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BULLETIN 102

STROMATOLITES IN THE DENAULT FORMATION, MARION LAKE, COAST OF LABRADOR, NEWFOUNDLAND

J. A. Donaldson

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By
J. A. Donaldson

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PREFACE

Stromatolites, under various names, have been recognized in late Precambrian or younger rocks almost since these rocks were first studied. Their organic origin has been proposed and questioned, and various attempts have been made to classify them.

The author in this report proposes a simple, practical classification based solely on outward appearance, and describes and figures his types. He shows how these have stratigraphic significance and may be used for correlation. He then goes on to speculate on the conditions and processes in and by which the various forms were developed.

J. M. HARRISON,
Director, Geological Survey of Canada

OTTAWA, August 21, 1962

Bulletin 102 — Stromatoliten in der Denault Formation, Marion See, Küste von Labrador, Neufundland.

Von J. A. Donaldson.

Eine beschreibende, nichtbiologische Klassifizierung der Stromatoliten wird gegeben und mögliche Art der Entstehung ist erwogen.

Бюллетень 102 — Строматолиты Деноултской свиты, оз. Марион, побережье Лабрадора, Ньюфаундленд.

Д. А. Доналдсон.

Дается описательная, небиологическая классификация строматолитов, а также рассматриваются возможные способы их происхождения.

STROMATOLITES IN THE DENAULT FORMATION, MARION LAKE, COAST OF LABRADOR

Abstract

Stromatolitic dolomite composes more than 45 per cent of the Denault Formation south of the northwest arm of Marion Lake, Coast of Labrador, Newfoundland. The Denault Formation, Proterozoic in age, occurs within the Labrador Geosyncline ('Labrador Trough').

Six distinct stromatolite forms are recognized, and five zones of stromatolites may be correlated in sections more than 2 miles apart. A descriptive, non-biologic classification is introduced, and possible origins for stromatolites are considered. Comparison with modern algal structures suggests that both sediment-binding and carbonate-precipitating algae contributed to the formation of the Denault stromatolites.

Résumé

La dolomie stromatolithique constitue plus de 45 p. 100 de la formation Denault, dans la région au sud du bras nord-ouest du lac Marion, sur la côte du Labrador (Terre-Neuve). La formation Denault, d'âge protérozoïque, appartient au géosynclinal du Labrador (fosse du Labrador).

Six formes distinctes de stromatolithes y ont été reconnues, et l'on peut établir la corrélation entre cinq zones de stromatolithes dans des sections éloignées de plus de deux milles. Le présent bulletin propose une classification descriptive et non biologique; il étudie également les origines possibles des stromatolithes. La comparaison faite avec les structures des algues modernes porte à croire que des algues qui servaient de liants aux sédiments et d'agents de précipitation au carbonate ont contibué à la formation des stromatolithes de la formation Denault.

CONTENTS

Illustrations

INTRODUCTION

This report summarizes a study of stromatolites in that part of the Proterozoic Denault Formation that outcrops along the south shore of the northwest arm of Marion Lake, Coast of Labrador, Newfoundland. Marion Lake is about 100 miles northwest of the Grand Falls on Hamilton River, and a few miles west of the height of land marking the boundary between Coast of Labrador, Newfoundland, and Quebec (Fig. 1). Schefferville, northern terminus of the Quebec North Shore and Labrador Railway, is about 35 miles west of Marion Lake. A preliminary geological

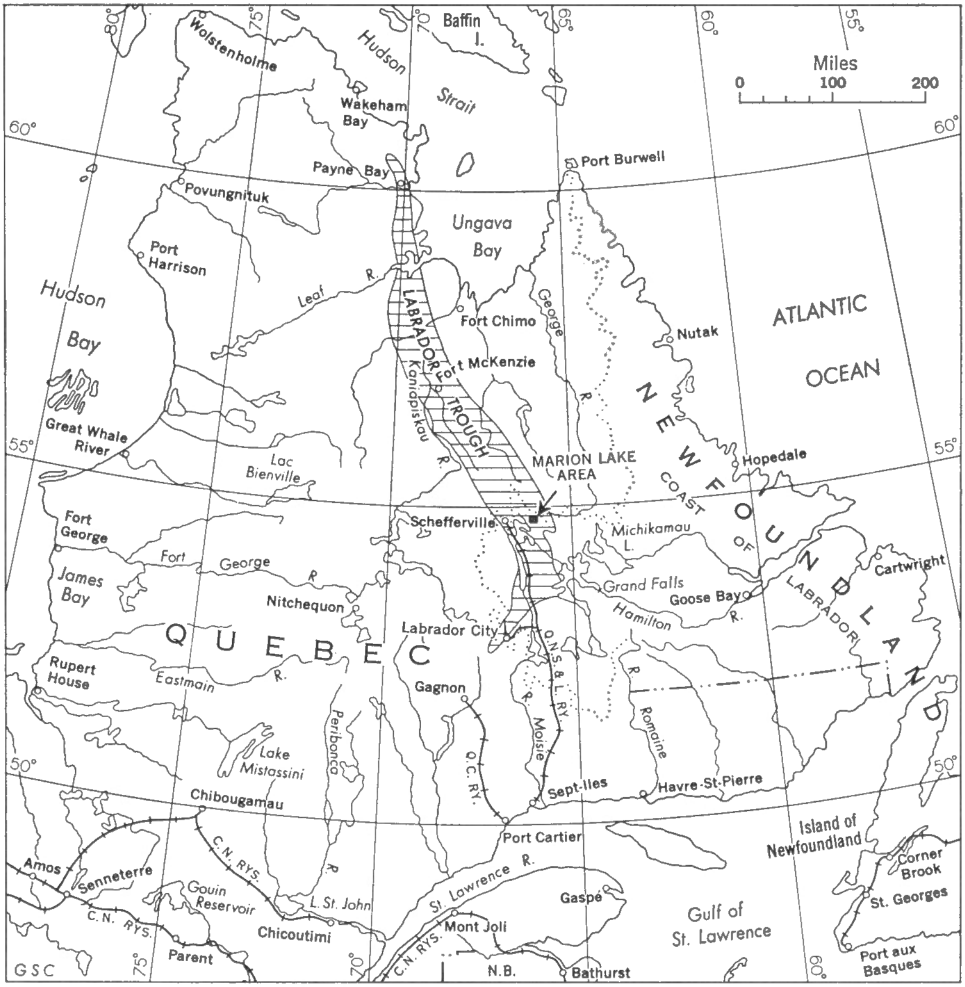

FIGURE 1 Index map.

map of the map-area (Donaldson, 1959)[1] shows the local setting of the Denault rocks containing the stromatolites described herein. A more comprehensive report, including descriptions of stratigraphic sections measured in the Denault, will be presented in a memoir being prepared.

This bulletin is an expansion of a section in the writer's doctoral thesis submitted to The Johns Hopkins University, Baltimore, Maryland. F. J. Pettijohn and Olcott Gates provided much appreciated guidance during laboratory study and preparation of the thesis manuscript. R. Thorpe and L. Prevec assisted willingly during the two weeks of the 1958 field season devoted to detailed mapping of the Denault Formation.

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[1] Names and dates in parentheses refer to publications listed in Bibliography.

DESCRIPTION OF THE DENAULT FORMATION

This formation is a distinctive lithologic unit of the Knob Lake Group, a Proterozoic[1] assemblage of sedimentary rocks and minor volcanic interbeds that composes more than half the sequence within the Labrador Geosyncline. In the type area at Knob Lake, the formation consists mainly of dolomite containing scattered seams, layers, and nodules of chert, and basal interbeds of slate and quartzite (Harrison, 1952, p. 8). In Marion Lake map-area, the formation,

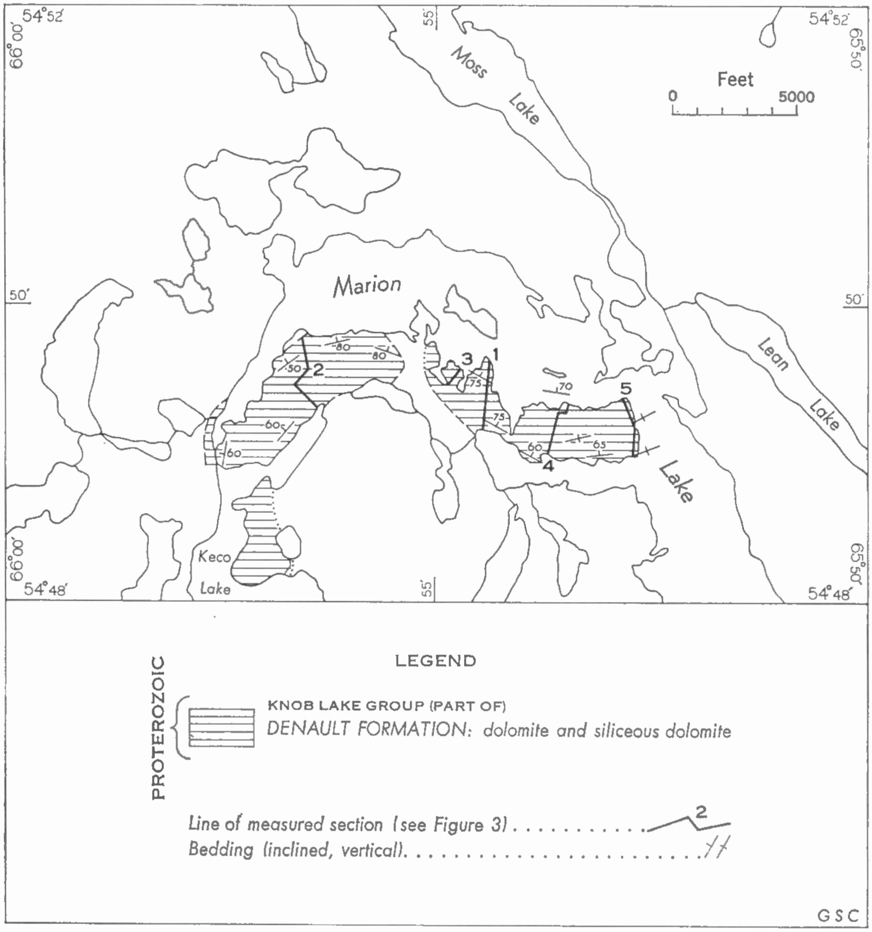

FIGURE 2 Part of Denault Formation, Marion Lake area, showing location of measured sections.

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[1] Two samples of gneiss developed from rocks of the Knob Lake Group, collected less than 25 miles south of Marion Lake, have been dated (muscovite, potassium-argon method) at 1,550 and 1,590 million years (Samples GSC 60-142, GSC 60-141, Wynne-Edwards, *in* Lowdon, 1961, p. 81).

recognized on the basis of similar lithology and equivalent stratigraphic position, differs most from that of the type area in thickness, the maximum thickness in Knob Lake area being about 600 feet (Harrison, 1952, p. 9) whereas in Marion Lake map-area it is more than 3,000 feet.

