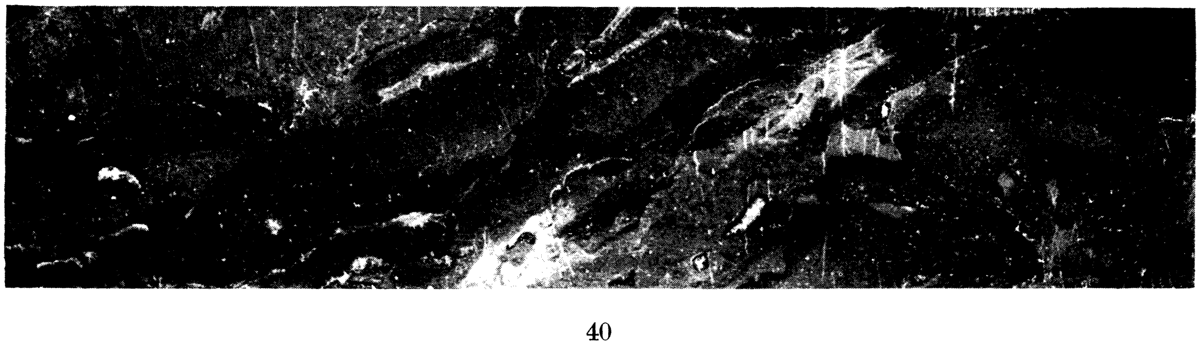

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Several stages of deposition can usually be distinguished. The mudstone generations will be designated as $M1$ *et seq.*, and the spars $S1$ *et seq.* in order of deposition. The basic depositional pattern is simple although the results may appear complicated. The earliest generation of carbonate mud ($M1$) occurs as 'flocculent' masses or isolated patches up to a few centimetres across. These are generally surrounded by later generations of geopetal mud, and spar (figure 23). Since $M1$ sometimes forms much less than half the total volume of muds present, and spar may occupy a volume equal to that of the muds, *most of the sedimentation was internal*, that is, below the main sediment/water interface on the bank.

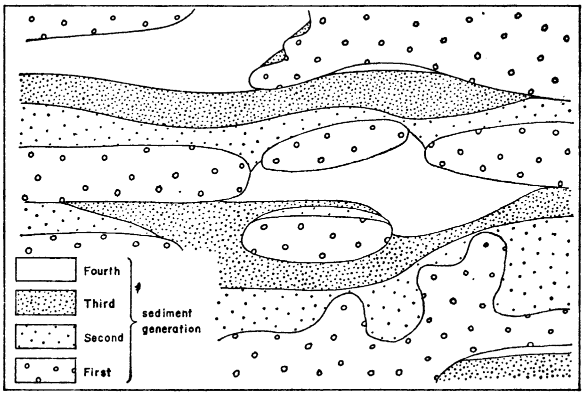

FIGURE 23. Multiple sedimentation: the basic pattern. Diagrammatic vertical section. Scale: about 2 × a commonly occurring size.

Both the number of mud generations and their arrangement vary. Typical examples are shown in figure 24, figure 37 plate 7, and figure 41 plate 8. Commonly, two main generations ($M1$ and $M2$) and perhaps one or two localized ones ($M3$ and $M4$) were deposited before any spar was precipitated. In some instances mud deposition continued until most available space was filled (figure 40, plate 7; S10005, S10035), the later

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DESCRIPTION OF PLATE 8

All figures are arranged so that the depositional tops of the specimens are uppermost.

FIGURE 41. Multicomponent calcite mudstone and *Stromatactis* spars. A few Bryozoa are present. At least five mud generations are readily distinguishable, all except the last being pre-spar. Note the arrangement of the generations and the variation within and between them.

Waulsortian bank limestone. Negative print (thus spar appears black and mudstone pale) of thin section S10050 B1 cut perpendicular to bedding. (Magn. × 3·5). Plain light.

FIGURE 42. A section through a multicomponent mud and spar system to show the composition and arrangement of 4 generations of geopetal internal sediment. The first two generations are pre-spar and rest either on earlier muds or on the bryozoan; the second two followed later after a layer of spar had grown.

Waulsortian bank limestone. Positive print of thin section S10049 B1 cut perpendicular to bedding. (Magn. × 10). Plain light.

FIGURE 43. Depositional structures produced experimentally in a jar of wet carbonate sediment. The grains have a wide size range. Fragments of turtle grass (*Thalassia*) are also present. Note the cavities, their shape and arrangement, and the distribution of the finer grades of sediment. (Magn. × 1·5).

generations then forming concentrations up to several centimetres thick (S 10032, S 10038). Usually, however, growth of spars began while considerable space remained and continued until the cavity was filled, only occasionally being interrupted by influxes of later muds (figure 25, figures 41 and 42, plate 8; S 10049 B1, S 10050 B1, S 10053). The final filling was usually of spar.

There is thus a direct relationship between the depositional pattern of the mudstone

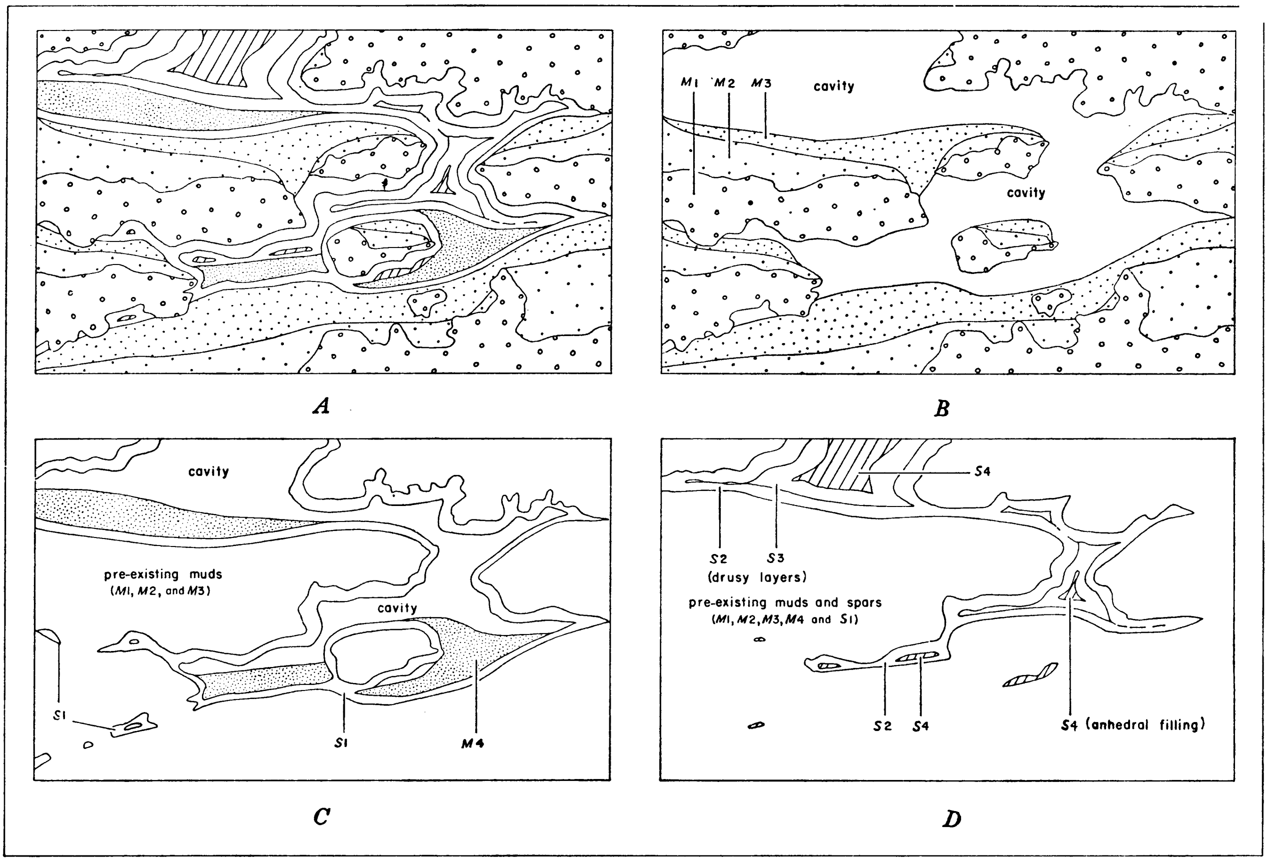

FIGURE 24. *A*, A typical multicomponent mudstone and spar system. *B–D*. The stages in its formation.
B, Pre-spar muds.
C, First drusy generation followed by a geopetal mud. Earlier generations left blank.
D, Two more drusy generations and the final anhedral filling. Earlier generations left blank.
Diagrammatic vertical sections. Scale: about 2 × a commonly occurring size.

