GEOLOGICAL SURVEY OF CANADA
BULLETIN 399

SUBMARINE CEMENTS AND FABRICS IN CARBONIFEROUS TO LOWER PERMIAN, REEFAL, SHELF MARGIN AND SLOPE CARBONATES, NORTHWESTERN ELLESMERE ISLAND, CANADIAN ARCTIC ARCHIPELAGO

G.R. Davies and W.W. Nassichuk

Energy, Mines and Resources Canada
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Type sections of the Upper Carboniferous, evaporitic Otto Fiord Formation (light coloured) overlain by the Upper Carboniferous to Lower Permian Hare Fiord Formation (dark coloured) as viewed from the ice on Hare Fiord about three miles east of Van Hauen Pass in northern Ellesmere Island. View is to the west and towards the pass. A major northwesterly - dipping thrust fault underlies the Otto Fiord Formation juxtaposing the latter with dark coloured Triassic rocks which are visible immediately above sea level. Photograph by R. Thorsteinsson, June 1, 1956.

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PREFACE

This report contributes to our knowledge of processes that affect the evaluation of porosity in carbonate rocks, and thus provides insights into their hydrocarbon potential. Geological evaluation of the Canadian Arctic Archipelago has progressed from a stage of regional geological interpretation, through more detailed "second generation" lithostratigraphic and biostratigraphic studies, to increasingly sophisticated analyses and interpretation of tectonics, sedimentation, and diagenesis. This bulletin records one of the latter steps in the process.

In this report, submarine cementation and related synsedimentary processes in Carboniferous and Permian carbonate rocks within the Sverdrup Basin in the Arctic Archipelago are documented, and their origin and significance discussed. The excellent state of preservation of the upper Paleozoic carbonates exposed under an arid Arctic climate has allowed extensive photographic documentation of submarine cements and related fabrics on both macro- and micro-scales. Accordingly, this "textbook" of submarine cementation provides a stimulus for ongoing research in carbonate petrology and related fields.

Elkanah A. Babcock
Assistant Deputy Minister
Geological Survey of Canada

PRÉFACE

Ce rapport contribue à nos connaissances des processus qui influent sur l'évaluation de la porosité dans les roches carbonatées, nous renseignant ainsi sur leur potentiel en hydrocarbures. L'évaluation géologique de l'archipel de l'Arctique canadien est passée du stade de l'interprétation géologique régionale, des études lithostratigraphiques et biostratigraphiques de "deuxième génération" plus détaillées, aux analyses et à l'interprétation de plus en plus poussées de la tectonique, de la sédimentation et de la diagénèse. Cet ouvrage fait état d'une étape dans le processus.

Dans ce rapport, la cimentation sous-marine et les processus synsédimentaires associés, dans les roches carbonatées du Carbonifère et du Permien à l'intérieur du bassin de Sverdrup, dans l'archipel de l'Arctique, sont documentés, et leur origine et leur signification sont analysées. L'excellent état de conservation des carbonates paléozoïques exposés à un climat arctique aride a permis d'accumuler une imposante documentation photographique sur les ciments sous-marins et les fabriques associées aux échelles tant macro que microscopique. Ainsi, ce "manuel" de cimentation sous-marine incite à poursuivre la recherche en pétrologie des carbonates et dans les domaines connexes.

Elkanah A. Babcock
Sous-ministre adjoint
Commission géologique du Canada

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Abstract

Carboniferous and Lower Permian carbonate rocks deposited within the Sverdrup rift basin and exposed on northwestern Ellesmere Island in the Arctic Archipelago represent a number of depositional settings, many of which are characterized by spectacular submarine cementation fabrics. Exposure and preservation of the carbonate fabrics is enhanced by the semi-arid, Arctic climate of northern Ellesmere Island. Submarine diagenetic fabrics were preferentially developed in shelf margin, reefal, and shelf foreslope to toe-of-slope carbonates. Documented reef types include anhydrite-enclosed algal buildups in the Carboniferous Otto Fiord Formation, Upper Carboniferous Waulsortian-type reefs buried within basinal rocks of the Hare Fiord Formation, and less clearly defined, shelf-margin, phylloid algal, and palaeoaplysinid buildups in the Carboniferous to Lower Permian Nansen Formation.

Submarine cements occur as dispersed micritic subpeloidal matrix cement; as multilayered isopachous radial-fibrous calcite, after magnesium calcite cement, in reef cavity systems; and as small hemispheres to large botryoids of radial-array calcite, after aragonite, in reef cavities and submarine fractures. Evidence of the submarine origin and composition of the original cement includes fabric relationships, microprobe elemental analyses, and carbon and oxygen isotope data.

The reefs are cut by submarine fractures rimmed by radial-fibrous submarine cements that are continuous with generations of submarine cement within primary reef cavities. The fractures were progressively filled by large aragonite botryoids and marine internal sediments, or by silty and dolomitized crinoidal sediment that heralded the onset of burial by the Hare Fiord basinal sequence.

Loss of primary porosity as the result of submarine cementation ranges from 10 to 80 per cent over large volumes of reefal rock mass. Submarine cementation occurs preferentially on the seaward side of shelf margins and reefs, apparently in response to wave, tidal or storm surge pumping. The spectacular exposures and preservation of the submarine diagenetic fabrics in these Arctic carbonates should provide an ongoing stimulus to research into the submarine and burial diagenetic processes in these rocks.

Résumé

Les roches carbonatées du Carbonifère et du Permien inférieur qui se sont déposées dans le bassin tectonique de Sverdrup dans le nord-ouest de l'î Ellesmere dans l'Arctique représentent plusieurs modes stratigraphiques dont un grand nombre sont caractérisés par des fabriques de cimentation sous-marine remarquables. L'exposition et la conservation des fabriques des carbonates sont rehaussées par le climat arctique semi-aride du nord de l'île Ellesmere. Des fabriques diagénétiques sous-marines se sont formées de façon préférentielle dans les carbonates de la marge continentale, des formations récifales et de l'avant-talus au pied de talus du plateau continental. Les types récifaux documentés comprennent des accumulations algaires dans l'anhydrite de la Formation d'Otto fiord du Carbonifère, des récifs de type waulsortien du Carbonifère supérieur enfouis dans des roches bassinales de la formation de Hare Fiord, et des accumulations algaires foliacées et paléoaplysinides de la marge continentale moins bien définies dans la formation de Nansen du Carbonifère au Permien inférieur.

Les ciments sous-marins se présentent sous forme de ciments à matrice subpéloïdal micritique dispersé; sous forme de calcite radialement fibreuse, isopache, multicouche, après du ciment de calcite de magnésium, dans des réseaux de cavités récifales; et sous une forme allant de petits hémisphères à de gros botryoïdes de calcite à disposition radiale, après de l'aragonite, dans des cavités récifales et des fissures sous-marines. L'origine sous-marine et la composition du ciment original ressortent des relations de fabrique, des analyses élémentaires à la microsonde, et des données sur les isotopes du carbone et de l'oxygène

Les récifs sont recoupés par des fractures bordées de ciments sous-marins radialement fibreux qui sont continus avec les générations de ciment sous-marin à l'intérieur des cavités récifales primaires. Les fractures ont été progressivement remplies de gros botryoïdes et de sédiments internes marins, ou par des sédiments crinoidaux silteux et dolomitisés qui ont présidé au début de l'enfouissement par la séquence bassinale de Hare Fiord. La perte de porosité primaire par cimentation sous-marine varie de 10 à 80 pour cent dans de gros volumes de masse rocheuse récifale. La cimentation sous-marine se produit de préférence du côté mer des marges et des récifs continentaux, apparemment en réponse au pompage sous l'action des vagues, des marées et des ondes de tempête. Les expositions spectaculaires et la conservation des fabriques diagénétiques sous-marines dans ces carbonates de l'Arctique devraient constituer un stimulus constant en matière de recherche sur les processus diagénétiques sous-marins et d'enfouissement dans ces roches.

Summary

Reefal, shelf margin, and foreslope carbonates that faced the open axial trough of Sverdrup Basin in Carboniferous and Early Permian time were subjected to a range of submarine diagenetic processes before burial. These rocks have been exhumed on northwestern Ellesmere Island in the Canadian Arctic Archipelago under conditions of a semiarid Arctic climate and glacial stripping, which have produced many spectacular exposures with exceptional preservation of diagenetic fabrics.

The hosts for the submarine fabrics include organic buildups and originally porous shelf-edge and slope units, in which filamentous algae, fenestellid and ramose bryozoans, phylloid algae, and palaeoaplysinids played significant but age-dependent roles. A new textural term, ''platestone'', is introduced for limestones characterized by loosely packed shelter frameworks of plate-like bioclasts with associated patches of primary marine sediment and ponded sediment, stabilized by pervasive submarine cements. The most spectacular submarine diagenetic fabrics are found in Waulsortian-type Upper Carboniferous reefs (as compared to classical Lower Carboniferous Waulsortian facies) that overlie axial (basin-centre) evaporites and are enclosed by deeper water shales and carbonates. The Waulsortian-type reefs provide the major source of data and illustrations of submarine diagenetic fabrics in this bulletin.

Submarine cements in the Carboniferous and Lower Permian carbonates on Ellesmere Island occur in several forms. Fine subpeloidal micritic cements in the carbonate sediment matrix contributed to early matrix lithification, but tend to be underestimated in terms of their contribution and significance to induration due to the more conspicuous, commonly spectacular and coarser, pore-filling submarine cements. The latter occur in two main morphologies: as multilayered isopachous rims of radial-fibrous (including radiaxial) calcite, neomorphic after magnesium calcite; and as small hemispheres to large botryoids of radial-array calcite, neomorphic after aragonite. Collectively, these three types of cements may form 80 per cent of the volume of metre-scale reefal rock units. A variant of the cavity-filling radial-array calcite, is a radial-array fabric formed by replacement of radiating crystals of aragonite that originally replaced the sediment matrix and magnesium calcite cements.

Submarine fractures that cut the carbonate units, particularly the Waulsortian-type reefs, are lined by radial-fibrous calcite cements and may be partly or completely filled by either, or a combination of, marine internal sediment and large aragonite botryoids. Fabric relationships indicate that the first generation of radial-fibrous cement lining the submarine fractures is directly contiguous and correlative with the second layer of radial-fibrous cement within the primary cavities of the reefal host, with late generation of cement in both settings also correlative.

The marine origin of the submarine cements is documented from petrofabrics and isotopic data that give mean values of $+5.4$ ‰ $\delta^{13}C$ and -3.5 ‰ $\delta^{18}O$ for radial-fibrous calcite, and $+5.7$ ‰ $\delta^{13}C$ and -2.8 ‰ $\delta^{18}O$ for botryoidal calcite.

The magnesium calcite composition of the precursor of radial-fibrous calcite is supported by textural data, by microprobe mean composition of 1.6 mole per cent $MgCO_3$, and by the presence of dolomite microcrystal inclusions. The interpretation that aragonite was the precursor of radial-array and botryoidal-array calcite again is supported by petrofabric evidence, by analogy with modern submarine aragonite botryoids, by below-detection mean levels of $MgCO_3$, and, most dramatically, by levels of Sr up to 8000 ppm (with no detectable aragonite or other strontium carbonate micro-inclusions) within larger masses of botryoidal calcite.

Step-like increases in $MgCO_3$ within each growth increment of radial-fibrous calcite, and also from the first to the last generation of the multilayered radial-fibrous cement (originally Mg calcite), are attributed to precipitation in a semi-closed pore fluid system that was periodically recharged by storm surges, and/or variation in the rate of crystal growth. Pulses of marine internal sediment, interlayered with and terminating cement generations, also probably were a product of storm surges. Fracture-lining cement generations are composed of couplets with a micritic and microcolumnar basal layer that may have been cyanobacterially controlled, grading outward into normal radial-fibrous calcite; these layers also show step-like increases in relict $MgCO_3$. Submarine fracturing occurred after initial stabilization of the reef by the first generation of magnesium calcite/radial-fibrous cement.

Onset of burial of Waulsortian-type reefs by silty and argillaceous sediments of the enclosing and overlying basinal sequence was heralded by the introduction of silty crinoidal sediment into submarine fractures and cement-lined, open, primary cavities in the reef mass. Burial diagenetic fabrics and processes in the Arctic carbonates are not described in this report, but have been summarized in an earlier paper. Submarine cements are preferentially developed in porous and permeable sediments

on the seaward or seaward-facing side of carbonate shelves, slopes and reefs. Potential mechanisms for pumping or maintaining the flow of seawater through the permeable sediments and rocks, to provide the source of calcium carbonate, include wave, tidal and storm pressure surges (on various time scales), but actual processes remain to be defined by modern in situ reef studies. Precipitation within reef cavity systems may be microbiologically controlled but, again, clarification is required from analysis of modern reef processes. Preference for magnesium calcite or aragonite precipitation may be controlled by the rate of crystal growth, in turn influenced by the level of carbonate ion concentration and degree of fluid shear (flow rate).

The exceptional exposures and degree of preservation of fabrics in the upper Paleozoic carbonates in the high Arctic setting allow documentation and illustration of submarine diagenetic fabrics at a level not often achieved at lower latitudes, where the rocks have been subjected to deeper weathering and plant cover. We hope that this bulletin will encourage future research on the diagenesis of the Carboniferous and Permian carbonates in the Arctic Archipelago.

Sommaire

Les carbonates récifaux, de la marge et de l'avant-talus du plateau continental, qui faisaient face à l'axe synclinal ouvert du bassin de Sverdrup à l'époque du Carbonifère et du Permien précoce ont été soumis à divers processus diagénétiques sous-marins avant d'être enfouis. Ces roches ont été exhumées dans le nord-ouest de l'île Ellesmere dans l'archipel de l'Arctique canadien sous un climat arctique semi-aride et sous l'action érosive des glaciers, donnant lieu à de nombreux affleurements spectaculaires caractérisés par un état exceptionnel de conservation des fabriques diagénétiques.

Les fabriques sous-marines sont logées dans des matières organiques accumulées et des unités de bordure de plateau et de talus originalement poreuses, dans lesquelles des algues, des fénestellides et des bryozoaires branchus filamentaux, des algues foliacées et des paléoaplysinides ont joué des rôles importants, mais variables en fonction de l'âge. Un nouveau terme textural, le "platestone", est introduit pour les calcaires caractérisés par des réseaux hôtes remplis de bioclastes meubles, assimilables à des plaques, parsemés d'îlots de sédiments marins primaires et de sédiments endigués stabilisés par des ciments sous-marins intrusifs. Les fabriques diagénétiques sous-marines les plus spectaculaires se trouvent dans les récifs du Carbonifère supérieur de type waulsortien (par rapport aux faciès waulsortiens classiques du Carbonifère inférieur) qui recouvrent les évaporites axiales (centre du bassin) et sont contenus dans les schistes argileux et les carbonates des eaux plus profondes. Les récifs de type waulsortien constituent la principale source de données et d'illustrations sur les fabriques diagénétiques sous-marines dans le présent bulletin.

Les ciments sous-marins dans les carbonates du Carbonifère et du Permien inférieur de l'île Ellesmere se présentent sous plusieurs formes. Des ciments micritiques subpéloïdaux fins dans la matrice de sédiments carbonatés ont contribué à la lithification précoce de la matrice, mais leur contribu tion et leur importance dans l'induration sont en général sous-estimées à cause des ciments sous-marins intersticiles plus évidents, qui sont généralement spectaculaires et plus grossiers. Ces derniers présentent deux grandes morphologies : bordures isopaques multicouches de calcite radialement fibreuse (y compris radiaxiale), néomorphique après la calcite de magnésium; et éléments allant de petits hémisphères à de gros botryoïdes de calcite disposée radialement, néomorphique après l'aragonite. Collectivement, ces trois types de ciments constituent 80 pour cent du volume des unités de roche récifale de l'ordre du mètre. Une variante de la calcite à structure radiale qui remplit les cavités est la fabrique à structure radiale qui s'est formée par substitution des cristaux rayonnants d'aragonite qui ont remplacé à l'origine les ciments de la matrice de sédiments et de la calcite de magnésium.

Les fractures sous-marines qui recoupent les unités de carbonate, particulièrement les récifs de type waulsortien, sont recouvertes par des ciments de calcite radialement fibreuse et sont partiellement ou entièrement remplies de sédiments internes marins, de gros botryoïdes d'aragonite ou d'une combinaison des deux. Les relations de fabrique indiquent que la première génération de ciment radialement fibreux qui recouvre les fractures sous-marines est directement contiguë et corrélée à la deuxième couche de ciment radialement fibreux à l'intérieur des cavités primaires de la formation récifale mère, avec une génération postérieure de ciment dans les deux emplacement également en corrélation.

L'origine marine des ciments sous-marins est documentée par des données sur les pétrofabriques et les isotopes desquelles se dégagent des teneurs moyennes de +5,4 ‰ $\delta^{13}C$ et de -3,5 ‰ $\delta^{18}O$ pour la calcite radialement fibreuse, et de -5,7 ‰ $\delta^{13}C$ et de -2,8 ‰ $\delta^{18}O$ pour la calcite botryoïdale. La composition de la calcite de magnésium du précurseur de la calcite radialement fibreuse est confirmée par des données de texture, par la composition moyenne, à la microsonde, de 1,6 mole

pour cent de $MgCO_3$, et par la présence d'inclusions microcristallines de dolomite. L'interprétation voulant que l'aragonite soit le précurseur de la calcite à structure tant radiale que botryoïdale est encore supportée par les données de pétrofabrique, par l'analogie avec les botryoïdes d'aragonite sous-marins modernes, par les concentrations moyenne sous le seuil de détection de $MgCO_3$, et surtout par les concentrations de Sr atteignant 8000 ppm (sans aucune aragonite ni autres micro-intrusions de carbonate de strontium détectables) à l'intérieur de masses plus grosses de calcite botryoïdale.

Les augmentations par paliers de $MgCO_3$ associées à chaque poussée de croissance de la calcite radialement fibreuse et accompagnant de la première à la dernière génération de ciment radialement fibreux multicouche (originalement de la calcite de Mg) sont attribuables à la précipitation dans un système de circulation intersticielle semi-fermé qui était périodiquement rechargé par les ondes de tempête, et/ou à la variation du taux de croissance des cristaux. Des impulsions de sédiments internes marins, alternant avec et se terminant par des générations de ciments, étaient aussi probablement le produit d'ondes de tempête. Les générations de ciment recouvrant les fractures sont composées de couplets comportant une couche de base micritique et microcolumnaire qui a pu subir un contrôle cyanobactérien, se transformant vers l'extérieur en calcite radialement fibreuse normale; ces couches présentent également des augmentations par paliers du $MgCO_3$ résiduel. La fissuration sous-marine s'est produite après la stabilisation initiale du récif par la première génération de calcite de magnésium/ciment radialement fibreux.

L'enfouissement des récifs de type waulsortien dans les sédiments silteux et argileux de la séquence bassinal tant mère que sus-jacente a débuté au moment de l'introduction des sédiments crinoïdaux silteux dans les fractures sous-marines et les cavités primaires ouvertes, recouvertes de ciment, dans la masse récifale. Les fabriques et les processus diagénétiques d'enfouissement dans les carbonates de l'Arctique ne sont pas décrits dans le présent rapport, mais ont été résumés dans un mémoire antérieur. Des ciments sous-marins se sont formés de façon préférentielle dans les sédiments poreux et perméables du côté tourné vers la mer des plateaux, talus et récifs carbonatés. Les mécanismes potentiels de pompage ou d'entretien de la circulation de l'eau de mer dans les sédiments et les roches perméables, assurant un approvisionnement en carbonate de calcium, comprennent les supressions accompagnant les vagues, les marées et les tempêtes (à diverses échelles de temps), mais les processus réels restent à définir dans des études in situ modernes sur les récifs. La précipitation à l'intérieur des réseaux de cavités récifales pourrait être contrôlée microbiologiquement, mais cela reste encore à clarifier par une analyse des processus récifaux modernes. La tendance à la précipitation de la calcite de magnésium ou de l'aragonite pourrait être contrôlée par le taux de croissance des cristaux, à son tour modifié par la concentration d'ions carbonates et le degré de cisaillement (débit) du fluide.

Les expositions et l'état de conservation exceptionnels des fabriques dans les carbonates du Paléozoïque supérieur dans le haut Arctique permettent de documenter et d'illustrer les fabriques diagénétiques sous-marines à un point rarement atteint aux latitudes plus basses où les roches ont été soumises à une altération plus intense et recouvertes d'une couche végétale plus épaisse. Nous espérons que ce bulletin suscitera de nouvelles recherches sur la diagénèse des carbonates du Carbonifère et du Permien dans l'archipel de l'Arctique.

INTRODUCTION

Reef and shelf-edge carbonate rocks of Carboniferous and Permian age in the northern Sverdrup Basin, exposed on Ellesmere Island in the Canadian Arctic Archipelago (Fig. 1), exhibit a variety of diagenetic fabrics; some neomorphic after generations of very early cements, others of later diagenetic origin (Davies, 1976, 1977a). The early cements and later diagenetic phases reduce or destroy the, commonly very high, primary depositional porosities in the carbonate units, thus downgrading their potential as reservoir rocks. Documentation of the diagenetic fabrics in the Arctic Archipelago carbonates is enhanced by their exposure under the present semiarid Arctic climate of northwestern Ellesmere Island, and by the lack of weathering and vegetational cover on extensive glacially scoured sections.

Our understanding of cementation and diagenesis in carbonate rocks has experienced several major advances during the last twenty years (Schneidermann and Harris, 1985). One of these advances centred on the documentation of diagenetic processes and products in Quaternary carbonates exposed to fresh (meteoric) water in vadose and phreatic environments (for reviews, see Bathurst, 1975; James and Choquette, 1983). Another major advance has been the recognition of early submarine cementation in modern coralgal reefs as a normal, rapid and pervasive process. Contemporaneously, ancient submarine cement fabrics have been recognized in reefal carbonates throughout the geological record. However, major gaps still exist in our knowledge of burial diagenetic processes affecting carbonate units enclosed in shales or other sediment types. In this burial setting, the composition and evolution of migrating fluids and the diagenetic influence on carbonate rocks of solutional and precipitational processes, under elevated temperatures and pressures, remain to be clarified. The Carboniferous and Lower Permian carbonate rocks exposed on northwestern Ellesmere Island straddle the range of diagenetic processes, from synsedimentary marine cementation to burial cementation and neomorphism, with less clearly identified evidence of meteoric diagenesis.

In this paper, we describe the principal submarine cements and other submarine fabrics in the Arctic upper Paleozoic carbonates, document their elemental and isotopic composition, and discuss their origin and significance. Although preliminary interpretations of burial diagenetic processes for the same group of rocks on northwestern Ellesmere Island have been published earlier (Davies, 1976), these processes and their products are not included in this paper as they lack the sampling, stratigraphic and analytical coverage necessary to develop a statistically valid and coherent burial diagenetic description and model. Because of the commonly spectacular fabric preservation in the Carboniferous and Lower Permian carbonates exposed on northwestern Ellesmere Island, the report includes many photographic illustrations of submarine cements and fabrics that we hope will serve as inspiration for ongoing research on the entire range of diagenetic processes in the Arctic Paleozoic carbonates.

Since our original work on the cement fabrics described in this paper, a number of significant advances have been made in the appraisal of reefal carbonates in Sverdrup Basin, including their stratigraphic and structural setting, diagenetic fabrics, isotopic character, and other characteristics. Principal amongst these advances are the reports by Beauchamp (1987) and Beauchamp et al. (1987). More descriptive papers of reef types have been presented by Davies and Nassichuk (1986); Davies, Beauchamp, and Nassichuk (1989); Davies and Nassichuk (1988c); Davies, Richards et al. (1988); Beauchamp et al. (1988); and Beauchamp et al. (1989a, b).

Carbonate textural classification

In this paper, the limestone textural classification of Embry and Klovan (1971), expanded from Dunham (1962), is used. However, an additional term, "platestone", is introduced for limestone textures characterized by loosely packed shelter frameworks of plate-like bioclasts with associated patches of primary marine sediment and ponded marine sediment trapped geopetally on the upper surfaces of the plates. Pervasive submarine cement providing synsedimentary lithification is a common, indeed necessary, factor in the preservation of the open meshwork character. The principal biotic elements contributing to platestone fabrics in Carboniferous-Permian sequences are fenestellid bryozoans, phylloid algae, and palaeoaplysinids; other taxonomic groups play similar roles in rocks of other ages.

Examples of platestone textures are illustrated in Figures 11, 12, 13A, 13B, and 18A.

Acknowledgments

The rocks described in this bulletin were collected by the authors while studying upper Paleozoic strata in the Sverdrup Basin during summer field operations with the Geological Survey of Canada from 1971 to 1974. Using data acquired in the same period the authors have published an addition 30 reports on Carboniferous and Permian sedimentology, carbonate petrography, regional stratigraphy and biostratigraphy in the Basin. Initial isotopic analyses were run in 1973 at the Denver Research Centre of Marathon Oil Company through the auspices of P.W. Choquette. The remaining isotopic analyses were conducted by H.R. Krouse of the Department of Physics, University of Calgary. Microprobe analyses were conducted under the guidance of

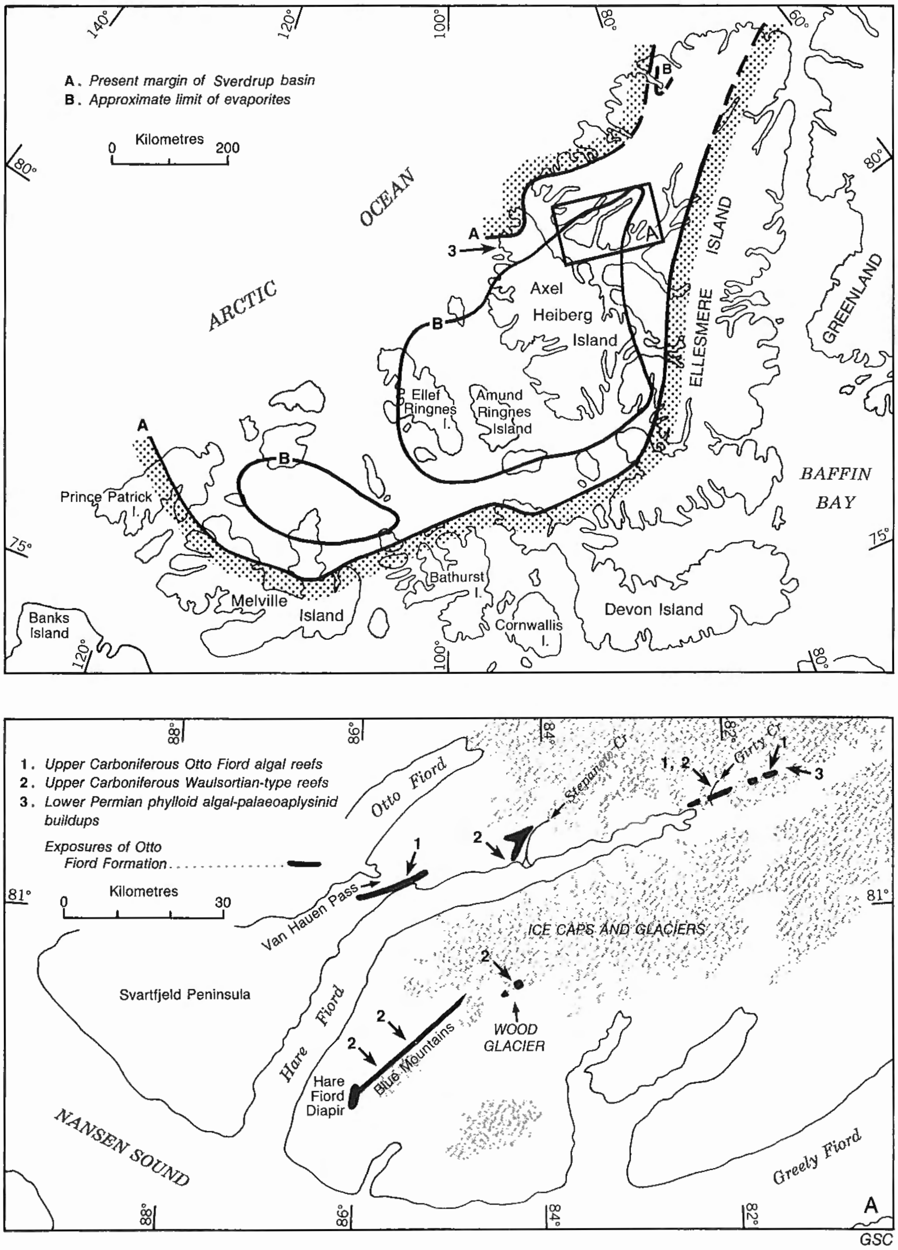

Figure 1. Map of the Canadian Arctic Archipelago, showing the general outline of the upper Paleozoic to Tertiary Sverdrup Basin (upper diagram), and locations of Carboniferous and Permian mounds and reefs on northwestern Ellesmere Island and northwestern Axel Heiberg Island (lower diagram).

E.D. Ghent of the Department of Geology and Geophysics, University of Calgary. Scanning electron microscopy also was run at the Department of Geology and Geophysics, with the assistance of A.E. Oldershaw.

GEOLOGICAL SETTING AND STRATIGRAPHIC RELATIONSHIPS

Sverdrup Basin is a rift basin (Thorsteinsson, 1974), 1000 km long and 400 km wide, underlying the northernmost islands of the Canadian Arctic Archipelago (Fig. 1). It formed in Early Carboniferous time through extension, faulting, and collapse of the Precambrian to Devonian rocks of the Franklinian Mobile Belt, the culmination of deformation that had continued from latest Devonian to earliest Carboniferous time during the Ellesmerian orogeny (Thorsteinsson and Tozer, 1970). Rocks within Sverdrup Basin were deformed in early Tertiary time by the Eurekan orogeny, leading to extensive faulting and folding in the eastern Arctic and minor deformation in the western Arctic.

The upper Paleozoic succession in Sverdrup Basin is represented by seven long-term transgressive-regressive sequences (Fig. 2) separated at the basin margin by major unconformities that pass basinward into equivalent conformities (Beauchamp et al., 1989a, b). The seven sequences encompass the following time intervals:

Sequence 1. Viséan
Sequence 2. Serpukhovian — Asselian
Sequence 3. Asselian —Sakmarian
Seqeunce 4. Sakmarian — Kungurian
Sequence 5. Kungurian
Sequence 6. Roadian — Wordian
Sequence 7. Wordian-post Wordian (?)

The time represented by each sequence is at least five million years, and thus they may be viewed as the product of second- and third-order sea-level fluctuations (Vail et al., 1977; Beauchamp et al., 1989a, b). Sequence 1 is characterized by early rift-phase lacustrine sediments (Davies and Nassichuk, 1988a, b). Carbonate rocks containing submarine cements and related fabrics described in this paper are included within the Early Carboniferous to Early Permian Sequences 2 and 3, occurring in the Otto Fiord, Hare Fiord and Nansen formations (Fig. 2). In the basin centre, Otto Fiord evaporites and interbedded marine carbonates overlie redbed clastics of the Borup Fiord Formation, and are in turn overlain by argillaceous limestone and shale of slope and basinal aspect in the Hare Fiord Formation. Small algal buildups within the Otto Fiord Formation, and large Waulsortian-like carbonate reefs that developed during the marine transgression that recorded transition from Otto Fiord evaporitic contitions to open-marine Hare Fiord environments, are two of the carbonate units that yield abundant evidence of pervasive submarine cementation in the Arctic carbonates.

In the basin margin or platform settings adjacent to the basin centre or axis, Sequences 2 and 3 are characterized by multicyclic shelf carbonates of the Nansen Formation. The Nansen carbonates both overlie and grade laterally and marginally into redbeds of the Canyon Fiord Formation. Shelf margin and slope carbonates of the Nansen Formation again are characterized by submarine cements and related submarine fabrics.

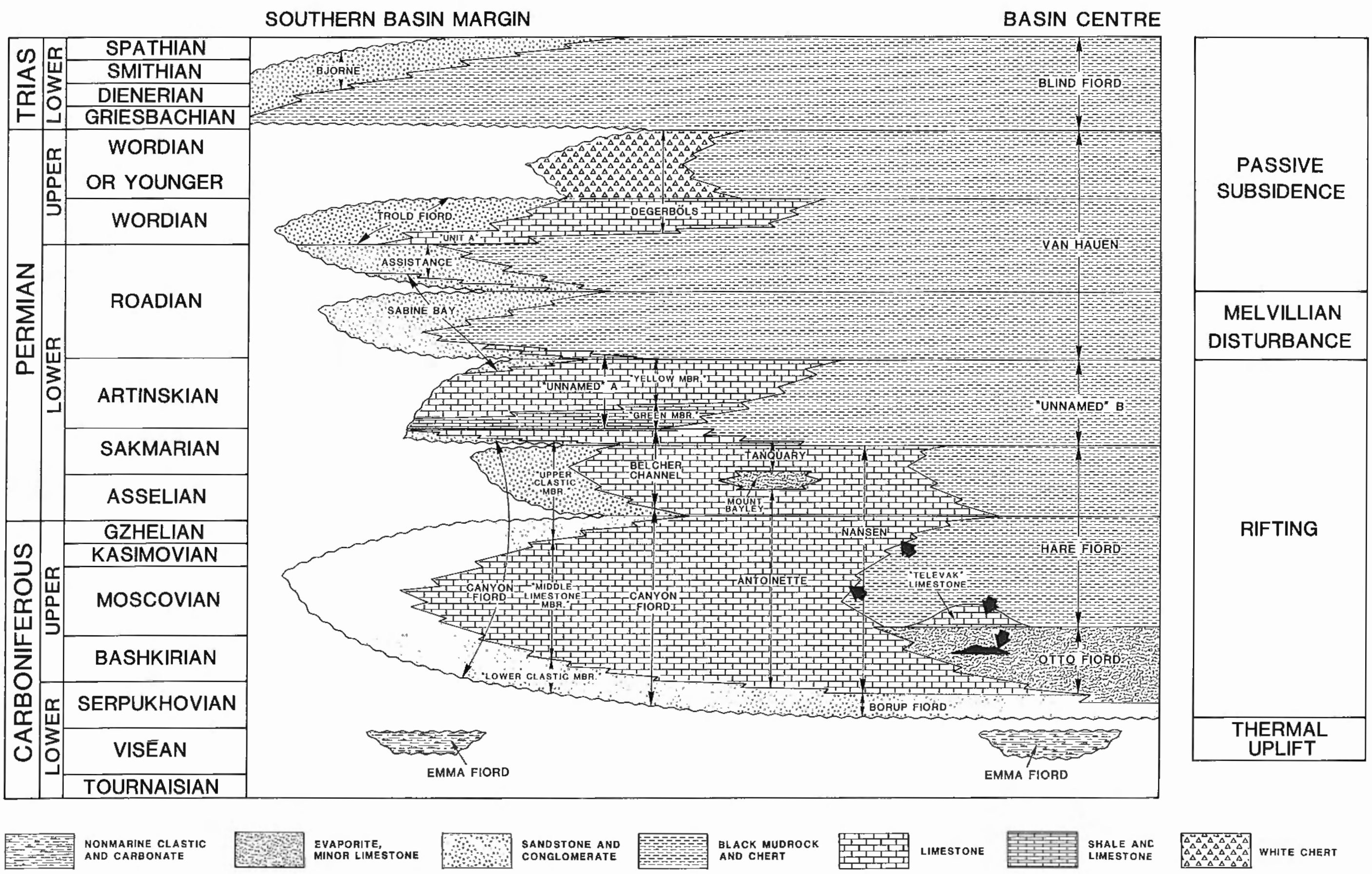

Figure 2. Upper Paleozoic second- and third-order transgressive-regressive sequences in the Sverdrup Basin along a schematic proximal-to-distal cross-section. Lower Triassic sequence also shown. Principal carbonate units with submarine diagenetic fabrics described and illustrated in this paper are indicated by arrows. (From Beauchamp et al., 1989b, Fig. 1.)

The carbonate buildups and other submarine-cemented units in the Sverdrup Basin Carboniferous to Early Permian successions are constructed by or dominated by tubular and phylloid algae, palaeoaplysinids, fenestellid and ramose bryozoans, *Tubiphytes*, crinoids and sponges (Fig. 3) (Davies and Nassichuk, 1986; Davies, Richards et al., 1988). Reefs or carbonate units constructed by algae, palaeoaplysinids and fenestellid bryozoans are the principal sources of data and the focus of descriptions in this report.

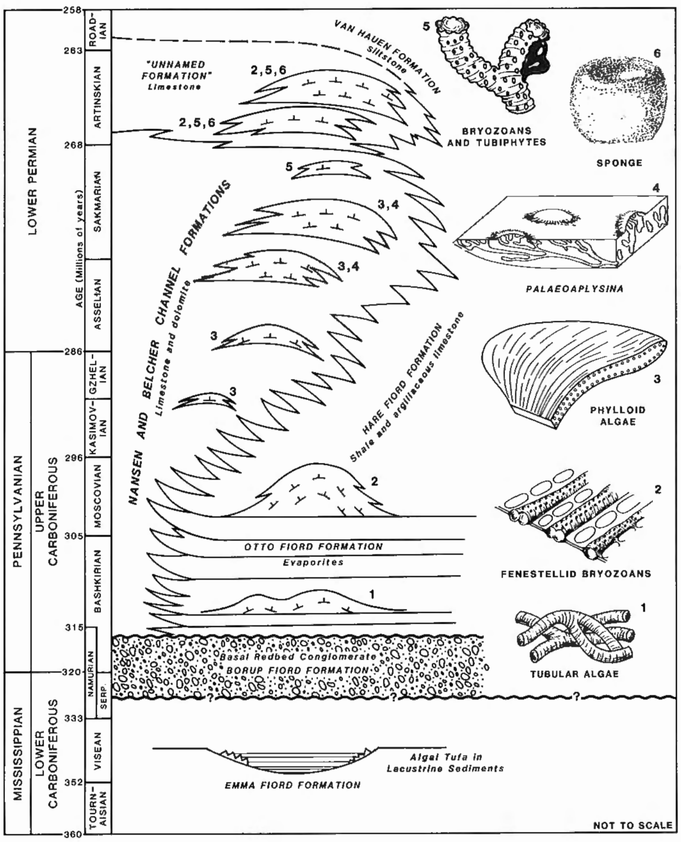

Figure 3. Schematic diagram of Carboniferous and Permian reefs and their principal organic contributors in the Sverdrup Basin. (Modified from Davies and Nassichuk, 1986.)

Although not reefal in character, the lacustrine tufas of the Emma Fiord Formation are included at the base of the diagram to complete the carbonate spectrum found within the Sverdrup Basin. Carbonates from the Belcher Channel (upper) and "unnamed formation" are not described in this paper.

CARBONATE UNITS WITH CEMENT FABRICS

Formations or units on northwestern Ellesmere Island containing carbonate cement fabrics described in this paper include the following:

1. The Otto Fiord Formation (Thorsteinsson, 1974; Nassichuk and Davies, 1980; Davies and Nassichuk, 1988c), an evaporite-dominant unit containing lower Bashkirian (lower Upper Carboniferous) tubular algal boundstone buildups enclosed in rhythmically interbedded anhydrite and limestone of subaqueous shelf aspect (Davies and Nassichuk, 1975).

2. The "Tellevak limestone member" of the basal Hare Fiord Formation ("basinal" setting), composed of Moscovian (Upper Carboniferous) fenestellid bryozoan "Waulsortian" reefs or mud mounds identical in all aspects (other than age) to classical Waulsortian buildups of Tournaisian (Early Carboniferous) age in Ireland, Belgium, and other localities throughout the world.

3. The Nansen Formation of Late Carboniferous to mid-Early Permian (Sakmarian—Artinskian) age, composed dominantly of cyclic shelf carbonates with shelf-edge buildups constructed of phylloid algae, palaeoaplysinids and bryozoans. In addition, the Nansen shelf margin is characterized by steeply dipping foreslope beds with allochthonous debris units, which also form debris flows, enclosed within the laterally equivalent basin-fill Hare Fiord Formation. These displaced carbonate units also contain a variety of cement fabrics and contribute to our understanding of diagenetic processes and products (Davies, 1977b, c).

The major focus and source of most of the descriptive and analytical data for this report are the Waulsortian-type buildups. However, material from the Otto Fiord reefs and Nansen buildups and allochthonous deposits provide additional documentation and illustrate the similarity and pervasiveness of diagenetic processes in carbonates of different settings. The geological framework for each of these carbonate units is described in the following section.