Rocks of the Denault Formation in the map-area were studied in detail along five sections (Fig. 2). Units, differentiated on the basis of lithology and sedimentary structures, were described and sampled, and contacts were indicated on the section. Sections are described in the forthcoming memoir.

Based on data from the measured section, nineteen units are recognized in the map-area (Fig. 3). They comprise four basic lithological types in the following approximate amounts:

Finely laminated siliceous dolomite	30%
Massive dolomite	20%
Stromatolitic dolomite	45%
Intraformational conglomerate	5%

The finely laminated siliceous dolomite is characterized by remarkably persistent tabular beds less than 1 cm thick, comprising numerous millimetre-thick laminations and cross-laminations. Commonly beds showing delicate cross-lamination are intercalated with beds composed of successive tabular laminations showing grain gradation of the waning-current type. The quartz content of the laminated siliceous dolomites is locally as high as 50 per cent but averages 20 to 30 per cent. Grain size is identical for both quartz and dolomite, ranging from 0.5 mm to less than 0.01 mm. Lamination is accentuated by differential weathering and colour differences dependent on the dolomite content. The highly siliceous laminations weather pale yellowish brown and stand out as thin ribs in contrast to the recessive, orange-weathering, dolomite-rich laminations. Lamination is indistinct on the uniformly cream to light grey, fresh surfaces, but is beautifully shown by polishing and staining surfaces cut normal to bedding (Pl. I A).

The massive dolomite exhibits indistinct, widely spaced stratification and contains less than 10 per cent detrital quartz. It is tough, light grey to white on fresh surfaces, and weathers dark grey. Joints are prominent and commonly occur in conjugate sets symmetrical with respect to bedding. Constituent dolomite grains, 0.2 to 1.5 mm in diameter, typically form a granoblastic mosaic, but patches containing sand-sized pellets of microcrystalline dolomite are common (Pl. I B).

Stromatolitic dolomite includes all lithological types in which stromatolites, as are defined in the following section, are dominant structures. Classification poses no problem, because stromatolite-rich beds are almost invariably in sharp contact with stromatolite-free beds. Further, because the various types of stromatolites commonly occur separately, the distribution of the different forms can be estimated. On the basis of the measured section data, the approximate abundance of the stromatolites, expressed as per cent of the Denault Formation at Marion Lake, is as follows: 10% columnar, hemispherical, and bulbous stromatolites; 5% digitate stromatolites; 25% undulatory stromatolites; 5% pisolitic stromatolites.

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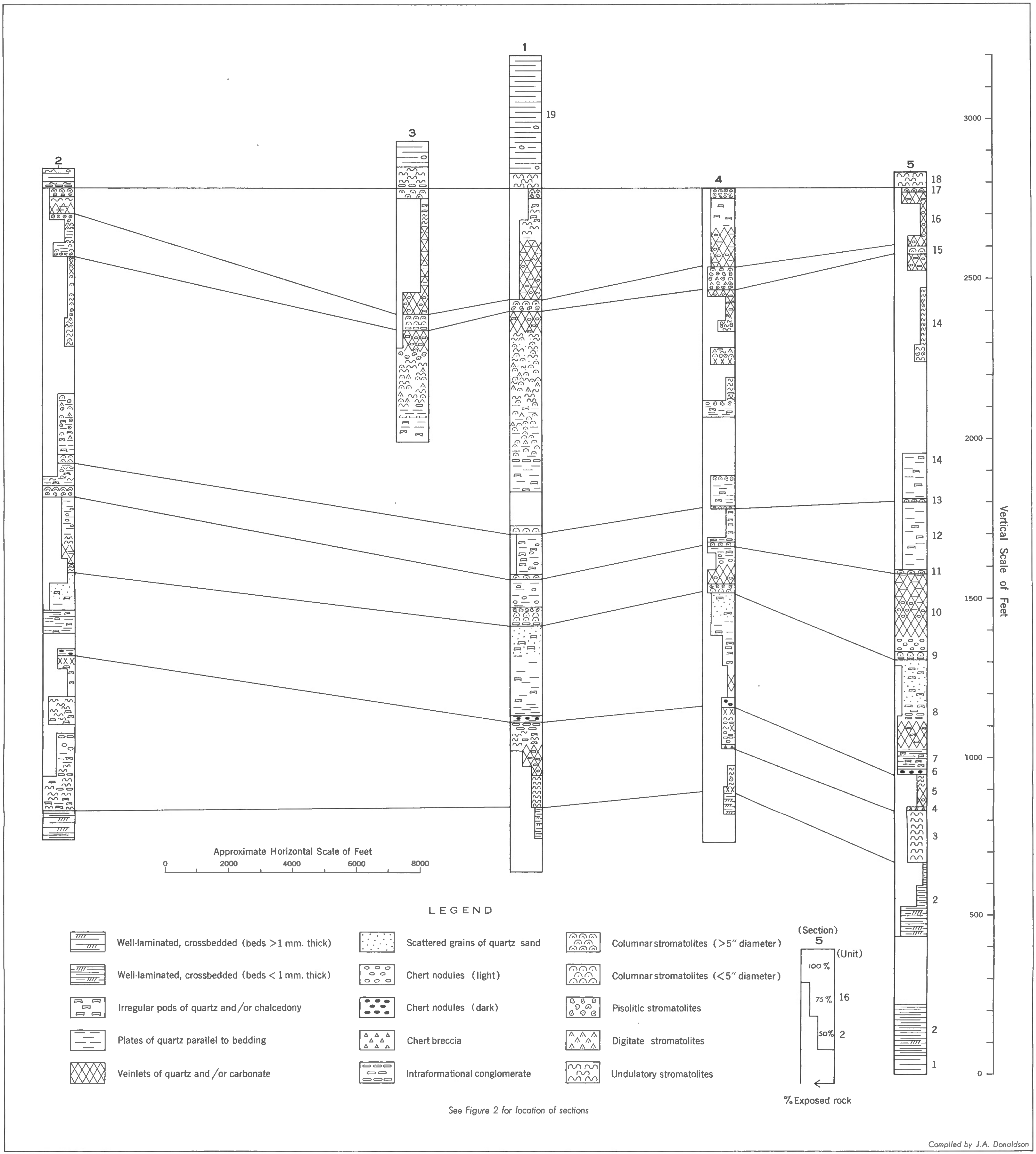

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Figure 3. Correlation of measured sections in the Denault Formation, Marion Lake area, Coast of Labrador, Newfoundland

To accompany G. S. C. Bulletin 102 by J. A. Donaldson

Two varieties of intraformational conglomerate are recognized. One variety is associated with beds of massive dolomite and typically forms layers a few feet thick containing abundant flat pebbles of massive dolomite in a matrix of pelletoid dolomite and dolomite cement. The other variety is associated with stromatolitic dolomite, and is described in the section on stromatolites.

DEFINITION AND CLASSIFICATION OF STROMATOLITES

The term 'stromatolite' derives from 'stromatolith' which was introduced by Kalkowsky (1908, pp. 68-69) to signify branched and domed calcareous bodies showing more or less even layered structure. Kalkowsky clearly did not incorporate requirement of organic origin in his definition, although he did document in his paper evidence supporting algal origin for typical stromatoliths in the Bunter Formation of Germany. Kalkowsky (op. cit., p. 69) contrasted stromatolith lamination to concentric lamination of associated oolites, but this distinction is not inherent in the present usage of the term stromatolite. Because structures similar to those described by Kalkowsky have been observed in sandstones, siltstones, and other sedimentary rocks, the term is not now restricted to calcareous organoform structures. Rezak (1957, p. 129) distinguishes stromatolites and fossil algae, applying the latter term to forms showing microstructures such as cell walls and reproductive organs. The term stromatolite is used here to signify any laminated sedimentary structure possibly formed as a result of algal activity. "Possibly formed" is included in the definition to allow sceptics as well as advocates of algal origin to apply the same name to structures of questionable origin. The similarity of shape (gross form and configuration of lamination) to that of modern algal structures is the most common reason for suspecting algal origin, but in some cases is not sufficient justification for the designation 'stromatolite'. Criteria for distinguishing stromatolites from similar structures of other origin are discussed in the next section.

Biologic nomenclature has long been applied to stromatolites, generic and specific names being assigned on the basis of form. Realizing that various algal species commonly combine to build structures analogous to stromatolites, Johnson (1946, p. 1089) attempted to justify continuation of biologic nomenclature on the basis that different assemblages of algae may form "colonies sufficiently different to be separated by megascopic characteristics". Even this position, however, is rendered untenable by the recent discovery that the same species or assemblages of species of algae may build strikingly different structures (Ginsburg, written comm., 1959). Because of this, Logan, Rezak, and Ginsburg (1960) proposed a purely descriptive classification of stromatolites, based on geometric shapes which are characteristic of algal structures formed in specific present-day environments. The classification used here, also purely descriptive, combines a single adjective indicative of gross form with the term 'stromatolite' to provide names definitive of distinctive stromatolites that have in the past been assigned biologic names. Table I shows the classification; generic names assigned to similar forms are parenthesized. The stromatolite classification is illustrated in Figure 4.

Table I

Descriptions of Six Basic Types of Stromatolites

Hemispherical stromatolites (*Collenia* Walcott): consist of successive hemispherical, convex-upward laminations. Laminations are of uniform thickness and are roughly concentric with respect to the centre of the basal surface.

Bulbous stromatolites (*Cryptozoon* Hall): these forms are attached at a point, and consist of successive balloon-shaped laminations which are thickest at the top and pinch out near the base.

Columnar stromatolites (*Archaeozoon* Mathew): cylindrical columns consist of successive hemispherical, convex-upward laminations, adjacent columns are tightly packed.

Digitate stromatolites (*Gymnosolen* Steinmann): consist of discrete cylindrical columns which commonly branch upwards into parallel columns of lesser diameter.

Pisolitic stromatolites (*Pycnostroma* Gürich): individual, subspherical, concentrically laminated bodies.

Undulatory stromatolites (*Weedia* Walcott): consist of laterally continuous laminations which have irregular wavy boundaries.

The 'descriptive adjective' classification is suggested in preference to the code-letter classification of Logan, *et al.*, in that many forms not included in the latter classification may be simply described (conical, turbinate, discoid, etc.), without compounding a formalized set of code-letters. Stromatolites described as hemispherical, hemispheroidal and domical, are recognized as similar in form; it matters little which adjective is applied. One of the three types recognized by Logan, *et al.* (1960, p. 1918) is classified on the basis of relationship between stromatolites (LLH — laterally linked hemispheroids). However, the writer has observed many field occurrences of only local linkage between closely packed columnar stromatolites, and also occurrences of faint lamination through interspaces between discrete digitate stromatolites, linking, but differing from, lamination within the stromatolites. Because linkage has environmental significance, it should certainly be noted and described, but because it may be sporadic and of different types, perhaps it should not be a basis for stromatolite nomenclature. Most descriptions of the type 'form-genera' include adjectives which appropriately describe gross form. Such adjectives, unencumbered by biologic names, provide a rational basis for stromatolite classification.