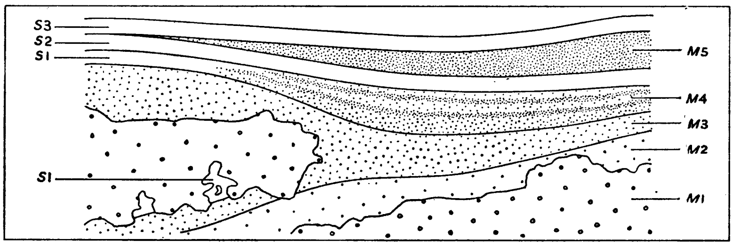

FIGURE 25. Diagrammatic vertical section through the deposits on a cavity floor showing typical relationships between spar and late mud generations. Scale: about 4 × a commonly occurring size. *M*1 to *M*3 are all pre-spar muds; *M*4 was deposited in a depression on the cavity floor while *S*1 was growing; *M*5 was deposited in a shallower depression during the interval following the formation of *S*2.

generations and the space left for spar. The form and arrangement of *Stromatactis* masses depend largely upon the factors which controlled mud deposition.

The mudstones of the generations themselves are not homogeneous but composite. Each generation represents a set of muds deposited in the normal superposition sequence, younger deposits overlying older. The later generations often have lamination which is laterally persistent. In contrast, the $M1$ masses (and rarely $M2$) are composed of small patches of sediment which frequently cannot be correlated with those in neighbouring parts of the same generation (figure 26*A*). However, despite local variation and lack of correlation, a broad pattern of compositional changes can be traced. Generally, the later generations even if laminated are more uniform in character and contain less coarse skeletal debris than earlier ones. Late concentrations of skeletal debris are found, but only locally. Some post-$M1$ generations are graded, becoming finer upwards.

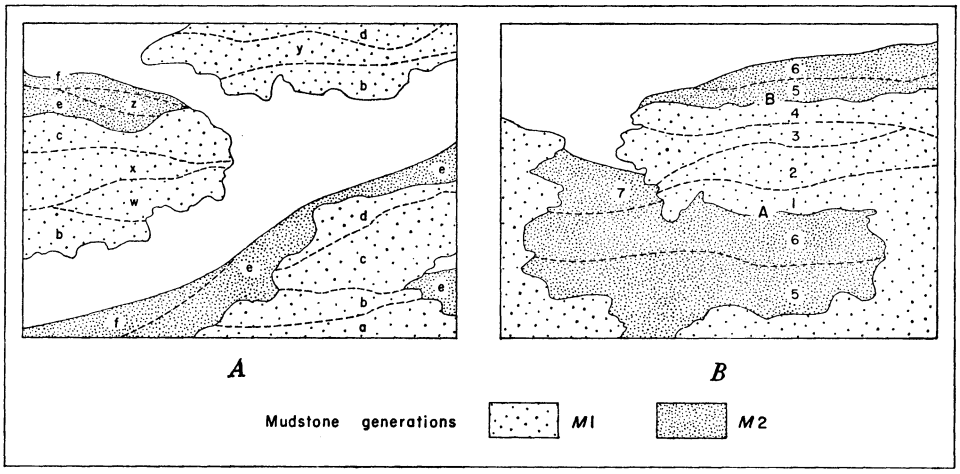

FIGURE 26. *A*, A hypothetical $M1/M2$ system showing the internal organization of the mud generations. a to f, and w to z, represent subdivisions of the generations distinguishable on minor compositional differences. They illustrate the type and degree of correlation to be expected between neighbouring patches. Often correlation between adjacent $M1$ masses is poorer than this (cf. figure 41, plate 8).

B, The time sequence of deposits in a simple $M1/M2$ system. Note the normal superposition sequence at B, and the reversed one at A (cf. figure 41, plate 8). Unfilled cavity space is left blank. Diagrammatic vertical sections. Scale: about 3 × a commonly occurring size.

These compositional changes and their spatial relationships are a useful aid to the identification of the mudstone generations if a sufficiently large area is examined. Study of a small area, say the size of an $M1$ patch, can easily lead to misinterpretation because it is then difficult to distinguish between normal superposition sequences and those where older muds overlie younger (figure 26*B*).*

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* The multicomponent system is best studied on polished rock surfaces in conjunction with peels or thin sections covering parts of the same area. Detection of small-scale variation within and between mudstone generations is aided by etching (15 % acetic acid) and staining the surfaces and thin sections. Stains for clays (e.g. safranin 0, light green) and differential stains for carbonate minerals (e.g. alizarin red S in acid or alkaline solution, see Friedman 1959, Warne 1962) are those commonly used. The tendency for early mudstone generations to be darker in colour than later ones is useful because the contrast can be increased photographically. In some instances, however, the colours are misleading because they do not coincide with the generations (cf. figures 38 and 39, plate 7).

(4) *Mudstones associated with sheet spars*

Like *Stromatactis*, the sheet spars undoubtedly represent cavity fillings. However, although the two forms may occur in the same bed, they differ in several important respects (cf. figures 37 and 38, plate 7). In the mudstone between the sheets of spar only tiny sparry masses are present (S10007, S10046, S10054) and the $M1/M2$ system, if it exists at all, is not well defined. Also, some mudstone structures are truncated at the margins of the sheet cavities. Thus, there is no clear relationship between the shape of the sheets and major structures in the associated mudstones.

Although the early mudstone generations are not sharply defined, later internal geopetal mudstones, sometimes pelleted, are often well developed (S10001 B1 and B2, S10002, S10003). Deposition of these muds locally modified cavity shape but rarely affected the over-all sheet-form. Like the later muds in the multicomponent system they were deposited either before or during sparry growth (figures 38 and 39, plate 7; S10003, S10007).

(*d*) *Origin of the structures and their relation to bank growth*

(1) *The multicomponent mudstones and* Stromatactis *spars*

Most workers during the last century have tackled the origins of such mudstones and spars as separate problems. Recently, a link between their depositional mechanisms has been suggested but no satisfactory explanation of the link has been offered. The close attention paid to the spars alone has really hindered their interpretation because the vital evidence lies in the surrounding mudstones. Detailed fabric analysis shows that the shape of the cavities occupied by spar was determined by the distribution of the various generations of the multicomponent mudstone system. The resemblance to organisms (p. 512) is thus misleading, but the systematic shape and arrangement of the cavities does imply that some regular and repetitive process was responsible for their formation.

The root of the problem lies in the association of small quantities of $M1$ with relatively large amounts of later, cavity-filling muds. There is often so little $M1$ that even if it formed a continuous 'meshwork' it surely could never have stood alone in its present position; some support would be needed. The presence of so much $M2$ between many of the $M1$ masses suggests, however, that $M1$ does not form such a 'meshwork' with $M2$ in the interstices (cf. Bathurst 1959, p. 516). The present configuration of mudstones and cavities is more simply explained if $M1$ and $M2$ moved into their present positions together. Similar depositional features can be produced experimentally in carbonate sediments, wet or dry, comprising a mixture of components with a wide size range. If a bottle of such sediment is shaken to destroy the original packing and then allowed to settle, the larger pieces pack with the finer particles to produce mechanical 'bridges' below which cavities form. Sometimes the larger pieces are in mutual contact, sometimes separated by fine sediments. The cavities tend to be spaced at roughly equal vertical intervals with sets of smaller ones between. Once they are in existence other fine sediment trickles down to rest on suitably arranged ledges (figure 43, plate 8). The large masses responsible for the bridging need not be rigid. They may be slightly cohesive grain aggregates formed by dewatering of the original sediment, or masses of organic tissue.

