Upper Devonian sponge-algal mud mounds, southern flank of Miette reef complex, Jasper National Park, Alberta, Canada

by

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ABSTRACT

A series of small mud mounds are exposed in the McConnell and Miette thrust sheets on the southern flank of the Miette reef complex. They occur on the southeastward inclined carbonate clinoforms of the late Frasnian Arcs Member. These mounds are rooted on marine, argillaceous lime mudstones and are surrounded by lime mudstones of several prograding clinoforms of the upper Arcs Member or dolomitic siltstones of the lower Ronde Member.

Mounds are approximately 17 to 36 m high and 32 to 81 m wide and columnar to domal in shape. The lower part of the mounds consists of sponge-rich wackestones and packstones, and locally laminar stromatoporoid boundstones. Calcareous green algae tend to predominate in the upper parts of the mounds.

Variable cavities occur and are filled with geopetal sediments, isopachous fibrous and blocky calcite cements. The most common cavity types, irregular and irregular stromatactoidal cavities, might be related to organic origins, possibly the decay of sponges in conjunction with submarine cementation.

Abrupt mound margins indicate that the mounds grew upwards more rapidly than the accumulation of the adjacent basin and clinoforming slope sediments. Vertical constrictions and shape changes suggest that the mounds developed in two or more distinct stages that tracked sea level rises.

The sediments in much of the laterally equivalent Arcs Member bank above the Miette reef complex proper a few kilometers to the north were deposited in very shallow water (< 1 to 2 m). This together with the geometry of the gently basin sloping carbonate clinoforms suggests that the water depths of mound initiation was 20 to 30 m, or the thickness of the mounds.

Initiation of the mounds took place in moderately agitated water with the deposition of sponge-rich wackestones. Later mound growth took place in more agitated conditions in which calcareous algal packstones were deposited.

The depositional environment of the Miette mud mounds was similar to the Ancient Wall and subsurface Meekwap wackestone/mudstone bioherms with respect to shallow water depths and water agitation. Laminar stromatoporoids, calcareous algae especially renalcids, and the massive colonial rugose coral *Phillipsastrea* are widely distributed in the Ancient Wall bioherms, but contain no obvious sponge material and have rare stromatactoidal cavities. The differences in the biota between these two localities could be due to differences in slope configuration and amounts of basin sediments being deposited.

Sponge-rich wackestones of the "récifs rouges" (Facies A), of the Upper Devonian mud mounds in Belgium are similar to the Miette mud mounds. However, the Belgium mounds are interpreted to have been deposited in much deeper water below storm wave base. The Miette mud mounds show that this facies is not depth dependent and can be deposited in very shallow water.

RÉSUMÉ

Une serie de petits monticules boueux sont exposés le long des couches de chevauchement McConnell et Miette sur le flanc sud du complex récifal Miette. Ils se trouvent sur les dépôts de pente à inclinaison sud-est appartenant au Membre des Arcs avec un âge Frasnien tardif. Ces monticules sont enracinés sur des mudstones argileuses calcaires d'origine marine et sont entourés par des mudstones calcaires du Membre des Arcs composées de plusieurs dépôts de pente progradants ou de siltstones dolomitiques du Membre inférieure de la Ronde.

Les monticules sont approximativement de 17 à 36 m de hauteur et de 32 à 81 m de largeure et ont une forme colunaire à domale. La partie inférieure des monticules consiste à des wackestones et des packstones riches en éponges, avec localement des boundstones à stromatoporoides. Les algues vertes calcaires tendent à prédominer dans les parties supérieures des monticules.

Des cavités variables sont présentes et sont obstruées de sédiments géopétales et de ciments calcitiques isopaques à forme fibreuse en partie radiaxiale et d'autres à forme bloquaire. Les types de cavité les plus commun, cavitées irrégulières et d'autres stromatocoidales irrégulières, peut être liées à des organismes à corps moux, possiblement la décompositon d'éponges en conjonction avec une cimentation marine.

Les marges abruptes des monticules indiquent que leur croissance vers le haut a été plus rapide par rapport à l'accumulation du bassin adjacent et des sédiments de pente. Les resserements verticaux et les changements de forme suggèrent que les monticules se sont développés en deux ou plusieurs étapes

distinctes ayant tracé les remontées du niveau marin.

Par dessus du complexe principal récifale Miette se touvant à quelques kilomètres vers le nord, la majorité des sédiments de l'équivalent latérale de la rive du Membre des Arcs ont été déposés dans des eaux peu profondes (< 1 à 2 m). Ceci avec la géométrie des dépôts de pente carbonatés à faible pente basinale suggèrent que la profondeur de l'eau correspondant à l'initiation des monticules était de 20 à 30 m, ou l'epaisseur des monticules.

L'initiation des monticules a pris place dans une eau modérément agitée avec le dépôt de wackestones riches en éponges. La subséquente croissance des monticules a pris place dans des conditions plus agitées permettant le dépôt de packstones alguaires calcaires.

L'environment de dépôt des monticules boueux Miette était similaire à celui des biohermes Ancient Wall et ceux wackestones/mudstones de subsurface Meekwap de point de vue profondeur et agitation d'eau. Des stromatoporoides laminaires, algues calcaires particulièrement renalcides, et le corail massive colonial rugose *Phillipsastrea* sont largement distribués dans les biohermes Ancient Wall, mais contient aucun materiel spongiaire et possède de rares cavités stromatactoidales. Les différences de biota entre ces localités peut probablement être dues aux différences dans la configuration de pente et les quantités de sédiments de basin en voie de dépôt.

En Bélgique, les récifs Rouges wackestones riches en éponges (Facies A) appartenant aux monticules boueux du Devonien Supérieur sont similaires à ceux des monticules boueux Miette. Cependant, les monticules belges sont interprétés d'être déposés dans une eau plus profonde en dessous de la base de vague de tempête. les monticules boueux Miette montrent que ce facies est independant de la profondeur et peut être déposé dans une eau peu profonde.

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CHAPTER 1. INTRODUCTION

1.1. Introduction

Mud mounds form early lithified structures that support a variable benthic fauna and flora in which the amount of skeletal elements is usually low. The origins of mud mounds throughout the Phanerozoic are controversial. A poor understanding of what stabilizes the particulate mud makes interpreting the genesis of mud mounds difficult. Also the origin of the different types of cavities which occur in the mud mounds are a matter of debate.

The Miette reef complex is an equidimensional buildup located just south of the Miette Hot Springs, Jasper National Park, Alberta (Figs. 1, 2 and 3). A series of small mud mounds occur on the southeastward inclined clinoforms of the Arcs Member of the Southesk Formation of the Miette reef complex (Figs. 3 and 4). These mud mounds have only been studied in a reconnaissance manner by Mountjoy (1965, unpublished) and ones immediately to the south were studied by Hedinger and Workum (1989).

The objectives is the study of the: 1) the type and distribution of fossils, 2) the type of matrix, 3) the types of cavities, 4) the shapes and configurations of the mounds, 5) the nature of the substrate, and 6) their relationships with flanking beds. These mud mounds were compared with those of the Ancient Wall reef complex with respect to their faunal composition.

Similar reefs and mud mounds occur in the Meekwap and Nisku shelfs in the adjacent subsurface to the east and southeast (Cheshire and Keith, 1977; Switzer *et al.*, 1994). Outcrops provide a better idea than limited subsurface cores concerning the lateral and vertical distribution of the fossils and different types of cavities and the relationships with adjacent facies. Also the general form of the mounds and stratigraphic relationships between the mounds and the adjacent slope strata can be better observed in outcrop where they can be walked out and mapped. These relationships place constraints on the lateral correlation of strata adjacent to the subsurface reefs and provide important information about rates of formation of the mounds relative to basin filling and sea level changes. However, a thick weathered coating on most mounds and inaccessibility of some parts of them made it difficult to map all parts of the mounds (Fig. 5).

1.2. Previous studies

Upper Mount Hawk mud mounds of the Miette reef complex have been studied in a reconnaissance manner by Mountjoy (1965, unpublished) and Hedinger and Workum (1989) who reported locations, sizes, configurations and stratigraphic positions. Similar but smaller mud mounds that occur on the south flank of the Ancient Wall reef complex were studied in detail by Mountjoy and Jull (1978) and Mountjoy and Riding (1981). The petrography, distribution and diagenesis of foreslope and basin sediments adjacent to the Miette and Ancient Wall carbonate complexes were studied in detail by Hopkins (1972).

1.3. Geological setting and stratigraphy

During the Middle and Late Devonian a shallow sea spread from the northwest over what is now Alberta and southern Saskatchewan. This sea deposited shales, limestones and evaporites and inundated the Miette area in the western part of Alberta during the early Frasnian (Mountjoy, 1965; 1989). The Upper Devonian strata were deposited in 3 major megacycles: Beaverhill Lake (IIa), Woodbend (IIb, IIc lower), and Winterburn (Arcs and Ronde-Simla; IIc upper IId) (Savoy and Mountjoy, 1995) (Fig. 10). The sediments of early Frasnian age gradually onlapped and buried the West Alberta Ridge (a positive feature that underlies the present Foothills; see Mountjoy, 1980) forming the extensive Flume carbonate platform during the Woodbend megacycle (Savoy and Mountjoy, 1995). Following submergence of the Flume carbonate platform, extensive reef-fringed carbonate complexes surrounded by shales developed in central Alberta (Mountjoy, 1965; 1989, Switzer *et al.*, 1994; Figs. 1 and 2). Following a major sea-level rise of the initial Winterburn megacycle, an extensive Arcs carbonate platform developed instead of reefs in the Rocky Mountain region south of 54°N, except for some very small patch reefs around the Jasper basin (Savoy and Mountjoy, 1995). The strata of this study (upper Mount Hawk Formation, Arcs and Ronde Members) form part of the Winterburn megacycle.

In the Miette thrust sheet, the Miette buildup has a width in a NW-SE direction of about 11 km, increasing to about 14 km in the McConnell thrust sheet (Figs. 2 and 3). In a NE-SW direction it has a width of at least 10 km and possibly 15 km depending on palinspastic reconstructions and the location of the hidden western margin of the buildup. The Arcs Member (Southesk Formation) extends an additional 5 to 10 km further basinward from the main reef complex (Peechee) in all directions (Mountjoy, 1965; 1989).

In the Miette buildup, carbonate sedimentation for the most part kept pace with sea level rises, and the depth of the surrounding basin gradually increased because of the slower rates of basin sedimentation (Mountjoy, 1965; 1989). The upper third of the buildup (Peechee) appears to represent a slowing of rates of sea level rise and a return to the circulation of oxygenated waters in the basin (Mount Hawk shales and limestones), which represent the main phase of basin filling (McLean and Mountjoy, 1994; Mountjoy, 1989). The Mount Hawk terrigenous and carbonate sediments prograded in stages westward across the Alberta basin and probably had a source from the north and northeast (Mountjoy, 1980; Stoakes, 1980; Switzer *et al.*, 1994). These upper Frasnian siliciclastic sediments eventually filled most of the basin and interfinger with basinward prograding carbonate banks of the Arcs and Ronde Members of the upper Southesk Formation adjacent to the reef complexes (Fig. 4).

The Miette carbonate mud mounds described in this thesis developed on slope carbonates or calcareous shales of the upper Mount Hawk Formation. These slope carbonates were shed from prograding Arcs carbonate banks of the Arcs Member (Figs. 4 and 5). Stratigraphic sections from the head of Poachers Creek, McConnell thrust sheet and head of Fiddle River, Miette thrust sheet (Fig. 2B) are shown in Appendices 1 and 2. The mounds were initiated on southeastward sloping prograding Arcs carbonate tongues or clinoforms adjacent to the Miette buildup (Fig. 3). The Ronde Member unconformably overlies mud mounds 2, 3, 4 and 5. Schematic geological columns at Poachers Creek, McConnell thrust sheet and the head of Fiddle River, Miette thrust sheet are shown in Figures 11 and 12.

1.4. Field work and methods

A total of about five weeks were spent at Poachers Creek and the head of Fiddle River (Fig. 3) between early July and mid August in 1994 and 1995. Both of these base camps were established utilizing Alpine Helicopters based in Hinton.

The configuration and size of the mud mounds, as well as lithological data and sample locations were recorded on oblique photographs taken from the helicopter or on foot (Figs. 5 and 6). Many sketches were also drawn using binoculars (Figs. 7, 8 and 9). Lithological observations and samples were obtained from most parts of mud mounds 1, 3 and 5, but only from the bases of mud mounds 2 and 4 because of steep slopes and inaccessibility (Fig. 6). No technical rock climbing was done.

Five mud mounds were investigated in detail using more than 160 rock samples. The location and numbers of most samples are shown in Figures 8 and 9. Also adjacent mounds were photographed and their overall morphology were compared with mud mounds 1 to 5. Many samples were cut and polished and point counts were made on 160 small thin sections (2.6 x 4.6 cm) to estimate the relative amounts of the skeletal components. Point counts were based on at least 100 points, excluding cavities. Rock matrix is included under other. The relative percentage (volume) of the cavities was estimated from hand specimens. Lime mudstones, wackestones and packstones were classified based on the amounts of skeletal elements and whether grain supported or not. The point count data are shown in Tables 2 to 6 and the relative abundance of the various components are shown in Figures 14 and 15.

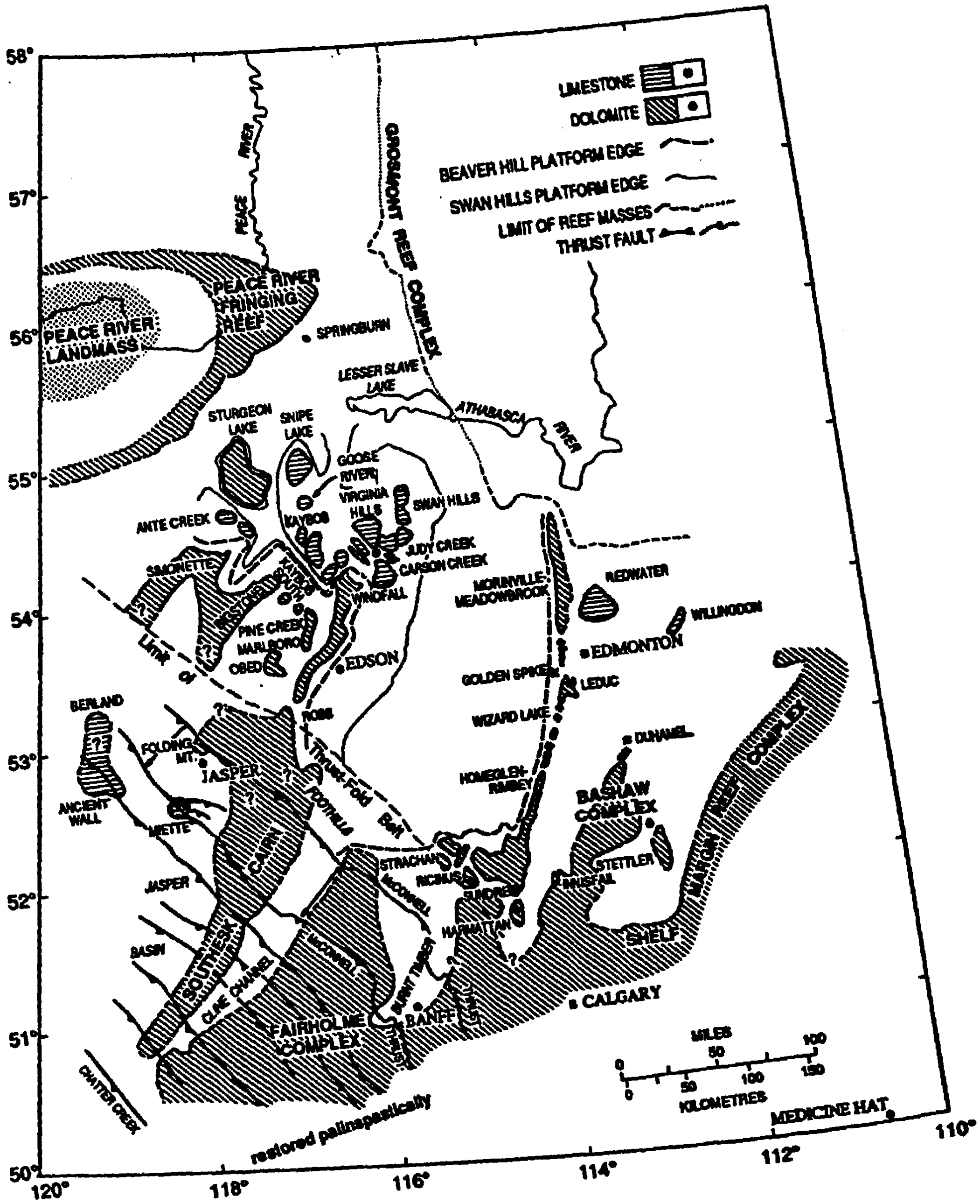


Figure 1. Middle and Upper Devonian reef complexes of central and southern Alberta and adjacent Saskatchewan. (from Mountjoy and Amthor 1994).

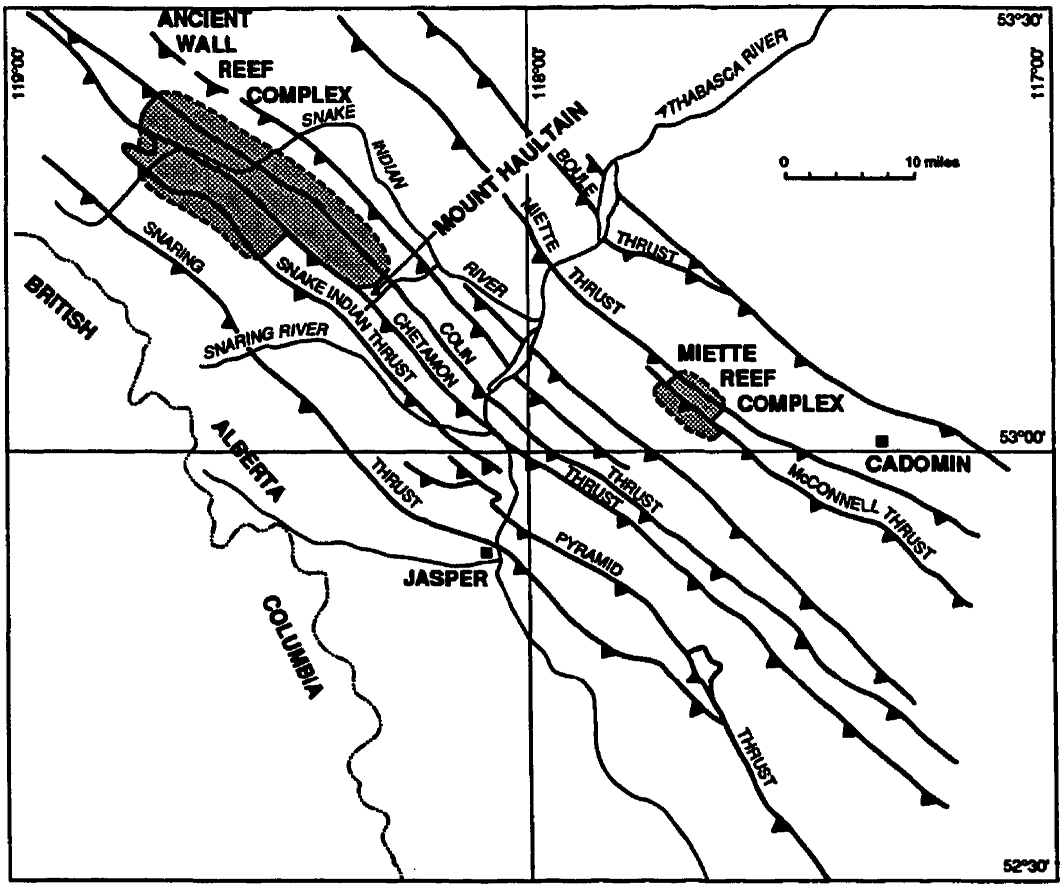


Figure 2. Map showing location of Miette reef and Ancient Wall reef complexes, Front Ranges, Jasper National Park.

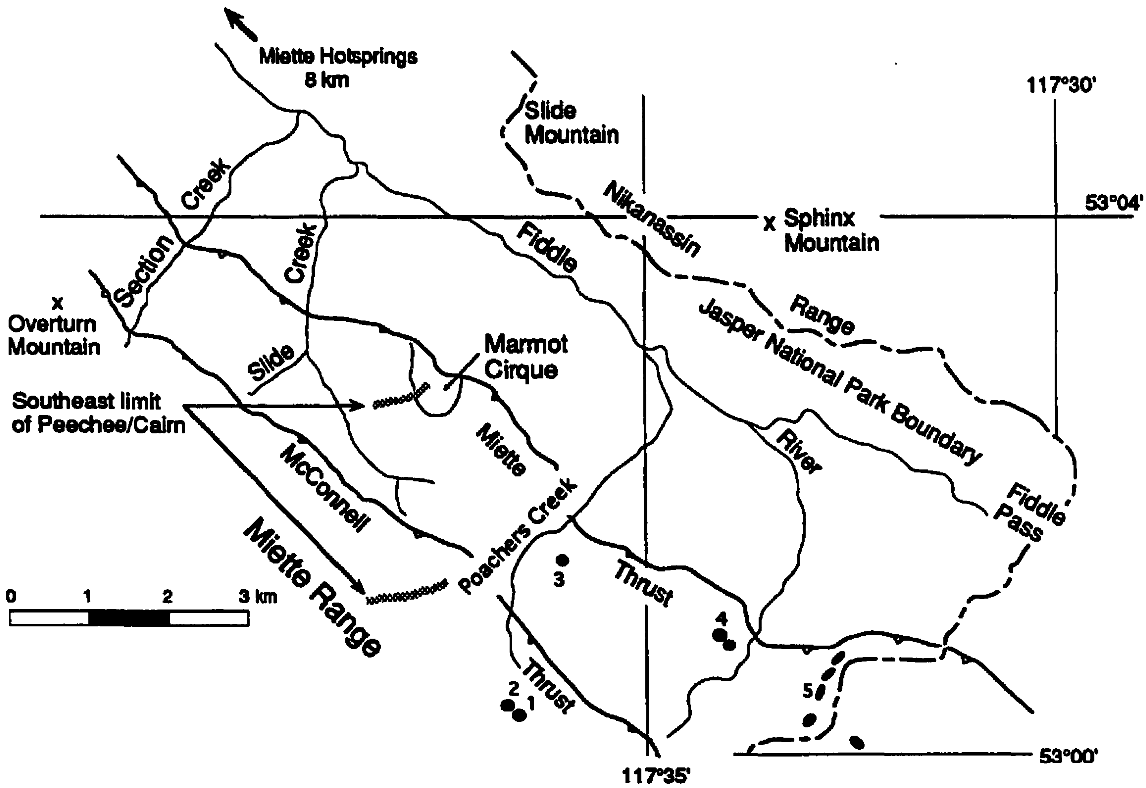


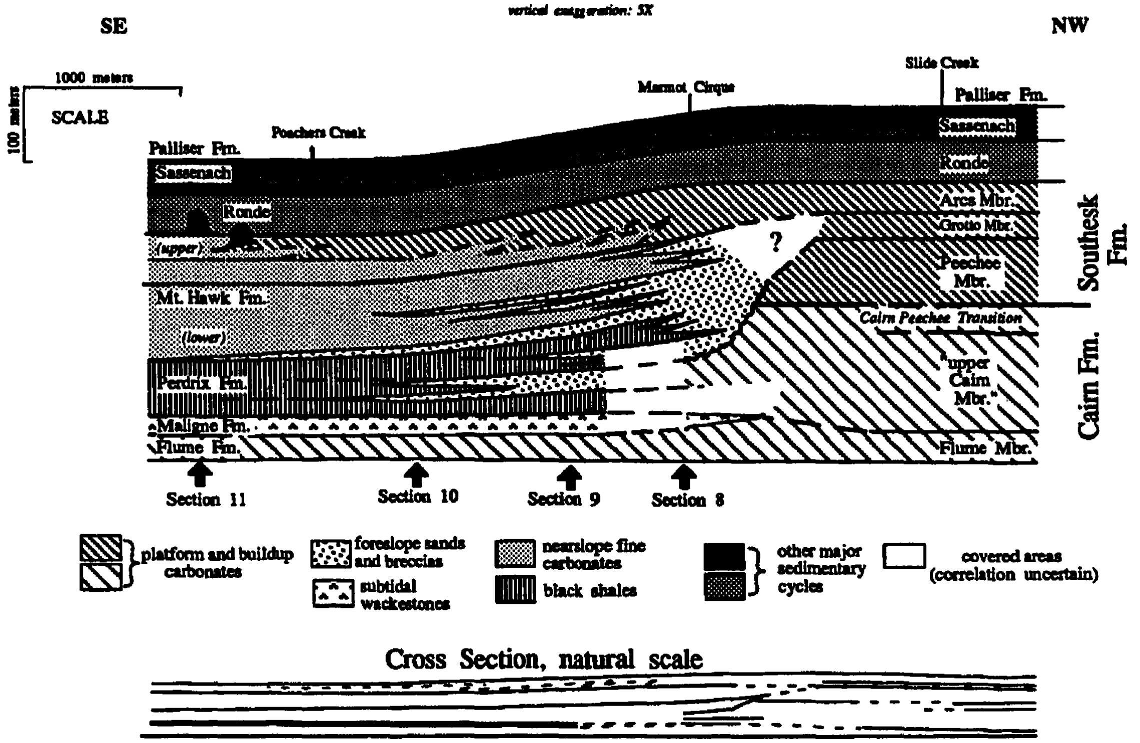
Figure 3. Location of five carbonate mud mounds in the Miette and McConnell thrust sheets in southeastern Jasper National Park. The mud mounds studied occur a few kilometers southeast of the southern margin of the Miette reef complex indicated by the stippled lines in the two thrust sheets.

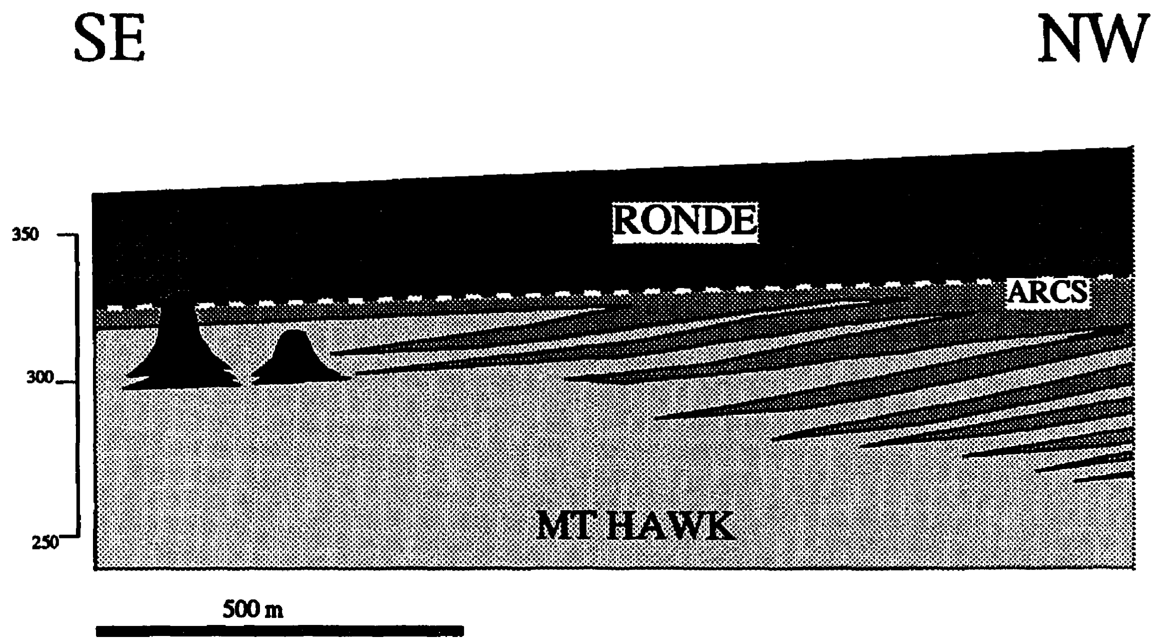
Figure 4A. Schematic geological cross section of the Miette reef complex and strata flanking the southeastern margin. Section locations refer to those of Hopkins (1972). The approximate position of the mud mounds are shown on the left side of the diagram showing that mounds were initiated in the upper part of the Arcs Member and near the base of the Ronde Member. Modified from Hopkins (1972).

Figure 4B. Schematic cross section showing southeastern sloping carbonate clinoforms and position of mud mounds for McConnell thrust sheet, southeastern margin of the Miette buildup.