POSSIBLE INORGANIC ORIGINS OF STROMATOLITES

Stromatolites are generally recognized to be related to algal activity, but because their organic origin has at times been questioned, possible inorganic origins are reviewed. Inorganic processes that have been proposed include:

Deformation of consolidated rock
Soft-sediment deformation
Inorganic precipitation and/or solution
Concretionary growth.

Deformation of Consolidated Rock

Transverse sections of columnar stromatolites superficially resemble sections normal to axes of repeated folds, but investigation of the third dimension obviously serves to distinguish between the two (Fig. 5A). However, some structures with a definite domical configuration have also been interpreted as products of deformation. Young (1944, p. 94) described rocks of the Dolomite Series of South Africa, which contain "domical-columnar structure" as: ". . . an assemblage of rocks whose members have adjusted themselves to compressive stresses in diverse manner according to their individual characters and circumstances, and that the result has been a shortening of the section in every direction". His argument for mechanical origin is based mainly on the presence of breccia zones between adjacent columns. However, he did not offer evidence to show that the "breccias" are truly of secondary origin. Furthermore, in two figures shown by Young (1943, Pl. 22, Fig. 2; Pl. 24, Fig. 2) lamination is clearly continuous between the columns. Such continuity of lamination is difficult to reconcile with "mylonitization between the columns" (Young, 1943, p. 98). In earlier papers (ibid., 1933, 1935, 1941), Young described as stromatolites, structures in the Dolomite Series essentially identical to the domical-columnar structures, and in a later paper (1946) he reported pisolitic stromatolites in the same rocks. Hardy and Williams (1959) briefly described columnar structures in the Ute Formation of northern Utah, and although these authors remarked that the structures "in no way resemble algal structures", they failed to state the differences. Furthermore, they compared the structures to similar ones mentioned by Dorf and Lochman (1940, p. 545), yet the organic origin for these latter structures was not contested (ibid., p. 547). Seaman (1944, p. 13) concluded that "dome-like" structures in the Kona Formation of the Marquette district were formed by deformation, but Greenman (1951, p. 112) convincingly demonstrated sedimentary origin for the structures. Greenman's evidence includes: stratigraphic restriction of the domical structures, lack of brecciation, asymmetry of the arches (convex upward laminations of adjacent stromatolites adjoin in a sharp V-shaped contact), tabularity of overlying and underlying beds, and association with clastic fragments of the domical structures.

Deformation of consolidated rock may produce structures similar in form to hemispherical, columnar, and undulatory stromatolites, but obviously will not produce branched or spherical structures. However, even in the domical forms, evidence such as listed in the previous paragraph serves to distinguish stromatolites from structures produced by post-consolidation deformation (Fig. 5A, B, C).

Soft-sediment Deformation

Many occurrences of non-planar lamination, ranging from gently undulatory to highly irregular, have been attributed to soft-sediment deformation. Some structures so produced may be mistaken for stromatolites, as was recognized by Schneiderhöhn (1921, p. 264), and conversely, perhaps some stromatolites may be misidentified as structures produced by soft-sediment deformation. Unlike structures formed by deformation of consolidated rock, those formed by soft-sediment deformation are stratigraphically restricted, are commonly bounded by planar stratification, and show little or no brecciation. Thus, most of the criteria applicable for recognition of post-consolidation deformation do not hold for penecontemporaneous deformation. However, of the structures formed by slumping and sliding — by far the most abundant mode of soft-sediment deformation — few resemble algal structures. Such deformational structures commonly involve extensive contortion of stratification, and typically show evidence of differential downslope movement such as overturned folds and subparallel thrust faults (*see* illustrations of Fairbridge, 1947).

Structures more likely to resemble algal structures are those formed by anisotropic compaction accompanying sedimentary loading. Compaction, slumping, and sliding all occur in response to gravity, but in contrast to slumping and sliding, for which movement is predominantly parallel with bedding, compaction involves differential movement normal to bedding. Compaction structures therefore lack the consistent asymmetry typical of structures formed by downslope movement. Characteristically they comprise successive irregular laminations which, in sections perpendicular to bedding, show undulatory or pinch-and-swell configurations. The differential compaction may be controlled by original high water or air content of the unconsolidated beds, or merely by compositional inhomogeneities. Structures so formed may well simulate algal structures, particularly those of algal-mat origin (analogous to undulatory stromatolites).

Perhaps the best criterion for distinguishing stromatolites from structures formed by soft-sediment deformation is evidence for or against contemporaneous origin of lamination irregularities. Irregularity of lamination due to algal activity is inherent, and erosion of individual laminations commonly serves to establish the primary origin (Fig. 5F). Irregularity due to soft-sediment deformation, however, is imposed on a sequence of numerous, initially near-planar laminations; erosion after creation of such irregularities shows only as a single unconformity, and any internal plastic adjustment between layers is clearly distinct from erosional truncations (Fig. 5D, E).

Inorganic Precipitation and/or Solution

The tufa domes of Lake Lahontan, Nevada, which in gross form resemble the domical types of stromatolites, were attributed to chemical precipitation by Russell (1885, p. 188). More recently, algal origin for at least some of the Lahontan tufas has been demonstrated (Jones, 1925, p. 7), and Scholl (1960) has attributed pinnacle-like structures at Searles Lake to algal precipitation around orifices of sublacustrine springs. Emig noted the common association of algae and tufa (or travertine), but, with reference to the deposits in Yellowstone Park, stated (1917, p. 59): ". . . there is no question but that travertine would be formed from the hot mineral water even if the plant life were absent. The vegetation in this particular instance, by its presence, acts only as a passive agent in determining the form and structure of the deposit, and does not necessarily take an active part in the precipitation of calcium carbonate." However, as pointed out in a study of Bahamian oolites by Newell, Purdy, and Imbrie (1960, pp. 492-493), there is quite an overlap between biochemical and physiochemical precipitation, because life processes may greatly influence overall physiochemical conditions.

A South African occurrence of travertine, apparently formed by inorganic precipitation of hot spring waters, is reported by Kupferburger (1935, p. 10) as showing "irregular, wavy, horizontal stratification." The deposit, which is approximately one half mile in diameter and as much as 200 feet thick, is described as a "crater" that was built up by evaporation of carbonate-rich waters released from a central spring. Ancient deposits of spring origin might be expected to show cross-sections of the conduit (Fig. 5G), but spring origin cannot be dismissed on the sole basis of unexposed channelways, as will be appreciated by those cognizant of the difficulty involved in locating feeders for volcanic flows.

Ohle and Brown (1954a, pp. 208-210) described "fingering" in "snurly rock" of the Bonterre dolomite. They at first interpreted the fingers as the product of solution, but in a later paper (1954b, pp. 935-936) they reinterpreted the fingers as algal structures. Because solution typically occurs along fractures and permeable beds, a plexus of anastomosing channelways is the normal result of extensive solution. Any tubular structures so formed can be expected to lack internal lamination, follow sinuous paths, and have irregular walls (Fig. 5K). Pipe-like structures attributed to upwelling of water through unconsolidated sediments, recently described by Allen (1961), are also characterized by such features.

Caliche, a lime-rich deposit formed in soils of semiarid regions mostly as a result of solution and precipitation, commonly contains structures that resemble pisolitic and undulatory stromatolites. Some structures in caliche have, in fact, been attributed to algal activity (Price, Elias, and Frye, 1946). Bretz and Horberg (1949), however, have convincingly shown that the structures can be explained by soil-forming processes alone. Important features of caliche include physiographic rather than stratigraphic control (Fig. 5H), and development of the typical caliche profile (op. cit., Fig. 2).

Hawley (1926) focused attention on the importance of osmosis in geological processes. He described several experiments that demonstrate the tendency for iron silicates to form tubular and branching structures in water glass solutions of various concentrations. He suggested that similar inorganic growth could produce algal-like filaments such as described by Gruner (1923), but he clearly did not suggest osmotic growth for stromatolites, stating in the same paper (Hawley, 1926, p. 443): "These mass effects (stromatolites) are so consistent in a given formation, show geographical variations, and so resemble structures now being formed by algae that they are best referred to an algal origin".

Two interesting examples of inorganic deposits resembling hemispherical stromatolites were briefly described by Wilson (1957, p. 22). One specimen formed about the nut of a revolving wheel in the refining plant of a brucite mine, and the other was deposited at the turn of a hot-water pipe. Although appeal cannot be made to revolving wheels and hot-water pipes in nature, the examples serve to indicate that strikingly similar structures can be produced in diverse ways.

Concretionary Growth

The term 'concretion' is here used for structures produced by in situ, post-depositional accumulation of mineral matter around a nucleus (Pettijohn, 1957, p. 197); in this restricted sense, concretionary growth may be regarded as a variety of inorganic precipitation.

Pisolites in bauxite deposits are commonly assigned to such origin (Gordon and Tracey, 1952, p. 27), and pisolites in limestones have also been interpreted as concretionary structures by some workers (Swineford, *et al.,* 1958, p. 115). The best criterion for recognition of post-depositional concretions is transection of bedding by the successive concentric shells (Fig. 5J). Pre-depositional accretionary structures such as algal pisolites are recognized by lack of such relationship to bedding. Commonly the presence of derived, water-worn fragments furnishes proof of pre-depositional origin (Fig. 5L).

DESCRIPTION OF THE DENAULT STROMATOLITES[1]

Columnar, Hemispherical, and Bulbous Stromatolites

Columnar stromatolites compose five zones in the Denault Formation (Fig. 3). Hemispherical and bulbous stromatolites are abundant in the lower parts of the zones, and these forms appear to represent early growth stages of the columnar stromatolites. In three of the zones, diameters of the columns range from 6 to 12 inches, and in the other two zones, they range from 2 to 8 inches. The columns stand perpendicular to bedding, show little upward variation in diameter, and in most places are closely packed (Pl. II A).

The structure of the stromatolites is marked by alternation of dark grey to black layers and light grey to buff layers, commonly accentuated by differential weathering (Pl. II A). The layers, invariably convex upward, range from 1 to 20 mm in thickness, and although individual laminae are relatively uniform, most tend to taper towards the margins (Pl. II B). The layering is commonly continuous through adjacent columns, forming laterally linked stromatolites (Logan, *et al.*, 1960, p. 1918), but also abundant are discrete stromatolites separated by interspaces a few inches wide, occupied by detritus composed mostly of fragments derived from the stromatolites.

Grain size ranges from 0.001 to 0.01 mm in the dark layers and from 0.01 to 0.05 mm in the light layers. The dark pigmentation is caused by less than 1 per cent carbon, dispersed as thin films between dolomite grain boundaries. Most layers are laminated, although some, notably those of very fine grain size and high carbon content, are essentially homogeneous (Pl. III). Lamination in the light coloured layers is marked by pellets, discontinuous streaks, and fragments of carbonaceous dolomite, locally separated by irregular patches of sparry dolomite. The less distinct but more uniform laminations in the dark layers are expressed by slight differences in grain size and carbon content. Quartz silt is abundant in the light coloured layers, but scarce to absent in the dark ones. Rather common are sharply truncated layers; overlying layers drape over such terminations, forming wedge-shaped spaces now occupied by coarsely crystalline dolomite (Pl. III). Unique to the dark layers are nebulous tube-like structures, 0.1 to 0.2 mm in diameter, within, and in most instances perpendicular to, the laminations (Pl. III).