This is a poor model in many ways, but the process it demonstrates is significant in the interpretation of the Waulsortian *Stromatactis* and multicomponent mudstone. If *M*1 acted as 'lumps' and *M*2 as fine sediment, repacking could account for the present structures. But, as *M*1 and *M*2 cannot have been reorganized in the manner of the experiment, how was the repacking caused? The absence of inversion or even marked tilting of the *M*1 masses precludes any vigorous disturbance, suggesting instead downward movement in a gently collapsing system. If this was the mechanism, some reason for the collapse must be sought. Only two processes seem possible:

(i) Mechanical or chemical removal of large quantities of *M*1-type sediment. A possible mechanism is erosion by water escaping during compaction (Bathurst 1958, p. 31).

This would mean that the present *M*1 masses are collapsed erosional remnants, and *M*2 is reworked *M*1. If so, the *M*1 masses should show clear signs of truncation and tilting of the micro-bedding structures. This is rarely seen. Compositional differences also rule out derivation of *M*2 direct from *M*1. Thus, removal of *M*1 cannot satisfactorily account for the collapse.

(ii) Removal of some other material originally surrounding the *M*1 masses.

Selective removal of another carbonate sediment is unlikely because this would affect both *M*1 and *M*2. Arguments similar to those just used are applicable here. But, decomposition of organic tissue could account for the slow collapse of sediment associated with it, and for the absence of erosional features at least during the early stages. Bathurst suggested (1959, p. 519) that similar mud- and spar-filled cavities in some English Carboniferous 'reefs' might represent the 'molds of an organism which decomposed after burial'. This cannot provide the answer here because the muds around the cavities are probably not in their original positions. On the other hand, if the muds were originally entrapped in a loose, sticky meshwork, perhaps of plant filaments* both the depositional features and their arrangement in the banks can be explained.

To simplify discussion, an arbitrary sedimentary 'cell' may be considered. Typically, the main *Stromatactis* sparry masses are spaced at roughly regular vertical intervals, alternating with multicomponent mudstones containing many smaller sparry patches. A cell is defined as the smallest part of the rock containing a complete set of these features. It comprises a large cavity, now spar-filled, and the underlying sediments down to the top of the next cavity (figure 27). In terms of the collapse hypothesis each cell is limited above and below by mechanical bridges. Now, following this hypothesis, because *M*1 and *M*2 are required at the same time for bridging to occur both must have been available locally. Assuming the simplest case, both could have been present in the cell volume (plus some allowance for collapse) supported by the organic tissue which occupied the remaining space. Most of the muds now forming the lower part of the cell may then have settled into their present position after decay of the organic material and formation of the bridges. This is reasonable, since each cell shows similar but not identical features and there is no evidence of mass movement of *M*2 sediments from one cell to another. It does not, however, rule out (i) formation of the bridges by progressive collapse from bottom to top of the bed, or (ii) downward movement of fine sediment from newly forming cells and its deposition as the later mud generations in older ones.

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* Dr A. G. Fischer has suggested that sponges might be more appropriate.

From such a sequence it could be predicted that (i) small cavities would form in the lower part of each cell due to incomplete filling by *M*2 of spaces below *M*1 masses, (ii) as progressively less *M*2 was available these cavities would increase in size upwards until the main, bridged cavity was reached, and (iii) during collapse some of the *M*1 masses might become compacted and flattened. (i) and (ii) have been verified in many specimens (figure 37 plate 7; figures 41 and 43 plate 8; S10000, S10009, S10050, S10056); (iii) has also been found (S10009, figure 37 plate 7), sometimes emphasized by a flattening of the bryozoan fronds towards the base of the cell (S10049).

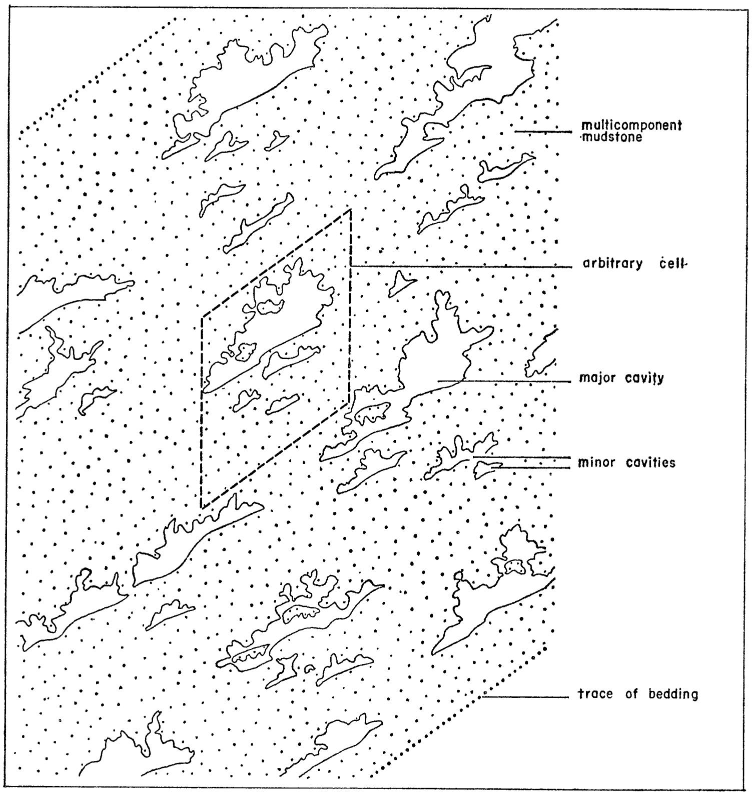

FIGURE 27. The arrangement of major and minor cavities in a bank bed and the limits of the arbitrary sedimentation cell described in the text. Diagrammatic vertical section. Scale: the major cavities may be about 10 cm across in the plane of the bedding (see figure 22*B*).

This collapse mechanism relies on the close association of two types of carbonate mud and organisms lacking rigid skeletons. It accounts for many sedimentary structures and can be extended to explain the origin of *M*1 and *M*2 but, since masses of organic tissue are involved, is it consistent with what is known of the banks themselves? The marked restriction of the multicomponent mudstone and cavity system to the banks and its arrangement in the bank beds surely implies a strong genetic link between the small- and large-scale structures. Vast quantities of calcite mudstone exist in the Irish Waulsortian and only vague explanations have been offered for its formation. The original carbonate mud is unlikely to have been produced away from the banks; in the neighbouring lagoon, the only possible source, the rocks are quite different.* Even supposing the mud was formed there

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* Because a selective trapping mechanism may have operated this is not a good argument by itself (cf. Pray 1958, p. 266).

the problem of transporting it across the tens of miles of mudbanks in the Complex seems insuperable. Local production of carbonate mud is thus favoured. There is no clear evidence concerning the mode of its formation. Direct precipitation, perhaps induced by plant photosynthesis, is possible, but so also is the disintegration of weakly calcified plants.

The form and development patterns of the banks have already been described (§ III). They are unlike those of other, mechanically controlled deposits, suggesting instead a powerful organic influence. As no evidence of a rigid skeletal framework survives and neither the shapes of the banks nor the bedding features are typical of framebuilt structures, soft organic baffles seem to provide the only satisfactory answer. The closest present-day analogues yet described are the *Thalassia* (turtle-grass)-covered banks in Florida Bay (Ginsburg 1956; Ginsburg & Lowenstam 1958).