Marmot Cirque Cross Section
Miette Reef Complex

vertical exaggeration: 5X





Vertical Exageration = 6.2x

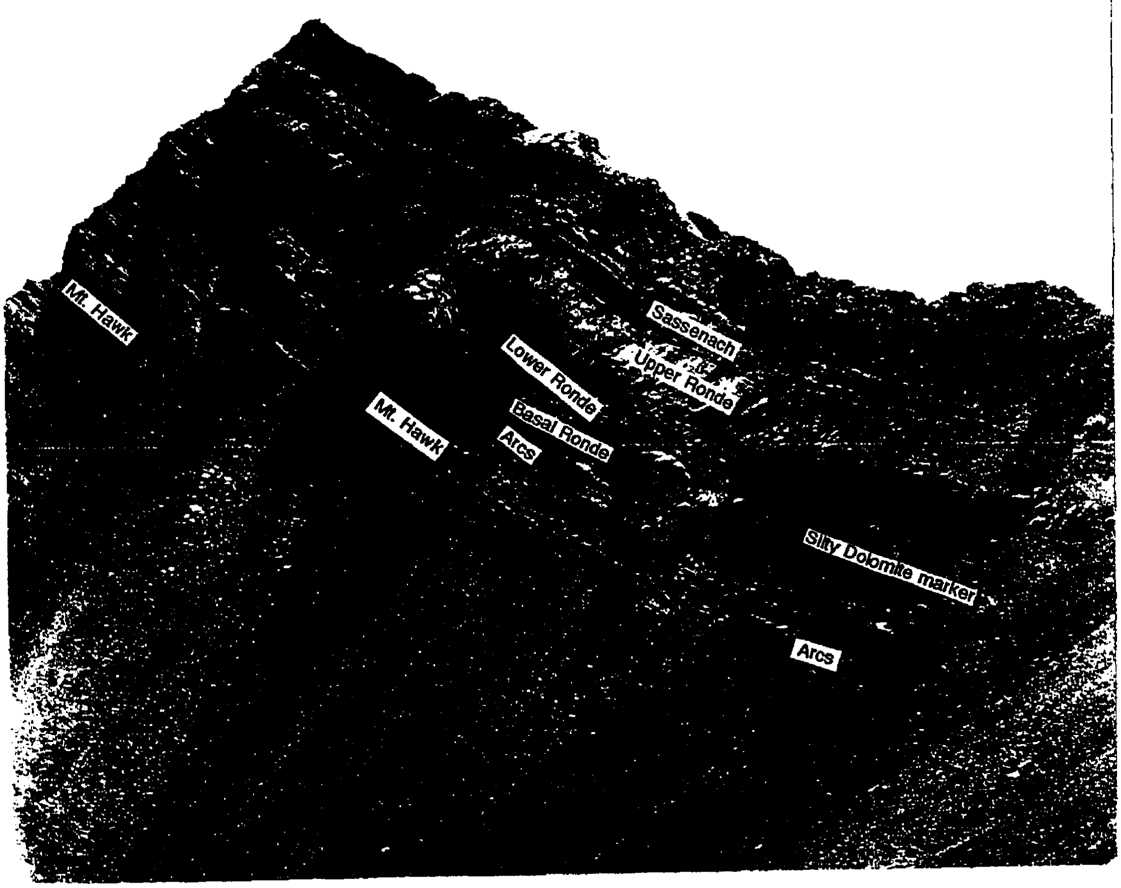
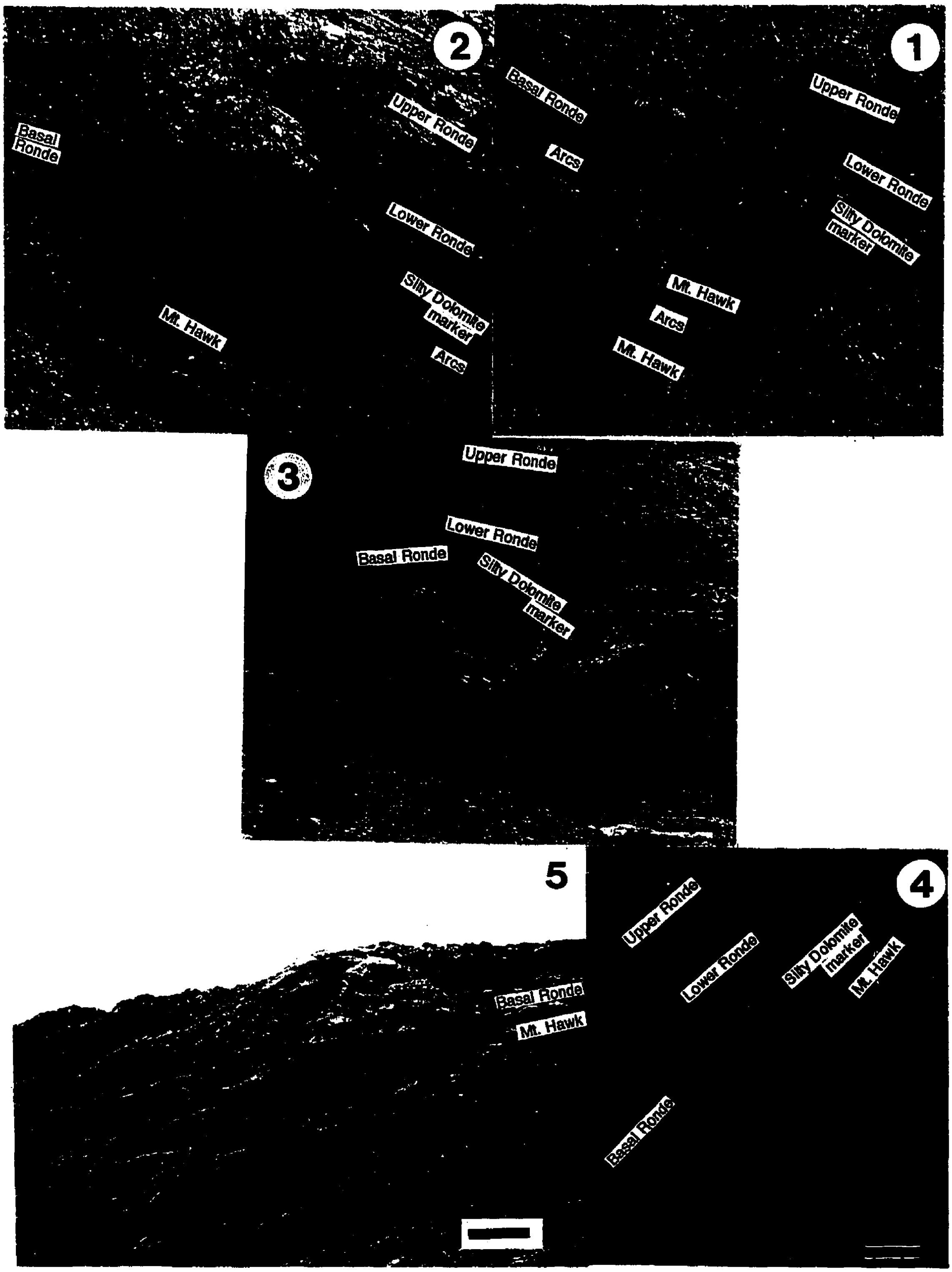


Figure 5. Mud mounds 1 (right) and 2 (left), McConnell thrust sheet, head of Poachers Creek viewed looking south showing shaly lower Mount Hawk and more carbonate rich upper Mount Hawk, overlain by Ronde Member, Sassenach Formation and Palliser Formation. Mud mound 2 is the prominent mound in the center left (to left of label - Lower Ronde), and mud mound 1 occurs to the right and has lower relief.

Figure 6. Mud mounds studied 1 - 5. Mounds 1 and 2 outcrop in McConnell thrust sheet, head of Poachers Creek and mounds 3 to 5 outcrop in Miette thrust sheet. Scale bars 10 m.



2
Basal Ronde
Upper Ronde
Lower Ronde
Silty Dolomite marker
Mt. Hawk
Arcs
1
Basal Ronde
Arcs
Upper Ronde
Lower Ronde
Silty Dolomite marker
Mt. Hawk
Arcs
Mt. Hawk
3
Upper Ronde
Lower Ronde
Basal Ronde
Silty Dolomite marker
5
Basal Ronde
Mt. Hawk
4
Upper Ronde
Lower Ronde
Silty Dolomite marker
Mt. Hawk
Basal Ronde

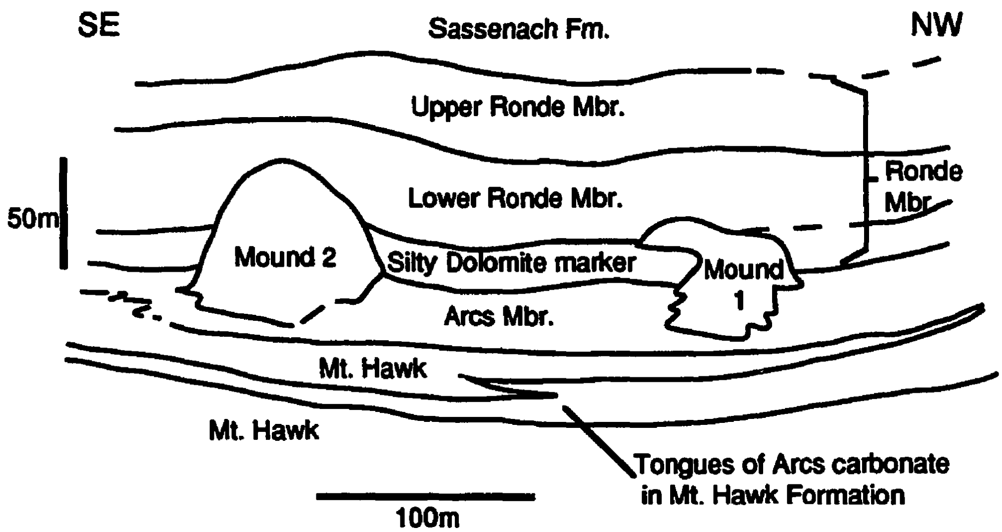


Figure 7. Stratigraphy adjacent to mud mounds 1 and 2 in the McConnell thrust sheet at the head of Poachers Creek (see Fig. 5). Silty dolomite marker forms the base of the Ronde Member.

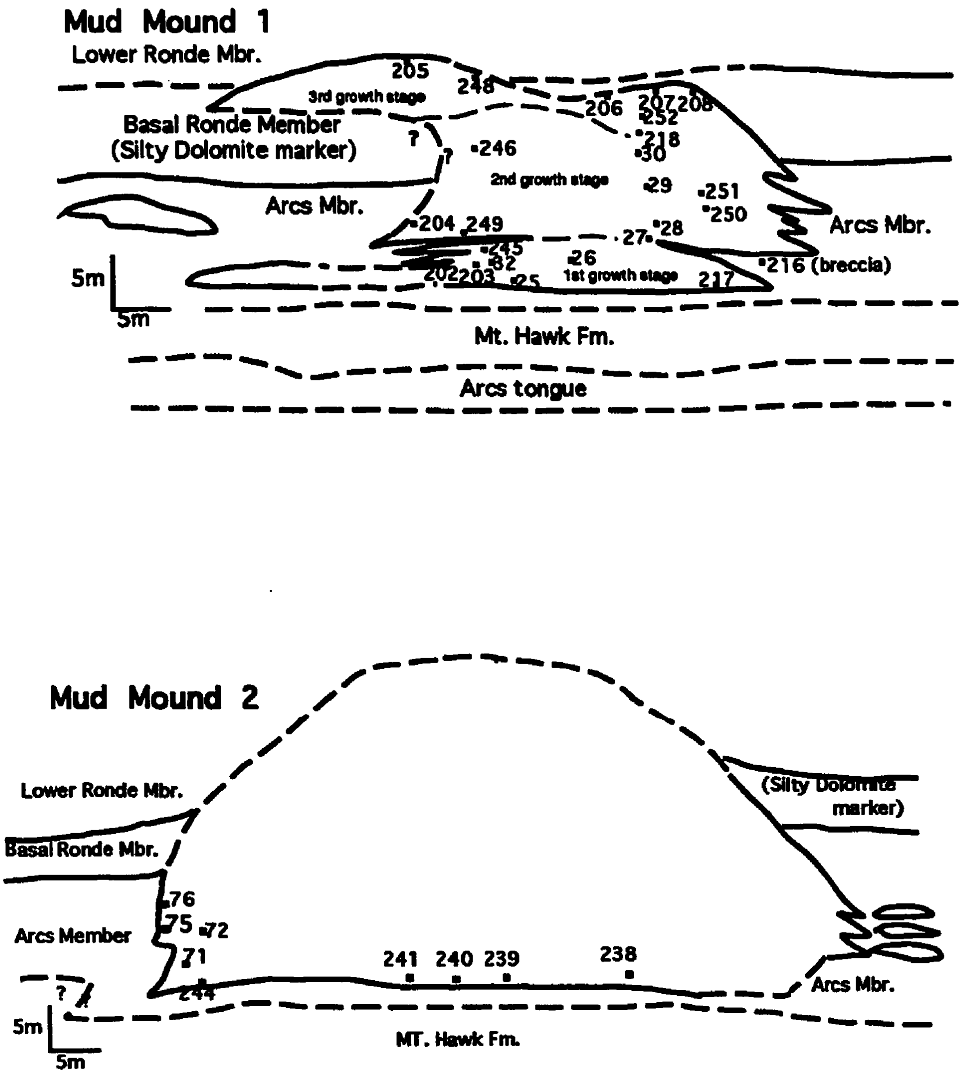


Figure 8. Configuration and sample localities of mud mounds 1 and 2, head of Poachers Creek, McConnell Thrust sheet.

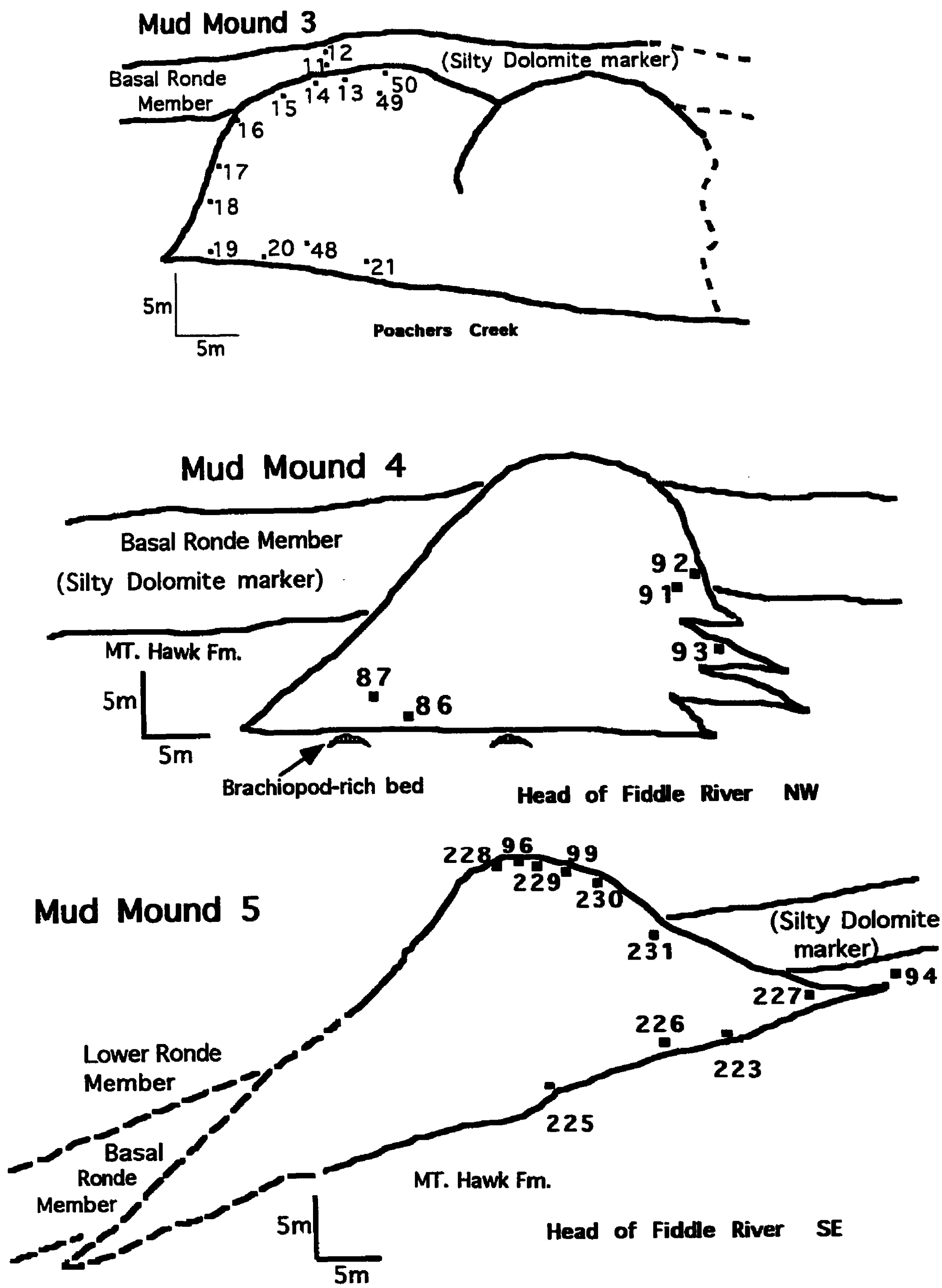


Figure 9. Configuration and sample localities of mud mounds 3, 4 and 5, Miette Thrust sheet.

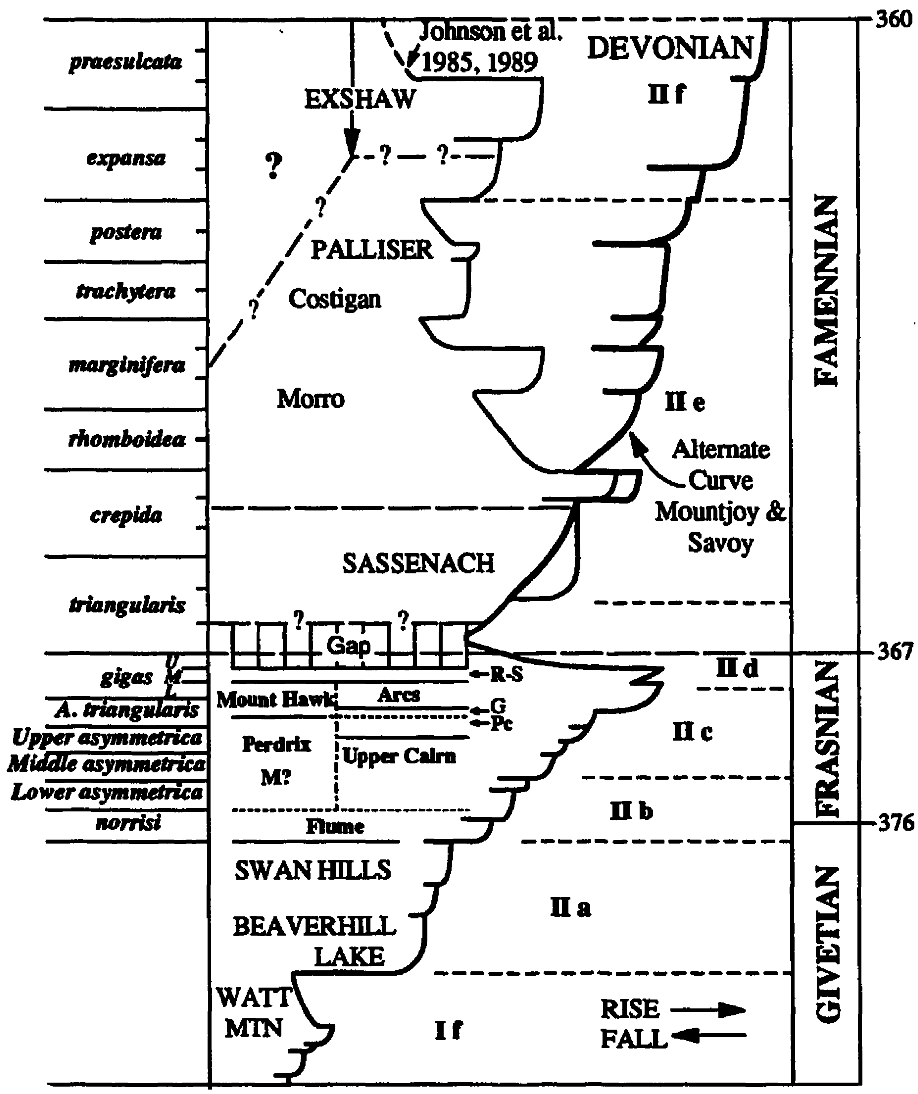


Figure 10. "Eustatic" sea level curve for the Devonian succession of the southern Canadian Rocky Mountains. Devonian stratigraphic units are plotted by age. Left column conodont zones. (Pc = Peechee, G = Grotto, and R-S = Ronde-Simla.) Modified after Savoy and Mountjoy (1995).

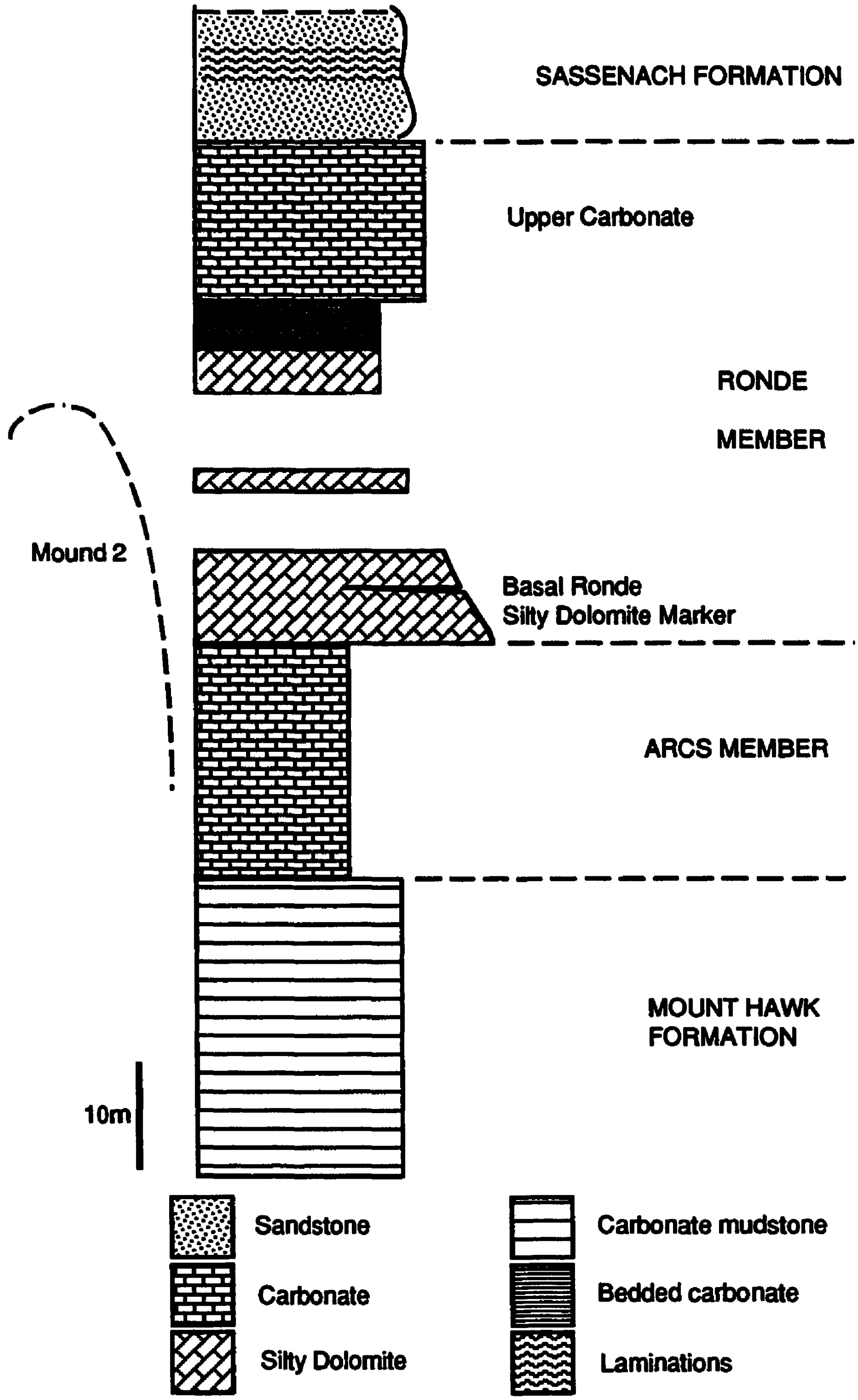


Figure 11. Schematic geological column, head of Poachers Creek, McConnell thrust sheet.

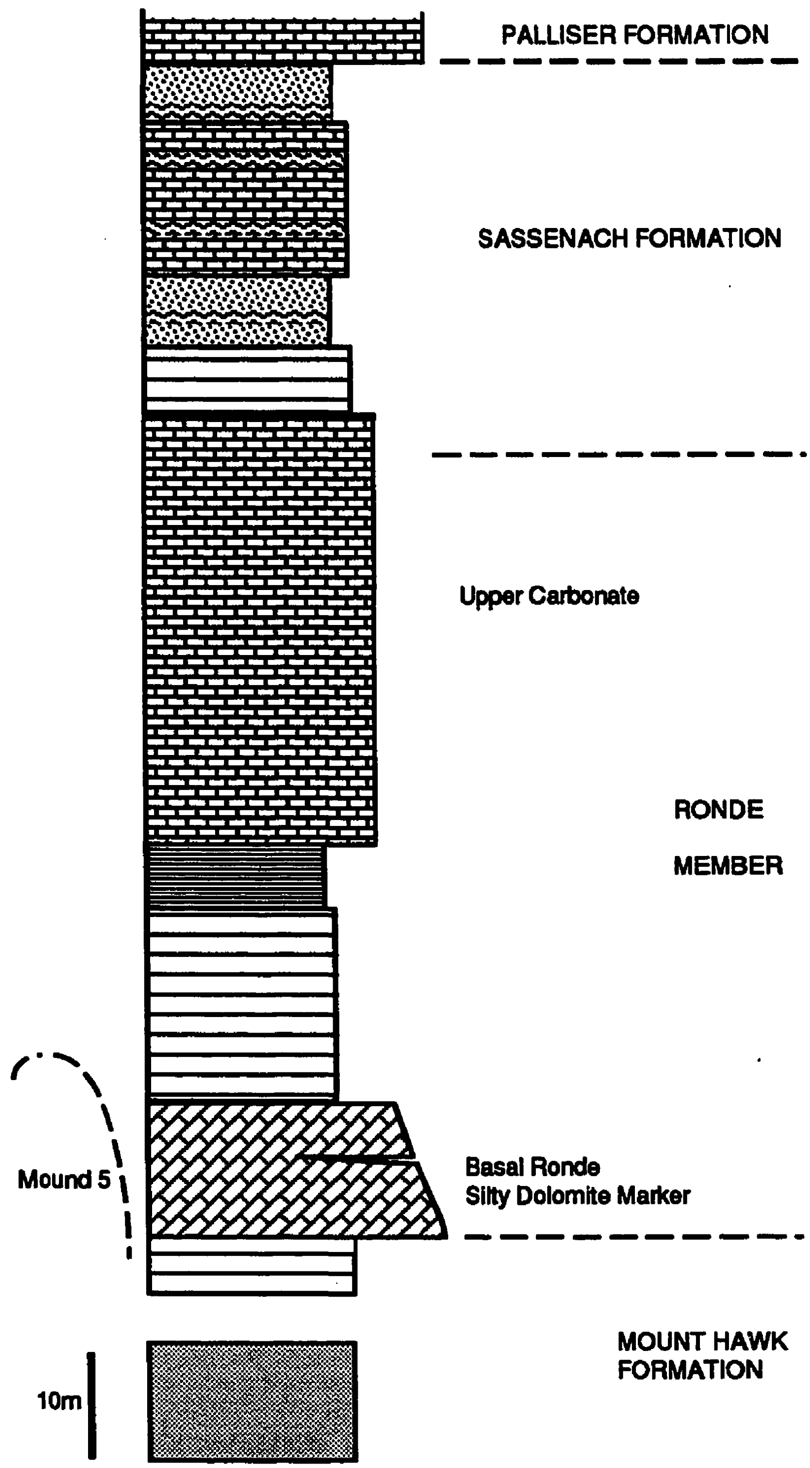


Figure 12. Schematic geological column, head of Fiddle River, Miette thrust sheet. See Figure 11. for legend.

CHAPTER 2. NATURE OF MUD MOUNDS

This chapter summarizes the occurrence, sizes and configuration, substrates, lithofacies, biota and cavity types in the Miette mud mounds.

2.1. Occurrence

The mud mounds adjacent to the Miette reef complex are massive and lack obvious internal layering. Mud mounds 1 and 2 occur in the McConnell thrust sheet about 2 km southeast of the southern margin of the Miette reef complex and were initiated in the upper part of the Arcs Member (Figs. 6, 7 and 8). Mud mounds 1 and 2 occur on the same clinoform and the lateral distance between these two mounds is about 100 m (Fig. 7). Another three (mud mounds 3, 4, and 5) occur in the Miette thrust sheet (Fig. 2) with mound 3 about 2.5 km southeast and mounds 4 and 5 about 5 km further basinward of the Miette reef margin. They occur at about the same stratigraphic level in the upper part of the Arcs (Figs. 6 and 9), except mound 5 was initiated close to the top of the Arcs Member (Fig. 9). Another small mound (about 5 m thick) occurs in the McConnell thrust sheet about 1 km northwest of mud mound 1 at a lower stratigraphic level. The mounds reported by Hedinger and Workum (1989) at the head of Whitehorse Creek south of mound 5 occur at a slightly higher stratigraphic level in the lower to middle Ronde Member.

2.2. Sizes and configuration

The size, shape, growth stages and interfingering relationships of the five mud mounds studied are summarized in Table 1. Mud mound 2 is the largest reaching a thickness of about 36.5 m. Mud mound 3 is the smallest being only 17 m thick. Variations in morphology of the mounds are unrelated to the size of the mounds. Most mounds (2, 3, 4, and 5) have a simple domal or conical shape (Figs. 8 and 9). However, mound 1 (Fig. 8) has an irregular morphology which suggests at least three successive growth stages. Stage 1 is tabular and the upper part of this stage retreats and interfingers with slope strata of the Arcs Member. The third stage of the mud mound 1 is tabular and progradational and interfingers southeastward with and extends over the basal Ronde Member, differing from the tabular shape of the middle growth stage (Figs. 6, 7 and 8).

Mud mounds 1, 2 and 4 have both abrupt (smooth) and interfingering (irregular) margins and mounds 3 and 5 have only abrupt margins. Mud mounds that have abrupt steep margins suggest that the growth rates of the mound were faster than the rates of basin sedimentation and that the mounds were being actively lithified as they formed. Interfingering margins predominate on the northwest (or upslope reefward) and lower parts of mud mounds 1 and 2 margins, suggesting that carbonate sediment derived from the Arcs Member platform was deposited at rates similar to the growth rates of the mound. The abrupt margins of most mud mounds dip steeper than 45° (see Figs. 6, 7, 8 and 9), whereas the interfingering portions generally dip less than 10°.

The basinward flank of the last stage of mud mound 1 extends a short distance over silty dolostones of the basal Ronde Member (Figs 6, 8). No obvious interfingering of these two units was observed suggesting that the third growth stage of mud mound 1 was deposited after the lower part of the basal Ronde Member. The upper part of mud mound 3 is overlain by siltstones and silty dolostones of the basal Ronde (Figs. 6 and 9). However the basal Ronde Member only onlaps or flanks a portion of mounds 1, 2, 4 and 5 depending on the stratigraphic level at which they were initiated and the height to which they grew.

2.3. Substrate and basal part of mud mounds

Mud mounds are situated on dolostones (presumably grainstones to wackestones) 1 to 2 meters thick containing more than 50% slope derived dark gray, carbonate mud clasts (Fig. 13A) or nodules characteristic of the Mount Hawk basin strata (Fig. 13B). These clasts were derived from lithified carbonate muds and appear to represent partially early cemented packstones and grainstones (Hopkins, 1972) that were transported down low sloping clinoforms. A 10 cm brachiopod-rich bed (Fig. 13C) in dark grey Mount Hawk interbedded shales and argillaceous limestones overlies the dolostone bed beneath mud mound 4.

The bases of the mounds consist of fossil-rich facies, such as sponge-bearing wackestones, packstones, and laminar stromatoporoid boundstones. These relationships suggest that the fossil-rich facies and associated dolostones may have formed higher areas suitable for the growth of organisms on which the mounds were established. Colonies of the branching coral *Thamnopora* developed in the basal part of mud mound 5 (Figs. 13D and 13E). Brachiopods and solitary rugose corals are also present in this basal bed. The 50 cm thick *Thamnopora* bed may have provided an environment suitable for growth of organisms, such as sponges, because corals and stromatoporoids are sometimes encrusted or overlain by sponges (see Biota section 2.5). No thickness variations or potential topographic highs were observed.

2.4. Lithofacies

The mounds consist mainly of lime mud and wackestones with variable amounts of skeletal fragments and pellets. Lime mudstones, wackestones and packstones are present in most mounds. The rocks are uniformly light gray to gray. Variable amounts of skeletal fragments and whole fossils occur in the lime mud. The mounds are massive, lack laminae or layering, and lack a well defined vertical zonation.

The overall amounts of identifiable skeletal fragments are highly variable and difficult to estimate in the mud mounds. Lime mudstones contain few skeletal fragments. Packstones contain high amounts of fine to very coarse grained skeletal fragments.

Lime mudstones are rare, medium gray in color, are poor in skeletal fragments and pellets and lack sedimentary structures (Fig. 16). They occur mainly in the lower parts of the mounds. Few cavities occur in the mudstones compared to the wackestones.

Wackestones are light gray to medium gray in color and contain variable fossil fragments and cavities. Wackestones are the most abundant lithofacies of the mounds (Figs. 16 and 17). Packstones are rare and occur mainly in the upper part of mud mounds 1, 2 and 3 (Figs. 17G and 17H). They are generally medium gray in color and contain scattered (floating) fine to very coarse grained skeletal fragments. Calcareous green algae (Figs. 22 and 23) and sponge spicules are major skeletal fragments. Blue-green algae (Fig. 24) such as *Girvanella* and *Sphaerocodium* predominate in the peloidal packstones. In addition there are varying amounts of foraminifers, echinoderms, gastropods, brachiopods, ostracods and trilobites (Fig. 25).

2.5. Biota

The most common skeletal components are calcareous green algae and sponges (Figs. 14 and 15). Calcareous green algae tend to predominate in the upper part of the mounds while sponge remains predominate in the lower part, as observed in mud mound 1 (Figs. 14 and 29) and in mud mounds 2 and 4 (Figs. 29 and 30). Reef building laminar stromatoporoids are common in the basal part of mud mound 1. Other organisms only occur in minor amounts except for ostracods and brachiopods (Figs. 14 and 15). Figures 29 and 30 schematically illustrate the distribution of the dominant skeletal components in each of the five mounds (see Figs. 8 and 9 for sample locations). The significance of these fossils in terms of types and distribution is discussed in Chapter 3.