Digitate Stromatolites

Digitate stromatolites typically form beds less than a foot thick. In longitudinal section, these stromatolites appear as upward-branching, finger-like structures 1 to 5 mm in diameter and less than 2 cm in height (Pl. IV). They exhibit domical, convex-upward laminations 0.05 to 1.0 mm thick, marked by thin, crenulate car-

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[1] All the specimens of stromatolites illustrated are preserved in the Palaeontological type collection of the Geological Survey of Canada, and have been assigned plant fossil type numbers. These numbers are recorded in the plate descriptions.

bonaceous films (Pl. V). The crenulations are remarkably regular, with ranges for wave length of 0.5 to 1.0 mm and for amplitude of 0.1 to 0.5 mm. Transverse sections illustrate the crenulate nature of the laminations, as well as the cylindrical configuration of the stromatolites (Pl. IV B). The widths of interspaces are of the same order as the diameters of the stromatolites, but close packing is locally common. The interspaces are typically occupied by carbonaceous dolomite showing pelletoidal texture and containing abundant fragmental detritus and quartz silt, in contrast to the stromatolites, which are remarkably free of clastic grains. Grain size ranges from 0.001 to 0.05 mm in the stromatolites, and from 0.01 to 0.2 mm in the matrix. Upward branching occurs at about the same horizon for adjacent stromatolites, the stems giving rise to as many as five subparallel branches. The branches are invariably narrower than parent stems, and commonly the sum of branch diameters approximates the stem diameter. Concave-upward laminations locally span interspaces, linking corresponding laminations in adjacent stromatolites. Interspace linkage is well illustrated in Plate V.

Pisolitic Stromatolites

Pisolitic stromatolites of the Denault Formation occur in buff to dark grey beds, 1 foot to 5 feet thick. The pisolites are spheroidal to ellipsoidal structures, 5 to 15 mm in diameter, characterized by concentric laminations 0.02 to 1.0 mm thick (Pl. VI A). They are composed almost entirely of dolomite grains, 0.001 to 0.02 mm in diameter, and less than 1 per cent finely divided carbon, mostly localized as thin, crenulate films marking the laminations. The scale of crenulation is identical to that of the digitate stromatolites. Composite pisolites containing two or more nuclei are abundant and some comprise concentric shells enveloping large fragments derived from earlier formed pisolites. Stromatolite fragments, oolites, superficial oolites, and structureless, carbonaceous pellets form most of the matrix, which in some beds equals or exceeds the volume of the pisolites (Pl. VI B).

Pisolites and matrix are cemented by a mosaic of clear dolomite having a grain size range of 0.02 to 0.2 mm. Many crystals composing the cement are elongate and show a preferred orientation of long axes normal to surfaces of both pisolites and matrix components. Microscopic examination with crossed nicols reveals that axes of elongation are roughly coincident with crystallographic c-axes. Notable also is an inward increase of grain size in the cement patches.

Undulatory Stromatolites

Undulatory stromatolites are the most abundant structures in the Denault Formation. Wavy lamination is characteristic, and is accentuated on weathered surfaces by siliceous layers that stand out as prominent crinkly ribs (Pl. VII A). Wave length of the undulations ranges from less than 1 mm to 5 cm; amplitude ranges from less than 1 mm to 1 cm. Fresh surfaces are light grey to buff, and weathered surfaces are light tan to cream buff. The siliceous layers are 1 to 10 mm thick and are 5 to 20 mm apart. Some can be traced for tens of feet, but in detail, most of the layers are discontinuous and some even branch laterally. The dolomitic layers commonly show faint irregular lamination, and thin sections reveal that pelletoid and fragmental textures predominate. The pellets are typically well-rounded, well-sorted, elliptical to spherical bodies less than 0.2 mm in diameter, and are set in a clear, coarsely crystalline dolomite cement (Pl. VII B). Pisolites and small columnar stromatolites occur sporadically throughout most beds, and locally compose layers that can be followed laterally from outcrop to outcrop.

Stromatolitic Conglomerate

A variety of intraformational conglomerate is associated with, and derived from, the stromatolitic zones. An example of such conglomerate can be seen in the upper part of Plate V. Thin, curled plates of carbonaceous dolomite are set in a clear, partly recrystallized matrix of silt-sized dolomite grains. The dark clasts are as much as 3 cm long, and have length to thickness ratios as high as 20:1. Most are laminated, and some are split along contacts between laminations. Terminations are angular to shredded, and rarely do the fragments show any evidence of water-wear.

ORIGIN OF THE DENAULT STROMATOLITES

No inorganic processes can adequately account for all the Denault stromatolites. The obvious evidence for primary origin, including truncation of individual laminae and restriction to stratigraphic zones, eliminates the possibility of origin by post-consolidation deformation. Soft-sediment deformation could perhaps give rise to structures resembling undulatory stromatolites, but could not produce pisolitic or digitate forms. Because true concretions are secondary structures, the arguments for primary origin suffice to eliminate concretionary origin. Inorganic precipitation can lead to formation of both pisolites and deposits showing undulatory lamination, but unless accompanied by organic activity, can hardly result in symmetrically branched or domical structures. Furthermore, the carbonaceous nature of the stromatolite zones cannot be dismissed as fortuitous. The most compelling argument in favour of organic origin, however, is the striking similarity of the Denault stromatolites to modern structures forming today as a direct result of algal activity (*see* comparisons under *Environment and Mode of Growth*).

The pisolitic, columnar, and digitate stromatolites of the Denault Formation are interpreted as algal structures. They occur in stratigraphically continuous zones which are probably biostromes. The possibility of inorganic origin for the undulatory stromatolites is recognized, but intimate association with the other stromatolites strongly suggests a common origin.

Carbon Content

Stromatolitic units in the Denault Formation consist almost entirely of dolomite with less than 1 per cent carbonaceous matter. Chemical analysis verified the presence of carbon. (K. Hoops, Geol. Surv., Canada, analyst.) Dark black residues obtained by digesting samples in excess hydrochloric and hydrofluoric acids readily oxidized at approximately 600°C, and examination by X-ray diffraction failed to detect crystalline structure. The carbon is probably present in amorphous form, or combined in organic compounds.

Rankama (1948, 1954) attempted to differentiate organic and inorganic carbon on the basis of carbon isotope ratios, but Craig (1954) questioned the validity of Rankama's conclusions, primarily on the basis of the assumption that C^{12}/C^{13} in the reservoir (the oceans) has remained constant through geologic time. Craig suggested that carbon in rocks classified as inorganic by Rankama's method may actually be organic, noting that free carbon cannot form from carbonate minerals in sedimentary rocks unless some reducing substance such as free hydrogen or metallic iron is present. Therefore most, if not all, free carbon in ancient sedimentary rocks probably is of organic origin. A more promising line of research involves tests for organic complexes especially amino acids (Abelson, 1954, 1956), but this line of research has not yet been pursued for the Denault.

Environment and Mode of Growth

Considerable data for interpreting stromatolites are available as a result of intensive study and detailed description of their modern algal analogues. Black (1933, p. 169) observed that algal structures with characteristic morphology form only above low water mark on Andros Island, although algae serve to bind sediments at greater depths without producing any internal structure. According to Ginsburg (1959, written comm.), discrete laminated algal structures, off the coast of Florida, seldom form at depths greater than 15 feet. Cloud (1942, p. 371) noted that because algae need light for photosynthesis, they do not grow profusely at depths greater than 10 metres. For the Denault stromatolites, independent evidence for shallow-water origin is provided by the association with intraformational conglomerates and the abundance of stromatolitic detritus.

Because algae grow in arctic to tropical waters, they provide no definite evidence of environmental temperature, but as pointed out by Cloud (1942, p. 370), they seem to grow more prolifically in warm water than in cold. The abundance of stromatolites in the Denault is at least suggestive of warm-water deposition.

Modern algal structures are abundant in both shallow-marine and lacustrine environments. They thrive in sea water (Ginsburg, 1958, p. 311), freshwater (Black, 1933, p. 169), and hypersaline water (Eardley, 1938, p. 1395). Cloud (1942, p. 372) at first thought that digitate stromatolites might indicate non-marine origin, but later (1945, p. 108) noted three occurrences of digitate stromatolites in marine strata. Algal structures similar to stromatolites of the pisolitic type grow in modern freshwater environments (Bradley, 1929, p. 219; Clarke, 1900; Murray, 1895; Roddy, 1915), but Twenhofel (1919) and Sando (1957, p. 38) have described pisolitic stromatolites in ancient sedimentary rocks of known marine origin, and Ginsburg (1960) reports unattached algal biscuits now forming off the Florida and Bahama coasts. Algae that produce structures of the hemispherical and undulatory types are now active in marine, brackish, and fresh waters in the Bahamas (Black, 1933, p. 169). Clearly, then, no specific type of stromatolite can be used as a salinity index, because all types of algal structures can form in both continental and marine environments.

Algae can contribute to carbonate deposition in three ways. Some, notably the coralline red algae, secrete lime within their cell walls. Algae may also, through photosynthesis, cause changes in the environment sufficient to initiate inorganic precipitation. Another important contribution is provided by the blue-green algae, which readily trap fine sediment within the framework of their mucilaginous thalli. The sediment-trap mechanism appears to be the most important mode of origin for algal structures analogous to stromatolites. Black (1933, p. 176) described algal mats in the Bahamas that trap fine detritus swept in by currents; Ginsburg and Lowenstam (1958, p. 311) reported similar mats along the Florida coast, and described an experiment in which an algal culture when covered by a layer of sediment 4 mm thick grew through the layer and re-established a surface mat within 24 hours. The alternation of carbon-rich and carbon-poor dolomite layers in the Denault columnar stromatolites is suggestive of sediment-trap origin, the carbonaceous layers representing alga-rich layers that formed during periods of quiescence, and the carbon-poor layers representing detritus swept in during periods of turbulence. Strong support is lent to this mode of origin by the observation that dolomite fragments and grains of quartz silt are abundant in the carbon-poor layers, but scarce in the carbon-rich layers.

The tabular fragments of carbonaceous dolomite in the stromatolitic conglomerates appear to be slabs of alga-reinforced layers stripped from columnar stromatolites by waves or strong currents. Common occurrence of sharply truncated dark layers in the columnar stromatolites (Pl. III) substantiates this interpretation.

Ginsburg (1957, p. 95) observed crenulated algal mats along the coast of Florida, and noted that the crenulations are produced by desiccation. Extreme drying causes contraction sufficient for disruption of the mats, resulting in irregular slabs several feet in diameter. Such a process may well be responsible for crenulations and local discontinuities of lamination in the undulatory stromatolites. Logan (1961) described extensive undulose algal mats now forming on tidal flats of Shark Bay, Western Australia. These mats, restricted to the upper intertidal and supratidal zones, give way seaward to low domical structures, and finally discrete club-shaped structures extending to the low water mark. Undulatory and domical stromatolites of the Denault Formation may record a similar relationship; abundance of fragmental detritus throughout both stromatolite varieties clearly indicates a shallow-water to intertidal depositional environment, and suggests that if algae were active, they were of the sediment-binding type.