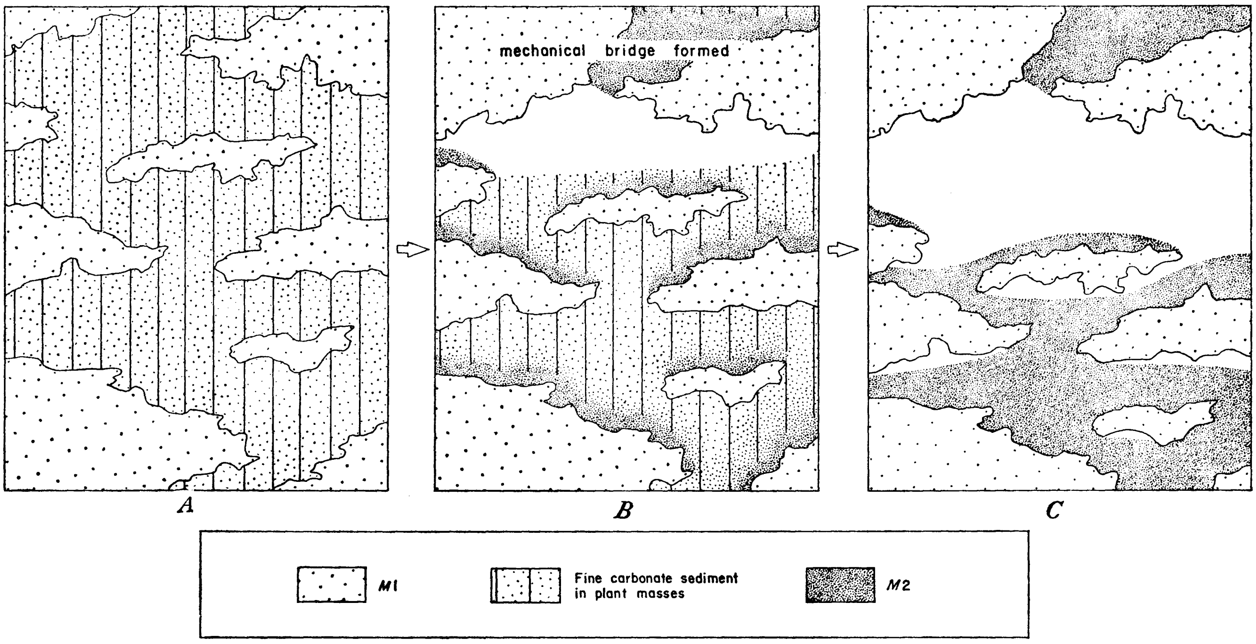

FIGURE 28. Diagrams illustrating the hypothesis that the sedimentary structures comprising a cell formed as a result of collapse following decay of an organic matrix.

A, Vertical section of part of bank bed immediately after cessation of growth. Patches of mud (*M*1) are isolated in organic masses which themselves contain fine carbonate sediment.

B, Decay of organic material well advanced. A mechanical bridge has been formed by the packing of *M*1 lumps and the new *M*2 which is falling from the decaying masses. Below the bridge both *M*1 and *M*2 are settling downwards and a cavity is opening above them.

C, Decay and collapse complete. *M*1 and *M*2 below the bridge have settled to the bottom of the cell, leaving open one large and several smaller cavities.

Scale: the major cavities may be about 10 cm across in the plane of the bedding.

A close relationship between the bank growth mechanism and the formation of the small-scale sedimentary structures is thus reasonable. The soft baffles needed to form the banks may be equated with the organic tissue (perhaps plant filaments or sponges) postulated to account for the formation of the sedimentary cell. Bryozoa doubtless had an important role but cannot have been the prime agents of bank formation. Although acting as baffles they can neither account for the original differentiation of the muds nor the subsequent readjustment.

On the basis of this conclusion a possible sequence of events may be outlined (figure 28).

(i) *Growth.* The banks grew through the accumulation of carbonate muds and skeletal debris retained, even on steep slopes, by soft organic meshworks. Skeletal debris was probably formed mainly by local break-up of indigenous organisms, but some may have been washed on to the banks. The fine-grained sediments were of two types. One, destined to become $M1$, comprised carbonate mud and skeletal debris which, after being washed about on the bank surface, was finally trapped and stabilized between the baffles. The other, subsequently the basis of $M2$, was produced or entrapped within, rather than between, the baffles.

(ii) *Burial and collapse.* As the bank grew upward, the organic material and associated sediments became buried. Decay began. Local pockets of mud, skeletal debris and perhaps pellets were by then sufficiently cohesive to act as lumps ($M1$). They were not cemented, or in any other way lithified, but simply more compacted and less watery than the carbonate sediment being released from the rotting organisms. This new sediment ($M2$), comprising loose grains and perhaps pellets, trickled downwards on release. Some packed with $M1$ lumps to form mechanical bridges; some, together with any loose material derived from $M1$, fell on to all available ledges and stayed there. As rotting proceeded the $M1$ and $M2$ below the bridges settled downwards and cavities gradually opened up in that position. Until the cavities formed there was no avenue for water circulation; hence the relatively passive movement of $M1$ and $M2$. Bridging may have been assisted by relict organic masses. Bryozoa, when present, would have had a marked influence at this stage.

(iii) *Movement of later internal sediments.* After decay and sediment readjustment the course of further events was determined by the extent of intercommunication between cavities within each cell, and from one cell to another. When communication was open the movement of internal sediments began. These were either introduced from outside once a cavity chain was in existence, or were derived locally from the cavity margins. Introduced muds came from the higher, younger parts of the bank. They either trickled down from the outer bank surface or escaped from newly formed cells. Probably their general fineness of grain was due to the filtering action of the intricate system through which they had to pass.

The smaller, isolated cavities in the mudstone, cut off from the sediment supply, naturally received none of these later muds.

(iv) *Spar deposition.* Deposition of the first sparry layer as a cavity lining effectively stopped any further collapse of the mud (for evidence of early spar precipitation see p. 526). In cavities forming part of an open circulation system the spar was deposited as distinct generations of drusy crystals before, during, or after introduction of the internal sediments. Because of the protective coating of early spar, the post-spar internal sediments cannot have been locally derived. As the deposition of spar and internal sediments proceeded the cavities became smaller, their supply of sediment was cut off, and water circulation gradually slowed to a standstill. Most of the spaces thus sealed off were, like the smaller cavities within the multicomponent muds, later filled with anhedral crystals of calcite.

Because of the progressive nature of the burial and decay involved in this sequence, a section through a growing bank bed could have shown soft muds with living organisms at the top and perhaps completely reorganized cells with cavities at the bottom. This may explain some of the vertical lithological variation now found in bank beds. A tendency for the top few inches of a bed to be relatively free of large *Stromatactis* masses has been noted on several occasions. Evidence from specimens (S 10051, S 10056) suggests that net downward movement of post-$M1$ muds led to their concentration at the bottom of the bed. The volume of this fine sediment was not great, but its removal from successively higher parts of the bed could have caused a reduction in the amount of bridging possible in the uppermost parts so that fewer large cavities formed there. If this vertical differentiation is of general occurrence it provides a method for assessing the extent of any erosion which followed deposition of a bed. It also emphasizes the difficulty of deducing the original state of the bank surface from evidence available now.

(2) *Sheet spars*

Structures in the mudstones show that the cavities occupied by sheet and *Stromatactis* spars did not have a common origin. There is no evidence that the sheet cavities were roofed by mechanical bridges and the collapse hypothesis cannot be applied.

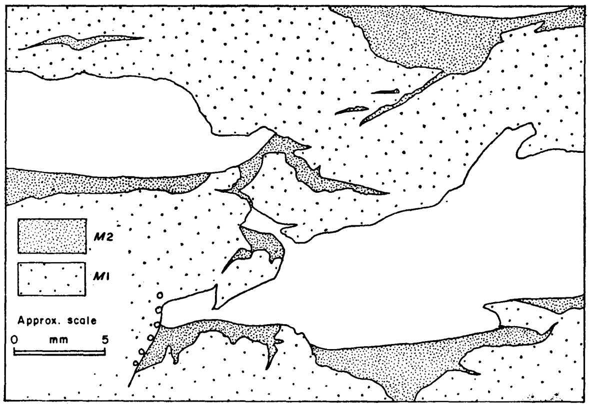

FIGURE 29. Ruptures in $M1$ infilled by $M2$ at the ends of two sheet cavities. Vertical section. Drawn from a specimen (S 10007) after study of both polished and etched surfaces. Later cavity fillings are omitted for clarity. $M1$ and $M2$ as used here simply represent two mud generations: they do not correspond to those associated with *Stromatactis* cavities.