Tubular-algal buildups in the Otto Fiord Formation

General setting

Tubular-algal boundstone reefs (Davies and Nassichuk, 1988c) are enclosed within the Upper Carboniferous cyclic shelf facies of the evaporitic Otto Fiord Formation, in its type area at Van Hauen Pass and along the northern cliff face of Hare Fiord, on northwestern Ellesmere Island (Fig. 4). The reefs occur between latitude 81°00′N/

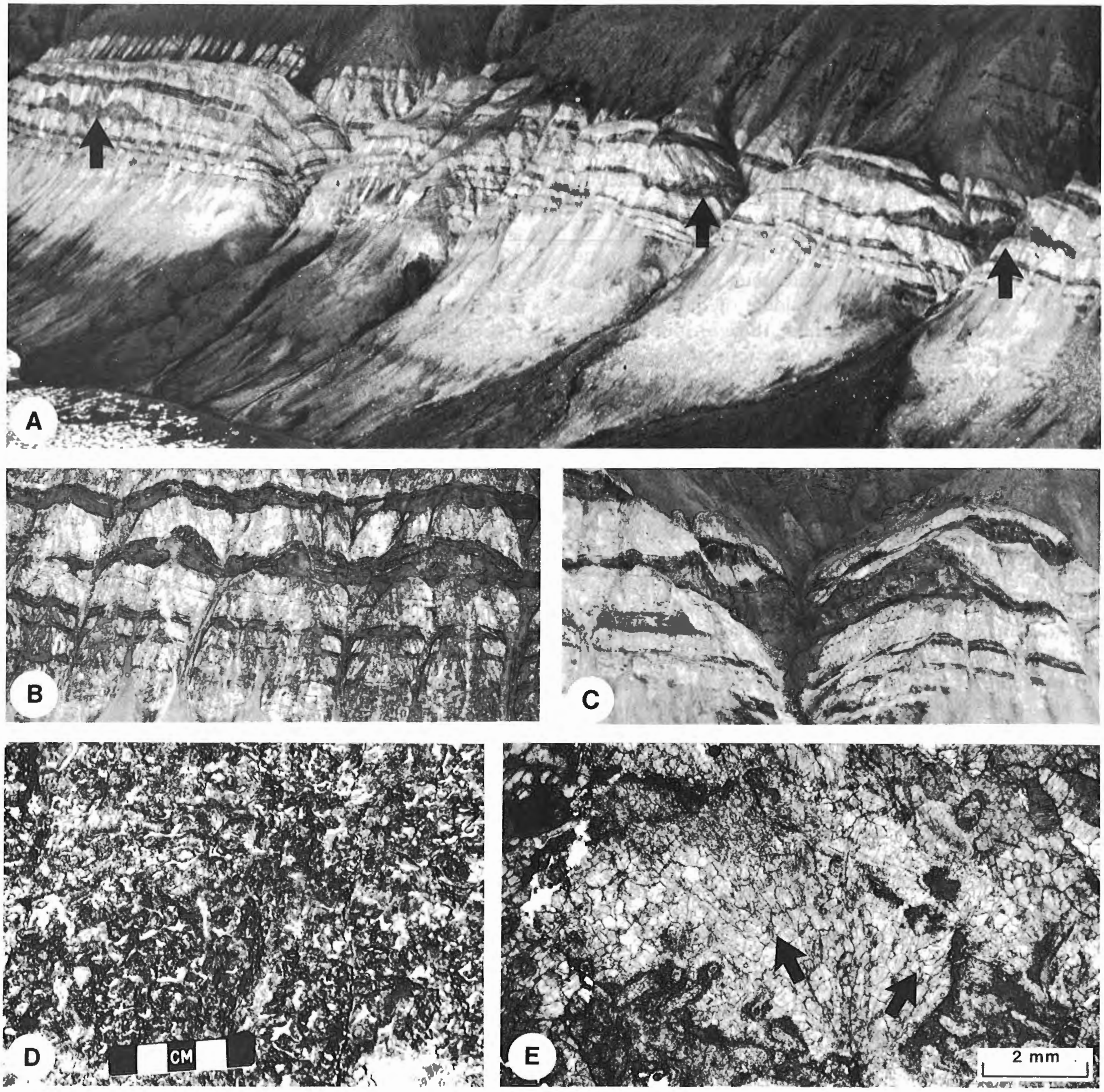

Figure 4. Upper Carboniferous algal reefs in the Otto Fiord Formation, Van Hauen Pass, northwestern Ellesmere Island.

A. *General view of outcrop of the type section of the Otto Fiord Formation, showing cyclic anhydrite (light grey) and limestone (dark grey), with algal reefs (arrows) developed at one horizon. Basinal carbonates and shales of the Hare Fiord Formation overlie the Otto Fiord Formation.*

B, C. *Detail of two of the algal reefs; the reef in (C) is cut by an erosional gully.*

D. *Typical mottled fabric in the exposed core of an Otto Fiord algal reef. The dark-coloured masses are radial-array calcite that has replaced submarine aragonite fabrics.*

E. *Thin section of beresellid and related algal "boundstone" fabric cemented by fringes of radial-fibrous submarine cement, and by partly-replacive fans of calcite, neomorphic after submarine aragonite (arrows).*

longitude 86°W, and latitude 81°15′N/longitude 81°W. Algal boundstone patch reefs range in size from about 12 m in thickness to about 35 m, and extend about 350 m along strike at Van Hauen Pass. The third dimension of the reefs is not exposed.

At its type locality at Van Hauen Pass, the Otto Fiord Formation is characterized by multiple cycles of dark marine limestone and lighter coloured anhydrite (Fig. 4). The cycles show an overall trend of increasing thickness upsection and individual limestone and anhydrite units within the cycles also thicken upward. Near the middle of the Otto Fiord section, which is up to 430 m thick, three or four reefs are exposed along one of the marine limestone units (Fig. 4A). The reefs (Fig. 4B, C) are multicyclic algal boundstone buildups stabilized by pervasive submarine cement (Fig. 4D, E).

The algal boundstone reefs in the Otto Fiord Formation at Van Hauen Pass on northwestern Ellesmere Island are the best documented buildups in the formation. Differences in colour and resistance to weathering of internal growth increments help to emphasize that the reefs are composite buildups of three or more vertically stacked and thickened limestone units, which are interbedded with anhydrite off the flanks of the reef. Apparent depositional dips on the flanks of the steepest margins of the reefs range from 25° to 30°.

In the off-reef setting, three, thin, dark coloured limestone beds with interbedded anhydrite are laterally equivalent to the reefs. These limestone beds may be traced directly into the reef, thickening and grading into the buildup along the flanks of the underlying platform. The interbedded anhydritic units concomitantly pinch out at the platform margin. The lower of the three limestone beds forms a basal marine limestone unit in the reef with a diverse marine biota. This is followed by the main algal boundstone core of the reef, and in turn by marine limestone correlated with the upper two of the laterally equivalent limestone beds. The entire reef sequence was then buried by thick bedded anhydrite that is 50 m thick in the inter-reef section.

The basal unit of the mound, apparently a thickened equivalent of the lowest of the three laterally correlative limestone beds, is formed of two to three metres of well bedded, dark coloured, slightly silty and argillaceous wackestone, containing a rich marine biota dominated by crinoids (pelmatozoans), but also containing brachiopods, ammonoids, bryozoans, gastropods, ostracodes, and foraminifers. The uppermost beds of this lower unit include fine grained, spiculitic and calcisphere-rich wackestone with large thick-valved ostracodes and the first algae.

The main core of the reefs consists of 20 to 30 m of branching tubular algal material in an organic boundstone texture infilled by pervasive submarine cement (Fig. 4D, E). The dominant varieties of algae are beresellid and donezellid types. The fabrics range from open meshworks of algal tubules with patches of pelletal wackestone matrix, to aggregates of fragmented tubules in grainstone and packstone textures; the latter probably represent storm or wave current reworking. Other skeletal components in the algal core include a few brachiopods, fenestellid bryozoans, crinoids, encrusting foraminiferids, ostracodes, and several other types of algae, including the red algae *Komia* and *Ungdarella*. On exposed surfaces, the core facies is characterized by a dark to light mottled fabric (Fig. 4D) that reflects textural differences between submarine cement arrays and later diagenetic cement infill.

The algal core is overlain by two limestone units, 3 to 4 m thick, that are buildup equivalents of the upper two limestone beds in the inter-reef setting. These post-core units are composed of dark coloured, slightly argillaceous, bioclastic wackestone with a varied marine biota, including crinoids, large brachiopods (including in-place spinose forms), ammonoids, bryozoans, sponges and sponge spicules, and foraminifers. The top bedding surface of this marine capping unit is marked by pyrite, many large brachiopods, articulated segments of crinoid columnals, ammonoids, and other marine organisms. It is interpreted as a marine hardground, and is overlain directly by anhydrite.

The depositional model and development history of the Otto Fiord buildups is discussed and illustrated in Nassichuk and Davies (1980), and Davies and Nassichuk (1988c); it will not be repeated here.

Diagenetic fabrics

The tubular-algal boundstone meshwork in the reef core is encrusted by a fringe of isopachous, inclusion-rich, radial-fibrous calcite interpreted as submarine in origin. Both predating and postdating the rim cement, and forming the major cement phase in the mound core, are radial arrays of polycrystalline calcite that form the characteristic dark-mottled fabric on outcrop surfaces (Fig. 4D). These arrays are up to several centimetres in length, and commonly radiate from a central nucleus on an algal filament. Thin sections reveal that the precursor of the radial arrays grew in primary cavities within the algal boundstone fabric, and by replacement of earlier rim cement and the algal tubules. These arrays are also interpreted as being of submarine origin, and to have been aragonite originally.

The radial calcite arrays commonly are postdated by zoned ferroan calcite spar and zoned ferroan dolomite. Less commonly, the earlier cements are followed by silica (that may also form as replacive chalcedony), anhydrite and fluorite. The origins of all these mineral phases are interpreted as burial diagenetic.

Waulsortian-type reefs in the Hare Fiord Formation

General setting

Bryozoan reefs or "mud mounds" of Waulsortian type, but younger than the classical Waulsortian buildups of Belgium, Ireland and elsewhere (with the exception of the U.S.S.R.), are exposed at a number of locations on Ellesmere and Axel Heiberg islands (Fig. 1) in the Canadian Arctic Archipelago (Davies, Richards et al., 1988). The largest exposed complex forms the core of the southern Blue Mountains (Fig. 5), 10 to 15 km southeast of Hare Fiord on northwestern Ellesmere Island (about lat. 80°45′N, long. 85°30′W), where the reefs are placed in the "Tellevak limestone", an informal member of the Hare Fiord Formation (Bonham-Carter, 1966; Thorsteinsson, 1974). Other reefs occur discontinuously for some 20 km northeast along the trend of the Blue Mountains (Fig. 1). A well exposed buildup occurs at the eastern extremity of the trend, immediately to the west of Wood Glacier (lat. 80°50′N, long. 84°15′W). Another buildup (Fig. 6A) occurs immediately west of the mouth of Stepanow Creek on the north side of Hare Fiord, northwestern Ellesmere Island (lat. 81°06′N, long. 84°15′W); a diversified Upper Carboniferous (Moscovian) ammonoid fauna from this reef, and from several reefs in the Blue Mountains, was described by Nassichuk (1975). Other reefs (Fig. 6B) occur at several locations within a complex facies change, exposed along the north side of a major valley extending east from the head of Hare Fiord, at about latitude 81°12′N, and longitude 81°15′W. Reefs also occur on northern Ellesmere Island north of Yelverton Pass (Mayr, pers. comm., 1986), and on Axel Heiberg Island (Davies et al., 1988).

The lower Moscovian (Atokan) bryozoan reef complex in the Blue Mountains is estimated to range in thickness from 120 to 550 m (Thorsteinsson, 1974); one isolated reef was measured at slightly more than 300 m in thickness. A complete section through a nearly vertical, glacially polished reef at Wood Glacier gives a thickness of 180 m. Lateral dimensions for the reef complex in the Blue Mountains range from several hundred metres to about 10 km.

The Waulsortian reefs on northwestern Ellesmere Island overlie limestone beds immediately above the uppermost evaporites in the Otto Fiord Formation. The reefs are generally buried by shales and argillaceous carbonates of the basinal Hare Fiord Formation. The upper contact between the reefs and the overlying Hare Fiord rocks is sharp, and the latter show local depositional infill against the reef topography.

The Moscovian bryozoan reefs on northwestern Ellesmere Island are composite buildups of multiple lenticular units of carbonate sediment, characterized by two end members:

1. Initially highly porous (shelter porosity) meshworks of fenestellid bryozoans in a rudstone (Embry and Klovan, 1971) or "platestone" fabric, with ponded bioclastic wackestone to packstone sediment, cemented pervasively by multiple generations of radial-fibrous isopachous cement, and forming up to 80 per cent of the rock mass (Fig. 7).

2. Bioclastic wackestone to packstone with grey lime-mud and a highly varied marine biota of fenestellid bryozoans, crinoids, brachiopods, fusulinaceans and other foraminifers, and a variety of algae; although early cementation is less clearly identifiable in this rock type, early submarine cementation by fine peloidal and micritic magnesium calcite probably was pervasive.

Between these two end members there is a wide range of lithological variation (Figs. 7, 8). One of the most significant is a variant of the bioclastic wackestone, characterized by the development of *stromatactis* or stromatactoid fabric (Fig. 9). These fabrics generally are most characteristic of reef margins where depositional slopes were greatest, but they also occur where there is no evidence of a clearly defined slope (at least within the two-dimensional plane of exposure).

Although fenestellid bryozoans are characteristic of the reefs as a whole, they are most abundant in the upper part, accompanied by crinoid columnals, ammonoids and some foraminifers. Lower in the reef section, beresellid (dasycladacean?) and other algae are common, and ooid and pisoid grainstones occur in a few beds. This vertical sequence from an algal-ooid to a bryozoan-crinoid-ammonoid association, correlative with increasing elevation of the mound above the sea floor, apparently records carbonate deposition during an overall transgressive and deepening marine incursion into the Sverdrup Basin trough; the lower algal-ooid facies may represent deposition during more restricted (metahaline?) conditions in early transgression, similar to the association found in carbonate units of the underlying Otto Fiord evaporite formation (Nassichuk and Davies, 1980).

The internal geometry of the reefs is a complex intergradation and, in some cases, cyclic repetition of the two end members and their variants, and the stromatactoid fabric. Superimposed on these units are structures related to submarine settling and fracturing:

1. Subvertical submarine fractures, which truncate primary sedimentation units and fabrics, and are lined by multiple generations of submarine cement. The

A. General view of Waulsortian-type reef complex forming the core of the Blue Mountains. Tents at left provide scale.

B. Oblique aerial view of isolated Waulsortian-type reef southwest of the complex in (A), showing underlying Otto Fiord evaporites (1), a probable basal carbonate ramp or platform on which the reefs grew (2), the reef (3), and enclosing and overlying basinal Hare Fiord Formation (4) with local drape.

Figure 5. *Upper Carboniferous Waulsortian-type reefs, Blue Mountains, northwestern Ellesmere Island.*

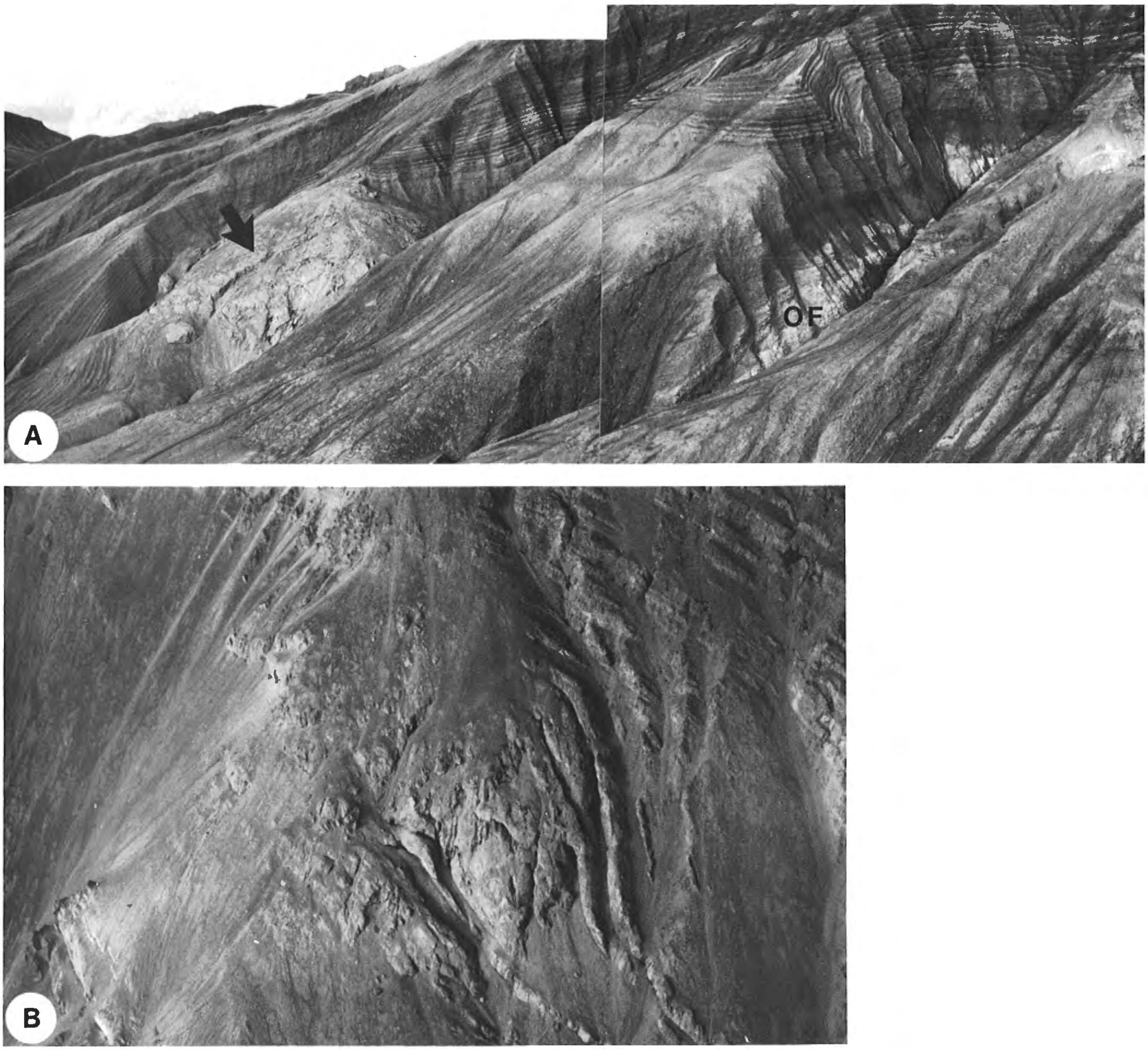

Figure 6. Upper Carboniferous Waulsortian-type reefs, northwestern Ellesmere Island.

A. Exhumed Waulsortian-type reef (arrow) enclosed in Hare Fiord rocks, immediately west of the delta of Stepanow Creek on Hare Fiord. Rich ammonoid biocoenoses occur on the flanks of this reef. The underlying Otto Fiord evaporite unit is exposed in the valley at right (OF).

B. Reef with draped flank and topset beds in transitional Hare Fiord/Nansen formation facies section immediately east of Girty Creek on Hare Fiord. Although this reef has not been examined in detail, its stratigraphic position and the composition of field samples suggest that it is of Waulsortian type.

initial generations of radial-fibrous cement in the fractures are interpreted as having been magnesium calcite, grading outward into hemispheres of botryoidal aragonite. The fractures are filled by horizontally bedded, marine, bioclastic and peloidal internal sediments that are interlayered with the submarine cements lining the fractures. Cavity-dwelling organisms (coelobites) also are common in the internal cavity system and sediment fill. Fracturing is attributed to stress created by differential settling and compaction of the early-cemented reef mass, similar to submarine fractures occurring in modern reefs off Bermuda and elsewhere.

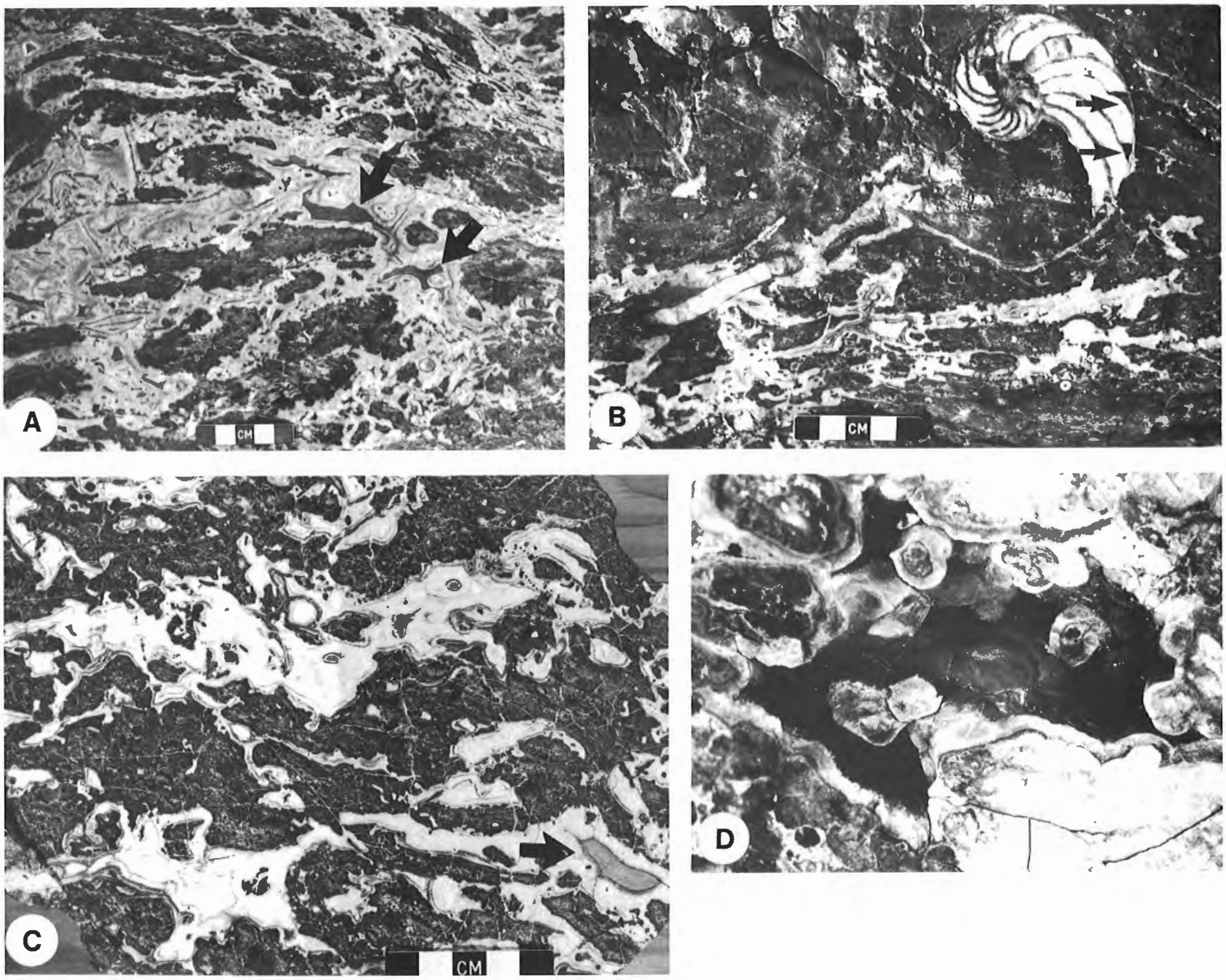

Figure 7. *Fabrics of Upper Carboniferous Waulsortian-type reefs, northwestern Ellesmere Island.*

A. Glacially polished surface in reef, showing dark-coloured patches of primary marine sediment intermixed with white to light grey banded, radial-fibrous submarine cements enclosing fenestellid bryozoan fronds. Patches of dolomitized crinoidal sediment (arrows) infill late-stage cavities and herald the onset of burial. Wood Glacier reef.

B. Glacially polished surface of reef, illustrating complex stromatactis-like fabrics lined or filled by radial-fibrous submarine cement (white, lower), with a nautiloid in longitudinal section at upper right (note geopetal infill - arrows). Wood Glacier reef.

C. Cut and polished surface of reef core fabric, showing typical intermixing of dark grey bioclastic and peloidal wackestone to packstone, and white to light grey banded radial-fibrous submarine cements. The patch of dolomitized internal sediment at lower right (arrow) infills a cement-lined residual pore connected to a submarine fracture. Blue Mountains reef.

D. Rare example of open residual primary porosity in a Waulsortian reef, with thick isopachous rims of radial-fibrous cement (after submarine, magnesium calcite cement) lining the cavity. Width of field is about 20 cm. Blue Mountains reef.

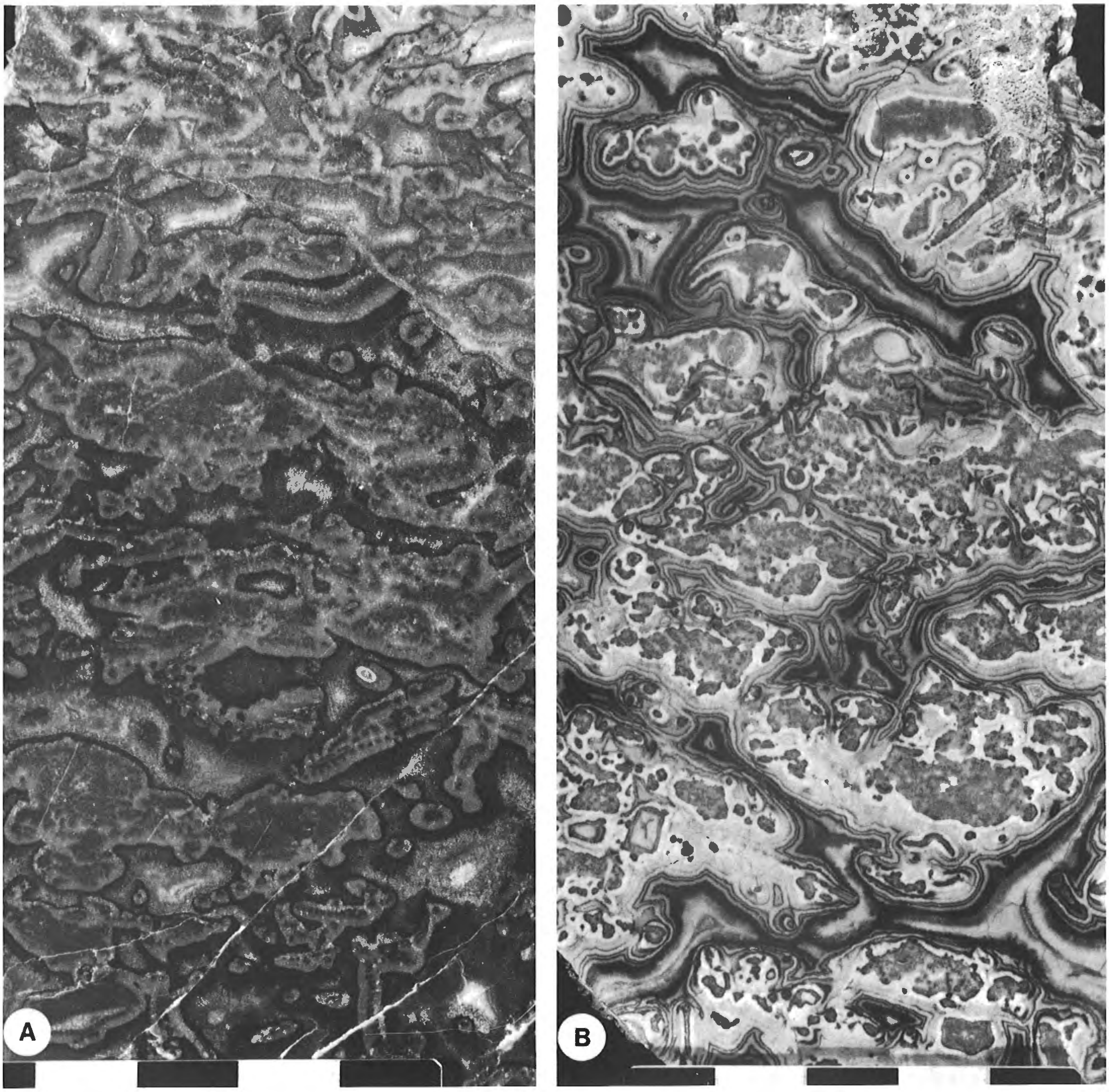

Figure 8. *Complex submarine-cemented fabrics, Waulsortian-type reefs, northwestern Ellesmere Island.*

A. Multiple generations of isopachous radial-fibrous submarine cement with intervals of marine internal sediment nucleated on horizontally bedded fragments of fenestellid bryozoans. Flank sample, west Stepanow Creek reef. Scale in centimetres.

B. Complex fabric with multiple generations of dark and light banded, radial-fibrous calcite filling cavity systems between earlier domains of submarine-cemented host sediment, modified by radial-array calcite after aragonite. Float sample, Blue Mountains reef. Scale in centimetres.

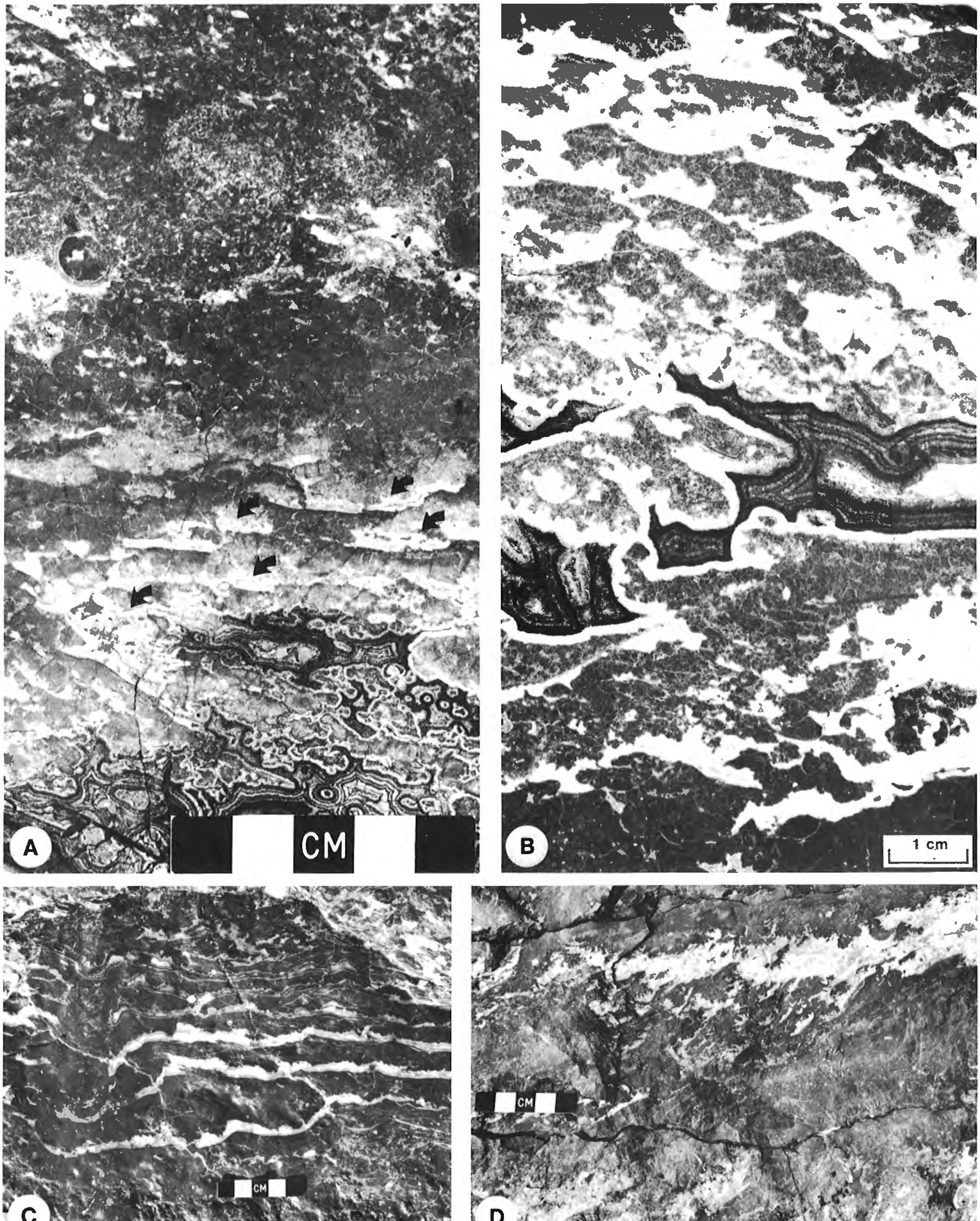
A
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Figure 9. Stromatactis fabrics in Waulsortian-type reefs, northwestern Ellesmere Island.

A. *Typical transition from complex, banded, submarine-cement fabric at base to stromatactis structures (arrows) infilled by white, radial-fibrous, submarine cement, overlain by muddier-textured bioclastic wackestone to mudstone. Blue Mountains reef.*

B. *Cut and polished slab, illustrating stromatactis with characteristic flat floors and irregular digitate roofs, infilled by banded, radial-fibrous, submarine cement. Blue Mountains reef.*

C. *Laminoid stromatactis fabric in reef (position relative to flank or slope not determined). Wood Glacier reef.*

D. *Inclined stromotactis fabrics from flank of reef. Blue Mountains reef.*

2. In the reef near Wood Glacier, northwestern Ellesmere Island (Fig. 1), displacement of submarine-cemented reef blocks during submarine fracturing created a large cavern at least several metres high and five metres or more in width. The fracture leading into the cavern is infilled by at least 25 cm of multiple generations of submarine cement. The cavern itself is filled with ooids and pisoids (oncoids) of precipitated envelopes of carbonate nucleated on gastropods and other organisms that inhabited the cavity system.

Two significant facies that are associated with the Waulsortian-type reefs, but are external to them and were controlled by reef topography, are:

1. Steeply dipping beds of fining-upward crinoidal grainstone to packstone (carbonate turbidites: Davies, 1977b) overlying the steep depositional flanks of the mound. These beds also contain submarine-cemented lithoclasts derived from the reef, as well as fusulinaceans and algae. The only evidence of an interfingering relationship between flank beds and the enclosing basinal Hare Fiord rocks is close to the base of the mounds, suggesting that the mounds developed a submarine relief of 300 m or more in late stages of growth.

2. Ammonoid coquinas at the base or on the flank of the mound, but external to it. The ammonoids, which include all ontogenetic stages, are highly concentrated and appear to have inhabited the surface of the reefs, after the formation of the entire reef mass but before burial.

Other aspects of Waulsortian-type reef lithofacies and depositional history are presented in Davies et al. (1988). In the remainder of this bulletin, Waulsortian-type reefs may be referred to simply as Waulsortian reefs.

Diagenesis

Pervasive submarine cementation was a major factor in the stabilization and accumulation of the Waulsortian reefs. The most obvious earliest generations of cement are in the form of multiple rims of isopachous, radiaxial to radial-fibrous calcite with abundant microinclusions. This cement is nucleated directly on the fenestellid bryozoans and other primary marine sediment framework, and is interpreted as being of submarine origin. Mud-rich bioclastic wackestone, however, probably also underwent early and pervasive submarine cementation, but in the less obvious form of fine micritic and peloidal cements. Early cementation of this muddier-textured sediment is indicated by the sharp truncation of such fabrics by submarine fractures that cut through the first generation of radial-fibrous cement, but not the later generations of submarine cement.

In larger primary shelter cavities, and in larger submarine fractures lined by multiple generations of inclusion-rich isopachous radial-fibrous cements, the isopachous rim cements are interlayered with, and progressively overlain by, hemispherical or botryoidal calcite fabrics that increase in size toward the centre of the former cavity systems. Similar coarse arrays of radiating calcite fabrics, formed by replacement of micritic sediment and isopachous rim cements, also occur within the reef fabric itself. All of these radial or botryoidal calcite array fabrics are interpreted as submarine in origin and initially of aragonite composition. The spectrum of submarine cement fabrics in these reefs is described in detail in the following sections of this paper.

Stromatactis

A corollary of the pervasive submarine cementation of the classical Waulsortian reefs and the upper Paleozoic reefs in the Arctic is the common occurrence of *stromatactis* or stromatactoid fabric (Fig. 9). In a recent review and reinterpretation of *stromatactis*, Tsien (1985) suggested that the enigmatic fabric is a replacement of colonial microbial accretions. Tsein (op. cit.) also presented, in tabular form (his Table 1), a summary of most of the current interpretations of the origin of *stromatactis*, and an extensive discussion of the various interpretations. The preferred interpretation by the present authors is that many *stromatactis* fabrics are the product of early submarine cementation of fluid-escape structures, created by displacement and sediment "stoping" in water-saturated, mud-textured carbonate sediment in unstable slope or compactional settings. This interpretation is essentially the same as that proposed in combination by Schwarzacher (1961), Heckel (1972), and Bathurst (1980), and refined by Wallace (1987). However, the close association of sponge spicules with other forms of *stromatactis*-like fabrics in some Arctic reefs suggests that decay of soft-bodied organisms such as sponges may have contributed to the formation of initial intrasediment cavity systems. This interpretation is supported by new evidence from Permian reefs in Sverdrup Basin (Beauchamp, 1987). A microbial precursor, as suggested by Tsien (op. cit.), is discounted by the present authors, at least for the majority of *stromatactis* fabrics in the Waulsortian-type reefs.

Shelf-edge buildups in the Nansen Formation

General setting

Throughout most of the Upper Carboniferous to Lower Permian shelf succession characterized by the Nansen Formation, carbonate and mixed carbonate-siliciclastic rocks occur in well bedded cyclic or rhythmic units (Davies, 1975, Fig. 6), commonly terminating in ooid or fusulinid grainstones. However, closer to the outer shelf margin, at or near the facies transition into coeval deeper-water sediments of the Hare Fiord Formation, massive lenticular units of relatively pure carbonate appear in the section on both Ellesmere and Axel Heiberg islands (Fig. 10). These buildups are most common in the uppermost Carboniferous and Lower Permian parts of the succession, and many are capped by ooid and fusulinid grainstones. They are constructed mainly of phylloid algae and plates of the enigmatic organism *Palaeoaplysina* (Davies and Nassichuk, 1973) with pervasive submarine cements in platestone textures (Figs. 11, 12). A wider variety of reefs and mounds occurs in shelf margin and shelf slope settings of the Nansen and Belcher Channel formations on southern or south-central Ellesmere Island, where bryozoans, *Tubiphytes* and sponges also contribute to organic buildups (Beauchamp, 1987; Beauchamp et al., 1988; Beauchamp et al., 1989a, b).

On northwestern Ellesmere Island, many of the best examples of reef fabrics from the Nansen Formation are found in glacial erratics scattered over the surfaces of glaciers at the head of Hare Fiord, where spectacular exposures of the Otto Fiord, Hare Fiord and Nansen formations are visible. Samples discussed in this paper, from the Nansen Formation in this area and elsewhere, are mainly from phylloid algal, palaeoaplysinid and bryozoan buildups.

Diagenesis

The most obvious cement fabrics in the reefal rocks of the Nansen Formation on northwestern Ellesmere Island consist of multiple generations of isopachous radial-fibrous calcite, nucleated directly on the organic framework or ponded marine sediment (Figs. 11, 12). This cement is interpreted as submarine in origin, and is described in detail in following sections. Further documentation and more detailed isotopic and geochemical analyses of these cements, from mounds in the Nansen Formation on south-central Ellesmere Island, have been presented by Beauchamp (1987). Other aspects of buildups in the Nansen Formation and equivalent formations on Ellesmere Island were documented in Davies and Nassichuk (1986); Davies, Richards et al. (1988); Beauchamp et al. (1988); and Beauchamp et al. (1989a, b).

Multiple-generation radial-fibrous submarine cement also occurs in steep foreslope beds of the Nansen Formation where the Nansen shelf facies grades into the Hare Fiord Formation basin facies (Davies, 1977b). Former large cavities in these foreslope beds, which have depositional slopes exceeding 30° and grade basinward into debris flows, also contain arrays of radial-botryoidal calcite, interpreted as neomorphic after aragonite of submarine origin. Blocks of shelf-margin shallow water carbonates, including phylloid-algal platestones with isopachous submarine cements, also occur within carbonate debris flows derived from the Nansen Formation and enclosed in the Hare Fiord Formation (Davies, 1977b).

DESCRIPTION OF CEMENTS AND DIAGENETIC FABRICS

Abbreviations

In the following sections, abbreviations for cement types and mineral components have been used for brevity. Some are adopted or modified from Sandberg (1985) and other authors, and some are newly introduced. They are as follows:

RFC — **Radial-fibrous calcite**: used in a broad sense for a range of isopachous calcite cement fabrics characterized by inclusion-defined radial-fibrous fabrics, but including radiaxial fibrous calcite (Bathurst, 1959, 1971; Kendall and Tucker, 1973) and possibly some fascicular-optic calcite (Kendall, 1977); all of these fabric types may occur within one cavity system.

RAC — **Radial-array calcite**: characterized by arrays of coarse calcite neospar, replacing radiating crystals of acicular aragonite, and commonly showing at least partial replacive relationships with the sediment host (the 'A' in RAC serves also as an indicator of the aragonite precursor).