Calcareous green algae

Calcareous green alga (Chlorophyta) is one of the largest and most important phyla of algae and includes a wide range of morphologies. These algae inhabit mainly terrestrial and freshwater environments (Fig. 22). Marine forms make up less than 15 percent of the total modern flora (Wray, 1977).

Calcareous green algae belong to three groups: Codiaceae, Dasycladaceae and Charophyceae. The first two are families that inhabit exclusively marine environments; the charophytes are nonmarine and have been variously considered to be either a separate division (phylum), or a different rank within the Chlorophyta (Wray, 1977). Marine green algae are primarily macroscopic plants with well defined cell walls. Portions of the thallus are impregnated or coated with calcium carbonate in some members of the Codiaceae which include the recent genus *Halimeda* and in all the Dasycladaceae.

Identifiable calcareous green algae observed in the Miette mud mounds are dasycladaceans, except for the Codiaceae *Bevocastria* (Fig. 23A) found in mud mound 1. A sketch of a living dasycladacean alga and an example of a dasycladacean limestone are shown in Fig. 22A. Skeletal remains of dasycladacean green algae are relatively abundant in all five mud mounds (Figs. 14 and 15). Calcareous green algae predominate in the upper parts of the mounds (Figs. 29 and 30). *Issinella* (Figs. 22B and 23B to E) is the most common genus of dasycladacean green algae in all five mounds. *Kamaena* (Figs. 23E and 23F), *Labyrinthoconus* (Fig. 23G) and *Evlania?* (Fig. 23H) are present locally.

Calcareous blue-green algae

Calcareous blue-green algae (Cyanophyta) are characterized by simple filaments and coccoid forms, generally of microscopic size in contrast to the variety of complex morphologies in calcareous green algae. Although both nonskeletal and skeletal blue-green algae are active in the deposition of carbonate sediments, nonskeletal species have been more important geologically because of their role in the formation of stromatolites and other algal-laminated sediments (Wray, 1977).

Sphaerocodium (Fig. 24) is the most common genus of Cyanophyta in the Miette mud mounds especially in mud mounds 3 and 5 (Fig. 15). *Girvanella* was not found in mound 4 and is rare in mounds 1, 2, 3 and 5. No extensive blue-green algal laminations were observed in outcrop and in hand specimens in the Miette mud mounds except one sample from mud mound 3 (Fig. 24H).

Sphaerocodium consists of branched, tubular filaments of microcrystalline calcite which develop encrusting forms. The transverse cross section of filaments is elliptical and is up to 70 μm in width. Two species, *S. munthei* (Figs. 16A and 24C) and *S. gotlandicum* (Figs. 24A and 24B), have been identified. *S.munthei* is smaller than *S. gotlandicum* (filaments of *S. munthei* are at most 20 µm in cross section). These algae consist of layers of filaments that encrust skeletal fossils (Figs. 16A, 24C, 24D, 24F and 24G).

Girvanella is characterized by tubular filaments of uniform diameter, composed of relatively thick, calcareous walls (Wray, 1977). *Girvanella* (Figs. 17D, 17G and 24E) was not observed in mud mound 4 and is rare in all of the mounds (Figs. 14 and 15). The external diameter of filaments of specimens is 20 µm maximum, similar to diameters of 10-30 µm noted by Wray (1977).

In the Miette mud mounds, only one renalcid specimen *Shuguria* (Fig. 23H) was found near the base of mud mound 3 (sample 48), although renalcids (*Izhella*, *Renalcis*) are widely distributed in the Upper Devonian carbonate mud bioherms of the Ancient Wall reef complex (Mountjoy and Jull, 1978; Mountjoy and Riding, 1981). These genera differ only in overall growth form which varies from simple colonies made up of a few chambers to complex aggregates with many chambers.

Sponges

The identification of sponges in thin sections and hand specimens is based on their microstructure. Sponge spicules in all five mud mounds tend to occur in lime mud-rich wackestone to fossil-rich packstone facies in the lower parts of these mounds (Figs. 29 and 30). Sponge spicules were observed in most samples in mud mounds 3, 4 and 5 (Figs. 29 and 30). The amounts of spicules present appear to gradual decrease up section in mud mounds 1 and 2. Sponge spicules are rare adjacent to interfingering basin siliciclastic sediment (about 5 m above the base of mound 1, samples 27 and 249, Table

2). Siliceous sponge spicules are the most abundant skeletal fragments in the wackestones.

Spicules exhibit a variety of shapes and most spicules are molds of megascleres. Irregular pores or spongiostroma are filled with blocky calcite and presumably represent calcification of some part of the original sponge (Fig. 18 shows for comparison the irregular shapes and sizes of various pores in modern sponges). Spicules are predominantly the fusiform type but complex forms such as triaxon (3 axes), tetraxon (4 axes) and triaxons (triaxon with 6 rays) are also present (Fig. 19). They vary in size and are up to 3 mm long. It is rarely possible to identify a sponge genus, family, or order from isolated spicules (Laubenfels, 1955). These megascleres are often found in sufficient abundance to appear to have formed a network for in-situ sponges (Figs. 20 and 21). In many cases, however, spicules are separated and were derived from a sponge framework when the sponge died resulting in spicules falling to the base of a cavity with long axes being oriented parallel to the bedding. Most spicules were dissolved and the molds or modified molds later filled with calcite spar.

Sponges consist of a network which is a combination of organic fibers and spicules. In living sponges the ectodermal cells (outer layers of the sponge network) are identifiable (Fig. 18). However, it is difficult to observe these outer layers in fossils. The organic fibers are a type of collagen. This jelly-like layer has numerous pore canals including choanocyte chambers, incurrent pores and voids for amoeboid cells as well as an osculum (Fig. 18). The sectional view of *Spongionella pulchella* (a recent Demosponge) shows a large number of small, irregular-shaped pores (Fig. 18C). Sponge spicules (megascleres and microscleres) are secreted by a single cell, or a group of cells, in the intermediate jelly-like layer. Most of such spicules are formed of metastable hydrous silica (Stearn and Carroll, 1989). The simplest spicules are needlelike oxeas (Fig. 19) and lie unconnected to one another in the soft tissue, and fall apart on the death of the sponge. More complex spicules have several radiating shafts or axes (Fig. 19). Complex spicules may interlock with adjacent ones to produce a framework.

Thus, in situ sponge body fossils appear to be a combination of small pore-rich organic fibers, and scattered spicules or a spicular framework, which can be recognized by interlocked spicules (Figs. 20 and 31). However recognition of what was originally sponge tissue and spicular framework is not always easy because of decay of the organic matter and dissolution and poor preservation of the siliceous skeletons and spicules (Brachert, 1991). Many examples of sponge microstructure have been published (e.g. Laubenfels, 1955; Fig.47. Majewske, 1974; pl.98, 99, 101, 102. Vos *et al.*, 1991; pl.3, 9. Brachert, 1991; Fig. 3). An interlocking framework of sponge spicules with numerous small irregular pores are illustrated in the photomicrograph of a fossil sponge (Fig. 20B). In the interior of fossil sponges numerous small irregular pores are filled with calcite cement (Figs. 20 and 31). These pores represent canals responsible for the aquiferous system that allows sponges to filter the water surrounding them for their life support (Fig. 18C).

Other Biota

Variable amounts of calcispheres, bispheres, foraminifers, stromatoporoids, corals, bryozoans, brachiopods, gastropods, trilobites, ostracods, crinoids and echinoids occur in minor amounts in the mud mounds (not in order of abundance). Calcispheres (distinguished from bispheres (up to

1mm) by smaller diameters and a dense and thicker wall) occur only in 3 samples from the lower and middle parts of mud mound 1.

Bispheres (Fig. 25A) have been classified as either foraminifers or algae (Toomey *et al.*, 1970; Mamet and Plafker, 1982). Bispheres occur in minor amounts in all the mud mounds except mud mound 4.

Foraminifers have been observed in all five mud mounds and commonly occur in packstones (up to 5% of all skeletal components in a sample). They tend to predominate in the upper part of the mounds (Fig. 14). All of them are plurilocular foraminifers including several chambered, uniserial foraminifers *Paratikhinella* (Fig. 17G), *Eonodosaria* (Fig. 23G), *Eogeinitzina* (Fig. 25C), and a planispiral test of *Nanicella* (Fig. 17H).

Stromatoporoids occur in all mounds except mud mound 5. Encrusting laminar stromatoporoids are present in the lower part of mud mound 1 (Figs. 32A, 32C, 33 and 34). *Amphipora* (Fig. 25E) and tabular *Stictostroma maclareni* (Fig. 32B) are also present. Transported fragments of coral such as colonial rugose *Pachyphyllum* (Fig. 25F) are locally present. Only one fragment of bryozoa was observed in mud mound 5 (Fig. 25G). The tabulate coral *Thamnopora* occurs in all five mounds and is the most common genus of cnidaria observed in the Miette mounds (Figs. 13D, 13E, 16C, 27A, 24D and 31C). However some corals could have encrusted parts of the mounds as took place in the Ancient Wall mounds (Mountjoy and Jull, 1978).

Brachiopods, ostracods and echinoderms occur in all mounds. Brachiopod spines often occur broken or badly bored by endolithic sponges (Fig. 35). Gastropods and trilobites occur in all mounds except mud mound 4. A pygidium of *Scutellum flabelliferum* occurs in mound 2 (Fig. 25H).

2.6. Cavities

The area occupied by cavities was estimated visually from hand specimens (Tables 2 to 6). The approximate area occupied by cavities is up to 40% in the lower part of mound 1 and is about 5% on average.

A wide variety of cavities occur in the Miette mud mounds and are classified as shelter, irregular, stromatactoidal and stromatactis (Fig. 26). The most common (about 80% of all cavities) are irregular cavities and stromatactoidal cavities, both have highly variable morphologies. The smooth bottom distinguishes stromatactoidal and stromatactis cavities from irregular cavities. Thus stromatactoidal and stromatactis cavities may be strictly a function of whether or not geopetal sediment is present in the cavities. Also it is difficult to distinguish geopetal mud from lime mud matrix. Both types of cavities have irregular upper surfaces. Sponge (endoliths) borings occur on brachiopod spines or other skeletal components (Fig. 35).

Most cavities contain geopetal sediments along their bases overlain by marine fibrous calcite cements. A few still have some open pore spaces, but nearly all are completely filled with calcite and/or dolomite cement.

Shelter cavities

Most shelter cavities are < 1 cm across. Shelter cavities occur beneath laminar and/or dendroid stromatoporoids (Figs. 32 and 33), or brachiopod shells (Fig. 16H). A few elliptical cavities (less than 1 cm) are also present. Some occur beneath laminar stromatoporoids (genus indeterminable) and approach 0.5 meters in length (Figs. 32A and 33). Shelter cavities beneath stromatoporoids occur in the basal part of mud mound 1 and their arrangement and distribution are illustrated in Figures 33 and 34. These sheet-like shelter cavities have thicknesses of about five to ten millimeters beneath laminar stromatoporoids (Fig. 33, arrows, 1 - 2 mm in thickness). Some branching or tabular stromatoporoids such as *Stictostroma maclareni* form shelter voids which are usually floored by lime mud (Figs. 32B and 32D). Shelter cavities which formed under brachiopod and ostracod shells are also common (Fig. 16H). Pellets or skeletal components have not been observed in the geopetal sediments. Shelter cavities are filled with fibrous calcite cement (in part radiaxial) followed by coarse blocky calcite (0.2 - 2 mm).

Irregular cavities and stromatactoidal cavities

Irregular and stromatactoidal cement-filled cavities (up to 10 cm across, Fig. 26) mainly occur in the lime mudstone and wackestone facies (Figs. 27 and 28) throughout the five mud mounds (approximately 5% on average but up to 40%) and are rare in the packstones. These cavities are characteristic of the mounds and are associated with sponge spicules (Figs. 27A and 27B) and inferred sponges (see Biota section 2.5.).

Irregular and stromatactoidal cavities are up to 10 cm wide and thick (Figs. 27 and 28). Some irregular and stromatactoidal cavities appear to be similar in shape to soft bodied organisms and are inferred to be of organic origin (Fig. 36, see section 3.4.). Stromatactoidal cavities have a relatively smooth bottom surface while irregular cavities have irregular bottom surfaces (Fig. 26). These cavities are filled with both fibrous and blocky calcite spar, but fibrous calcite cement predominates. Minor dolomite occasionally replaces limestone or occurs as cement in cavities in the basal part or the margins of some mounds (Fig. 16G). Some cavities contain small (a few millimeters to a centimeter) open pores in their centers. They are most abundant in the lower part of mud mound 1.

Stromatactis cavities

Typical stromatactis cavities occur in minor amounts in the Miette mud mounds (less than 1% of all cavities). They are spar bodies floored with internal geopetal sediments (Fig. 26), similar to those of the classic Devonian Belgium mud mounds, with flat to undulose, smooth lower surfaces, and digitate upper surfaces Tsien (1985a) described stromatactis as a mass of fibrous calcite enclosed by irregular micrite masses whose morphology is characterized by a smooth, although often undulose or stepped lower surface; and by irregular, embayed and digitated flanks along the upper surface. However a number of authors described stromatactoidal cavities as stromatactis (e.g. Pratt, 1995; Figs. 25 and 27. Stenzel and James, 1995; Figs. 4 and 9). Recently Bourque and Boulvain (1993, p. 608) redefined stromatactis as "a spar network whose elements have flat to undulose smooth lower surfaces and digitate upper surfaces, made up principally of isopachous crusts of centripetal cement and embedded in finely crystalline limestone".

Only a few possible stromatactis cavities were observed near the top of mound 5 (Figs. 28D and 28E) and in the basal part of mound 2. They are partly filled with geopetal sediments and overlain by fibrous calcite.

2.7 Vertical zonation

Common features of biogenic mounds are their well defined vertical zonation which is energy dependent. The zones change with increasing agitation from 1) a mud mound stage, through 2) skeletal mound stage, 3) skeletal mound to reef stage, to 4) a sand shoal if the mound crest reaches rough water (James and Bourque, 1992). These mounds are inferred to have formed below the base of large metazoan growth near the base of the photic zone.

The Miette mounds lack a well defined vertical zonation and thus differ from many biogenic mounds. Such a lack of a vertical depth zonation could, however, result if the mounds kept pace with a slow sea level rise. Sea level changes for the Miette mounds can be deduced from the Arcs carbonate clinoforms adjacent to the mounds and on which the mounds were initiated (Fig. 37). Each carbonate clinoform represents a time of low siliciclastic input and deposition, interpreted to occur during a sea level rise and stillstand. These clinoforms prograded basinward over siliciclastics of the previous lowstand and possibly late highstand. With a slight lowering of sea level siliciclastic sediments would again reach this area and fill in part of the slope and basin adjacent to the Arcs carbonate sand bank. However, according to the model of James and Bourque (1992) mounds formed during late high stand systems tract should show a complete depth-zoned vertical sequence. The Miette mud mounds formed during 3 to 6 clinoforms (Fig. 37) and thus developed during several sea level paracycles. Thus the Miette mounds lack a vertical zonation, not because of the lack of sea level changes, but because they formed in shallow water and could keep pace with any sea level change. Also they were able to develop sufficient topographic relief that they were not affected very much by siliciclastic sedimentation.

2.8 Summary

Mounds are approximately 17 to 36 m high and 32 to 81 m wide and columnar to domal in shape. The lower part of the mounds consists of sponge-rich wackestones and packstones, and locally laminar stromatoporoid boundstones. Calcareous green algae predominate in the upper parts of the mounds.

Abrupt mound margins indicate that the mounds grew upwards more rapidly than the accumulation of the adjacent basin siliciclastic and carbonate clinoforming slope sediments. Vertical constrictions and shape changes suggest that the mounds developed in two or more distinct stages that tracked sea level rises. The sediments in much of the laterally equivalent Arcs Member bank above the Miette reef complex proper were deposited in very shallow water (< 1 to 2 m). This together with the geometry of the clinoforms suggests that the water depth of mound initiation was about the thickness of the mounds, or 20 to 30 m. The Miette mounds lack a well defined vertical depth zonation because they formed in shallow water and could keep pace with any sea level change.

A variety of cavities are present and are filled with geopetal sediments, isopachous fibrous and blocky calcite cements. The most common cavity types, irregular and irregular stromatactoidal cavities, might be of organic origin, and possibly resulted from the decay of sponges.

Figure 13. Mount Hawk argillaceous carbonates directly beneath mud mounds and *Thamnopora* in the basal part of mud mound 5.

A. Dolostone a few meters thick containing slope derived carbonate mud clasts (arrows, some appear to be nodules) in strata underlying mud mound 5. These dark "clasts" were presumably derived from the adjacent carbonate slope to the northwest that formed a basin sloping surface or clinoform (see Fig. 4). Hammer 33 cm long. Top towards hammer head.

B. Representative hand specimen of dolostone with dark mud nodules (nd), from bed underlying mud mound 4. Coin 23 mm in diameter. Arrow indicates top.

C. Brachiopod mudstone facies overlying the dolostone, from just beneath mud mound 4. Coin 23 mm in diameter.

D. Colony of branching tabulate coral *Thamnopora* (top half of photograph) from basal part of mud mound 5 (small arrows indicate mud clasts). Hammer 33 cm long. Large arrow indicates top.

E. Close-up of D showing in-situ colony of *Thamnopora*, mud mound 5. Brachiopods (b) and solitary (horn) rugose corals (r) are also present in this bed. Scale bar 5 cm.

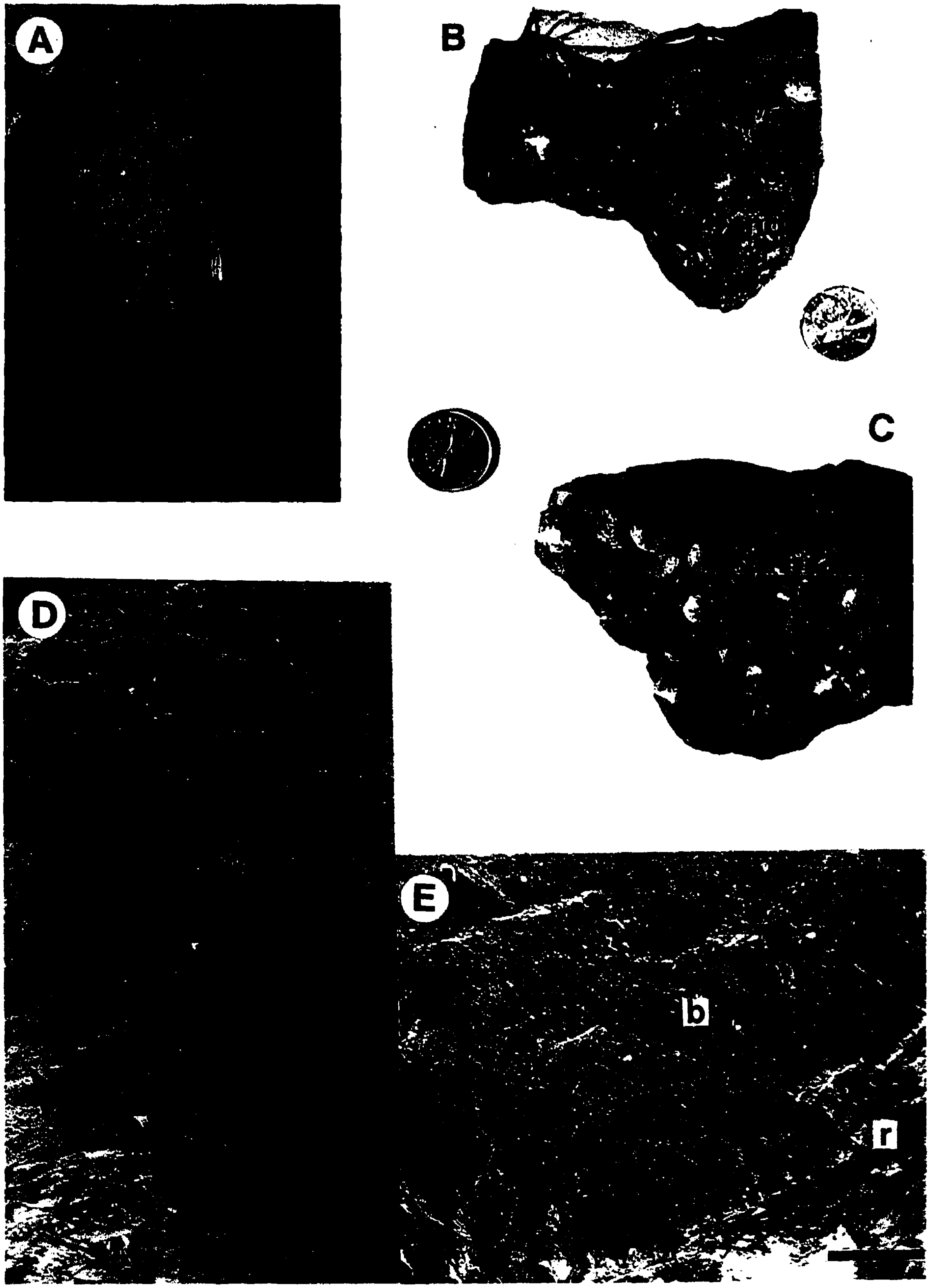
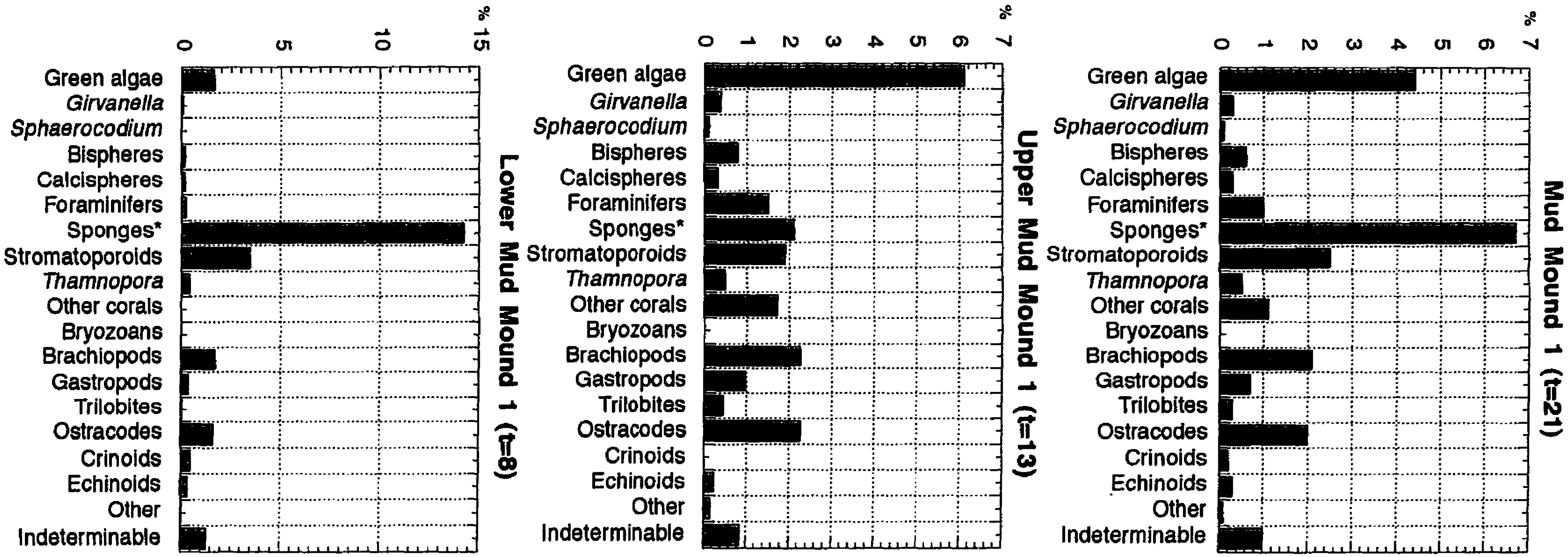

A
B
C
D
E
b
r

Figure 14. Occurrence of skeletal components in mud mound 1 (t = number of thin sections examined). The mound is divided into upper (second and third stages) and lower parts (first stage) about 5 m above the base at point of maximum siliciclastic interfingering (see Fig. 8). Sponges* include textures suggestive of sponges and molds of spicules (see text).


Lower Mud Mound 1 (t=8)
Upper Mud Mound 1 (t=13)
Mud Mound 1 (t=21)
%
Green algae
Girvanella
Sphaerocodium
Bispheres
Calcispheres
Foraminifers
Sponges*
Stromatoporoids
Thamnopora
Other corals
Bryozoans
Brachiopods
Gastropods
Trilobites
Ostracodes
Crinoids
Echinoids
Other
Indeterminable

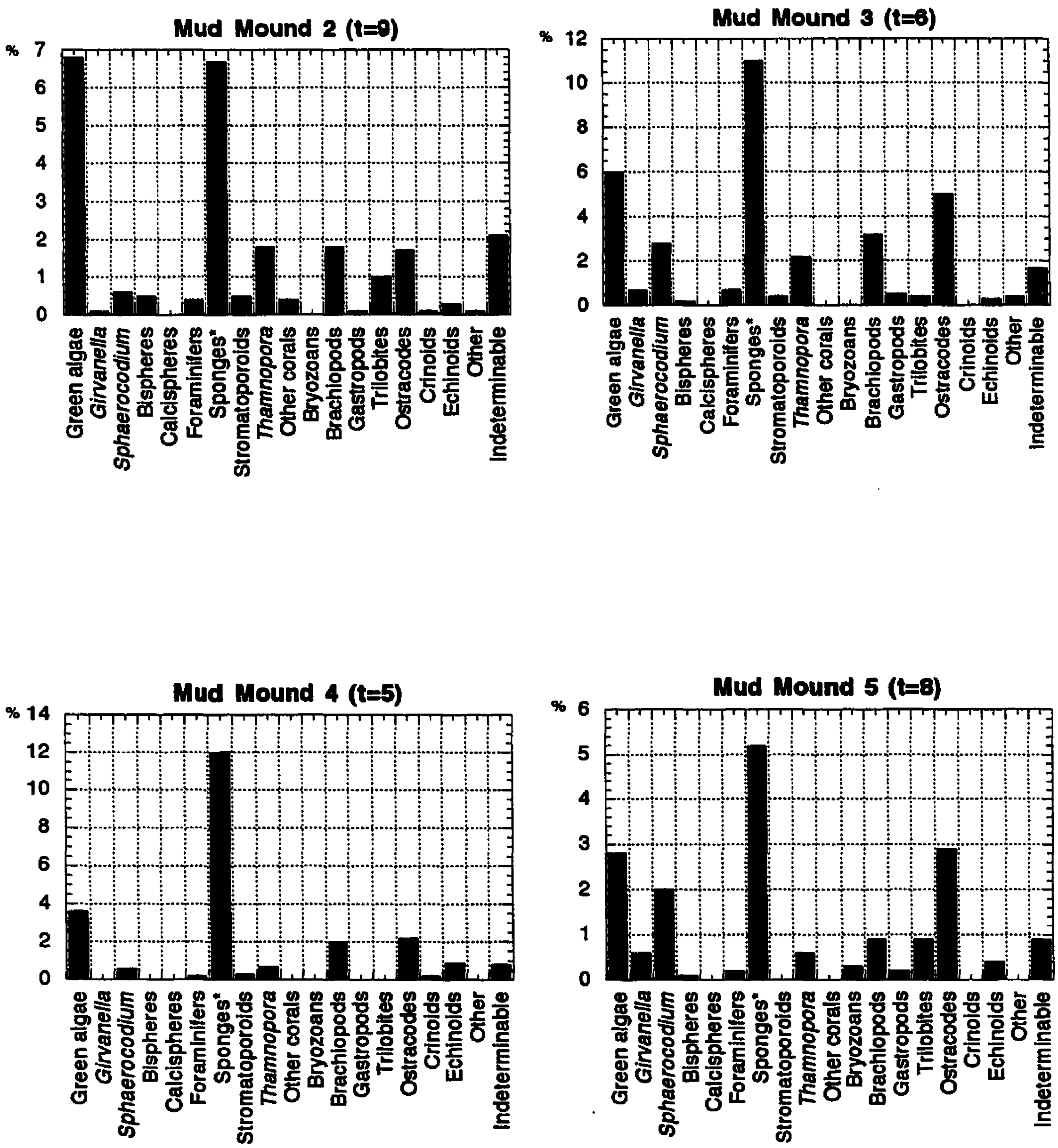


Figure 15. Occurrence of skeletal components in mud mounds 2 through 5 (t = number of thin sections examined). Sponges* include textures suggestive of sponges and molds of spicules (see text).

Figure 16. Photomicrographs showing skeletal elements in wackestones and lime mudstones.

A. Sponge spicule-rich facies. Spicules are mostly monaxon (fusiform) type but triaxon or tetraxons are also present at upper left. Blue-green algae *Sphaerocodium munthei* (s) grew around unknown skeletal element. Bored fragment of *Thamnopora* (t). Sample 28, middle part of mud mound 1. Top uncertain.

B. Spongioform texture and sponge spicules oriented horizontally in lime mud between calcite filled cavities. Sample 240, mud mound 2. Top uncertain.

C. Spicule-rich lime mud facies with a fragment of *Thamnopora* (arrow) and irregular cavities (left). Sample 240, mud mound 2. Top uncertain.

D. Skeletal fragments including calcareous green algae and trilobite spine (arrow). Sample 206, mud mound 1. Top of photo is depositional top.

E. Spicule-rich lime mud facies. Spheres are transverse section of spicules. Sample 32, mud mound 1. Top of photo is depositional top.

F. Wackestone facies showing fossil fragments. (m) is lamellar wall structure of a mollusk. (tr) is trilobite. Sample 252, mud mound 1. Top uncertain.

G. Partly dolomitized (upper left) wackestone facies with sponge spicules and calcareous green algae (arrows). Sample 25, mud mound 1. Top uncertain.

H. Brachiopod with geopetal. Top of photo is depositional top.

Scale bars 0.5 mm.