In contrast to laminations in the columnar and undulatory stromatolites, laminations in the pisolitic and digitate stromatolites contain only minor fragmental dolomite and quartz silt, even though clastic particles are abundant between the digitate structures and in the matrix binding the pisolites. This suggests that growth of the pisolitic and digitate stromatolites occurred mainly by direct precipitation rather than by trapping of sediment. Concentrically laminated bodies similar to the pisolitic stromatolites of the Denault are formed in contemporary environments by lime-precipitating algae (Murray, 1895; Clarke, 1900; Roddy, 1915), and modern algal structures analogous to the digitate stromatolites have been shown to grow in the same way (Bradley, 1929, p. 215; Pia, 1933, p. 147).

The pisolitic stromatolites grew unattached, as indicated by the complete envelopment of successive laminations around a nucleus. Truncation of laminations and abundance of large pisolite fragments in the matrix demonstrate rough water conditions. The digitate stromatolites, however, exhibit no truncation of lamination, and their parallel, upward-branching habit demonstrates growth from a fixed base. Fragmental detritus commonly occupies interspaces between the digitate stromatolites, but it is much finer grained than detritus associated with the pisolitic stromatolites. The digitate stromatolites evidently developed in quieter waters than did the pisolitic stromatolites. Perhaps both types were formed by the same algae, and intensity of turbulence controlled the morphology. Laminations in both pisolitic and digitate stromatolites show the same range in thickness, and are marked by thin carbonaceous films that exhibit a delicate crenulate or 'scalloped' outline, suggesting similarity of origin. Possibly differences in the thickness of the laminae, which in the digitate stromatolites can be laterally correlated, record response to changes in temperature, salinity, light intensity, or other environmental factors. Differences in the thickness of a single lamina, exhibited by some of the pisolitic stromatolites, may well be a result of differential growth in response to light. Frequent lack of lamination truncation in such pisolites at least suggests that they grew in quieter waters, and hence could have an upper side. Some pisolites have two or more sets of laminations, each set showing asymmetry of thickness in a different direction, with or without truncation of laminations composing the adjacent inner set. This suggests intermittent undisturbed growth, periodically interrupted by increase in energy sufficient to flip the pisolites into new orientations. Such cyclic growth has been clearly demonstrated for algal biscuits forming in modern seas (Ginsburg, 1960, p. 30).

Correspondence of lamination thicknesses at coincident levels in adjacent digitate stromatolites is regarded as evidence for growth at the depositional interface. If the structures did grow freely above the interface, some remarkable control would have to be active to maintain identity of elevation for the small columns. Furthermore, occurrence of laminae spanning some of the interspaces and linking identical laminae in the stromatolites leaves little doubt that the structures merely poked through the detritus, growing upward at a rate more or less corresponding to the rate of sedimentation. Sudden influx of detritus may have been responsible for upward branching of the digitate stromatolites, sufficient detritus lodging in prominent crenulation depressions to cause local cessation of growth. The arborescent structure could also have originated as a result of associated organic activity. Burrowing organisms in modern marine environments frequently attack algal structures, and Ginsburg (written comm., 1959) believes that surface lesions so produced could result in upward branching.

Abundance of pellets in the stromatolite zones provides further information about the depositional environment. Although pellets may form in various ways, they provide, regardless of their origin, a reliable indication of shallow water (Beales, 1958, p. 1866). Calcareous pellets have been ascribed to faecal, accretionary, and clastic origin, but pellets formed by all three processes are found in present-day shoal environments (Illing, 1954).

At least some of the Denault pellets are of clastic origin, because sequences from angular fragments of stromatolites to rounded grains can be traced, even within single thin sections. However, some specimens contain pellets showing remarkable similarity of size and shape, and notably lack associated fragments suggestive of attritional origin. The preponderance of elliptical to rod-like cross-sections is intriguing, in view of the frequency with which such shapes characterize pellets of known faecal origin (Eardley, 1938, p. 1404; Illing, 1954, p. 24). Accretionary origin must also be considered, but pellets developed in this way are typically equant, and generally have botryoidal 'grapestone' shapes (Illing, 1954, p. 26). Perhaps accretion involving algal activity (Wood, 1941) can result in elliptical and irregular-shaped pellets such as are present in the Denault.

The possibility of organic wounding as a cause for branching of digitate stromatolites has been mentioned. Also suggestive of additional organic activity are the tubular structures, 0.1 to 0.2 mm in diameter, seen in carbonaceous layers of the domical stromatolites (Pl. III). Ginsburg (1960, p. 33) described tubular structures in modern algal biscuits that represent burrows of polychaete worms, and noted that the worms convert the algal-bound laminations to faecal pellets. Tubular structures in the Denault stromatolites may record similar activity, or may represent fossilized algal filaments such as are illustrated by Bradley (1929, Pl. 30 A).

Also of environmental significance is evidence for early lithification of the stromatolites. As already noted, broken pisolites are abundant, fragments of digitate stromatolites occur locally in digitate units, and clasts in some intraformational conglomerates consist almost entirely of slabs derived from domical stromatolites. Penecontemporaneous fragmentation rather than later erosion is clearly indicated by relationships such as unconformities within composite pisolites, and sharp truncation of single layers within domical stromatolites. The angularity of the fragments predicates substantial coherence of source stromatolites, and therefore lithification essentially contemporaneous with growth of the structures must be assumed. This conclusion lends further support to an interpretation of mud-flat origin, in view of Ginsburg's observation (1957, p. 95) that thorough lithification of Recent carbonate sediments occurs only in the intertidal zones.

Primary Precipitation of Dolomite

In dolomites of known replacement origin, original textures and structures are generally obscured or destroyed, and there is a notable increase in grain size. In the Denault, however, extremely delicate structures have been preserved, clastic textures are readily recognized, and many of the rocks are composed of dolomite grains a few microns in diameter. A primary rather than a replacement origin is therefore suggested for dolomite of the Denault Formation.

The possibility that direct precipitation of carbonate is recorded by digitate and pisolitic stromatolites has already been noted, and in view of the abundant evidence for early lithification and penecontemporaneous reworking, comminution of algal structures may have yielded the dolomite composing the associated rocks. Although inorganic precipitation contingent upon life processes of the non-coralline blue-green algae (the group that now forms structures analogous to stromatolites) has not been investigated, Chave (1954, p. 281) has shown that some types of coralline red algae secrete calcite containing as much as 30 per cent magnesium carbonate in solid solution.

Plass (1956, p. 313), in order to explain the propensity for modern plants to grow more luxuriantly in an atmosphere enriched in carbon dioxide, has suggested that early plants developed in an atmosphere containing considerably more carbon dioxide than it does today, and that modern plants have not evolved sufficiently to adapt fully to the present atmosphere. With an atmosphere rich in carbon dioxide, the problems of primary dolomite are less formidable, in view of the successful precipitation of dolomite in the laboratory under increased partial pressure of carbon dioxide (Chilingar, 1956, p. 2262). Perhaps during Proterozoic times, because of a factor such as high carbon dioxide pressure, algae were capable of either secreting, or causing precipitation of, pure dolomite.

Diagenesis

One of the most striking features of the undulatory and domical stromatolites is the abundance of quartz and chert interlayers which accentuate lamination of the structures. Quartz and chert also occur in the massive dolomites, mostly as joint fillings, and chert nodules are locally abundant in the laminated siliceous dolomites. The various modes of occurrence are stratigraphically controlled (Fig. 3), suggesting early introduction of the silica. Chert in patches and in nodules appears to replace dolomite, and in the nodules especially, relict bedding affords definite evidence for replacement. Much of the quartz, however, appears to have filled spaces, as evidenced by colloform banding and disposition of quartz crystals. C-axes are typically normal to the walls of the pods and layers that the quartz crystals form. Coarse-grained dolomite locally shows the same relationship, notably in patches bounding wave-torn layers in domical stromatolites (Pl. III). Primary cavernous structure due to desiccation of algal layers is proposed to account for most of the spaces, although penecontemporaneous solution, as has been suggested by Bathurst (1959, p. 506) for similar relationships, may have been an important factor.

OTHER OCCURRENCES OF STROMATOLITES IN PROTEROZOIC ROCKS OF CANADA

Although stromatolites occur widely in Proterozoic rocks of Canada, most records in the literature are limited to no more than brief mention of "algal structures", or "cryptozoons". A few reports, however, contain descriptions, discussions, or illustrations of stromatolites, and references to these reports are included in the following summary of Proterozoic occurrences:

Seal Lake area, Labrador (less than 150 miles east of Marion Lake). Brummer and Mann (1961, p. 1369, and Pl. 3) illustrated hemispherical and pisolitic stromatolites from a 30-foot limestone bed in the Wuchusk Formation. Most of the structures are less than 3 inches in diameter, but a few are as much as 2 feet.

Mistassini area, Quebec. Neilson (1953, pp. 19-20, and Pl. 3) and Wahl (1953, pp. 24-25, and Pl. 4) described columnar, hemispherical, and conical stromatolites in several members of the Albanel Formation. These stromatolites, ranging from a few inches to more than 10 feet in diameter, occur in light grey carbonaceous dolomite. In an earlier description of stromatolites in the Albanel Formation, Norman (1940, p. 519), mentioned "Pisolitic structures . . . in small irregular 'reefs' ".

Belcher Islands. Moore (1918, pp. 420-428, Figs. 9-14) described "spherical to subspherical bodies consisting of concentric layers", 1 inch to 15 inches in diameter, in slightly carbonaceous limestone of the Belcher Islands. G. D. Jackson (pers. comm.) noted that columnar and hemispherical stromatolites occur in several dolomite units of this area. In the Richmond Gulf area, east of Belcher Islands, stromatolites are also reported in cherty limestones and dolomites of the Nastapoka Group (Bergeron, 1957, p. 109).

Northwest Territories. Rutherford (1929, pp. 258-259, and Pl. 1) reported domical stromatolites in limestones east of Great Slave Lake. Recent reconnaissance mapping by the Geological Survey of Canada has shown stromatolitic dolomite and limestone to be abundant throughout large areas of Northwest Territories (G. M. Wright and J. A. Fraser, pers. comm.)[1].

Athabasca area, Saskatchewan. L. P. Tremblay (pers. comm.) has observed stromatolites in calcareous conglomerates associated with siltstones in the upper part of the Martin Formation. The structures, mostly less than 6 inches in diameter, typically consist of finely crenulated, incomplete shells capping limestone pebbles. They occur in a zone less than 5 feet thick and as much as 200 feet long. Stromato-

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[1] R. N. McNeely, student assistant to J. A. Fraser during the 1962 field season, has studied and described stromatolites in Proterozoic rocks of the Bathurst Inlet area, Northwest Territories (McNeely, 1963, Proterozoic Stromatolites; Unpub. B.Sc. Thesis, Queen's Univ., Kingston, Ontario). Of special interest is the presence of the hydrocarbon impsonite in vugs within conical stromatolites of the Parry Bay Formation.

lites occur also in dolomites of the Carswell Formation, south of Lake Athabasca (Fahrig, 1961, p. 18).