BAC — **Botryoidal-array calcite**: characterized by coarse botryoidal to spherulitic arrays of calcite,

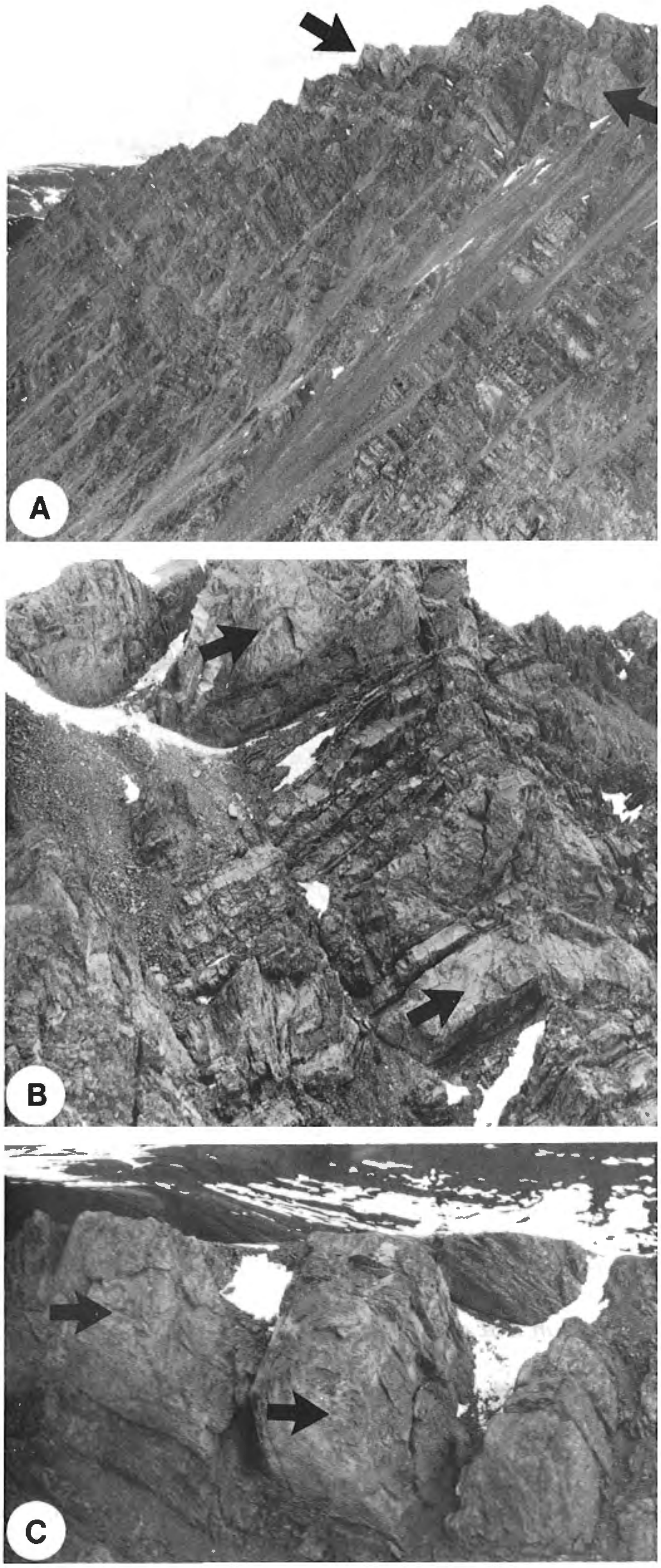


Figure 10. Lower Permian palaeoaplysinid mounds or reefs in the upper Nansen Formation, close to Hare Fiord facies transition, northwestern Axel Heiberg Island.

*A. Oblique aerial view of Nansen section, with **Palaeoaplysina** buildups near the top of the succession (arrows).*

*B, C. Oblique aerial views of resistant limestone units (arrows) constructed of **Palaeoaplysina**, enclosed in well-bedded Nansen facies.*

replacing radial-concentric (botryoidal to spherulitic) aragonite with a convex outer margin and internal concentric growth lines; formed originally in open pore space.

HMC — High-magnesium calcite.

Paragenetic sequence

The principal submarine cements and related diagenetic processes and fabrics in the Carboniferous and Permian carbonates on Ellesmere Island, in general order of formation, include the following (outlined schematically in Fig. 45):

1. Subpeloidal, micritic, calcite cement in matrix fabrics

2. Radial-fibrous calcite (RFC) and associated radiaxial fibrous and fascicular-optic calcite, forming multiple generations of isopachous cement, commonly interlayered with marine internal sediment, in primary cavity systems

3. Submarine fracturing, generally between the first and second RFC generations (RFC:1 and RFC:2) or soon after

4. Radial-fibrous calcite (RFC) lining submarine fractures

5. Radial-array calcite (RAC), after aragonite replacing matrix fabrics

6. Botryoidal-array calcite (BAC), formed by neomorphic replacement of hemispheres of aragonite precipitated in open primary reef cavities and within submarine fractures lined by RFC

7. Infill of submarine fractures and interconnected primary reef cavities and conduits, either by synsedimentary peloidal and microbioclastic lime mudstones with coelobites, or by crinoidal sediment derived from the surrounding and overlying Hare Fiord Formation; the latter event marks the onset of burial

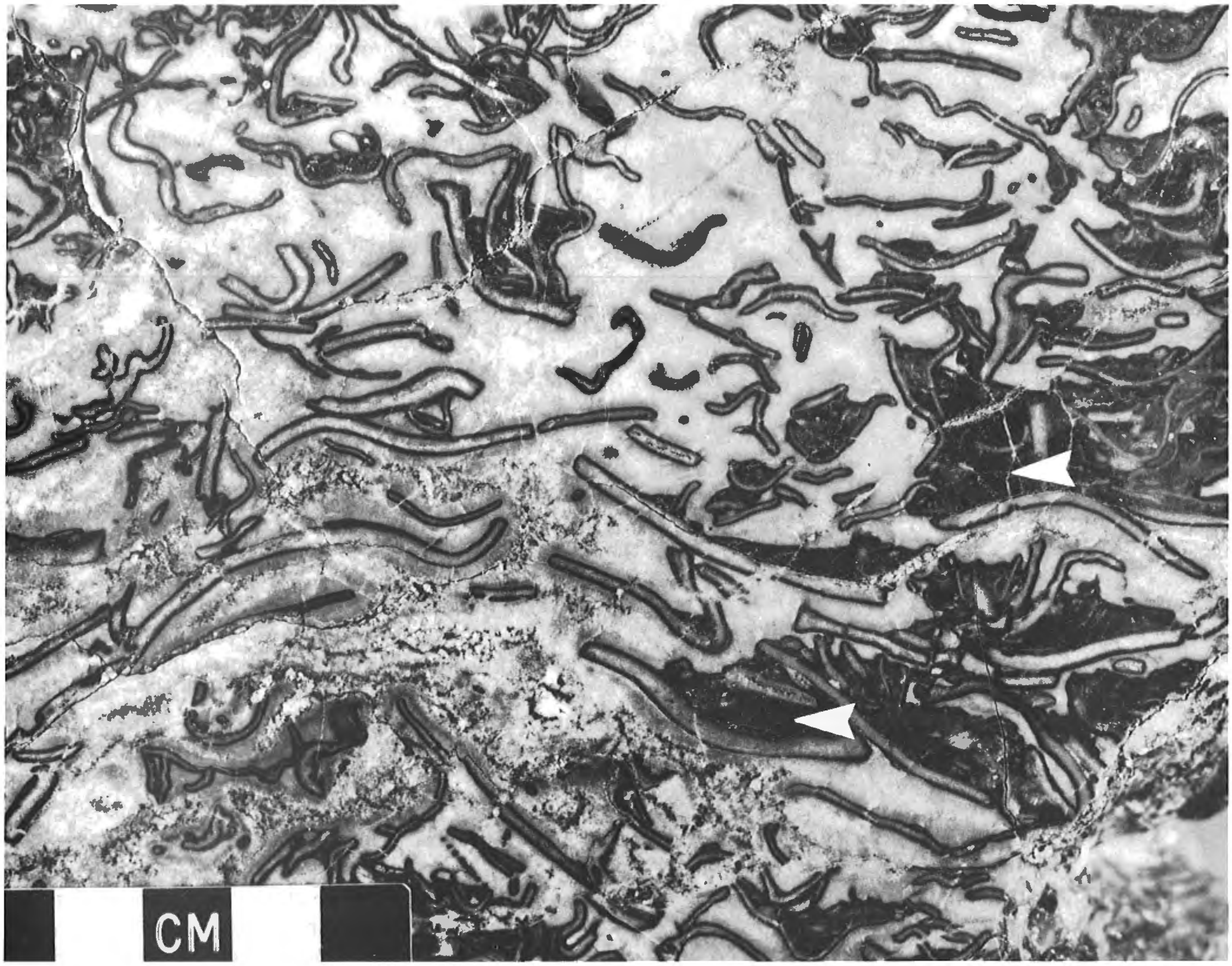


Figure 11. *Cut and polished slab of phylloid algal "platestone" of probable Early Permian age, with shelter fabric characterized by ponded primary marine sediment (dark-coloured patches - arrows) and pervasive, light grey, radial-fibrous, submarine cement. Float, Nansen Formation, Girty Creek, northwestern Ellesmere Island.*

8. Post-burial (and possibly meteoric) diagenetic processes and products; these are not described in this paper, but include: precipitation of chalcedonic silica, megaquartz, and zoned ferroan calcite in reef cavities; formation of two sets of oblique microfractures infilled by ferroan calcite (earlier set) and normal calcite (later set); migration, entrapment and thermal degradation of oil; and precipitation of sparry calcite in residual pore space (Davies, 1976). Authigenic fluorite, anhydrite and/galena also occur in trace amounts. Physical (mechanical) and physico-chemical compaction, stylolitization, and tectonic fracturing are other post-burial diagenetic process that were active in the upper Paleozoic rocks in the Arctic.

Radial-fibrous calcite cements

Description and origin of texture

Radial-fibrous calcite (RFC) cements (as defined in this report) are the most pervasive and volumetrically most abundant of the cement fabrics in the Waulsortian buildups on Ellesmere Island, and in many of the other cemented reef fabrics and foreslope breccia units. Included in the RFC category are all inclusion-rich ("cloudy"), multiple-generation, isopachous, calcite cements (Figs. 13, 14) that are preserved as elongate crystals of calcite, oriented approximately normal to the substrate, in primary reef cavities and lining submarine fractures. The overall category

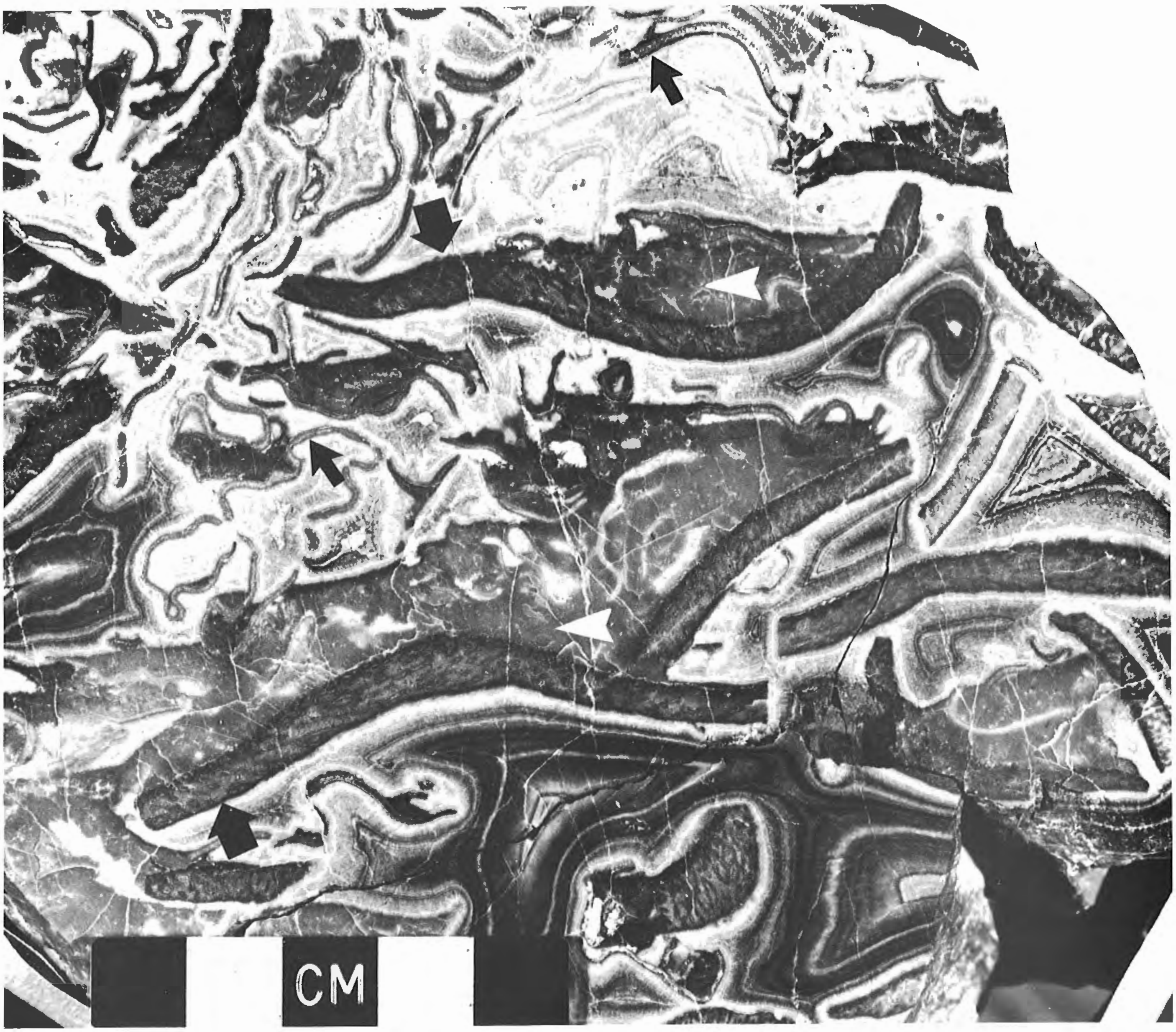
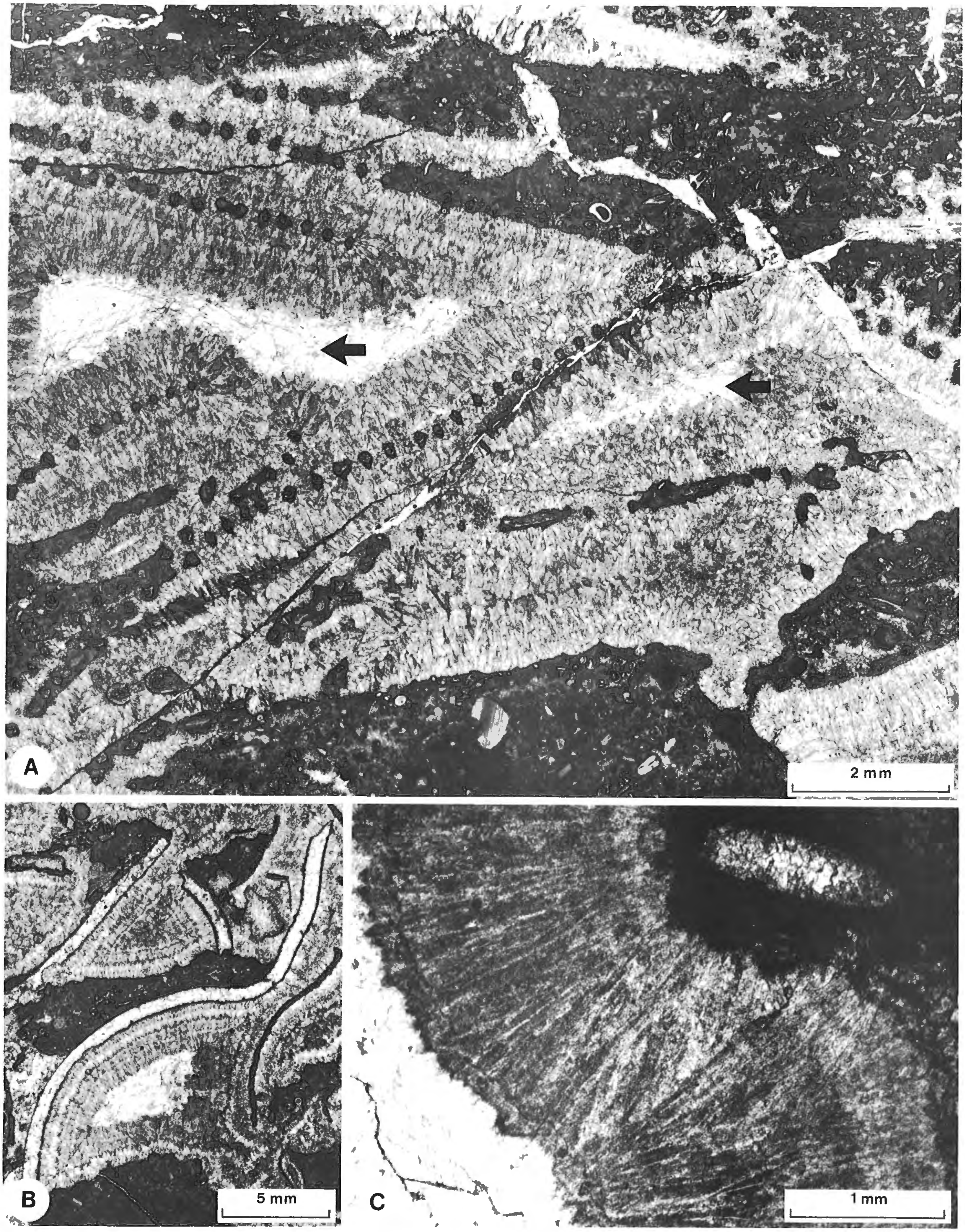


Figure 12. Cut and polished slab of ***Palaeoaplysina*** *(large arrows) and phylloid algal (small arrows) "platestone" of probable Early Permian age, with shelter fabric and ponded primary marine sediment (white arrows), and banded radial-fibrous calcite replacing submarine cements. Float, Nansen Formation, Girty Creek, northwestern Ellesmere Island.*

of RFC includes the specific type of calcite cement termed radiaxial fibrous calcite by Bathurst (1959, 1971), and described in detail by Kendall and Tucker (1973) and with revisions by Kendall (1985). This variety is characterized by a pattern of subcrystals within each larger crystal of the fibrous fabric that diverges away from the cement substrate, and by a pattern of distally-convergent, fast-vibration directions (optic axes, or C-axes); the resulting fabric shows curvature of cleavage traces, twin lamellae, and glide planes (Kendall, 1985). In addition, the RFC cement category includes fascicular-optic calcite (Kendall, 1977, 1985) that is similar to radiaxial fibrous calcite, but is distinguished by the presence of a divergent pattern of fast-vibration directions coinciding with the distribution of subcrystals (Kendall, 1985). Radial-fibrous calcite, in the restricted sense of Kendall (1985), refers to inclusion-rich isopachous cements that resemble the other fibrous cement types but do not exhibit any marked undulose extinction; Kendall (op. cit.) noted that transitions between all three cement fabrics (radiaxial, fascicular-optic, radial-fibrous) are common.

Within larger cement-lined cavities containing RFC in the Arctic Island reefs, both of the specific varieties of radiaxial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B
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C
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Figure 13. *Characteristics of radial-fibrous calcite (RFC) after high-magnesium calcite submarine cements (thin section photomicrographs).*

A. Inclusion-rich multi-generation isopachous RFC nucleated on fenestellid bryozoan zoaria with ponded marine sediment in core of Waulsortian-type reef. Clear calcite spar filling residual pore space (arrows) is post-burial phase. Blue Mountains reef.

B. Multi-generation, isopachous RFC cement in phylloid-algal "platestone" with ponded sediment; lighter-coloured calcite spar filling residual pore space formed during post-burial phase. Nansen Formation, Girty Creek.

C. Relict fascicular fabric defined by inclusions in RFC. Blue Mountains reef.

fibrous and fascicular-optic calcite have been identified. However, there also are variants that do not appear to fall strictly into either of these categories. Given the variability of fabrics in these cements within individual cavity systems, yet clearly derived from the same environmental-diagenetic source, all varieties of inclusion-rich, radial-fibrous cements are included in one RFC category in this report.

In their initial interpretation of radiaxial fibrous calcite, Kendall and Tucker (1973) proposed that this fabric results from the replacement of an acicular carbonate cement, and that the present calcite crystal structure is the product of both inherited and neomorphic fabrics. Kendall (1985) revised this interpretation, based on examination of cement samples from the Devonian reef complexes of Western Australia, to one in which the crystal fabrics of radiaxial fibrous cement are primary, and the unusual convergent-divergent optical/crystal fabrics are attributed to split-crystal growth.

Neomorphic iron zonation

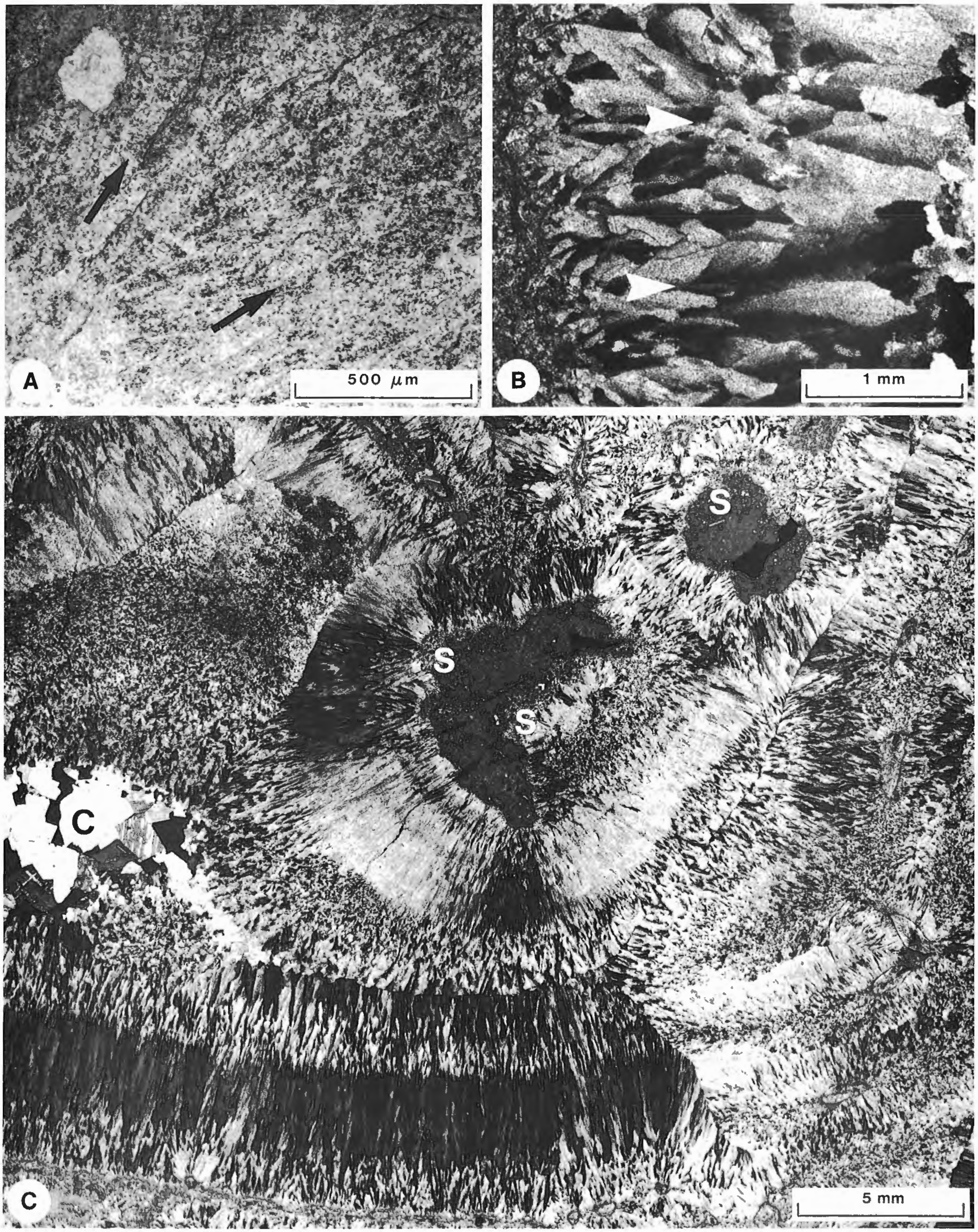
In the RFC fabrics from the Arctic reefs, including specific radiaxial fibrous varieties, a replacement (neomorphic) origin after an original fascicular cement is indicated by inclusions that appear to define radiating bundles of acicular fibrous crystals (Fig. 13C). Staining of the same fabrics by potassium ferricyanide, particularly overstaining with high-strength solutions, defines a secondary pattern of larger iron-zoned calcite crystals superimposed on the fascicular fabric. As the iron zonation is clearly correlative with and parallel to the iron zonation in zoned ferroan calcite (ZFC) of burial origin, but directly overlying the RFC calcite, our interpretation is that an original fascicular cement fabric has been neomorphosed to a coarser radial-fibrous calcite fabric. Since the iron zonation in the RFC fabric is parallel to the zonation in the zoned ferroan calcite cement emplaced during early burial, the most logical conclusion is that the neomorphism of the precursor cement occurred during burial, contemporaneously with and by the same pore fluid as the ferroan calcite cement. Even if the iron zonation in the RFC represents another phase of "recrystallization" of an earlier neomorphic replacement of the fascicular cement, there remains little doubt that the present fabric is an overprint of the ZFC burial diagenetic event. The diagram of neomorphic development of radiaxial fibrous calcite published by Kendall (1985, Fig. 2), particularly the stage of partial replacement (*ibid.*, lower diagram), exhibits the same sawtooth pattern of iron zonation that is preserved in the Arctic RFC fabric.

The evidence indicates that, as an overall category, the RFC cement in the Arctic rocks, regardless of present textural variants, was emplaced originally as submarine-cement (of HMC composition, as documented in following sections), with radiating acicular (fascicular) to fibrous crystal habits. This cement was later neomorphosed to low-magnesium calcite, either during early burial and at the same time as emplacement of ferroan calcite, or with a later neomorphic overprint, indicating "recrystallization" at the same time as precipitation of ferroan calcite during burial.

Distribution and fabric relationships of RFC

If there is a pattern to the relationship between true radiaxial fibrous calcite and non-radiaxial fibrous calcite in the Arctic rocks, it is that later and often thicker generations of cement in cavities are of non-radiaxial type. The fascicular pseudomorph fabric, defined by inclusions and crystal boundaries in the thicker fibrous calcite, suggests that it replaced a more densely packed, longer, and thus less divergent, aggregate of acicular crystals than the radiaxial calcite. Following the interpretation of Kendall and Tucker (1973) that the divergence of the precursor crystal aggregates controls the morphology of radiaxial crystals, we may argue that the more nearly parallel nature of the thicker, more densely packed cement generations inhibited development of the radiaxial crystal habit. This interpretation is supported to some extent by the narrower, more elongate form of the present crystals of non-radiaxial fibrous calcite type.

The radiaxial crystal habit (curved twin lamellae) occasionally appears to be accentuated in RFC in the Arctic rocks, immediately adjacent to microfractures, where the calcite crystals have been subjected locally to increased stress. However, Kendall and Tucker (1973) discounted stress as a factor in the formation of the curved lattice in radiaxial calcite.


A
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S
S
S
C
C
5 mm

Figure 14. Characteristics of radial-fibrous calcite (RFC) submarine cements, Waulsortian-type reefs, Blue Mountains.

A. Abundant inclusions in indistinct radiating fabric, giving typical "cloudy" and dark colour to RFC cements. Direction of crystal growth indicated by arrows.

B. RFC under cross-polarized light, illustrating typical curved to undulose extinction. Cement substrate is to left. Direction of crystal growth indicated by arrows.

C. RFC fabrics under cross-polarized light, illustrating undulose extinction and relict fascicular textures. S = substrate sediment; C = post-burial calcite spar.

In the Waulsortian-type reefs and other Arctic Island buildups, RFC invariably forms the first generation of cement in the reef cavity system. The cement forms an isopachous rim around the cavity (Fig. 13A); that is, unless complicated by input of internal sediments, the rim of RFC is of similar thickness on the floor, walls, and roof of the cavity. Total thickness of a multi-generation layer of fibrous cement varies with setting, but may exceed one centimetre. In the Waulsortian reefs, fibrous calcite may comprise 30 to 60 per cent by volume of the rock in depositional units that are several metres in thickness, while, at a scale of decimetres, over 90 per cent by volume may be cement (Figs. 7A, 8A). In the upper 200 m (of 250 m total thickness) of one Waulsortian reef on Ellesmere Island, a rough estimate places 10 to 30 per cent of the rock volume in the RFC category; thus, loss of porosity and permeability is a significant consequence of this type of cementation.

The most common type of primary cavity or pore system containing RFC, in the Arctic reef and shelf-edge rocks, is of shelter type, controlled by fenestellid bryozoan zoaria or the plates of phylloid algae and palaeoaplysinids (Figs. 11-13); algal plate fabrics in modern submarine-cemented rocks in the British Honduras barrier reef contain similar primary pore systems (Ginsburg and James, 1973a). Many of the calcite-filled former cavities resemble "*stromatactis*" fabrics (Fig. 9); in some, a primary shelter framework (not always preserved in the plane of section), enhanced and stabilized by very early cementation and modified by internal sedimentation, clearly is the source. In others, particularly in micrite-dominant fabrics, a process of differential compaction and flowage of lime mud, similar to that proposed by Heckel (1972) and others and most recently by Wallace (1987), is the apparent mechanism. Other discrete cavity systems containing RFC in the Arctic rocks are related to fractures and foreslope sedimentary breccias.

Before describing in more detail the morphology and composition of fibrous calcite, the paleogeographic distribution of this cement type should be stressed. In the rocks of the carbonate shelf facies characterized by the Nansen Formation, and the more localized Waulsortian reefs, RFC is found most commonly (thickest development) in primary pore systems of reef, mound, and shelf foreslope units. Further, within the reefs and shelf-edge units, RFC cements are more common higher in the units, corresponding with increased elevation above the surrounding sea floor (but also with increased volume of skeletal plates and shelter pore volume). A general analogy may be made between this distribution and the distribution of submarine cements in modern coralgal reefs; contemporaneous submarine cementation in modern reefs appears to occur preferentially close to the sediment/water interface on the seaward side of high-relief carbonate barriers. Wave- and tidal-generated hydrostatic pressure differentials, acting across such porous and permeable carbonate masses, may provide the pumping mechanism required to maintain water flow through the pore system (Matthews, 1974, p. 242, 243).

Inclusions in RFC

Optical and scanning-electron microscopy reveal that inclusions in the Arctic RFC fabrics are abundant, and are variable in size; most are 1 μm in size or smaller. Many appear to be gas or liquid filled, others are opaque. Microprobe analyses of a few larger opaque inclusions detected only carbon; some of this carbon may have been introduced as mobile hydrocarbons during neomorphism, but carbon residues after bacterial oxidation are another possible source. Kendall and Tucker (1973, p. 368) suspected that many of the inclusions in radiaxial calcite were composed of oxidizable organic matter. However, SEM photographs of fractured surfaces in Arctic RFC (Fig. 15) show that many of the inclusions appear as microvoids that probably were filled by liquid and/or gas phases. Microprobe analyses of RFC at beam diameters greater (up to 10 μm) than inclusion size revealed scattered low residuals of Na, K, and Cl; these elements may have been present in brine-filled inclusions.

Inclusions and microvoids in RFC occur in three general distributions:

a. Disseminated throughout the calcite fabric, giving the characteristic "cloudiness" (Figs. 13A, 14A) and brown colour in transmitted light; exceptions occur at crystal interfaces (Fig. 15), where the neomorphic crystal lattice immediately adjacent to the interface is inclusion free, and where the distribution of inclusions apparently pseudomorphs the original acicular crystal fabric

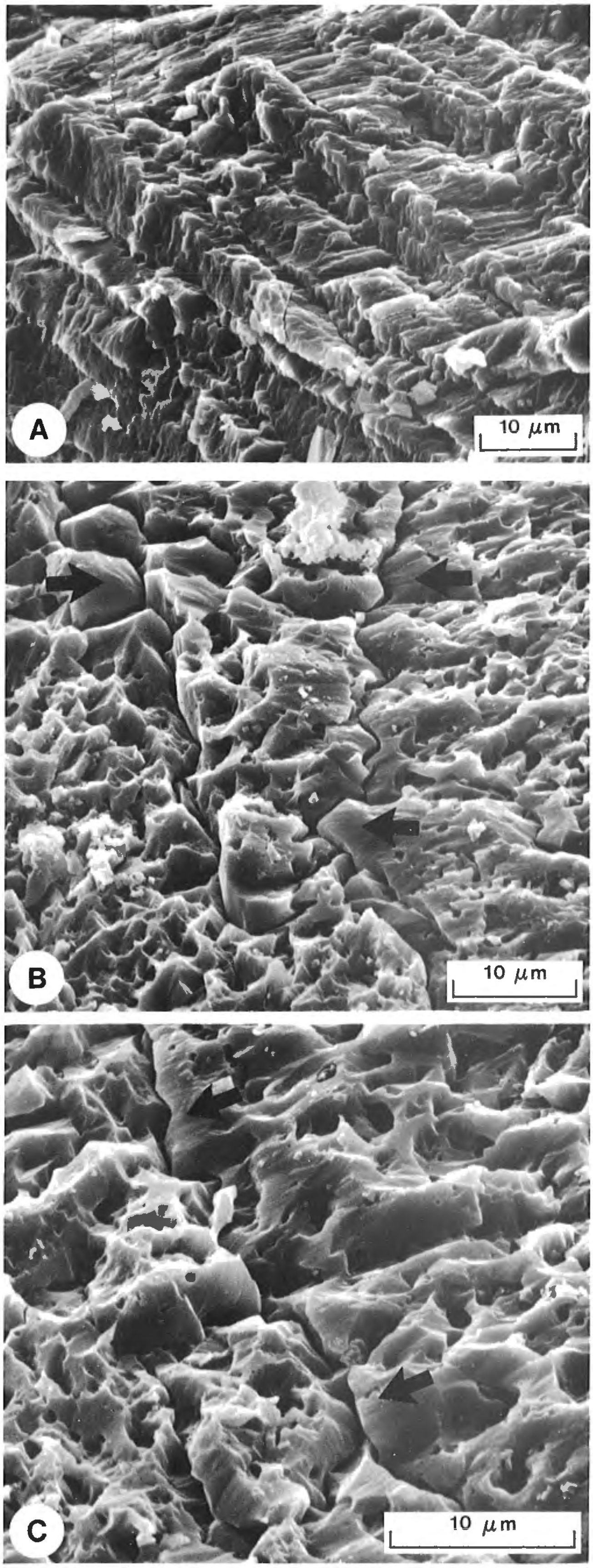

Figure 15. *SEM illustration of microfabrics in radial-fibrous calcite (RFC), Blue Mountains reef.*

A. Low-magnification view of RFC fabric, showing subparallel crystallites defined by rows of inclusions or vacuoles.

B. Detail of fabric, illustrating abundance of micro-inclusions and vacuoles within the centres of crystals, with the outer margins bordering the interlocking crystal boundaries relatively vacuole-free (arrows). The vacuoles may have been fluid and/or gas filled.

C. Detail of boundary between adjacent crystals of RFC fabric, showing the often subrhombic shape of the vacuoles, and the non-vacuolate margin (arrows).

(Fig. 13C), outlining clear pseudoacicular zones about 5 to 10 μm wide.

b. Inclusions may also record growth increments of the original cement generations, preserved as concentric or parallel layers of impurities within the fibrous crystals and roughly paralleling the cavity wall (Fig. 13A, B). Some restructuring of these primary "growth lines" may have occurred during neomorphism.

c. Some of the more prominent concentrations of inclusions in RFC are found to be aggregates of impurities apparently reconcentrated (or introduced?) during neomorphism of the primary HMC cement to the RFC fabric. Inclusions of this type (Fig. 16A) may define pyramidal terminations of neomorphic calcite at the boundary between RFC fabric and overlying zoned ferroan sparry calcite (ZFC), and neomorphic zonation within the RFC crystals themselves (Fig. 16B, C). At high magnifications, some zones of concentrated impurities within RFC appear as aggregates of opaque particles, defining or outlining small (10 μm or less) rhombic crystals of calcite (not dolomite) that appear to be aligned parallel with the curved twin lamellae or cleavage traces of the host radiaxial crystal. These rhombic microcrystals probably record a step in the neomorphism of the primary HMC cement to LMC, terminated and enclosed by a local concentration of bituminous organic material; it is improbable that they are a direct relict of the primary cement fabric. These types of organic-rich inclusion zones, marked by darker colour of the cement, tend to be more common in later generations of radiaxial fibrous calcite or normal RFC.

Scanning electron microscopic examination of RFC fabrics from the Arctic reefs reveals a basic

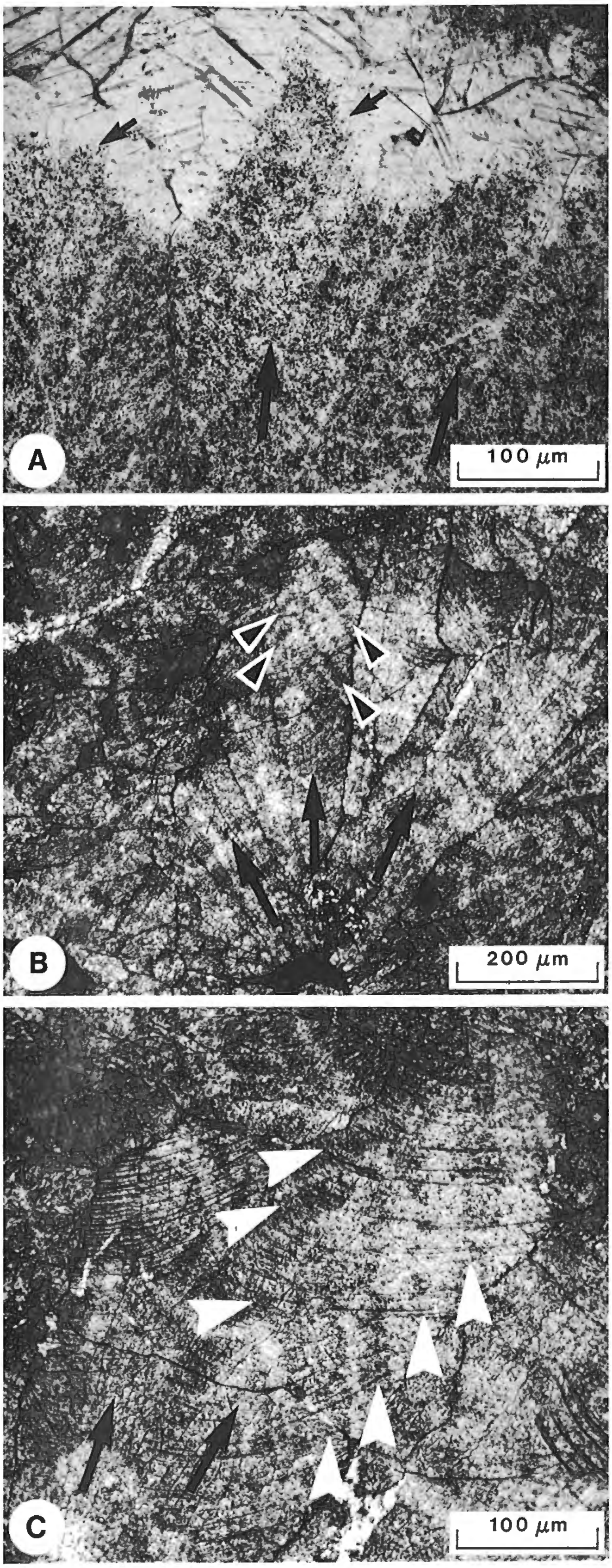

Figure 16. Microfabrics of radial-fibrous calcite (RFC) submarine cements, Blue Mountains reef. Direction of crystal growth indicated by elongate arrows.

A. Pyramidal terminations (short arrows) defined by abundant inclusions in RFC at the transition into zoned ferroan calcite of burial diagenetic origin. The pyramidal termination is parallel to neomorphic pyramidal iron zonation within the RFC (B, C).

B. RFC nucleated on fenestellid bryozoan zoaria, with traces of iron zonation (small arrows) revealed by overstaining with potassium ferricyanide. The pyramidal zonation is parallel to and contiguous with stronger ferroan (precipitational) zonation in overlying, post-burial, ferroan calcite cement. The zoning in the RFC is interpreted as a neomorphic overprint, indicating that replacement (neomorphism) of the submarine cement occurred contemporaneously with precipitation of zoned ferroan calcite during early burial.

C. Detail of RFC crystal from upper centre of (B), illustrating pyramidal iron zonation (white arrows) in crosscutting relationship to "curved" cleavage traces in RFC (specifically, radiaxial fibrous calcite in this example).

microstructure of radiating bundles or arrays of fibres. The fibres are about 40 µm wide, and 500 to 600 µm long. Each fibre is enclosed in a "spongy" calcite fabric (Fig. 15) with many rhombic-shaped holes (microvoids) that are arranged in crystallographic orientation. The fibres are hexagonal or pseudohexagonal in crystal form, with some evidence of individual fibres formed of two half-crystals with a planar (twin) boundary.