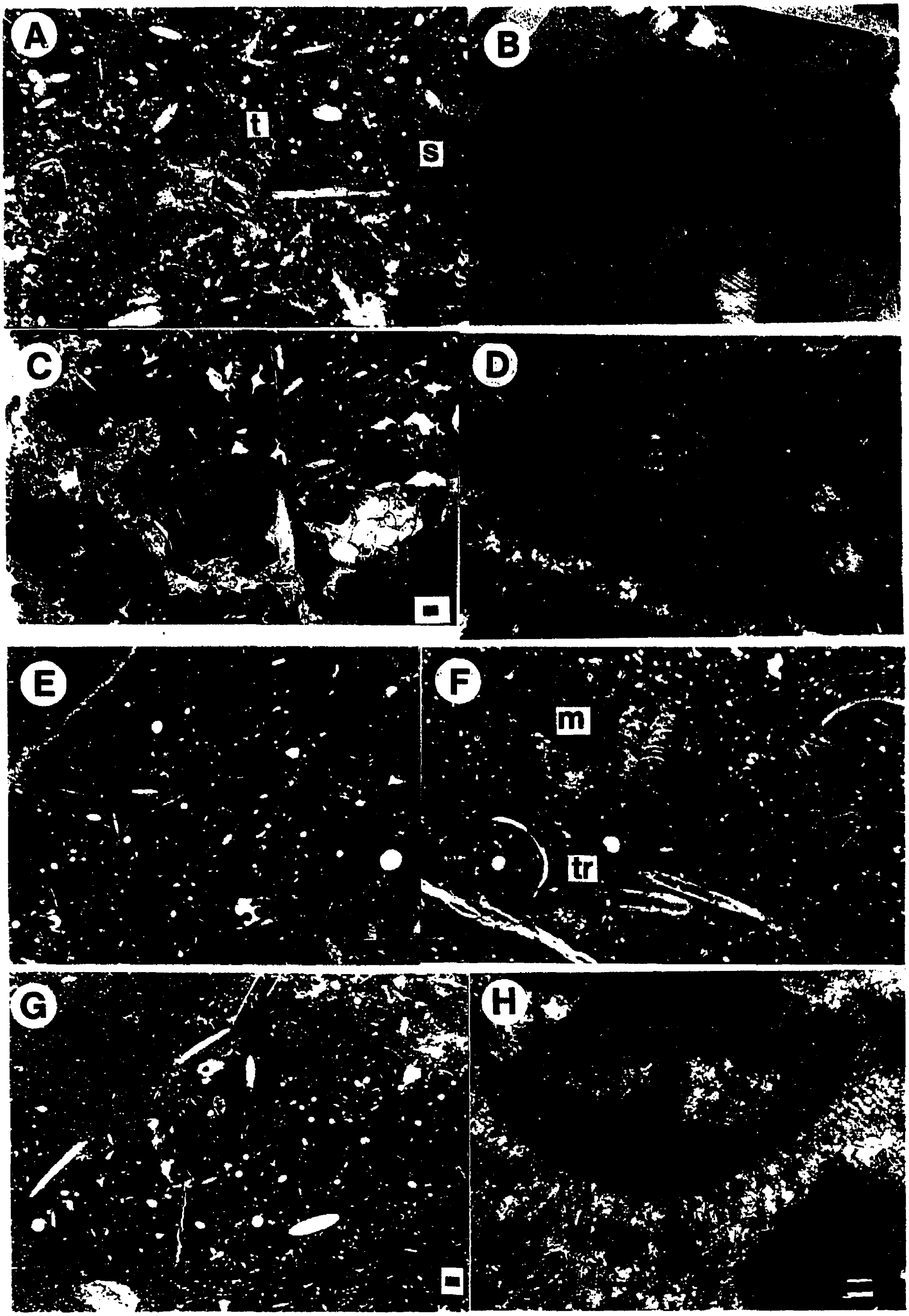

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Figure 17. Photomicrographs showing wackestone and packstone facies.

A. Spicule-algal wackestone facies showing monaxon spicules and calcified thallus of green algae (arrows). Sample 17, mud mound 3. Top uncertain.

B. Stromatoporoid fragments and ostracode valves with geopetal sediment (arrow). Sample 72, mud mound 2. Top of photo is depositional top.

C. Representative wackestone facies with abundant fragments of calcareous green algae (upper, the elliptical shaped fossils show transverse sections of thallus), foraminifers and gastropod (g). (o) is ostracode with geopetal sediment. Top of photo is depositional top.

D. Blue-green algae *Girvanella* (gr) and *Sphaerocodium gotlandicum* (arrows). Top uncertain.

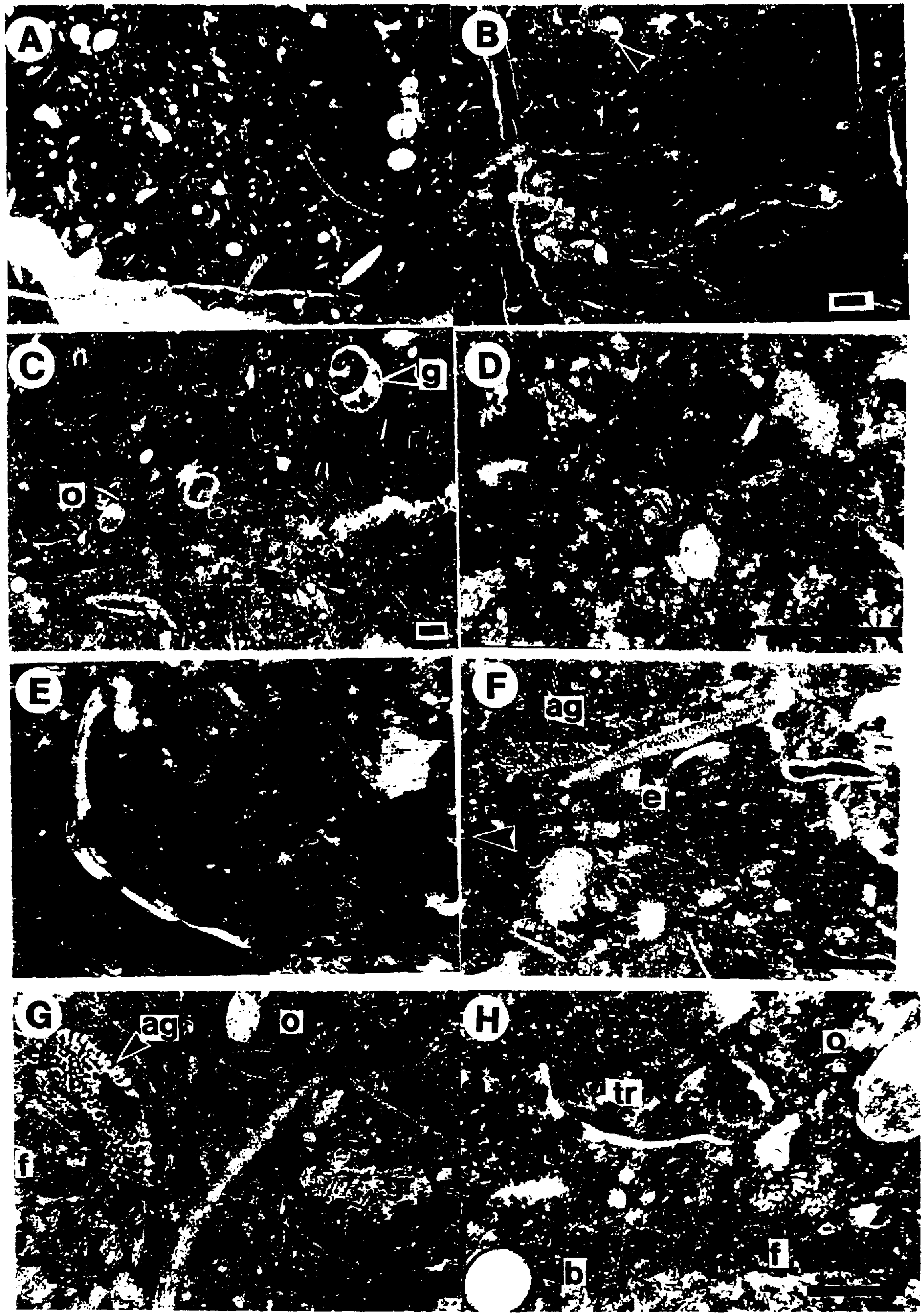
E. Cephalon of trilobite (left) and microbial filaments, probably *Sphaerocodium* (small arrows). Top to left.

F. Fossiliferous wackestone with calcareous green alga *Labyrinthoconus* (ag) and echinoid spine (e). Large arrow indicates top.

G. Packstone with skeletal components of calcareous green alga (ag), ostracode (o), foraminifer *Paratikhinella* (f) and tubular filaments of *Girvanella* (gr). Top of photo is depositional top.

H. Fossiliferous wackestone-packstone with a trilobite fragment (tr), geopetal sediment in ostracode (o), plurilocular foraminifer *Nanicella* (f) and bisphere (b). Top of photo is depositional top.

Photomicrographs C through H are from sample 30, mud mound 1. Scale bars 0.5 mm.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e
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ag
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H
o
tr
b
f

Figure 18. Sponge anatomy

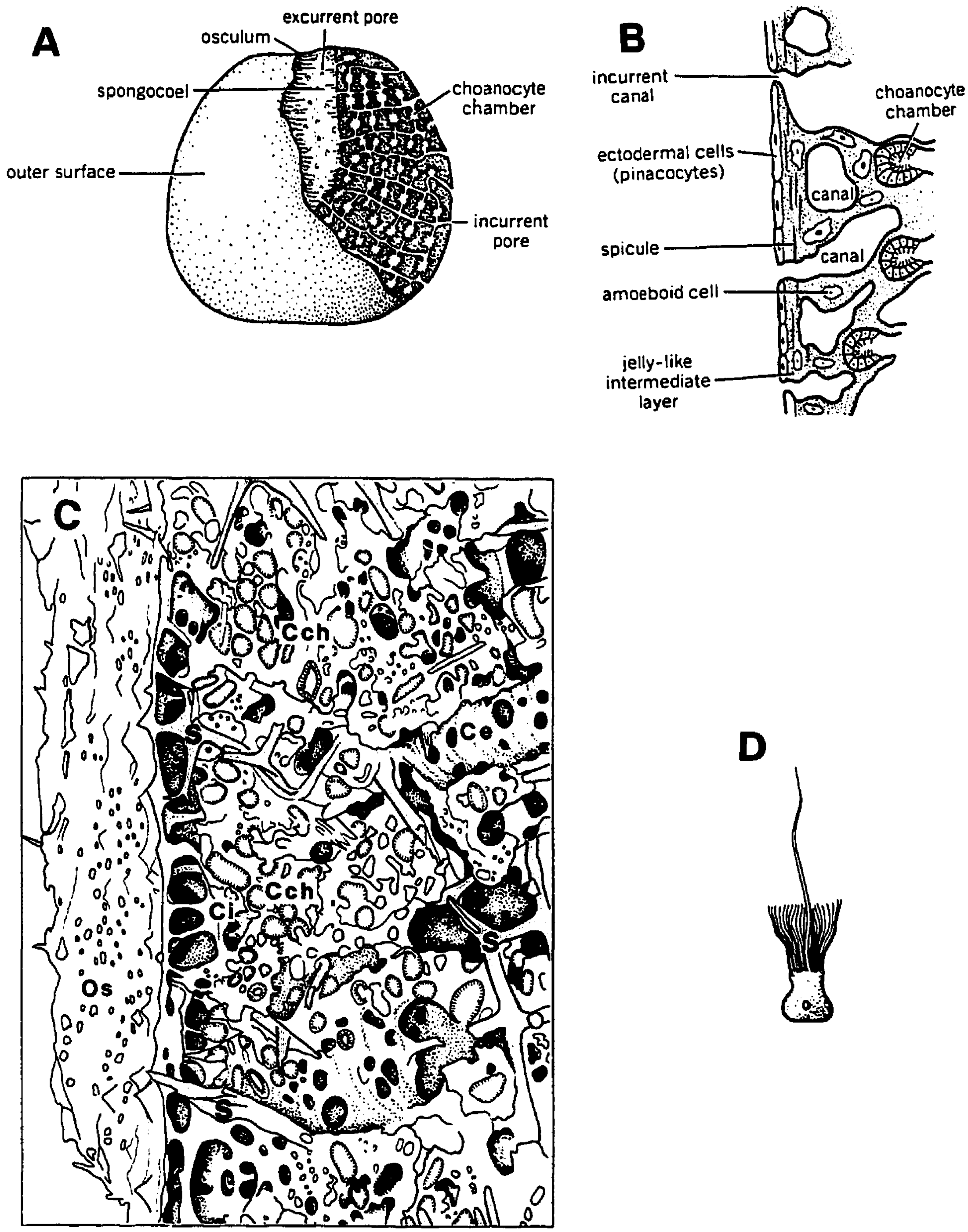
A. Small typical rhagon type (vase-shaped) demosponge cut away to show the canal systems and choanocyte chambers. These are much enlarged for clarity.

B. Diagrammatic cross section of the outer surface showing the cell layers and canals. The cells are a few micrometers across.

C. The aquiferous system that allows sponges to filter the water surrounding them is responsible for their life support. This cross section view of modern sponge *Spongionella pulchella* shows a large quantity of small open pores (Os) on the surface of the sponge. These ostia (Os) are the points of entry for water. The water then passes into the aquiferous subpinacodermal cavities, where it is conducted by a network of inhalant canals (Ci) to the spherical or tubular choanocytes chambers (Cch). These chambers are lined with choanocytes, cells that are characteristic of sponges (Fig. 18B). The water enters the choanocyte chambers through incurrent pores, and it exits through a single orifice called the osculum (Fig. 18A). A network of confluent exhalant canals (Ce) leads to the osculum, a rather large opening through which the filtered water is expelled to the exterior. The entire structure is supported by a skeleton formed by a network of spicules (S).

D. An isolated choanocyte showing its flagellum (a whiplike extension) and collar of fine cilia.

(A, B and D are from Stearn and Carroll, 1989. C is from Vos *et al.*, 1991.)


A
excurrent pore
osculum
spongocoel
choanocyte chamber
outer surface
incurrent pore
B
incurrent canal
choanocyte chamber
ectodermal cells (pinacocytes)
canal
spicule
canal
amoeboid cell
jelly-like intermediate layer
C
Cch
S
Ce
Cch
Ci
S
Os
S
D

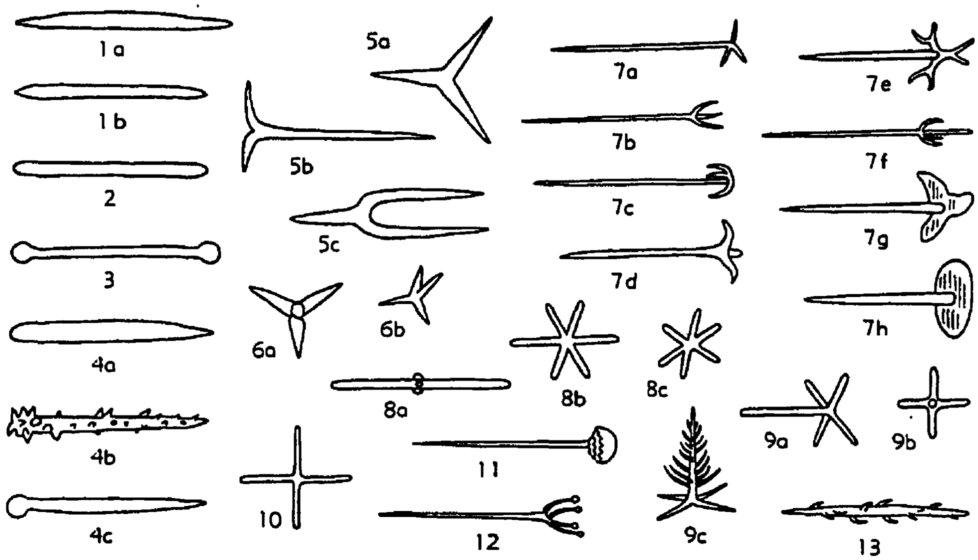


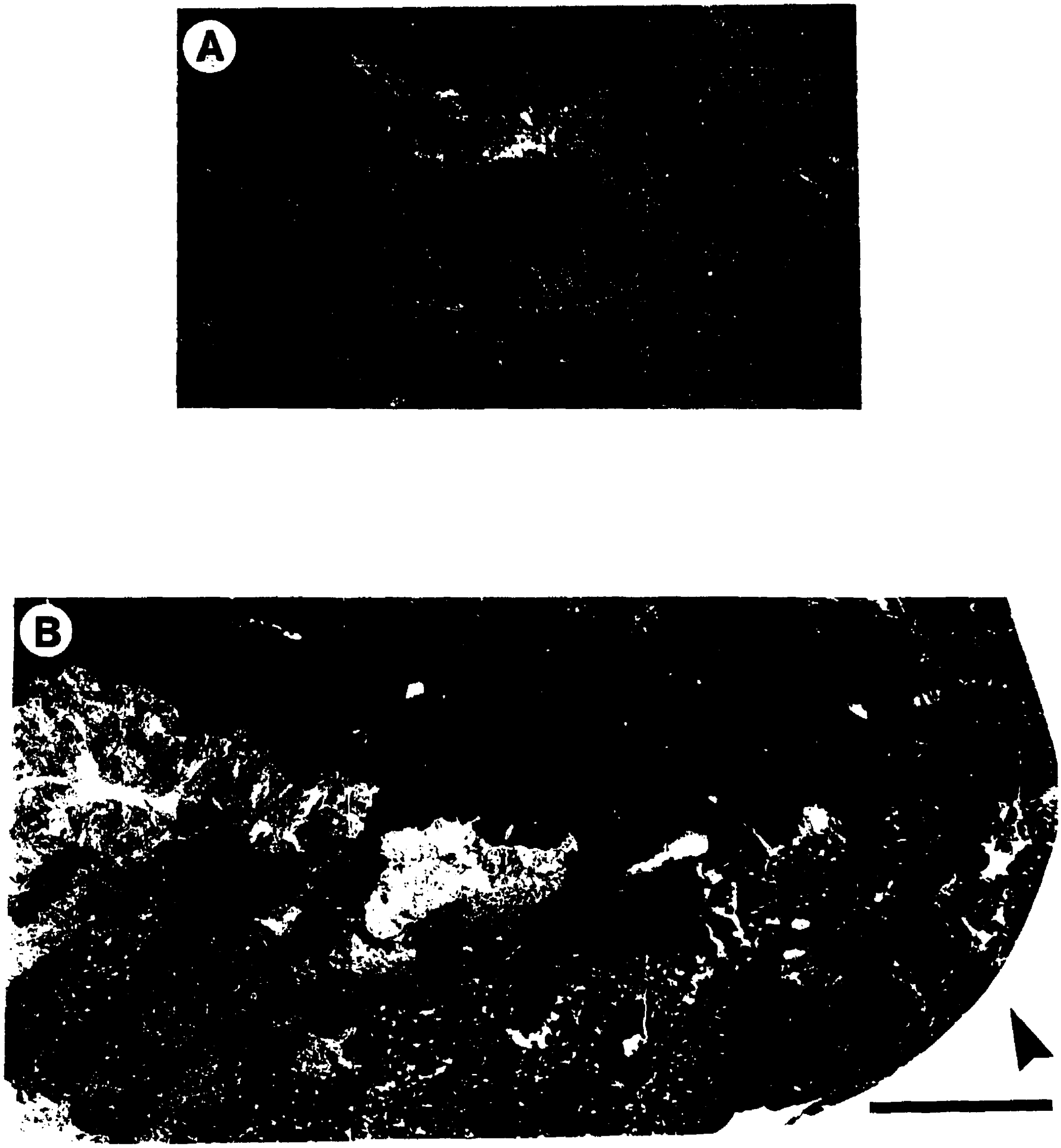
Figure 19. Different types of megasclere siliceous sponge spicules (approximately x100). From Laubenfels (1955).

1. Oxeas; 1a, fusiform; 1b, hastate.
2. Strongyle.
3. Tylote.
4. Style; 4a, smooth; 4b, spiny (acanthose); 4c, tylostyle.
5. Triacts; 5a, regular (triaxon); 5b, sagittal; 5c, tuning-fork.
6. Calthrops (tetraxon); 6a,b, from different viewpoints.
7. Triaenes (tetraxons); 7a, orthotriaene; 7b, protriaene; 7c, anatriaene; 7d, plagiotriaene; 7e, dichotriaene; 7f, mesotriaene; 7g, phyllotriaene; 7h, discotriaene.
8. Hexacts (triaxons); 8a, modified from resembling strongyle; 8b, c, regular forms.
9. Pentacts (triaxons); 9a, oblique view; 9b, end view; 9c, pinule.
10. Stauract.
11. Clavule.
12. Scopule.
13. Uncinate.

Figure 20. An inferred sponge fossil.

A. Outcrop photo of oblique longitudinal cross section of rhagon (vase-shaped) structure (see Fig. 18A) of calcite spar filled cavity representing what was originally a siliceous sponge (see Fig. 21 concerning outline of sponge). Sample 203, mud mound 1. Scale bar 20 mm. Top of photo is depositional top.

B. Well preserved spongiostroma with a spicular network, sample 203 (Fig. 20A), mud mound 1 (see Fig. 21 concerning position thin sectioned). This example suggests that part of the sponge body now calcified appears to be a combination of pore-rich organic textures and rigid spicular framework recognized by interlocked spicules. The numerous small pores (spar filled voids) appear to represent canals (compared with Fig. 18, see text). Scale bar 5 mm. Arrow indicates top.


A
B

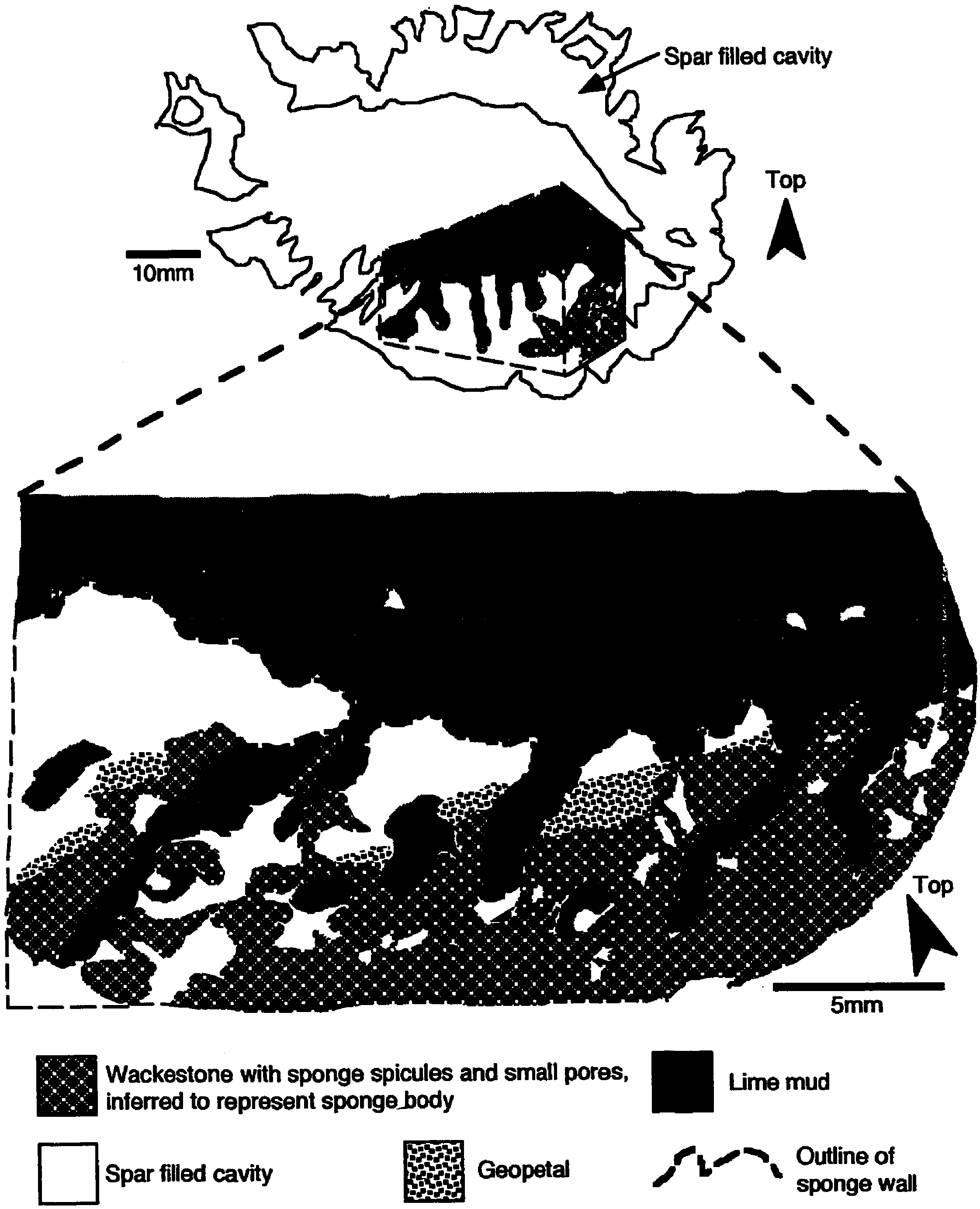


Figure 21. Tracing of Figure 20 showing the position of the thin section and inferred outline of sponge wall (Sample 203).

Calcite spar filling cavity (Fig. 20A) which once may have been occupied by sponge tissue. This cavity was probably produced as a result of partial decay of sponge tissue (see text).

Figure 22. Examples of calcareous green algae.

A. Thin section of Paleogene marine limestone from Guatemala composed of skeletal remains of calcareous green algae (Dasycladaceae) and sketch of analogous living sediment-producing plant (from Wray, 1977).

B. Reconstruction of the branching habit of *Issinella devonica* (from Mamet and Roux, 1981).

A

B

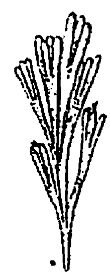


Figure 23. Calcareous green algae in wackestone facies of mud mounds.

A. Mold of *Bevocastria?* thallus (arrows) showing characteristic right angle branching. Sample 248, mud mound 1. Top of photo is depositional top.

B. A fragment of in-situ branching green algae *Issinella* (arrow). Sample 205, mud mound 1. Top of photo is depositional top.

C. Longitudinal section of *Issinella* (arrow) in spicule-rich wackestone, sample 17, mud mound 3. Top uncertain.

D. Calcite spar filled *Issinella* thallus (arrow). Sample 72, mud mound 2. Top uncertain.

E. Algal wackestone with *Issinella* (i) and *Kamaena* (k). Sample 72, mud mound 2. Top of photo is depositional top.

F. Algal wackestone with *Kamaena* (k), transverse sections of calcareous green algae (ag), ostracode valves (o), and bisphere (b). Sample 30, mud mound 1. Top of photo is depositional top.

G. *Labyrinthoconus* (l) and foraminifers (*Eonodosaria*) (f). Sample 30, mud mound 1. Top of photo is depositional top.

H. *Evlania?* (e), renalcid *Shuguria* (s) and transverse section of sponge spicule (sp) in wackestone. Sample 48, mud mound 3. Top uncertain.

Scale Bars 0.5 mm.

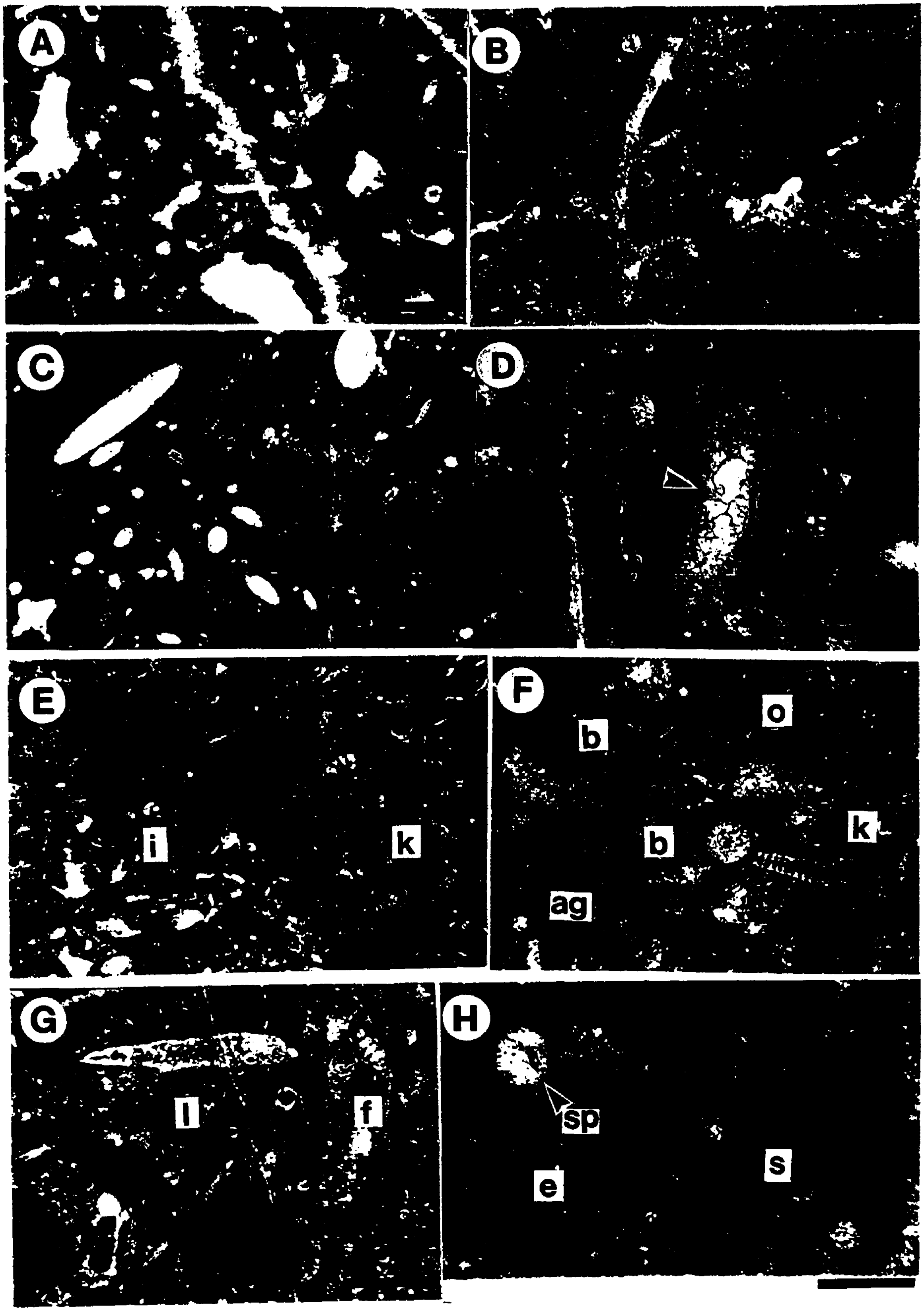

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Figure 24. Calcareous blue-green algae in mud mounds.

A. Typical branching habit of *Sphaerocodium gotlandicum*. Tubular spherical filaments are seen in transverse cross sections. Sample 227, mud mound 5. Top of photo is depositional top.

B. *S. gotlandicum* showing branching, tubular filaments (upper left) and transversely cut filaments with beaded appearance (right). Sample 75, mud mound 2. Top uncertain.

C. *S. munthei* (small arrows) growing on a skeletal grain. (s) is cross-like (stauract) sponge spicule. Sample 75, mud mound 2. Top uncertain.

D. *Sphaerocodium* encrusting tabulate coral *Thamnopora*. Corallites are also filled with this alga. Sample 21, mud mound 3. Top to left (arrow).

E. Interwoven tubular filaments of *Girvanella* (centre) with pelleted sediments. Sample 28, mud mound 1. Top uncertain.

F. *Sphaerocodium* (arrows) encrusting a large monaxon megasclere surrounded by calcite cement. Sample 49, mud mound 3. Top of photo is depositional top.

G. *Sphaerocodium* encrusting a skeletal grain (probably ostracode) within irregular cavity filled with calcite cement. Sample 218, mud mound 1. Top uncertain.

H. Densely clotted peloidal fabric and irregular intervals of lime mud between layers of *Sphaerocodium* (arrows). Sample 21, mud mound 3. Top of photo is depositional top.

Scale bars 0.5 mm.