Arctic Islands. In an outline of Proterozoic stratigraphy of the Canadian Arctic Archipelago, Blackadar (1957, p. 99) stated: "Cryptozoon reefs have been noted in the Rensselaer Bay sandstone and what may be algae were collected from a calcareous layer in the sandstone unit on Somerset Island."

Avalon Peninsula, Newfoundland. W. D. McCartney (pers. comm.) has observed gently domed structures in calcareous beds of the Conception Group. They are discrete, laminated forms, 8 to 10 inches in diameter, and occur widely scattered throughout the containing beds.

Rocky Mountains, British Columbia. Domical stromatolites occur in units of dolomite and minor limestone of the Kitchener, Gateway, and Roosville Formations of the Purcell System (G. B. Leech, pers. comm.). Typically they are closely packed and less than 1 foot in diameter.

Lake Superior region, Ontario. Stromatolites in cherts of the Gunflint Formation, north shore of Lake Superior, include cabbage-like and biscuit-shaped forms up to 6 inches in diameter, cauliflower-shaped heads 1 foot to 2 feet in diameter, and a reef-like structure approximately 20 feet long and 10 feet wide, characterized internally by "thimble-like or tube-shaped structures" (Moorehouse, 1960, p. 8). Cherts of the Gunflint Formation containing reef-like mounds and "algal banding" are also described and illustrated by Goodwin (1960, pp. 49-52).

Sudbury Basin, Ontario. "Algal-like" forms in graphitic limestones of the Whitewater Group have recently been described, illustrated, and discussed by Thomson (1960). Undulatory layering predominates, but hemispherical and cabbage-like structures occur, and both pisolites and oolites are "distributed throughout the algal-like forms" (ibid., p. 68).

SUMMARY

The gross form, internal lamination, carbon content, and stratigraphically restricted occurrence of the stromatolites described herein leave little doubt as to their organic origin, and because analogous structures are constructed as a result of algal activity in modern environments, algal origin is postulated for them. Undulatory, columnar, hemispherical, and bulbous stramatolites are interpreted as structures recording the influence of algal mats in environments of dominantly clastic sedimentation; digitate and pisolitic stromatolites are interpreted as structures produced by carbonate-precipitating algae.

The Denault stromatolites reflect a shallow-water to intertidal environment throughout the time of deposition for as much as 45 per cent of the Denault Formation south of Marion Lake. Stable shelf conditions are inferred, and because the Denault beds (truncated at Marion Lake by a major fault) comprise a sequence more than 3,000 feet thick, shelf conditions during Denault times probably obtained several miles farther eastward, perhaps even as far as the present eastern boundary of the 'Labrador Trough'.

Domical and digitate stromatolites provide a reliable indication for determining the tops of beds, and have been so used with success by many geologists. Stromatolites have also been used successfully for correlation, and their use in local correlation for a part of the Denault Formation has here been demonstrated. Units such as the Denault Formation, in which several distinctive stromatolites occur in zones, are particularly promising for more extensive correlation.

A brief summary of other occurrences indicates the widespread distribution of stromatolites in Proterozoic rocks of Canada. Further study should lead to a better understanding of these interesting but commonly enigmatic structures.

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FIGURES 4 and 5

FIGURE 4

Form-Classification of Stromatolites

A. Hemispherical stromatolites (*Collenia*).

B. Bulbous stromatolites (*Cryptozoon*).

C. Columnar stromatolites (*Archaeozoon*).

D. Undulatory stromatolites (*Weedia*).

E. Digitate stromatolites (*Gymnosolen*).

F. Pisolitic stromatolites (*Pycnostroma*).

Figure 4

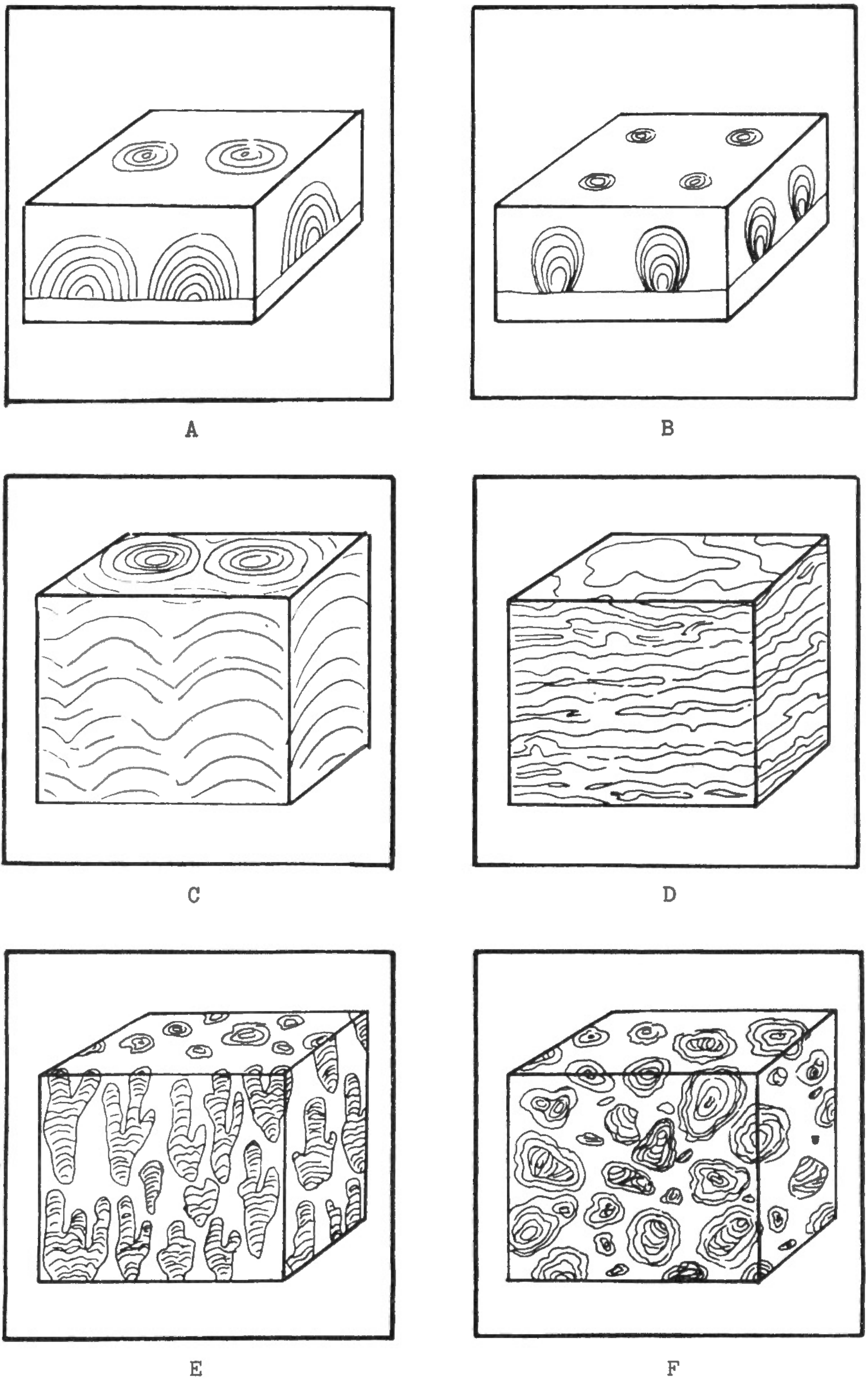


FIGURE 5

Comparison of Stromatolites and Similar Structures

A. Section normal to axes of small folds, resembling longitudinal section through laterally-linked domical stromatolites. Sections parallel to the fold axes prove the resemblance to be superficial.

B. Domical structures produced by deformation. No well-documented examples are known, but even if extant, their secondary origin should be readily recognized.

C. Various domical stromatolites. Relationship to overlying and underlying beds, configuration of laminations, and abundance of derived detritus serve to distinguish from A, B.

D. Soft-sediment slump structures. Note local displacements, parallelism of laminations, and asymmetry of contorted strata.

E. Soft-sediment compaction-structures simulating lamination configuration of undulatory stromatolites.

F. Undulatory stromatolites. Evidence for reworking of contorted layers and the presence of other stromatolites distinguished from E, F.

G. Travertine deposited around a spring conduit. Note relationship to older beds.

H. Caliche profile showing physiographic control and gradational relationship to source beds.

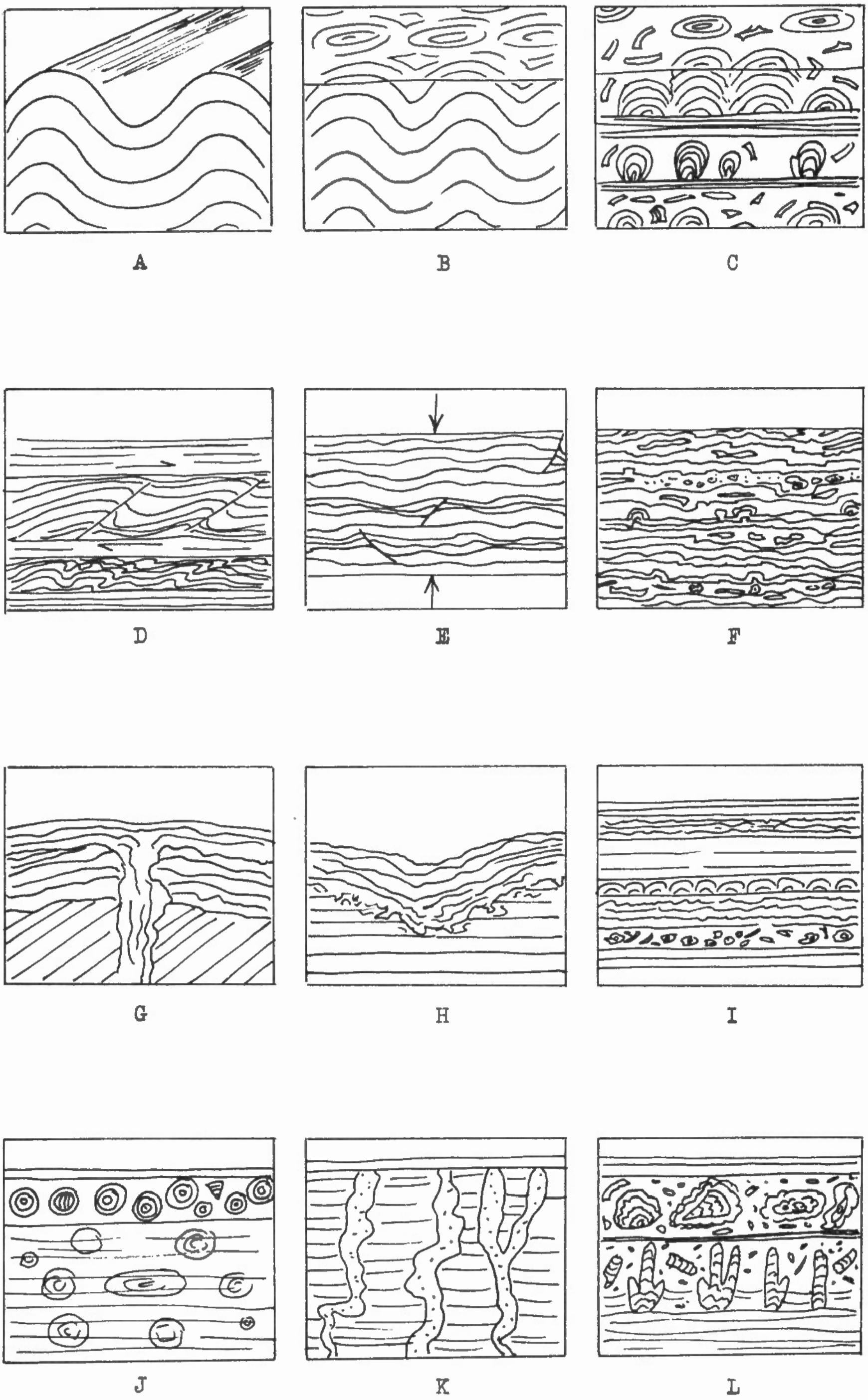
I. Undulatory stromatolites. Thin, laterally extensive units conformable with enclosing beds, and associated with other stromatolites.