RFC cement sequences

In the Waulsortian reefs, thick rims of RFC are nucleated directly on primary carbonate sediment and on large skeletal plates and bryozoan zoaria (Fig. 13). Cements in some cavity systems within the reefs form a sequence, grading from thin fibrous crusts with organic encrustations to thick RFC; in more detail, this sequence (Fig. 17A) is as follows:

a. An irregular but continuous rim, about 100 µm thick, composed of short fibrous calcite crystals nucleated directly on bryozoan zoaria and primary sediments; interpreted as the earliest generation of incipient RFC cement, followed by:

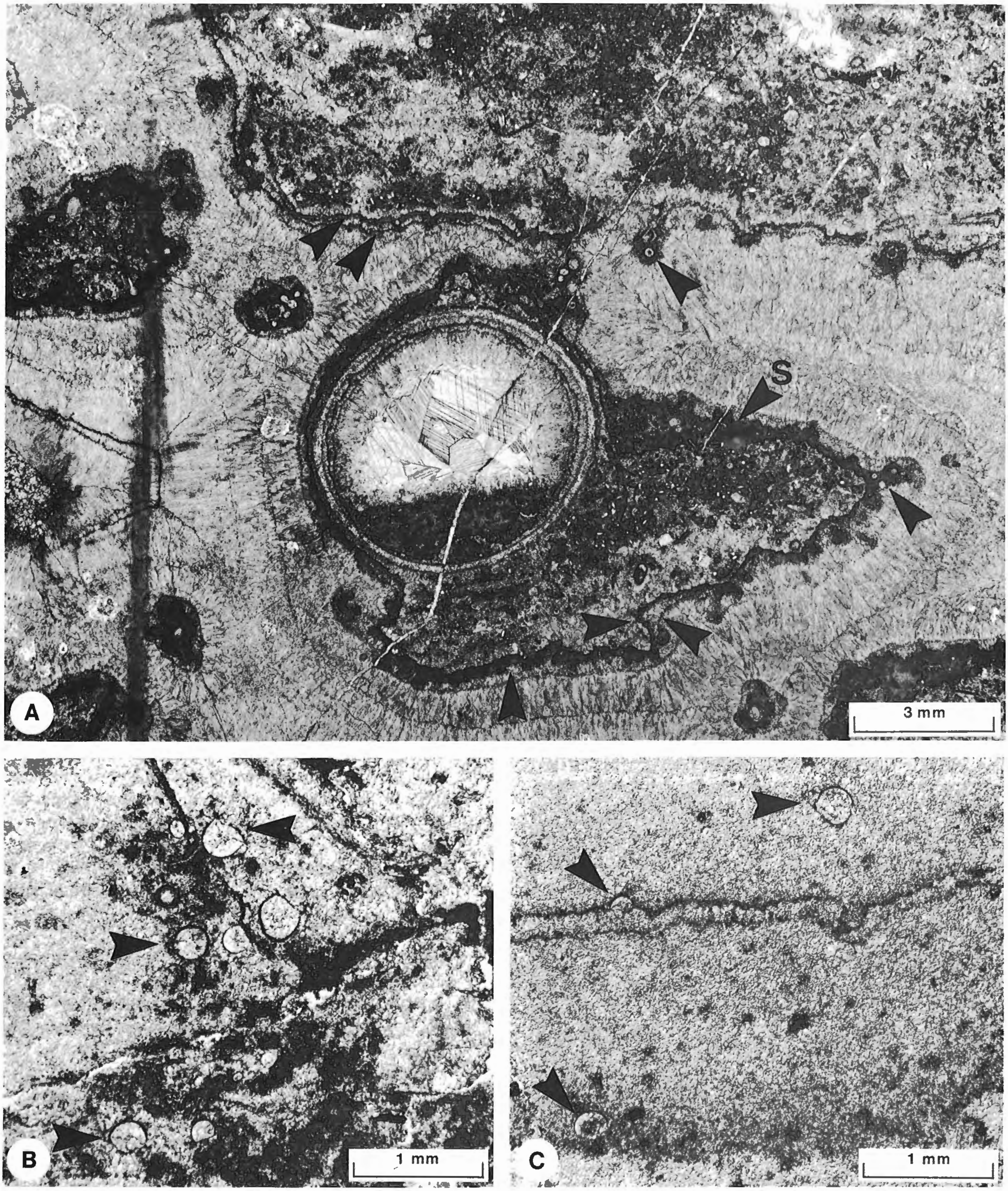
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Figure 17. Organic and cyanobacterial(?) encrustation in radial-fibrous calcite (RFC) submarine cements, Waulsortian-type reefs, Blue Mountains.

A. *Unicellular and indistinct micritic coatings and intergrowths (arrows) of possible cyanobacterial origin, on and in early generations of RFC in a primary shelter cavity of the reef. Organic-like coatings formed synchronously with deposition of internal sediment (S). Note the geopetal internal sediment in the bioclast at left centre; the internal cavity above the sediment is lined with RFC submarine cement and infilled by post-burial calcite spar.*

B, C. *Examples of unicellular organisms (arrows) encrusting growth surfaces and enclosed within RFC. The micro-organsisms resemble the foraminiferid(?)* ***Tuberitina.***

b. A very irregular, dark-coloured, micritic rim (crystal size 5 μm and less), indistinctly peloidal in texture, averaging 250 μm in thickness around the walls and roof of the cavity, but grading into and correlative with 5 mm or more of micritic peloidal and bioclastic internal sediment on the floor of the cavity and on skeletal projections (geopetal fabric). Components of this internal sediment (Fig. 17B) include peloids, discrete fecal pellets, ostracodes, a few bryozoan fragments, and some unidentified tubular and spherical encrusting organisms. The distribution of the irregular micrite layer around the walls and roof of the former cavity indicates it was, in part, a cement; in texture, it is not unlike "micritic" HMC cement found in modern coral reefs (Ginsburg and Schroeder, 1973), and described in more detail by Macintyre (1985). The dark "organic"-like texture of this micritic layer suggests that a cyanobacterial process may have controlled its accumulation. This rim may be followed by:

c. Another generation of RFC about 100 μm thick, similar in composition to the first cement generation, followed by:

d. Another thin micritic rim, correlative with a very limited phase of internal sedimentation, which grades directly into the base of the first thick but compositionally identical generation of RFC.

RFC and internal sediments

Generations of RFC frequently alternate with generations of internal sediment (Fig. 18); up to eight cycles of internal sedimentation and cementation have been identified in Nansen Formation phylloid algal and palaeoaplysinid "platestone" fabrics (Fig. 18A). Commonly, one or more generations of internal sediment may be red or pink, suggesting oxidation of iron (organic) compounds. Internal sediment in the bryozoan mounds, with few exceptions, is peloidal in texture (occasionally with some crustacean-like fecal pellets with internal canals), intermixed with abundant ostracodes (Fig. 18A) and rarer foraminifers and bryozoan fragments. The ostracodes and possibly the foraminifers form part of the cavity-dwelling (coelobite) community. The internal sediment probably was emplaced as a peloidal grainstone or packstone, cemented by penecontemporaneous magnesium calcite and/or aragonite, and modified later by neomorphism. Periods of accumulation of internal sediment on the floors of cavities correspond with irregular, indistinctly peloidal and micritic rims around the walls and roofs of the cavities, preserved now between growth increments of RFC (Fig. 17A); some of these surfaces may be slightly corroded, with the micritic rims possibly of cyanobacterial origin, as noted earlier.

RFC in allochthonous shelf-edge carbonates derived from the Nansen Formation (Davies, 1977b) and now enclosed in the Hare Fiord Formation (see Davies, 1977b, Figs. 8, 11) are overlain directly by internal sediments containing fusulinids, crinoids, and other marine fauna apparently introduced during displacement.

Pigmentation of pink and red layers of internal sediment found occasionally in reef rocks and foreslope tongues in the Sverdrup Basin appears to be due to the oxidation of iron compounds associated with organic matter; translucent reddish brown pigmented material in irregular shapes and in spheroids, in the size range 10 to 20 μm, are the major source of colour in some layers. Internal sediments associated with modern submarine cements in the British Honduras barrier reef (Ginsburg and James, 1973b) also contain a few reddish brown, oxidized, sediment layers with ferric iron present (N. James, pers. comm., 1974); subaerial exposure is not a requisite for this phenomenon. Correlation between the emplacement of internal sediments and oxidizing water conditions may suggest an abnormal event, such as a major storm surge.

In the lower flank beds of Waulsortian reefs in the Blue Mountains area of Ellesmere Island, peloidal internal sediments are part of a more complex paragenetic sequence of initial cementation: early fracturing, post-fracture cemention, internal peloidal sedimentation, and then several more phases of early and late cementation. In more detail, the sequence is identified as follows (Fig. 19):

a. Loosely packed fenestellid bryozoan zoaria and perched primary sediments in a "platestone" fabric were cemented by generation 1 of RFC (RFC:1) and by peloidal micritic matrix cement (PMC)

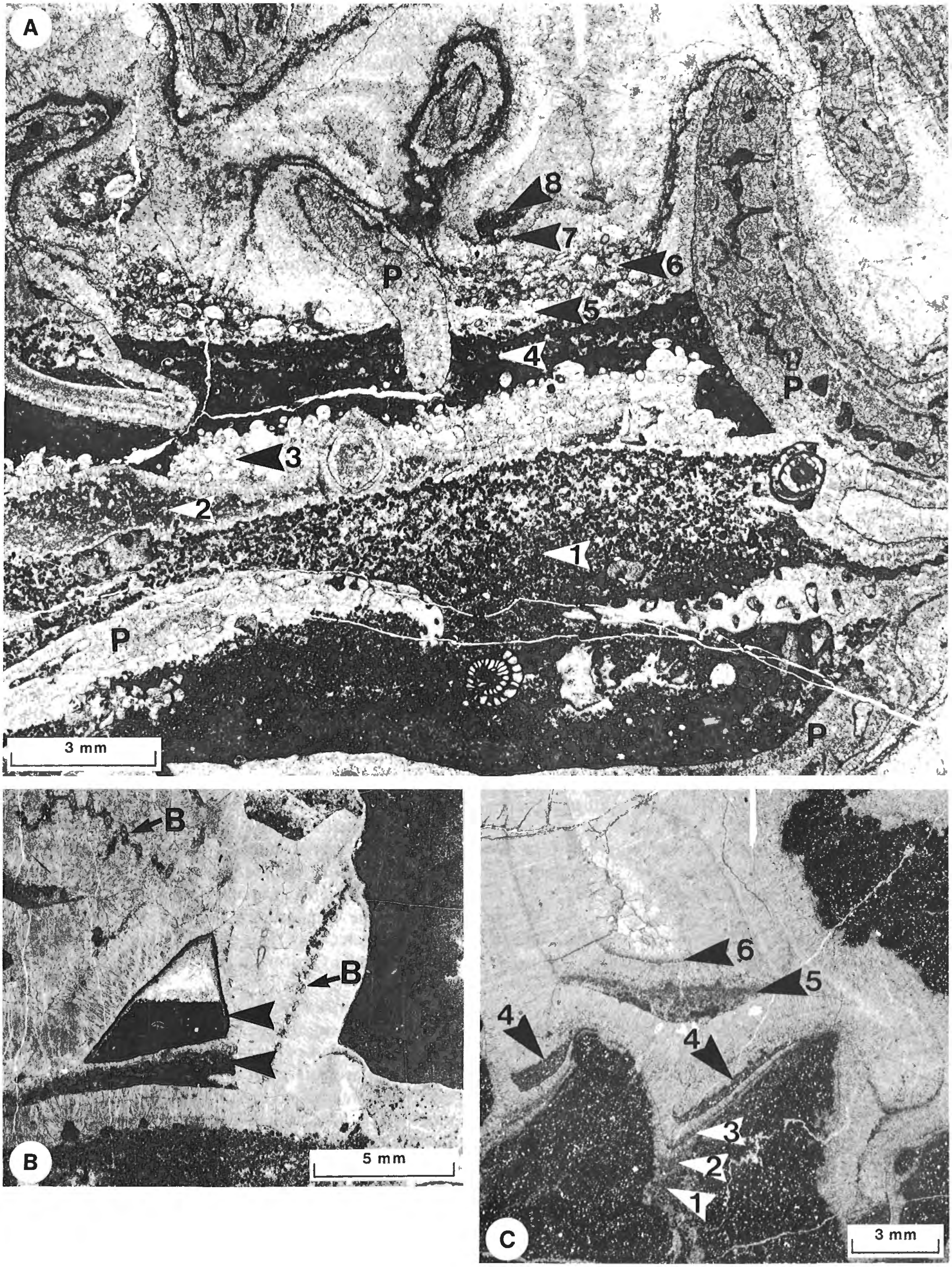
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Figure 18. *Marine internal sediment in radial-fibrous calcite (RFC) cemented fabrics, northwestern Ellesmere Island.*

A. Primary ponded marine sediment, containing fusulinids, grading upward into peloidal packstone (1) of probable internal origin, followed by at least seven generations of interlayered RFC submarine cement and internal sediment (2-8). Several of the sediment generations are composed dominantly of ostracodes, representing the intracavity coelobite community. Upper Carboniferous palaeoaplysinid ("proto-palaeoaplysinid") platestone; Nansen Formation, Girty Creek. P = proto-palaeoaplysinid plates.

B. Multiple generations of internal sediment (arrows) in arch-shaped former primary shelter cavity lined by multiple generations of RFC, nucleated on fenestellid bryozoans (B). Fabric at upper right is truncated by a submarine fracture, cemented by a thin rim of fracture-lining RFC, and infilled by darker-coloured internal sediment that may be genetically related to either or both of the layers of internal sediment in the former cavity at left centre.

C. "Rotated" internal sediment layers (arrows, 1-6) interlayered with RFC at the toe of a foreslope bed containing displaced blocks of slope debris. Host block has rotated downward to left between earlier and later stages of cementation and internal sedimentation. Relationship of this fabric to former aragonite arrays and to toe of slope setting is illustrated in Figure 32.

b. RFC:1 and the host sediment were fractured, and the cemented blocks displaced relative to each other, forming a submarine fracture cavity

c. A thin layer of internal sediment settled out onto the floor of the cavity system, forming a microgeopetal fabric

d. A second generation of RFC (compositionally identical to RFC:1) formed over RFC:1 where it lined original primary pores, and on the truncated edges of RFC:1 and the host sediment on the walls of the fracture

e. Internal sediment, indistinctly laminated and composed of peloids with a few scattered ostracodes, was mechanically introduced to partly fill the remaining primary and fracture cavity systems

f. Remaining pore space above the internal sediment was partly filled by an isopachous rim of RFC (identical compositionally to RFC:1 and 2)

g. At a later diagenetic stage (post-burial), all remaining void spaces were filled by zoned ferroan calcite (ZFC), followed by low-iron calcite and dolomite, accompanied by development of microfractures.

Composition of RFC cements

Elemental composition

Analyses of the elemental and isotopic composition of RFC in the Arctic rocks reveal no compositional differences between radiaxial and other types of inclusion-rich fibrous cements. Consequently, all fibrous cements again are treated here as one group (RFC).

Microprobe analyses of RFC from Waulsortian reefs and Nansen shelf-edge buildups show the following elemental means and trends (Table 1; Fig. 20A, B):

1. A mean of 1.60 ± 0.24 (99% confidence limit) mole per cent $MgCO_3$

2. Mn generally below detection (<160 ppm), but with rare spot values between 300 and 400 ppm in the outer increments of RFC

3. Fe generally below detection (<150 ppm), but with a number of spot analyses averaging about 500 ppm within a range of 200 to 900 ppm

4. A very irregular distribution of Sr, generally below microprobe detection (<300 ppm), but with some spot values in the range 500 to 600 ppm Sr; atomic absorption spectroscopy shows a Sr mean of about 300 ppm (range 240 to 350 ppm) for a few samples of RFC

5. K always below detection (<190 ppm); Cl very irregular in distribution with a mean of 330 ppm within a range of 300 to 500 ppm; and Na normally close to the detection limit (140 ppm) with a few spot values to 200 ppm.

Because of the poor quality of surfaces produced by polishing the inclusion-rich RFC, a beam diameter of 7 to 10 μm was used for microprobing. Consequently, this gives an "averaging" affect for most elements. Magnesium is distributed inconsistently through the RFC, and shows several trends (outlined in a following section). That much of this Mg substitutes for Ca in the calcite lattice is suggested by displacement of the d(104) spacing in X-ray diffractograms; the degree of displacement corresponds to a $MgCO_3$ content in calcite of about 2 mole per cent, and is thus of the same general magnitude as the microprobe data. However, individual spot analyses for Mg in RFC range up to nearly 4 mole per cent $MgCO_3$.

TABLE 1

Elemental and isotopic composition of carbonate phases in Carboniferous and Lower Permian reefs, Canadian Arctic Archipelago

Sample Base	mol% $MgCO_3$	Fe/ppm	Sr/ppm	Na/ppm	Cl/ppm	K/ppm	$\delta^{13}C$ ‰ PDB Mean	$\delta^{13}C$ ‰ PDB Range	$\delta^{18}O$ ‰ PDB Mean	$\delta^{18}O$ ‰ PDB Range
Skeletal calcite: Brach. Bryoz. Crinoid	0.6 (3). . . . . . 0.7 (7) 1.5 (3).	mn. 350; sp. 650 mn. 800; sp. 1500	nd. bd. to 1300	nd. bd. to 140	nd. bd to 300	nd. bd. to 400	+5.5; +6.1		-1.9; -3.1	
Radial-fibrous calcite (RFC)	1.60%0.24*	bd. to 900 mn. 500	bd. to 600; mn. 300[a]	bd. to 140	mn. 330	bd.	+5.4%±0.8	+4.2 to +6.3	-4.2%±2.0	-1.9 to -7.1
Fracture-lining calcite (RFC & micritic layer)	1.62%0.27*	bd. to 1050; mn. 300	bd.[m] 250[a]	bd. to 140; sp. 200	200 to 400	bd.	+5.4%±1.1	+3.0 to +6.3	-3.3%±1.5	1.8 to -6-0
Radial-array calcite (RAC)	1.62%0.21*	mn. 300; sp. 750	nd.	nd.	nd.	nd.	+5.7%±0.8	+4.5 to +6.9	-2.8%±1.5	-0.5 to -5.5
Botryoidal-array calcite (BAC)	Small: nd. Large: bd.-trace	nd. bd.	sp. 1100[a] sp. 7800, 8300[a] mn. 7480%1240 max. 10 700	nd.	nd.	nd.	(BAC/RAC undiff'd)			

bd. = below detection
a = atomic absorption spectroscopy; all other elemental data from microprobe (m)
mn. = mean
sp. = highest spot values from microprobe
nd. = no data
(1) = number of microprobe analyses where limited (< 10); in isotope data, if only two analyses, both values are given, separated by semicolon; if only one analysis, no range indicated.

To decipher more clearly the actual distribution of Mg, selected sites in RFC were scanned by the electron beam using a beam diameter of 1 μm or less. Beam-scanning photographs (Fig. 21) reveal scattered domains of Mg enrichment 2 to 4 μm in size; some have a crude rhombic shape. Clearly, occasional high spot readings of up to 4 mole per cent $MgCO_3$, using a 7 to 10 μm beam, simply may be an averaging affect of such small high-Mg domains enclosed in calcite with an overall lower Mg content. Although these domains of Mg enrichment have not been correlated optically with dolomite inclusions or authigenic crystals in the fibrous calcite, they undoubtedly do represent very small dolomite crystals. Essentially identical Mg domains identified by Macqueen and Ghent (1970, Fig. 1) in Mississippian echinoderm calcites were shown to be dolomite. Macqueen and Ghent (op. cit., p. 1314) favoured an exsolution origin for the echinoderm dolomite crystals, with the inferred source of Mg being the original HMC mineralogy of the echinoderm skeleton. This interpretation is supported by later work done by the same authors on Quaternary echinoderm calcites (Macqueen et al., 1974). Lohman and Meyers (1977), working with inclusion-rich calcite fabrics in Lower Carboniferous (Mississippian) carbonates from bryozoan buildups in New Mexico, also concluded that microdolomite crystals, 1 to 10 μm in size, enclosed in the calcite were prime evidence of a HMC precursor.

Microprobe traverses across RFC (Fig. 20A, B) reveal two interrelated trends:

a. Within each generation of cement, Mg content tends to increase from the base outward to a maximum at the end of each crystal increment, with a crude mean increment of about 0.5 mole per cent $MgCO_3$

b. Superimposed on this pattern is an overall trend of increasing Mg within the complete multi-generation cement layer, from a mean of about 1.3 at the base to 2.2 mole per cent $MgCO_3$ in the outer generation. This trend often is modified by a sharp drop in $MgCO_3$ level in the outermost rim of the RFC toward the level of $MgCO_3$ in overlying calcite spar (post-burial phase).

The occasional higher values of Fe (to 900 ppm) in RFC (Fig. 20A, B), revealed by microprobe, probably correlate with discrete zones of Fe enrichment, revealed by staining with overstrength potassium ferricyanide solution (Fig. 16); the stain shows that the Fe distribution pseudomorphs stages of neomorphic replacement of the original cement fabric by calcite, and thus the Fe is partly or totally of secondary neomorphic origin. Spot values for Fe tend to be higher at cement increment boundaries, and in the outermost RFC where it is overlain by post-burial ferroan calcite.

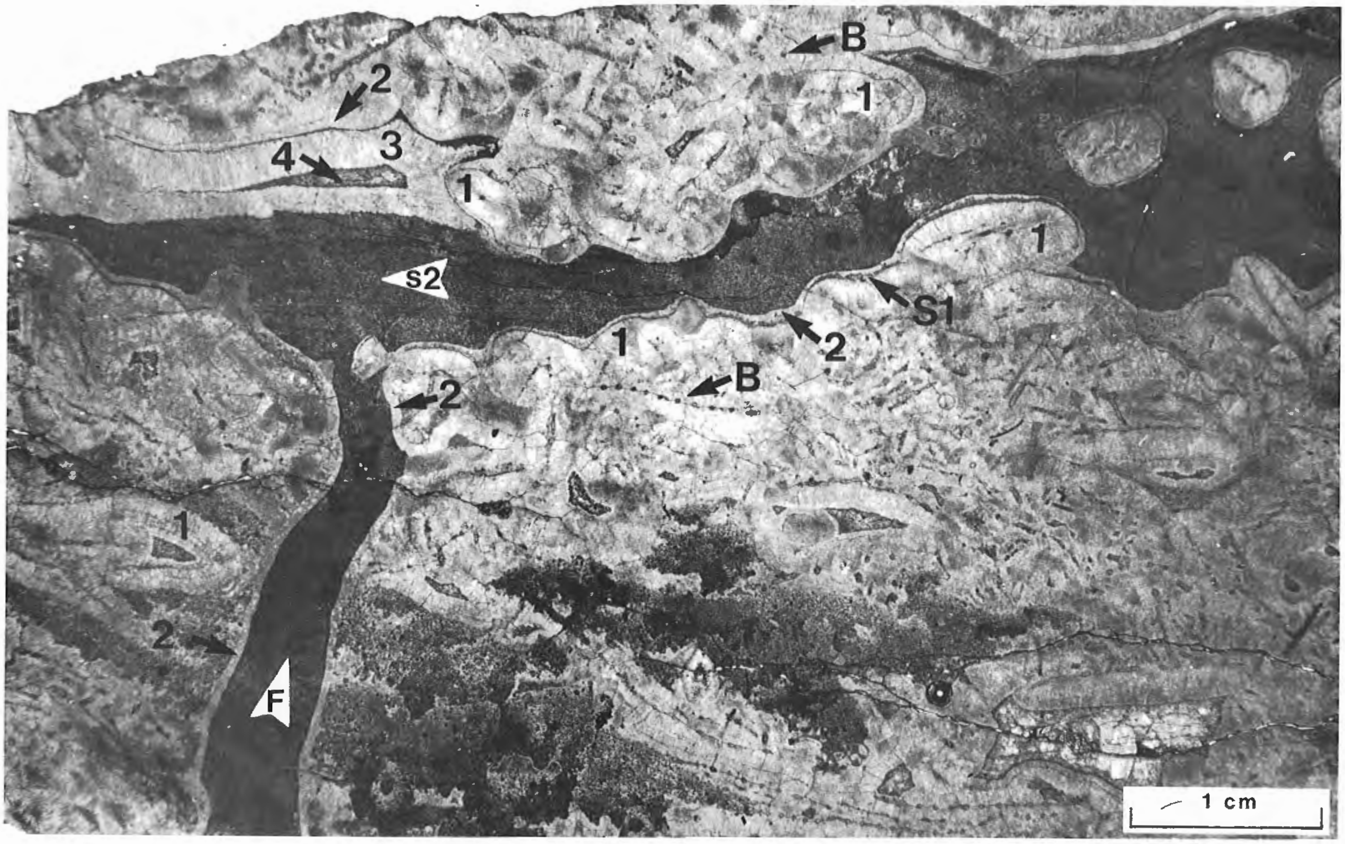


Figure 19. Complex fabric in Waulsortian-type reef in the Blue Mountains, illustrating micro-scale submarine fracturing and truncation of fenestellid bryozoan (B) platestone with pervasive first-generation RFC (1), and with thin RFC cement (2) lining the fracture (F) and also lining the primary shelter cavity running across the field of view at mid-centre. A thin layer of internal sediment on the floor of the former cavity (S1) separates RFC 1 and 2. The fracture and most of the primary shelter cavity were then filled with fine peloidal marine internal sediment (S2), containing ostracodes and foraminiferids. The roof projection in the centre of the primary cavity apparently acted as a barrier to sediment flow (from the upper right?), leaving the residual cavity on the left to be mainly filled by another RFC generation (3) with a final infill of post-burial zoned ferroan calcite spar (4).

The spot analyses for Cl and Na that are above background levels probably are "averaged" values for these elements in the micron-sized fluid-filled inclusions scanned by the 10 μm beam. The data show that Cl levels are higher in RFC than in later sparry calcite precipitates (and earlier bryozoan skeletal calcites).

Stable carbon and oxygen isotopic composition

Stable isotope values for the Arctic RFC (Table 1; Fig. 22; see also Davies and Krouse, 1975) have the following means and ranges (all relative PDB standard):

1. $\delta^{13}C$ mean of +5.4 ± 0.8‰ within a range of +4.2 to +6.3
2. $\delta^{18}O$ mean of -4.2 ± 2.0‰ within a range of -1.9 to -7.1.

Nearly half of the analyses (total 14) lie close to the isotopic composition of skeletal calcites of undoubted marine origin that serve as a check on the expected isotopiccomposition of contemporaneous marine calcite; these values are:

1. $\delta^{13}C$; brachiopod: +4.8, +5.2; bryozoan: +5.5, +6.1
2. $\delta^{18}O$; brachiopod: -0.7, -2.0; bryozoan: -1.9, -3.1.

The enrichment in ^{13}C in all samples, and the slight depletion in ^{18}O for many, are consistent with a marine precipitation mechanism for the origin of the precursor cement now preserved as RFC; submarine aragonite and magnesium-calcite cements in modern coralgal reefs generally fall within the range +2 to +4‰ for $\delta^{13}C$, and -1.0 to +4.5 for $\delta^{18}O$ (Ginsburg, Schroeder, and Shinn, 1971; Ginsburg and James, 1973a, b; Goreau and Land, 1974).

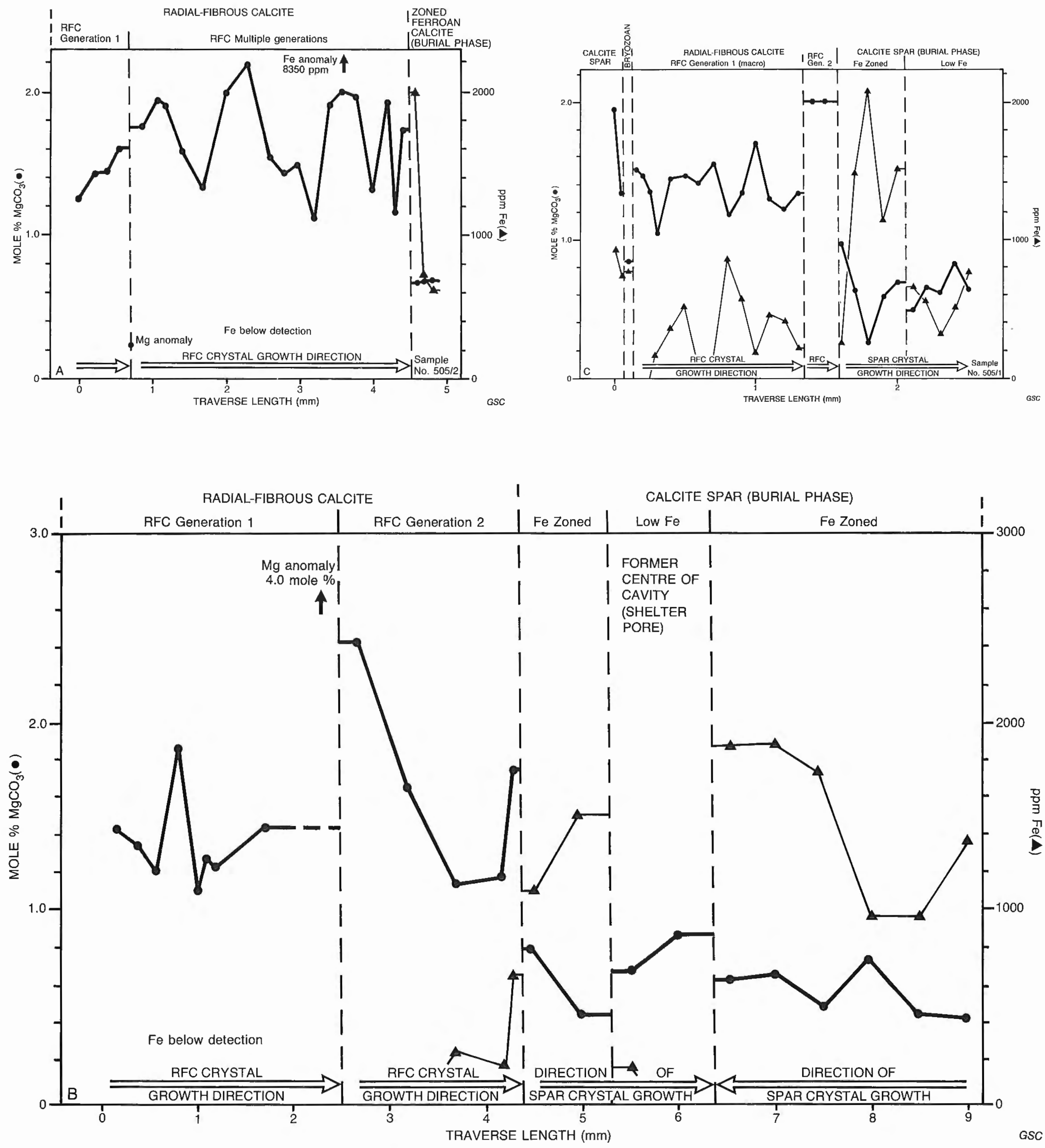


Figure 20 (A-H). Microprobe traverses for Mg and Fe across radial-fibrous calcite (RFC) and overlying post-burial zoned ferroan calcite and later-burial non-ferroan calcite spar. Some of the traverses also include spot readings on skeletal calcite. The data emphasize the relatively high residual Mg (as mole % $MgCO_3$) in the RFC, stepwise increase in Mg outward through each generation of RFC, and below-detection Fe in RFC. In contrast, zoned ferroan calcite shows high but variable Fe and low Mg, with postburial calcite spar cement low in both elements. To avoid excessive "sawtooth" profiles, values have been correlated to fabric boundaries in the polished sections.

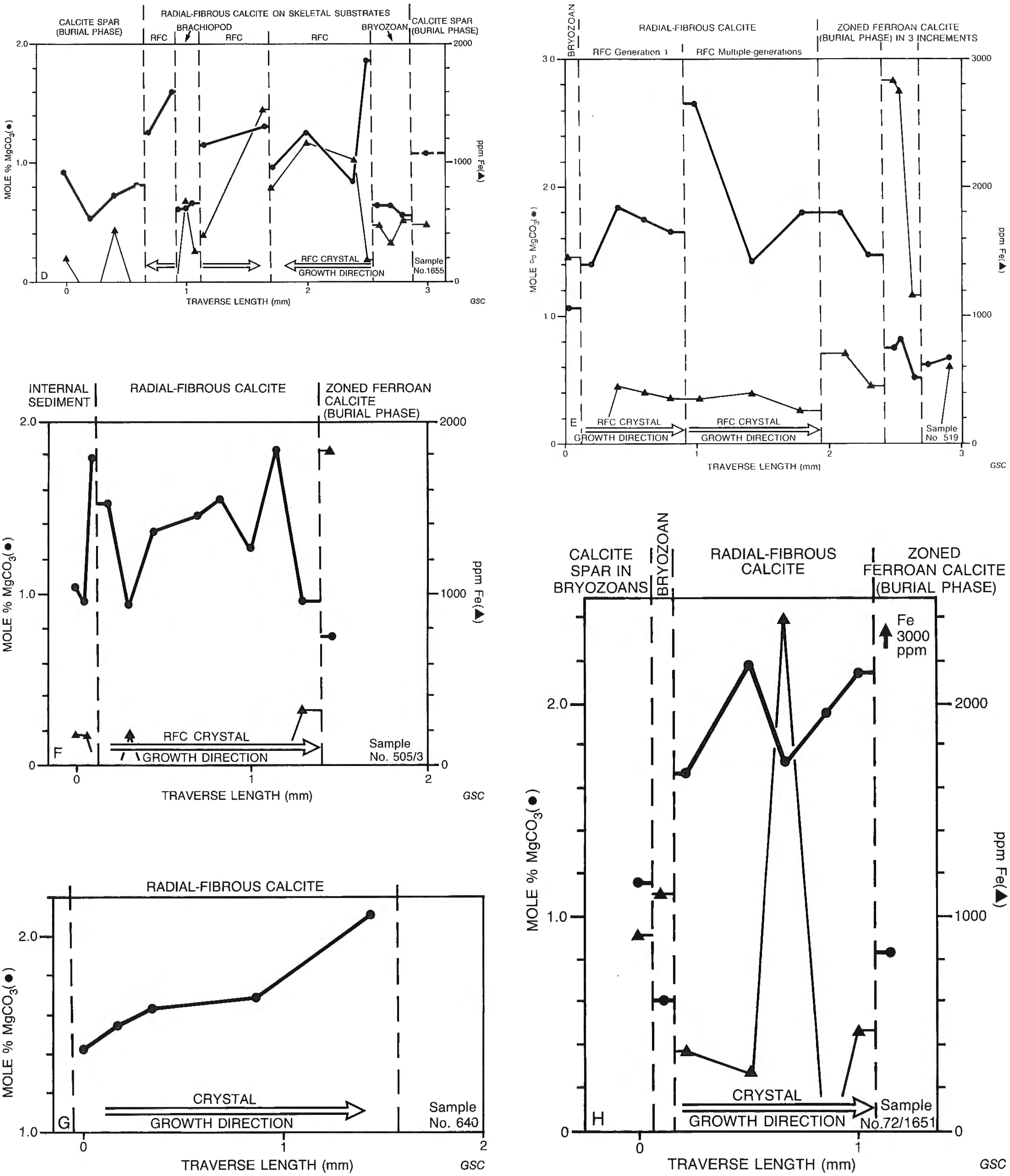


Figure 20. Continued

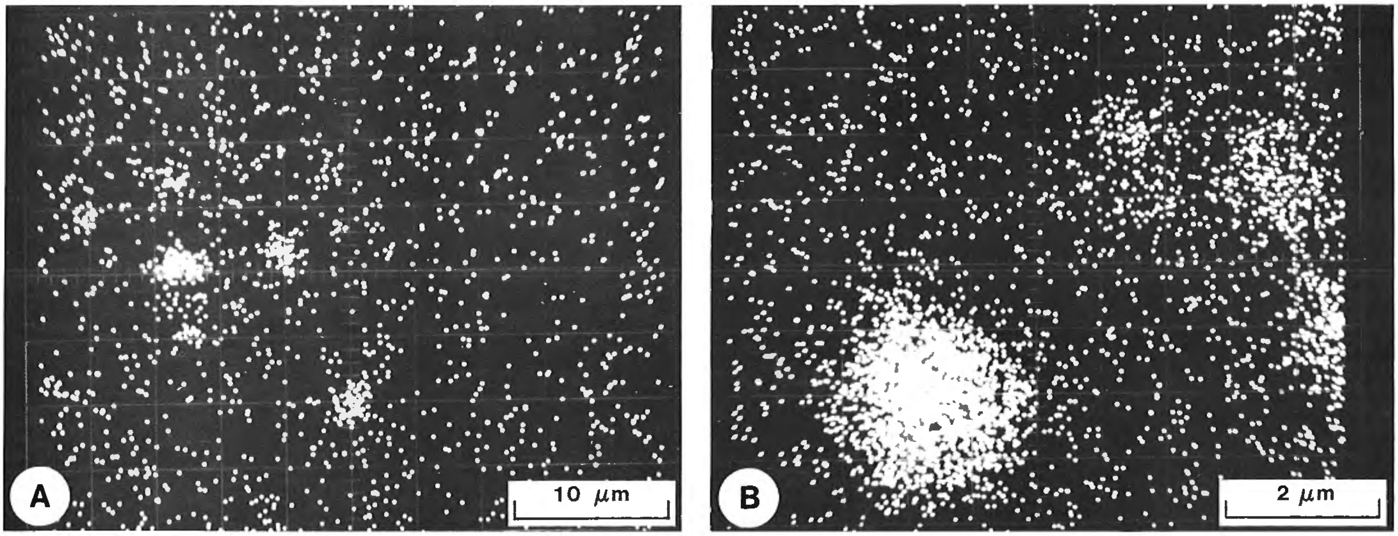


Figure 21. Microprobe electron beam scan photographs of radial-fibrous calcite (RFC) scanned for Mg.

A. *Scan showing scattered domains of Mg concentration interpreted as dolomite microcrystals exsolved from the original high-magnesium calcite precursor of RFC.*

B. *Detail of crudely rhombic Mg domain, suggestive of dolomite microcrystals.*

However, the degree of enrichment in the heavy carbon isotope in the Arctic Paleozoic cements is higher than might be expected for normal marine isotopic composition; a possible mechanism is presented by Beauchamp et al. (1987).

RFC and micritic calcite as fracture-lining cements

Several types of fracture systems are found in the Arctic carbonate units. Many fractures clearly are of late diagenetic origin; they truncate all other fabrics, and are filled with sparry calcite. Other fractures particularly characteristic of the Waulsortian buildups are lined by multiple generations of RFC and BAC cement, and are filled with carbonate sediment of either contemporaneous marine origin or derived from the overlying and enclosing Hare Fiord Formation. The most spectacular of these latter fractures, and the best for documentation of cement paragenesis, are found in the Waulsortian reefs (Fig. 23); similar synsedimentary fracture systems in Waulsortian buildups are found elsewhere (Pray, 1965; Cotter, 1966; Philcox, 1971; and others).

Fractures in the Waulsortian reefs vary in width from a few centimetres to several metres. Their vertical dimensions are variable; some are traceable for tens of metres. The sediment fill commonly is partly or totally dolomitized, silty, crinoidal and bioclastic packstone (Fig. 23B) and, less commonly, red peloidal wackestone. Sediments of the former type are found in, and are characteristic of, the enclosing and overlying Hare Fiord Formation (but not underlying units; compare with Pray, 1965). These relationships prove that the fractures and the cements that line their walls predate burial of the mound.

The walls of the fractures are lined by multiple generations of light and dark grey banded RFC and micritic cement (Figs. 24, 25). Total thickness of cement layers normally is a few centimetres, but may reach 15 cm or more. Walls of sediment-filled fractures truncate primary marine sediment, bryozoan zoaria, other bioclasts, and one or more generations of RFC cement nucleated on the bryozoans and sediment (Figs. 23A, 25A, 26). However, at the time of fracture formation, cement-lined cavernous and shelter pore systems within the reefs were still open, so that lateral apophyses or cavity systems opened from the sides of the fractures (Figs. 23A, 26). Consequently, the earliest generations of fracture-wall RFC and micritic cement may be traced into the lateral cavities (Fig. 26). In several examples, the *first generation* of fracture-lining micritic and RFC cement may be traced directly into and shown to be synchronous with the *second generation* of RFC cement within the laterally interconnected primary reef cavity system, where the latter conformably overlies the first generation of RFC within the reef cavity system (Fig. 26). Such a relationship clearly establishes the synchroneity of cementation by RFC (or, strictly, its HMC precursor), the formation of fractures, and cementation within the fractures. Further, it confirms that the primary RFC, the fracture itself, and the fracture-lining cement were all products of the same environment. Related fabrics (Fig. 27) show similar

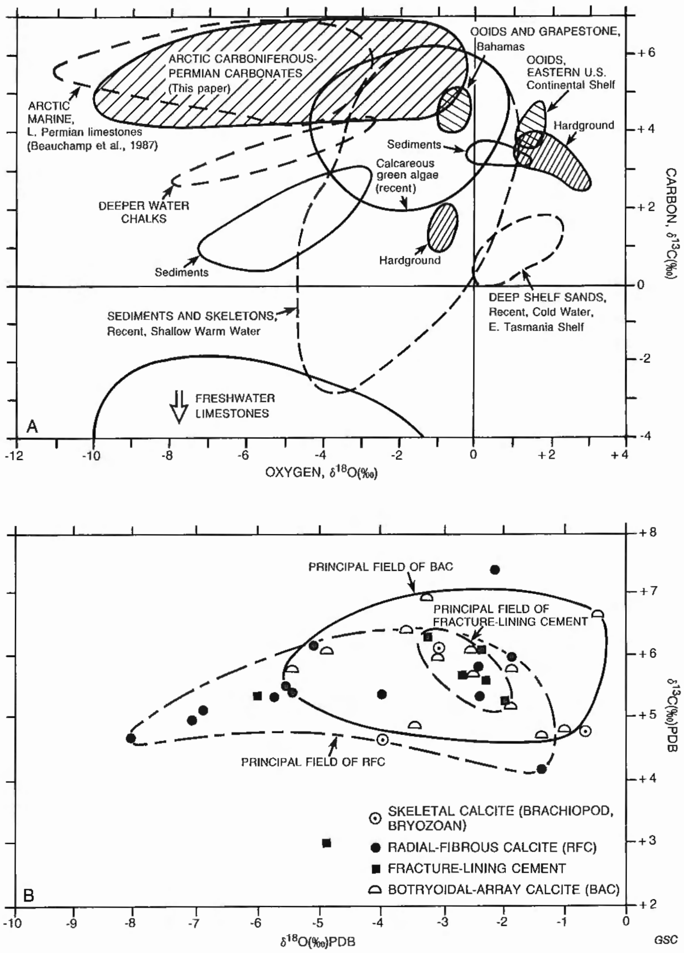


Figure 22. Oxygen and carbon isotope data from Carboniferous and Permian carbonates, northwestern Ellesmere Island.