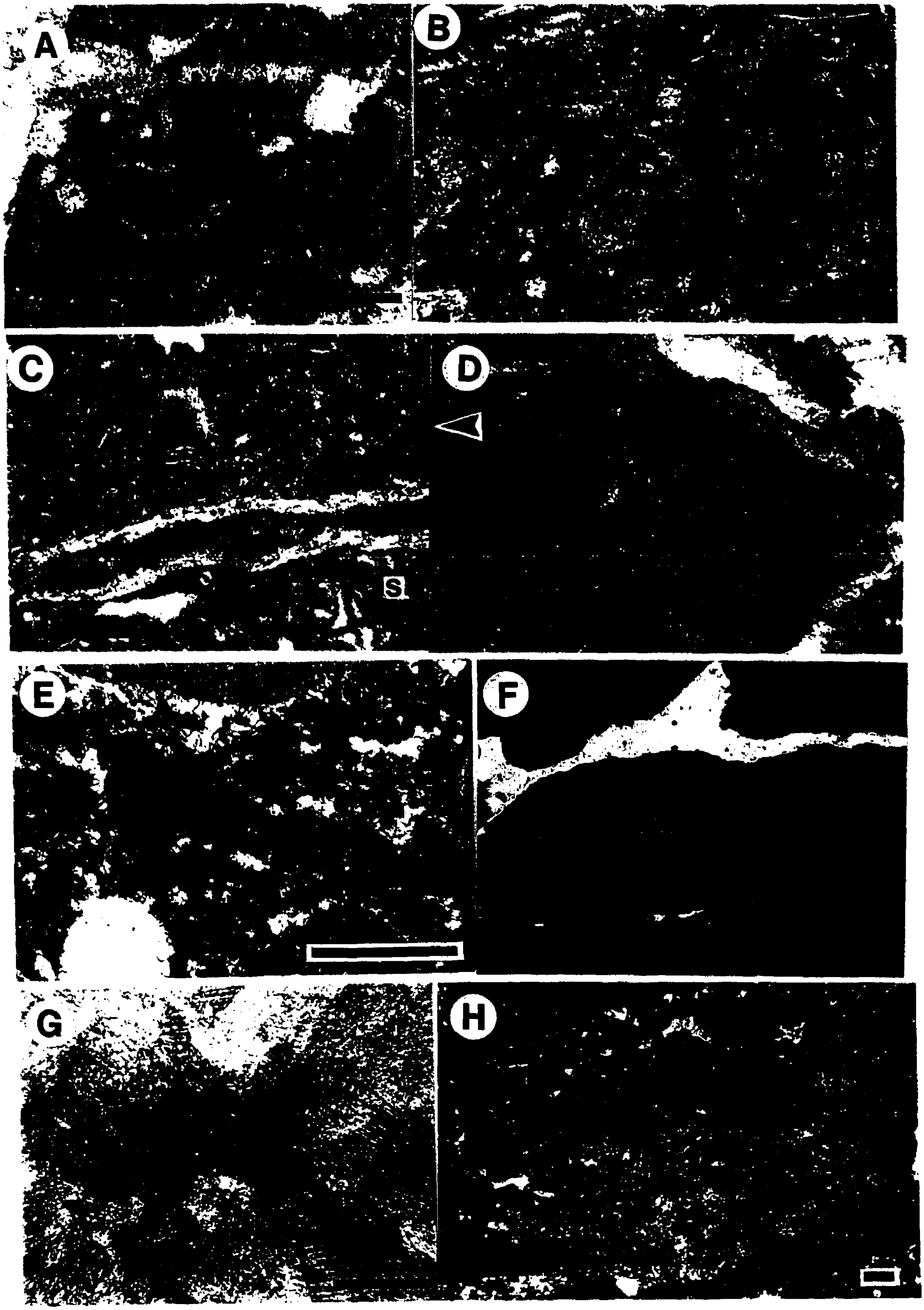
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Figure 25. Fossils and skeletal components in mud mounds.

A. Four subcircular to elliptical, thin walled remains of bispheres (arrows). Shelter cavity occurs beneath the two smaller bispheres and the right one is floored by geopetal sediments. Sample 28, mud mound 1. Scale bar 1 mm. Top of photo is depositional top.

B. An algal incertae sedis *Palaeomicrocodium*. Sample 207, mud mound 1. Scale bar 0.5 mm. Top uncertain.

C. Seven chambered uniserial foraminiferal test of *Eogeinitzina*. Sample 207, mud mound 1. Scale bar 0.5 mm. Top uncertain.

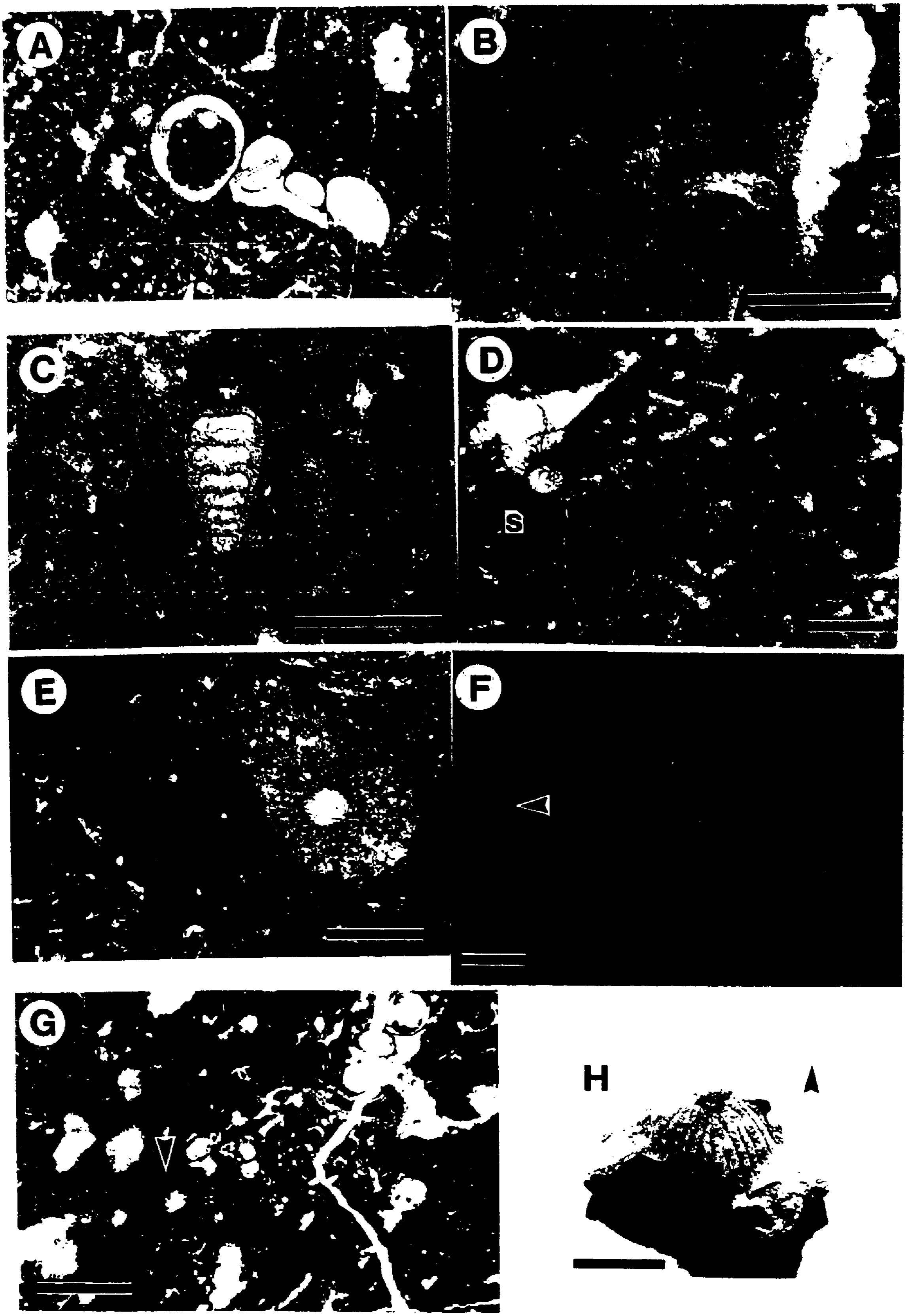
D. *Sphaerocodium* (small arrows) and spongiostroma. (s) is sponge spicule. Sample 227, mud mound 5. Scale bar 0.5 mm. Top of photo is depositional top.

E. Cylindrical coenosteum of *Amphipora* with an axial canal. Sample 21, mud mound 3. Scale bar 1 mm. Top of photo is depositional top.

F. Transported fragment of colonial rugose coral *Pachyphyllum* showing corallites. Cemented skeleton was not dolomitized. Arrow indicates solitary rugose coral. Sample 204, mud mound 1. Scale bar 2 mm. Top uncertain.

G. Specimen of bryozoa (arrow) in algal-rich wackestone. Sample 96, mud mound 5. Scale bar 1 mm. Top uncertain.

H. Pygidium of trilobite *Scutellum flabelliferum* from mud mound 2. Scale bar 2 cm. Arrow indicates front.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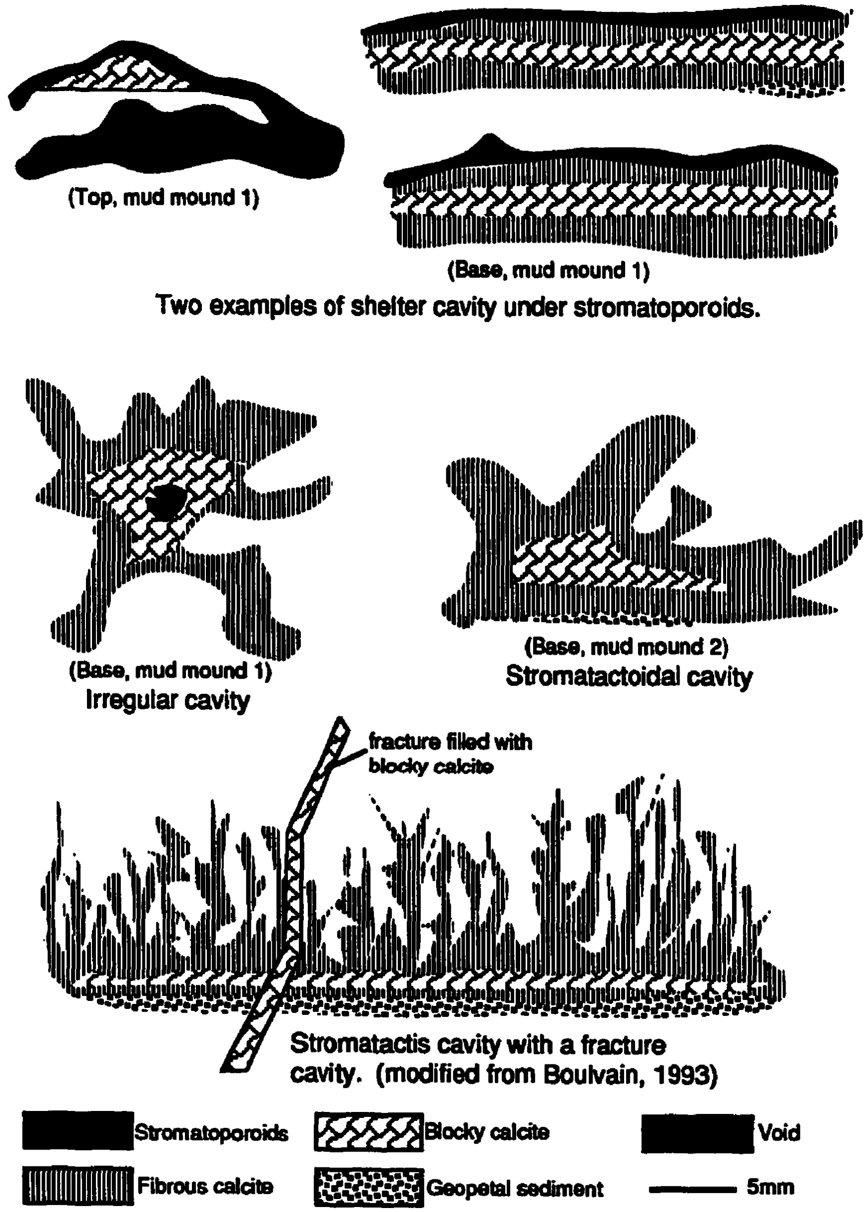

Figure 26. Types of Miette mud mound cavities.

Figure 27. Irregular cavities filled with fibrous calcite in spicule-rich wackestone and lime mudstone facies.

A. Irregular cavity surrounded by spicule-rich wackestone facies and partly filled with fibrous calcite (radiaxial?). Dolomite cement (d) fills the remaining pore space. Fragment of tabulate coral *Thamnopora* (t) occurs within cavity. Sample 26, mud mound 1. Large arrow indicates top.

B. Irregular cavity partly filled with fibrous calcite (radiaxial?) surrounded by lime mud with scattered sponge spicules. Geopetal lime mud floors the cavity (arrows). Blocky calcite spar (light) occurs inside of fibrous calcite and open voids (dark) at center of cavity. Sample 92, mud mound 4. Top of photo is depositional top.

C. Irregular cavity in lime mudstone. Arrows indicate geopetal sediment. Sample 217, mud mound 1. Top of photo is depositional top.

Scale bars 5 mm.

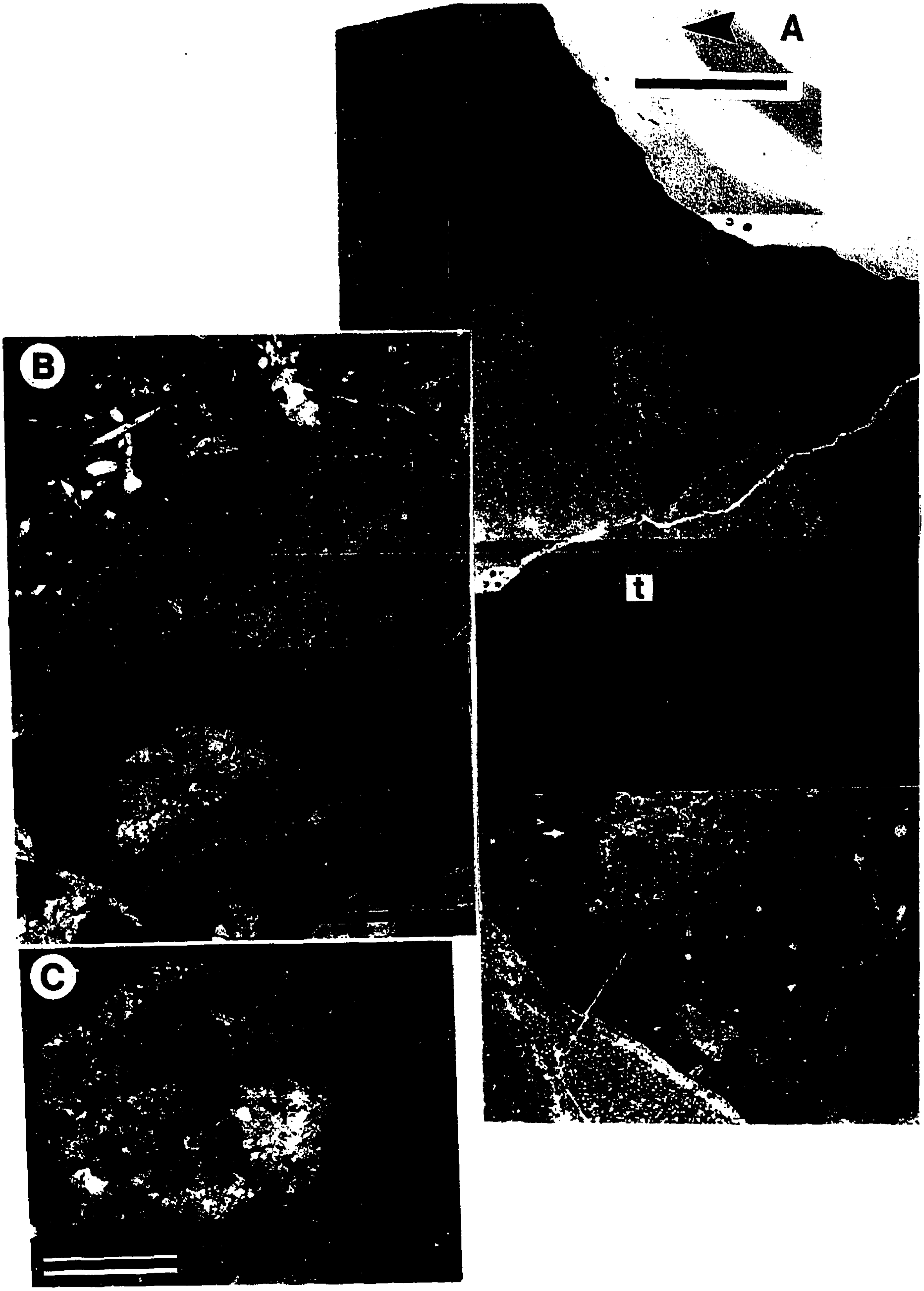
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Figure 28. Irregular cavities and stromatactoidal cavities.

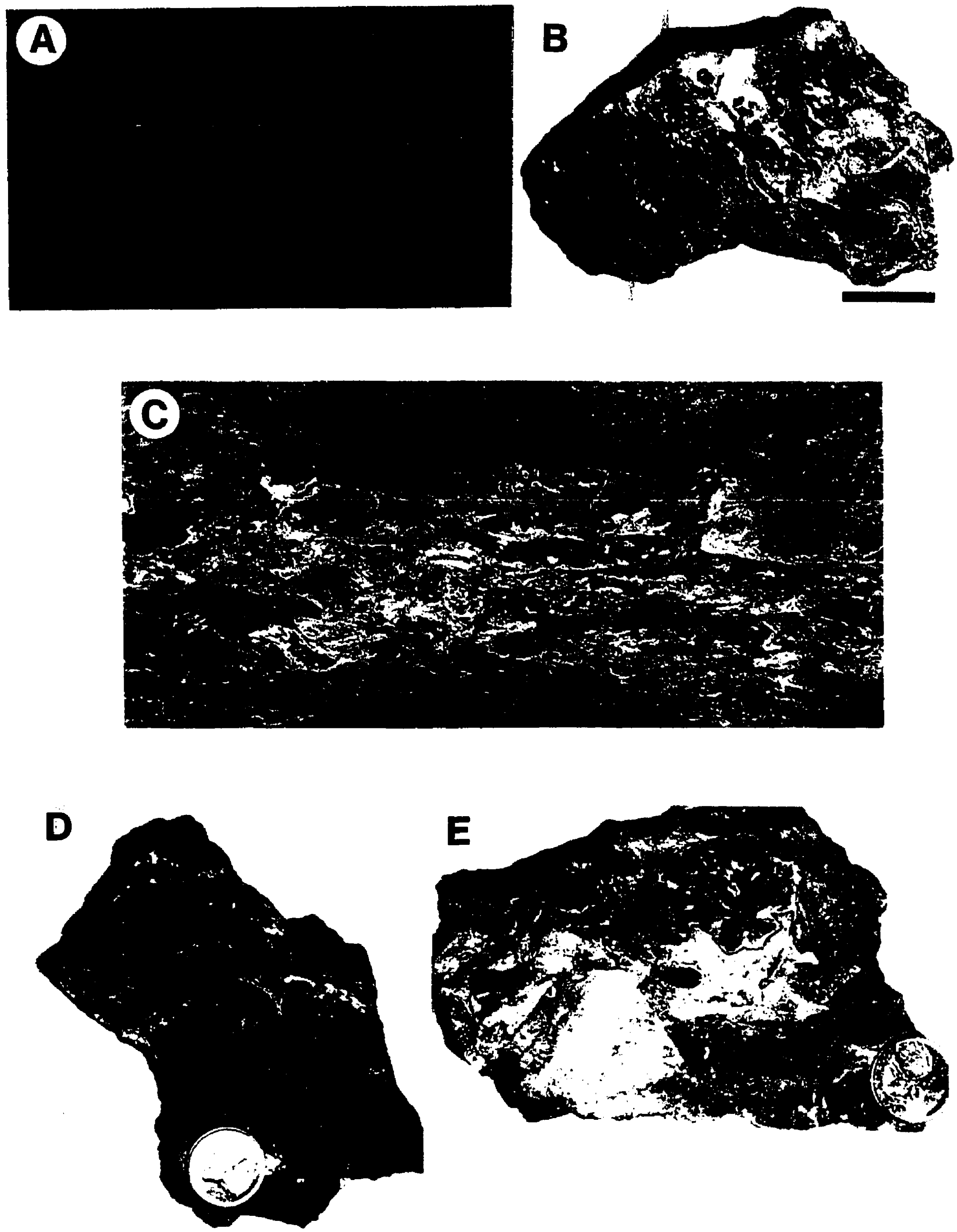
A. An irregular cavity filled with fibrous calcite with open voids. From lower part of mud mound 1. Lense cap is 62 mm in diameter.

B. An irregular cavity filled with fibrous calcite. Sample 99, mud mound 5. Scale bar 30 mm.

C. Stromatactoidal cavities (arrows) from the basal part of mud mound 2. Lense cap is 62 mm in diameter.

D,E. Examples of small stromatactoidal (possibly stromatactis) cavities. Sample 99, mud mound 5. Coins are 23 mm in diameter.

Top of photographs is depositional top.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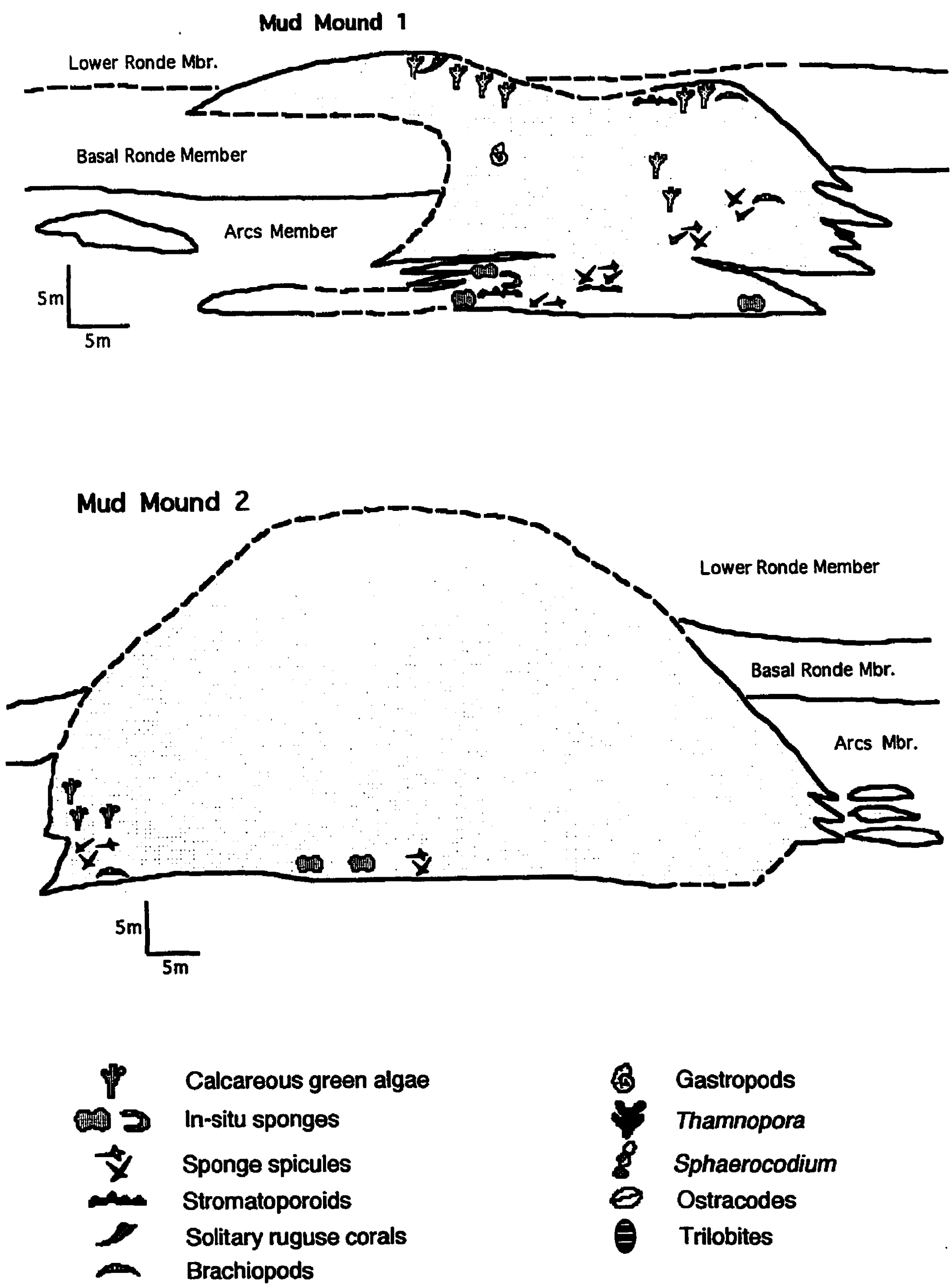

Figure 29. Distribution of biofacies within mud mounds 1 and 2. See Figure 8 for sample locations.

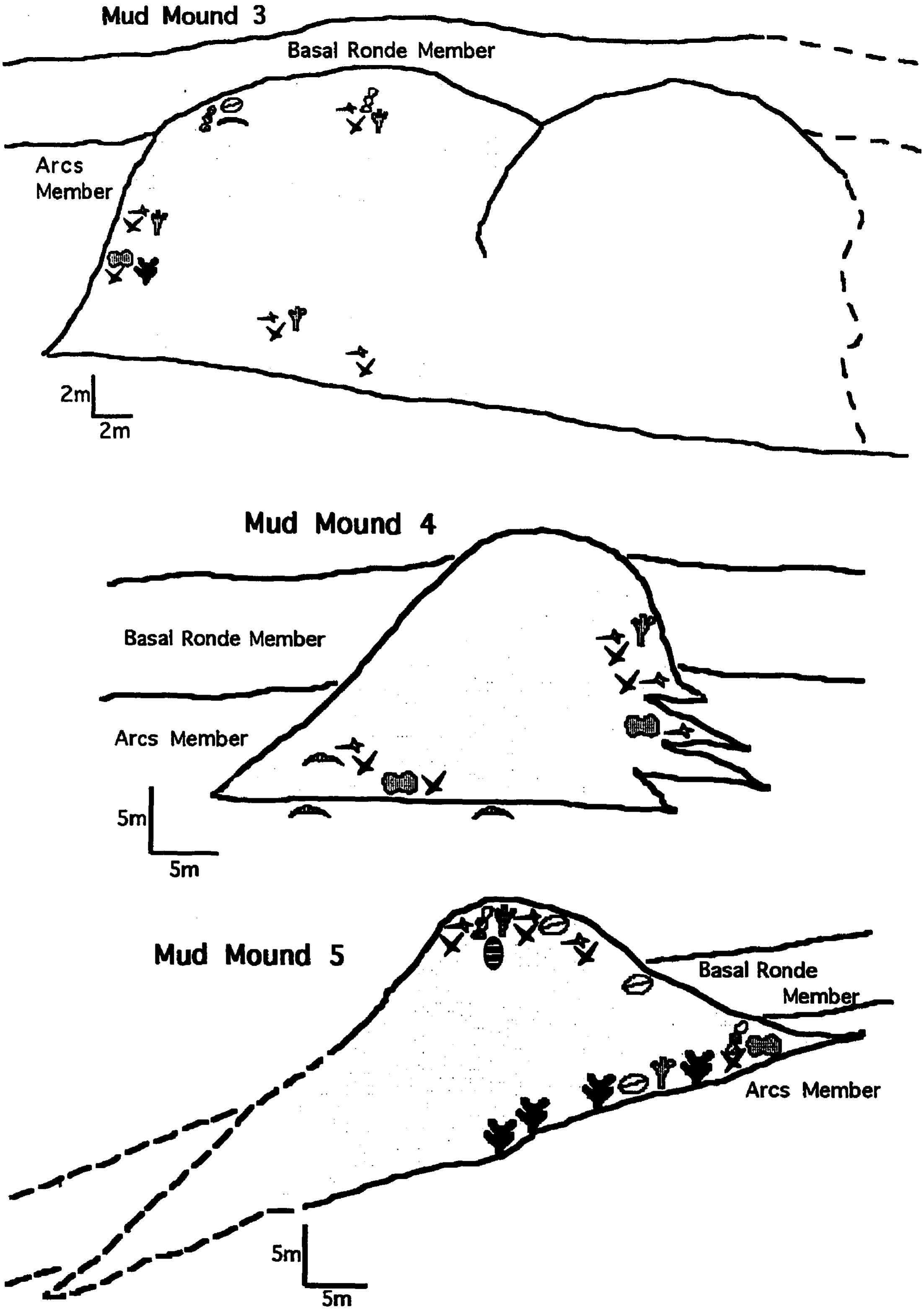

Figure 30. Distribution of biofacies within mud mounds 3 to 5. See Figure 29 for legend and Figure 9 for sample locations.

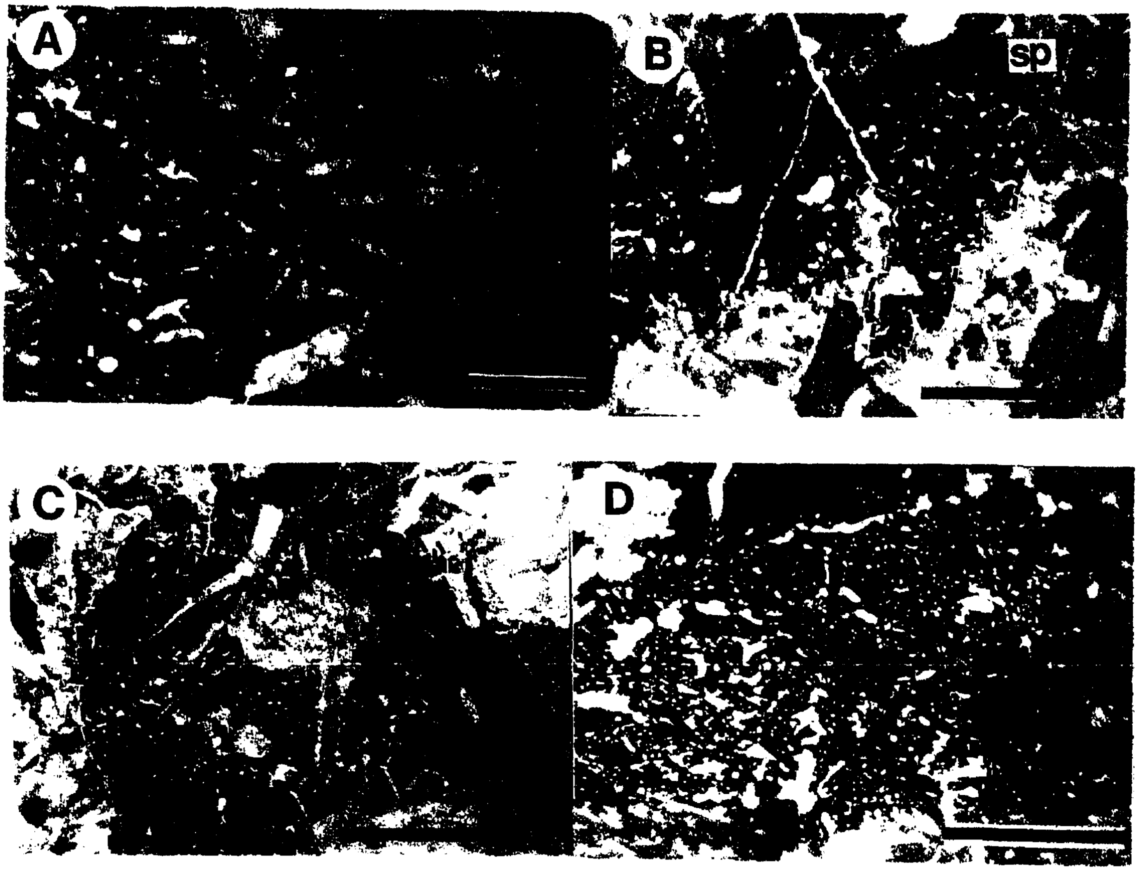

Figure 31. Inferred sponge fossils.

A. Porous texture in lime mud interpreted to be part of a calcitized sponge wall includes a large monaxon spicule (arrow). Sample 87, mud mound 4. Scale bar 2 mm. Top uncertain.

B. Abundant small open pores in lime mud inferred to be part of a calcitized sponge wall (sp). Sample 18, mud mound 3. Scale bar 5 mm. Top uncertain.

C. *Thamnopora* (centre) surrounded by large area of dark wackestone with several small cavities and spicules (arrows) filled with calcite cement inferred to be encrusted material that was formed or precipitated by sponges (outlined by dashed line). Sample 18, mud mound 3. Scale bar 5 mm. Top uncertain.