J. Concretionary beds overlain by unit containing inorganic pisolites. Bedding transects concretions, and successive shells of pisolites are smooth and centrosymmetric.

K. Solution pipes. Note lack of lamination within tubular structures, sinuous configurations, and irregular boundaries.

L. Pisolitic and digitate stromatolites. Pisolites with typical crenulate laminations show great variety in shape and lack of radial symmetry. Digitate structures are laminated and originate at a common horizon. Note abundance of reworked detritus associated with both types of stromatolite.

Figure 5



PLATES I to VII B

PLATE I

A. Finely laminated siliceous dolomite. Polished surface showing numerous graded laminations and a cross-stratified bed. Dark coloration indicates high content of quartz silt. Scale in centimetres. (*See* p. 4.) 112300.

B. Massive dolomite. Clastic texture is partly obscured by recrystallization, and solution along microstylolites. Photomicrograph, plane polarized light, x20. (*See* p. 4.) J.A.D.

PLATE I A

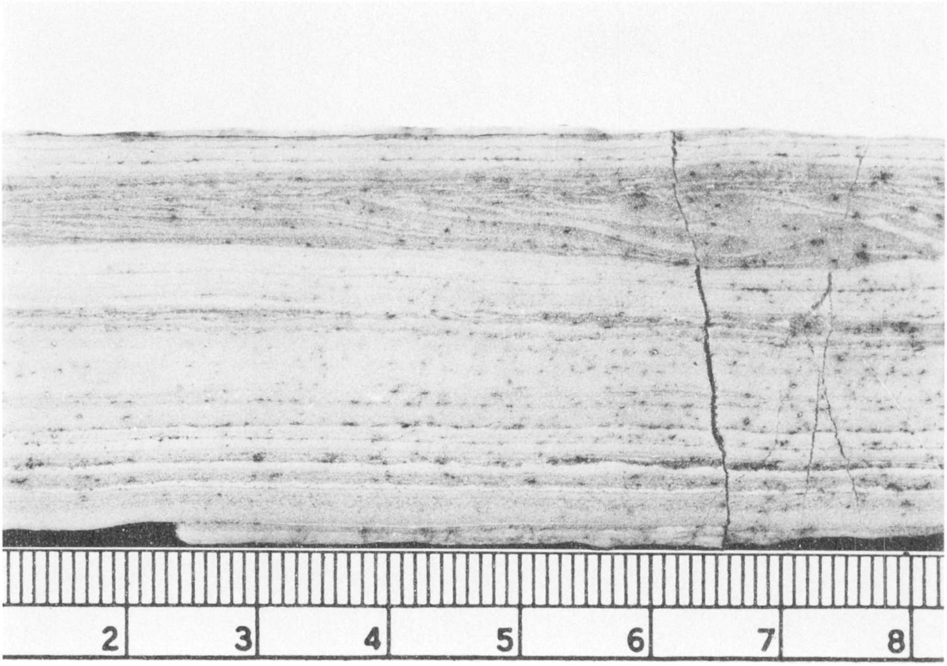


PLATE I B

PLATE II

A. Columnar stromatolites. Convex-upward lamination accentuated by differential weathering. Note close packing of columns. Scale extended 1 foot. (*See* p. 12.) 112255.

B. Hemispherical stromatolite. Acid-etched longitudinal section showing sharply truncated central dark layer, clastic nature of interspace detritus, and tendency of layers to taper towards margins. Scale in centimetres. (*See* p. 12.) GSC Plant No. 13131.

PLATE II A

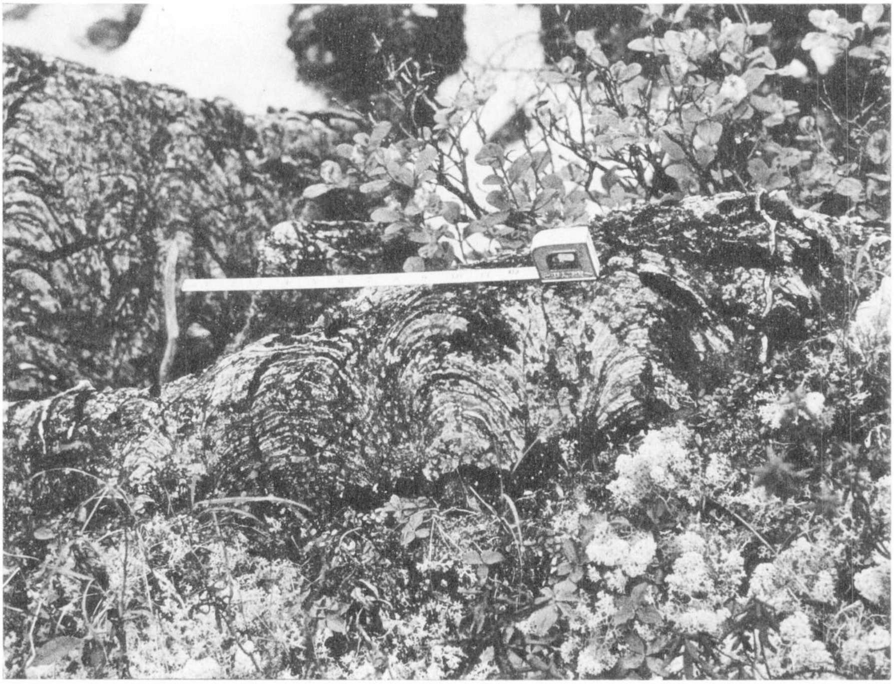


PLATE II B

PLATE III

Hemispherical stromatolite. Thin section showing detail of lamination. Note abundance of pellets in light layers and tubular structures in some dark layers. Truncation of central layer interpreted as the result of vigorous wave action. Triangular light coloured area, centre of photograph, consists mostly of coarsely crystalline dolomite. Plane polarized light, x5. (*See* p. 12.) GSC Plant No. 13131.

PLATE IV

A. Digitate stromatolites. Surface cut parallel with axes of columns and etched in acid. Note abundance of interspace detritus, and local linkage of laminae. Scale in millimetres. (*See* p. 12.) GSC Plant No. 13132.

B. Digitate stromatolites. Similarity of lamination to that of pisolitic stromatolites is illustrated by this transverse cut polished section. Scale in centimetres. (*See* p. 13.) GSC Plant No. 13133.

Plate IV A

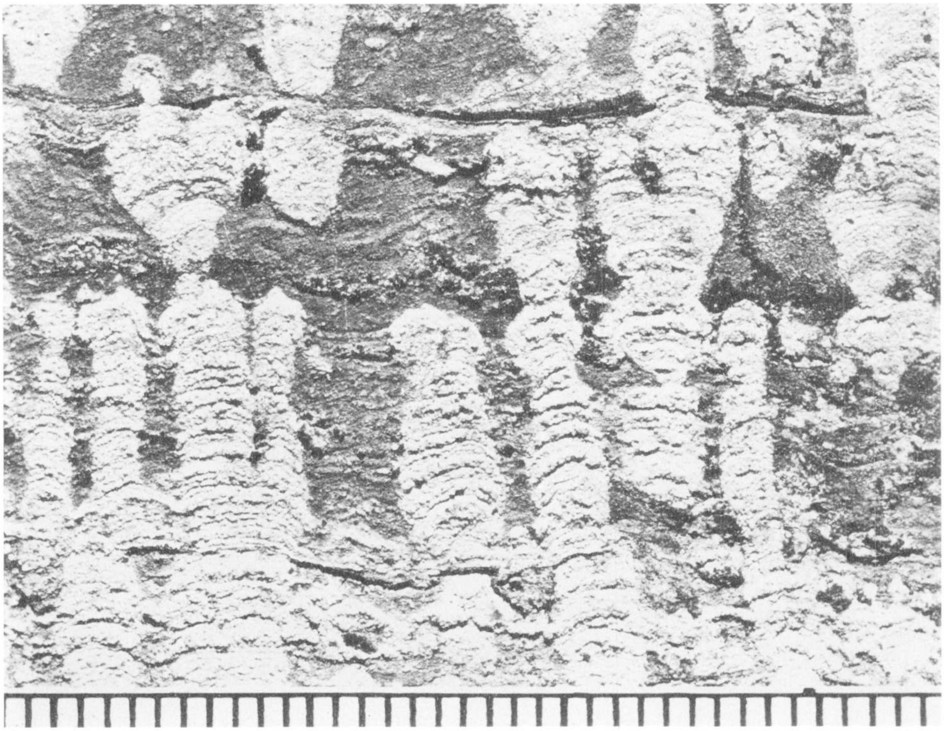


Plate IV B

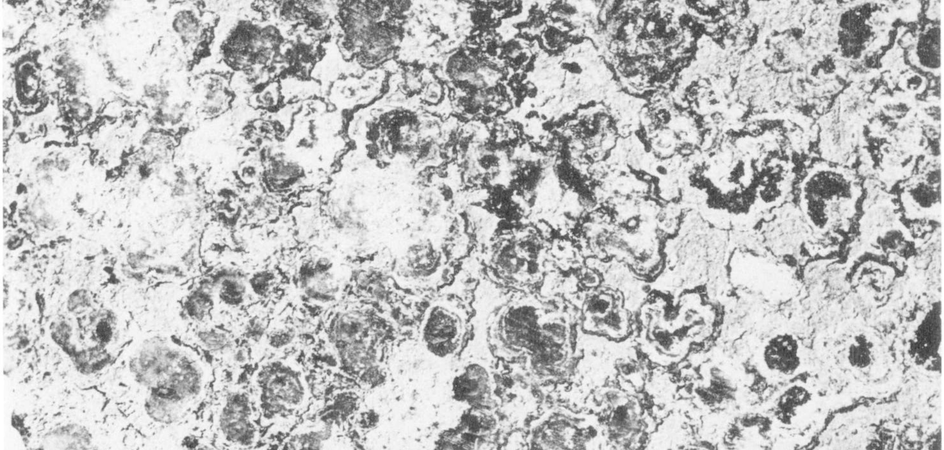


PLATE V

Digitate stromatolites. Photomicrograph shows correspondence of lamination thicknesses at coincident levels. Note derived fragment at lower left, and overlying stromatolitic conglomerate. Plane polarized light, x4.5. (*See* p. 12.) GSC Plant No. 13132.