A. Crossplot of carbon and oxygen isotope compositions for recent sediments and other carbonate phases, with general field of Arctic Carboniferous-Permian samples (this report) superimposed. Comparison of the data provides strong evidence of a marine origin for the Arctic carbonates. These carbonates are more strongly enriched in the heavy isotope of carbon than most other carbonates; Beauchamp et al. (1987) provided an oceanic stagnation/thermoholine stratification explanation for this phenomenon. (After Milliman, 1974, and James and Choquette, 1983.)

B. Detail of carbon and oxygen isotope signatures of RFC, botryoidal array calcite (BAC), zoned ferroan calcite (RFC), and associated carbonate phases, from the Arctic upper Paleozoic sample suite.

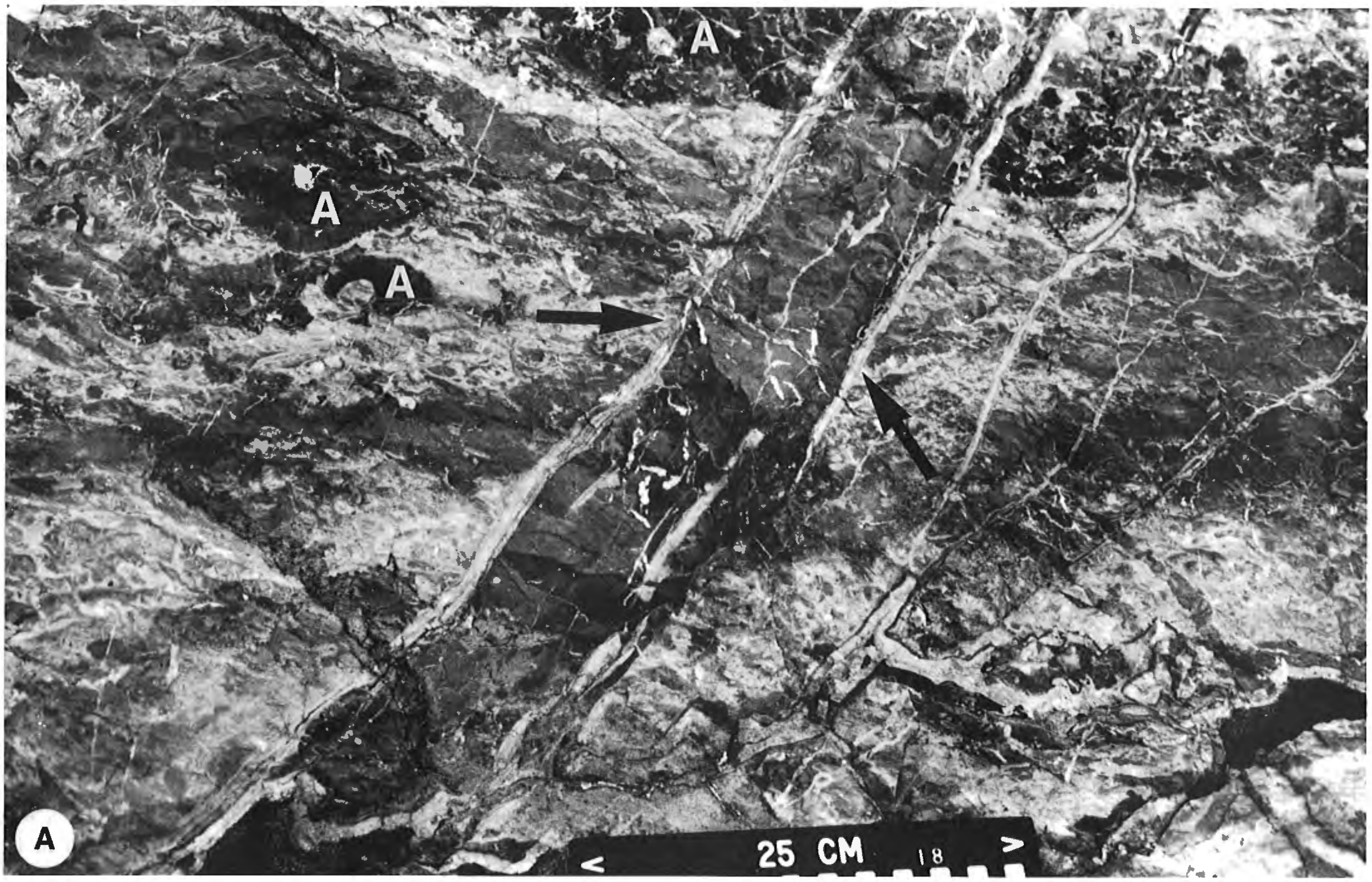
relationships between the RFC in primary reef cavities and that in fractures.

Thin sections reveal that the banding in fracture wall cement results from two types of fabric. In one, more common in thinner fractures with cement rims 1 to 2 cm thick, the banding results from alternations of dark coloured micritic cement with thicker layers of RFC (Figs. 25A, 26). The micritic cement normally is the first generation, closest to the fracture wall; it reappears at the base of the next layer of RFC and in successive generations, commonly displaying an apparently corroded contact with the underlying RFC substrate.

The micrite cement is organized into an irregular yet crudely systematic "knobby" or microcolumnar fabric (Fig. 25A); projections are spaced 0.5 to 1 mm apart. Unidentified unicellular encrusting organisms (Fig. 25B) are scattered through the micrite cement, along with indistinct peloidal grains or clots of dense micrite. More rarely, the marine encrusting organism *Tuberitina* is found on and within these early cement layers. The overall impression of the micrite cement microstructure is suggestive of a non-skeletal, organic/biological (cyanobacterial?) origin, yet there is no incontrovertible support for this interpretation. A possible recent analogue is the "microstromatolitic", Mg-calcite, pelleted-micrite cement of submarine origin in the reefs of Jamaica (Land and Goreau, 1970, Fig. 6).

Microcolumnar micritic cements pass gradationally outward into thicker layers of RFC cement (Fig. 25A). The transition is marked by multiple generations of micritic cement that become thinner and more widely dispersed outward (toward the fracture cavity), as they are separated by progressively thicker but irregular layers of RFC, finally grading into the main RFC layer. This entire cycle is repeated several or many times through the entire fracture-wall cement layer. An individual fracture-cement couplet thus may be defined as composed of a basal microcolumnar micrite cement layer with an abrupt basal contact, grading outward, through a mixed micrite-fibrous zone, into thick RFC cement. It should be stressed that this RFC apparently is identical in petrographic character and elemental and isotopic composition to RFC in the primary reef pore system.

In a few samples taken at the boundary between fracture-lining cements and marine peloidal sedimentary fill (not dolomitized crinoidal sediment fill), pulses of internal sedimentation within the fracture cavity are found to alternate with layers of micritic and/or RFC cement (Fig. 24B). Micritic cement layers between generations of RFC cement in the fracture wall lining may be traced directly into, and thus are correlative with, the layers of marine internal sediment. Thus, for the fracture-lining cement couplet described earlier, the abrupt termination of an earlier RFC cement layer by a micrite cement layer containing



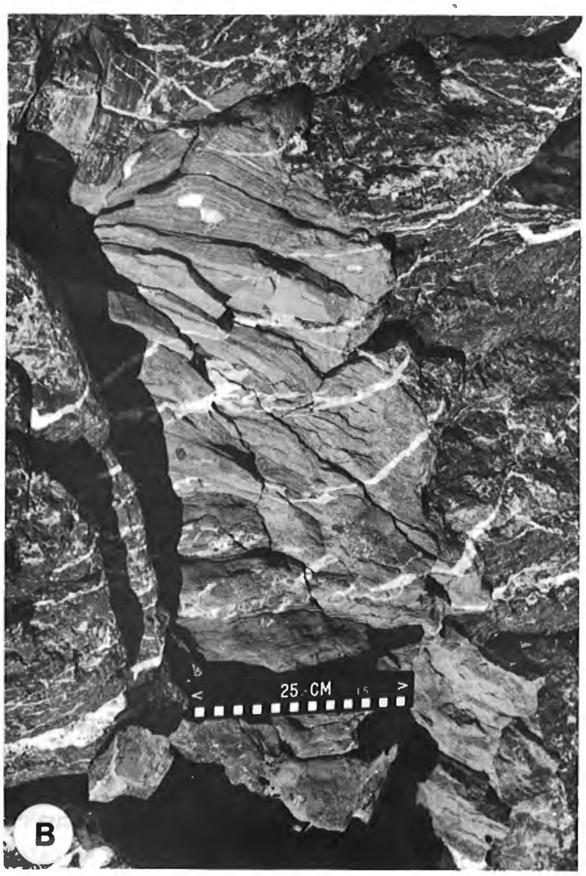


Figure 23. Sediment-filled submarine fractures in Upper Carboniferous Waulsortian-type reefs, northwestern Ellesmere Island.

A. Large submarine fracture rimmed by multiple generations of fracture-lining radial-fibrous calcite (RFC) cements, and infilled by marine peloidal sediment. The core of the reef was cemented by one or several generations of white RFC submarine cement before fracturing. The fracture-lining RFC generations are continuous with RFC cements in primary reef cavities truncated by the fracture (arrows), and become indistinguishable from the generations of cement away from the fracture. Darker-coloured masses of botryoidal-array and radial-array calcite (after aragonite) are present in primary reef cavities (A), and developed preferentially on the roofs of the cavities. Blue Mountains reef.

B. Submarine fracture infilled by dolomitized crinoidal wackestone to packstone, heralding the onset of burial by the enclosing Hare Fiord Formation. The rock mass is cut by tensional fractures infilled by white calcite, probably related to Late Cretaceous or Tertiary thrust faulting and folding. Wood Glacier reef.

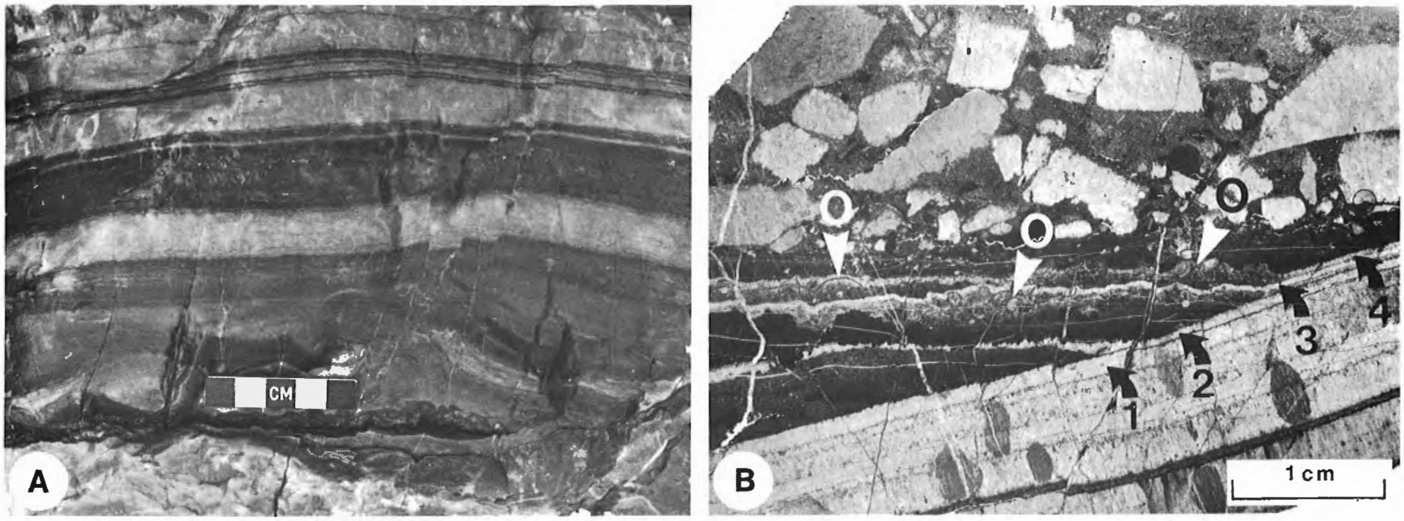


Figure 24. *Submarine fracture fabrics, Waulsortian-type reefs, northwestern Ellesmere Island.*

A. Massive-banded calcite cement at least 15 cm thick, lining a large cavern filled by oncoids, ooids and coated bioclasts (mainly gastropods and pelecypods). This fracture-lining cement is at least superficially the same fabric as submarine fracture-lining cement, but, given its thickness, a possible vadose flowstone origin cannot be totally discounted. Wood Glacier reef.

B. Multiple generations of marine internal sediment interlayered with generations of RFC fracture-lining cement (1-4). The coelobite community within the submarine fracture cavity is recorded by ostracode valves (O) in the internal sediment. The upper generation of sediment contains angular fragments of RFC cements, suggesting another phase of fracturing.

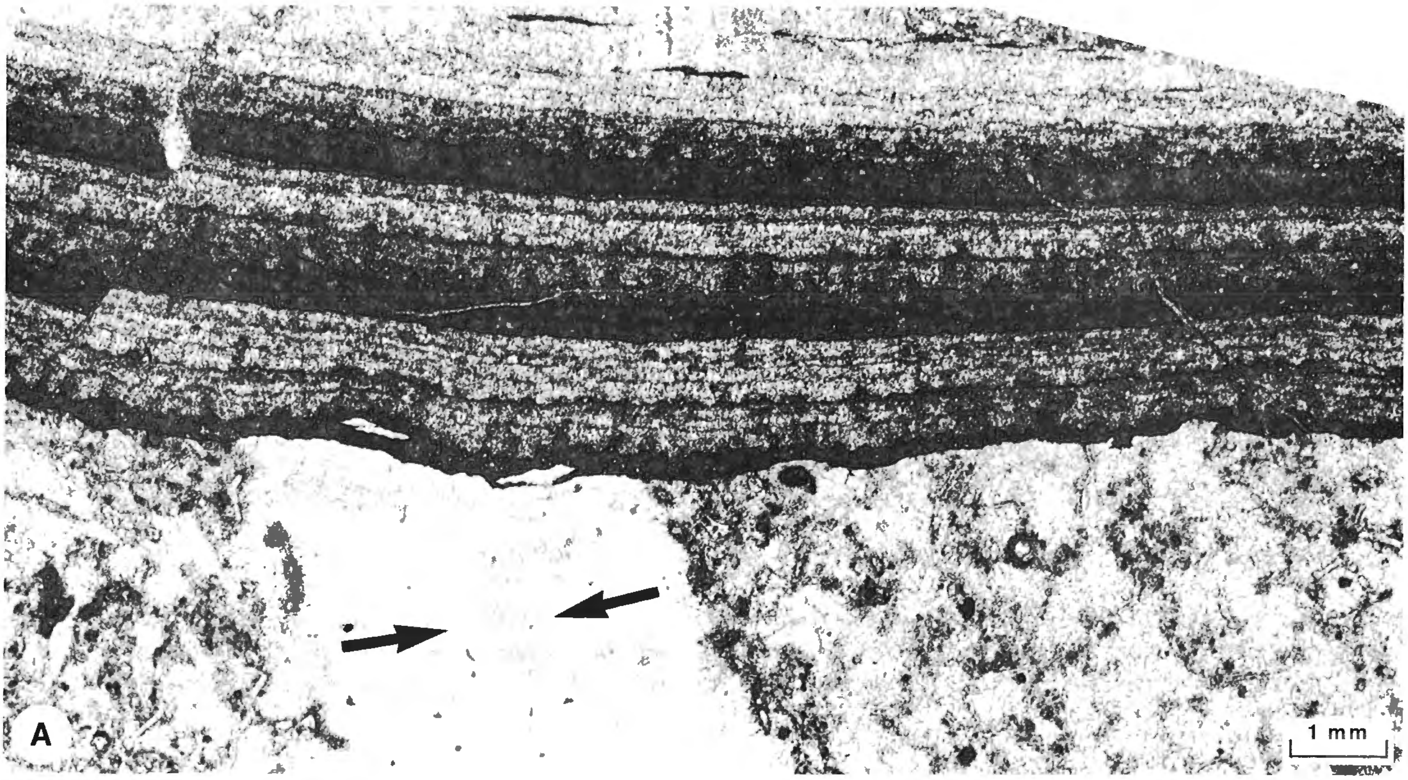
poorly defined peloidal grains may represent abrupt influx of sediment into the fracture cavity. Where alternation or interfingering of fracture-wall cement and fracture-fill sediment is found, the sediment is a peloidal wackestone containing fragments of submarine cement, many ostracodes (Fig. 24B), and a few crinoid ossicles; this type of marine sediment predates the dolomitized crinoidal sediment derived from the overlying Hare Fiord Formation, which infills many of the larger fractures and heralds the onset of burial.

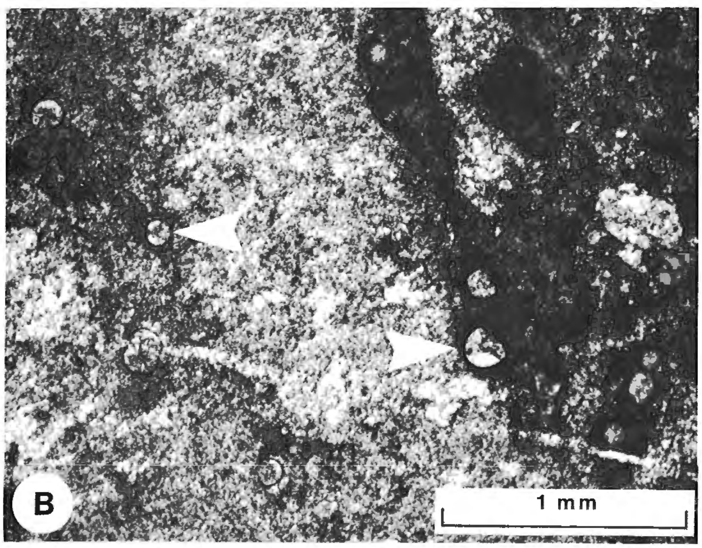
The second major type of banded fracture-lining cement is found in thicker layers of larger fractures, where individual dark and light cement generations are up to one centimetre or so thick. In this type of cement, the lighter layers are composed variously of thin micritic cement, or thicker, cemented, peloidal sediment with scattered ostracode valves and a few tubular foraminiferids; both may be related to a pulse of sediment into the fracture. The darker grey bands are composed of small radiating hemispheroids of radial-array calcite (RAC) or botryoidal-array calcite (BAC) two to three millimetres in radius, contrasting strongly with the more continuous and regular layering of RFC in other types of fracture cement. Further descriptions of RAC and BAC fabrics and composition are presented in a following section.

Composition of micritic and RFC fracture-lining cements

Microprobe and spectroscopic analyses of micritic and RFC fracture-lining cement (but specifically excluding RAC and BAC components) show the following compositional means or trends (Table 1; Fig. 28):

1. A mean of 1.62 ± 0.27 (99% confidence limit) mole per cent $MgCO_3$
2. Mn below detection (<160 ppm)
3. Fe varying from below detection to 1050 ppm, with a mean of about 300 ppm Fe; the highest spot values are in the microcolumnar, micritic cement layers (which may include some detrital sediment)
4. Sr below detection (<300 ppm) by microprobe, but about 250 ppm by atomic absorption spectroscopy for a few samples
5. K below detection (<190 ppm); Cl variable, but with spot values between 200 and 400 ppm; at detection limit (140 ppm) for Na.





A. Multiple generations of RFC fracture-lining cement overlying a truncated fenestellid boundstone host cemented prior to fracturing by one major generation of RFC submarine cement (arrows) plus pervasive matrix cement. Major fracture-lining cement generations are recorded by "couplets", commencing with a basal micritic microcolumnar or "microstromatolitic" layer grading outward into a thicker generation of RFC that is internally a multi-generation cement. The micritic layer is interpreted as being probably organically or cyanobacterially controlled. The cement generations clearly are influenced by some type of rhythmic organic and/or environmental process.

B. Example of unicellar organisms (arrows) encrusting or enclosed in fracture-lining cement. Some of the encrusters resemble the foraminiferid(?) ***Tuberitina****. Compare with Figure 17.*

Figure 25. *Microfabrics of fracture-lining radial-fibrous calcite (RFC) cements, Waulsortian-type reefs, Blue Mountains.*

Isotopic composition of the fracture-lining cements shows the following trends:

1. $\delta^{13}C$ mean of +5.4 ± 1.1‰, within a range of +3.0 to +6.3‰
2. $\delta^{18}O$ mean of -3.3 ± 1.5‰, within a range of -1.8 to -6.0.

Most points of discussion under "Composition of RFC cement" also are relevant for the fracture-lining cement. A comparison of elemental and isotopic data (Table 1) shows that there is no significant difference between the composition of primary-pore RFC and fracture-lining RFC and micritic cements.

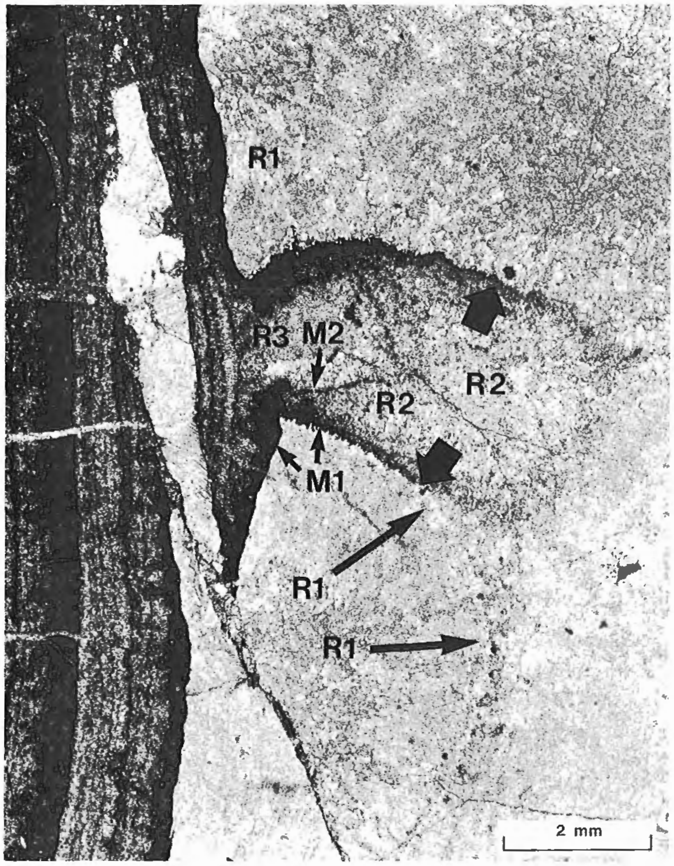


Figure 26. Submarine cement relationships at the intersection of a radial-fibrous calcite (RFC) cement lined primary reef cavity (broad arrows) and a submarine fracture lined by micritic and RFC fracture-lining cements (left). The first major generation of RFC (R1) in the reef host (which may include several internal generations) is truncated at the fracture surface, and is partly rimmed by the micritic, "microcolumnar" basal cement of the first generation of fracture-lining cement (M1). The second major generation of RFC cement in the primary reef cavity (R2) continued to precipitate while the thick micritic layer was forming at the fracture, since a thin micritic layer (M2) caps RFC 2 and is continuous with the outer part of the thick micritic basal layer. RFC generation 3 (R3) in the primary cavity appears to be continuous with the first RFC layer of fracture-lining cement. The fabric is complicated by a tectonic fracture cutting obliquely from lower centre to upper left.

Plots of microprobe data by traverse (Fig. 28) across fracture-lining cements show the following trends or relationships:

1. For each micrite to RFC cement couplet, Mg increases from the base outward, from a mean about 1.3 mole per cent $MgCO_3$ to about 2.0 or higher
2. The lowest Mg and highest Fe spot values are in the micritic cement zone.

The petrographic, elemental and isotopic data indicate a close spatial, temporal, and compositional relationship between fracture-lining RFC cements and RFC in primary reef cavities, providing supporting evidence of a common diagenetic environment. However, in contrast with RFC in internal cavity systems, the fracture-lining RFC cements show a decline in Mg (as $MgCO_3$) from the base outward in each succeeding generation. As the outer cement generations commonly grade into aragonite arrays, this reduction in relict Mg may record changes in the microenvironment/composition of the pore fluid, or possibly changes in crystal growth rate and Mg absorption.

Cavity-filling, botryoidal-array calcite

Some of the most spectacular fabrics in the Arctic Waulsortian reefs and Nansen shelf-edge carbonates are masses of botryoidal-array calcite (BAC) that occupy RFC-lined internal reef and fracture cavities (Figs. 29-31), and cavities within RFC-cemented foreslope breccias (Figs. 32, 33). These masses of calcite are interpreted as neomorphic, after radiating arrays of acicular aragonite of submarine origin. Although small hemispheroids or botryoids, ranging in radius from about 1 to 4 cm, are common, some grew to immense sizes (Fig. 31B). A glacial erratic of BAC observed in a moraine on Hare Glacier, below cliffs of the Nansen Formation, contained radial masses measuring 22 cm along the radius of the botryoidal fabric; both the base and the top of the array were missing, indicating that the original concentric mass was even larger.

Analogues for the precursor of botryoidal calcite are found in modern reefs. Ginsburg and James (1973a, b) found botryoidal masses of aragonite in submarine cavities at depth in the British Honduras Barrier Reef. Schroeder (1972) recognized microscale, aragonitic, spherulitic cements in the modern reefs of Bermuda. Aissaoui (1985) has documented other examples of marine botryoidal aragonite.

BAC is found in primary reef cavities lined by RFC, in fracture cavities in the Waulsortian buildups, and in larger shelter cavities in shelf foreslope breccia (debris) beds (Figs. 32, 33). In all of these settings, it appears that the primary acicular aragonite mass grew in free space, and commonly but not exclusively from the roof or walls of the cavity. In fractures, the botryoidal masses may be partly enclosed by marine internal sediment, and may replace some of the sediment.

As noted at the end of the preceding section on fracture-lining RFC cements, thicker and more clearly banded

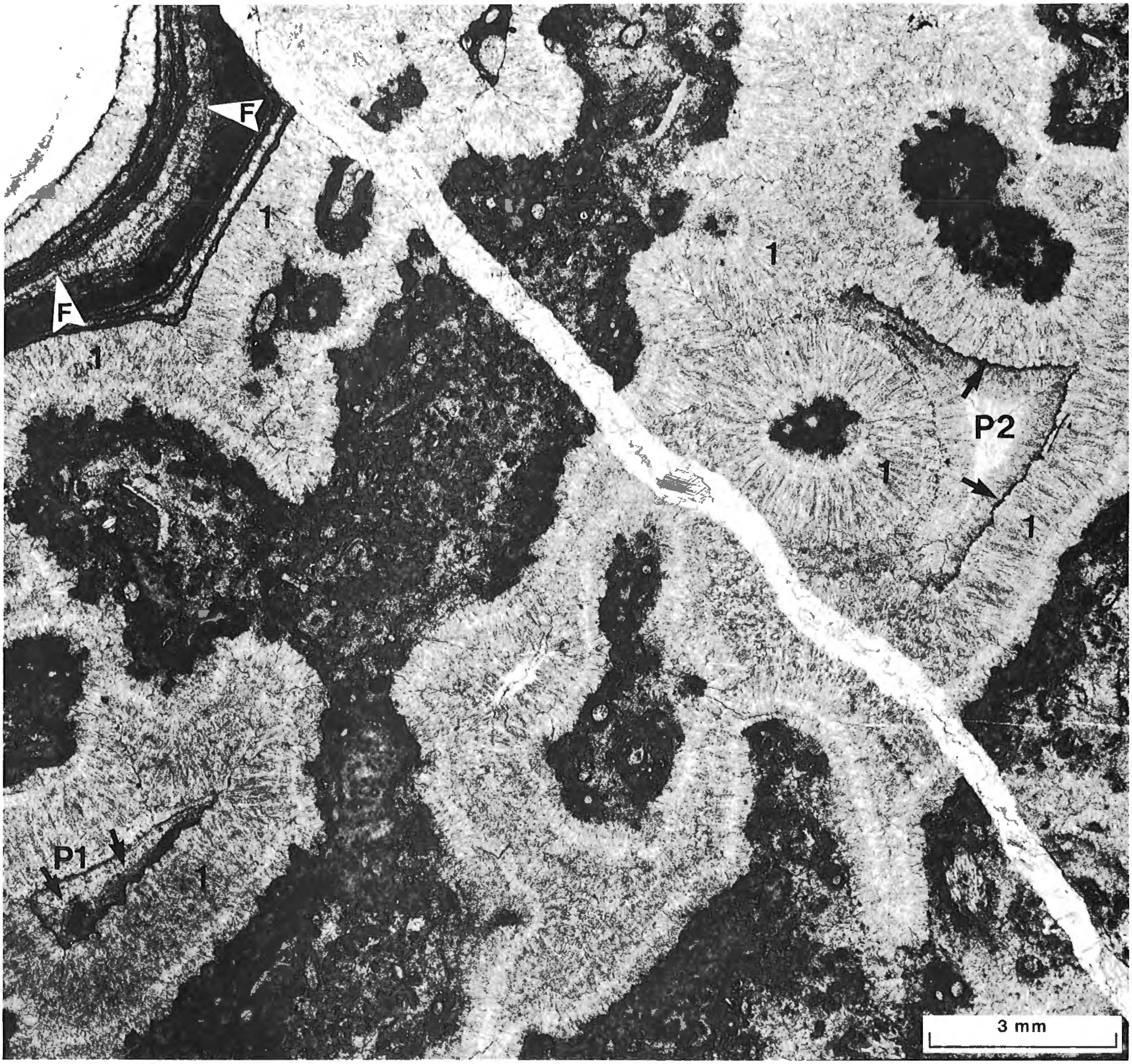


Figure 27. Fabric relationship between submarine fracture cement and cements in internal reef cavities. Fracture-lining cement at upper left (F) overlies the first major generation of RFC cement (1) in the reef host, and is represented in a proximal cement-lined pore by internal peloidal sediment (P1) and indistinct RFC cement, and by a micritic rim followed by well developed second-generation RFC in a more distal pore (P2). Submarine fracturing thus occurred after precipitation of the first major generation of RFC in the reef host, but before the second generation. The fabric is cut diagonally by a tensional microfracture infilled by post-burial calcite spar. Blue Mountains reef.

fracture-lining cements may be composed of interlayers of RFC and small hemispheroids of BAC. The latter fabrics, only a few millimetres thick in the first few layers, appear to have formed partly by replacement (after the micritic layers of the fracture-lining cement), but mainly as space-filling hemispheroids lining the fracture (Fig. 34A, B). The outermost layer of cement, lining the fracture cavity, may be preserved as a layer of normal RFC cement (Fig. 34A). Alternatively, the radiating fans of BAC may increase dramatically in size toward the fracture centre, partly draped

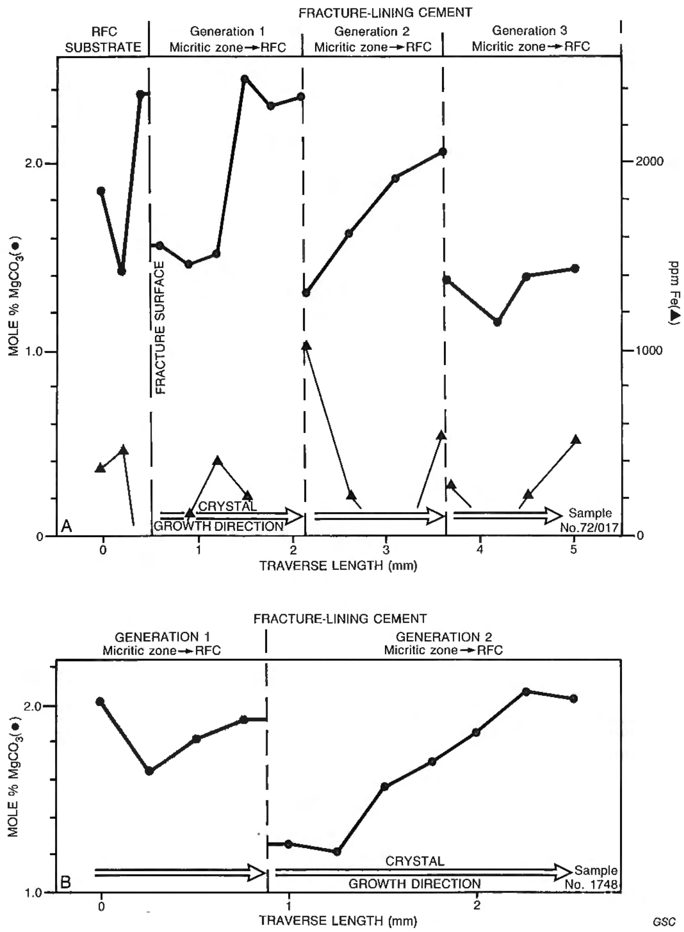


Figure 28. *Microprobe traverse across fracture-lining micritic and RFC cements. Waulsortian-type reefs, Blue Mountains.*

A. Traverse for Mg and Fe. Each generation of cement shows a trend of outward increasing Mg with one traverse indicating an overall decrease in Mg from the first to the last (outer) generation of fracture-lining cement. The relatively high Mg values support the interpretation of a high-magnesium calcite precursor for the fracture cement.

B. Traverse for Mg, showing similar stepwise increase across each cement generation.

over by, or displacing, layers of peloidal marine internal sediment and RFC cement, but eventually interconnecting to form spectacular masses of BAC up to tens of centimetres in radius (Figs. 29, 35).

These larger botryoidal masses grew within the fracture cavity system, but may also have replaced some cavity-fill sediment. Significantly, their smaller predecessors within the fracture-lining cement (Fig. 34) were clearly part of the fracture-cementing process, and thus of submarine origin.

Thin sections of cavity-filling BAC (Figs. 33-35) reveal that the neomorphic calcite fabric is composed of irregular crystals elongated parallel to the original radial acicular fabric. The crystals are brown in transmitted light, and contain many micro-inclusions. Frequently, this fabric is replaced by patches of clearer, more equant crystals of sparry calcite. In thin sections of the largest botryoidal masses, a more distinctly elongate calcite fabric is seen to have been preserved, with concentric growth increments of the original fabric marked by lines of inclusions or sub-crystals.

Argument against purely open-space precipitation of the precursor aragonite is supported by evidence of the partial replacement of rims of earlier RFC, and of marine internal sediment layers, between coalescing masses of BAC. At these partly replacive contacts, "feathery" terminations, pseudomorphic after acicular aragonite crystals, are preserved. This evidence of at least local replacement growth emphasizes the close interconnection between the cavity-filling BAC and replacive RAC fabrics described in the following section.

The original cavity-filling botryoidal aragonite was replaced preferentially by calcite spar, commonly with some associated dolomite. Replacement of this type is documented best for replacive RAC fabrics, and is treated more fully in the following section. As petrographic and isotopic data also are very similar for the two types of fabric, there is little doubt that BAC and RAC represent two intergradational end members — one free-forming (BAC), and the other replacive (RAC) — of a spectrum of growth forms of submarine aragonite, developed under similar geochemical conditions and probably more or less synchronously.

Botryoidal aragonite fabrics and their calcitized replacements also have been recorded in the Permian reef complex of west Texas, the Waulsortian buildups in New Mexico, and elsewhere (Mazzullo and Cys, 1977, 1979; Mazzullo, 1980; Sandberg, 1985: the last paper provides a comprehensive review of aragonite cements and fabrics in ancient limestones).

Composition of cavity-filling, botryoidal-array calcite

Compositional analyses of cavity-filling BAC have been limited to a few samples. The data (Table 1; Fig. 22) reveal that:

1. In the centre of very large masses (least "altered") of cavity-filling BAC, Mg is below the detection limit by microprobe

2. In the same samples, microprobe analyses give a mean for Sr of 7480 ± 1240 ppm, with a maximum spot value

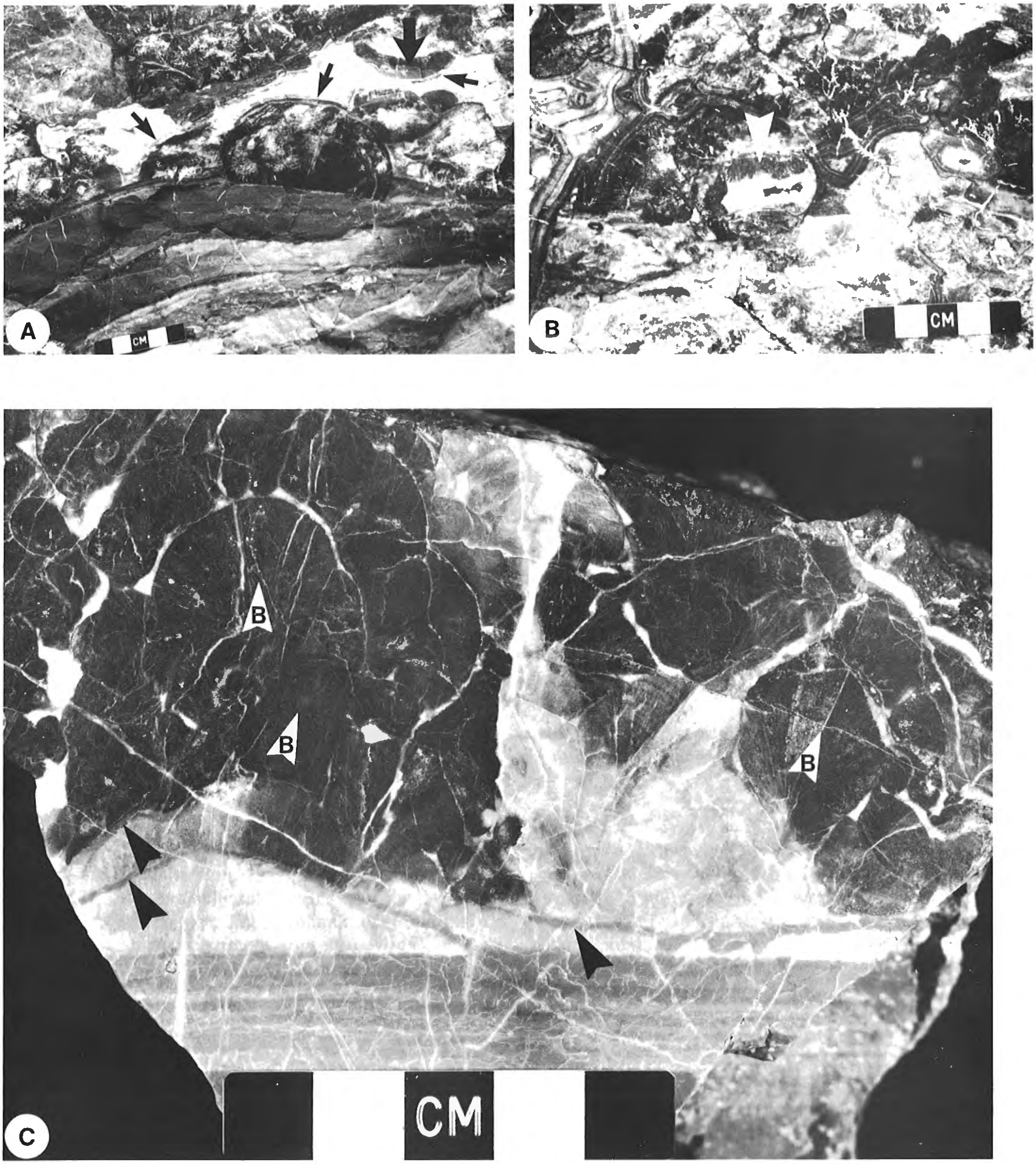

A
CM
B
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Figure 29. Examples of botryoidal-array calcite (BAC) after submarine aragonite, northwestern Ellesmere Island.

A. Dark-coloured BAC hemispheres up to 10 cm in diameter in a fracture cavity partly filled by fracture-lining cement and internal sediment (base), and by post-burial calcite spar (white). One of the botryoids is pendant from the roof of the fracture (large arrow). All of the BAC masses are overlain by, and thus postdated by, a rim of RFC submarine cement (small arrows). Upper Carboniferous to Lower Permian Nansen Formation, east Girty Creek, northwestern Ellesmere Island.

B. Dark-coloured BAC (arrow) pendant from the roof of a primary cement-lined reef cavity, adjacent to a submarine fracture (Fig. 23A, upper right) and rimmed by banded fracture-lining cement (upper right). Waulsortian-type reef, Blue Mountains.

C. Spectacular arrays of light and dark coloured BAC (B) gradational outward into a fracture cavity, and overlying and intergrown with layers of marine peloidal and foraminiferal internal sediment (arrows) deposited within the fracture cavity.