Sometimes there is a marked shape resemblance between the upper and lower surfaces of the sheets, suggesting cavity formation by parting along cracks. This similarity may be deceptive (cf. figures 38 and 39 plate 7). The actual shape of the cavity floor below the later muds often does not match that of the roof. Nevertheless, the extensive sheet form of the cavities, their arrangement in the banks, and the truncation of some mudstone structures at their margins are features consistent with cavity formation by shear-failure of the mud followed by internal erosion due to moving water (cf. Schwarzacher 1961, p. 1494). Supporting evidence is found in rupture structures in the mudstones at the ends and margins of the cavities (figure 29). These structures are never associated with the other cavity systems.

Sheet spars have never been seen to intersect those of *Stromatactis* type. Indeed, the two are mutually exclusive although often found in the same bank bed. Since the sheet cavities are not associated with multicomponent mudstones they may represent the response of those muds lacking the support of organic 'meshworks' to mechanical stresses on the bank slopes. In areas where the meshwork was present the muds would be held until slow collapse established a stable state. The absence of Bryozoa from the sheet cavities tends to confirm this interpretation.

The localization of shear, the great area of some sheets, and the means of roof support remain unexplained. Shear cavities up to a few centimetres long will stay open in wet muds, but larger ones may never form. Concentrations of organic matter (living or dead) perhaps formed layered discontinuities which localized shear and provided a means for the preservation of the resulting cavities.

The internal geopetal sediments, often well represented in the cavities, pose a separate problem. The pre-spar examples may represent reworked local material but they also resemble the post-spar generations which must have been introduced. A reliable criterion differentiating local and distant source muds has yet to be found.

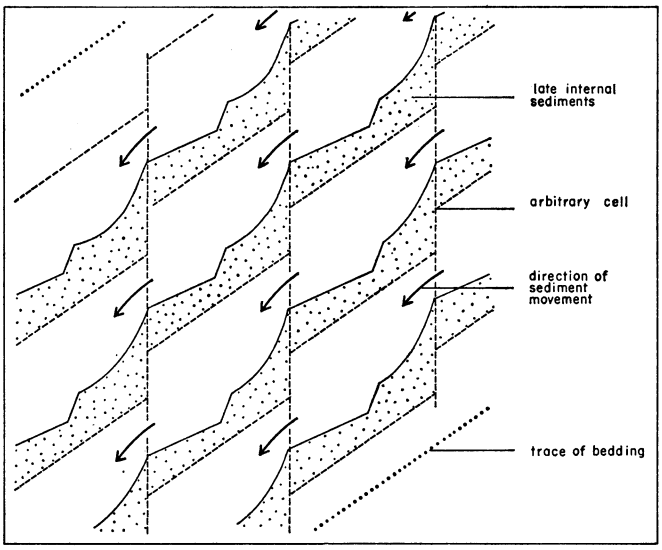

FIGURE 30. Internal cascade sedimentation: a possible mechanism for the arrangement of the later mud generations whose upper surfaces slope and step down-dip. The stepping is explained in figure 31. Diagrammatic vertical section.

(*e*) *Orientation of* Stromatactis *spars relative to bank beds*

The relationship already noted (p. 490, figure 4) between the attitude of bank beds and the orientation of sparry masses within them, can now be examined in terms of sedimentary structures and the collapse hypothesis.

In inclined bank beds the upper surfaces of geopetal muds underlying the spars show, in general, a downward stepping and tilting. This probably resulted from cascading of fine sediment downwards through a series of interconnected cavities (figure 30). Such a process can be reproduced experimentally with comparable results. Now, since the spars occupy cavities remaining after most sediment movement had ceased, their shape was directly controlled by the position of mechanical bridging in the bed and the final attitudes of the other mudstone components (figure 31). The tendency for the late muds to become arranged in descending steps on the cavity floor rather than in a single accumulation at the bottom end caused relative elongation of the cavity. The orientation of this elongation is thus related to the depositional dip of the bed and is genetically connected with the origin of the banks themselves. Cavities in inclined beds may be similar in shape to those in horizontal beds but have a different orientation. Schwarzacher (1961, p. 1495) was forced to postulate two separate mechanisms to account for this.

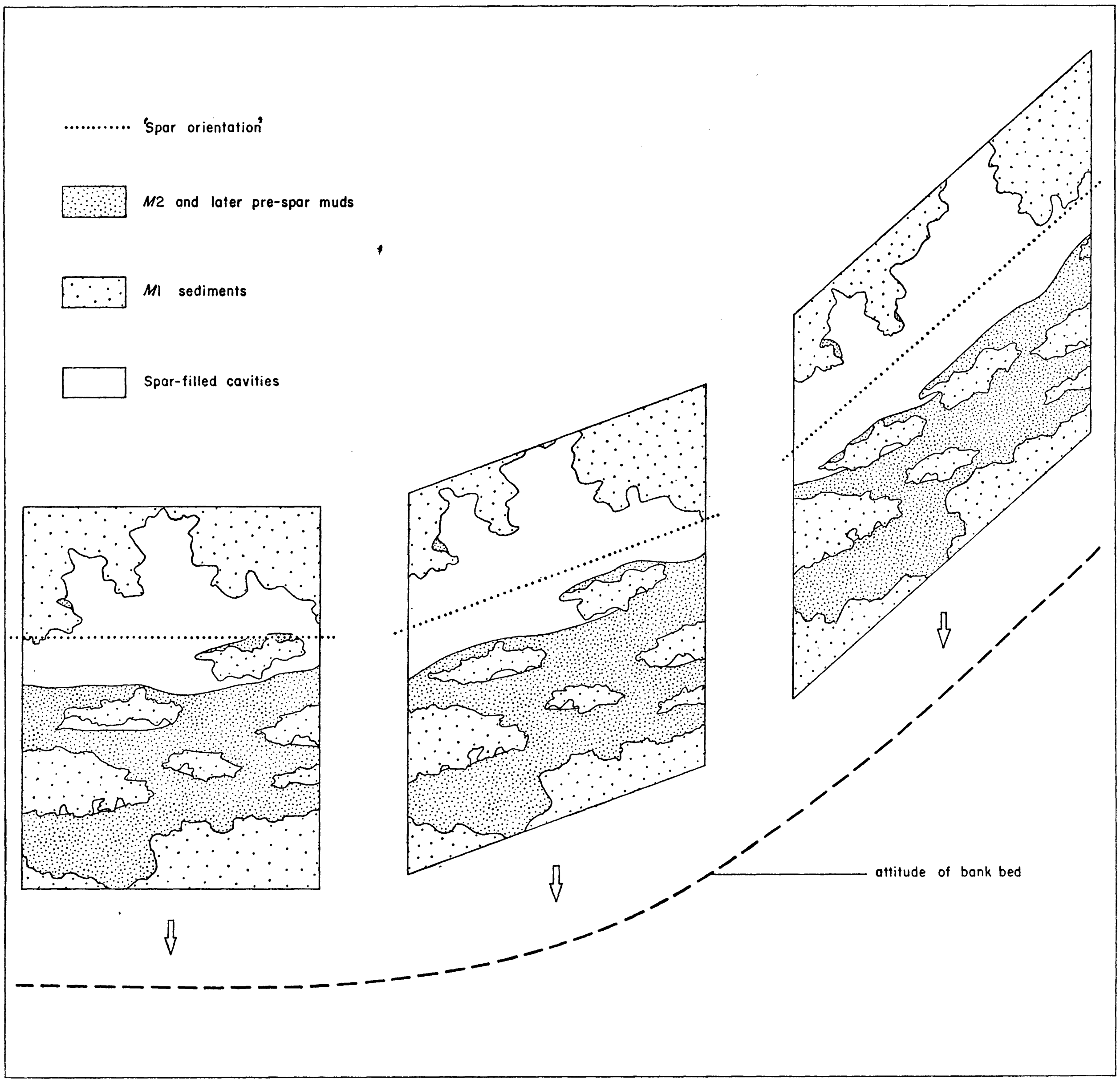

FIGURE 31. Diagrammatic vertical sections of three cells from different parts of a bank bed to show the direct relationship between the orientation of sparry masses and bed attitude. The shape of the cavity occupied by spar depends upon the arrangement of the mechanical bridge, *M*1 patches, and later muds. *M*1 patches of the same shapes are used in all three diagrams: only their arrangement is altered. Scale: the major cavities may be about 10 cm across in the plane of the bedding.