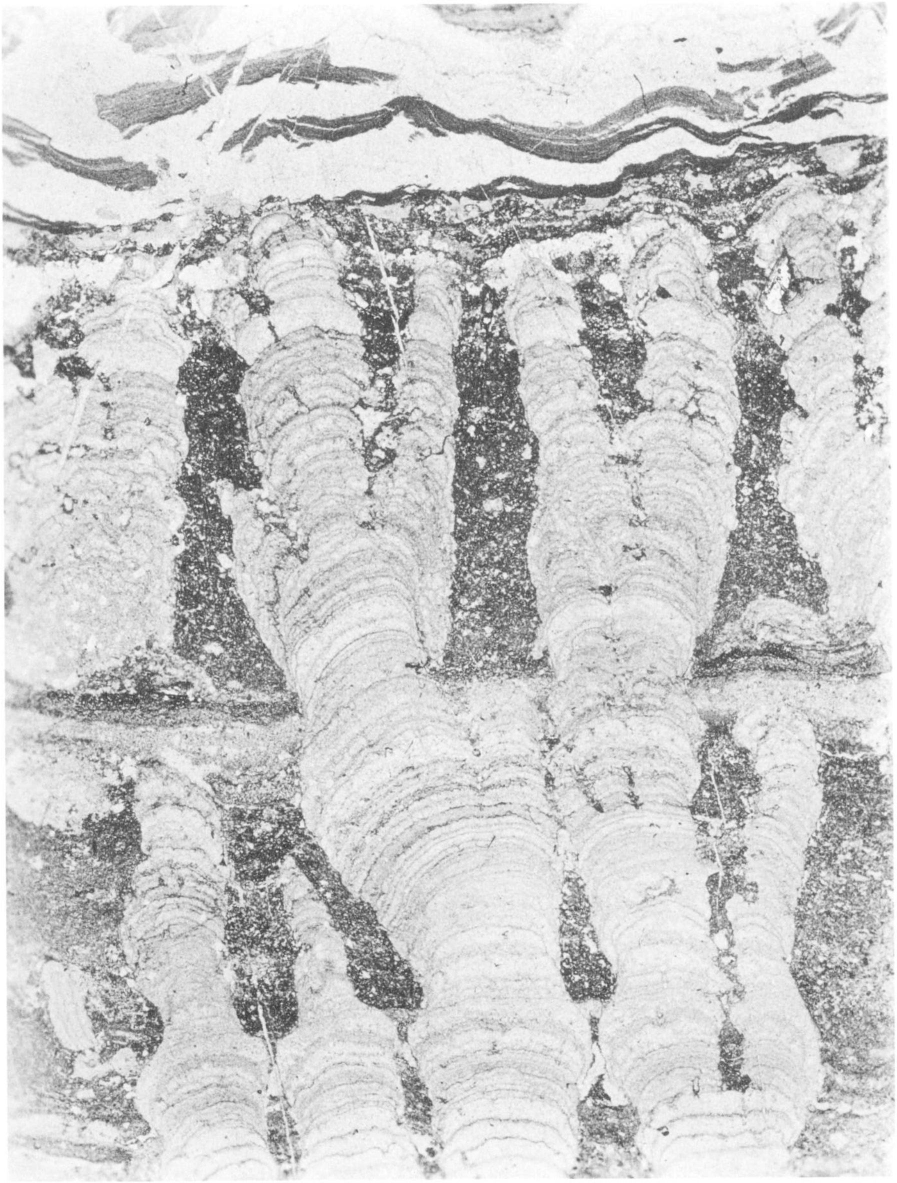


PLATE VI

A. Pisolitic stromatolites. Weathered surface showing abundance of pellets in the matrix. Note asymmetry of lamination in some of the pisolites. Scale in centimetres. (*See* p. 13.) GSC Plant No. 13134.

B. Matrix of pisolitic stromatolites. Carbonaceous pellets, nascent pisolites, and fragments derived from stromatolites are cemented by clear crystalline dolomite. Photomicrograph, plane polarized light, x5.5. (*See* p. 13.) GSC Plant No. 13134.

Plate VI A

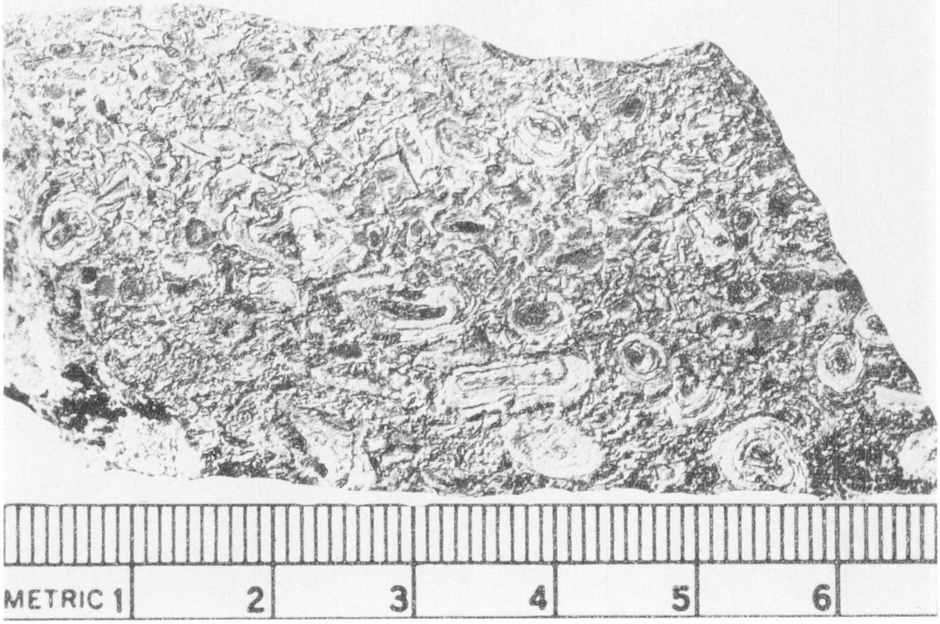


Plate VI B

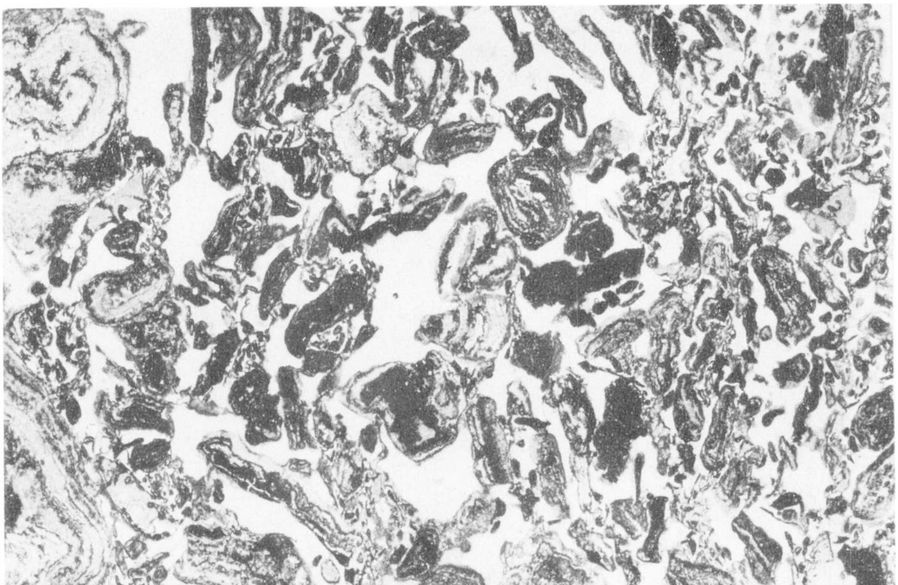


PLATE VII

A. Undulatory stromatolites. Differential weathering accentuates characteristic structure. Top of specimen faces right, as indicated by asymmetric domical nature of the laminations. Abundance of siliceous ribs and pods is typical. Scale in millimetres. (*See* p. 13.) GSC Plant No. 13135.

B. Pelletoidal dolomite. Photomicrograph of thin section cut from undulatory stromatolite showing reworked layers containing typical ellipsoidal to rod-shaped pellets. Clear areas are patches of coarse-grained dolomite, in part as cavity-infillings, and in part representing recrystallized dolomite. Plane polarized light, x20. (*See* p. 14.) GSC Plant No. 13136.

Plate VII A

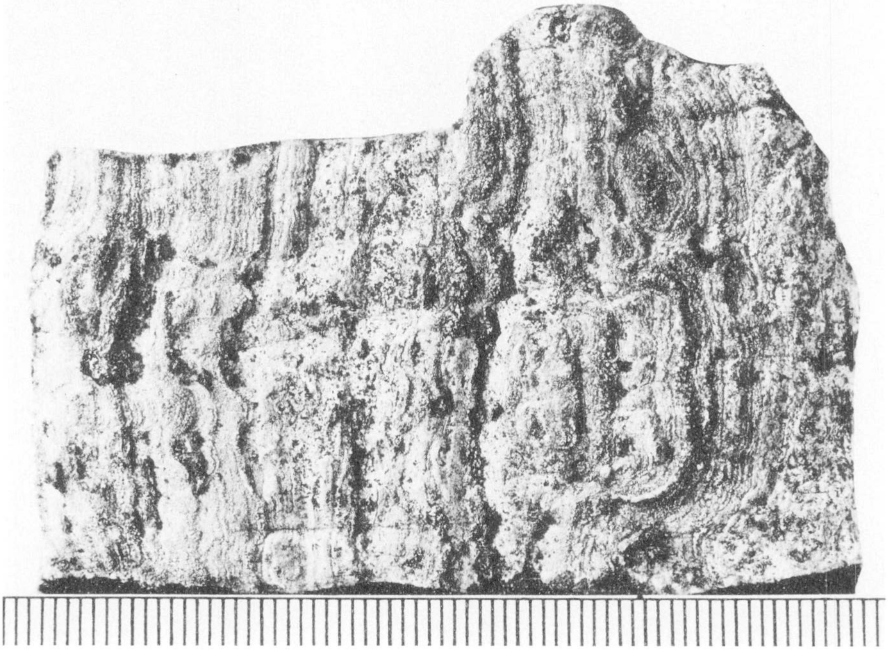


Plate VII B