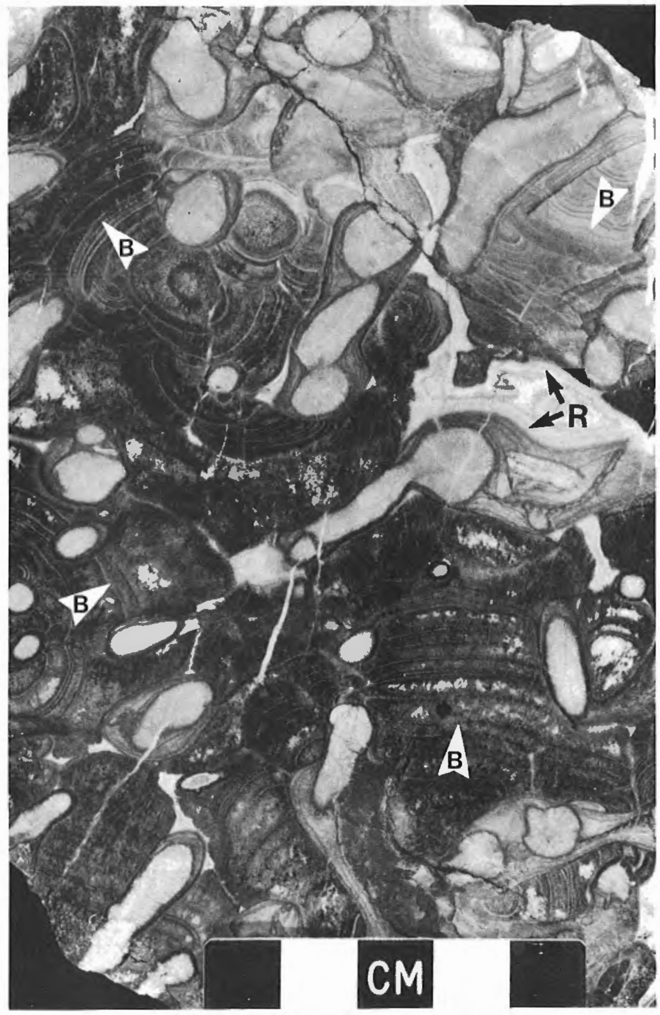


Figure 30. Multilayered, concentric, botryoidal-array calcite (BAC) cement (B) in a ramose bryozoan boundstone recovered as float on Hare Fiord Glacier below massive exposures of the Nansen Formation, and probably of Lower or Upper Permian age by analogy with ramose bryozoan faunas elsewhere on Ellesmere Island. The former aragonite fabrics are postdated by RFC cements (R).

of 10 700 ppm Sr. Two analyses for Sr by AAS gave values of 8300 and 7800 ± 50 ppm in the same type of massive BAC (X-ray diffraction analysis confirms a calcite rather than aragonite composition). A smaller hemisphere of BAC from a fracture cavity had a Sr value of 1100 ± 50 ppm by AAS

3. $\delta^{13}C$ mean of 5.7 ± 0.8‰, within a range of +4.5 to 6.9

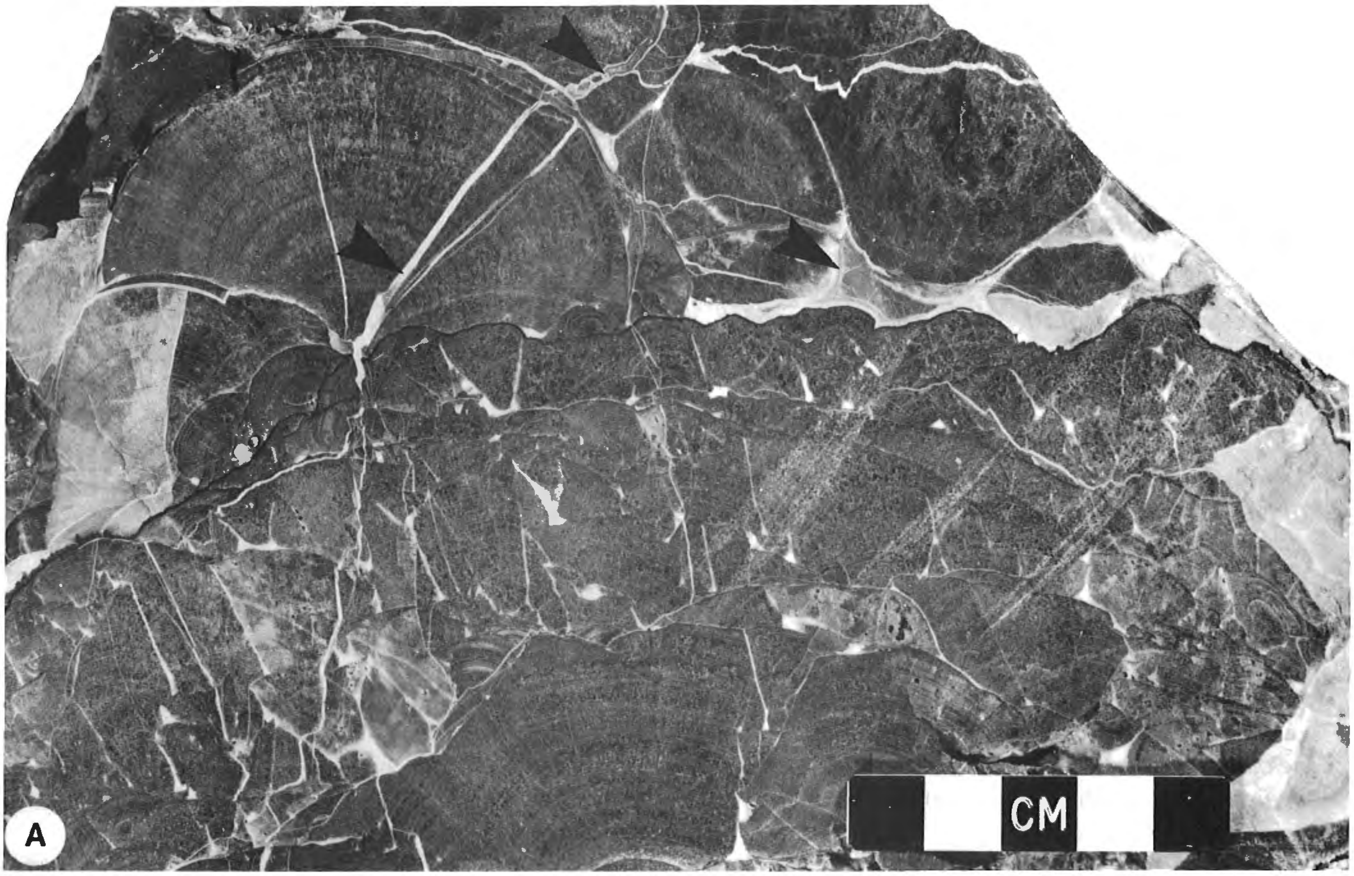
4. $\delta^{18}O$ mean of -2.8 ± 1.5‰, within a range of -0.5 to -5.5.

The very high Sr values (mean 7500 to 8000 ppm) in the massive BAC are of the same magnitude as Sr in modern, marine, organic and inorganic aragonite (Kinsman, 1969). Preservation of Sr in calcite at this level suggests that neomorphic replacement of aragonite by calcite took place in a more or less "closed" microsystem (Kinsman op. cit., p. 500). The samples with high Sr values were selected deliberately from within the centres of large masses exceeding 20 cm in thickness; apparently within such a homogenous mass, there was little or no loss of Sr from the diagenetic microsystem, so that it became incorporated in the calcite, although not necessarily all by substitution. X-ray diffractograms show no remnant aragonite or recognizable strontium carbonate phase in these samples, nor does microprobe analysis (microscan) reveal any discrete strontium mineral phases (at least in a size greater than a few microns). The lack of detectable Mg provides additional evidence in favour of an aragonite precursor and "closed-system" neomorphism, without the introduction of Mg during replacement.

The isotope data, derived from 6 samples, show that BAC is nearly identical in isotopic composition to RFC (Table 1; Fig. 22).

Replacive radial-array calcite

Replacive radial-array calcite (RAC) is a neomorphic calcite fabric pseudomorphic after radiating fans of acicular



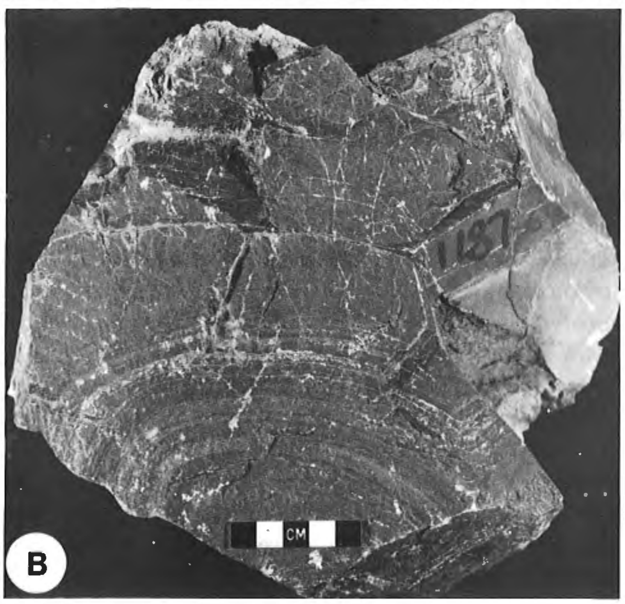


Figure 31. Botryoidal-array calcite (BAC) after aragonite, recovered as float from Hare Fiord Glacier below massive exposures of the Nansen Formation.

A. Hemispherical botryoids of BAC lined and cut by fractures cemented by RFC cement (arrows). Patches of marine peloidal sediment also occur within the fabric.

B. Part of a very large mass of BAC, apparently of similar origin to (A).

crystals of aragonite that grew mainly or totally by replacement within the original carbonate sediment host. It is intergradational with BAC.

Growth of the original acicular aragonite probably was genetically and temporally related to the growth of cavity-filling botryoidal aragonite (BAC). Replacive RAC fabrics are most common in the algal mounds and some bedded carbonate units within the Otto Fiord Formation, and in the lower one hundred metres or so of the Waulsortian reefs (Figs. 36-39) where they overlie the Otto Fiord Formation. They also are found in *Tubiphytes*, bryozoan and algal framestones in the Nansen Formation (Fig. 40), and in Nansen shelf foreslope units.

Replacive RAC, like BAC, appears in outcrops and on rock slabs as black, radiating, fan-shaped to subspherical masses of calcite (Fig. 36). In thin sections (Figs. 37, 38), the radiating and laterally interpenetrating fans are transparent brown, due to abundant micro-inclusions in the calcite crystals. Individual fans are up to 3 cm in radius; they generally radiate from a point source (Fig. 38).

The original acicular crystals have been replaced by neomorphic calcite spar, individual crystals of which normally are elongate (up to several millimetres in length), and parallel to the precursor acicular fabric; the micro-inclusions in the sparry calcite apparently were inherited from the acicular precursor. The terminations of the acicular fans are feather-edged (Fig. 38), commonly with minute scalenohedral overgrowths of less inclusion-rich calcite at the end of each original acicular crystal; this feather-edge, although modified by the neomorphic overgrowth, suggests an aragonite precursor (Folk and Assereto, 1974). More rarely, blunt pinacoidal terminations, apparently pseudomorphing original "square"-ended aragonite crystals, are preserved (Fig. 39). Growth increments in RAC, if present, are recorded by concentric lines or surfaces spaced one millimetre or so apart. Other aspects of the neomorphic fabrics in RAC (and in BAC) are similar to those described by Sandberg (1985) for ancient aragonite cements.

The replacive nature of the aragonite precursor of RAC is shown by the truncation of primary sediment fabrics, the incorporation of unreplaced bioclasts and sediment pockets within the RAC fans, and the truncation and replacement of RFC cements (Figs. 37, 38, 40). Replacive fabrics do not intersect later diagenetic ferroan or sparry calcite crystals. As a general rule, the acicular fans do not replace the primary calcitic skeletons of bryozoan zoaria, fusulinids and other calcitic bioclasts, although there are a number of exceptions (Fig. 40). Zoarial segments of fenestellid bryozoans commonly are found totally enclosed within RAC fabrics, or forming a "shadow" fabric with fan growth terminated against one side but continuing past on both flanks (Fig. 38); a wedge shaped pocket of unreplaced primary sediment or cement thus is preserved in the "shadow" of the bryozoan on the distal side of the aragonite (RAC) fan.

Although the criteria listed here for undoubted replacive growth of RAC fabrics are valid for most samples, there are anomalies. Commonly, the curved terminal boundary of a former acicular fan will correspond with the base of a thick layer of RFC cement lining a primary reef cavity. This type of relationship is equivocal; did the RFC precursor cement precipitate on the aragonite fan fabric, and thus postdate it, or did the base of the RFC layer represent a natural boundary and limit for aragonite replacement? As there are many examples of replacement of RFC by RAC (Figs. 37, 38, 40), the latter certainly postdates some of the RFC cements; however, the converse also is demonstrable in these rocks, thus confirming the early diagenetic nature of the replacive aragonite fabric and the overall synchroneity of both high-magnesium calcite (now RFC) and aragonite (now RAC/BAC) fabrics.

Further indication of the original aragonitic composition of RAC (and BAC) is the evidence of a solution-moldic stage during replacement by calcite (Fig. 41). Commonly, larger arrays of both RAC and BAC contain remnants of former solution voids, many oriented parallel to concentric growth layers of the original aragonite. These voids have been infilled at a later stage by coarse, subequant calcite spar (burial stage), commonly with scattered crystals of zoned dolomite.

Shinn (1969) illustrated an example of modern, replacive, spherulitic or radiating aragonite fabric from the Persian Gulf, in which the aragonite crystals partly replace skeletal grains in an indurated sub-bottom sediment layer. Essentially indentical fabrics have been described from the Permian reef complex of west Texas and Permian algal mounds in New Mexico by Mazzullo and Cys (1977, 1979); similar fabrics also occur in uppermost Permian reefs of China (Fan, pers. comm., 1988).

Composition of replacive radial-array calcite

The following compositional means and trends have been determined from a small number of samples of replacive RAC (Table 1; Fig. 42):

1. A mean of 1.62 ± 0.21 mole per cent $MgCO_3$
2. Fe very irregular in distribution, with a mean about 300 ppm and spot values up to 750 ppm
3. No Sr, Mn, Na, K, or Cl analyses (see composition of cavity-filling botryoidal calcite for Sr in similar fabrics)
4. $\delta^{13}C$ mean of +5.8 ± 0.7‰ within a range of 4.8 to 6.6
5. $\delta^{18}O$ mean of -2.5 ± 1.1‰ within a range of -1.0 to -4.9.

The mean and the spread of Mg spot values in the RAC essentially are the same as for RFC. The level of Mg contrasts with the negligible Mg (below detection) in massive BAC, yet petrographically they appear to have had the same precursor aragonite mineralogy. The higher Mg in the replacive RAC fabric may have been inherited from Mg-bearing primary sediment and RFC during replacement, and from micro-inclusions of unreplaced material.

Microprobe traverses of RAC (Fig. 42) that parallel the original fabric from centre to margin of original aragonite

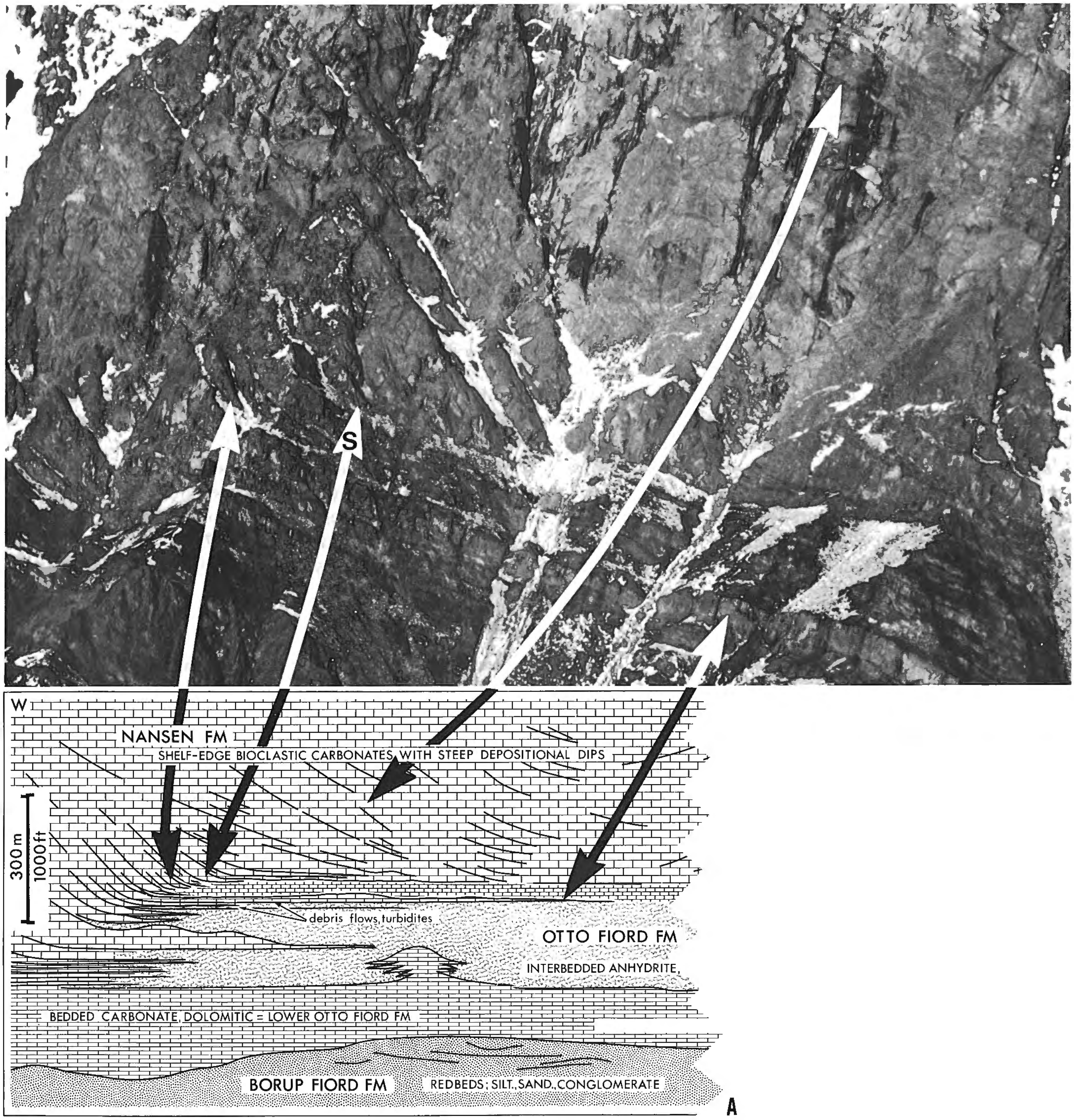
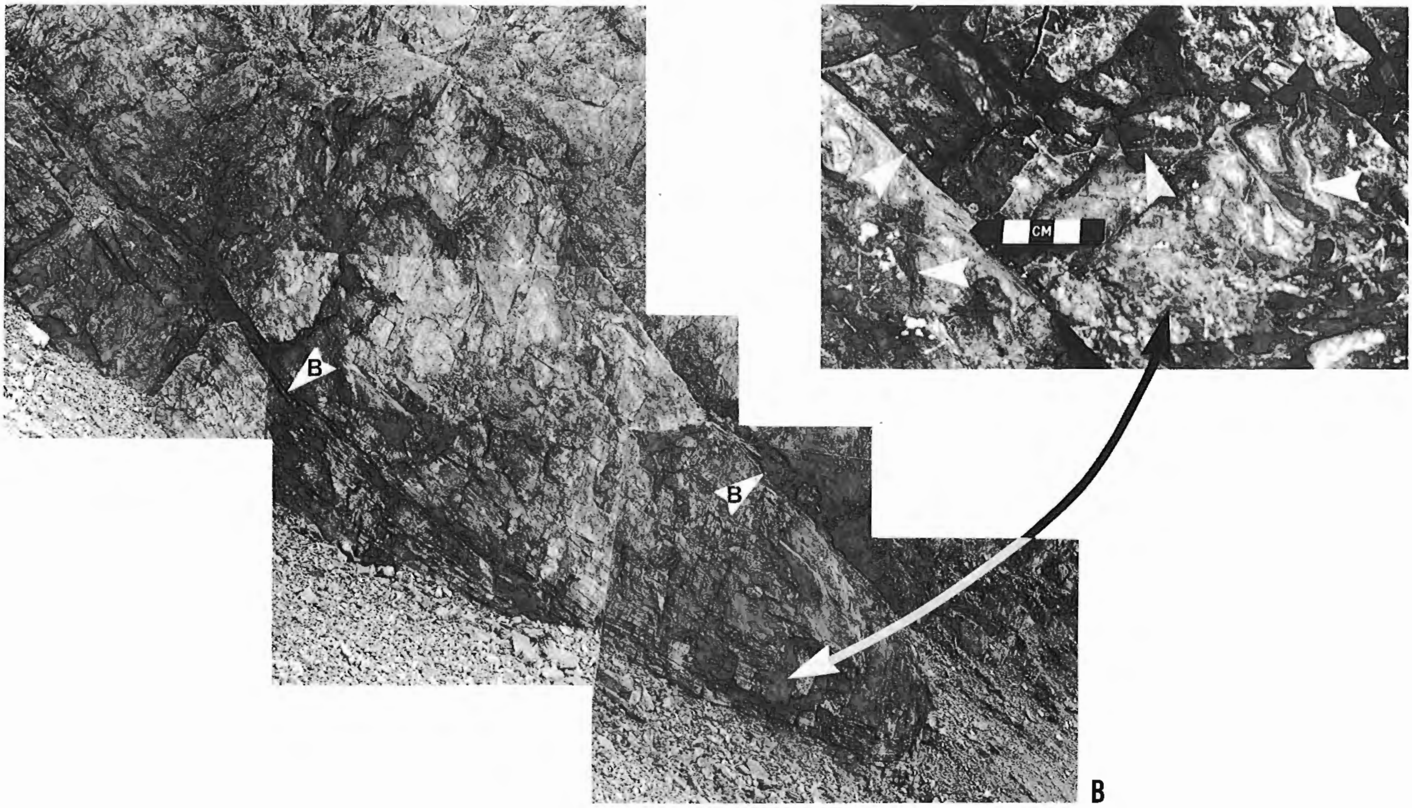


Figure 32. *Foreslope deposits in the Nansen Formation, Hare Fiord, east of Girty Creek (Fig. 1).*

A. Correlation of aerial photograph of the north face of Hare Fiord with the panel diagram from Davies (1977b, Fig. 11), illustrating the setting of submarine-cemented toe-of-slope carbonate beds (S arrows) at the base of steeply dipping foreslope beds. The toe-of-slope beds thin and flatten out into carbonate debris beds and turbidites. Detail of the toe-of-slope bed at left-centre (bed labelled 'S' at right) is illustrated in Figure 32B.

B. Photomosaic of toe of steeply dipping foreslope bed illustrated in Figure 32A, showing down-slope thinning and decrease in dip, recorded by bedding planes (B). Inset at upper right illustrates pervasive submarine cement fabrics (S) and subhorizontal geopetal fabrics below and within cement infill.



fans (see next section) record the irregular distribution of Mg in the RAC, and the decline in Mg, accompanied by local peaks of Fe, into the secondary calcite spar that overlies it.

Isotope values agree once again with a marine origin for the carbon in these fabrics, and argue against any exchange with isotopically-light (carbon or oxygen) diagenetic solutions.

Sedimentary fill in submarine fractures and interconnected cavity systems

Large-scale, submarine, fracture-fill sediments in the Arctic carbonates (in contrast to small-scale, marine, internal sediment layers interbedded with submarine cement fabrics) fall into several categories:

1. Pinkish red to buff-grey, peloidal wackestone, packstone, and mudstone. Cement-lined submarine fractures with this type of fill occur in the Nansen Formation shelf-edge carbonates, and in the Waulsortian reefs, where they apparently were derived from overlying, or laterally correlative, synchronous marine sediments or ammonoid-rich red limestones (''ammonitico-rossos'') that accumulated in topographic depressions on the reef surface.

2. Buff-brown, crinoid-rich, silty packstone and wackestone; many containing a few brachiopods, rare fusulinids, gastropods, and trilobites, and intraclasts of skeletal wackestone and fracture-lining cement (Fig. 43A). This sediment type is the most common type of fill in early fractures in the Waulsortian reefs, and also infills large relict cavities lined by submarine cements and interconnected by the fracture system (Fig. 43A, B). Fine sand and silt sized quartz grains may constitute about 30 per cent of the matrix in this sediment fill. The fill commonly is bedded or laminated, in places ripple laminated, and frequently crudely size-graded. Dolomitization is common, the degree of matrix dolomitization varying from little or none to almost total obliteration of skeletal components. Sediments of the same type, also silty and dolomitized, characterize the lower units of the Hare Fiord Formation that surround and overlie the Waulsortian reefs.

3. Subhedral crystalline dolomite, with little or no trace of original clastic sediment texture; interpreted as the end product of dolomitization of crinoidal wackestones. The dolomite crystals are commonly cloudy and zoned.

At the time of submarine fracture formation in the Waulsortian reefs, RFC cement rimmed cavities, in a spectrum of sizes, still remained open within the mounds.

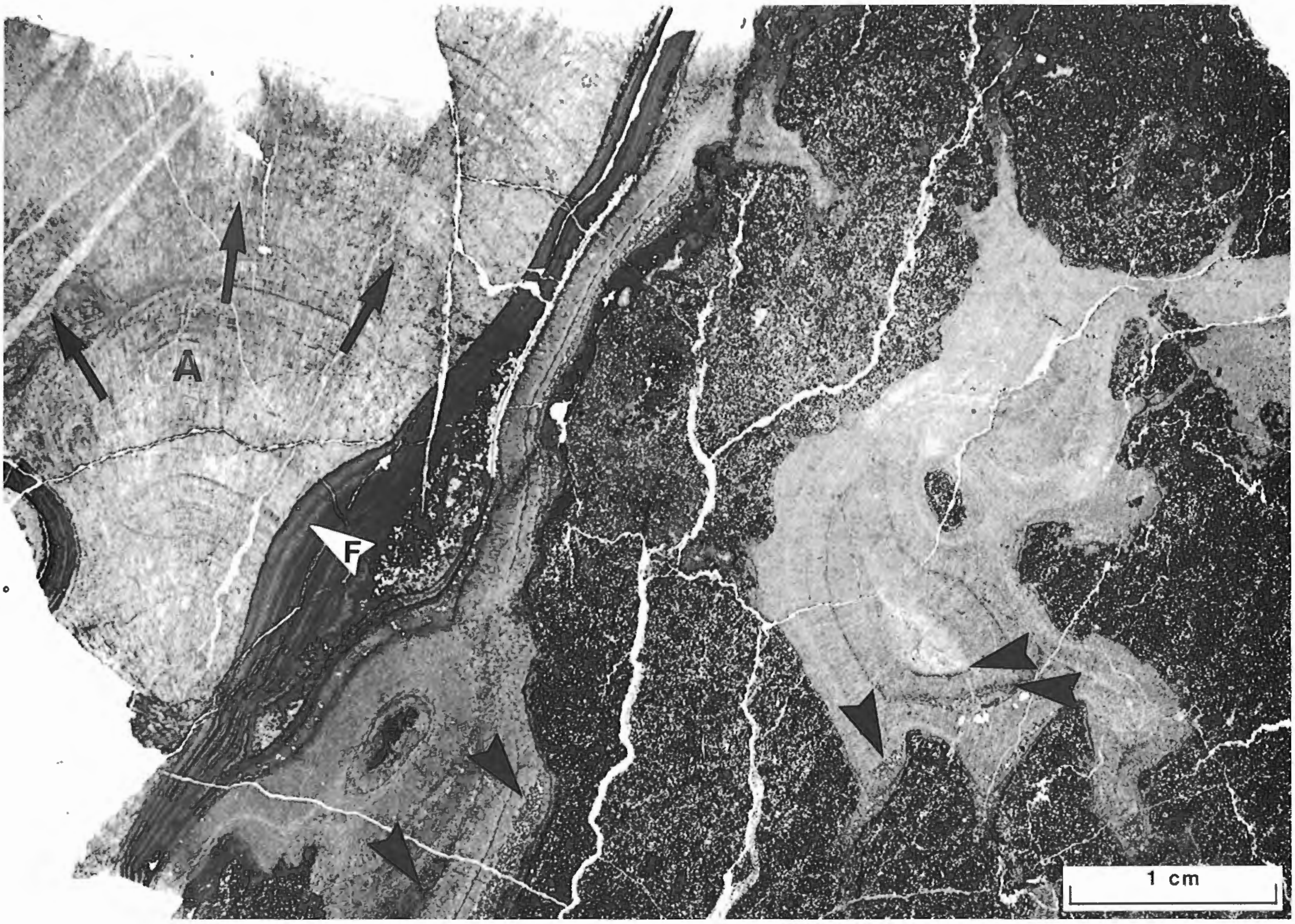


Figure 33. Thin section photomicrograph of submarine-cemented toe-of-slope fabrics from the location illustrated in Figure 32B. Silty argillaceous limestone of the deep-water host contains irregular collapse cavities infilled by multiple generations of radial-figrous calcite (RFC) submarine cement, with rotated internal sediments (arrowheads; see Figure 18C for detail). The steeply dipping submarine collapse-fracture cavity at left is lined by RFC fracture-lining cement (F), and part of an array of BAC (A). Elongate arrows indicate growth direction of precursor aragonite crystal array. Carboniferous, Nansen Formation, east of Girty Creek.

Where fractures intersected these cavity systems, and were not subsequently blocked by fracture-lining cement, the fracture-filling crinoidal sediment was able to infiltrate many of these cavities or conduits (Fig. 43A, B). The externally derived sediments in these fracture-associated primary cavities commonly are laminated, crudely size graded, and may be ripple crosslaminated. They are finer grained than the sedimentary fill in the major fracture systems, probably due to the loss of larger crinoids and other clasts by the filtering or "sieving" effect of apertures within the conduit system. The level of filling within caverns was governed by the size and position of apertures ("pore throats"), and by projections from the cavern roof (Fig. 43A).

The contact between dolomitized fracture-fill sediment and RFC cements lining these partly filled cavities commonly shows irregular truncation of one or more generations of the fibrous calcite (Fig. 43C). RFC on the walls and roof of the cavities, above the level of sediment fill, is unaffected or may show an indistinct corroded surface. The internal sediment was dolomitized after deposition; euhedral rhombs replace RFC at the contact. The mechanism responsible for partial removal or replacement of the upper layers of RFC may have been pre-dolomite solution, mechanical abrasion, replacement during dolomitization, or a combination of these processes. Petrographic examination suggests that replacement during dolomitization of the adjacent sediment fill, perhaps on slightly abraded surfaces, was the major control.

The emplacement of crinoidal infill of fractures and interconnected conduits in the Waulsortian reefs of Ellesmere Island is interpreted as marking the onset of burial; as Hare Fiord sediments began to accumulate on the flanks and

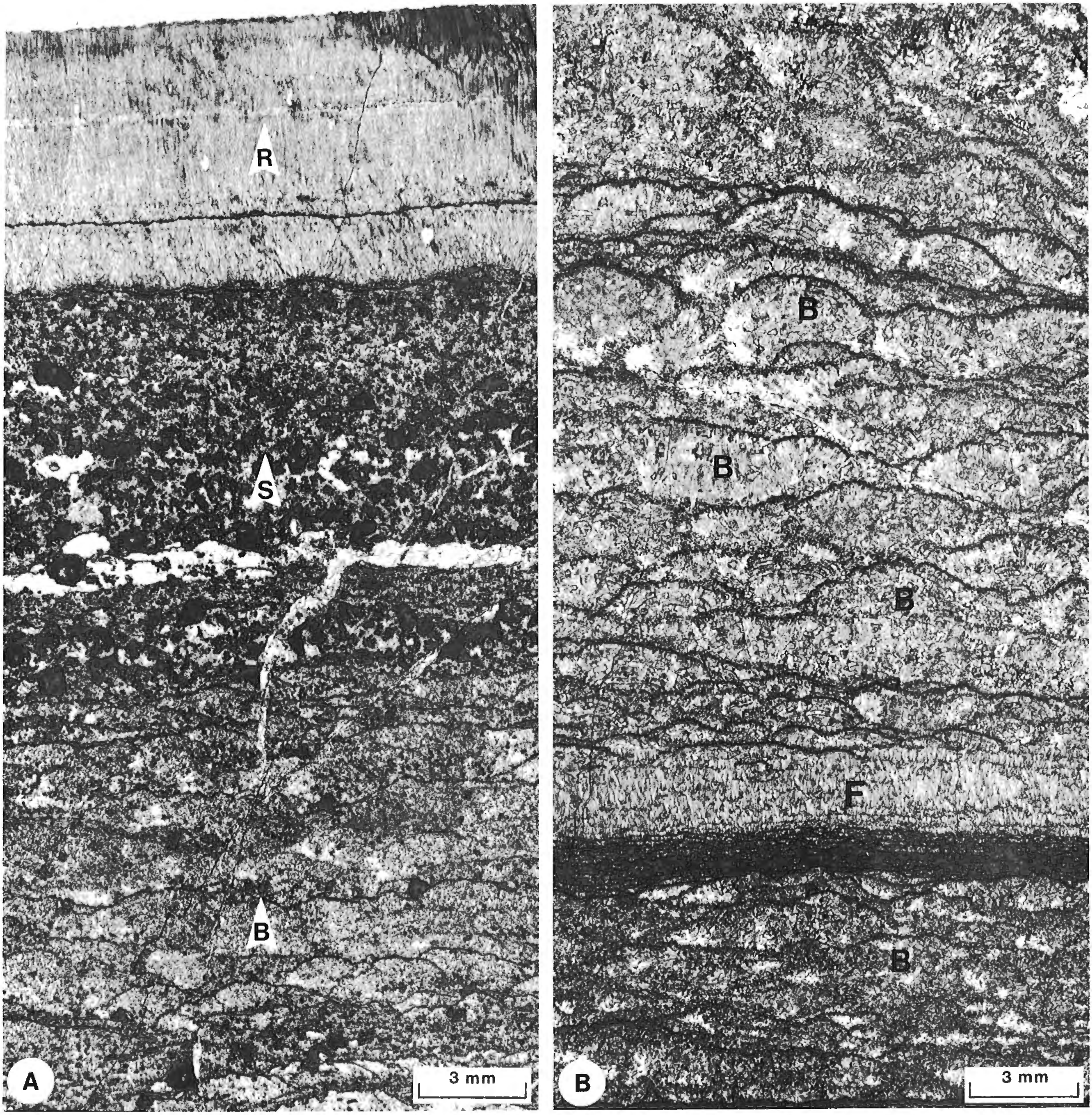


Figure 34. *Development of botryoidal-array calcite (BAC) after aragonite in fracture-lining cement, Waulsortian-type reefs, Blue Mountains reef, northwestern Ellesmere Island.*

A. *Succession of submarine cements and internal sediment within a thick, fracture-lining cement layer. From the base upward (in direction of accumulation) the succession is: BAC (B), composed of small coalescing hemispheres of calcite, partly replacive; marine internal peloidal sediment (S) with scattered ostracods and foraminiferids; and several generations of RFC (fascicular-optic?) cement (R).*

B. *Detail of BAC fabric, showing coalescing hemispheres of BAC (B) after aragonite, with a more normal micritic-RFC fracture-lining cement layer (F) in the lower part.*

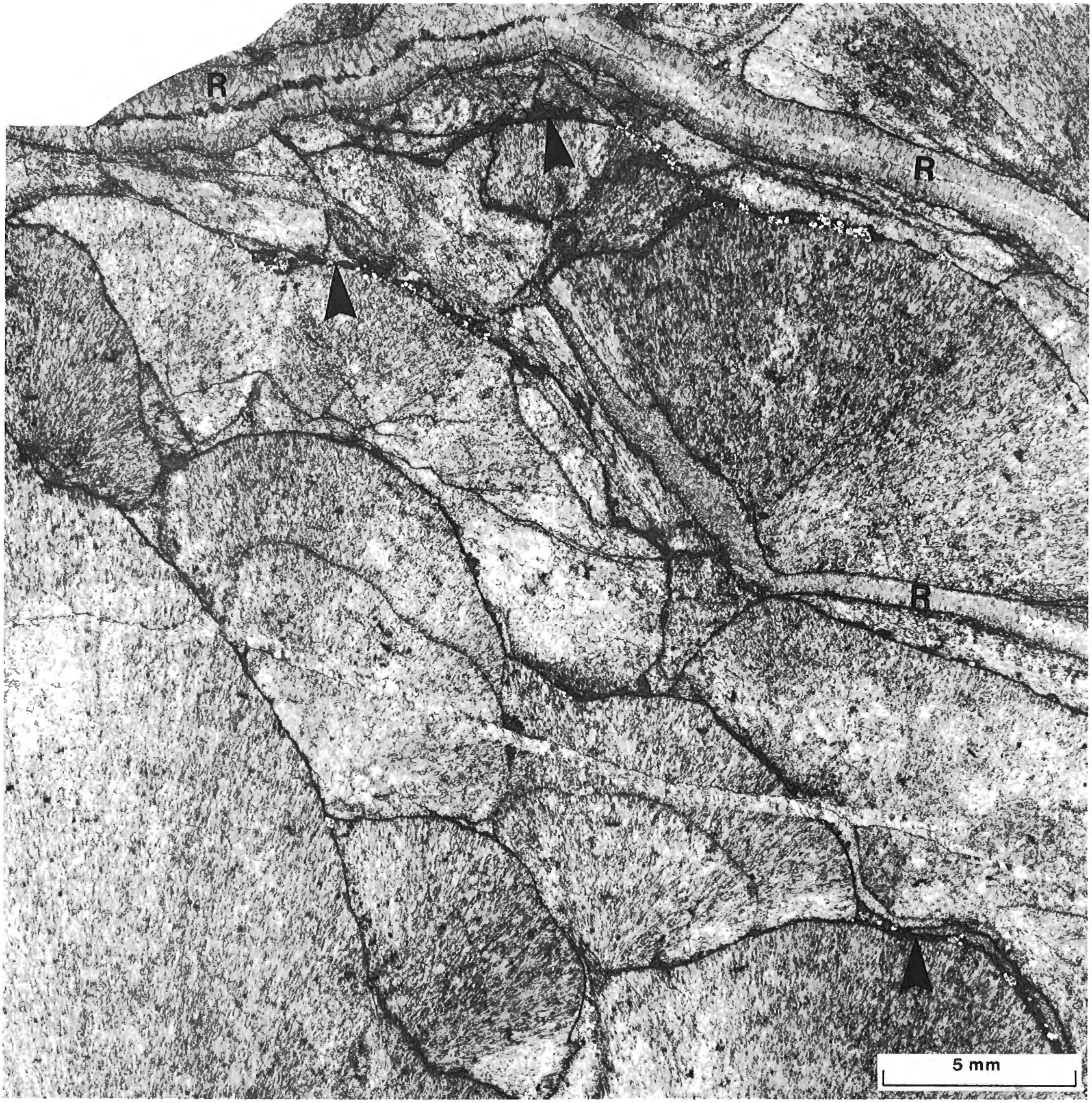


Figure 35. *Detail of botryoidal-array calcite (BAC), after aragonite, in fracture-lining cement from the Nansen Formation, east of Girty Creek, northwestern Ellesmere Island. The thin section photomicrograph is of the upper BAC hemispheres illustrated in Figure 29C; the lower hemispheres (not shown) overlie, and are intergrown with, layers of marine internal peloidal sediment containing ostracodes and foraminiferids. The BAC fabrics are intergrown and coalesce, and are overlain by partly replaced residues of internal sediment (arrows). Microfractures lined by RFC submarine cements (R) cut through the BAC fabric.*

eventually over the top of the buildups. There is no evidence of any type of submarine process following burial. The remaining diagenetic fabrics and products identified in these rocks are interpreted as being of post-burial origin (Davies, 1976); they are not described in this paper, although a typical submarine to post-burial cement sequence is illustrated in Figure 44.

Figure 36. Combination replacive radial-array calcite (RAC) and botryoidal-array calcite (BAC) in displaced block from a Waulsortian-type reef in the Blue Mountains of northwestern Ellesmere Island. The dark-coloured subspherical masses are nucleated on a light grey primary sediment host, and are overlain by banded RFC submarine cements (R). Width of view about 1 m.

Composition of fracture-fill sediment

Little attention has been given to the elemental composition of dolomitized fracture-fill sediment. Several stable isotope analyses give values of +6.3 to +7.7‰ $\delta^{13}C$ and -4.5 to -5.4‰ $\delta^{18}O$ for the replacement dolomite. The ^{13}C values are higher than the means for RFC and some other diagenetic fabrics (Table 1), but enrichment in ^{13}C bydolomite relative to co-precipitated calcites is expected (Choquette, 1968; and others).

DISCUSSION

Submarine (synsedimentary) diagenesis

Submarine diagenetic processes and products are summarized in schematic form in Figure 45, and the relative timing of these events is outlined graphically in Figure 46.

Origin of radial-fibrous calcite (RFC)

Radial-fibrous calcite in the Arctic rocks is interpreted as the neomorphic replacement by calcite of laterally competitive, radiating (fascicular) bundles of acicular magnesium calcite that precipitated as early submarine cements (Davies, 1977a). The interpretation of the origin of fibrous calcite as submarine is not new; up to the time this text was originally prepared (1975-76), Newell (1955) had attributed fibrous calcite in the Permian reef complex of west Texas and New Mexico to replacement of an early fibrous submarine cement, probably aragonite, and Pray (1965), Cotter (1965, 1966), Stone (1972), and others had interpreted fibrous cements in Mississippian bryozoan (Waulsortian) buildups as early submarine in origin. Kendall and Tucker (1973) inferred an acicular crystal habit for the precursor of radiaxial fibrous calcite; their paper considered in detail the

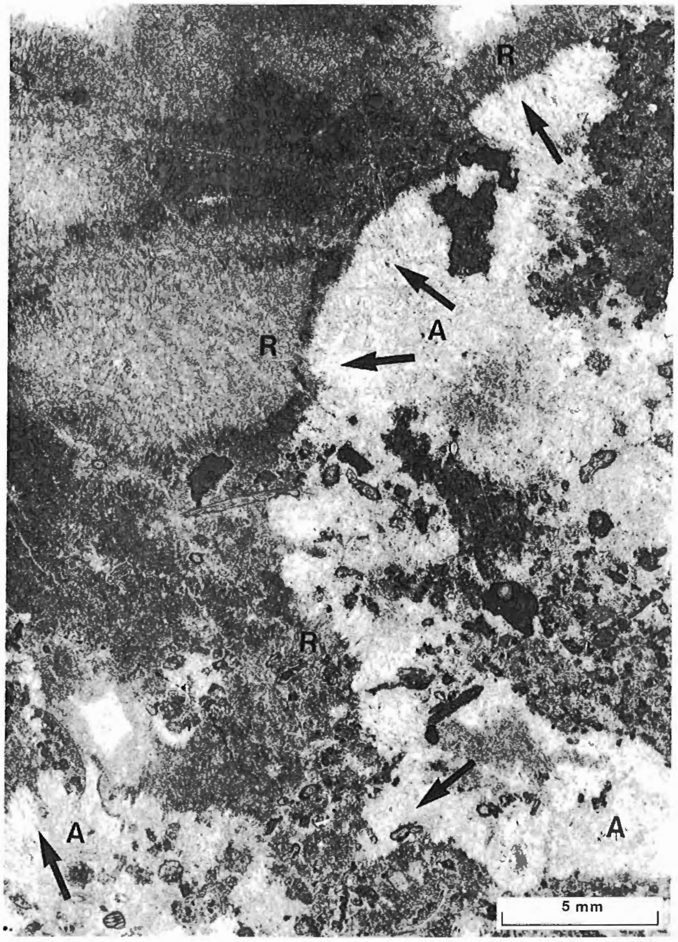


Figure 37. Radial-array calcite (RAC), after aragonite, replacing sediment host and part of several radial-fibrous calcite (RFC) cement generations (R) in a Waulsortian-type reef, Blue Mountains, northwestern Ellesmere Island. Direction of replacive growth of the original aragonite arrays (A) is indicated by arrows. Note that bioclasts tend to be preserved within the RAC, while peloidal and micritic sediment matrix is replaced.

mechanism of neomorphic replacement of this acicular fabric, and was later revised (Kendall, 1985).