If the collapse hypothesis is correct, the spar orientation measured in the field defines bank forms systematically modified from the original growth mounds. If, as suggested, collapse was progressive (p. 522), these modified forms may only differ from their living state in being somewhat flattened.

(*f*) *Time of spar deposition and lithification*

Several lines of evidence show that some of the spars formed early. Certainly, the banks were soon relatively rigid structures, as the draping of lagoonal rocks over them shows (e.g. at Carrickboy, p. 493). This would be anomalous if only carbonate mud were present.

Early spar formation is demonstrated by the exposure in Carrickboy quarry of an inclined erosion surface on the side of Bank 2 (see figure 6). The truncation of the sparry masses in the bank at this surface shows that at least some of the spar grew before the erosional episode.

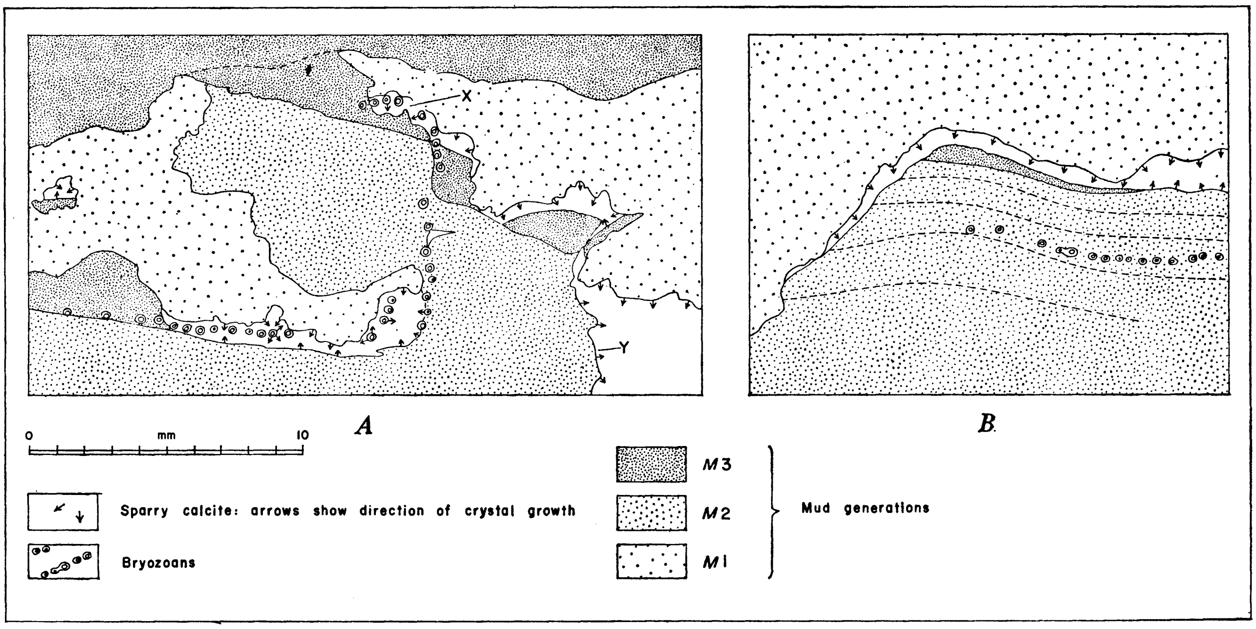

FIGURE 32. Early formation of spar on cavity roofs in a Waulsortian bank limestone (S 10049). Drawings enlarged from acetate peels taken perpendicular to bedding. Distribution of mud generations was determined on polished, etched and stained surfaces of the same area.

A, Section across the irregular junction between two layers in the bank bed. For simplicity the upper one is labelled *M*3 although it can be subdivided. Spar formed on the roofs of cavities in the lower layer (e.g. at *X*) before *M*3 was introduced. The vertical face on *M*2 at *Y* is thought to result from pre-spar internal erosion.

B, A cavity in the lower layer. Evidence here supports the time sequence deduced from *A* and also shows that spar was forming before *M*2 sedimentation had finished.

The most detailed information on the time relationship between mud and spar deposition has been found on a specimen (S 10049) showing an actual 'bedding' surface. This surface represents a minor interruption within a bank bed and is partly erosional. Spar was growing on the roofs and walls of cavities in the lower part of the bed before the first sediments deposited after the interruption trickled into them (figure 32*A*). In one cavity, spar was apparently growing on the roof while muds of its own multicomponent system were being deposited on the floor (figure 32*B*). Thus, precipitation occurred during formation of the bed and before lithification of the muds.* Confirmation of this sequence

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* The *Stromatactis* with truncated tops recorded by Lecompte (1937, p. 6, pl. II figure 2) and Bathurst (1959, p. 518) may also be explained by the early formation of spar. Erosion of carbonate mud until the more resistant spar was uncovered, followed by further mud deposition, could give the appearance of truncation.

is found in Schwarzacher's statements (1961, pp. 1495 and 1501) that calcite crystallization occurred before, and lithification after, the formation of his 'reef' conglomerates.

As the only sparry masses which cross from one bank bed to another are later veins, the *Stromatactis* and other spars may always have been deposited and the cavities substantially filled before the formation of the next bed. Deposition of the first spar layer may have sufficiently stiffened the bank beds to stop further collapse, and provided a 'framework' supporting the bank until the mud lithified. If this were so, and collapse of each bed occurred before deposition of the next, the present shape of a bank may be little different from that during growth.

Present-day submarine carbonate sediments give little information on the mode of deposition of the type of spar found in Waulsortian limestones. Early precipitation of void-filling carbonate cements mainly seems to occur today in intertidal environments or during subaerial exposure in the zone of meteoric waters (Emery *et al.* 1954, pp. 148 and 149; Ginsburg 1953, 1957 pp. 95 and 96; Kornicker 1958, p. 168; Revelle & Fairbridge 1957, p. 258). Under conditions of complete submergence small-scale precipitation occurs in 'grapestones' (Illing 1954, p. 30, plate 3. 8 and 3. 9) and just below low tide level in some reefs (Emery *et al.* 1954, p. 149).

Spar is found in all the Waulsortian banks extending to the bottom of the bank beds and the transition to lagoon or other off-bank facies (figure 35 plate 6). Thus, if it was deposited during tidal changes, every bank, irrespective of height, was exposed at frequent intervals to the level of the sea floor. This seems unlikely. No lithological or faunal evidence suggesting that the banks were ever subjected to intertidal or subaerial conditions has been recognized. On the contrary, organisms such as crinoids would surely not survive exposure. Even the known erosional features could easily have formed under water. The presence on the banks of a dense covering of organisms inhibiting formation of features normally associated with shallow, agitated water or even intermittent exposure, could lead to misinterpretation. However, it seems more reasonable on present information to conclude that the banks were always submerged. Spar precipitation from sea, rather than meteoric water, is thus favoured. Physico-chemical conditions at the site of precipitation can only be surmised, but they were probably markedly different from those at the surface of the banks.

V. CONCLUSIONS

The Waulsortian banks formed as local accumulations of carbonate mud and skeletal debris. On available evidence their formation is best explained by the sediment-baffling action of organisms, possibly plants or sponges. These had no rigid skeletal parts and have not been preserved. Bryozoa also acted as baffles but were not the prime agents of bank growth. Framebuilding was unimportant and the term 'reef' is best avoided.

The characteristic climax form of the banks did not arise by chance. It is apparently a limiting form, the steepest slopes perhaps representing the critical angle beyond which the organic cover was unable to support sediment. Further study is required to determine the influence of water movement on bank morphology.