D. Area of lime mudstone with numerous pores and articulated spicules (arrows) is inferred to have been a calcitized part of the wall or body of a sponge. Sample 86, mud mound 4. Scale bar 5 mm. Top uncertain.

Figure 32. Shelter cavities.

A. Shelter cavities beneath laminar stromatoporoids from base of mud mound 1 (for photomicrograph see Fig. 33). Hammer 33 cm long.

B. Shelter cavity beneath a branch of tabular stromatoporoid *Stictostroma maclareni*. Sample 206, mud mound 1. Scale bar 5 mm. Top of photo is depositional top.

C. Shelter cavity beneath laminar stromatoporoid (series of small arrows) and irregular cavities (ic) are filled with fibrous calcite spar and blocky calcite. Laminar stromatoporoid is encrusted by an inferred sponge (see Fig. 31 for similar textures and text). (g) is a mold of gastropod. Sample 216, mud mound 1. Scale bar 5 mm. Top of photo is depositional top.

D. Shelter cavities with geopetal lime mud under dendroid stromatoporoid. Fracture filled with calcite at lower right. Large arrow indicates gastropod partly filled with geopetal lime mud. Sample 32, mud mound 1. Scale bar 5 mm. Top of photo is depositional top.

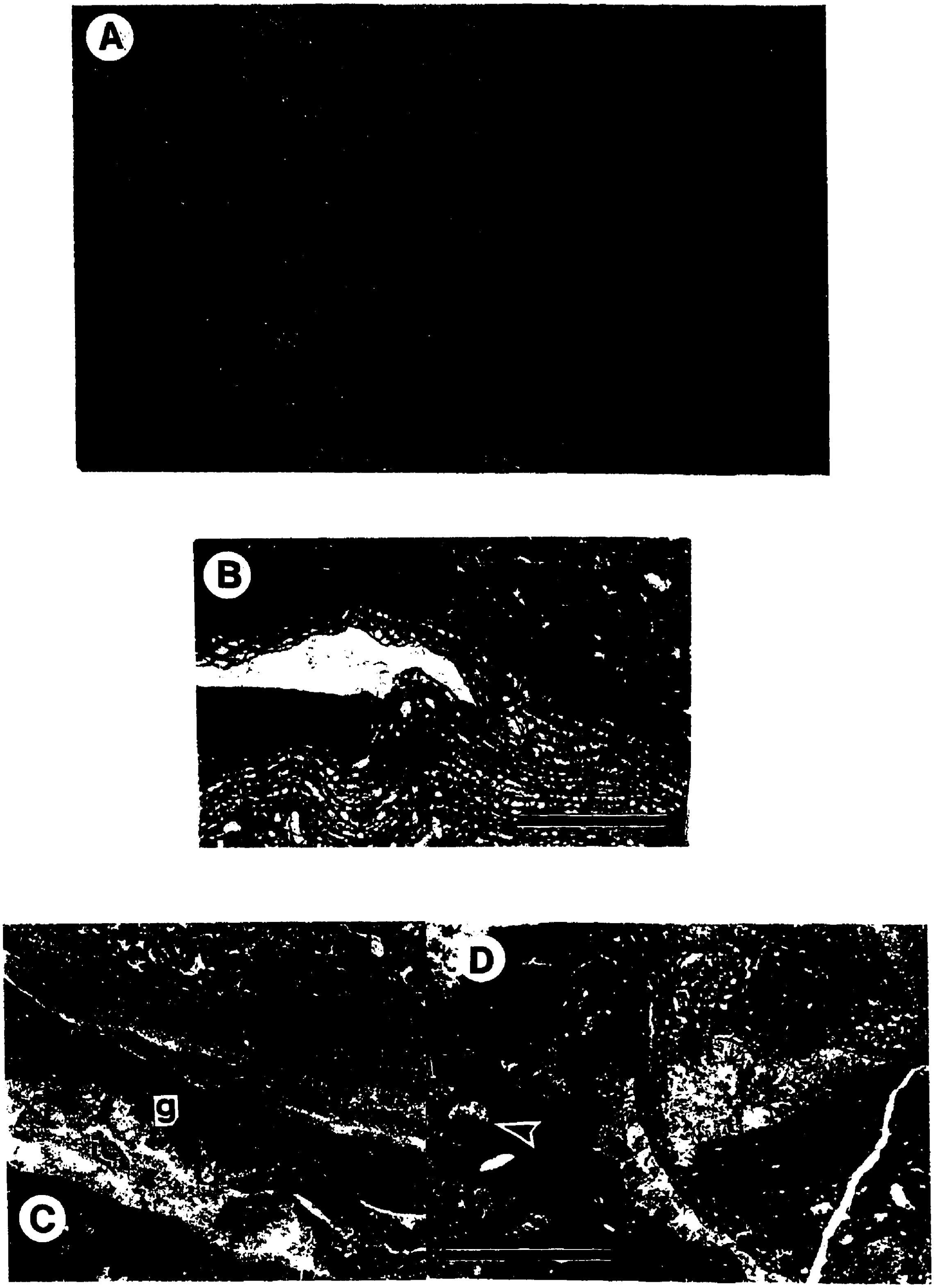
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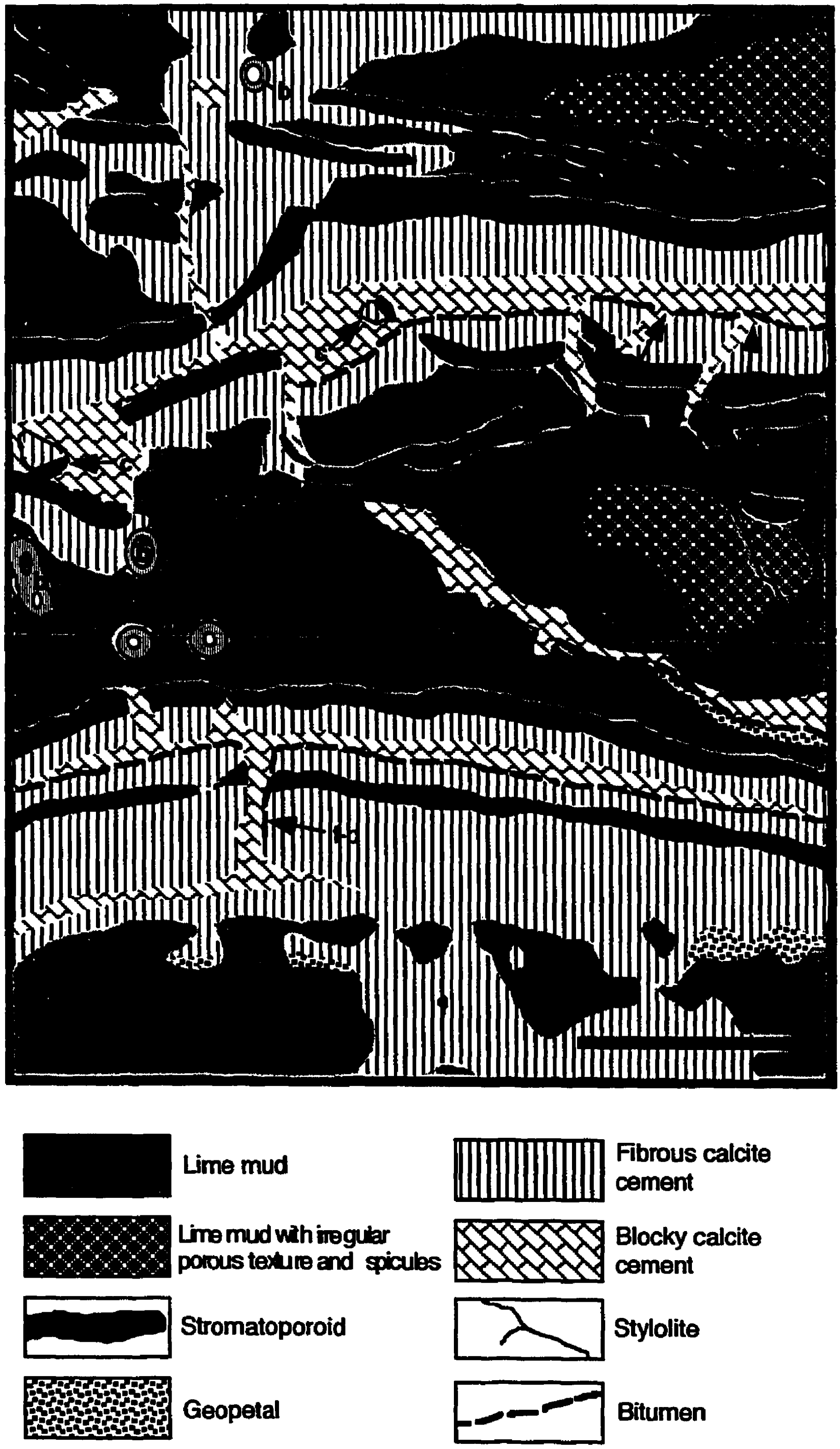
Figure 33. Photomicrograph of shelter cavities from part of outcrop shown in Fig. 32A. Arrows indicate laminar stromatoporoids (genus indeterminable). Sample 202, mud mound 1. See Fig. 34 for tracing of main features. Scale bar 10 mm. Top of photo is depositional top.

Figure 34. Shelter cavities beneath laminar stromatoporoids, mud mound 1. (Tracing of Figure 33.)

Shelter cavities beneath laminar stromatoporoids are filled with locally geopetal sediment, fibrous calcite (radiaxial?) and blocky calcite (coarse crystalline calcite). Fracture extends from top left to middle left cross cutting fibrous cement-filled shelter cavities (blocky calcite postdates fracturing). Irregular inclined cavity (ic) is also floored by geopetal sediments, filled with blocky calcite cement and cross cut by an irregular bitumen lined stylolite.
Bitumen occurs between the blocky and the fibrous calcite. Two sequences of fractures occur; 1)cross cutting fibrous calcite and residue of bitumen (b-f) and 2) bitumen emplacement predating fracturing and before blocky calcite cementation (f-b). Stylolitization occurs earlier than fracturing because fracture cross cut stylolite (s). (b) brachiopod spines.

The diagenetic sequence is as follows:
1) Cavities developed beneath laminar stromatoporoids in lime mudstone matrix.
2) Geopetal sediments floored some cavities.
3) Fibrous calcite cementation.
4) Stylolitization.
5) Fracturing (breaking stromatoporoids and fibrous cements (c)).
6) Bitumen emplacement (f-b).
7) Fracturing (b-f).
8) Blocky calcite cementation in centres of shelter cavities and along fractures.

Scale bar 10 mm. Top of figure is depositional top.


Lime mud
Fibrous calcite cement
Lime mud with irregular porous texture and spicules
Blocky calcite cement
Stromatoporoid
Stylolite
Geopetal
Bitumen

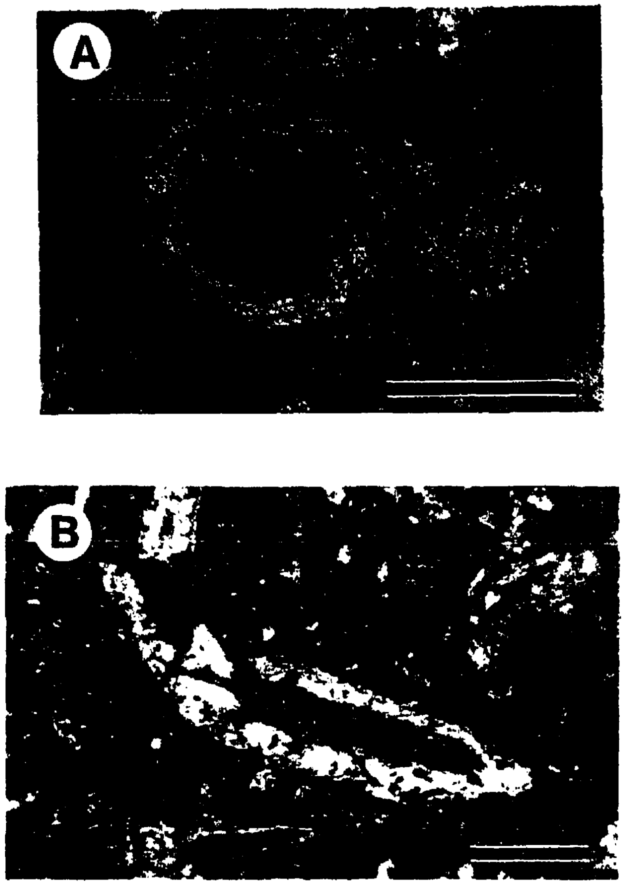


Figure 35. Examples of bioerosion.

A. Brachiopod spines have often been observed being broken or bored by endolithic sponges. Sample 17, mud mound 3.

B. Skeletal fragment with probable sponge (endoliths) borings. Sample 30, mud mound 1.

Scale bars 0.5 mm. Top uncertain.

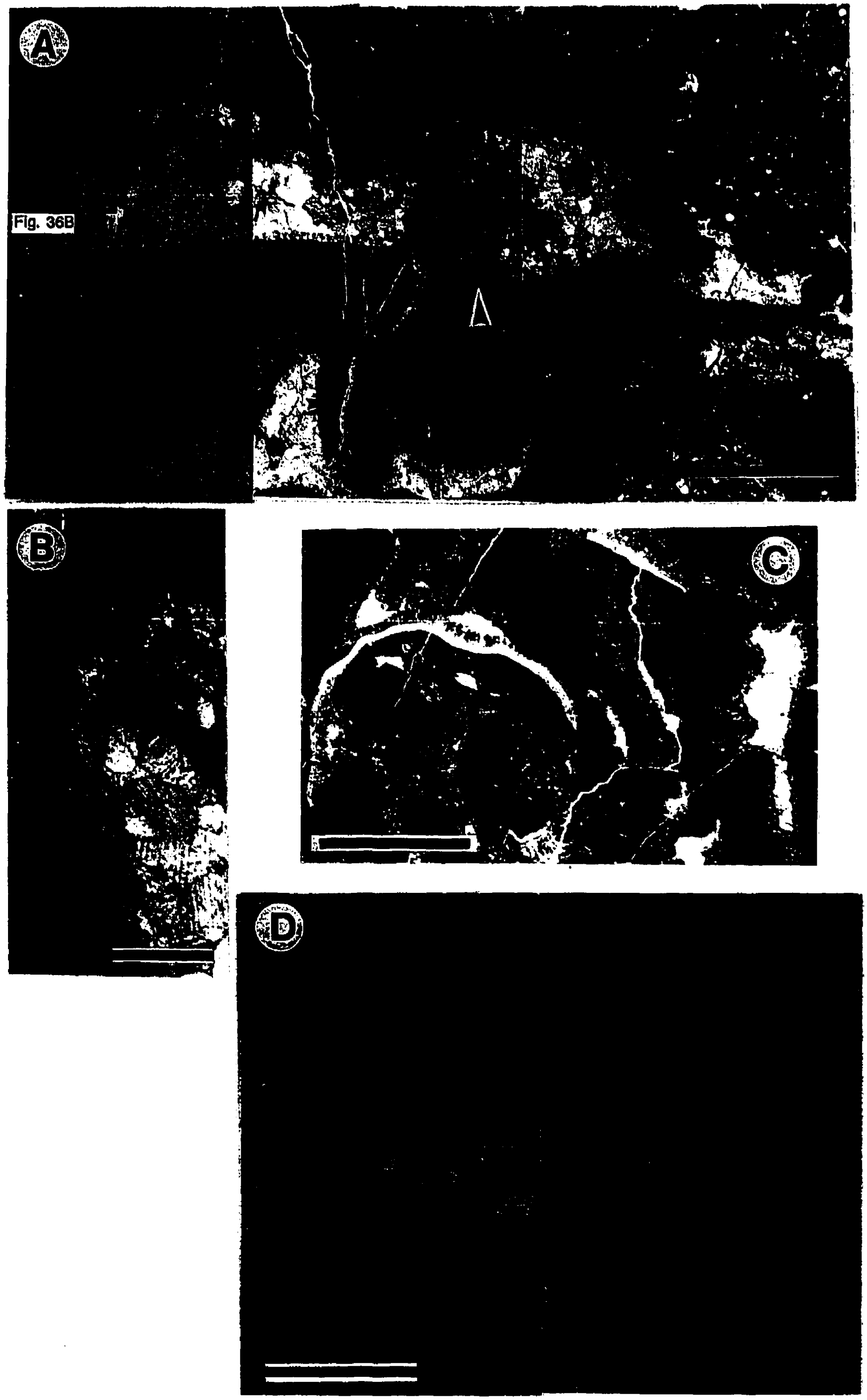
Figure 36. Irregular cavities inferred to be the organic origin.

A. An irregular shaped cavity inferred to be of organic origin. An encrusting organism (probably a sponge suggested by Fig. 36B) might have started to grow in open space (large arrow) under shell of gastropod (small arrows). Sample 246, mud mound 1. Scale bar 5 mm. Top of photo is depositional top.

B. Enlargement of left edge of the cavity of Figure 36A showing a spicule projecting from the cavity (arrow). Scale bar 1 mm. Top of photo is depositional top.

C. An irregular cavity on convex side of brachiopod shell (small arrows) inferred to have originated from the decay of an organism. Large arrow indicates top. The shell might have been transported. Sample 208, mud mound 1. Scale bar 5 mm.

D. An irregular cavity filled with a thin rim of fibrous calcite followed by calcite spar associated with fragments of *Thamnopora* (small arrows). In situ*Thamnopora* (in place, not by fracturing, suggested by thin fibrous calcite around fragments, dashed line) floating within the cavity, inferred sponge texture surrounding a fragment of *Thamnopora* (lower left, see also Fig. 31C) and spicules surrounding the cavity might indicate that fragments of *Thamnopora* were once encrusted by sponges. Fractures are present (large arrows). Sample 241, mud mound 2. Scale bar 5 mm. Top of photo is depositional top.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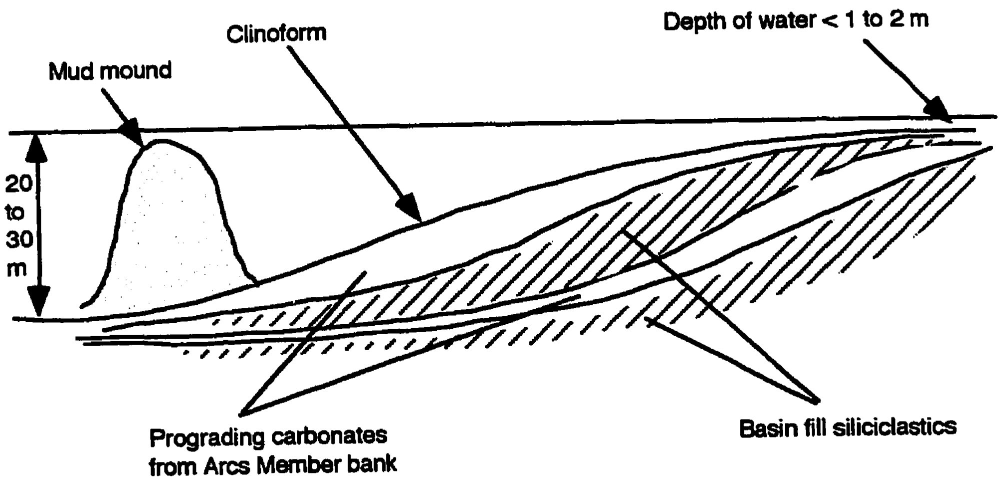


Figure 37. Position of mud mounds relative to carbonate clinoforms that extend southeastwards from the southern margin of the Miette reef complex. The depth of the water for grainstones and packstones in Arcs bank is based on laminated fenestral textures and exposure surfaces. (Mountjoy, 1965, 1989; Mountjoy and Burrowes, 1982). Mud mounds were initiated in about 20 to 30 m depth of water where the slope of the clinoform begins to flatten.

Table 1. Character of five mud mounds.

	McConnell thrust sheet		Miette thrust sheet		
No.	1	2	3	4	5
Width (max.) (m)	40	81.5	32	40	> 45
Thickness (max.) (m)	22	approx. 36.5	17	21	20
Form	Mushroom shape with broad base	Broad domal shape	Massive domal shape with vertical margins	Conical shape with rounded top	Flattened conical shape
Number of growth stage	3	1	1	1	1
Margin and flanking beds	Interfingering	Interfingering along north western margin	Abrupt margins with no interfingering	Interfingering along north margin	No interfingering

CHAPTER 3. DEVELOPMENT OF MUD MOUNDS

This chapter outlines the depositional environment, depth of water, significance of coral and stromatoporoid growth forms, origin of lime muds, role of organisms in mound accretion, early lithification, origin of cavities and the paragenetic sequence.

3.1 Depth and type of depositional environment

The depth of water which sustained the growth of mud mounds is estimated to be shallow. This is based on the sedimentary structures and geometry of the clinoforming surfaces, well displayed by carbonate tongues in the Arcs Member adjacent to the Miette reef complex. The sediments in much of the laterally equivalent Arcs Member bank above the Miette reef complex proper were deposited in very shallow water (< 1 to 2 m), indicated by the occurrence of laminated fenestral textures, exposure surfaces and grainstones (Mountjoy, 1965, 1989; Mountjoy and Burrowes, 1982; Fig. 37). Therefore, the maximum water depth of mound initiation is estimated to be about the thickness of the mounds, between about 20 and 30 m.

Depth and mound initiation

The bases of five mud mounds are located at slightly different stratigraphic levels in the uppermost Arcs Member depending on their geographic location (Figs. 3, 8 and 9). Mud mounds 1, 2 and 3 were initiated at about the same level (about 12 m below the base of Ronde) but mud mounds 4 and 5 were initiated at higher (later) levels about 7 m and 2 m, respectively, below the base of the Ronde Member. Thus mounds 1, 2 and 3 were probably initiated first and mud mound 5 last, using the base of the Ronde Member as a time marker. Other mounds nearby like the inaccessible mound southwest of mound 5 (Fig. 3) were initiated after deposition of the basal Ronde (silty dolomite marker) as were mounds located further south near the headwaters of Whitehorse Creek studied by Hedinger and Workum (1989). Hence the mounds were initiated at successively younger stratigraphic levels as the basin was progressively filled by carbonates that prograded southeast from the Miette reef complex and interfingered with basin siliciclastics (Figs. 3 and 4).

The shallow water depths of 20 to 30 m (Fig. 37) suggest that the environment for mound initiation was one of moderate agitation (not strong except during storms). This is supported by broken fossil fragments and the many disoriented sponge spicules. Moreover, some well preserved sponges appear to be in situ, and were deposited in wackestones, suggesting moderate energy levels (Figs. 16A, 16C, 16E, 27A and 27B). The presence of packstones in the upper part of most mounds suggests moderate agitation (Fig. 17). The coeval flanking sediments consist of muddy facies presumably deposited in quieter environments near wave base.

Mounds 1, 2 and 3 appear to have been initiated at similar water depths, since they occur at about the same stratigraphic level. Those further basinward such as mounds 4 and 5 at the head of Fiddle River may have been initiated in slightly deeper water, but their initiation at higher stratigraphic levels argues for the same or shallower water depths.

Algal abundance and relation to depth

The main factor controlling algal abundance is the clearness of the water (Toomey *et al.*, 1970), although some algae such as *Halimeda* in Florida Bay are capable of growing in muddy waters. Calcareous green algae indicate deposition in the photic zone. If modern forms are reliable indicators, codiaceans and dasycladaceans generally suggest water depths less than 25 m (Wray, 1977). Dasycladacean algae are most common in water depths less than 5 m (Wray, 1977). The predominance of calcareous green algae in the upper parts of mud mounds 1, 2 and 4 also suggests deposition in shallow water which is supported by textural and stratigraphic evidence. Filamentous and coccoid blue-green algae are most common in intertidal environments, although some species occur in deeper water marine environments (Wray, 1977). Blue-green algae such as *Girvanella* probably lived in shallow water environments because they utilized light for photosynthesis. However, Riding (1975) doubted the usefulness of *Girvanella* as a depth indicator in palaeoenvironmental studies because there are no clear limits which can be set on its depth of occurrence.

The usefulness of benthic calcareous algae as depth indicators in palaeoenvironmental studies is dependent upon the level of identification (i.e. genus, Riding, 1975). Although narrower depth limits for lower taxonomic levels have been demonstrated in recent green and red algae (e.g., Adey, 1966), recognition of such fine zones at the generic level in the ancient has yet to be accomplished. In the Palaeozoic, problems of correctly identifying calcareous algae further restrict their use as depth indicators (Riding, 1975).

The predominance of calcareous algae and foraminifera in the upper part of the mounds supports shallow, strongly agitated water conditions (high light intensity and abundant oxygen).

Preservation of sponges with respect to hydrodynamics

Most siliceous sponge spicules have been dissolved and so have the siliceous skeletons. Brachert (1991) suggested that dissolution of the siliceous skeleton of sponges is mainly controlled by hydrodynamic forces. As water turbulence and temperature are increased, silica dissolution is accelerated with respect to lime mud formation, producing poorly preserved sponges or even prohibiting fossilization. In contrast rapid cementation of carbonates results in well-preserved sponge fossils (Fig. 20). Relatively well-preserved in-situ calcitized sponges (Fig. 31), occur only in the lower part of the mounds (Figs. 29 and 30), suggesting that the environment was less agitated and perhaps that these carbonates underwent rapid cementation. The presence of submarine cements and primary cavities indicates that the cementation was early. The upper part of the mounds lack in-situ calcitized sponges and the scattered spicules support a more agitated and shallower environments.

Growth forms of stromatoporoids and corals

The relationship between the shapes of organisms and the environment is one of the oldest and most controversial topics in biology and paleontology (James and Bourque, 1992). To reconstruct the relationship between depth zonation and growth forms of stromatoporoids one must rely on examples from ancient reefs because of the lack of appropriate modern analogs. Kobluk (1975) studied the relationships between stromatoporoid morphologies and paleoecology of the southeast margin of the Miette carbonate complex. Following earlier researchers he recognized seven distinct stromatoporoid growth morphologies at Slide Creek and suggested that morphological variation in stromatoporoids was at least partly environmentally controlled.

Stearn (1975) noted that certain arguments are used to suggest that tabular and encrusting forms are characteristic of quiet water fore-reef slopes rather than turbulent reef crest zones. The presence of very thin laminar stromatoporoids (about 1 mm in thickness) in the lower part of mud mound 1 and associated wackestones supports the interpretation that this mound might have started to grow under deeper water, quiet to moderately agitated conditions. Although James and Bourque (1992) suggested that plate-like stromatoporoids, bound together by algae, microbes and/or cement, are also known to have occurred in agitated water environments (e.g. James and Bourque, 1992, Fig. 12), no evidence of algal binding was observed in the laminar stromatoporoids in the lower part of mound 1.

James and Bourque (1992) illustrated depth zonation of modern reefs based on scleractinian coral reefs. The reef facies lies between about 10 m (the base of surface wave action) and 100 m. This is an environment of diverse reef-builders varying in shape from hemispherical to branching, to columnar, to dendroid, to sheet-like (James and Bourque, 1992; Fig. 12). Examples from modern reefs provide important information concerning interactions between growth pattern of corals and environmental factors. James and Bourque (1992; Fig. 12) placed branching corals at or close to wave base. The presence of colonies of branching tabulate coral *Thamnopora* in the basal part of mud mound 5 (Figs. 13D and 13E) could suggest somewhat less agitated water conditions for initiation of mud mound 5. Branches of *Thamnopora* would not have tolerated high wave energy.

Mount Hawk sediment

The mud mounds developed on slope carbonates or calcareous shales of the upper Mount Hawk Formation. Lithologies of the upper Mount Hawk Formation (fine mudstones) suggest that the depositional conditions during initiation of mud mounds was quiet to moderately agitated. It is unlikely that these carbonate mudstones and shales were deposited under high energy because they lack laminations and wave or current sedimentary structures (Appendices 1 and 2). The presence of laminar stromatoporoids in the upper part of the Mount Hawk Formation also supports a low agitated environment (see previous section).

Origin of Lime Muds

The origin of the lime muds could be related to the mechanical breakdown of calcareous skeletons (Chave, 1964), the disintegration of algae, lime mud transported off the shallow Arcs carbonate bank to the north, and inorganic or organic mediated micrite cements (Mountjoy and Jull, 1978; Mountjoy and Riding, 1981). Essentially it is impossible to distinguish between these various origins. However most of the carbonate mud appears to be of mound derivation because of the lack of intertonguing flanking deposits. Much of it may be from the breakdown of skeletal elements or diagenesis. A considerable amount may have been deposited as micrite cements as shown for the Ancient Wall mud mounds (Mountjoy and Jull, 1978; Mountjoy and Riding, 1981), but this is difficult to prove.

3.2 Role of organisms in accretion of mounds

Accretion of the mounds is interpreted to have been facilitated by trapping, binding and stabilizing organisms living on and in the mound, including stromatoporoids, sponges, calcareous green algae rooted in the sediment and calcareous blue-green algae. Binding and stabilization was probably aided by inorganic cementation of the lime mud and fibrous cements lining most cavities. Laminar stromatoporoids, that occur in the basal part of mud mound 1 (Figs. 32 and 33), probably helped bind sediment. Sponges appear to have played an important role as trappers and bafflers of lime mud especially spiculate sponges (James and Bourque, 1992). They are sessile organisms composed of a spicular skeleton enclosed in a body of organic matter. The growth potential of such organisms is high, although their fossilization potential is low. From recent hexactinellid sponge bioherms on the continental shelf of western Canada Conway *et al.*, (1989) suggested that siliceous sponges trap fine suspended detritus as a result of their filter-feeding mode of life. They observed that surfaces of sponge bioherms were densely colonized with hexactinellid sponges. Core data indicate a succession of sponges form the basic structure of the mounds and that these modern mounds actively accrete sediment by means of the filter-feeding mode of living sponges (Conway *et al.*, 1989). The Upper Devonian Miette mud mounds may be similar to these modern bioherms in terms of sponge activities but the water depths of 150 to 250 m are much deeper. Sponges sometimes encrusted or grew over hard skeletons of corals or stromatoporoids (Figs. 31C and 32C) as in the base of mud mound 5 where *Thamnopora* colonies are encrusted by sponges (Figs. 13D, 13E and 31C).

Sponges might have been killed off by the invasion of siliciclastic sediment. Where basin sediments interfinger with mud mound 1 about 5 m above the base (Fig. 8) the amount of sponge materials is low compared to other samples of the mounds (Table 2, samples 27 and 249). Siliceous sponges occur with calcareous green algae in the middle part of mud mound 1 suggesting that these sponges favored carbonate depositional environments and were not capable of colonizing siliciclastic materials. The change from sponges to calcareous green algae towards the top of the mounds occurs in mud mounds 1, 2 and 4 and suggests that this distribution is related to a shallowing upward sequence and a change from moderate to strong agitation.

Calcareous green algae are one of the most abundant skeletal elements within the mounds. The small delicate skeletal organisms such as dasycladaceans and codiaceans trap sediments as well as produce significant skeletal elements especially in the upper part of mounds. The modern codiacean algae *Halimeda* appears to be a principal sediment producer on the Belize reef margin. *Halimeda* is abundant both on sediment slopes and on rock surfaces around and between coral plates throughout the reef margin above the 65 m break in slope. These algae grow prolifically to a depth of between 67 and 73 m (average 70 m; James and Ginsburg, 1979).

The presence of calcareous blue-green algae such as *Sphaerocodium* or *Girvanella* would have helped to stabilize lime muds because the role of blue-green algae (cyanobacteria) as sediments trappers, as seen in stromatolites, is well known. Definite blue-green algal fragments occur in 23 out of 49 well-studied thin sections. The presence of *Girvanella* and *Sphaerocodium* filaments are suggestive of organic mats (Fig. 24H) and microbial masses, and suggests that these organisms played roles in sediment accumulation and stability. Most living species of blue-green algae, whether a single cell or groups of cells, are enclosed in mucilage (Wray, 1977). In filamentous algae cells occur in rows or strands, called trichomes, within a mucilaginous sheath. Under certain conditions, such as the existence of significant amounts of mucilage, calcium carbonate is deposited in the sheath not in the cells (Wray, 1977).