Criteria supporting a marine, phreatic, precipitational origin for the precursor of RFC cements have been discussed in the preceding sections; they are summarized schematically in Figure 47. Similarly, the principal criteria for a magnesium calcite precursor for RFC are illustrated schematically in Figure 48.

Radial-fibrous calcite: diagenetic environment and processes

By analogy with submarine cementation in modern reefs, precipitation of the Paleozoic cements probably began within centimetres of the actively accreting sediment surface of the reefs. Primary shelter pore systems below plates of fenestellid bryozoans, phylloid algae, *Palaeoaplysina*, and other bioclasts (depending on age), modified by varying amounts of unsorted primary bioclastic sediment, were preferred sites of phreatic marine precipitation. The factors that influenced precipitation in these cavity systems are not yet clearly understood. Obviously, the cavities represent stable substrates in a carbonate-saturated (supersaturated) water system, with a reduced water flow rate compared to the rate at the active sediment surface; nucleation and crystal growth might be enhanced in this setting for these reasons alone. However, the possibility of other physical and biochemical controls within the cavity system cannot be discounted. Di Salvo (1973) noted that the highest crops of bacteria in modern reef environments occur within internal cavities (dysphotic region) and that the metabolism of these bacteria might influence carbonate equilibrium reactions. Current emphasis on the role of cyanobacterial processes in reef cavities and in carbonate sedimentation/diagenetic processes in general add weight to this argument, but further verification is required. Changes in Eh and pH are probable consequences not only of microbiological reactions, but also of progressive restrictions in internal pore-water flow rates, as cementation and internal sedimentation progress and as conduits and apertures (pore throats) become more restricted; these changes in turn may affect cementation processes.

Precipitation in reef cavities of a fibrous or acicular cement may have been the preferred habit, because of the high Mg:Ca ratio of the precipitating seawater-source pore fluid (Folk, 1974; Given and Wilkinson, 1985). The high density of fluid and other inclusions in the submarine cements, now RFC, also reflects rapid crystal growth. There is a general trend toward longer crystals with a lower density of inclusions in successive generations of RFC crystals approaching the cavity centre; this trend in turn may be a product of decreasing pore-water flow rates, and thus decreasing crystal growth rates, as the pore system became progressively more restricted by cementation — that is, a possible self-regulatory system.

The distribution pattern of Mg in RFC (Fig. 20), if accepted as inherited (but reduced and modified by diagenesis) from the primary cement crystals, indicates that the amount of Mg incorporated into the crystal lattice (by substitution and/or within inclusions) increased during growth of each crystal increment. This may have been due to a progressive increase in the Mg:Ca ratio of the residual pore water, if interchange through the reef pore system was restricted during each cement generation, as the partition coefficient for Mg in $CaCO_3$ (calcite) is much lower than 1. Consequently, calcite incorporating some Mg into its lattice during precipitation from a pore solution similar to seawater should show a progressive increase in Mg in a "closed" diagenetic system. A similar effect of increasing Mg would be produced by progressive increase in pore solution

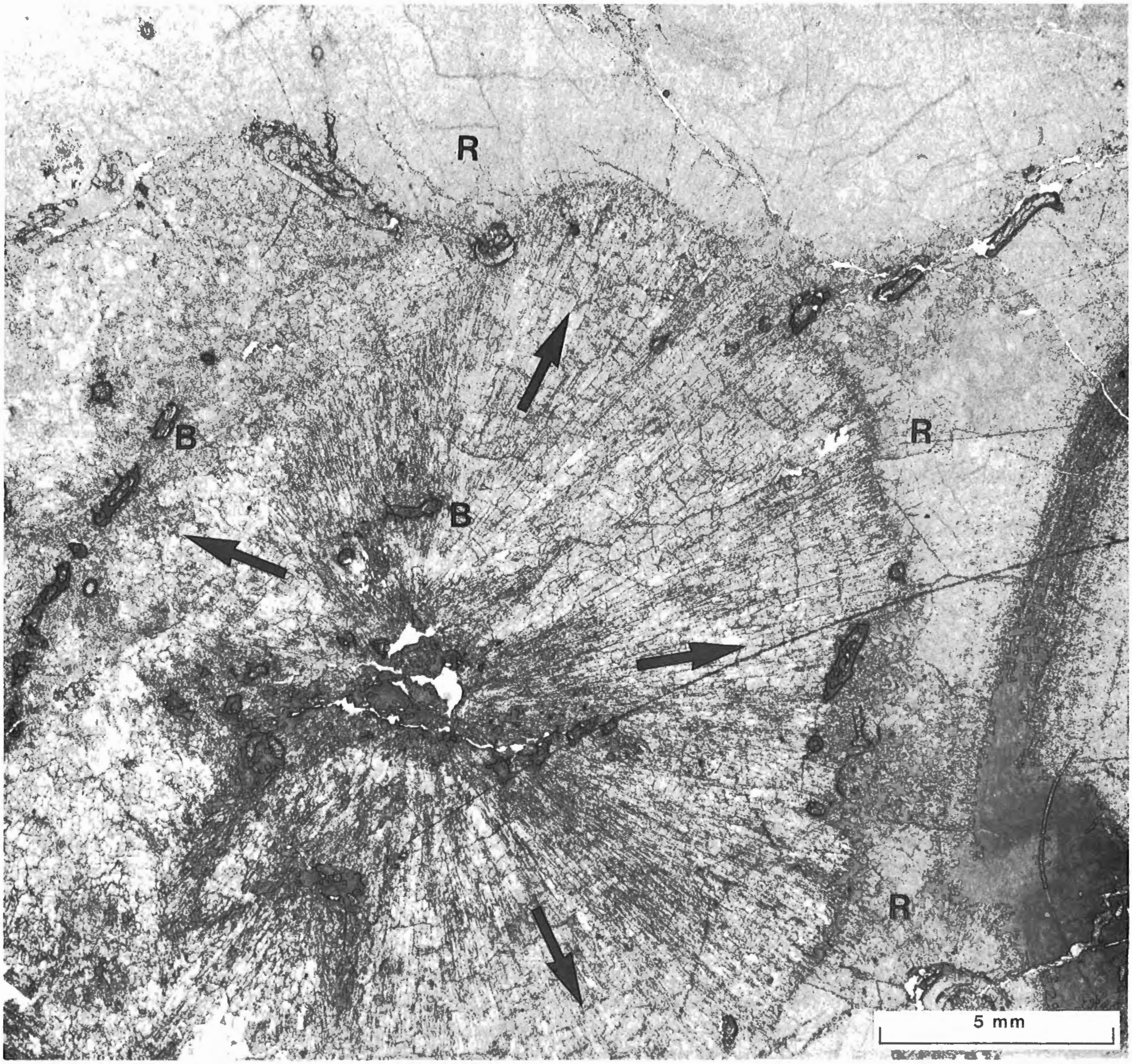


Figure 38. *Radial-array calcite (RAC), after aragonite, replacing parts of several generations of radial-fibrous calcite (RFC) cements (R), with fenestellid bryozoan zoaria (B) preferentially preserved within the RAC fabric. Direction of growth of replacive aragonite precursor is indicated by arrows. RAC fabric has a "feather" edge, and is composed of radially arrayed, elongate and interlocking calcite spar crystals. Waulsortian-type reef, Blue Mountains, northwestern Ellesmere Island.*

temperatures (Katz, 1973), but that appears to be an unlikely factor in the submarine reef environment. Another controlling factor in the levels of Mg in magnesium calcite is the rate of crystal growth (Given and Wilkinson, 1985); the slower the crystal growth, the more magnesium is expelled from the surface layer and the lower the magnesium content. Using this concept, the increase in (residual) Mg content in each increment of RFC in the Arctic carbonate could record a progressive increase in the rate of growth during precipitation of each cement layer (but then contrary to the interpretation in the preceding paragraph).

The multiple increments of RFC cement in reef cavities and fracture-linings suggest that pore solutions experienced periodic fluctuations or changes in composition. Pulses of cementation might have been linked to mechanisms that

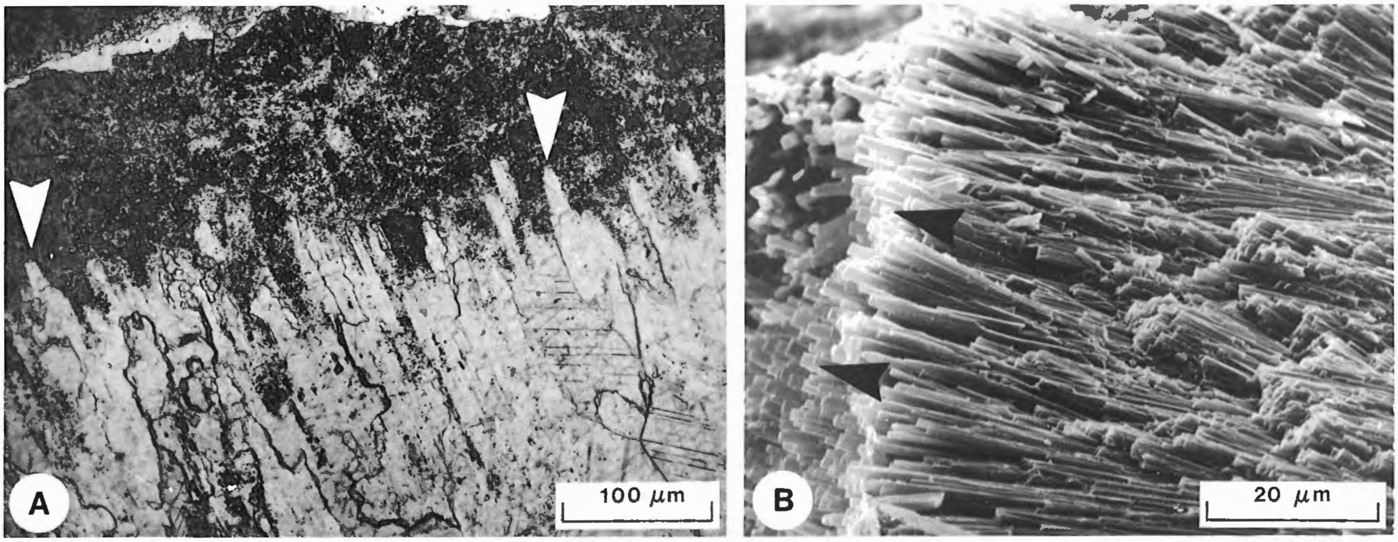


Figure 39. *Comparison of radial-array calcite cement fabric with modern marine aragonite cement.*

A. *Tapering and blunt (pinacoidal?) terminations (arrows) on radial-array calcite (RAC) interpreted as being pseudomorphic after aragonite. The terminations are preserved as textural contrast between inclusion-rich radial-fibrous calcite (RFC) cement that is partly replaced, and inclusion-free calcite spar of the RAC fabric. Waulsortian-type reef, Blue Mountains.*

B. *Modern submarine aragonite cement from Shark Bay, Western Australia, illustrating typical tapering and blunt terminations (arrows) of fascicular aragonite, for comparison with A. SEM photograph.*

controlled recharge of the pore fluid in the internal cavity system of the reef — tidal cycles, storm pulses, or seasonal changes. It is possible that pulses of internal sediment, which commonly are interlayered with submarine cement generations, represent storm-generated surges through the reef pore system, with the recharge of carbonate-supersaturated pore water then producing another generation of cement around the cavity and over the internal sediment. Such a process of cementation linked to periodic recharge suggests a self-regulating process that might produce a predictable thickness increment of cement, reflecting pore volume, saturation levels, and flow rate. Perhaps cyanobacterial activity, re-established after each storm surge, may have assisted or controlled precipitation through changes in pCO_2, pH, and other biochemical microparameters.

Enrichment in the heavier ^{13}C stable isotope of carbon in RFC results from kinetic and equilibrium fractionation reactions during precipitation of the initial cement. Cements in modern reefs also are enriched in ^{13}C relative to ^{12}C, and also tend to be enriched in ^{18}O relative to ^{16}O. However, the degree of ^{13}C enrichment in the Paleozoic cements (5 to 6‰) is higher than for modern cements; this may point to a higher $^{13}C/^{12}C$ ratio in Paleozoic seawater, particularly in depositional basins with evaporitic associations. Beauchamp et al. (1987) defined a strong latitudinal gradient for $\delta^{13}C$, with the Sverdrup Basin characterized by the highest values. This is attributed to oceanic stagnation and thermocline stratification in the basin, resulting in preservation of large masses of ^{12}C-enriched organic matter in the deep basin, and consequent enrichment of residual dissolved carbonate species in ^{13}C. In addition, further enrichment may have been promoted by the escape of CO_2 from evaporating brines formed during intermittent closure of the basin in Carboniferous time. Major fluctuations in sulphur isotope ratios in Paleozoic evaporites, attributed in turn to fluctuations of sulphur isotope ratios in contemporaneous seawater, might be used as argument to support this statement, as carbon, oxygen, and sulphur form part of a complex interrelated system influenced by common factors — biochemical, Eh, and others. The slight depletion in ^{18}O relative to ^{16}O in RFC, although usually not extreme, probably results from exchange reactions between the calcite and ^{18}O-deficient water (probably at the time of neomorphic replacement of the original cement); because of its position in the carbonate molecule, and the fact that there are three oxygen atoms for each carbon atom, oxygen is more readily affected by isotopic exchange reactions than carbon.

The more extensive RFC cements in the upper Paleozoic carbonate succession on northwestern Ellesmere Island appear to be confined primarily to reefs or biogenic mounds in a shelf-edge setting or in the lower part of a transgressive sequence (particularly the Waulsortian reefs). One obvious

Figure 40. *Thin section photomicrograph of radial-array calcite (RAC), after aragonite, illustrating replacement growth habit. The RAC has partly replaced the ramose bryozoan at centre (B), and has replaced part of the thick generation of radial-fibrous calcite (RFC) submarine cement (R) lining the bryozoan framework. Direction of growth of the original aragonite arrays is indicated by arrows. The RAC does not replace the post-burial calcite and dolomite phases, which infill residual pore space (C) and postdate the aragonite. Note the concentric growth increments preserved in the RAC at left as lines of inclusions. From the Nansen Formation float slab illustrated in Figure 30.*

control on this distribution is the presence of high porosities and permeabilities in the reefal host. However, other factors, such as the mechanism of flow ("pumping") through the reef cavity system, may also play significant roles; these are not yet clearly understood.

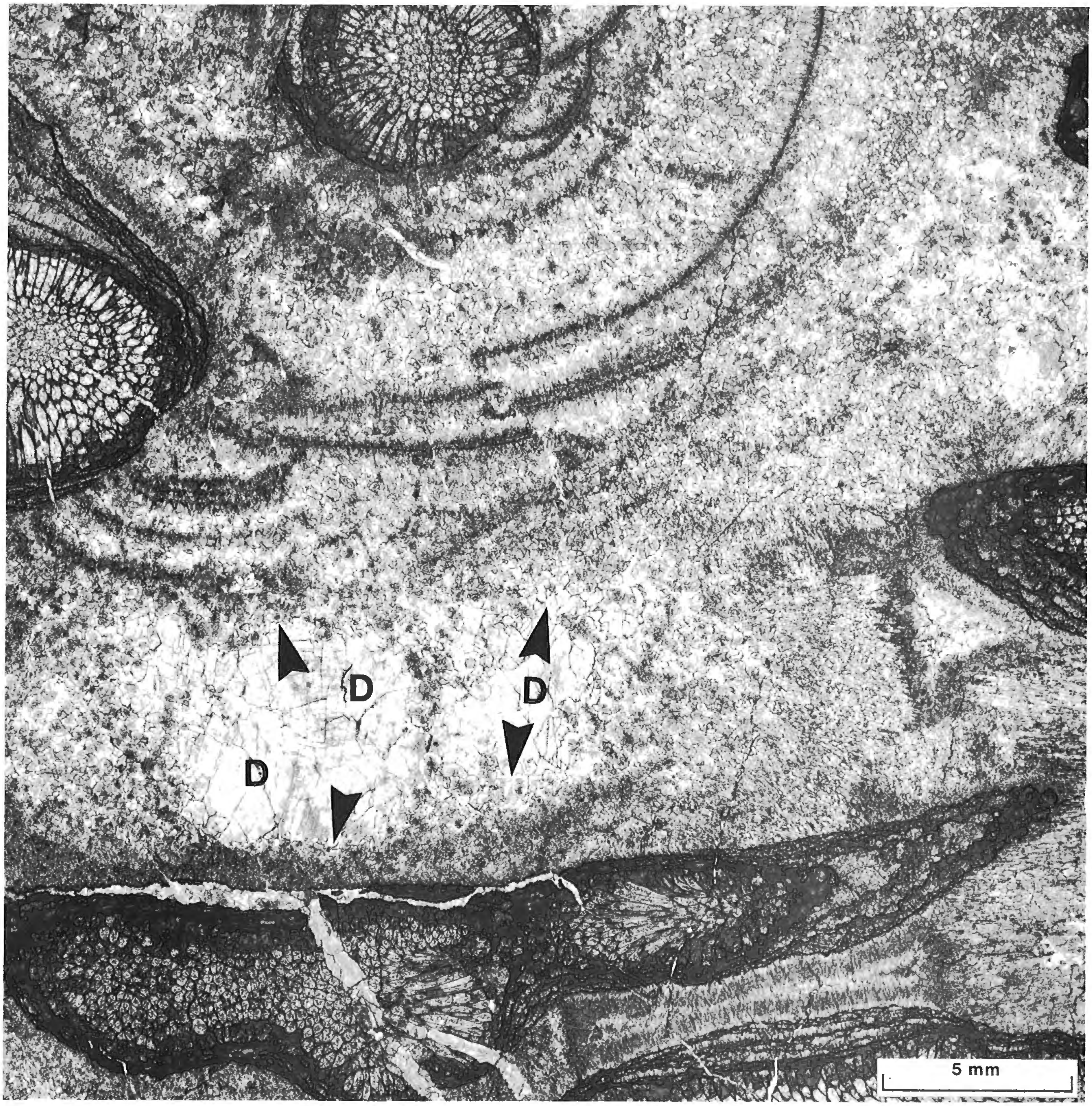


Figure 41. Solution fabrics in radial-array calcite (RAC), after aragonite. The massive aragonite precursor has been locally dissolved to form moulds (arrows) that have subsequently been infilled by calcite spar and baroque dolomite (D). Collapse of the overall fabric is indicated by dislocation of the inclusion-defined concentric growth increments at upper centre. Same sample as Figure 40.

The RFC cements are developed best in porous carbonate sediments that projected above the surrounding basin floor, facing an open seaway. For cementation to be more than superficial, flow of water had to be maintained continuously or periodically through the pore systems of these sediments. According to Bathurst (1971, 1975) pore-water exchange in the magnitude of 50 000 to 100 000 pore volumes is required for carbonate cementation. With their particular geographic and bathymetric setting, the porous sediments below the water interface were subjected to the pressure surges of large waves, generated by winds having a fetch of at least scores of kilometres and probably hundreds of kilometres. The

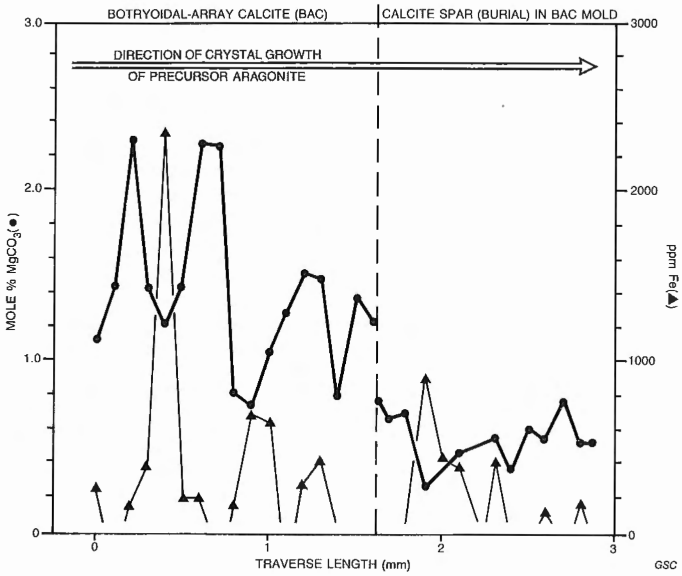


Figure 42. Microprobe traverse for Mg and Fe along growth increment of replacive radial-array calcite (RAC), and across solution mould infilled by zoned ferroan and non-ferroan calcite spar. Higher spot values of Mg, similar to the levels in radial-fibrous calcite (RFC), probably represent residual Mg after replacement of RFC by RAC. Waulsortian-type reef, Blue Mountains, northwestern Ellesmere Island.

pressure gradient asserted by successive wave trains (particularly under abnormal storm conditions) passing across a permeable mass of sediment is one possible mechanism for pumping, or at least stimulating, flow of marine water through the internal pore system of a reef (Matthews, 1974). However, this mechanism does not explain flow of water into, and cementation within, isolated stromatactoid cavities enclosed in low-permeability carbonate muds; other processes must be involved. In some basins, flow through porous reefs may have been induced by pressure gradients controlled by tidal fluctuations; the Sverdrup Basin, however, may have had little tidal influence. Whether tidal, wave pulse, or storm surge, mechanisms of this type apparently were responsible for preferential cementation of seaward-facing barrier reefs and other reefs in modern seas. They also may have driven throughflow of seawater in the pore systems of the Paleozoic reefs, although other processes undoubtedly were also involved and perhaps even dominant.

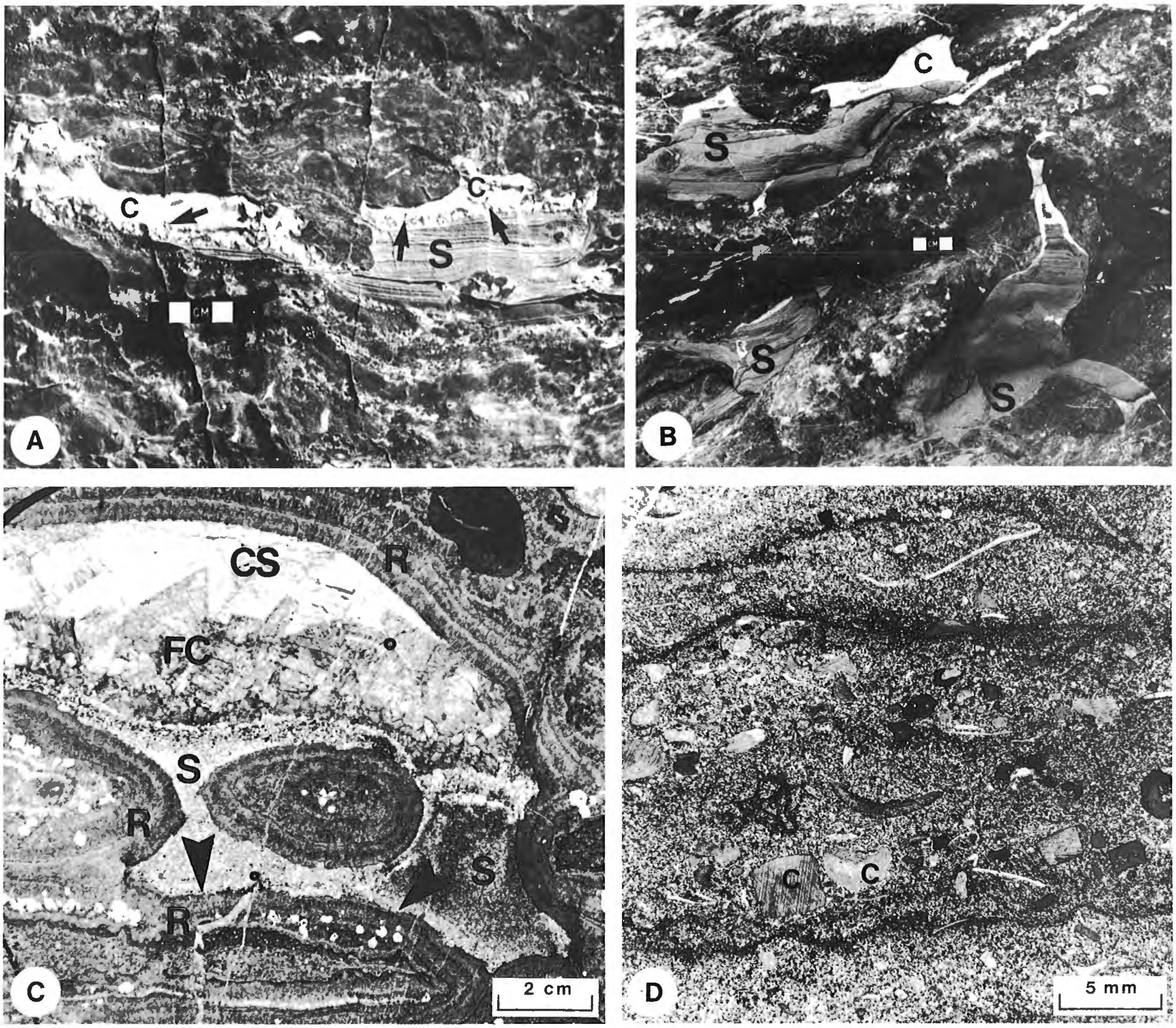
The flow of seawater into and out of a submarine-cemented Quaternary fringing reef off Jamaica, through vertical boreholes, was observed by Land et al. (1989), who recorded a maximum inflow rate of 86 cm sec $^{-1}$. Flow of water in and out of the open holes, however, does not appear to be related to simple changes in sea-surface elevation due to normal tides, to wind-driven wave surges, or to dispersion by meteoric discharge from coastal aquifers. Land et al. (op. cit.) concluded that yet-undefined factors, perhaps non-seasonal convergence or setup by wind along the Jamaican coast, interacting with local submarine topography or conduit flow below the observation wells, must be responsible. They also argued that, given the indications of relatively high flow rates into the reef, submarine cementation may be more the result of high-volume throughflow of oversaturated surface seawater, rather than the product of chemical or microbiochemical processes within the reef cavity system.

Emplacement and movement of internal sediments in permeable reefs, both modern and ancient, may be related to *abnormal* rather than normal events. Major storms, with their attendant surges in wave-generated pressure gradients, may be responsible for much, if not all, internal sedimentation. Internal sediments interfere with normal cement precipitation in cavities, causing preferential attenuation of crystal growth on the floors of cavities; as a consequence, individual cement layers may be thicker on the walls and roof of a cavity than on the floor, where they are interlayered with internal sediments.

Recent and Paleozoic submarine cements and fabrics — comparisons

In modern coralgal reefs, micritic magnesium calcite, commonly with a peloidal texture, is the most common cement type, followed in decreasing abundance by fibrous and acicular aragonite, and fibrous magnesium calcite (Cullis, 1904; Land and Goreau, 1970; Shinn, 1971; Schroeder, 1972; Ginsburg and Schroeder, 1973; Aissaoui, 1985, 1988; and others). Although less obvious than the RFC and BAC cements, subpeloidal micritic cement is a pervasive component of the matrix sediment in most of the Arctic upper Paleozoic reefs. Fibrous and acicular aragonite and calcite all exhibit crystal growth as laterally competitive radiating cones (fans in two dimensions) of elongate crystals. Both aragonite and calcite form isopachous cement rims within and around skeletal clasts and as cavity linings. Shinn (1971, Figs. 3, 4) illustrated isopachous rims of magnesium calcite cements in Bermuda cup reefs, which in thin section (op. cit., Fig. 4) are "cloudy", due to abundant inclusions — similar to the Paleozoic cements. This modern calcite cement is overlain by cemented peloidal internal sediment, again analogous to the Paleozoic fabrics.

The best documented and illustrated modern analogues to the upper Paleozoic radial-fibrous cements are the fibrous magnesium calcite cements of Mururoa Atoll in the Pacific Ocean (Aissaoui, 1988). Comparison of Figures 2, 4 and 5 from Aissaoui (op. cit.) with Figures 8 to 15 in this report reveals many similar to identical fabrics. The Mururoa fibrous magnesium calcite cement forms in multiple generations, totalling thicknesses of up to 1.5 cm, and consists of radiating bundles with imperfect undulose extinction and



with both dispersed and locally concentrated inclusions, which impart a darker colour. $MgCO_3$ content ranges from 14.4 to 16.9 mole per cent; isotopic signature is +0.7‰ PDB for carbon, and +2.8‰ PDB for oxygen.

The nucleation of these modern submarine cements on marine organic skeletons and sediments, their radiating fibrous or fascicular habit, isopachous form, and relationship to marine internal sediments, are criteria used in this paper to support the interpretation of a similar marine origin for the Arctic RFL cements. We have outlined earlier the arguments for and against aragonite or magnesium calcite as the predecessor of RFC. The common occurrence of thin micritic layers in some Paleozoic fibrous cements, and particularly the peloidal-micritic cement layers with microcolumnar fabric found in some fracture-lining cements (Fig. 25), bears comparison with micritic and peloidal magnesium calcite cements in modern reefs. A specific analogue for the microcolumnar fabric in fracture-lining cements in the Arctic rocks may be the "microstromatolitic", magnesium calcite, pelletal-micrite cement described by Land and Goreau (1970, Fig. 6) from modern Jamaican reefs. Sequential precipitation of magnesium calcite and aragonite cements in a variety of crystal habits and textures is common in modern reefs (Schroeder, 1972; and others); sequential precipitation of peloidal magnesium calcite, followed by fibrous-acicular magnesium calcite may have produced the rhythmic fracture-lining cements in the Arctic reefs. Alternatively, since the micritic cement generations in the fracture-lining cements may be correlated with an interval of fracture-fill sedimentation, by peloidal and micritic

Figure 43. Invasion of fractures and primary reef-cavity conduits in Waulsortian-type reefs by dolomitized crinoidal and silty sediment, as an indicator of the onset of burial by the Hare Fiord Formation.

A. *Primary reef-cavity system lined by submarine radial-fibrous calcite (RFC) cement and infilled by crosslaminated dolomitized sediment (S), followed by the development of ferroan calcite crystals (arrows) enclosed in white calcite spar (C) - both post-burial phases. Note the "damming" effect on sediment input by the dark grey roof pendant at the centre of the cavity, which restricted internal sediment to a thin floor layer in the sub-cavity at left. The internal sediment is interpreted as having entered the cavity via interconnected primary conduits connected by submarine fractures that are now filled by the same type of internal sediment (e.g., Figure 23B, from the same reef as the cavity-fill illustrated in this figure). Wood Glacier, Waulsortian-type reef.*

B. *Fracture-interconnected primary cavity systems in submarine-cemented reef mass, partly infilled by dolomitized silty and crinoidal internal sediment (S) with horizontal bedding, followed by white, post-burial, calcite spar (C). The dip of the enclosing beds, relative to the horizontal bedding in the internal sediment fill, suggests a flank setting. Wood Glacier, Waulsortian-type reef.*

C. *Thin section photomicrograph of cavity-fill sequence in Waulsortian-type reef. Primary reef cavity is lined by multiple generations of RFC cement (R) and is partly infilled by geopetal dolomitized internal sediment (S), forming a corroded contact with the RFC (arrows), and followed by zoned ferroan calcite (FC) and by non-ferroan calcite spar (CS). The last two phases are post-burial cements. Note also the geopetal distribution of chalcedonic quartz (white patches) in RFC on the floor of the former cavity. Wood Glacier, Waulsortian-type reef.*

D. *Thin section photomicrograph of silty, dolomitized wackestone to packstone internal sediment, typical of figures A and B, illustrating the presence of crinoids (C), brachiopod fragments, and other bioclasts. The biotic assemblage, silt content, and dolomite replacement are all characteristic of the enclosing Hare Fiord Formation basinal facies, and support the interpretation that this dolomitized internal sediment, in submarine fractures and reef cavities, heralds the onset of burial. Wood Glacier, Waulsortian-type reef.*

sediment, the layer of micritic cement may represent a period when turbid, muddy water (storm-generated?) inhibited growth of acicular cement crystals.

Internal sediments of contemporaneous marine origin are very common in modern coralgal reefs (Shinn, 1971; Ginsburg and Schroeder, 1973; Aissaoui, 1988; and others). Many of the internal sediments are cemented, and frequently occur in multiple generations, alternating with layers of cement. The most common components of the modern internal sediments are micritic peloids, some recognizable fecal pellets, and a variety of micro-organisms and larger or fragmented skeletal grains. Smooth-shelled ostracodes, commonly with articulated valves, are one of the more abundant micro-organisms in internal sediments in modern reefs (Shinn, 1971; Ginsburg and Schroeder, 1973, Table 1). These and other organisms are part of the coelobite community (Ginsburg and Schroeder, 1973), indigenous to the internal cavity systems of reefs. In the Arctic upper Paleozoic rocks, smooth-shelled and articulated ostracode valves are the most abundant micro-organisms in internal sediments associated with RFC cements (Fig. 18A). In some samples, unicellular and tubular organisms encrust, or are enclosed in, generations of RFC cement. The ostracodes and encrusting organisms were vagile (motile) and sessile components, respectively, of the coelobite community within the early cavity systems of the Waulsortian reefs.

Fracturing and fracture-cementation of reef rocks; process and timing

Fracturing and dilational or rotational displacement of carbonate rocks that have undergone very early cementation are processes that are not unique to the Arctic rocks. Pray (1965) and Cotter (1965, 1966) found sediment-filled dilational fractures in early-cemented Mississippian bryozoan mounds in Montana and New Mexico; there are many other examples in the literature. Fracturing and displacement also are common processes in modern submarine-cemented reefs. Large dilational fractures have been found by Shinn (1971, Figs. 2, 7) in algal cup reefs off Bermuda. Goreau and Land (1974, Fig. 3) illustrated a narrow canyon in the fore reef escarpment of a Jamaican reef, which may be a large dilational fracture. Joints and open fissures up to 15 m long were noted by Ginsburg and James (1973a, b) in the submarine-cemented escarpment of the British Honduras barrier reefs. Extensive fore reef megabreccias, composed of cemented reef rock, at the foot of modern barrier and other reefs (Ginsburg and James, 1973a, Fig. 6) are in themselves direct evidence of brittle fracture and gravitational displacement of the cemented reef face.

There is an obvious relationship between pervasive early marine cementation in both modern and ancient reef rocks and their mechanical failure by fracturing and jointing. The

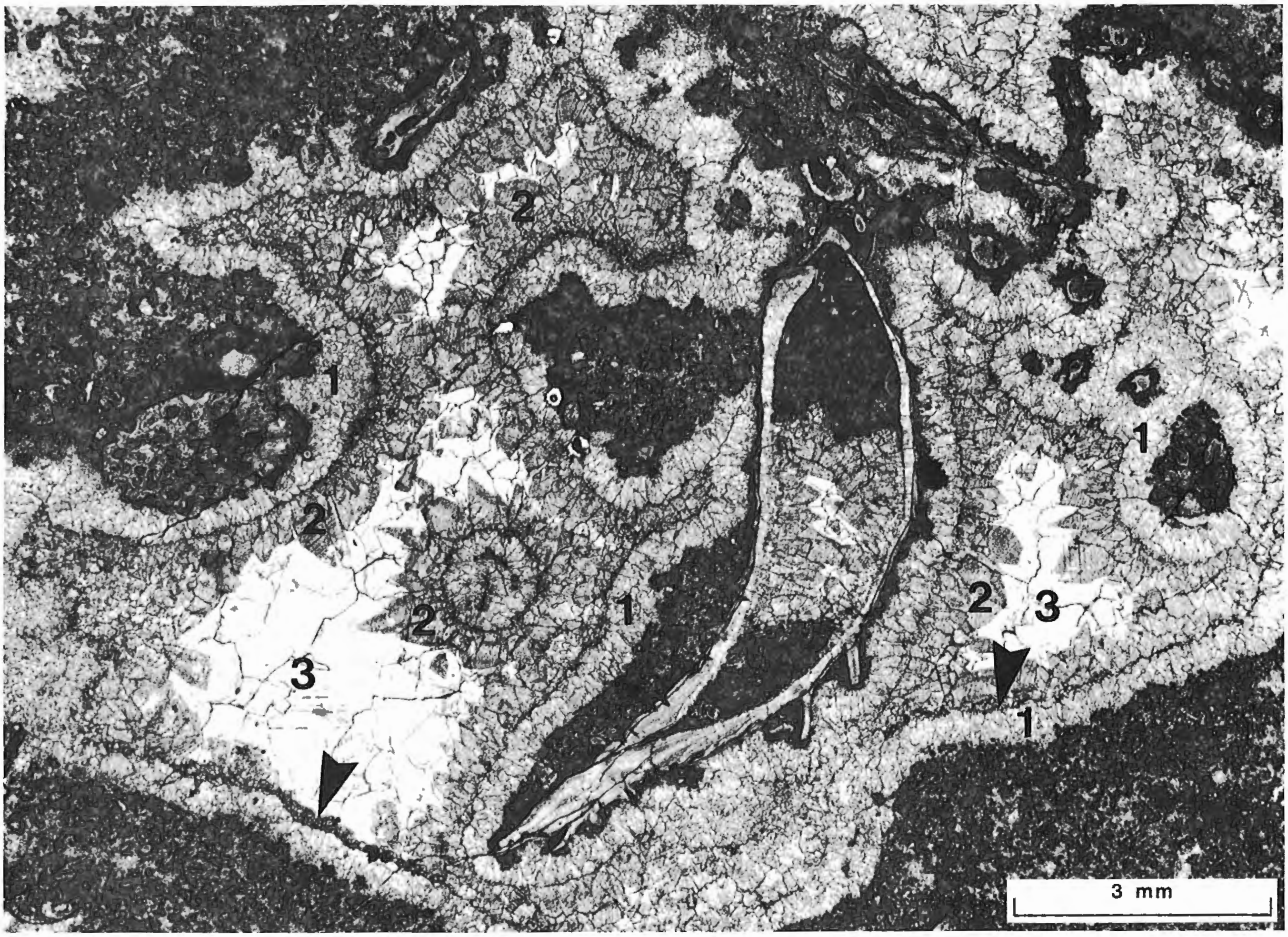


Figure 44. Submarine to post-burial cement sequence in a primary shelter-cavity from a Waulsortian-type reef, Blue Mountains, northwestern Ellesmere Island. The initial fenestellid bryozoan and brachiopod framework, with ponded peloidal marine sediment, is cemented by isopachous RFC submarine cement (1) with internal sediment (arrows). A corroded surface marks the termination of growth. This stage was followed by the formation of zoned ferroan calcite (2), stained with potassium ferricyanide, that in turn grades outward into iron-poor calcite spar (3). The last two stages are interpreted as the product of post-burial diagenetic processes.

cemented reef masses are elevated above surrounding substrates, are underlain by differentially cemented and compacting substrates, and are subjected to a variety of physical and biological erosional forces. Fracturing followed by dilational or rotational displacement and downslope gravitational transport of blocks are the expected responses to these stresses by a cemented rock mass. Allochthonous blocks and finer debris of cemented shelf-edge limestones, buried in the deeper water sediments of the Hare Fiord Formation on Ellesmere Island (Davies, 1977b), are further proof of early cementation of the Paleozoic shelf-edge sediments and of the relationship between early cementation, fracturing, and displacement.

At both field and thin section scales, it is possible to demonstrate that some if not all of the cement-lined fractures in the Arctic Waulsortian reefs truncated the first major generation of RFC (RFC:1) cement, but predated later generations of RFC (Figs. 25, 26). If fibrous cements are of submarine origin, then fracturing also occurred within the submarine environment, and as a very early event. Further, at least the earliest generations of fracture-lining cement also are of submarine origin, as they may be traced into laterally interconnected cavity systems and shown to be synchronous with the second and later generations of RFC within the reef cavity system (Figs. 26, 45). As early and late generations of fracture-lining cements are identical, it is reasonable, therefore, to believe that all fracture-lining cements were precipitated while the reefs were in the submarine environment.

A maximum time constraint (relative to reef evolution) for the development of fracturing is imposed by the nature of

Figure 45. Summary sketch of submarine diagenetic products and processes in Upper Carboniferous Waulsortian-type reefs of northwestern Ellesmere Island.