The calcite mudstones are lithified carbonate muds (calcite or aragonite). They are not the recrystallized products of sand-sized primary grains although as aggregates they may have behaved as even larger masses. Local production of the mud is favoured. The mode of its formation is unknown. Possible processes are direct physico-chemical precipitation perhaps induced by organic processes such as photosynthesis, or disintegration of weakly calcified organisms.

Most of the sparry masses are cavity fillings. The cavities were not formed by erosion of once-continuous muds. Those of *Stromatactis* type probably developed as a result of collapse following decay of the organic baffles; the others, of sheet form, apparently opened along planes of shear in unsupported muds. Soon all became spar-lined and further collapse was prevented. The muds lithified later.

When compared with the size of the Complex the individual banks were not large, the largest of the knoll forms investigated being not more than a few hundred yards in diameter. Because of bank aggregation, the present-day thickness of a Waulsortian mass may bear little relation to the height of the component banks at the time of growth. This original sea floor relief may never have greatly exceeded 50 ft.

Details of the environmental conditions are difficult to deduce from information available at present. Even the characteristic sedimentary structures are interpreted as collapse effects giving only indirect evidence of the state of the growing banks. The organic communities, present or inferred, may provide the best record of conditions; a palaeoecological study of individual banks is needed. The baffles may have been responsible for the absence or obscurity of mechanically controlled primary structures. They may also have disguised evidence showing that, say, the banks grew up to sea level.

The great areal spread of the Complex remains puzzling. Although it formed a barrier between lagoon and mudbelt its extent contrasts markedly with the narrow growth zones of modern barrier reefs. Such spread may imply uniform conditions over large areas; it may also reflect the tolerance and functional simplicity of the organic communities forming the banks.

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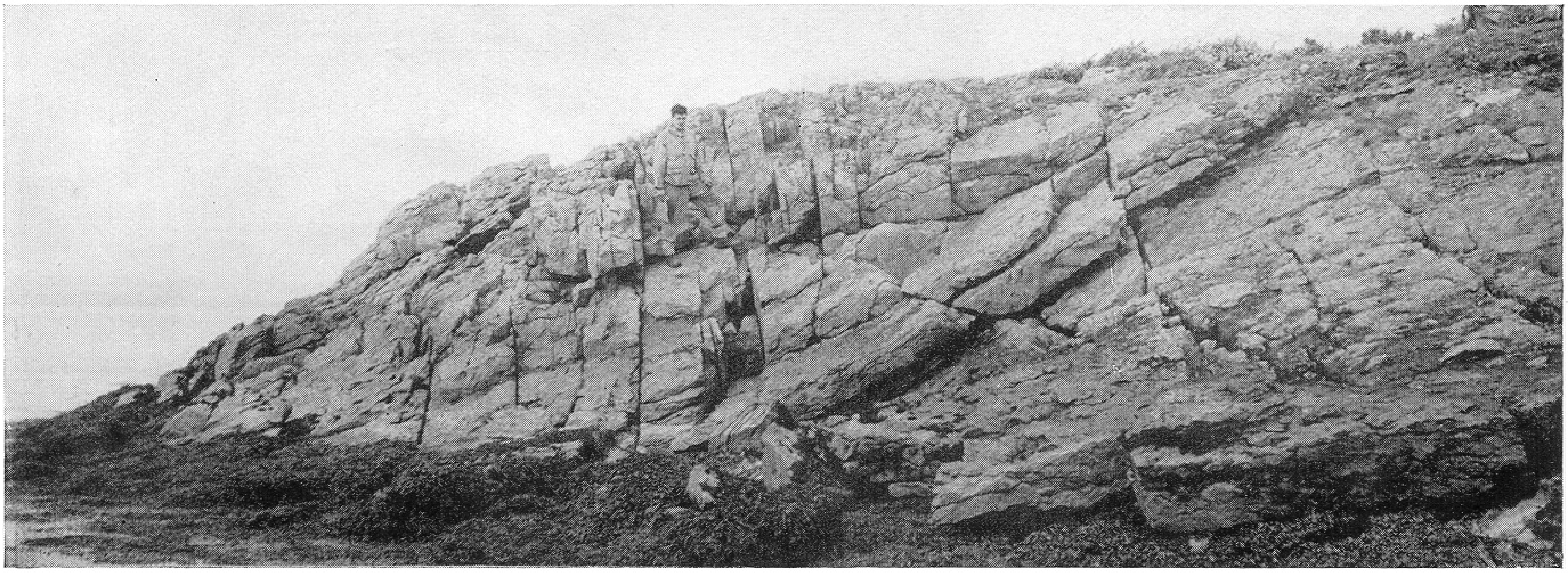

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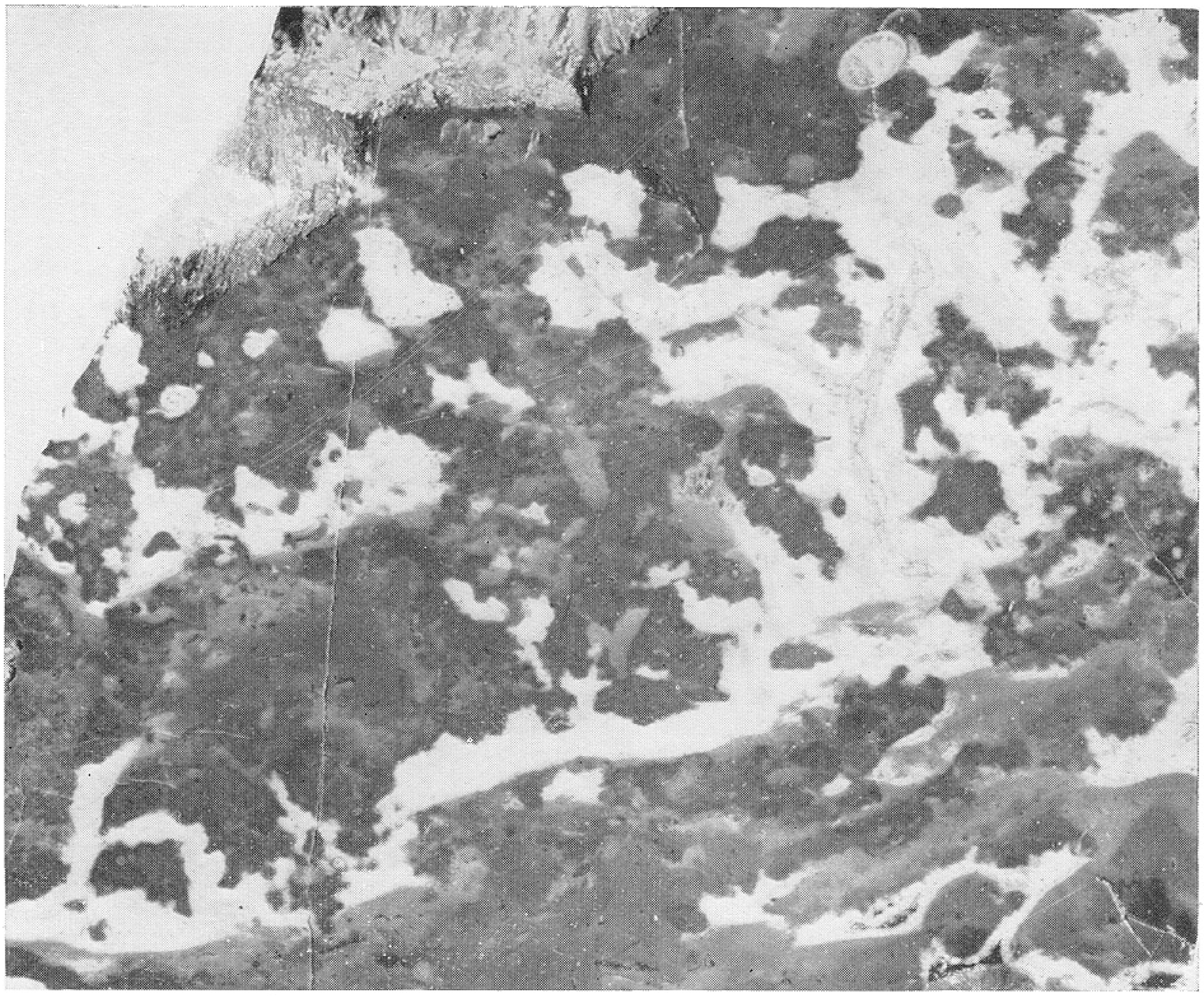