3.3 Early lithification

The massive structure of the mounds without flanking detritus and the general lack of interfingering relationships with basin strata indicates that the mounds largely accumulated in place and were built up in such a way that little sediment was lost from them. The mounds must have been the carbonate mud factory since they are largely surrounded by siliciclastic sediments (James and Bourque, 1992).

Trapped and/or baffled lime muds must be stabilized or lithified in some way in order to form mud mounds. The different mound cavities noted in Chapter 2 (Fig. 26) would have been related to the development of mounds because these cavities are restricted to the mounds, and are not found in flanking beds. Early lithification must occur before or at the same time as cavity formation, as cavities would have collapsed without lithification. Mountjoy and Jull (1978) and Mountjoy and Riding (1981) suggested the presence of early micrite cements of probable submarine origin for lithification using evidence such as thin, dark bands of micrite rimming irregular cavities, thin rims of micrite around borings in stromatoporoids, eroded crust and downward accumulation of renalcid micrite in Ancient Wall reef mud bioherms. Though it is exceedingly difficult to distinguish sedimentary or particulate micrite from micrite cement

(James and Ginsburg, 1979), early lithification is generally indicated by the absence of compaction features (i.e. open packing in packstone; draping of overlying formation).

More specifically early lithification for the Miette mud mounds is suggested by the following evidence. The remains of delicate calcareous green algae are common throughout the mud mounds, especially in the upper part of the mounds where many are well preserved (Fig. 23), suggesting that they were lithified at an early stage shortly after deposition thus preventing further breakage and erosion. The presence of calcitized sponges (Fig. 31) also suggests that the mounds were lithified at a very early stage (see section 3.1.). Many shelter cavities occur beneath laminar stromatoporoids in the basal part of mud mound 1. As they are very thin (about 1mm or less) it is doubtful whether these laminar stromatoporoids could sustain a load of sediments above them without early lithification, otherwise they would probably collapse.

3.4 Origin of cavities

The origin of cavities in mud mounds is controversial and a topic of much debate, especially for stromatactis cavities which commonly occur in many Paleozoic mud mounds. Several origins have been proposed for the genesis of stromatactis cavities, such as inorganic mud accumulation and its early cementation (Heckel, 1972; Mountjoy and Jull, 1978; Bathurst, 1980; Mountjoy and Riding, 1981), cyanobacterial accretion (Pratt, 1982, 1986, 1995), microbial production of lime mud (Monty et al.; 1982, Monty 1995; Lees and Miller, 1985), sponge construction (Bourque and Gignac, 1983, 1986; Kerans, 1985; Kerans et al., 1986; Bourque and Boulvain, 1993). Most agree that these mounds were cemented early in a submarine environment and that stromatactis results from centripetal cementation of syndepositional or early diagenetic cavities. The origin of the different cavities are briefly discussed and outlined below.

Shelter cavities

Shelter cavities in the mounds were mostly open pore spaces beneath fossil fragments. Early deposition of fossil fragments (brachiopods and laminar stroms) creates a small cavity below the fossil. Continued sedimentation takes place on top and around the fragment, resulting in the shelter cavity.

Irregular and stromatactoidal cavities

Irregular and stromatactoidal cavities might be interpreted as organic in origin, perhaps related to sponges, because of their morphologies, textures and other evidence discussed below. In many cases sponge spicules are observed around cavities (Figs. 20, 27 and 36). Sometimes spicules stick out of irregular cavities which have the morphologies and cavity margins of possibly decayed encrusting sponges (Fig. 36). Encrusting sponges might have started to grow in open spaces beneath shell fragments and continue to encrust them (Fig. 36A). Another example of an irregular cavity which is associated with fragments of *Thamnopora* might also be explained as being of sponge origin (Fig. 36D). *Thamnopora* floating within the cavity as well as calcitized sponges and spicules surrounding the cavity might indicate that *Thamnopora* fragments were once encrusted by sponges (Fig. 31C).

Calcite filled cavities associated with definite sponge textures (Figs. 20 and 21) are good examples of cavities that probably formed by the decay of sponge tissue. The shape of the spar-filled cavity clearly indicates a rhagon type (vase-shaped) siliceous sponge (Fig. 20A). Lime muds filled the area adjacent to the rhagon and outline the indentations of the possible sponge. The spar-filled cavity had to be sustained by something before lithification of lime mud. There is no doubt that the cavity represents the mold of a sponge. There are remains of sponge texture (clearly distinguished from lime mud matrix) within the voids (Figs. 20B and 21). Geopetal lime muds that floor the voids may have taken place immediately after death of the sponge. Unfortunately this is the only example observed in the five mud mounds studied. Sponges have such variable growth shapes that they could form highly irregular cavities of different sizes. It is suggested that at least some of the irregular and stromatactoidal cavities may have been occupied by sponges and resulted from the decay of sponge tissue during or after partial to complete submarine lithification and cementation of portions of the mud mounds.

Cavities due to soft-bodied organisms Several researchers have suggested that the irregular shaped cavities may have formed by the decay of soft-bodied organisms. Some examples related to lithistid sponges include sponge framework voids (e.g. Bourque and Gignac, 1983, 1986; Kerans, 1985; Kerans et al., 1986; Bourque and Boulvain, 1993), decay of sponge tissue (e.g. Beauchamp, 1989) and silica dissolution of sponges skeletons (e.g. Brachert, 1991). Bourque and Gignac (1983,1986) noted that the Silurian stromatactis-bearing reef mounds of Quebec consist, in part, of pelletoidal networks (concentrations of pellet-like bodies) which resemble the associated sponge *Malumispongium hartnageli.* These sponges underwent changes during their fossilization, from a siliceous skeleton of closely packed spicules to a pelletoidal fabric with scattered molds of spicules, perhaps by bacterial activity(?) without destroying the morphology of the sponge wall (Bourque and Gignac, 1983). Bourque and Gignac (1983, 1986) also suggested that stromatactis may have originated as early marine cemented cavities in a sponge network and as cavities created by the decay of local uncemented sponge tissues. However, these mounds were devoid of fossil sponges. The presence in the red stromatactis facies of the Frasnian Belgium mud mounds of sponge body fossils and sponge spicular networks in various stages of preservation more convincingly supports the interpretation that sponges were significant in the accretion of these mud mounds especially in mounds devoid of fossil sponges but rich in diorganized spicules (Bourque and Boulvain, 1993). Facies A in the Belgium mud mounds consists of patchy microspar with uniform or pelletoid or vermiform texture containing ubiquitous sponge spicules, commonly disorganized and scattered in the microspar. In several instances actual spicule networks are observed even though sponge bodies are not evident. Where sponge body fossils are common spicular networks are well preserved but in some cases is poorly preserved or absent. All transitions occur in stromatactis limestones lacking obvious sponge bodies from barely discernible sponge-spicule network to meshworks of small-canal-like (veriform) structures that have a spongy appearance. Bourque and Boulvain (1993) suggest that these structures represent different stages of early diagenesis and preservation of the sponge communities and early-cemented spicule-rich organic mats.

Beauchamp (1989) interpreted irregular shaped cavities in Lower Permian sponge-bryozoan buildups in southwestern Ellesmere Island, Canada as the remnants of sponges buried rapidly within mud-rich sediments. In situ spicular networks within large irregular cavities occur throughout most of these buildups and these cavities are most abundant within spicule-rich facies.

Stromatactis cavities

Bathurst (1980,1982) proposed early lithification of crusts for the origin of stromatactis cavities, especially for those that are sheet-like and stacked one above the other (zebra spar sheets) and form up to 40% of the rock. He suggested that stromatactis is the cement (and sediment) fill of a system of cavities which developed between submarine inorganically cemented crusts on the sea floor. The geometry of the stromatactis cavities results from partial or incomplete cementation of some layers or crusts, with maximum induration occurring at their upper surfaces and decreasing downwards. Later winnowing of unlithified sediment beneath these cemented layers excavated cavities with some of the reworked material forming geopetal fillings. This sequence explains the smooth floor or top of the geopetal sediment and the irregular to digitated roof similar to the morphology of a cement filled stromatactis cavity.

Bourque and Gignac (1983, 1986) and Bourque and Boulvain (1993) explain stromatactis as being the enlargement and modification of original growth cavities of the sponge network concurrently with the decay and collapse of regions of unlithified sponge tissue in conjunction with early cementation during bacterial decay of organic matter, based on the determinant role of sponges in facies construction of the mud mounds.

It is difficult to apply Bathurst's inorganic origin for stromatactis cavities to the Miette mud mounds, because only parts of some mounds have successive layers of stromatactis or stromatacoidal cavities. However, these cavities could form in an irregular manner by inorganic micrite cementation and construction. Stromatactis cavities in the Miette mounds may also be related to sponges similar to the stromatactoidal cavities (see previous section) or formed in a manner similar to that suggested by Bourque and Boulvain (1993).

Stromatactis cavities may be a special type of stromatactoidal cavity having a highly digitate roof (Fig. 26).

3.5 Geopetal sediment

Most cavities are floored with internal geopetal sediments. Commonly geopetal sediments occur within shells such as brachiopods, ostracods and gastropods (Fig. 16H). Irregular stromatactoidal cavities are also partly filled with geopetal sediment (Fig. 27). The internal sediments consist of lime muds and peloids. No fossils or skeletal elements were observed within these geopetal sediments. Thus they can not be demonstrated to be of marine origin. However the presence of submarine fibrous calcites that fill the cavities strongly suggests these geopetal sediments are marine.

3.6 Paragenetic sequence

The timing of cementation is considered to be early because of the general lack of replacement dolomitization within the mounds whereas some flanking beds are dolomitized. Replacement dolomitization is interpreted to have taken place at buried depths greater than about 500 m (Mattes and Mountjoy, 1980; Mountjoy and Amthor, 1994). Much of the cementation of the matrix probably took place early, sealing off these rocks from later diagenetic fluids such as the shallow burial dolomitizing fluids (Mattes and Mountjoy, 1980).

Following deposition of internal marine geopetal sediment, a first stage of marine isopachous fibrous calcite cement and a later blocky calcite spar filled the cavities. In the case of the irregular cavities and stromatactoidal cavities commonly isopachous fibrous cement occurred first beginning at the cavity wall, followed by blocky calcite spar (Figs. 27B, 27C and 36). Shelter cavities beneath shells or laminar stromatoporoids and fracture cavities are commonly filled with blocky calcite spar without isopachous fibrous cement (Fig. 33), presumably because these cavities were isolated early from the sea floor.

The general sequence of diagenesis is: 1) early lithification of matrix (and formation of cavities); 2) geopetal sediment; 3) isopachous fibrous calcite; 4) local dolomite cement; 5) stylolitization; 6) fracturing; 7) bitumen emplacement; 8) late fracturing; and 9) blocky calcite cementation (Fig. 34).

Oblique, or locally nearly vertical, sub-parallel fractures are filled with blocky calcite and locally bitumen (Figs. 32D, 33 and 34). These fractures sometimes cross cut all earlier and most late diagenetic features (Figs. 33 and 34). At least two episodes of fracturing occurred as indicated by fracturing predating and postdating bitumen emplacement.

3.7 Summary

The Miette mud mounds were initiated in water depths of 20 to 30 m based on the geometries of the gently basin sloping clinoforms. Most mounds accumulated up to or close to sea level as shown by the stratigraphic relationships. The mounds were exposed during the subsequent sea level fall at the end of Arcs/Niksu deposition prior to Ronde/Calmar deposition.

The sponge-bearing stromatactoid wackestones that occur in the lower parts of most mounds is suggestive of quiet to moderately agitated waters. Calcareous algae and foraminifera predominate in the upper parts of the mounds suggesting shallower and more agitated water environments. The massive structure of the mounds without flanking detritus and the general lack of interfingering with basin strata indicates that the mounds largely accumulated in place and were built up in such a way that little sediment was lost from them. Accretion of the mound was facilitated by trapping, binding and stabilizing organisms living on and in the mound, including stromatoporoids, sponges, calcareous green algae rooted in the sediment and calcareous blue-green algae. Binding and stabilization appears to have been aided by inorganic cementation of the lime mud and fibrous cements that line most cavities.

Irregular and stromatactoidal cavities may be organic in origin, perhaps related to sponges, because of their morphologies and textures. Calcite filled cavities associated with definite sponge textures are good examples of cavities that probably formed by the decay of sponge tissue. Some of the other irregular and stromatactoidal cavities may have been occuppied by sponges on the basis of abundant sponge spicules that are associated with them. Other cavities may be inorganic resulting from irregular inorganic cementation by micrite and accumulation of sediments during buildup development.

CHAPTER 4. COMPARISON WITH OTHER DEVONIAN MUD MOUNDS

In this chapter the Miette mud mounds are compared with Fransian mud mounds of the Ancient Wall reef complex, Meekwap buildups in the Alberta Basin, and Belgium "récifs rouges"

4.1 Ancient Wall reef complex

A series of small carbonate mud, coral-algal-stromatoporoid bioherms (about 7.5-23 m across and 4-6 m high) were deposited on the seaward margin of the Arcs platform on the southeast flank of the Upper Devonian (Frasnian) Ancient Wall reef complex, Mount Haultain (Mountjoy and Jull, 1978; Mountjoy and Riding, 1981) (Figs. 1, 2 and 38). They grew in a moderately agitated, fore-reef environment. Small bioherms spaced at irregular intervals occur on top of, attached to, adjacent to, or basinward down the fore-reef slope from a stromatoporoid-coral-rich unit of the Arcs equivalent carbonate platform that extends about 2000 m southward (basinward) over Perdrix foreslope strata (Fig. 39). The bioherms represent deposition during a sea level rise possibly related to the transgression that initiated sequence 4 (Fig. 39). The main characteristics of the Ancient Wall bioherms and the Miette mud mounds are summarized in Table 2.

The location and development of the bioherms (mud mounds) appear to be mainly related to the presence of a suitable lithified substrate and favorable water depths for both the Miette mud mounds and the bioherms of the Ancient Wall reef complex. At Ancient Wall the stromatoporoid-coral unit or the adjacent slope megabreccia (bioherm 6, Fig. 38) formed a foundation on which the bioherms were initiated. In the Miette mud mounds, the bed with concentrated *Thamnopora* under mud mound 5 may have played a similar role as a hard substrate or might have been a favorable foundation for initiating sponge encrustation as discussed in the previous chapter. Sediment stabilizing is evidenced by laminar stromatoporoids in the lower part of mud mound 1 and by the stromatoporoids and corals in the Ancient Wall bioherms. Stromatoporoids and corals formed an interlocking framework locally in the Ancient Wall bioherms where they were sufficiently abundant (Mountjoy and Jull ,1978). However these authors suggested that many of stromatoporoids and corals appear to have encrusted cemented substrates.

Mountjoy and Jull (1978) suggested 25-50 m as the water depth of the Ancient Wall bioherms and Mountjoy and Riding (1981) suggested about 30-50 m for the bioherm 6 located basinward on top of upper megabreccia unit down the fore-reef slope (Fig. 38). These water depths are close to wave base and therefore these bioherms were probably subject to gentle to moderate and in part strong current action (Mountjoy and Jull, 1978; Mountjoy and Riding, 1981). Water depths of about 20-30 m are interpreted for the mud mounds in the Miette reef complex (see Chapter 3.1. concerning water depth). Based on the evidence such as the presence of codiaceans and dasycladaceans, the preservation of sponges, growth forms of stromatoporoids and corals, and Mt. Hawk sediment mentioned in Chapter 3.1, the condition of water is interpreted as being of moderate (initiation of the mounds) to strong (upper part of the mounds) agitation. Hence, the environment of the Ancient Wall bioherms and that of the Miette mud mounds were similar with respect to depth of water and degree of agitation.

Laminar stromatoporoids, calcareous algae especially renalcids, and the massive colonial rugose coral *Phillipsastrea* are relatively abundant and widely distributed in the carbonate mud bioherms of Ancient Wall reef complex (Mountjoy and Jull, 1978; Mountjoy and Riding, 1981). Sediment stabilizing of fenestral-like mudstones by renalcids appeared to be common in the bioherms, and in the basal part of the bioherms. The *Izhella*, *Renalcis* and *Epiphyton* together with early micrite cementation performed a supporting and stabilizing role in the micrites and wackestones (Mountjoy and Riding, 1981). Encrusters of the lime mud - wackestone substrate include almost all stromatoporoids, calcareous algae, and some *Phillipsastrea* colonies. Large colonies of *Phillipsastrea* may, to a limited extent, be sediment binders and trappers (Mountjoy and Jull, 1978).

In the Miette mud mounds sponge spicules are the most abundant skeletal components with calcareous green algae next in abundance. Laminar stromatoporoids and corals such as *Thamnopora* occur locally but are not common. Calcareous blue-green algae such as *Sphaerocodium* and *Girvanella* are common constituents. Only one specimen of renalcids (*Shuguria*, Fig. 23H) was found near the base of mud mound 3. The differences in the biota between these two localities could be due to the differences in sedimentology such as interference of basin sediments and nature of the slope, because the water depths and the conditions of water agitation of these two areas were similar but the configurations and contacts with flanking beds are different (Table 2). The Ancient Wall bioherms faced a deeper relatively open sea, whereas the Miette mud mounds reflect a lower angle more muddy slope (Figs. 4 and 39). The bioherms in the Ancient Wall reef complex have mound or domal forms and are surrounded by and in sharp contact with Mount Hawk basin strata. The sharp (abrupt) contacts between flanking beds suggest that these bioherms grew faster than basin or adjacent platform sedimentation, or formed when little basin sediment was being deposited and were not interrupted by siliciclastic sediments. The organisms in the bioherms may have been little disturbed by muddy conditions and siliciclastic detritus. On the other hand, mud mounds 1, 2 and 4 adjacent to the Miette reef complex have interfingering (irregular) margins (Figs. 8 and 9). This suggests that the growth of these mud mounds was in part coeval with the basin Mount Hawk sedimentation. Interfingering of basin sediments occurs in the lower part of mud mound 1 where sponge remains are rare (Fig. 29, Table 3). Sponges in the Miette mud mounds appear to have been more tolerant of muddy conditions than corals and renalcids in the Ancient Wall mounds Mountjoy and Jull (1978) suggested that the depth of water above Ancient Wall bioherm 3 (Fig. 38) increased to about 25 m or more stopping organic activity. During basin filling with Mount Hawk sediments, it appears that conditions were too muddy or sedimentation was too rapid for the development of either stromatoporoid-coral bioherms, or renalcid mud mounds, even though favorable waters of intermediate depth existed (Mountjoy and Jull, 1978). The mounds in the Ancient Wall reef complex were terminated and buried by basin siliciclastics as sea level continued to rise.

The Ancient Wall mounds contain abundant fenestral-like cavities and rare stromatactis-like cavities (Mountjoy and Jull, 1978), whereas the most abundant type of cavity in the Miette mud mounds are irregular and stromatactoidal cavities. The differences in types of cavities might be related to differences in biota between these areas and perhaps to less muddy conditions along the margin of the Ancient Wall complex.

4.2 Meekwap Buildups, subsurface of Alberta Basin

Several small wackestone/mudstone buildups and/or patch reefs up to 20 m thick occur along the Meekwap carbonate shelf margin in the Swan Hills - Sturgeon Lake part of the central Alberta subsurface. The Meekwap carbonate shelf is a northwest extension of the Nisku carbonate shelf that is somewhat younger than the West Pembina Nisku reefs (Switzer et al., 1994). The

Meekwap shelf prograded southward and southwestward into the Cynthia Basin. These buildups, described briefly by Cheshire and Keith (1977), locally consist of abundant fenestral, renalcid micrite/wackestones with variable amounts of calcareous algae (renalcids) and thin laminar stromatoporoids, termed in part *Renalcis* boundstone. The buildups are flanked by wackestones to grainstones with laminar stromatoporoids, *Euryamphipora*, *Stachyodes* and *Thamnopora*. Where these buildups are dolomitized they form petroleum reservoirs. These buildups are similar in most respects to the mud mounds and bioherms of Ancient Wall (Mountjoy and Riding, 1981). They are similar in some respects to the Miette mud mounds and appear to have grown on similar clinoforms in upper slope settings. Conditions for the development of additional isolated reefs and mounds appear to occur northeast of the Miette reef complex along the northern margin of the Wild River Basin.

4.3 Belgium mud mounds

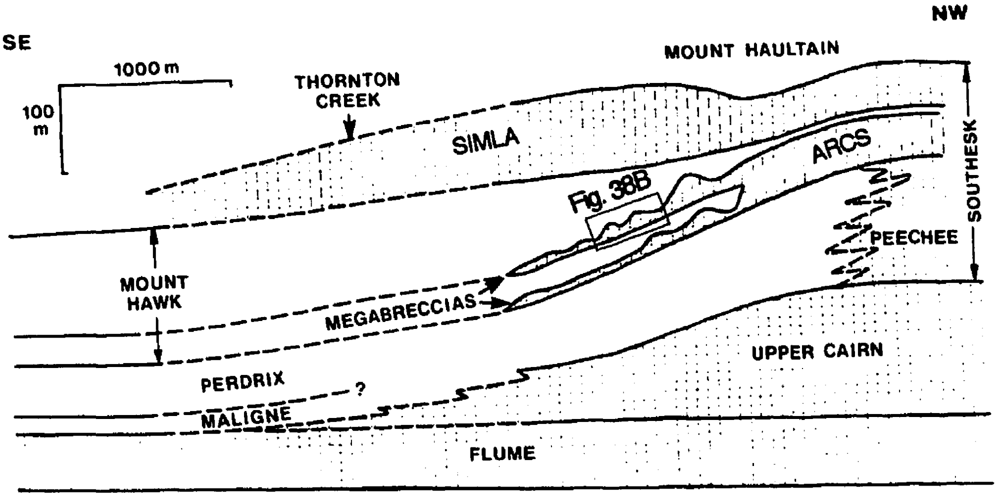
One of the best known examples of mid-Paleozoic mud mounds are the Frasnian "récifs rouges" of Belgium. They contain three major facies. Facies A consists of red, sponge-rich mudstones with stromatactis interpreted to represent deposition below storm wave base, Facies B consists of pink coral-stromatoporoid mudstones and wackestones deposited in the subphotic zone, and Facies C consists of gray coral-thrombolite-calcimicrobe strata of the shallowest photic zone (Fig. 40). The sponge-rich wackestone facies in the lower part of the Miette mud mounds are comparable with Facies A of "récifs rouges" and the upper part of the Miette mounds with calcareous green algae are similar to Facies C. James and Bourque (1992) suggested that the late Devonian (Frasnian) "récifs rouges" are deep water carbonate mounds and show a depth-dependent vertical succession of facies (Fig. 40). With the exception of some calcimicrobial mounds of Facies C, which appear to have been able, like modern calcareous algae, to grow in high-energy environments, most mounds are interpreted as occurring in preferred quiet water locations, 1) downslope on gently dipping platform margins, 2) in deep basins, and 3) widespread in tranquil reef lagoons or wide shelf areas (James and Bourque, 1992).

In the case of the Miette mounds branching *Thamnopora* colonies in the basal part of mud mound 5 appear to be comparable to the branching corals in Facies C of "récifs rouges". However the shallowest facies in the Miette mounds (Fig. 37) consist of sponge-rich or green algal wackestones which are similar to the deepest Facies A of the "récifs rouges". In the Belgium "récifs rouges" Facies A has been interpreted to be much deeper occurring below storm wave base, although little direct evidence for deep water was presented by James and Bourque (1992). The sponge-rich wackestone facies in the Miette mud mounds occur in much shallower waters at depths less than 30 m above storm wave base and thus in the photic zone (Fig. 37). Thus in the Miette mud mounds the stromatactis, sponge-bearing wackestones occur in shallow water environoments. This casts doubt on the deep water interpretation applied to Facies A of the Belgium "récifs rouges"

4.4 Summary

The Miette mud mounds are similar to some aspects of the Ancient Wall and Meekwap mounds and buildups, and to Facies A of the sponge-rich wackestones of the "récifs rouges" of the Upper Devonian Belgium mud mounds. However, the Miette mounds lack abundant calcareous algae and contain only a few encrusting stromatoporoids and corals compared to the other mounds. The Miette stromatactis, sponge-bearing wackestone mounds were deposited in shallow moderately agitated waters ranging from 1 to 30 m deep, in an upper fore reef slope. Elsewhere stromatactis wackestones have been interpreted as a deep water facies deposited below wave base. The Miette mounds show that this facies is not depth dependent as has been previously suggested.

A



B

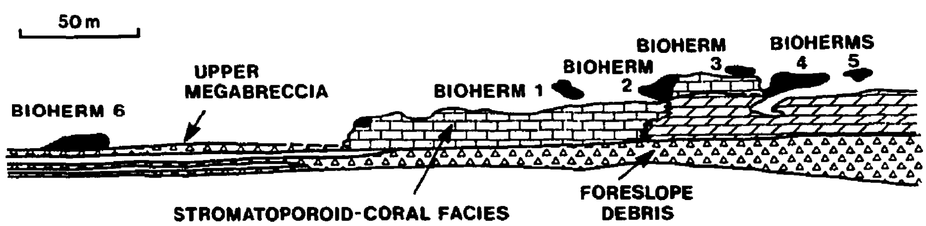


Figure 38. Stratigraphic cross section of southeastern margin, Ancient Wall reef complex.

A. Illustrates stratigraphic relationships at Mount Haultain showing the transition to basinal facies. The foreslope bioherms occur on or above the upper megabreccia bed and stromatoporoid-coral reef-margin facies of the Arcs Member (modified from Mountjoy and Riding, 1981).

B. Relative positions of bioherms on top of or close to a basinward tongue of the upper Arcs Member (from Mountjoy and Riding, 1981). For general setting see Fig. 38A.

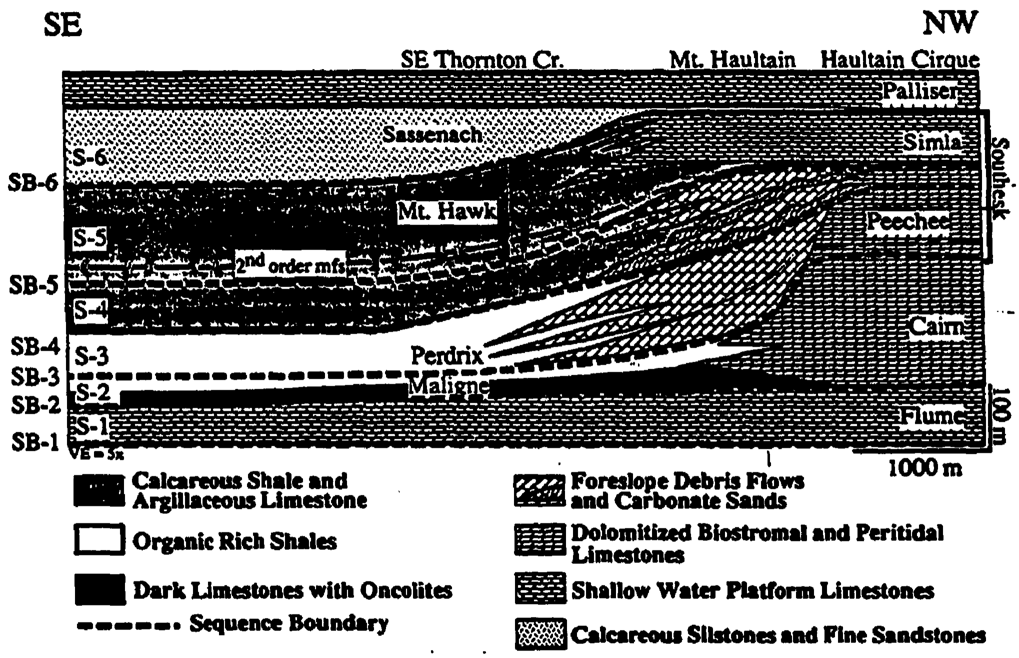


Figure 39. Schematic geological cross section of the Ancient Wall reef complex and strata flanking the southeastern margin of the reef complex showing 6 sequences (S1 to S6) from Van Buchem et al. (1995). S = Sequence, SB = Sequence boundary.

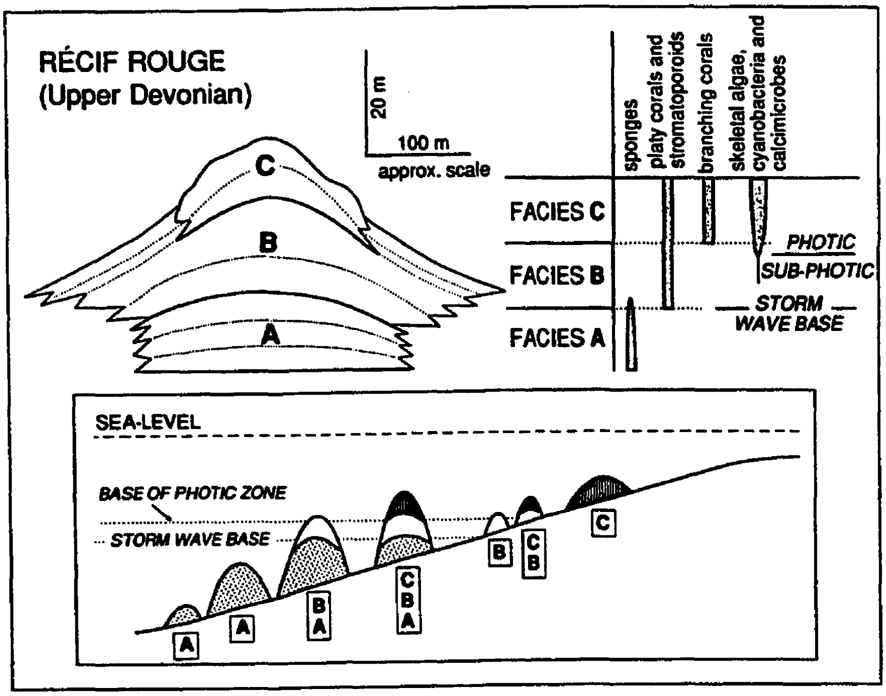


Figure 40. Facies mosaic and vertical succession of Upper Devonian "récifs rouges" of Belgium.

(Top, left) complete facies succession; dotted lines are growth surfaces. (Top, right) ecological assemblages and depth zonation. (Inset) Conceptual model of distribution of various types of monogenic and composite mounds on a slope with stacking order of facies for each mound. Facies A = red, stromatactis, sponge-rich mudstone mound; Facies B = pink coral/stromatoporoid/mud mound; Facies C = gray coral/thrombolite/calcimicrobe mound. From James and Bourque (1992, Fig.18).

Table 2. Summary of main characteristics of the Ancient Wall bioherms and the Miette mud mounds.

	Ancient Wall bioherms	Miette mud mounds
Width (m)	7.5 - 23	32 - 81.5
Thickness (m)	4 - 6	17 - 36.5
Form	Mound, domal or elongated form	Conical to domal except mushroom shape of mud mound 1
Number of growth stage	1	1 - 3
Internal bedding	Poor to massive, indistinct	Massive
Margin and flanking beds	Sharp, no gradational contacts with flanking detritus	Interfingering or abrupt
Lithology	Micritic to wackestone	Mainly wackestone
Nature of biota	Frame-building organisms include laminar and hemispherical colonies of Phillipsastrea, renalcid algae, encrusting calcareous algae, and laminar stromatoporoids	Siliceous sponges, calcareous green and blue-green algae, and laminar stromatoporoids

CHAPTER 5. SUMMARY AND CONCLUSIONS

The five mud mounds that flank the southeast margin of the Miette reef complex consist of lime mudstones, and sponge-skeletal wackestones and packstones. The lower parts of the mounds are characterized by sponge and laminar stromatoporoid wackestones to boundstones. Mound 5 contains a basal *Thamnopora* rich bed. The upper parts of the mounds contain more calcareous green algae packstones, with minor amounts of sponge spicules.