1. *"Platestone" fabrics of fenestellid bryozoans forming primary shelter-cavity framework*
2. *Primary marine sediment, locally ponded on bryozoan zoaria*
3. *First generation (or macro-generation) of submarine cement, with internal growth increments of radial-fibrous calcite (RFC) nucleated on bryozoans and marine sediment*
4. *Encrusting organisms in/on RFC*
5. *Multiple generations of internal sediment between generations of RFC*
6. *Surface of RFC cement (3) truncated by submarine fracture (right)*
7. *Second generation (or macro-generation) of RFC cement in primary shelter reef cavity, continuous with basal micritic layer of fracture-lining cement and with second generation of RFC bracketed by internal sediment at left (5)*
8. *Multiple generations of fracture-lining cement composed of couplets of a micritic, microcolumnar basal layer and an outer (internally multilayered) RFC zone*
9. *Encrusting organisms in/on micritic and RFC layers*
10. *Development of small botryoidal-array calcite hemispheres (after aragonite) in fracture-linin cement, followed by later stage of RFC (8); or developing into*
11. *Large coalescing cones or hemispheres of botryoidal-array calcite (BAC)*
12. *Radial-array calcite, neomorphic after aragonite, that has replaced peloidal and micritic sediment and RFC fabrics.*

the sediment fill; the fractures and the lining cement were formed prior to the burial of the mounds by crinoid-rich sediments of the Hare Fiord Formation that fill the fractures where they were open to the reef surface.

Not all of the fractures were filled by this post-burial sediment. Some fractures were filled by wall to wall accretion of cement. Indeed, fractures with the thickest linings of RFC cement (up to 20 cm) do not contain dolomitized post-burial

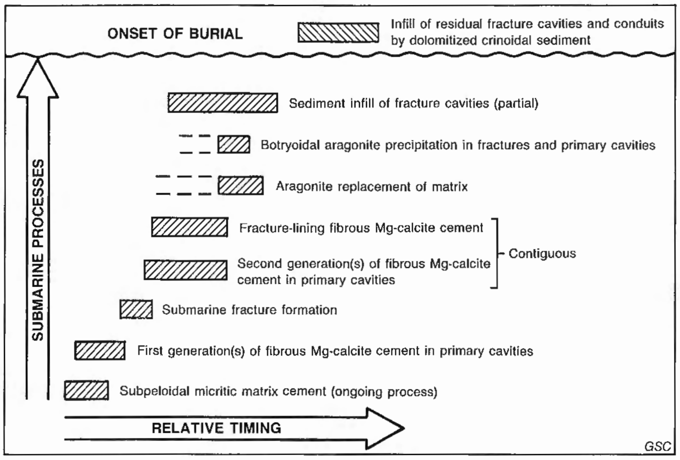


Figure 46. *Diagrammatic representation of the approximate relative timing of submarine processes and products in Arctic upper Paleozoic carbonates.*

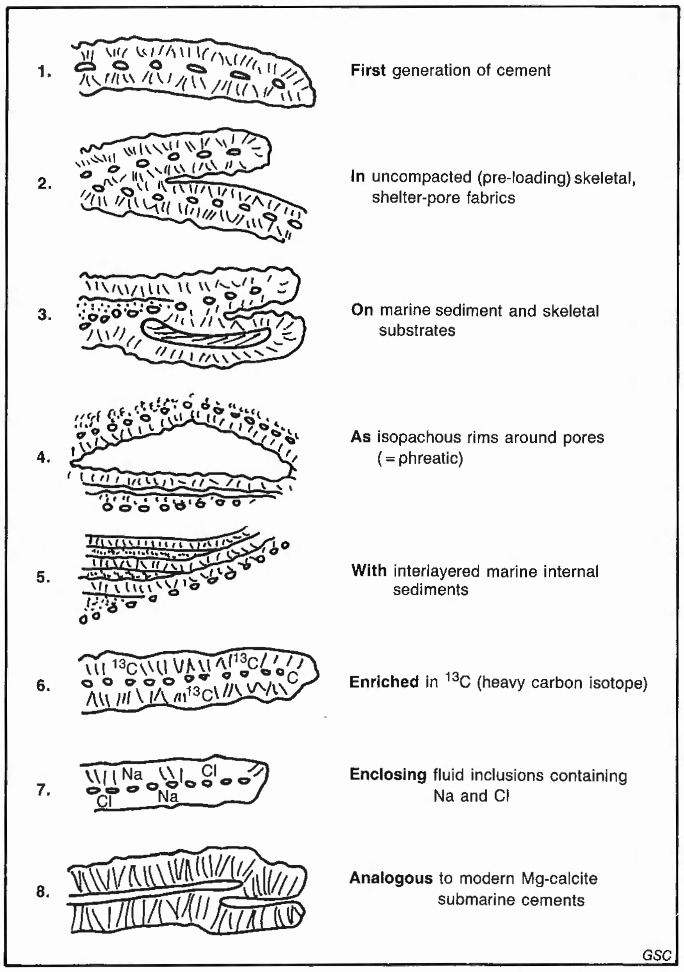


Figure 47. *Summary of principal lines of evidence for marine phreatic (submarine) precipitational origin of radial-fibrous calcite (RFC).*

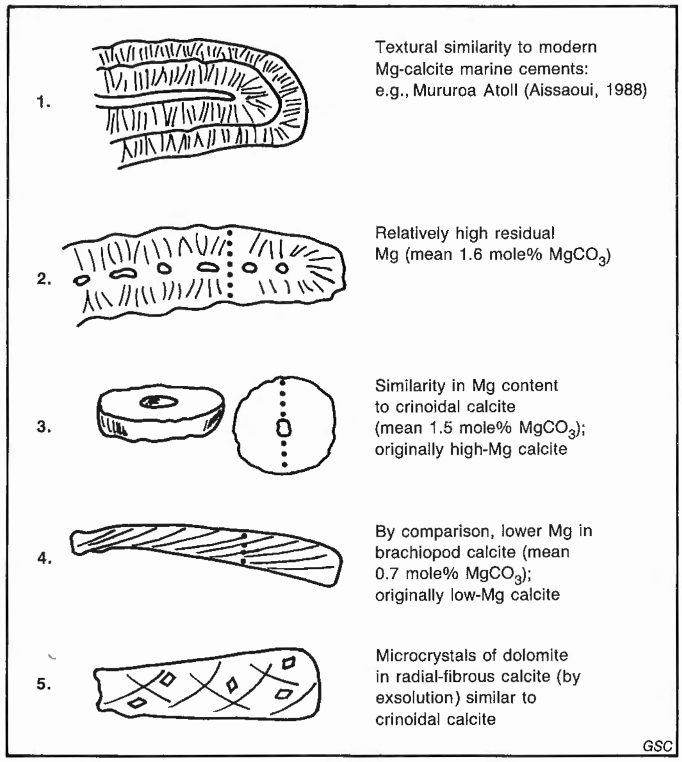


Figure 48. *Schematic summary of evidence that high-magnesium calcite was the precursor to radial-fibrous calcite (RFC) as a submarine cement.*

sediment fill, and may not have been connected through to the surface of the cemented mound mass. Fractures of this type may have been subject to the preferential development of BAC within the former fracture cavity, simply because of the preserved open space.

Fractures also contain internal sediments other than the more obvious dolomitized crinoidal sediment. Syn-cementation internal sediments, characterized by peloids and abundant ostracodes (thus identical to the internal sediments interlayered with RFC cements within the internal cavity system of the reefs), but also containing fragments of fracture-lining cement and crinoid ossicles, are found within some fractures; these *undolomitized* internal sediments alternate with layers of fracture-lining cement (Fig. 24B) and also were of marine origin.

The cement couplets characteristic of many fracture-lining cements, grading from a darker coloured, micritic, microcolumnar layer into a RFC layer, probably represent a response to periodic input of contemporaneous internal sediment (pre-burial) into the fracture system. As for internal cavities, input of muddy water and sediment temporarily "poisoned" growth of the primary acicular cement crystals; such a pulse of internal sedimentation may have been a response to an abnormal (storm) event. Renewed precipitation incorporated lime mud and scattered calcispheres and other micro-debris into the basal layers of the new cement generation. Whether direct organic control (cyanobacterial?) was responsible for the "microcolumnar" fabric cannot be determined, but is suspected.

In elemental and isotopic composition, fracture-lining cements essentially are identical with reef-cavity RFC cements; if it is accepted that the latter are of marine origin, so too are the fracture cements (and the fractures). Another similarity is the increase in Mg within each increment of cement. Again, this suggests a progressive increase in the Mg:Ca ratio of the precipitating solution as $CaCO_3$ precipitated out as cement, with a concomitant increasing uptake of Mg by partition into the cement crystal lattice, and/or changes in the rate of crystal growth. The slight increase in ^{13}C and ^{18}O in fracture-lining RFC relative to reef-cavity RFC calcite also may be significant, yet slightly less so than the enrichment in both heavy isotopes shown by cavity-filling BAC/RAC fabrics after aragonite.

Origin and timing of radial-array and botryoidal-array calcite fabrics

Replacive and cavity-filling BAC/RAC fabrics are considered to be neomorphic after radiating, point-source cones, hemispheres and botryoids of submarine aragonite, for the following reasons:

1. The extreme acicular crystal form, feather-like arrays, and blunt pinacoidal crystal terminations are most characteristic of aragonite (Folk and Assereto, 1974; Folk, 1974)

2. The high Sr content (mean 8000 ppm, spot values to 10 000 ppm), preserved within the center of massive BAC, is of the same magnitude as Sr in modern marine aragonite precipitates; its preservation reflects microscale, "closed-system" diagenesis (Kinsman, 1969)

3. There are modern marine analogues of replacive and botryoidal aragonite fabrics.

In isotopic composition, both BAC and RAC are similar to reef-cavity and fracture-lining RFC cements. Once again, the enrichment in ^{13}C and slight depletion in ^{18}O suggest precipitation or crystal growth in a water system of marine source, with no significant isotopic exchange with isotopically "light" water during later diagenesis.

The replacive fabrics of RAC both predate and postdate generations of reef-cavity isopachous RFC calcite (Figs. 37-40), but always predate later ferroan sparry calcites, dolomite, and other sparry calcite phases. The largest botryoidal masses of aragonite originally formed within the former cavity systems of cement-lined fractures, large cement-lined primary cavities, and in cement-lined interclast cavities in shelf foreslope breccias. Between these two extremes (obvious replacement *versus* free-space growth), there is a spectrum of radiating acicular fabrics of RAC.

The occurrence of RAC and BAC between layers of RFC in fracture-lining cements suggests contemporaneity of the two types of precipitate (Fig. 34A). In a few examples, the interrelationship between hemispherical masses of RAC/BAC calcite with overlying layers of internal sediment, within a thick unit of fracture-lining cement, shows that the original aragonite either displaced a soft marine sediment layer or formed prior to deposition of the sediment layer (Figs. 29C, 35). In either interpretation, aragonite emplacement was penecontemporaneous with internal sedimentation, and thus with RFC cement of the fracture lining. As the fracture-lining cement apparently formed while the reef remained in the marine environment, and as there is no other evidence of emergence, the replacive and cavity-filling BAC/RAC fabrics are added to the range of phenomena occurring within the submarine environment.

BAC and RAC fabrics of the types described for the Arctic Waulsortian reef and the Nansen Formation shelf-edge and foreslope carbonates have also been found, in the same area, in the algal buildups and interbeds within the anhydrite-dominant Otto Fiord Formation (Fig. 4).

Of additional significance are the occurrences of apparently identical RAC/BAC fabrics in fractures, tepees, and other cavity systems, in the shelf-edge facies of the Capitan reef complex in the Permian of New Mexico and west Texas (Dunham, 1972, Figs. II-11 to 22, 42, 67, 68; Mazzullo, 1980), in Permian algal mounds in New Mexico (Mazzullo and Cys, 1979), and in latest Permian reefs of China (Fan, pers. comm., 1988). In these rocks, radiating fans of calcite crystals (druse fans of Dunham) form dark coloured roof and floor deposits in fractures and other cavities, and may be enclosed by (internal) sediments containing ostracodes, encrusting foraminiferids, and the enigmatic organism *Tubiphytes*. Dunham (*ibid.*) notes that the druse fans and sediments appear to have been penecontemporaneous in deposition or growth, and that *Tubiphytes* (a marine organism) encrusts the sediments and druse fans. Significantly, these spherulitic-fabric relationships are apparently identical to those in the Arctic rocks and thus support the interpretation of a marine diagenetic origin for the latter, yet, conversely, strengthen the argument against the general inference by Dunham that the druse fans and associated fabrics in the Capitan reef are of subaerial meteoric origin (Dunham, 1972, section II).

Radiating fans of calcite crystals replacing aragonite apparently are common in tepee structures other than in the Capitan reef area; Burri et al. (1973, Fig. 4) found similar fabrics in tepee structures of Lower Jurassic age in Morocco, while Folk and Assereto (1974) described crusts, hemispheres and large rays of calcite after aragonite (up to 20 cm long) in Triassic tepee structures in Italy. The aragonite crystals in the Italian tepee fabrics have inverted to a mosaic of equant sparry calcite, and are associated closely with curved-lattice "baroque" dolomite; the same neomorphic fabric and associated dolomites characterize the acicular fabrics in the Arctic rocks.

Folk and Assereto (1974, p. 34, 35) attributed precipitation of these fabrics to a marine-vadose environment within sediments subjected to periodic storm flooding. Aragonite rays formed apparently in a magnesium-rich environment, and the dolomite in a mixed meteoric-marine hypersaline environment.

Before considering the possible geochemical controls for submarine aragonite growth, some additional clues provided by modern carbonate studies are worth considering. In submarine-cemented rock layers below hypersaline lagoons of the Persian Gulf, radiating acicular "fan druses" of aragonite, some at least 7 mm in radius, replace skeletal particles (Shinn, 1969, Fig. 20); this fabric relationship essentially is identical to that inferred for the predecessor of RAC fabrics in the Arctic rocks. De Groot (1969) found that precipitation of aragonite in the Persian Gulf lagoonal rocks is promoted by the stability of the substrate and by high supersaturation for aragonite in the cementing sediment layers (compared with a lower level of supersaturation in surface lagoon waters). Significantly, the Mg:Ca ratio for all water samples from below the sediment/water interface in the lagoon was higher than that for lagoon water (approximately one third more Mg^{2+} in solution than in lagoon water), and H_2S was present in most samples. Folk (1973) and Folk and Land (1975) have stressed the relationship between salinity and magnesium in controlling the type of carbonate polymorph to be precipitated in various primary and diagenetic environments. Aragonite precipitation, and perhaps early replacive diagenesis by aragonite, may be favoured by higher ionic concentrations of Mg^{2+}, and possibly also of $SO_4{}^{2-}$ in solution (Railsback and Anderson, 1987).

Schroeder (1972, Figs. 2, 3) found radiating acicular fans or cones of aragonite as part of a spectrum of submarine cements in Quaternary reefs in Bermuda. Schroeder's "aragonite spherulitic cement", possibly an analogue for smaller varieties of the Arctic, cavity-filling, spherulitic, calcite cement, forms radiating fans up to 400 μm in radius, in cavities between layers of red algae, in intraskeletal pores, and in pelecypod boreholes; the fans or cones of aragonite grow from both roof and floor of individual cavities. Closely spaced concentric growth lines are apparent in some spherulitic cements; similar growth increments are found in the Arctic botryoidal acicular cements. Significantly, the modern aragonite spherulitic cements appear to be confined to partly or totally restricted pore systems; such pores may have higher levels of carbonate supersaturation, and higher Mg:Ca ratios.

Undoubtedly, the most spectacular examples of spherulitic acicular aragonite in modern sediments are those found by Ginsburg and James (1973a, b) in the reef wall of the British Honduras barrier reef and atolls (Fig. 49). Botryoidal aragonite, up to 3 cm in radius, grows most commonly downward from the roof of primary cavities in the Honduras reefs, but also from the floor and sides — where they may overlie or be interlayered with marine internal sediments (Fig. 49B). Ginsburg and James (1973b) noted the similarity between sediment-floored cavities filled with botryoidal aragonite and "*stromatactis*" fabrics of Paleozoic reef limestones. Sediment- and cement-filled structures in the Arctic Paleozoic rocks, identical to classic "*stromatactis*" fabrics, also are interpreted as being of submarine origin. The botryoidal aragonite in the Honduras reef has a $\delta^{18}O$ value of +4.6‰, a $\delta^{13}C$ value of +3.2‰, and an average Sr content of 9000 ppm, all characteristic of marine precipitation (although with some fractionation favouring the heavy isotopes). Benthonic foraminiferids also occur within some aragonite growths. Other spectacular forms of botryoidal aragonite from reefal settings, but of Pleistocene age, have been described and illustrated by Aissaoui (1985).

More recently, James et al. (1988) described the calcification of platy, encrusting, aragonitic algae (Peyssonneliaceae) from modern marine environments, and suggested that the late Paleozoic phylloid algae may have been closely related to these modern aragonitic forms. Of particular significance to submarine-cement processes, the authors noted that small aragonite botryoids, which form an extracellular hypobasal layer beneath the cellular thallus, may have acted as nuclei for botryoidal aragonite submarine cements that characterize a number of Carboniferous and Permian reefal facies (Arctic, Permian reef complex of east Texas, and New Mexico). In the upper Paleozoic reefs on Ellesmere Island, the pervasive development of botryoidal aragonite cements (BAC, RAC), on a wide variety of biotic substrates (bryozoans, phylloid algae, palaeoaplysinids) and in a variety of settings (primary reef cavities, submarine fracture cavities), argues against a significant control by a precursor, algal-hosted, aragonite nucleus.

The preceding discussion confirms that:

a. BAC and RAC fabrics replacing acicular aragonite are found in carbonate rocks of various ages, in primary or early-formed cavities and fractures

b. Similar aragonite fabrics are found as submarine precipitates and as replacive fabrics in modern reefs or cemented carbonate sediments

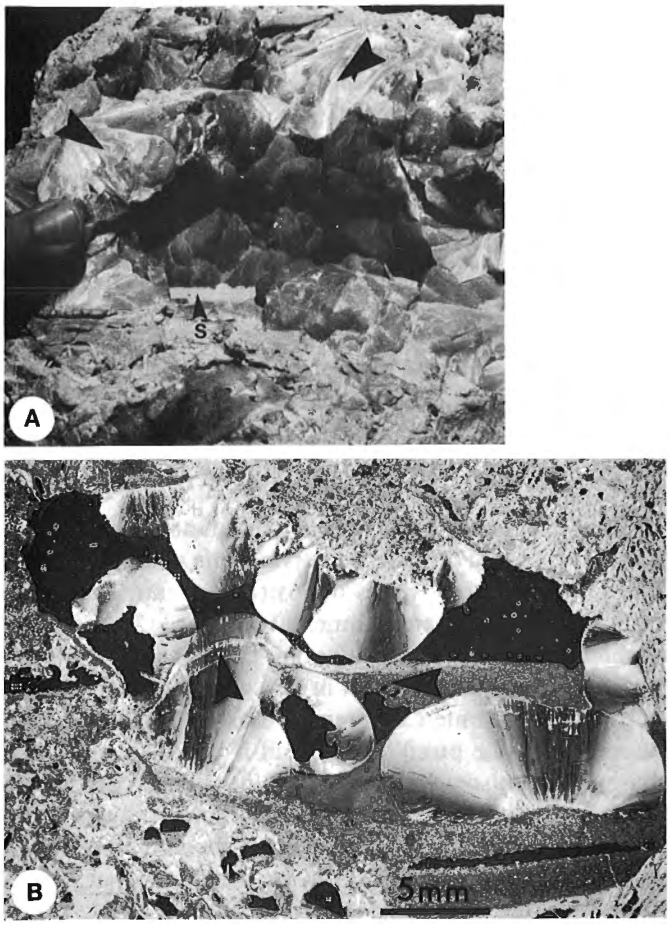


Figure 49. Modern (Holocene) submarine botryoidal aragonite from internal cavities in the foreslope of the British Honduras Barrier Reef (James and Ginsburg, 1979). (Photos supplied by N. James.)

A. Aragonite botryoids (arrows) protruding from floor and roof of a reef cavity. Botryoids at the base are partly covered by internal sediment (S).

B. Thin section photomicrograph of aragonite botryoids growing from the floor and roof of a cavity, and partly covered by, and enclosing (arrow), marine internal sediment (cf. Figure 29C, this report).

c. Most if not all of the acicular aragonite growths are in part contemporaneous with deposition of marine internal sediments and encrustation by, or deposition of, marine organisms.

We conclude that the cavity-filling and replacive RAC/BAC fabrics in the Arctic upper Paleozoic reefs and shelf-edge rocks are a product of internal submarine diagenesis in rocks that remained submerged within the marine environment. As growth of large arrays of aragonite probably occurred under a particular set of geochemical conditions, growth by replacement and by precipitation in water-filled cavities probably was contemporaneous. Further, as small aragonite fans in fracture-lining cements first occur only in the middle and outer generations of cement, and as they tend to increase in size outward, with the largest botryoidal masses occurring in the former fracture-cavity, conditions favourable for growth of these types of hemispherical aragonite masses may have reached a critical stage after the formation of fractures and during and after fracture-wall cementation. What were the geochemical and hydrodynamic conditions favourable to early diagenetic nucleation and growth of botryoidal masses of aragonite?

Although we have physical descriptions of radiating arrays of aragonite, or their replacive BAC/RAC fabrics, in both recent and ancient rocks, we have very little geochemical data to support a precipitation model. Magnesium, sulphate, and possibly other ions in solution, promote the crystallization of aragonite at the expense of calcite (Folk, 1974; and others). Further, the ionic concentration of magnesium and other elements in solution may control the crystal morphology of aragonite. Within some unknown constraints, an increased ratio of Mg:Ca in solution may promote the growth of longer acicular crystals of aragonite (Folk, 1973; Given and Wilkinson, 1985).

Folk (1973) also suggested that, if nucleation and crystallization rates are slow, the tendency toward longer acicular crystals may be enchanced. Slow crystallization may also favour the growth of radiating masses of acicular crystals from a few nucleation sites (characteristic of the point-source growth habit of radiating arrays of aragonite), rather than the many closely spaced nucleation sites and highly competitive crystal growth habit of early marine HMC cements. A general paucity of aragonite nuclei on the substrate also may be a factor.

In contrast to the suggestion by Folk (1973) that slow rates of crystallization may favour more elongate circular crystals, thus, by inference, aragonite over magnesium calcite, Given and Wilkinson (1985) indicated that a high rate of crystal growth, controlled by high carbonate ion concentrations and with high fluid shear, favours aragonite over magnesium calcite.

In the massive reef facies of the Capitan Formation of the Permian Reef Complex in west Texas (Mazzullo, 1980; Given and Wilkinson, 1985), former aragonite botryoids apparently always predate magnesium calcite cements. The aragonite was precipitated in reef cavities that were still mainly open and interconnected, and magnesium calcite was precipitated in partly filled cavities, with progressive construction of pore throats. This succession is explained as the product of declining fluid shear and declining rate of crystal growth.

In the Arctic reefal, shelf-edge, and slope carbonates, there are three major exceptions to the temporal relationships found in the Permian Reef Complex. Aragonite botryoids and arrays postdate magnesium calcite cements in:

a. Large submarine fracture cavities, where botryoids show a progressive increase in size toward the centre of the cavity

b. Toe-of-slope debris flow units, where aragonite botryoids postdate magnesium calcite, rim cements

c. Replacive, radial-array, aragonite (RAC) fabrics, where aragonite replaces host sediment previously cemented by subpeloidal magnesium calcite cement, and also replaces rims of fibrous magnesium calcite cement (RFC).

In the fracture settings, the succession of aragonite after magnesium calcite may be explained in terms of increased fluid shear, if the fracture was opening progressively under continued stress and displacement, so that fluid flow in the older, late-stage fracture was higher than in the incipient stage. A fluid shear mechanism, however, does not appear relevant to the replacement mode of aragonite growth (RAC) fabric. An alternative mechanism involving changes in micropore fluid composition by bacterial(?) or other microbiological processes, resulting in high carbonate ion saturations (which also favour aragonite over magnesium calcite; Given and Wilkinson, 1985), is suggested but unsupported by any data.

In a pore-water system with reduced permeability — a condition that must have existed within the main mass of the Arctic Waulsortian reefs, mounds, and shelf-edge rocks after extensive HMC submarine cementation — the Mg:Ca ratio in pore waters may have been higher than that of marine source water or pore water close to the sediment/water interface. De Groot (1969) found increased Mg:Ca ratios in submarine aragonite-cemented rock layers below Persian Gulf lagoons. With continuing precipitation of large volumes of either HMC or aragonite cement in pore systems and on fracture walls within the interior of the Arctic reefs, an increase in the Mg:Ca ratio in residual pore water in the more restricted parts of the pore system is predictable (assuming flushing by seawater was not totally efficient). Further, the rate of fluid movement through the partly occluded, deeper, internal pore system of the mound would be less than the rate in more porous and permeable, cemented sediments near the sediment/water interface.

This interpretation is supported to a degree by the apparent progressive enrichment in Mg during precipitation of RFC cement within internal cavities and in fracture-lining cements, as suggested by microprobe data on residual Mg distribution (Figs. 20, 28). Further, it is common to find that, for thick aggregates of RFC cements in primary cavity systems, the outermost generation commonly is the thickest (longest primary crystals), is composed of normal fibrous rather than radiaxial fibrous calcite, and generally contains fewer inclusions. These characteristics may correlate with higher Mg in the precipitating solution (hence longer acicular crystals) and a slower rate of crystallization (thus less competitive, more parallel growth, less inclusions). As we have demonstrated earlier in this paper, some, if not all, fracturing occurred after precipitation of the first generation of RFC cement, but before later generations of RFC cement. Thus, the thicker, less inclusion-rich generations of cements found in some primary cavity systems probably postdate fracturing, and may be synchronous with precipitation of fracture-lining cement; and thus also may be synchronous with at least the first aragonite arrays.

The abundance of RAC in algal mounds and bedded units in the Otto Fiord Formation deserves some attention, as the Otto Fiord strata were deposited in an evaporite ($CaSO_4$-dominant) environmental setting. As calcium sulphate is removed by precipitation from normal seawater, there is an overall enrichment in SO_4 and Mg relative to Ca (particularly if some Ca is removed as $CaCO_3$ before the onset of sulphate precipitation, and if other SO_4 and Mg phases do not also precipitate out). Under these conditions, porous carbonates in the contemporaneous hypersaline environment might be invaded by solutions with high Mg:Ca and SO_4:Ca ratios; both of which are conditions that should favour the precipitation and growth of aragonite (Folk, 1974).

We noted earlier that RAC and, to a lesser extent, cavity-filling BAC fabrics, are developed preferentially in the lower 100 m or so of the Waulsortian reefs. The possibility that this distribution is controlled in part by upward fluid migration of solutions enriched (relatively) in Mg and SO_4, from the immediately underlying sulphate evaporites of the Otto Fiord Formation, cannot be discounted. Water expressed from the sulphate units during conversion (dehydration) of gypsum to anhydrite may have played some role in such a process, but this process is unlikely to have occurred within the time-frame deduced for acicular aragonite formation. Further, a sulphate evaporite source for SO_4-rich connate water is not readily identified for RAC/BAC fabrics in Nansen Formation shelf-edge rocks along the northwestern margin of the Sverdrup Basin.

Emplacement of fracture-fill crinoidal sediments

Up to the fracture-fill stage in the sedimentary and diagenetic evolution of the Paleozoic carbonates, the various processes and products have been attributed to formation, precipitation, or replacement in normal or slightly modified (Mg-enriched) seawater. The next event records a change in depositional and environmental conditions for the Waulsortian reefs (less clearly defined for shelf-edge rocks), and marks the onset of burial processes. This event is the emplacement of crinoidal sediments within the cement-lined fracture system and associated conduits in the cemented carbonates.

The source of these crinoid-rich sedments, with admixed quartz silt and bioclasts, is the basal sediment of the Hare Fiord Formation. The Hare Fiord deposits flank and overlie the Waulsortian reefs, infiltrating the fractures where they remained open to the surface. Filling of lateral conduits was controlled by the size and geometry of apertures, so that only finer, "filtered" sediment penetrated into smaller cavity systems. Ripple laminae and other sedimentary structures provide proof of active mechanical emplacement by flowing water. All other diagenetic processes and products postdating crinoidal sediment infill of fractures have been attributed to burial diagenesis (Davies, 1976).

"Aragonite seas": temporal relationship between megatectonics, seawater chemistry, and marine cements

From a global perspective, the Carboniferous and Permian periods were a time of continental collision and accretion that led to the construction of the supercontinent Pangea during the Permian and Triassic (Worsley et al., 1984). This process of continental accretion is part of a predictable pattern of supercontinent fragmentation, dispersal, and assembly that is directly correlative with global sea level variance (Fig. 50), and is a major controlling factor in determining paleoclimate and the chemistry of the atmosphere and hydrosphere (Worsley et al., 1986; Wilkinson and Given, 1986).

Paleolatitudinal reconstructions by Keppie (1977) place Canada between latitudes 20°S and 20°N in the Early Carboniferous (see Davies, Richards, et al., 1988, Fig. 3), and between 0°N and 40°N in the Late Permian (op. cit., Fig. 4). The Sverdrup Basin of the Arctic Archipelago was within 10° of the equator during Early Carboniferous time and at about 30°N during Early Permian time.

Northern Hemisphere, Early Carboniferous paleoclimates were characterized by high humidity (Frakes, 1979), and probably relatively high (seasonal) temperatures. Extensive coal deposits in central to eastern North America and in Europe attest to this climatic regime, and to the proliferation of land plants. In contrast, the Permian, and particularly the Late Permian, was a time of increasing global aridity (Frakes, 1979), which extended into and culminated in the Triassic. Global continental and seawater temperatures also appear to have decreased from Carboniferous through Permian time.

Global sea-level reconstructions, based on coastal onlap (Hallam, 1984) and on seismic stratigraphy (Vail et al., 1977; Summerhayes, 1986), demonstrate a similar but not identical pattern of declining sea level from Early or mid-Carboniferous to Late Permian time (Fig. 50). During Early Carboniferous time, global sea level rose until approximately the late early Viséan, at which time, estimates by Hallam (1984) place it at about 350 m above present day sea level. It fell to below present levels during latest Permian to earliest Triassic time (Hallam, 1984) or slightly later (Vail et al., 1977). The sea-level curve of Vail et al. (op. cit.) differs significantly from that of Hallam (1984) by showing a major eustatic drop at the end of Early Carboniferous time (about 325 Ma), and during late Early Permian time (around 260 Ma). The major eustatic events and numerous subordinate oscillations (Ross and Ross, 1985) greatly influenced Carboniferous and Permian sedimentation in the Western Canada and Sverdrup basins (Beauchamp et al., 1989a b; Henderson et al., in press; Richards et al., in press).

The overall decline in sea level from the early Viséan to the Permian, in combination with the influences of other environment parameters, exerted a strong influence on the endemism of upper Paleozoic biota, areal distribution and thickness of marine sediments, fluvial processes, and configuration of epicontinental seas. The dominant control on upper Paleozoic sea-level change was tectonic, although glaciation in the Southern Hemisphere (Caputo and Crowell, 1985) caused significant oscillations. The principal tectonic mechanism causing the overall decline in sea level from Carboniferous to Permian time was the progressive accretion of continental plates in late Paleozoic time, culminating in creation of the Pangea supercontinent (Fig. 55).

The composition of the hydrosphere in Carboniferous and Permian time also underwent a series of subtle chemical changes, paralleling global changes in climate and sea level. Many of these changes, specifically trends in strontium, carbon, oxygen, and sulphur isotope composition, demonstrate a close parallelism to global sea-level change and to the supercontinent assembly/fragmentation cycle (Fig. 50). Although not yet fully understood, changes in seawater chemistry in late Paleozoic time may have influenced the mineralogy and precipitation of submarine cements, and the type and degree of mineralization of phylloid algae, palaeoaplysinids, and other reef-building organisms.

Wilkinson and Given (1986) suggested that carbonate cements in shallow marine carbonate sequences show a secular change in mineralogy that correlates closely with global eustacy and the Wilson cycle (Fig. 50). Rising sea level and high atmospheric pCO_2 (from increased volcanism) during periods of fragmentation and dispersal of supercontinents favoured precipitation of equant calcite ("greenhouse" mode of Fischer, 1981, and "calcite seas" setting), whereas falling sea level during supercontinent assembly and stasis (specifically, Late Carboniferous and

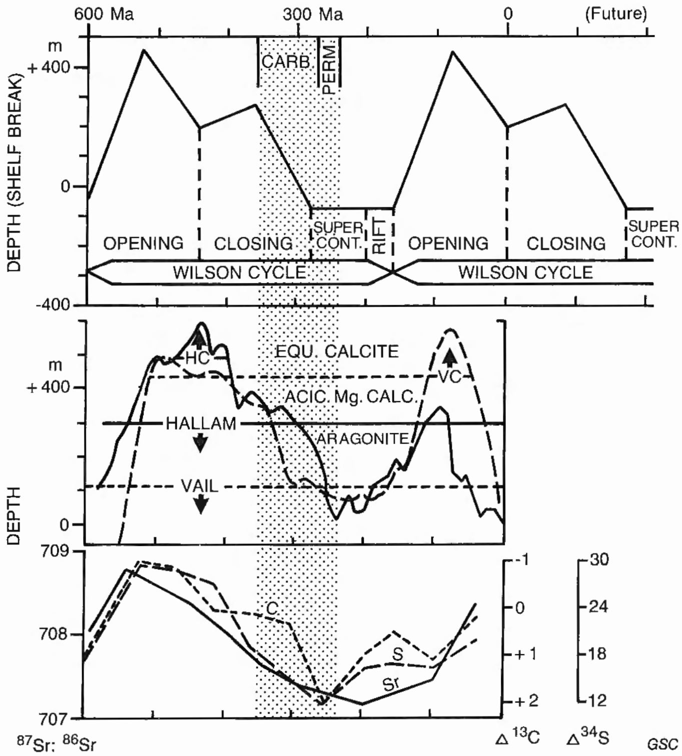


Figure 50. *Correlation of tectonic cycles, sea level curves, and secular changes in seawater chemistry and stable isotopes. (Modifed from Wilkinson and Given, 1986; Worsley et al., 1986.)*

The Carboniferous-Permian time zone is shaded. The "Wilson" cycle in the upper plot reflects a major plate-tectonic periodicity of about 500 million years, and is projected into the future (at right). The datum for sea level is the present shelf-slope break. The middle plot compares simplified sea level curves of Hallam (1984) and Vail et al. (1977), and the stability fields of equant calcite, acicular magnesium calcite, and aragonite as marine precipitates (VC = Vail calcite limit, HA = Hallam aragonite limit, etc.). The lower plot demonstrates secular changes in stable isotopes of carbon, sulphur and strontium. Overall, the plots demonstrate the close parallelism between tectonic events, sea level, and seawater chemistry, and the greater stability of magnesium calcite and aragonite submarine cements in the Upper Carboniferous and Permian.

Permian time) favoured precipitation of aragonite and magnesium calcite due to lower atmospheric pCO_2 ("icehouse" mode of Fischer, 1981, and "aragonite seas" setting).

CONCLUSIONS

Although most of the data, illustrations and interpretations presented in this paper were based on fieldwork and laboratory analysis in the early to mid 1970s, the spectacular nature of the exposures of upper Paleozoic rocks on northwestern Ellesmere Island, and the state of preservation of the rock fabrics, renders them still of great scientific interest and validity for comparative applications. This span of time also coincides with the transition from a growing, but still tentative, recognition of the pervasive occurrence of submarine cements in both modern and ancient reefal carbonates, to the general acceptance today of submarine cementation as a normal, common and often critical stage in the development of many reefal and shelf-margin to slope carbonates.

Although pore-filling macrofabrics such as isopachous magnesium calcite and botryoidal aragonite, or their calcitic replacements, are the most obvious and commonly spectacular submarine diagenetic fabrics, the pervasive cementation of the primary marine sediment, by finer micritic to subpeloidal cements, must not be overlooked or discounted. Induration of the matrix sediment plays a key role in overall reef stability, aggradation, and rigidity, with the last factor contributing to fracturing within the submarine setting, as a response to substrate loading, differential compaction, and stress.

With the acceptance of submarine cementation as a common and often pervasive process in reefal rocks in the geological record, and the growing volume of descriptive and compositional data on submarine cements, greater attention must be focused on physical, chemical and microbiochemical processes operating within the reef cavity system. Obviously, most of the advances must come from studies of modern reefs, but the geological record can also provide clues to processes and leads to specific questions that should be investigated in modern reefs. For example, the step-like zonation of Mg in each growth increment of radial-fibrous calcite in the Arctic submarine-cemented rocks suggests that the precursor magnesium calcite cements may have shown a similar compositional trend (but at higher concentrations); is this controlled by growth rate, flow rate, carbonate ion concentration, or other factors or combination of factors? What are the thermodynamic, microchemical and other factors that control replacement of carbonate sediment and magnesium calcite cement by arrays of acicular aragonite? What mechanism apparently allows retention of 8000 ppm strontium in calcite neomorphic after aragonite? What are the controls on fluid flow through the reef pore system that allow almost total occlusion of pore space (and particularly of permeability), which may have formed up to 80 per cent of the original rock mass? This last process has a direct bearing on the understanding and prediction of porosity loss by this type of cementation in subsurface reefal reservoirs. Other similar questions that may guide research in modern reef systems may be derived from our description of the Arctic Paleozoic submarine cements.

The pervasive character of submarine cements and the consequent loss of primary porosity, in the Carboniferous and Lower Permian reefs and shelf-margin carbonates exposed on northwestern Ellesmere Island, clearly downgrades the reservoir potential of their equivalents in the subsurface. However, different tectonic and environmental settings at the shelf margins in other sectors of Sverdrup Basin may reduce the potential for pervasive cementation by submarine cement (for example, if bathymetric relief on the seaward margin was lower than suggested by the northwestern Ellesmere shelf margin and reefs). Development of subaerial unconformities with consequent meteoric diagenesis and/or dolomitization may enhance porosity in different tectonic settings.

On a global scale, many other Carboniferous and Lower Permian shelf margins and reefs show pervasive submarine cementation similar to that of the Arctic carbonates. It is significant to note the discovery and development of the supergiant Tengiz oilfield (Shebaldin et al., 1988) in the North Caspian Basin of the USSR. This field produces from Carboniferous and possibly Lower Permian reefal carbonates (capped by Permian salt). Well documented similarities between Carboniferous and Permian carbonate rocks in the USSR and Sverdrup Basin suggest possible compositional comparisons, if not tectono-sedimentary (basin type) similarities.

Ongoing research on the upper Paleozoic carbonates of Sverdrup Basin will undoubtedly contribute to new insights into, and clarification of, both submarine and burial diagenetic processes and products. Comparison with new data coming from analysis of modern reef systems will assist in these advances. This bulletin may help to stimulate the process.

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APPENDIX

ANALYTICAL PROCEDURES

Analytical procedures used to examine and analyse the upper Paleozoic carbonates included standard thin section petrographic techniques, stained acetate peels, scanning electron microscopy, electron microprobe analyses, wet-chemical and atomic absorption spectrometry for Sr, X-diffraction, and isotope geochemistry. Two of these analytical procedures are discussed in more detail in the following sections.

ELECTRON MICROPROBE ANALYSIS

The electron microprobe used for this study was an Applied Research Laboratories EMX-SM model, housed in the Department of Geology and Geophysics at the University of Calgary. Principal elements analysed were Ca, Mg, Fe, and Sr, with a few analyses for Mn, Na, K, and Cl. For the major elements, standards used were Macrae calcite, Oberdorf dolomite, Ivigtut siderite, and strontianite EPS94. After subtraction of background values, amounts of CaO, MgO, FeO and SrO were determined using direct ratios, and the empirical correlation factors of Bence and Albee (1968); results from the latter are used in this paper. Because CO_2 content was not analysed, the oxide values were corrected to carbonate, and summed; if the total obtained fell outside the range of 98 to 102 per cent, the analysis (spot) was rejected. About 550 multielement spot analyses, in traverses or groups, were used in this study. About 30 beam-scanning photographs were made at various scanning rates to illustrate the distribution of Mg, Fe, and Sr in various calcite and dolomite fabrics.

Means and standard deviations (at 99% confidence level) for microprobe data, grouped by fabric type, are presented in Table 1. Selected traverses for Mg and Fe, and selected beam-scanning photographs, are illustrated by figures in the text.

ISOTOPE ANALYSIS

Carbon and oxygen isotope ratios for an initial batch of 6 samples were determined by mass spectrometer at the Denver Research Centre of the Marathon Oil Company, Colorado, through arrangements made by P.W. Choquette. About 50 additional samples have been analysed subsequently using the mass spectrometer in the Stable Isotope Laboratory of the Department of Physics at the University of Calgary, under the supervision of H.R. Krouse. This instrument has a 12-inch radius, 90° magnetic analyser with triple collection of masses 44, 45 and 46. Ratios of ion currents were displayed digitally, and were corrected by the method of Craig (1957). Standards used include Solonhofen, Friedman's T.S. standard, Akiyoshi's standard, and CK13 aragonite; different published values for these standards by various authors required some data manipulation. Fair reproducibility of results was found for data for the same samples run by Marathon and by the Stable Isotope Laboratory.

The $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios in this paper are expressed as per mil deviation from the ratio in the PDB standard as:

$$\delta^{13}C \text{ or } \delta^{18}O‰ = \frac{R(\text{Sample}) - R(\text{Standard})}{R(\text{standard})} \times 10^3$$

where R is the isotope ratio for either element

General summaries of isotopic composition and controls in carbonates, with references to earlier work, are provided by Bathurst (1971), Hoefs (1973), and Milliman (1974). A summary of the isotopic data for the Arctic Paleozoic rocks has been published earlier (Davies and Krouse, 1975; Davies, 1977a).