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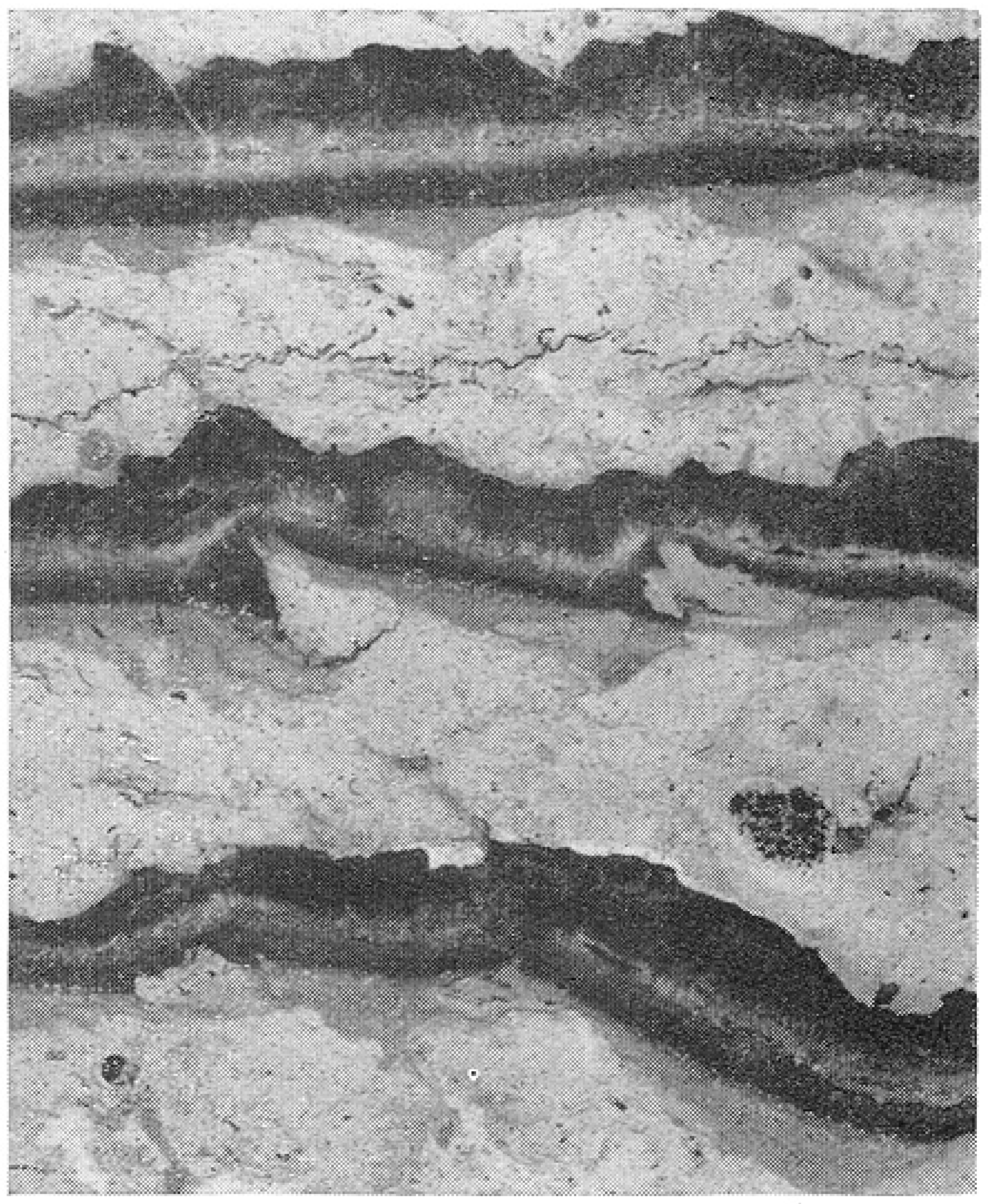

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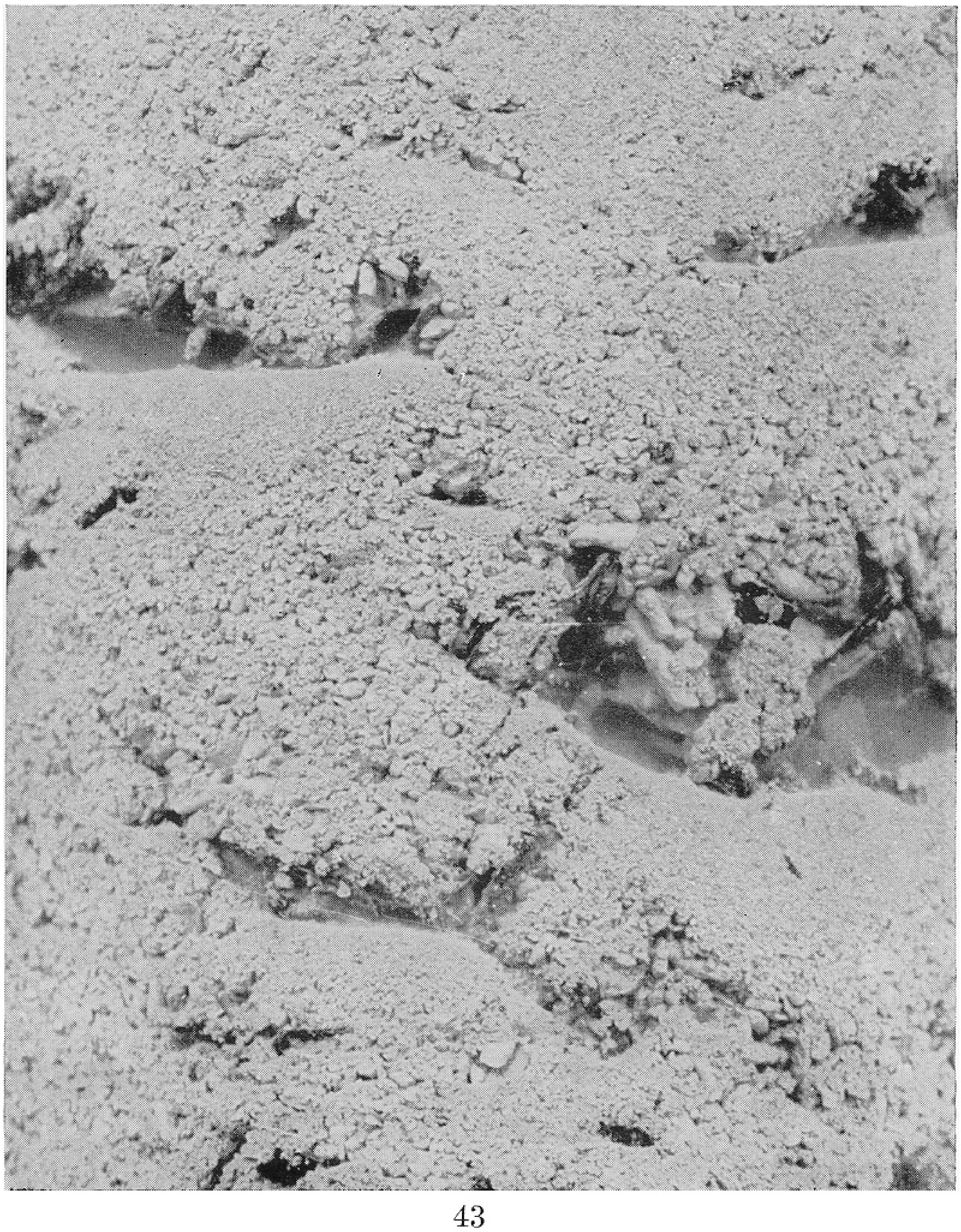

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