Lime mud was accreted by trapping, binding, stabilizing and encrusting organisms living on and in the mound. Siliceous sponges in the lower part of the mounds and calcareous green algae in the upper part of the mounds, appear to have played key roles in the accretion and development of the mounds.

The depths of water for initiation of the mud mounds is estimated to be about 20 to 30 m on the basis of their position on upper slope carbonate clinoforms. They occur adjacent to very shallow water sediments (< 1 to 2 m) of the Arcs Member bank deposited over and lateral to the main part of the Miette reef complex.

The occurrence of thin laminar stromatoporoids and in-situ sponges in predominantly wackestone to mudstone facies suggests moderate agitation during the initiation of the mounds. Moreover, limemudstones and calcareous shales of the underlying Mount Hawk lack shallow water sedimentary structures suggesting low energy levels during mound initiation. Packstone facies and more green algae indicate stronger agitation in the upper parts of the mounds.

Colonies of the branching tabulate coral *Thamnopora* in the basal part of mound 5 locally appear to have formed a suitable foundation for growth of siliceous sponges and other organisms that may have helped to initiate this mound. Other mounds appear to have been initiated where stromatoporoids, sponges and calcareous green algae trapped and bound sediment on the upper slope carbonate clinoforms

The abrupt contacts between flanking beds suggest that the mud mounds grew faster than basin or adjacent platform sedimentation and were not interrupted by siliciclastic sediments, and that most of the carbonate mud, wackestone and packstone originated in the mound. The mounds accreted to near sea level based on the sharp contacts with surrounding and capping sediment. The mounds were exposed during a lowstand when the basal Ronde silts were deposited around the upper parts of the mounds.

Shelter cavities occur beneath laminar stromatoporoids and brachiopod shells. The most common cavity types, irregular and stromatactoidal cavities, might be of organic origin, possibly related to the decay of sponges as indicated by the abundant sponge spicules. A few stromatactoidal cavities are typical stromatactis. Many cavities are floored with internal geopetal sediments. Lithification occurred early before or at the same time as cavities were formed, in order to preserve these cavities.

The mud mounds were tightly cemented early and cavities were filled with fibrous calcite and blocky calcite cement. The general sequence of diagenesis is: 1) early lithification of matrix (and formation of cavities); 2) geopetal sediment; 3) isopachous fibrous calcite; 4) local dolomite cement; 5) stylolitization; 6) fracturing; 7) bitumen emplacement; 8) late fracturing; and 9) blocky calcite cementation.

Although some minor porosity remains mainly in irregular shaped cavities, nearly all primary porosity is occluded. Consequently the Miette mud mounds have little reservoir potential. Likely the early lithification of the mounds prevented shallow burial dolomitizing fluids from entering them.

The Miette mud mounds are similar in some aspects to the Ancient Wall and Meekwap mounds and buildups, and to Facies A of the sponge-rich wackestones of the "récifs rouges" of the Upper Devonian Belgium mud mounds. However, the Miette mounds lack abundant calcareous algae and contain only a few encrusting stromatoporoids and corals compared to the other mounds. The differences in the biota between Miette and Ancient Wall and Meekwap could be due to differences in slope, water circulation and amounts of basin sediments deposited during mound accretion. The Ancient Wall bioherms, which contain no obvious sponge material and have rare stromatactoidal cavities, support a possible inorganic cementation origin for the irregular and stromatactoidal cavities.

The sponge-rich Facies A of the Upper Devonian mud mounds ("récifs rouges") in Belgium have similar characteristics to the Miette mud mounds. However, the Belgium mounds are interpreted to have been deposited in much deeper water below storm wave base, compared to the shallow water sponge-rich Miette mounds that accumulated in the photic zone above storm wave base.

REFERENCES

Adey, W.H., 1966. Distribution of saxicolous crustose corallines in the northwestern north Atlantic. Journal of Phycology, v. 2, p. 49-54.

Bathurst, R.G.C., 1980. Stromatactis - origin related to submarine cemented crusts in Paleozoic mud mounds. Geology, v. 8, p. 131-134.

Bathurst, R,G,C., 1982. Genesis of stromatactic cavities between submarine crusts of Paleozoic carbonate mud buildups. Journal of the Geological Society of London, v. 139, p. 165-181.

Beauchamp, B., 1989. Lower Permian (Artinskian) sponge-bryozoan buildups, southwestern Ellesmere Island, Canadian Arctic Archipelago. *in:* Reefs, Canada and Adjecent Areas. Geldsetzer, H.H.J., James, N.P., and Tebbutt, G.E. (eds.). Canadian Society of Petroleum Geologists, Memoir 13, p. 575-584.

Boulvain, F., 1993. Sédimentologie et diagenèse des monticules micritiques "F2j" du Frasnian de l'Ardenne. Serv. géol. Belg. Prof. Pap., 1993/2, N° 260, pp. 436.

Bourque, P.-A. and Boulvain, F., 1993. A model for the origin and petrogenesis of the red stromatactis limestone of Paleozoic carbonate mounds. Journal of Sedimentary Petrology, v. 63, p. 607-619.

Bourque, P.-A. and Gignac, H., 1983. Sponge-constructed stromatactis mud mounds, Silurian of Gaspe, Quebec. Journal of Sedimentary Petrology, v. 53, p. 521-532.

Bourque, P.-A. and Gignac, H., 1986. Sponge-constructed stromatactis mud mounds, Silurian of Gaspe, Quebec. Journal of Sedimentary Petrology, v. 56, p. 461-463.

Brachert, T.C., 1991. Environmental Control on Fossilization of Siliceous Sponge Assemblages: A Proposal. *in:* Fossil and Recent Sponges. Reitner, J. and Keupp, H. (eds.). Springer-Verlag, Berlin, p. 543-553.

Bridges, P.H. and Chapman, A.J., 1988. The anatomy of a deep water mudmound complex to the southwest of the Dinantia platform in Derbyshire, UK. Sedimentology, v. 35, p. 139-162.

Camoin, G. and Maurin, A.-F., 1988. Roles of micro-organisms (bacteria, cyanobacteria) in the formation of mud mounds: Examples from the Turonian strata of Jebels Bireno and Mrhila (Tunisia). Comptes Rendu Academie Sciences, Paris, Série II, p. 401-407.

Chave, K.E., 1964. Skeletal durability and preservation. *in:* Approaches to Paleoecology. Imbrie, J. and Newell, N.D. (eds.). John Wiley & Sons, New York, p. 377-387.

Cheshire, S.G. and Keith, J.W. 1977. Meekwap field, a Nisku (Upper Devonian) shelf edge reservoir. in: Devonian and Mississippian Carbonate reservoirs. McIlreaeth, I.A. (ed.) Canadian Society of Petroleum Geologists, Calgary, p. 23-45.

Conway, K.W., Barrie, J.V. and Luternauer, J.L., 1989. Sponge bioherms on the continental shelf of western Canada. *in:* Current Research Part H. Geological Survey of Canada, Paper 89-1H, p. 129-134.

Heckel, P.H., 1972. Possible inorganic origin for stromatactis in calcilutite mounds in the Tully Limestone, Devonian of New York. Journal of Sedimentary Petrology, v. 42, p. 7-18.

Hedinger, A.S. and Workum, R.H., 1989. Uppermost Frasnian reefs, Jasper Basin, Alberta. *in:* Reefs, Canada and Adjecent Areas. Geldsetzer, H.H.J., James, N.P., and Tebbutt, G.E. (eds.). Canadian Society of Petroleum Geologists, Memoir 13, p. 466-470.

Hopkins, J.C., 1972. Petrography, distribution and diagenesis of foreslope and basin sediments, Miette and Ancient Wall carbonate complexes (Devonian), Alberta. Unpublished Ph.D. thesis, McGill University, Montreal.

James, N.P. and Bourque, P.-A., 1992. Reefs and Mounds. *in:* Facies Models: Response to sea level change. Walker, R.G. and James, N.P. (eds.). Geological Association of Canada, p. 323-348.

James, N.P. and Ginsburg, R.N., 1979. The seaward margin of Belize barrier and atoll reefs. International Association of Sedimentologists Special Publication, n. 3, pp. 191.

Kobluk, D., 1975. Stromatoporoid paleoecology of the southeast margin of the Miette carbonate complex, Jasper Park, Alberta. Bulletin of Canadian Petroleum Geology, v. 23, p. 224-277.

Kerans, C., 1985. Petrology of Devonian and Carboniferous carbonates of the Canning and Bonaparte Basins. *Western Australian Mining and Petroleum Research Institute,* **Report 12.**

Kerans, C., Hurley, N.F. & Playford, P.E., 1986. Marine diagenesis in Devonian reef complexes of the Canning Basin, Western Australia. In: *Reef Diagenesis* (Ed. by J.H. Schroeder and B.H. Purser), pp. 357-380. Springer Verlag, New-York.

Land, L.S. and Moore, C.H., 1980. Lithification, micritization and syndepositional diagenesis of biolithies on the Jamaican Island slope. Journal of Sedimentary Petrology, v. 50, p. 357-370.

Laubenfels, M.W., 1955. Porifera. *in:* Treatise on invertebrate paleontology, Part E. Moore, R.C. (ed.). University of Kansas and Geological Society of America, pp. 122.

Lees, A. and Miller, J., 1985. Facies variation in Waulsortian buildups, Part 2; Mid-Dinatian buildups from Europe and North America. Geological Journal, v. 20, p. 159-180.

MacGeachy, J.K., 1978. Geological Significance of Boring Sponges on Barbados reefs. Unpublished Ph.D. thesis, McGill University, Montreal.

Machel, H.-G., 1986. Early Lithification, Dolomitization, and Anhydritization of Upper Devonian Nisku Buildups, Subsurface of Alberta, Canada. *in:* Reef Diagenesis. Schroeder, J.H. and Purser, B.H. (eds.). Springer-Verlag, Berlin. p. 336-356.

Macintyre, I.G., 1985. Submarine cements - the peloidal question. *in:* Carbonate Cements. Schneidermann, N. and Harris, P.M. (eds.). Society of Economic Paleontologists and Mineralogists Special Publication, n. 36, p. 109-116.

Majewske, O.P., 1974. Recognition of Invertebrate Fossil Fragments in Rocks and Thin Sections. Culillier, J. and Schürmann, H.M.E. (eds.). International Sedimentary Petrographical Series XIII. pp. 101.

Mamet, B.L. and Plafker, G., 1982. A Late Devonian (Frasnian) Microbiota from the Farewell-Lyman Hills Area, West-Central Alaska. Geological Survey Professional Paper 1216-A. pp. 21.

Mamet, B.L. and Roux, A., 1981. Note sur le genre Issinella (Algue verte paléozoique). Rev. Micropaleontol., 23 3/4, p. 151-158.

Mattes, B.W. and Mountjoy, E.W., 1980. Burial dolomitization of the Upper Devonian Miette buildup, Jasper National Park, Alberta. *in:* Concepts and Models of Dolomitization. Zenger, D.H., Dunham, J.B. and Ethington, R.L. (eds.). Society of Economic Paleontologists and Mineralogists Special Publication, n. 28, p. 259-297.

McLean, D.J. and Mountjoy, E.W., 1994. Allocyclic control on Late Devonian buildup development, southern Canadian Rocky Mountains. Journal of Sedimentary Research, Stratigraphy and Global Studies, v. B64, p. 326-340.

Monty, C.L.V., 1982. Cavity and fissure dwelling stromatolites (endostromatolites) from the Belgian Devonian mud mounds. Ann. Soc. géol. Belg., 105, p. 343-344.

Monty, C.L.V., Bernet-Rollande, M.C. and Maurin, A.F., 1982. Re-interpretation of the Frasnian classical 'reefs' of the southern Ardennes, Belgium. Ann. Soc. géol. Belg., 105, p. 339-341.

Mountjoy, E.W., 1965. Stratigraphy of the Miette Reef complex and associated strata, eastern Jasper National Park, Alberta. Geological Survey of Canada, Bulletin 110, pp. 113.

Mountjoy, E.W.,1980, Some questions about the development of Upper Devonian carbonate buildups (reefs), Western Canada. Bulletin of Canadian Petroleum Geology, V. 28, p. 315-344.

Mountjoy, E.W., 1989. Miette reef complex (Frasnian), Jasper National Park, Alberta. Canadian Society of Petroleum Geologists, Memoir 13, p. 497-505.

Mountjoy, E.W. and Amthor, J.E., 1994. Has burial dolomitization come of age? Some answers from the Western Canada Sedimentary Basin. *in:* International Association of Sedimentologists Special Publication, n. 21, p. 203-229.

Mountjoy, E.W. and Burrowes, O.G., 1982. Upper Devonian Miette reef complex, Jasper National Park, Alberta. International Association of Sedimentologists, 11th International Congress on Sedimentology, Field Excursion 27A Guidebook, McMaster University, Hamilton, pp. 57.

Mountjoy, E.W. and Jull, R.K., 1978. Fore-reef carbonate mud bioherms and associated reef margin, Upper Devonian, Ancient Wall reef complex, Alberta. Canadian Journal of Earth Sciences, v. 15, p. 1304-1325.

Mountjoy, E.W. and Riding, R., 1981. Foreslope stromatoporoid-renalcid bioherm with evidence of early cementation, Devonian Ancient Wall reef complex, Rocky Mountains. Sedimentology, v. 28, p. 299-319.

Pratt, B.R., 1982. Stromatolitic framework for carbonate mudmounds. Journal of Sedimentary Petrology, v. 52, p. 1203-1227.

Pratt, B.R., 1986. Sponge-constructed stromatactis mud mounds, Silurian of Gaspe, Quebec-discussion. Journal of Sedimentary Petrology, v. 56, p. 459-460.

Pratt, B.R., 1995. The origin, biota and evolution of deep-water mud-mounds. *in:* Carbonate Mud-Mounds. Monty, C.L.V., Bosence, D.W.J., Bridges, P.H. and Pratt, B.R. (eds.). International Association of Sedimentologists Special Publication, n. 23, p. 49-123.

Riding, R., 1975. Girvanella and other algae as depth indicators. Lethaia, v. 8, p. 173-179.

Ross, R.J.Jr., Jaanusson, V. and Friedman, I., 1975. Lithology and origin of Middle Ordvician calcareous mudmound at Meiklejohn Peak, Southern Nevada. Geological Survey Professional Paper 871, pp. 48.

Savoy, L.E. and Mountjoy, E.W., 1995. Cratonic-margin and Antler-age foreland basin strata (Middle Devonian to Lower Carboniferous) of the southern Canadian Rocky Mountains and adjacent plains. *in:* Stratigraphic Evolution of Foreland Basins, SEPM Special Publication, n. 52, p. 213-231.

Shinn, E.A., 1968a. Burrowing in Recent lime sediments of Florida and the Bahamas. Journal of Paleontology, v. 42, p. 879-894.

Shinn, E.A., 1968b. Practical significance of birds eye structures in carbonate rocks. Journal of Sedimentary Petrology, v. 38, p. 215-223.

Shinn, E.A., 1969. Submarine lithification of Holocene carbonate sediments in the Persian Gulf. Sedimentology, v. 12, p. 109-144.

Stearn, C.W., 1975. Stromatoporoid assemblages, Ancient Wall Reef Complex (Devonian), Alberta. Canadian Journal of Earth Sciences, v. 12, p. 1631-1667.

Stearn, C.W. and Carroll, R.L., 1989. Paleontology: The Record of Life. John Wiley & Sons, Inc., pp. 453.

Stenzel, S.R. and James, N.P., 1995. Shallow-water stromatactis mud-mounds on a Middle Ordovician foreland basin platform, weatern Newfoundland. *in:* Carbonate Mud-Mounds. Monty, C.L.V., Bosence, D.W.J., Bridges, P.H. and Pratt, B.R. (eds.). International Association of Sedimentologists Special Publication, n. 23, p. 127-149.

Stoakes, F.A., 1980. Nature and control of shale basin fill and its effect on reef growth and termination: Upper Devonian Duvernay and Ireton Formations of Alberta, Canada. Bulletin of Canadian Petroleum Geology, v. 28, p. 345-410.

Switzer, S.B., Holland, W.G., Christie, D.S., Graf, G.C., Hedinger, A.S., McAuley, R.J., Wierzbicki, R.A. and Packard, J.J., 1994. Devonian Woodbend - Winterburn strata of the Western Canada sedimentary basin (Chapter 12). in:Geological Atlas of the Western Canada Sedimentary Basin. Alberta Geological Survey, p. 165-202.

Tsien, H.H., 1985a. Origin of stromatactis - a replacement of colonial microbial associations. *in:* Paleoalgology: Contemporary Research and Applications. Toomey, D.F. and Nitecki, M.H. (eds.). Springer-Verlag, Berlin, p. 274-289.

Tsien, H.H., 1985b. Algal-bacterial origin of micrites in mud mounds. *in:* Paleoalgology: Contemporary Research and Applications. Toomey, D.F. and Nitecki, M.H. (eds.). Springer-Verlag, Berlin, p. 290-296.

Toomey, D.F., Mountjoy, E.W. and MacKenzie, W.S., 1970. Upper Devonian (Frasnian) algae and foraminifera from the Ancient Wall carbonate complex, Jasper National Park, Alberta, Canada. Canadian Journal of Earth Sciences, v. 7, p. 946-981.

Tucker, M.E. and Wright, V.P., 1990. Carbonate Sedimentology. Blackwell Scientific Publications, Oxford, pp. 482.

Van Buchem, F., Eberli, G.P., Whalen, M.T., Mountjoy, E.W. and Homewood, P., 1995, High and low frequency sedimentary and geochemical cycles in the Upper Devonian carbonate system of Western Canada: implications for outcrop to subsurface correlations. American Association of Petroleum Geologists Bulletin, v. 79, p. 1253.

Vos, L.D., Rützler, K., Boury-Esnault, N., Donadey, C. and Vacelet, J., 1991. Atlas of Sponge Morphology. Smithsonian Institution Press, pp. 117.

Walls, R.A. and Burrowes, G., 1985. The role of cementation in the diagenetic history of Devonian reefs, Western Canada. *in:* Carbonate Cements. Schneidermann, N. and Harris, P.M. (eds.). Society of Economic Paleontologists and Mineralogists Special Publication, n. 36, p. 185-220.

Wallace, M.W., 1987. The role of internal erosion and sedimentation in the formation of stromatactis mudstones and associated lithologies. Journal of Sedimentary Petrology. v. 57, p. 695-700.

Wilson, J.L., 1975. Carbonate Facies in Geologic History. Springer-Verlag, Berlin, pp. 471.

Wood, R., 1990. Reef-building sponges. American Scientist, v. 78, p. 224-235.

Wray, J.L., 1977. Calcareous Algae: Developments in Paleontology and Stratigraphy. Elsevier, Amsterdam, pp. 185.

Appendix 1. Stratigraphic section, head of Poachers Creek, McConnell thrust sheet.

	Thickness in meters
Sassenach Formation (12 m+)	
Sandstones, gold brown, with algal laminations.	12 +
Ronde Member (50 m)	
Limestone, lt gray, massive, silty, resistent.	16
Limestone, dark gray, thin bedded.	5
Dolostone, gray, silty.	4
Covered interval.	8
Dolostone, gray, resistent, abundant laminar corals and solitary corals.	2
Covered interval.	6
Dolostone, light gray, silty, resistent, laminar stromatoporoids and *Amphipora*.	9
Arcs Member (23 m)	
Carbonates, gray, silty, slightly bedded, laminar stromatoporoids, *Disphyllum* and *Thamnopora*, small elliptical cavities.	23
Mount Hawk Formation (29 m+)	
Carbonate mudstones, grayish black, massive, laminar stromatoporoids, brachiopods, solitary corals, *Disphyllum* and *Thamnopora*.	29 +

Appendix 2. Stratigraphic section, head of Fiddle River, Miette thrust sheet.

	Thickness in meters
Palliser Formation (4 m+)	
Limestone, grayish white, limy, sandy, massive.	4 +
Sassenach Formation (34 m)	
Sandstones, grayish white, limy, fine, occasionally medium, with algal laminations and boulbous stromatolite.	5.5
Limestone, grayish white, limy, fine sandy, well bedded, algal lamination with truncation.	15
Sandstones, whitish gray, silty, with laminations, brachiopods, elliptical cavities.	7
Limestone mudstones, blackish gray, dolomitic, silty, slightly bedded, brachiopods and *Amphipora*.	6.5
Ronde Member (81 m)	
Limestone, gray to blackish gray, argillaceous to silty, massive, resistent, laminar stromatoporoids, colonial corals, solitary corals, gastropods, nautiloids, megalodonts, *Thamnopora* and *Amphipora*.	42
Limestone, dark gray, silty, thin bedded.	7
Limestone mudstones, gray to dark gray, dolomitic, silty, brachiopods, laminar stromatoporoids, solitary corals, nautiloids and gastropods.	19
Dolostone, gray, silty, massive, resistent, silty and sandy laminations, laminar stromatoporoids, solitary corals, *Disphyllum*, *Thamnopora* and *Amphipora*, trace fossils, elliptical cavities, nodules.	13
Mount Hawk Formation (28 m+)	
Limestone mudstones, grayish black, massive, laminar stromatoporoids, brachiopods, solitary corals, gastropods, *Disphyllum* and *Thamnopora*, with mud clasts.	6

Covered interval.	5
Limestone mudstones, blackish gray, brachiopods, solitary corals, gastropods, trace fossils.	17+

APPENDIX 3. TABLES 3 TO 7 LISTING PROPORTIONS OF DIFFERENT COMPONENTS DETERMINED BY POINTCOUNTING FOR MOUNDS 1 TO 5.

Table 3. Proportion of different skeletal components determined by pointcounting of selected thin sections in Mud Mound 1.

Sample No.	25	217	203	32	26	245	216	27	249	28	250	251	29	30	246	252	206	207	208	248	205
% of cavity in hand specimen	1	5	5	10	5	40	3	5	5	3	20	25	10	3	5	3	3	1	10	5	1
Green algae	2	1	0	2	2	3	1	6	3	6	0	0	13	33	6	9	8	15	11	16	16
Girvanella	0	0	0	0	0	1	0	0	1	1	1	0	0	3	0	0	0	0	0	1	0
Sphaerocodium	0	0	0	0	0	0	0	0	0	1	0	0	0	2	0	0	0	0	0	0	0
Bispheres	0	0	0	0	0	2	0	0	1	3	0	2	0	1	2	4	0	1	0	1	0
Calcispheres	0	0	0	0	0	2	0	0	0	0	0	0	3	0	2	0	0	0	0	0	0
Foraminifers	2	0	0	0	0	0	0	1	2	1	0	0	1	11	1	4	4	5	3	1	4
Sponges*	25	24	30	16	20	15	8	6	1	21	2	5	0	1	7	0	0	0	0	0	0
Stromatoporoids	0	0	0	23	5	0	8	0	0	0	0	0	0	0	0	0	34	3	0	5	0
Thamnopora	0	0	0	0	2	2	0	0	0	2	0	0	0	0	5	0	0	5	0	0	0
Other corals	0	0	0	0	0	0	0	0	1	2	0	2	0	0	0	0	0	12	1	4	20
Bryozoans	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Brachiopods	2	0	0	0	2	7	2	5	2	3	0	4	1	9	0	1	3	1	14	1	4
Gastropods	1	0	0	1	0	0	2	0	1	4	0	0	0	4	12	0	0	0	0	0	1
Trilobites	1	0	0	0	0	0	0	0	0	0	0	0	0	5	2	1	1	1	1	0	0
Ostracodes	5	1	1	2	1	4	1	3	2	3	2	3	5	9	6	4	2	1	0	3	0
Crinoids	1	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Echinoids	1	1	0	1	0	1	0	0	0	1	0	0	0	2	0	0	0	0	0	1	2
Others	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	1	0	0
Indeterminable	7	2	0	1	2	1	0	2	1	0	0	0	2	5	0	3	0	2	3	2	2
Total counts	186	116	114	143	101	139	118	129	141	194	61	65	109	222	156	200	175	221	137	122	241

Sponges* include textures suggestive of sponges and molds of spicules (see text).

Table 4. Proportion of different skeletal components determined by pointcounting of selected thin sections in Mud Mound 2.

Sample No.	244	241	240	239	238	71	72	75	76
% of cavity in hand specimen	3	5	5	3	5	5	0	0	0
Green algae	3	8	3	1	1	6	41	27	24
Girvanella	0	0	0	0	0	0	0	1	0
Sphaerocodium	0	0	0	0	0	2	2	6	1
Bispheres	2	0	0	0	0	3	0	0	1
Calcispheres	0	0	0	0	0	0	0	0	0
Foraminifers	0	0	0	0	0	0	1	4	2
Sponges*	0	31	25	3	1	10	8	6	2
Stromatoporoids	0	0	0	0	0	0	8	0	0
Thamnopora	1	7	4	0	0	0	0	3	11
Other corals	0	0	0	0	0	0	0	2	5
Bryozoans	0	0	0	0	0	0	0	0	0
Brachiopods	3	0	0	1	1	5	5	7	5
Gastropods	0	0	0	0	0	0	0	0	1
Trilobites	1	0	0	0	0	4	3	5	3
Ostracodes	2	1	1	1	0	5	10	4	3
Crinoids	0	0	0	0	0	0	0	1	0
Echinoids	0	0	0	1	0	0	2	2	1
Others	0	0	0	0	0	0	0	0	1
Indeterminable	5	2	1	1	0	5	4	7	6
Total counts	98	153	108	202	127	155	194	220	209

Sponges* include textures suggestive of sponges and molds of spicules (see text).

Table 5. Proportion of different skeletal components determined by pointcounting of selected thin sections in Mud Mound 3.

Sample No.	21	48	18	17	15	49
% of cavity in hand specimen	1	10	5	1	0	3
Green algae	6	7	2	15	4	9
Girvanella	1	0	1	1	1	1
Sphaerocodium	6	0	0	0	6	7
Bispheres	0	0	0	0	1	0
Calcispheres	0	0	0	0	0	0
Foraminifers	1	1	0	2	1	0
Sponges*	15	10	22	24	0	13
Stromatoporoids	2	0	0	2	0	0
Thamnopora	7	0	9	3	0	0
Other corals	0	0	0	0	0	0
Bryozoans	0	0	0	0	0	0
Brachiopods	6	2	3	3	6	2
Gastropods	0	2	1	0	0	0
Trilobites	0	0	2	1	0	0
Ostracodes	6	4	0	7	11	5
Crinoids	0	0	0	0	0	0
Echinoids	2	0	0	1	0	0
Others	0	2	0	0	0	0
Indeterminable	7	1	0	4	1	1
Total counts	167	84	131	154	86	107

Sponges* include textures suggestive of sponges and molds of spicules (see text).

Table 6. Proportion of different skeletal components determined by pointcounting of selected thin sections in Mud Mound 4.

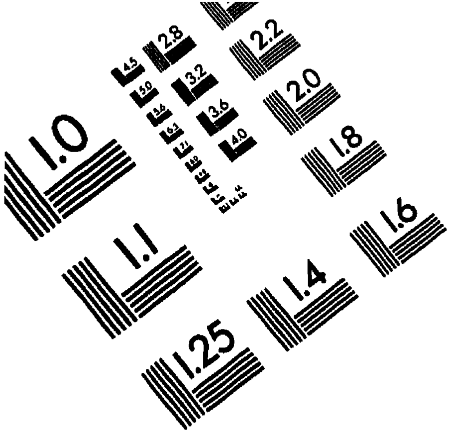
Sample No.	86	87	93	91	92
% of cavity in hand specimen	3	5	2	2	10
Green algae	8	8	2	3	6
Girvanella	0	0	0	0	0
Sphaerocodium	2	3	0	0	0
Bispheres	0	0	0	0	0
Calcispheres	0	0	0	0	0
Foraminifers	2	0	0	0	0
Sponges*	36	15	20	12	15
Stromatoporoids	3	0	0	0	0
Thamnopora	0	1	0	6	0
Other corals	0	0	0	0	0
Bryozoans	0	0	0	0	0
Brachiopods	3	9	2	0	1
Gastropods	0	0	0	0	0
Trilobites	0	0	0	0	0
Ostracodes	3	4	0	4	5
Crinoids	0	0	0	0	1
Echinoids	0	2	0	2	2
Others	0	0	0	0	0
Indeterminable	1	1	1	1	2
Total counts	210	143	186	224	96

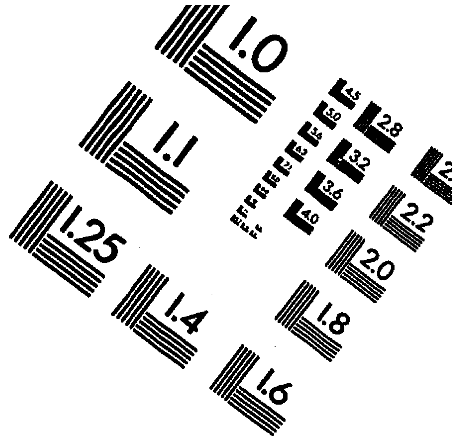
Sponges* include textures suggestive of sponges and molds of spicules (see text).

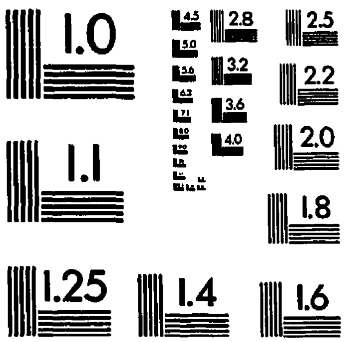
Table 7. Proportion of different skeletal components determined by pointcounting of selected thin sections in Mud Mound 5.

Sample No.	226	227	231	230	99	229	96	228
% of cavity in hand specimen	10	2	2	5	5	3	1	2
Green algae	5	8	4	0	1	6	12	1
Girvanella	2	2	2	0	0	0	2	0
Sphaerocodium	0	13	8	1	0	0	7	3
Bispheres	0	0	0	0	1	0	0	0
Calcispheres	0	0	0	0	0	0	0	0
Foraminifers	0	0	0	1	1	0	0	0
Sponges*	3	18	6	18	4	10	5	15
Stromatoporoids	0	0	0	0	0	0	0	0
Thamnopora	2	0	0	0	3	1	0	0
Other corals	0	0	0	0	0	0	0	0
Bryozoans	0	0	0	0	0	4	1	0
Brachiopods	3	4	0	0	3	0	0	1
Gastropods	0	0	0	0	0	1	1	0
Trilobites	0	2	0	0	0	2	7	0
Ostracodes	5	3	11	4	5	0	5	7
Crinoids	0	0	0	0	0	0	0	0
Echinoids	0	1	2	0	1	1	1	0
Others	0	0	0	0	0	0	0	0
Indeterminable	1	1	1	0	3	1	3	0
Total counts	139	229	254	192	118	212	130	189

Sponges* include textures suggestive of sponges and molds of spicules (see text).

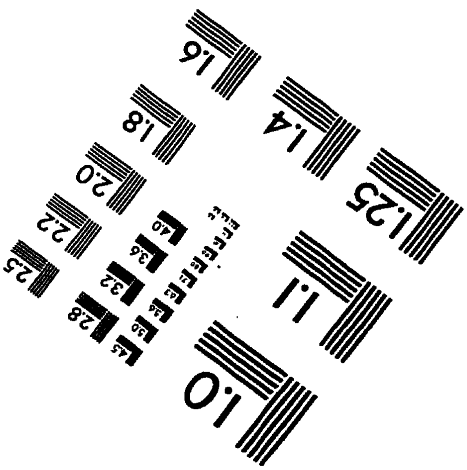






150mm

6″



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